IEA Heat Pump Programme

Annex 35

Application of Industrial Heat Pumps

Final Report

Part 1

Operating Agent: Germany

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Preface
This project was carried out within the Heat Pump Programme, HPP which is an Implementing agreement within the International Energy Agency, IEA.

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of over 40 Implementing Agreements.

The IEA Heat Pump Programme
The Implementing Agreement for a Programme of Research, Development, Demonstration and Promotion of Heat Pumping Technologies (IA) forms the legal basis for the IEA Heat Pump Programme. Signatories of the IA are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the IA collaborative tasks or “Annexes” in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex. The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

The IEA Heat Pump Centre
A central role within the IEA Heat Pump Programme is played by the IEA Heat Pump Centre (HPC). Consistent with the overall objective of the IA the HPC seeks to advance and disseminate knowledge about heat pumps, and promote their use wherever appropriate. Activities of the HPC include the production of a quarterly newsletter and the webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the IEA Heat Pump Programme and for inquiries on heat pump issues in general contact the IEA Heat Pump Centre at the following address:

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Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Final Report

Part 1

Prepared by
Members of Annex 35/13

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Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
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Executive Summary

Prepared by
Members of Annex 35/13

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1 Introduction

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important global challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. In particular industrial heat pumps (IHPs) offer various opportunities to all types of manufacturing processes and operations. IHPs are using waste process heat as the heat source, deliver heat at higher temperature for use in industrial processes, heating or preheating, or for space heating and cooling in industry. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications. Industries that can benefit from this technology include food and beverage processing, forest products, textiles, and chemicals.

The introduction of heat pumps with operating temperature below 100 °C is in many cases considered to be easy, however, higher temperature application still require additional R&D activities for the development of high temperature heat pumps, integration of heat pumps into industrial processes and development of high temperature, environmentally sound refrigerants.

In this context, the IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry

The Annex 35/13 started on 01. April 2010 and expired on 30. April 2014 with 15 participating organisations from Austria, Canada, Denmark, France, Germany (Operating Agent) Japan, The Netherlands, South Korea and Sweden.

The Annex comprised an overview in the participating countries of the industrial energy situation and use, the state of the art and R&D projects in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications and in the wider application of industrial heat pumping technologies. The annex has been subdivided in the following tasks:

- Task 1: Market overview, barriers for application
- Task 2: Modeling calculation and economic models
- Task 3: Technology
- Task 4: Application and monitoring
- Task 5: Communication.

2 Market overview, barriers for applications

The Task 1 Report summarized the present energy situation in general and the industrial energy use and related heat pump market subdivided into participating countries. Based upon these findings focus will be given to further work to meet the challenges for the wider application of industrial heat pumping technologies.
Although heat pumps for the industrial use became available on the markets in the participating countries in recent years, just very few carried out applications can be found. To distinguish the reasons for this situation, application barriers were also a part of the survey in Task 1:

- Lack of knowledge:

  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers and decision makers in the industry have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.

- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump.

- Long payback periods:

  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.

- High temperature application
  From the technical point of view one barrier can be identified regarding to the temperature limits of most commercially available heat pumping units. Many applications are limited to heat sink temperatures below 65°C the theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps including refrigerants for heat sink temperatures up to and higher than 100°C.

  The barriers can be solved, as shown in the results of the Annex: short payback periods are possible (less than 2 years), high reduction of CO_2-emissionen (in some cases more than 50 %), temperatures higher than 100°°C are possible, supply temperatures < 100 °C are standard.

3 Modelling calculations and economic models

The Task 2 Report intended to outline how the integration of IHP in processes is supported by computer software, i.e. by modeling.

In order to 'update' the Annex 21 screening program in the sense of a 'modern' development taking the original goals into account a proposal has been made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base to be used within the simultaneous optimization. Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

This concept of integrating a heat pump into a process is 'below' the sophisticated methods given by H.E. Becker [Methodology and Thermo-Economic Optimization For Integration of Industrial Heat Pumps, THÈSE NO 5341 (2012), ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, Suisse, 2012]. Presently it is impossible to state whether such a development is unprecedented, relevant and needed.

The scoping analysis of existing models shows that the difference between 'pure' pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Regarding the integration of heat pumps into a process, codes like OSMOSE or CERES (amongst may be others) look promising.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

The goals of Task 2 should be carefully reconsidered if a "new Task 2" team should be constituted. The State of the Art as well as industrial needs of research organizations, large companies as well as of energy consultants should be critically reviewed. We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models. In the whole context we consider the thesis of H.C. Becker (directed by F. Maréchal) as key reference due to the systematic methodology, based on pinch analysis and process integration techniques, to integrate heat pumps into industrial processes

4 Technology

The scope of the Task 3 Report was to identify in the industrial sector appropriate heat pumps as a technology of using waste heat effectively and for meeting future industrial and environmental requirements.

Commercially available heat pumps can supply heat only up to 100 °C. As industrial waste heat, available at low-temperatures, represents about 25 % of the total energy used by the manufacturing industry, R&D work has to be focused on high-temperature heat pumps able to recover heat at relatively low temperatures, generally between 5°C and 35°C for hot water supply, hot air supply, heating of circulating hot water and steam generation at temperatures up and higher than 100 °C.

Some development of the industrial heat pump using R-134a, R-245fa, R-717, R-744, hydro carbons, etc. has been made recently. However, except for R-744 and the flammables R-717 and HCs which are natural refrigerants with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3CH2CH2CH2CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

5 Applications and monitoring

The **Task 4 Report** focused on operating experiences and energy effects of representative industrial heat pump implementations, in particular field tests and case studies.

Industrial heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Consequently, heat pumps can facilitate energy savings when conventional passive-heat recovery is not possible

The economics of an installation depends on how the heat pump is applied in the process. Identification of feasible installation alternatives for the heat pump is therefore of crucial importance. Consideration of fundamental criteria taking into account both heat pump and process characteristics, are useful. The initial procedure should identify a few possible installation alternatives, so the detailed project calculations can concentrate on a limited number of options.

The commercially available heat pump types each have different operating characteristics and different possible operating temperature ranges. These ranges overlap for some types. Thus, for a particular application, several possible heat pump types often exist. Technical, economic, ecological and practical process criteria determine the best suited type. For all types, the payback period is directly proportional to installation costs, so it is important to investigate possibilities for decreasing these costs for any heat pump installation.

The survey with a total of 150 projects and case studies has tried to present good examples of heat-pump technology and its application in industrial processes, field tests and commercial applications along with an analysis of operating data, when available, in accordance with the annex definition of industrial heat pumps, used for heating, ventilation, air-conditioning, hot water supply, heating, drying, dehumidification and other purposes.

6 Final Conclusions and future actions

The IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

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The programme and work has been mainly concentrated on the collection of statistical energy and environmental data and information related to industry as well as the present status of R&D and the application of heat pumps in industry. In total **39 R&D projects and 115 applications** of heat pumps in industry, in particular the use of waste process heat as the heat source, have been presented and analyzed by the participating countries.

It has been shown that in many companies and especially in SMEs, only very little and aggregated information on the actual thermal energy consumption is available and disaggregated data such as consumption of individual processes and subprocesses therefore has either to be estimated or determined by costly and time-consuming measurements, which often requires the integration of several processes at different temperature levels and with different operating time schedules. The exploitation of existing heat recovery potentials often requires the integration of several processes at different temperature levels and with different operating time schedules. Different technologies available for heat supply have to be combined in order to obtain optimum solutions.

Basis for the modeling calculation and economic models activities (Task 2) has been the update of the IHP screening program, to determine how industrial heat pumps could be used in different applications, developed and presented in "Annex 21 - Global Environmental Benefits of Industrial Heat Pumps (1992 -1996)".

The IHP screening program has been analyzed and converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. This new, converted version would in principle be ready for any modifications, updates of data and models as well as for extensions. However, during the execution of Task 2 it became obvious that the authors consider this approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We simply noticed that the formulation of the corresponding item in the legal text did not take this situation into account. However, parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

Although the Annex has been prolonged by one year, mainly because of missing results from Task 2, nearly none of the deliveries could be finished as foreseen, due to the fact that most participants are not concerned directly with modeling and software aspects and a large underestimation of the wide range of software tools with their very different scopes.

Taking into account the results of the annex with detailed information on statistical data, R&D results and case studies, a possible follow-up annex should be concentrated on a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept should be:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
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Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

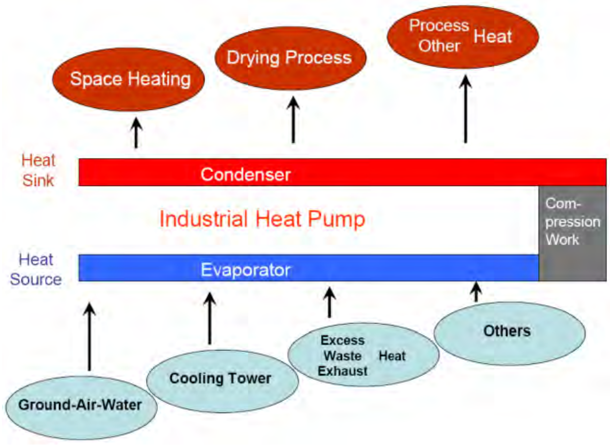
Policy Paper

Prepared by
Members of Annex 35/13

Application of Industrial Heat Pumps

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important global challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy. While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Industrial heat pumps (IHP) are active heat-recovery devices that increase the temperature of waste heat in an industrial process to a higher temperature to be used in the same process or another adjacent process or heat demand



Annex 35 / 13

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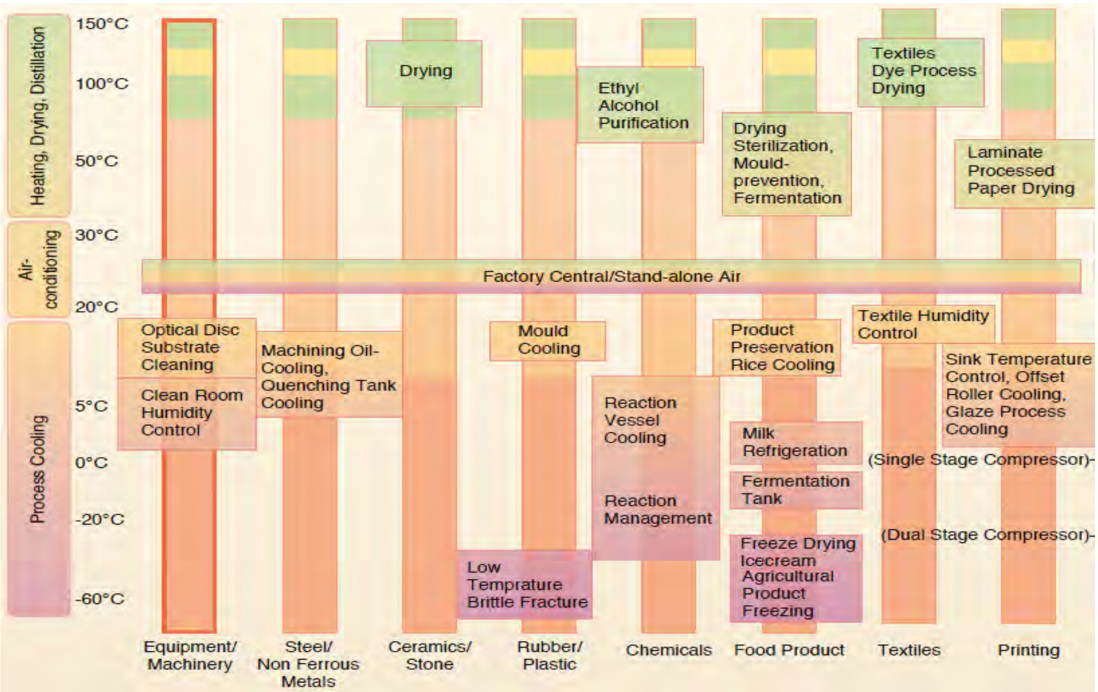
Industrial Heat Pump Applications



Barriers for application and solutions

Heat pumps for the industrial use are available on the markets in the participating countries in recent years, just very few carried out applications can be found. To distinguish the reasons were a part of the survey in the annex:

- Lack of knowledge:
  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers and decision makers in the industry have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.
- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump
- Long payback periods:
  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.
- High temperature application
  Many applications are limited to heat sink temperatures below 65°C. The theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps including refrigerants for heat sink temperatures up to and higher than 100°C.

The barriers can be solved, as shown in the results of the Annex: short payback periods are possible (less than 2 years), high reduction of CO_2-emissionen (in some cases more than 50%), temperatures higher than 100°°C are possible, supply temperatures < 100°C are standard.

The integration of industrial heat pumps into processes

The methods of integration IHPs in processes range from applying rules by hand to far advanced mathematical optimization and are discussed in the literature. The Task 2 Report outlines specifically how the integration of IHPs in processes is supported by computer software, i.e. by modeling.

In order to 'update' the Annex 21 screening program in the sense of a modern development retaining the original goals, a proposal has been made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

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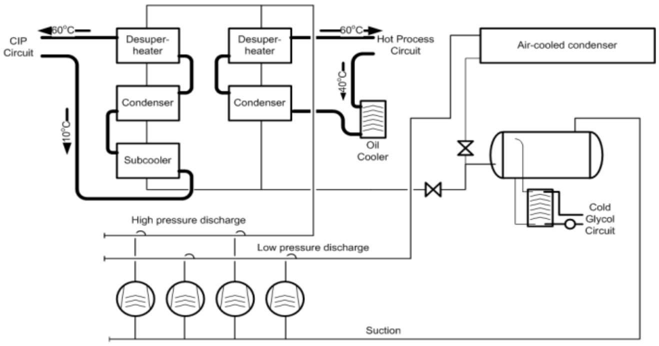
This concept of integrating a heat pump into a process is 'below' sophisticated mathematical optimization models and could therefore be considered as an **add-on** to the widely used programs based on pinch analysis enhancing their capabilities.

Examples of existing Installations

Heat pump in Food and Beverage industry - Combine heating and cooling in chocolate manufacturing (UK)

The chocolate manufacturing process also requires cooling capacity for certain steps of the process. These simultaneous demands for cooling capacity and heating capacity allowed the replacement of the heating and the cooling system by a combined cooling and heating installation. The idea was to install a Single Screw compressor Heat Pump combining Heating and cooling.

The Heat source consists in cooling process glycol from 5°C down to 0°C this evaporates Ammonia at -5°C and the heat pump lifts it to 61°C in one stage for heating. Process water is finally heated from 10°C to 60°C.



Based on the clients previously measured heating and cooling load profiles the analysis showed that to meet the projected hot water heating demands from the 'Total Loss' and Closed Loop' circuits, the selected heat pump compressors would have to produce 1.25 MW of high grade heat. To achieve this demand the equipment selected offers 914 kW of refrigeration capacity with an absorbed power rating of 346 kW. The combined heating and cooling COP, COP_{hc}, is calculated to be a modest 6.25. For an uplift of 17 K in discharge pressure the increase in absorbed power was 108 kW boosting the COP_{hi} to an impressive 11.57.

The initial thinking for the customer was to get a 90°C hot water heat pump. Indeed, some application demand required 90°C. However the total demand for this temperature level was around 10% of the whole hot water consumption. Designing a heat pump installation for such temperature would not be interesting in terms of performances and efficiencies. It was decided to install the heat pump producing 60°C hot water. When the small amount of 90°C water is required, the incremental heat is supplied now by a small gas boiler heating up the water from 60°C up to 90°C.

In parallel, other alternatives for the heating were assessed like a central gas fired boiler, combined heat power or geothermal heat pump. Qualitative and quantitative assessments (cost, required existing installation upgrade, future site growth…) defined that the best alternative solution for this project was the heat pump. So a correct analysis and understanding of the real need for the installation allow installing the right answer to the real Nestle needs.

Nestlé can save an estimated £143,000 per year (166,000 € per year) in heating costs, and around 120,000 kg in carbon emissions by using a Star Neatpump. Despite the new refrigeration plant providing both heating and cooling, it consumes £120,000 (140,000 €) less electricity per year than the previous cooling only plant.

Another impact of the complete project (combined heating and cooling, additional gas boiler for the 90°C water peak demand, etc.) decreased the total water consumption from 52,000 m³/day down to 34,000 m³/day.

The Nestlé system recently won the Industrial and Commercial Project of the Year title at the 2010 RAC awards.

Hybrid heat pump at Arla Arinco (Denmark)

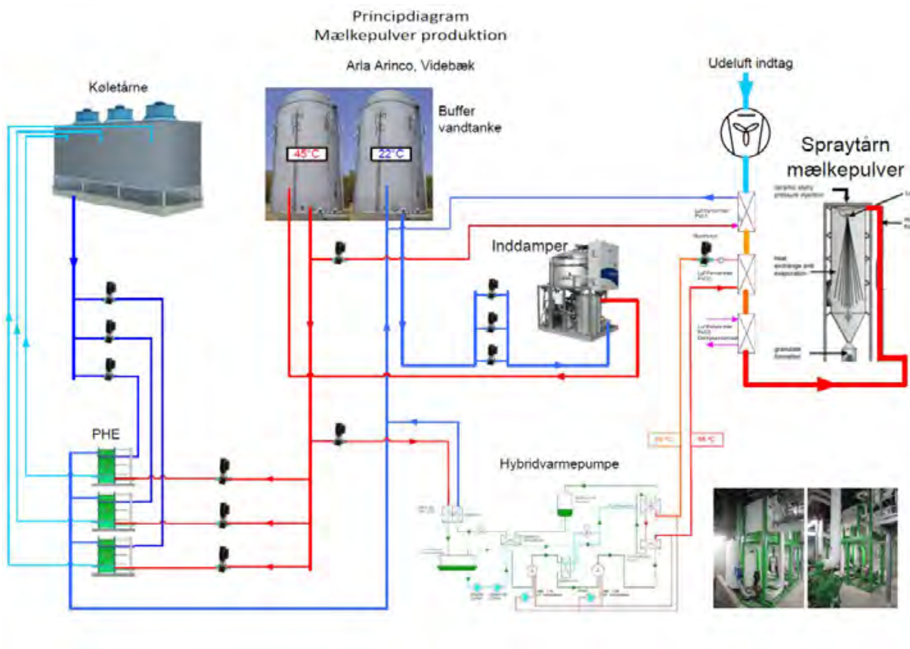
A heat pump of 1.25 MW was installed utilizing energy from 40° C cooling water – energy that was discharged to the environment prior to this project. The installed heat pump preheats drying air for milk powder to around 80° C through a water circuit.

The heat pump is installed in an application where ambient air is heated to 150 °C for drying milk powder. Previously this was done by a natural gas boiler. During the project the philosophy was to:

1. Minimize the energy demand
2. Incorporate direct heat exchangers as far as possible
3. Consider whether a heat pump is the best solution for the remaining energy demand.

The type of the heat pump is a Hybrid (compression/absorption) with the refrigerant NH_3/H_2O with a capacity of 1.25 MW.

Following these steps it became obvious that the best solution would be a heat pump only doing part of the heating towards 150 °C. It was also noticed that pre heating of the ambient air was possible through direct heat exchanging utilizing cooling water from an evaporator. The installation was thus changed to consist of three stages where the first is preheating to 40 °C using cooling water, second stage is heating from 40-80 °C using the heat pump – also recovering heat from the cooling water and third stage is heating from 80-150 °C using the existing gas boiler. Due to fluctuations in cooling and heating demands, two buffer tanks have been installed eliminating variations in the cooling system and ensuring steady conditions for the heat pump.



With a COP of 4.6 the heat pump approximately halves the energy cost compared to natural gas that is replaced. A high number of annual operation hours (around 7,400), ensures a considerable reduction in energy expenses. The analysis throughout the project also led to other energy reductions as well as direct pre heating of ambient air, thus the project as a whole caused substantial savings making this approach very profitable. Energy savings represent a tradable value in the Danish system for energy reductions. Because of the considerable amount of energy savings in this particular case, around half of the investment was financed through this value leading to a simple payback time of around 1.5 years and being very profitable from a life time perspective.

Another conclusion from the project is that engineering, design, construction, commissioning and operation of a heat pump plant of this size is comparable to that of industrial refrigeration plants.

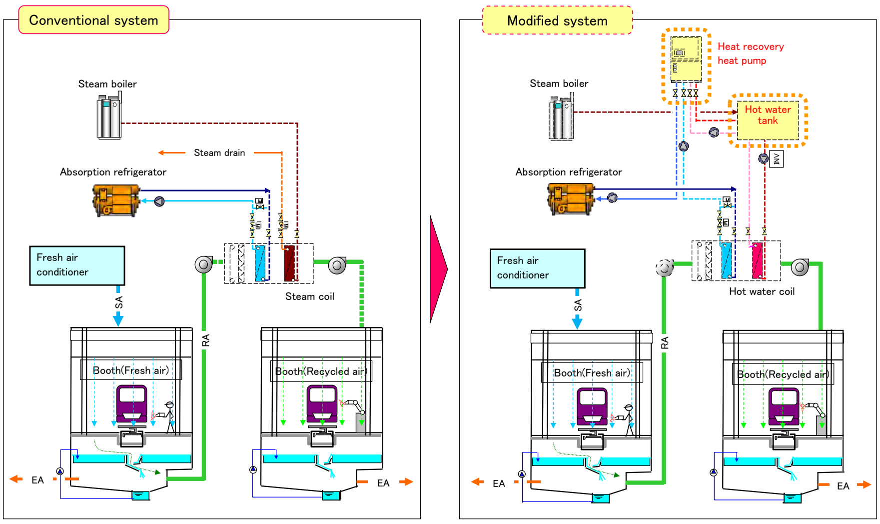
Adoption of Heat Pump Technology in a Painting Process at an Automobile Factory (Japan)

In a painting facility of an automobile factory, a great deal of energy is consumed by heating and cooling processes, the power supply, system controls, lighting, and so on. Generally, most primary energy sources are gas and electricity. Most heating and cooling needs in a painting process are supplied by direct gas combustion, steam, hot water, and chilled water generated by a refrigerator, most of the primary energy for which is gas. In terms of energy efficiency ratio, electrical energy was believed to be lower in energy efficiency than gas energy, because electrical energy uses only around 40 % of input energy while gas energy is able to use almost 100 % of direct gas combustion. However, heat pump technology has greatly improved, and the energy efficiency ratio is increasing accordingly, so highly efficient heat pumps have been introduced also into industrial processes in recent years.

There are three main advantages which we can gain from heat pump technology. The first is the heat recovery system, the second is efficient heat source equipment, and the third is simultaneous usage of cooling and heating, which is believed to be the most efficient usage. Simultaneous usage of heating and cooling can be applied to processes of pretreatment/electro-deposition, booth/working area air conditioning, and waterborne flash-off equipment. Hence, adoption of heat pump technology in this equipment is considered. The highest effect from adoption of heat pump technology in these cases is in booth recycled air conditioning and waterborne flash-off equipment.

Conventionally, the heat source system of a recycled air conditioner in the paint booth consists of a gas absorption refrigerator and a boiler. The recycled air conditioner was cooled by the gas absorption refrigerator, and reheated by boiler steam. In the meantime, the heat recovery heat pump enables us to supply both the heat for cooling and reheating concurrently. This modified system is provided to ensure system reliability and lower carbon emissions by utilizing existing equipment, such as the gas absorption refrigerator and the boiler, and also for backup purposes.

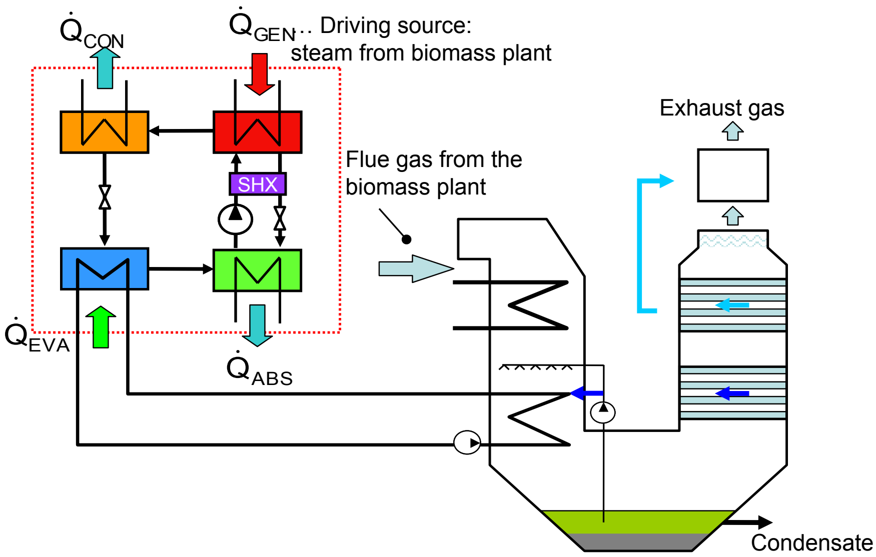
The heat pump makes it possible for the system to reduce running costs by about 63 %, to reduce CO_2 emissions by about 47 % per month, and to reduce primary energy consumption by about 49 % per month as compared with the conventional boiler. Consequently, the pay-back period would be estimated at 3～4 years.



Absorption heat pump for flue gas condensation in a biomass plant

Schweighofer Fibre GmbH in Hallein (Austria) is a woodworking industrial company and part of the Austrian family enterprise Schweighofer Holzindustrie. Their core business is the production of high-quality cellulose and bioenergy from the raw material wood by an efficient and environmentally-friendly use. A biomass power plant including a steam generator supplies the in-house steam grid and covers the company's energy demand at the site. The capacity of this cogeneration plant, which is fired by 77 % of external wood and 23 % of in-house remants, amounts to about 5 MW_{el} and 30 MW_{th}. Beside the in-house power supply of Schweighofer Fibre GmbH the biomass plant also delivers electricity for about 15,000 households and heat for the local district heating grid.

The AHP offers the possibility to use the condensation heat of the flue gas by upgrading its temperature level, even thou the return flow temperature of the existing district heating grid is higher than the dew point temperature of the flue gas. At evaporating temperatures of the AHP lower than 50 °C the flue gas gets sub cooled below the dew point temperature. Hence, the temperature level of the condensation heat of the flue gas is lifted up to a useful level for the district heating. Otherwise, the condensation heat of the flue gas could not be used and would be dissipated to the ambient.

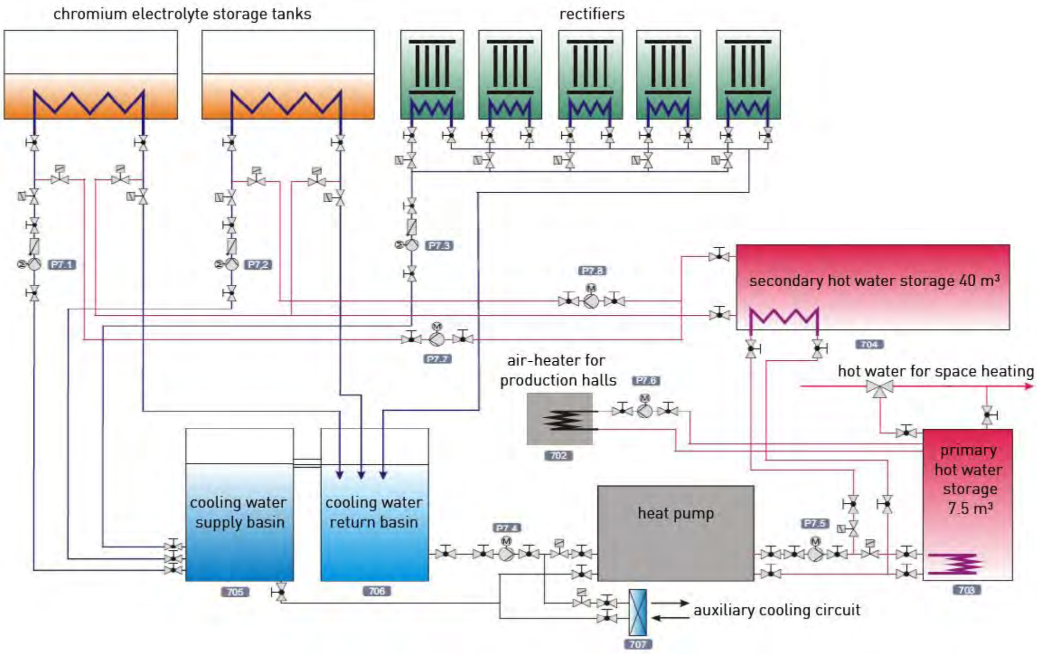


The applied AHP is a single-stage Water/LiBr absorption heat pump with a solution heat exchanger (SHX) and a heating capacity of ca. 7.5 MW. The driving source of the AHP is steam from the biomass heating plant at ca. 165 °C. According to the existing monitoring system the AHP operates with a seasonal performance factor (SPF) of about 1.6. Due to the high efficiency and the high operating hours of the AHP this industrial heat pump application enables a significant fuel and emission reduction. Additionally to the ecological advantages this application offers an economical benefit for the operator of the plant.

The benefits are energy savings of ca. 15,000 MWh/a, a higher performance and no vapour discharge system is required.

Metal processing (Germany)

Thoma Metallveredelung GmbH is an electroplating company that offers a various surface treatments. The company is a very active driver for the rational use of energy in the electroplating industry. In a research project funded by Deutsche Bundesstiftung Umwelt (DBU) a concept for a new energy saving hard chromium line was developed. Chromium plating is a technique of electroplating a thin layer of chrome onto metal objects. This is done by immersing the objects into a bath of chromium electrolyte. By applying direct electric current, chromium is plated out on the object´s surface. Usually only 20 % of the electric energy are used to create the chromium coating. The remaining 80 % are converted into waste heat. As the electroplating process is very temperature-sensitive cooling has to be applied to the electroplating bath.



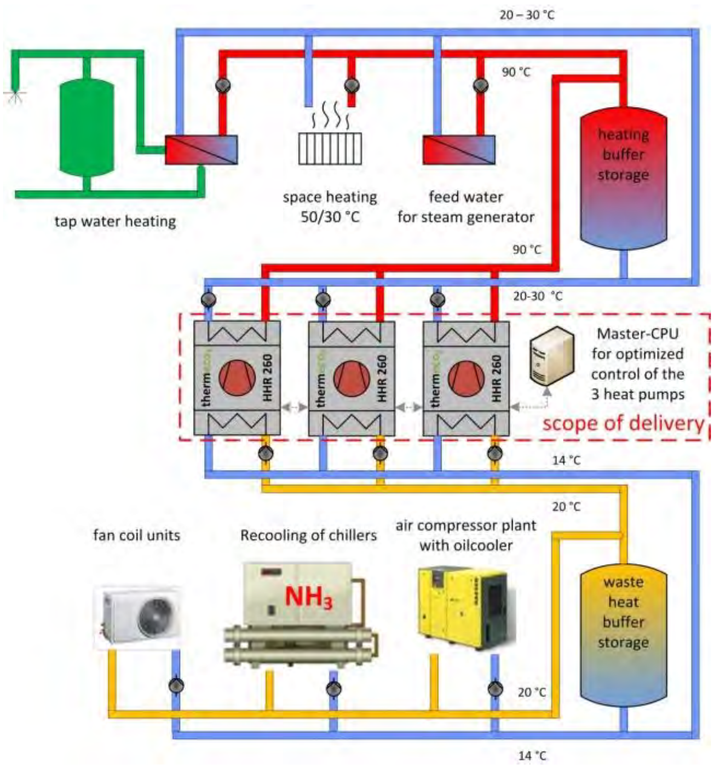
The company has increased the over-all efficiency of this process to more than 90 % by improving the electroplating process and integrating a heat pump to reuse the generated waste heat. By increasing the current density from 50 A/dm² to 90 A/dm² the efficiency of the electroplating process could be increased to 24 %. To maintain a good surface quality the temperature of the bath had to be raised to more than 60 °C. As the process still produces a large heat surplus, the electrolyte tanks as well as the current rectifiers are cooled by a water circuit. The cooling water returns to a collecting basin at a temperature of 60 °C. Because in the company there is no heat needed at 60 °C, the cooling water basin serves a heat source for a heat pump. The heat pump has a heating capacity of 143 kW and produces hot water at 75 to 80 °C. At this temperature level hot water is used for space heating and to supply others baths of the coating line. A 7.5 m³ storage serves as a buffer for space heating. Due to higher heating loads the process heat storage has a larger volume of 40 m³. Both heating and cooling system are operated bivalent. In case of a malfunction of the heat pump a groundwater well serves a heat sink for the cooling water, while an oil-fired heater covers the heating demand. The heat pump system covers 50 % of the heat demand and saves 150,000 l oil per year. Another positive effect of the new hard chromium line is significant process improvements. The coating hardness could be increased by 10%, while the plating rate could be increased by 80 %. For planning and implementation of the project experts from different engineering disciplines had to work together. The coordination of this work took a lot more effort than expected before. Nevertheless Thoma Metallveredelung GmbH is very satisfied with the result and plans to install similar heat recovery systems in their other coating lines. Furthermore the whole system was designed using standard components. In this way other electroplating companies can adapt the system without infringing property rights.

Slaughter House in Zurich (Switzerland)

In 2011, a new thermeco$_2$ heat pump system for hot water generation and heating was put into operation in the slaughterhouse Zurich. With a capacity of 800 kW, the plant is the largest ever built in Switzerland. The thermeco$_2$ machines deliver the required 90 °C with better COPs compared to other refrigerants. The heat pump system is built up of 3 heat pumps thermeco$_2$ HHR 260.

The heat pump uses waste heat of an existing Ammonia refrigeration machine, an oilcooled air compressor plant and the installed fan-coil units as heat source. For this reason the heat is collected in a waste heat buffer storage connected with the heat pump evaporators. Because of the closed waste water circulating loop no special measures to avoid corrosion are necessary.

The warm side of the heat pumps is connected with a hot water buffer storage. The consumer (warm water for slaughtering and cleaning purposes, feed water for a steam generator and the heating system) are provided from this buffer storage using their consumer pumps tailored to the particular demand.



Because of the extremely low space requirement, this large heat pump system could be installed in a container system on the roof of the slaughterhouse in a short distance to urban residential development. Only authorized personal has access to the container and CO_2 sensors have been installed that activate an alarm when healthy concentration levels are exceeded.

All of the thermal energy for the slaughterhouse Zurich was previously provided with steam boilers. The customer's decision for a high temperature heat pump system with CO_2 as a refrigerant on this scale had several reasons. The efficiency advantages of the high temperature heat pump system clearly have priority. Running this heat pump plant the city of Zurich, represented by the Umwelt- und Gesundheitsschutz Zürich (UGZ) and the Elektrizitätswerk Zürich (ewz) as Contractor make an important contribution towards the "2000 Watt Society" of the city of Zurich. In the calculated overall balance of the slaughterhouse, CO_2 emissions can be reduced by approx. 30 %. By using the heat pump system, 2,590 MWh from fossil fuels can be saved per year, representing an annual reduction in CO_2 emissions of 510 tonnes.

R&D high temperature heat pumps

EDF France in cooperation with industry is working on the development of high temperature industrial heat pumps with new working fluids to reach temperatures higher than 100 °C:

Alter ECO Project

This project includes the development and industrial testing of HPs capable of operating at 140 °C in condensation mode, equipped with scroll compressors and working with a new blend.

Publication: Experimental results of a newly developed very high temperature industrial heat pump (140 °C) equipped with scroll compressors and working with a new blend refrigerants.

Technical specifications :

- Condensation temperature : 77 to 140 °C
- Evaporation temperature : 30 to 60 °C
- Compressors max power : 75 kWe
- Condenser max power : 200 kWt

The compressor power is 75 kW. The machine performances have been characterized to demonstrate the technical feasibility. For each evaporation temperature (from 35 to 60 °C by step of 5 °C), the condensation temperature is increased by step of 5 °C from 80 up to 140 °C.

Test campaigns over 1,000 hours were carried out in industrial-like conditions to demonstrate the reliability.

The efficiency of heat recovery up to 125 °C is demonstrated. Good performances are obtained. For higher temperatures, the technological feasibility is demonstrated but some further developments have to be carried out to increase the efficiency and the economic viability: 2 stage compressors (it is designed for a given pressure ratio), expansion valve, etc.

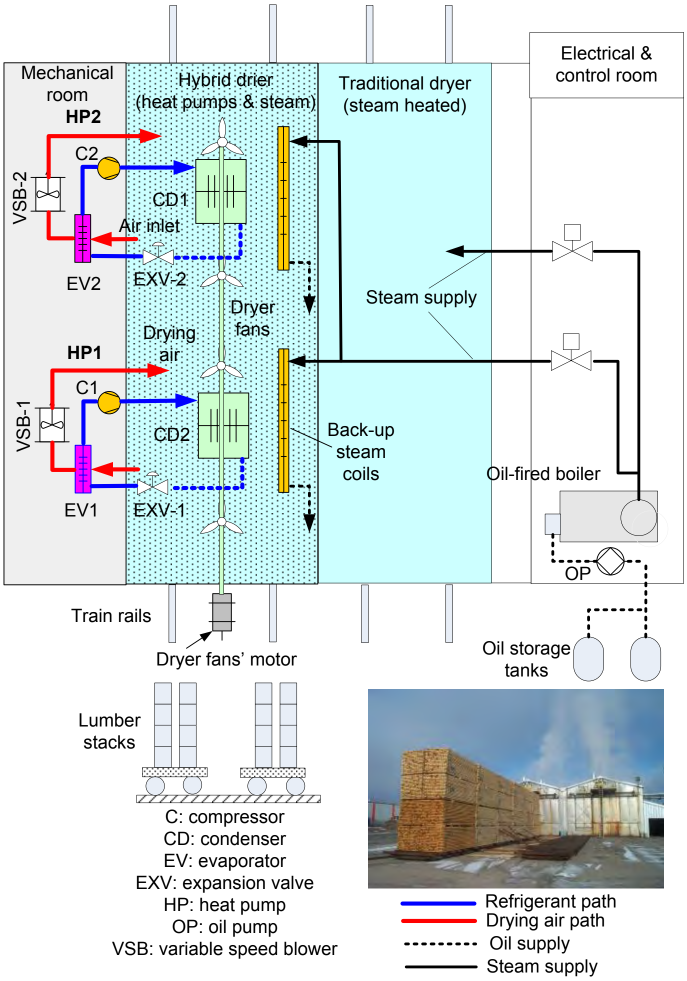
All this demonstrates the prototype reliability and the capacity to use this newly developed machine for industrial purposes.

PACO Project

Heat pump using water as a refrigerant is an interesting solution for waste heat recovery in industry. Water is nontoxic, non-ignitable and presents excellent thermodynamic properties, especially at high temperature. Water HP development is complex, notably due to water vapor compression. The compression ratio of centrifugal and lobe compressors is low. It prevents gas temperature from rising more than 20 °C. For now, the only technical solution able to overcome this drawback with moderate costs is to put two lobe compressors in series. However, theses compressors are less reliable than the others and their efficiency is low. Thus, the development of a novel water compressor is needed. Screw and centrifugal compressors on magnetic bearings seem to be the most promising technology. Discussions with the compressor manufacturers, and the numerical simulations show that the COP can be increased up to 80 % if such a compressor is integrated on a water heat pump. The price of this prototype compressor is very high, but it should decrease with the development of the market. Thus, the payoff would be guaranteed and the water heat pump would become an industrial reality.

High-temperature drying heat pump

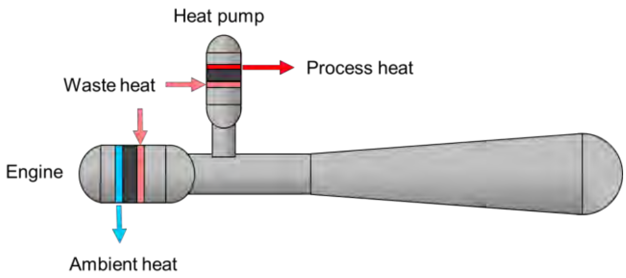
An industrial-scale, high-temperature heat pump-assisted dryer prototype, including one 354 m^3 forced-air wood dryer with steam heating coils and two high-temperature heat pumps (see Figure) has also been studied in Canada. Finished softwood lumber is produced in standard sizes, mostly for the construction industry. Softwood, such as pine, spruce and fir (coniferous species), is composed of vertical and horizontal fiber cells serving as a mechanical support and pathway for the movement of moisture. These species are generally dried at relatively high temperatures, but no higher than 115 °C, and thus high-temperature heat pumps coupled with convective dryers are required. An oil-fired boiler supplies steam for wood preheating and supplemental (back-up) heating during the subsequent drying steps. The dryer central fans force the circulation of the indoor drying air and periodically change their rotation sense to make more uniform and, thus, to improve the overall drying process and the wood final quality. Each heat pump includes a 65 kW (nominal electrical power input) compressor, an evaporator, a variable speed blower and electronic controls located in an adjacent mechanical room. Both remote condensers are installed inside the drying chamber. The high-temperature refrigerant (HFC-236fa) is a non-toxic and non-flammable fluid, having a relatively high critical temperature compared to the highest process temperatures. Expansion valves are controlled by microprocessor-based controllers that display set points and actual process temperatures. The industrial-scale prototype demonstrates that, as a clean energy technology compared with traditional heat-and-vent dryers, the high-temperature heat pump-assisted dryers offer very interesting benefits for drying resinous timber. Its actual energy consumption effectively is between 27.3% and 56.7% lower than the energy consumed during the conventional (steam) drying cycles, whereas the average reduction in specific energy costs, compared to the average costs of the Canadian conventional wood drying industry (2009), is of approximately 35 %.



Thermo Acoustic Heat Transformer

Thermo acoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts.

Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology. When thermal energy is converted into acoustic energy, this is referred to as a Thermo acoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the re-verse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as shown below.



The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site.

Basic characteristics of refrigerants suitable for high temperature heat pump

Some development of the industrial heat pump using R-134a, R-245fa, R-717, R-744, hydro carbons, etc. has been made recently. However, except for R-744 and the flammables R-717 and HCs which are natural refrigerants with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3CH2CH2CH2CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

Operating Agent: Annex 35/13 Application of industrial Heat Pumps

Information Centre on Heat Pumps and Refrigeration (IZW e.V.)

IZW is a German society for the promotion of research and development of heat pumps and refrigeration, to contribute to the reduction of the primary energy consumption and CO_2 emissions and the improvement of the energy-efficiency and environmental protection at the heat production, refrigeration and in the manufacturing industry.

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Members:

What is the IEA Heat Pump Programme?

The Programme is a non-profit organisation funded by its member countries. It is the foremost worldwide source of independent information and expertise on environmental and energy conservation benefits of heat pumping technologies.

What is the aim of the Heat Pump Programme?

The aim is to achieve widespread deployment of appropriate practical and reliable heat pumping technology systems that can save energy resources while helping to protect the environment.

Why is that important?

The world's energy and climate problems are well known. The buildings sector is responsible for a very considerable proportion of greenhouse gas emissions. Heat pumps are a key technology in the solution to break this trend.

What needs to be done?

By disseminating knowledge of heat pumps worldwide, we contribute to the battle against global warming. In order to increase the pace of development and deployment of heat pumps for buildings and industries, we need to increase R&D efforts for heat pumps, and we need to implement long-term policies for further deployment of heat pumps.

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Basics of Industrial Heat Pumps

Final Report

(Status: 01.09.2014)

Prepared by
Operating agent
IZW e.V.

Contents

1 Introduction

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy.

About 30 % of the global energy demand [IEA, 2013] and CO_2 emissions are attributable to industry, especially the big primary materials industries such as chemicals and petro-chemicals, iron and steel, cement, paper and aluminium. Understanding how this energy is used, the national and international trends and the potential for efficiency gains, are crucial.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. The heat pump markets are currently growing at a steady pace, however, in many countries focused mainly on residential heat pumps for space heating and cooling as well as domestic hot water. Heat pumps for high temperature applications and industrial use have often been neglected, as the share of energy cost has been low for companies and thus investments to improve production normally have a much higher priority than investments in energy efficiency. Increased use of energy has, to some extent, been an indication of economic growth.

Industrial heat pumps (IHPs), however, offer various opportunities to all types of manufacturing processes and operations. Increased energy efficiency is certainly the IHPs most prominent benefit, but few companies have realized the untapped potential of IHPs in solving production and environmental problems. IHPs can offer the least-cost option in getting the bottlenecks out of production process to allow greater product throughput. In fact, IHPs may be an industrial facility's best way of significantly and cost-effectively reducing combustion related emissions [Leonardo, 2007].

Industrial heat pumps are using waste process heat as the heat source, deliver heat at higher temperature for use in industrial process heating or preheating, or for space heating and cooling in industry. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications as well as heating and cooling of industrial and commercial buildings. Industries that can benefit from this technology include food and beverage processing, forest products, textiles, and chemicals.

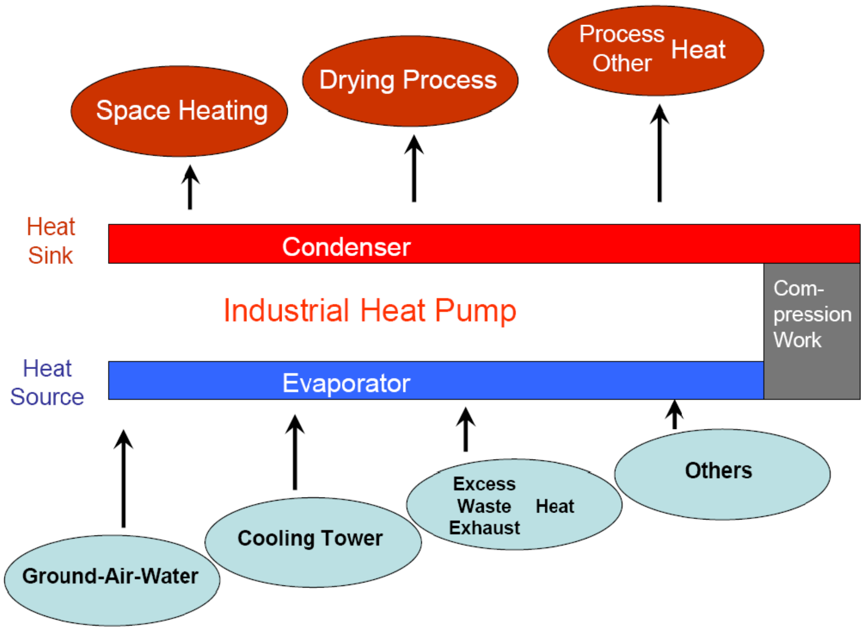

Figure 1-1: Heat sources and heat sinks in industrial heat pumps

While the residential market may be satisfied with standardized products and installations, most industrial heat pump applications need to be adapted to unique conditions. In addition a high level of expertise of heat pumps and processing is crucial.

Industrial heat pumps within this annex are defined as heat pumps in the medium and high power ranges which can be used for heat recovery and heat upgrading in industrial processes, but also for heating and cooling in industrial buildings.

Their potential for energy conservation and reduction of CO_2-emissions are enormous and at this moment not naturally a part of policy papers. The following problems and respective needs for research are related to the market introduction of IHPs:

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants
- uncertainty by potential users as to HP reliability
- lack of necessary knowledge of heat pump technology and application by designers and consulting engineers.

On the other side, IHPs have the following advantages in comparison to heat pumps for space heating:

- high coefficient of performance (COP) due to low temperature lift and/or high temperature levels
- long annual operating time
- relatively low investment cost, due to large units and small distance between heat source and heat sink
- waste heat production and heat demand occur at the same time.

2 Physical principles

A heat pump is essentially a heat engine operating in reverse. Its principle is illustrated below.

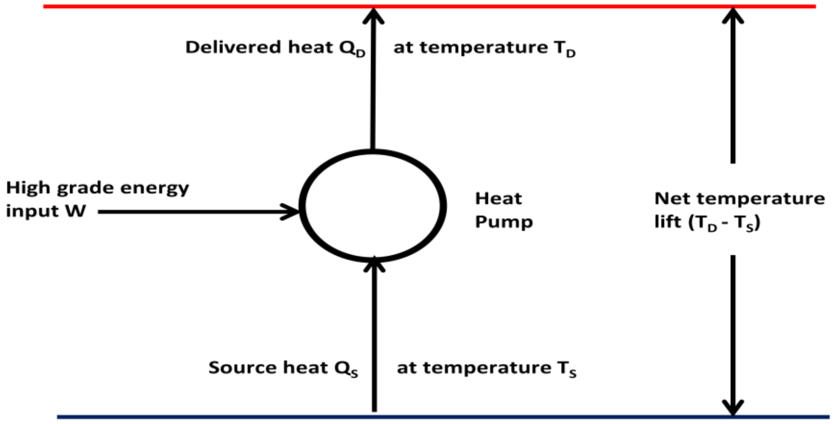

Figure 2-1: Heat pump principle

From the first law of thermodynamics, the amount of heat delivered Q_D at the higher temperature $T_D$is related to the amount of heat extracted Q_S at the low temperature T_S and the amount of high grade energy input W by the equation

$$Q_D = Q_S + W$$

Compared to heat pumps for space heating, using heat sources such as ground or water, IHPs often have the following advantages:

- high coefficient of performance due to low temperature lifts and/or high temperature levels;
- long annual operating times;
- relatively low investments cost, due to large units and small distances between heat source and heat sink;
- waste heat production and heat demand occur at the same time.

Despite these advantages, the number of heat pump installations in industry is almost negligible compared to those installed for space heating.

Note:
A coefficient of performance (COP) can be defined as

$$COP = \frac{Q_D}{W}$$

The Carnot coefficient of performance

$$COP_c = \frac{T_D}{T_D - T_S}$$

represents the upper theoretical value obtainable in a heat pump system.

In practice attainable coefficients of performance are significantly less than COP_c. Unfortunately, it is difficult to compare the COPs of different categories of IHP, which differ widely for equivalent economic performance. When comparing heat pump systems driven by different energy sources it is more appropriate to use the primary energy ratio (PER) defined as

$$PER = \frac{usefull\ heat\ delivered}{primary\ energy\ input}$$

The equation can be related to the coefficient of performance by the equation

$$PER = \eta \times COP$$

where η is the efficiency with which the primary energy input is converted into work up to the shaft of the compressor.

3 Heat pump technology

3.1 Criteria for possible heat pump applications

The first step in any possible IHP application is to identify technically feasible installation alternatives, and possibilities for their economic installation.

In simple operations, where the process in which the IHP will be used only consists of a few streams with obvious sink and source, the need for a thorough assessment is normally not necessary. In these cases, only the characteristics of the sink and source are of importance for the feasibility and selection of the IHP. The obvious parameters are:

- heat sink and source temperature;
- size (in terms of heat load) of the sink and source;
- physical parameters of the sink and source, such as phase and location

Industrial heat pumps are used in the power ranges of 50 – 150 kW and 150 to several MW.

The sink and source temperatures determine which IHP types can be used in a specific application. These types can be categorized in various ways, e.g. as mechanically- or heat-driven, compression or absorption, closed or open cycles.

3.2 Thermodynamic processes

The most important thermodynamic processes for industrial heat pumps are:

- closed compression cycle - electric driven or gas-engine driven
- mechanical (MVR) and thermal (TVR) vapour recompression
- sorption cycle
- absorption–compression cycle
- current developments, e. g. thermo acoustic, injections

and will be described in the next chapters.

3.2.1 Mechanical compression cycles

The principle of the simple closed compression cycle is shown below.

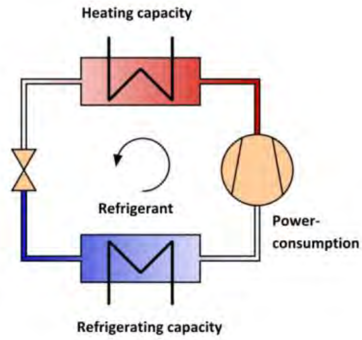

Figure 3-1: Closed compression cycle

Four different types of compressors are used in closed compression cycle heat pumps: Scroll, reciprocating, screw and turbo compressors.

Scroll compressors are used in small and medium heat pumps up to 100 kW heat output, reciprocating compressors in systems up to approximately 500 kW, screw compressors up to around 5 MW and turbo compressors in large systems above about 2 MW, as well as oil-free turbo compressors above 250 kW.

3.2.1.1 Vapour injection

In the economizer vapour injection (EVI) cycle, see figure below, a heat exchanger is used to provide additional sub-cooling to the refrigerant before it enters the evaporator. This sub-cooling process provides the increased capacity gain measured in the system. During the sub-cooling process, a certain amount of refrigerant is evaporated. This evaporated refrigerant is injected into the compressor and provides additional cooling at higher compression ratios, similar to liquid injection.

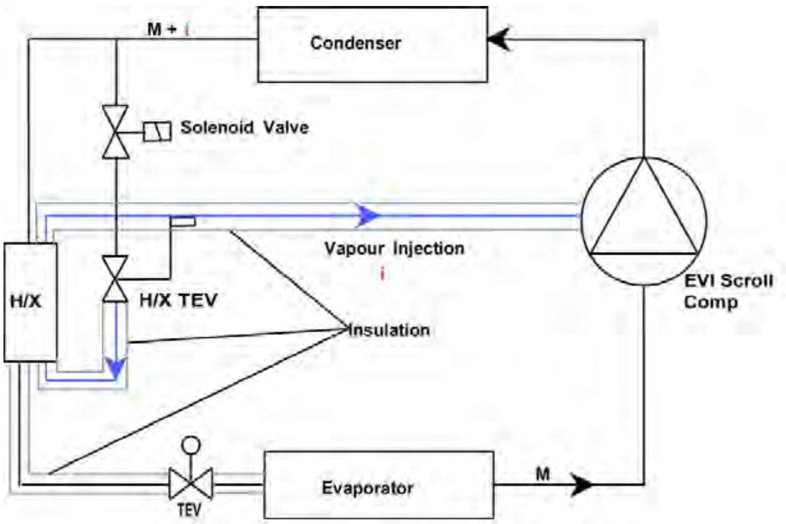

Figure 3-2: Vapour injection

3.2.2 Thermal compression cycles

3.2.2.1 Absorption heat pumps

Absorption heat pump cycles are based on the fact that the boiling point for a mixture is higher than the corresponding boiling point of a pure, volatile working fluid. Thus the working fluid must be a mixture consisting of a volatile component and a non-volatile one. The most common mixture in industrial applications is a lithium bromide solution in water ($LiBr/H_2O$) and ammonia water (NH_3/H_2O).

The fundamental absorption cycle has two possible configurations: absorption heat pump (AHP, Type I) and heat transformer (AHP, Type II), which are suitable for different purposes.

The difference between the cycles is the pressure level in the four main heat exchangers (evaporator, absorber, desorber and condenser), which influence the temperature levels of the heat flows.

The application of absorption cycles for high temperature heat recovery systems calls for the investigation of new working pairs. To qualify as a potential working pair, a mixture of two substances has to fulfil stringent requirements with respect to thermodynamic properties, corrosion and safety hazards like toxicity and inflammability.

Based on a thermodynamic analysis of an absorption heat pump cycle a systematic search for new working pairs has been required, e. g. investigation of organic compounds.

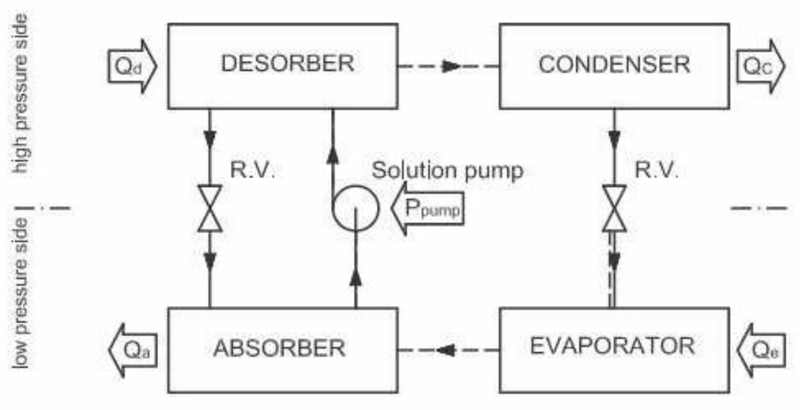

Figure 3-3: Absorption

3.2.2.2 *Absorption-compression hybrid*

The hybrid heat pump combines substantial parts of both absorption and compression machines - it utilizes a mixture of absorbent and refrigerant and a compressor as well. An important difference between hybrid and absorption cycle should be noticed - the absorber and desorber in the hybrid heat pump are placed in a reversed order than in the absorption machine, i.e. desorption in the hybrid cycle occurs under low temperatures and pressures and absorption under high temperatures and pressures.

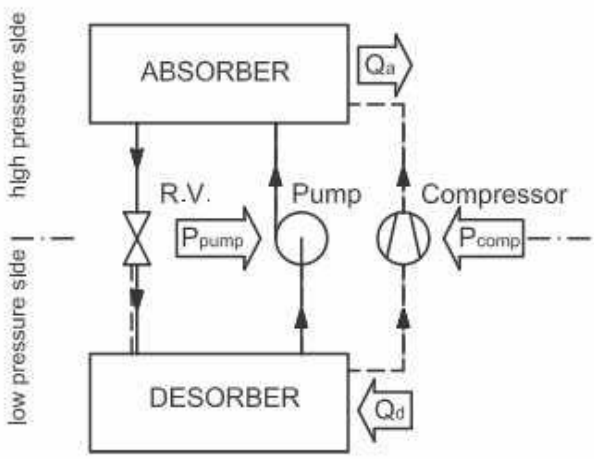

Figure 3-4: Absorption – compression hybrid

3.2.3 Mechanical vapour recompression (MVR)

Mechanical vapour recompression is the technique of increasing the pressure and thus also the temperature of waste gases, thereby allowing their heat to be re-used. The most common type of vapour compressed by MVR is steam, to which the figures below refer. There are several possible system configurations. The most common is a semi-open type in which the vapour is compressed directly (also referred to as a direct system). After compression, the vapour condenses in a heat exchanger where heat is delivered to the heat sink. This type of MVR system is very common in evaporation applications

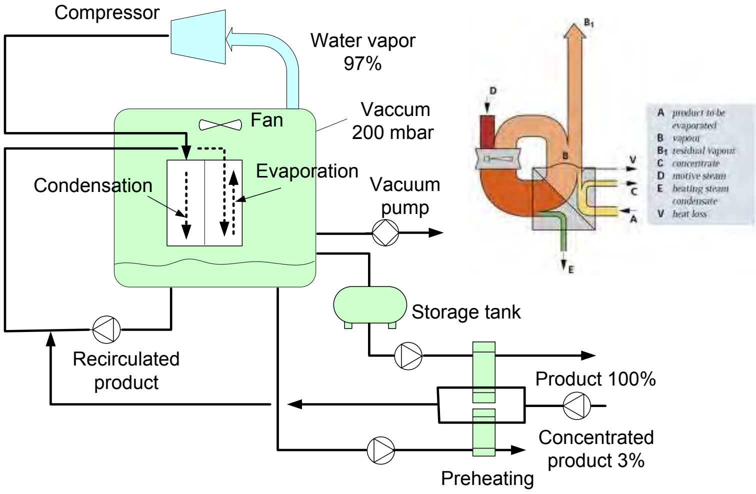

Figure 3-5: Mechanical vapor recompression [Bédard, 2002]

The other type of semi-open system lacks the condenser, but is equipped with an evaporator. This less usual configuration can be used to vaporize a process flow that is required at a higher temperature, with the aid of mechanical work and a heat source of lower temperature.

3.2.4 Thermal vapour recompression (TVR)

With the TVR type of system, heat pumping is achieved with the aid of an ejector and high pressure vapour. It is therefore often simply called an ejector. The principle is shown in the figure below. Unlike MVR system, a TVR heat pump is driven by heat, not mechanical energy. Thus, compared to an MVR system, it opens up new application areas, especially in situations where there is a large difference between fuel and electricity prices.

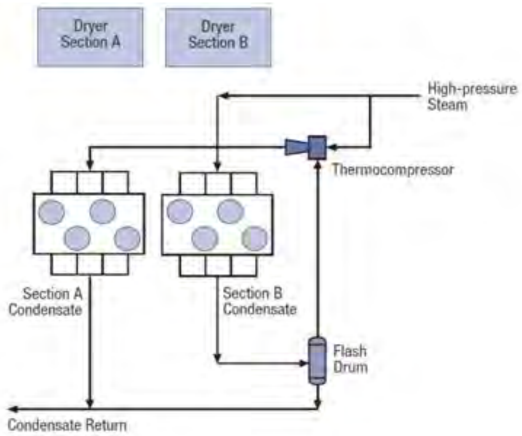

Figure 3-6: Thermal vapor recompression, Example from Japan

The TVR type is available in all industrial sizes. A common application area is evaporation units. The COP is defined as the relation between the heat of condensation of the vapour leaving the TVR and heat input with the motive vapour.

3.2.5 Thermo acoustic (TA)

The acoustic energy is subsequently being used in a TA-heat pump to upgrade waste heat to usable process heat at the required temperature. The picture below visualises the whole system. The TA-engine is located at the right side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site.

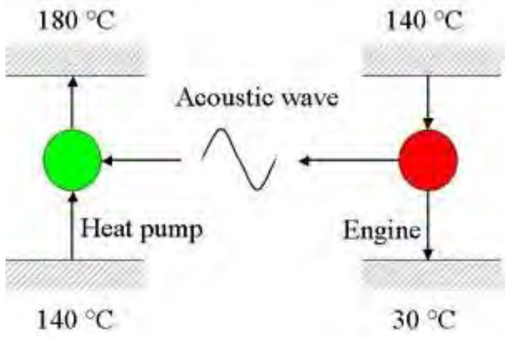

Figure 3-7: Thermo acoustic heat pump

3.3 Refrigerants suitable for high temperature heat pump

Many industrial processes have heating demands in the temperature range of 90-120 °C. At the same time, waste heat holding typically a temperature of 30-60 °C is available. Efficient heat pumping technologies are therefore attractive in order to reduce the specific energy consumption (kWh/product amount). The present, most common refrigerants, in particular HFCs are limited to heat distribution temperatures of around 80 °C. For temperature above 100 °C additional R&D is required.

Industrial heat pump using R-134a, R-245fa, R-717, R-744 and hydrocarbons (HC), etc. However, except for R-744 and the flammables R-717 and HCs, which are natural refrigerants with extremely low global warming potential (GWP.) HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Table 3-1: Refrigerants, considered to be suitable for IHPs

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3-CH2-CH2-CH2-CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

4 Energetic and economic models

As a consequence of the first law of thermodynamics all energy that is put into a process will also, in a steady state situation, leave the process. The energy leaves the process in the shape of product, waste heat and other losses.

The temperature level of the waste heat is determined by process fundamentals and process equipment design, and is thus, for an existing plant, set. However the temperature level which the waste heat appears and can be used is determined by the design of the utility systems, i.e. cooling water and air. This essential difference is often overlooked when discussing waste heat utilization.

The amount and temperature level of the waste heat can be determined by process integration methods, e.g. pinch analyses. These methods are powerful tools and give a total picture of the situation at the plant including the possibilities for internal use of the heat.

There are several competing alternatives to utilize waste heat and it is normally not obvious which is the most favorable. The heat can internally be better used for heating purposes and in new or modified process parts. Heat pumping is also an alternative which today is common practice in some branches but has a large potential to grow in others. Another option is to use the heat for heating demands outside the plant in a district heating system.

To be able to increase the awareness of possibilities and to select between the alternatives, a high level of expertise for system design, process integration and planning is crucial. Design software on process integration and design plays an important role at this stage. However, this seemingly being a complex approach needing a lot of high level expertise, simple straight forward solutions on a small scale should not be overseen.

4.1 Pinch analysis

Pinch analysis is a methodology for minimising energy consumption of chemical processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimising heat recovery systems, energy supply methods and process operating conditions. It is also known as process integration, heat integration, energy integration or pinch technology [Monard, 2006].

The process data is represented as a set of energy flows, or streams, as a function of heat load (kW) against temperature (deg C). These data are combined for all the streams in the plant to give *composite curves*, one for all *hot streams* (releasing heat) and one for all *cold streams* (requiring heat). The point of closest approach between the hot and cold composite curves is the pinch temperature (pinch point or just pinch), and is where design is most constrained. Hence, by finding this point and starting design there, the energy targets can be achieved using heat pumps to recover heat between hot and cold streams. In practice, during the pinch analysis, often cross-pinch exchanges of heat are found between a stream with its temperature above the pinch and one below the pinch. Removal of those exchanges by alternative matching makes the process reach its energy target.

4.2 EINSTEIN expert system

EINSTEIN is an **E**xpert system for an **In**telligent **S**upply of **T**hermal **E**nergy in **IN**dustry [Heigl, 2014].

For optimising thermal energy supply in industry, a holistic integral approach is required that includes possibilities of demand reduction by heat recovery and process integration, and by an intelligent combination of efficient heat and cold supply technologies.

EINSTEIN is a tool-kit for fast and high quality thermal energy audits in industry, composed by an audit guide describing the methodology and by a software tool that guides the auditor through all the audit steps.

The main features of EINSTEIN are:

1. the data processing is based on standardized models for industrial processes and industrial heat supply systems;
2. Special tools allow for fast consistency checking and estimation of missing data, so that already with very few data some first predictions can be made;
3. Semi-automation: the software tool gives support to decision making for the generation of alternative heat and & cold supply proposals, carries out automatically all the necessary calculations, including dynamic simulation of the heat supply system, and creates a standard audit report
4. A basic questionnaire helps for systematic collection of the necessary information with the possibility to acquire data by distance.

The software tool includes modules for benchmarking, automatic design of heat exchanger networks, and design assistants for the heat and cold supply system.

It is a methodology that works out energy efficient solution for your production process based on renewable energy sources, e.g. heat pumps. This will lead to a significant reduction of your operating cost. The benefits of Einstein are:

- Increase in know-how for local auditors
- Reduction of energy costs and CO_2 emissions
- Improved competitiveness and saving for your company by a reduction of operating costs
- Road map for realisation of energy concepts with an economic consideration.

The present status of EINSTEIN does not include heat pumps for heat recovery and process integration. However, a new project – EINSTEIN III is presently in the stage of approval as part of the European Commission research programme EE-16-2014 "Organisational innovation to increase energy efficiency in industry", which include industrial heat pumps.

5 Research and development

Appropriate heat pump technology is important for reducing CO_2 emissions and primary energy consumption as well as increasing amount of renewable energy usage in industrial processes. The expansion of industrial applications is also important for enhancing these effects further more. In particular, development and dissemination of high-temperature heat pumps for hot water supply, heating of circulating hot water, and generation of hot air and steam are necessary. Specific problem areas are

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants

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Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Task 1:
Heat Pump Energy situation, Energy use, Market overview, Barriers for application

Final Report

(Status: 31.05.2014)

Prepared by the
Participants of Annex 35/13

Contents

1 Summary

The world rising energy prices and environmental concern set focus on energy conservation and use of renewable energy sources.

In this context, the IEA HPP-IETS Annex 35/13 has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

The heat pump markets are currently growing at a steady pace, but in many countries, however, is focused mainly on residential heat pumps for space heating and domestic hot water. While the residential market may be satisfied with standardised products and installations, most industrial heat pump applications need to be adapted to unique conditions.

The work in the Annex in task 1 starts by making an overview in the participating countries of the industrial energy situation and use, the state of the art in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications. Based upon these findings focus will be given to further work to meet the challenges in the wider application of industrial heat pumping technologies.

2 Introduction

Improving energy efficiency is the single most important first step toward achieving the three goals of energy policy: security of supply, environmental protection and economic growth.

Nearly a third of global energy demand and CO_2 emissions are attributable to industry, especially the big primary materials industries such as chemicals and petrochemicals, iron and steel, cement, paper and aluminium. Understanding how this energy is used, the national and international trends and the potential for efficiency gains, is crucial.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Some of these additional reductions may not be economic in the short- and medium-term, but the sheer extent of the potential suggests that striving for significant improvements is a worthwhile and realistic effort. A systems approach is needed that transcends process or sector boundaries and that offers significant potential to save energy and cut CO_2 emissions.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. They are presently widely used mainly on residential buildings for space heating and domestic hot water and are expected to spread to the industrial sector to be used for heat recovery and heat upgrading in industrial processes and for heating, cooling and air-conditioning in industrial buildings.

The introduction of heat pumps in food and beverage manufacturing factories and wood drying with operating temperature below 100 °C is in many cases considered to be easy, however, higher temperature application still require additional R&D activities for the development of high temperature heat pumps, integration of heat pumps into industrial processes and development of high temperature refrigerants.

In this context, the IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the IEA Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

The work in the Annex starts by making an overview in the participating countries of the industrial energy situation and use, the state of the art in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications. in the wider application of industrial heat pumping technologies.

The Task 1 Report summarized the present energy situation in general and the industrial energy use and related heat pump market subdivided into the annex 35/13 participating countries. Based upon these findings focus will be given to further work to meet the challenges for the wider application of industrial heat pumping technologies.

Table 2-1 gives an overview of general indicators worldwide, in OECD countries as well as European Annex participating countries.

Table 2-1: General indicator for 2008[1]

	Population (million)	GDP (billion 2000 USD)	Energy production (Mtoe)	Net Imports (Mtoe)	CO_2 emission (Mt of CO_2)
World	6 688	40 482	12 369		29 381
OECD	1 190	30 504	3 864	1 765	12 630
Annex Countries Europe	193,2	5 051	422	440,3	1 378
France	64	1 515	137	139	368
Germany	82	2 095	134	211	803
The Netherlands	16,4	449	67	34	178
Sweden	9,3	297	33	20	46
Austria	8,3	226	11	26	69
Denmark	5,5	178	27	-4,7	48

The following Figures present energy consumption, CO_2-emissions and industrial energy consumption in the 27 EU countries:

Figure 2-1 shows the final energy consumption in the EU 27 countries subdivided by energy source in 2007.

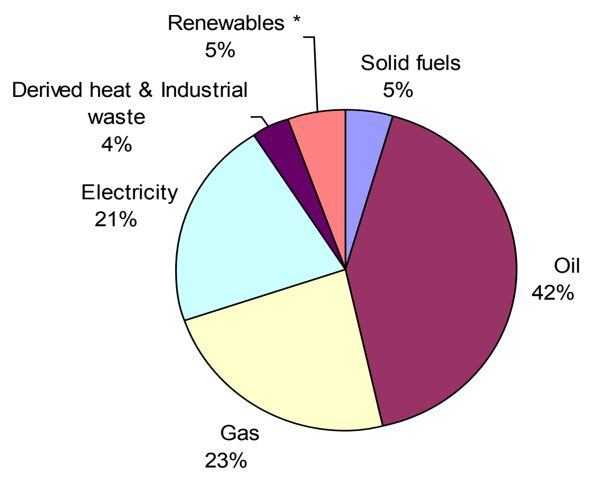


Figure 2-1: EUR27 final energy consumption by fuel 2007 (Mtoe)[2]

[1] INTERNATIONAL ENERGY AGENCY - Tracking Industrial Energy Efficiency and CO_2 Emissions – Energy Indicators 2007

[2] European Commission / ENERGY - EUROPE 2020 initiative - Energy Efficiency Plan 2011, Statistical pocketbook 2010

Figure 2-2 shows the final energy consumption in 2007 subdivided by sectors. 28 % of total energy consumption is used by the industry, number two after the transportation with 32 % and before the household with 25 %.

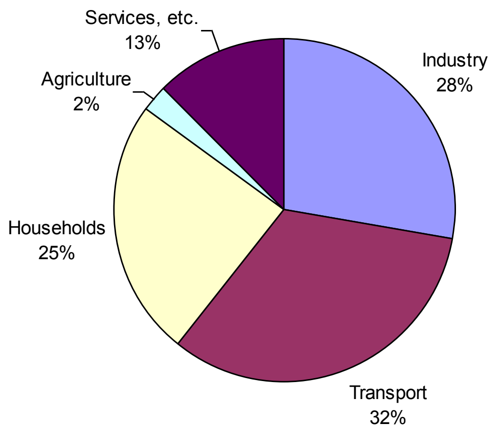


Figure 2-2: EU27 final energy consumption by sectors 2007 (Mtoe)[3]

The CO_2-emissions by sectors in the 27 EU countries are presented in Figure 2-3 with 22.3 % emitted by the industry.

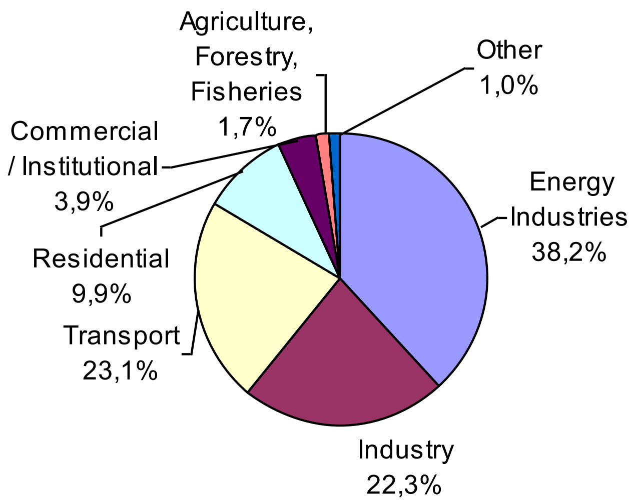


Figure 2-3: Eu27 CO_2 -emissions by sector 2007 (Mt)[3]

Figure 2-4 shows the European industrial final energy consumption by sectors in the 27 EU-countries, dominated by the Iron and Steel, Chemical, Non-mineral products and Paper and Printing industries.

[3] European Commission / ENERGY - EUROPE 2020 initiative - Energy Efficiency Plan 2011, Statistical pocketbook 2010

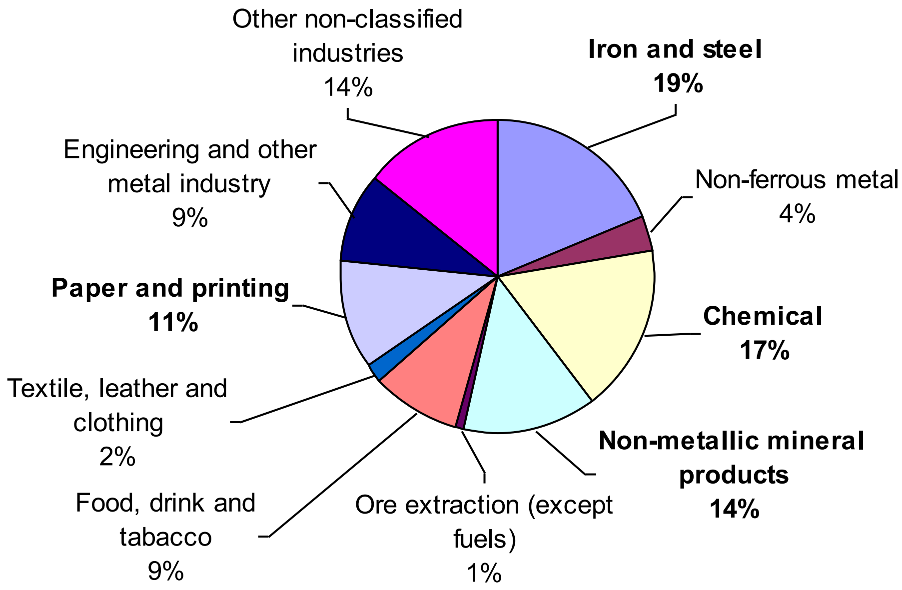
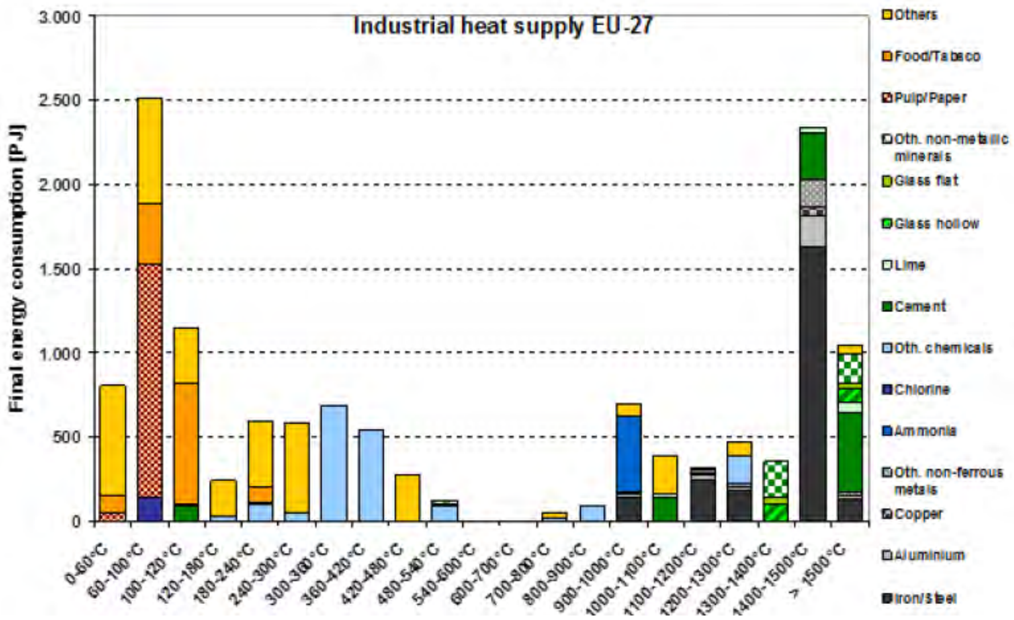


Figure 2-4: EU27 industrial final energy consumption by sectors 2008 (Mtoe)[4]



Source: SP Technical Research Institute of Sweden

Figure 2-5: EUR 27 final energy consumption by sectors as function of temperature

[4] European Commission–Eurostat -2008

3 Austria

3.1 Industrial Energy use in Austria 2009

The energy consumption in Austria has nearly doubled in the last 40 years, both in terms of combined total consumption as well as final consumption, according to Statistics Austria (2010a).

In recent years the use of renewable energy in Austria increased disproportionately due to various measures such as awareness campaigns, a variety of fundings or the creation of legal framework (Statistics Austria 2010c). A very high share of 68% of Austria's electricity supply was covered by renewable energy from hydro, wind, PV, geothermal heat and biomass. Hence, "green" electricity is in the leading position by the use of renewable energy, followed by "green" heat for district heating from biomass and geothermal energy with a share of 36%, the direct use of renewable energy from bio-heat, ambient-, geothermal- and solar-heat for heating applications with a share of 30% and biofuels[5] with a share of 7% of transport fuel. (Statistics Austria 2010c)

Despite a steady increase in the use of renewable energy sources, the bulk of Austrian energy consumption is still covered by fossil fuels such as oil and gas. This fact presents a growing problem especially as far as emissions of greenhouse gases and the security of the Austrian energy supply is concerned, as 70% of these fossil fuels have to be imported from foreign countries. Austria's dependency on foreign energy supplies amounted 64.8% in 2009 (EU average 2007 is 53.1%) and this share is steadily increasing. (Statistics Austria, 2010a)

The final energy balance split in energy carriers in Austria is shown in Table 3-1 and Figure 3-1. In 2009, 39% of the overall final energy demand in Austria (1057 PJ) was covered by oil and 17% by gas, as shown in Figure 3-1 and Table 3-1 (Statistic Austria, 2010b). Thus, the reduction of this high dependency on these fossil fuels should be focused in Austria. Keeping in mind the CO_2-emission and that only around 13% of the crude oil demand and 20% of the gas consumption are covered from Austrian sources, this offers a high ecological and economical potential (Statistic Austria, 2010a).

[5] biodiesel and bioethanol

Table 3-1: Austria's final energy balance per energy carriers in 2009 (Statistic Austria, 2010b)

Energy carrier	[PJ]
Oil[6]	423
Gas[7]	175
Coal[8]	22
Electricity	208
District Heat	64
Renewable[9]	166
Total	1057

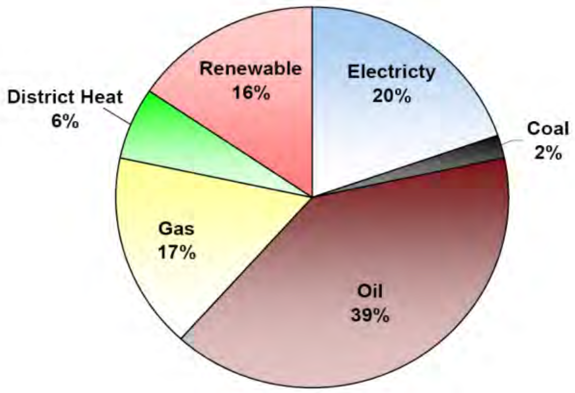


Figure 3-1: Austria's final energy balance per energy carrier in 2009 in percentage (Data based according to Statistics Austria, 2010b)

The Austria's energy demand can be classified in three main sectors:

- industry,
- transport and
- miscellaneous.

The industry sector includes the entire producing and manufacturing area in Austria. The transport sector is composed of the internal navigation, air-, rail- and road-transport as well as pipeline transport. Miscellaneous contains the aggregated domestic energy demand, including commercial and public services as well as agriculture.

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6 Oil includes: crude oil, refinery feedstock, gasoline, kerosene, fuel oil, other oil products and refinery gas (Statistics Austria, 2010b)

7 Gas includes natural gas and gasworks gases (Statistics Austria, 2010b)

8 Coal includes hard coal, lignite, BKB, peat, coke, blast furnace gas and coke oven gas (Statistics Austria, 2010b)

9 Renewable includes all energy carriers as waste, fuel-wood, bio-fuels, ambient-heat, hydro- and wind-power and PV (Statistics Austria, 2010b)

Table 3-2 represents the distribution of the final energy use across the different sectors. As shown in Figure 3-2, the final energy use in Austria is approx. uniformly distributed to the three main sectors. With a share of 29% of Austria's final energy demand, the industry offers the possibility to reduce the whole energy demand and lower the CO_2-emissions significantly.

Table 3-2: Distribution of the Austria's final energy use in 2009 across the main sectors (Statistics Austria, 2010b)

Sector	Final energy use [PJ]
Industry	308
Transport	357
Miscellaneous	392
Total	1057

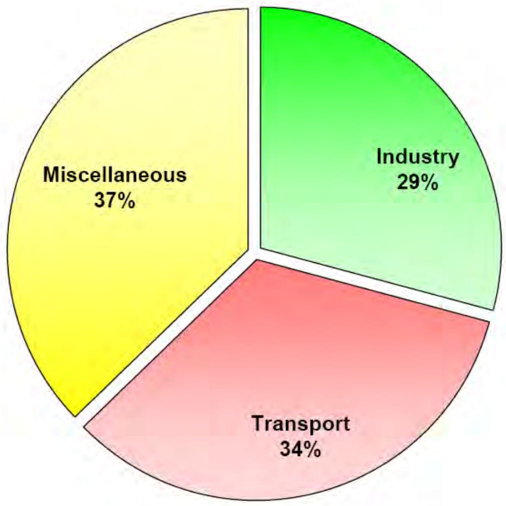

Figure 3-2: Distribution of the final energy use in Austria in 2009 across the main sectors in percentage (Data based to Statistics Austria, 2010b)

3.1.1 Energy use in the manufacturing industry

The balance of the different energy carriers in the Austrian industry is shown in Table 3-3. The most energy intensive industrial sector in Austria is the pulp, paper and print industry, followed by the non-metallic minerals processing and the iron and steel industry, as shown in Figure 3-3. Other industrial sectors with a high energy demand are found in the chemical and petrochemical industries. The Austrian manufacturing industry used about 308 PJ of final energy in 2009.

Table 3-3: Distribution of energy carriers in each industrial sector in Austria 2009 (Data according to Statistics Austria, 2010b – values for final energy consumption)

Austrian Industry Sectors	Electri-city	Coal[10]	Oil[11]	Gas[12]	District Heat	Rene-wab-le[13]	Total
	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]
Iron and Steel	13,2	8,2	2,2	16,3	0,2	0,6	**40,6**
Chemical and Petrochemical	13,4	0,5	0,6	14,6	2,1	6,5	**37,7**
Non-ferrous Metals	3,0	0,2	0,3	4,2	0,1	0,0	**7,7**
Nonmetallic Minerals	7,4	6,6	3,3	13,3	0,0	10,5	**41,1**
Transport Equipment	2,7	0,0	0,2	1,4	1,4	0,0	**5,7**
Machinery	11,5	0,0	1,5	7,4	1,1	0,7	**22,1**
Mining and Quarrying	2,5	0,0	0,4	1,6	0,0	0,0	**4,5**
Food Tobacco and Beverages	6,8	0,1	2,3	11,4	1,2	0,5	**22,4**
Pulp, Paper and Print	16,1	2,6	0,9	22,0	0,7	21,3	**63,7**
Wood and Wood Products	6,0	0,0	0,2	2,8	2,1	14,8	**25,8**
Construction Industry	2,5	0,0	16,0	1,7	0,5	1,9	**22,6**
Textiles and Leather	1,8	0,0	0,3	1,9	0,0	0,0	**4,1**
Miscellaneous Industries	5,4	0,0	0,4	1,8	0,5	1,5	**9,7**
Total	**92,1**	**18,2**	**28,5**	**100,6**	**9,9**	**58,4**	**307,7**

According to Figure 3-3 and Table 3-3 gas and electricity are obviously very important energy carriers in the Austrian industry, due to the fact, that both are used in every industrial sector. Particularly, 22 PJ of the pulp, paper and print industry's energy demand is covered only by gas. The share of renewable energy use is very high in some industrial sectors, e.g. 57% in the wood working industry or 33.5% in the pulp paper and print industry, as shown in Figure 3-3. However, there is still a need to reduce the gas demand in nearly all industrial sectors.

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10 Coal includes hard coal, lignite, BKB, peat, coke, blast furnace gas and coke oven gas (Statistics Austria, 2010b)

11 Oil includes: crude oil, refinery feedstocks, gasoline, kerosene, fuel oil, other oil products and refinery gas (Statistics Austria, 2010b)

12 Gas includes natural gas and gasworks gases (Statistics Austria, 2010b)

13 Renewable includes all energy carriers as waste, fuel-wood, bio-fuels, ambient-heat, hydro- and wind-power and PV (Statistics Austria, 2010b)

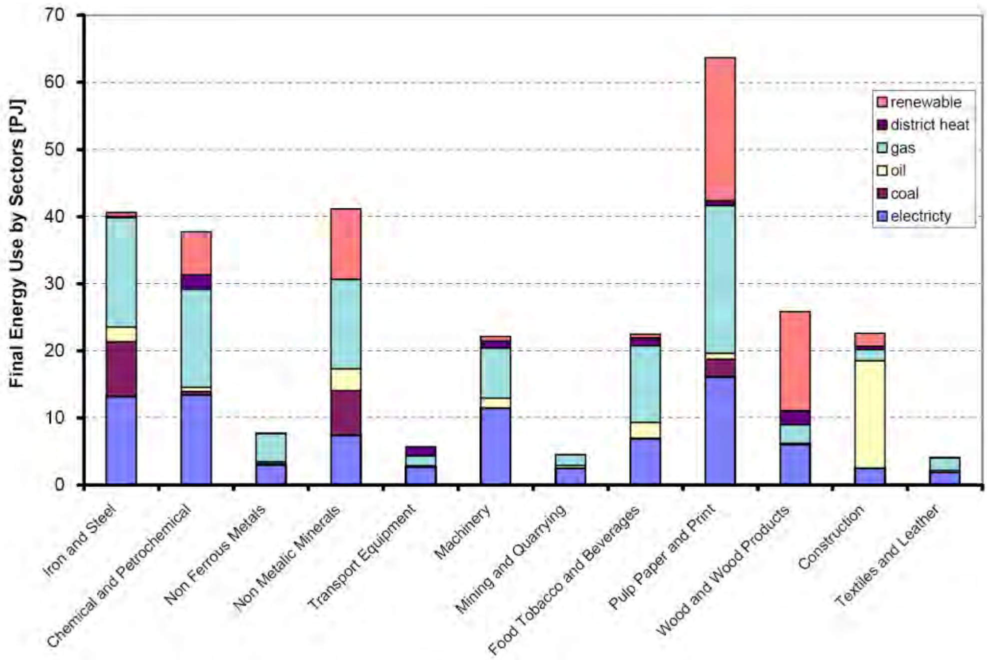

Figure 3-3: Distribution of energy carriers in each industrial sector in Austria 009 (Data according to Statistics Austria, 2010b – values for final energy consumption)

As shown in Figure 3-4, gas is still the most used energy carrier for the Austrian industry and covers 33% of the overall final energy demand, closely followed by electricity with a share of 30%. 48% of the overall final energy consumption in the industry has been covered by gas, oil and coal and only 19% by renewable energy. The problems caused by the extensive use of fossil fuels are the import- and price-dependence from foreign countries as well as CO_2-emissions, as mentioned before. In order to improve this situation, the application of industrial heat pumps offers the possibility to substitute a part of the fossil energy use by upgrading waste heat to process heat.

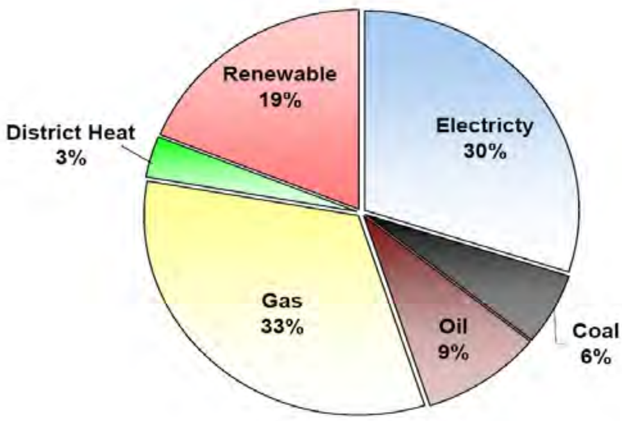

Figure 3-4: Final energy balance of the different energy carriers in Austrian Industry, 2009 in percentage (Data according to Statistics Austria, 2010b)

3.1.2 Heat demand of Austrian Industry

In order to determine the heat demand based on the overall final energy consumption of the Austrian industry, a share of 74% has been assumed for Austria for the year 2002 according to Vanonni et al. (2008). Assuming that this share has not changed from 2002 to 2009, the heat demand in the Austrian industry amounts to 228 PJ in 2009, based on the overall final energy consumption in the Austrian industry of 308 PJ according to Statistics Austria, 2010b. Even if this share would be a little bit lower, the heat demand represents the bulk of all energy functions in the Austrian industry.

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3.2 Market overview

3.2.1 Austrian Industry

Austria is declared as an industrial country, even though the service sector takes the biggest share of the Austrian economic performance. The reason for this is that it is difficult to make a clear distinction between production and service in Austria. To permit an international comparison this two segments are considered together in the category "Production of goods". According to Austria 2006 (2006) it can be concluded that the industry remains the principal driver of economic activities and development in Austria. (Austria 2006, 2006)

Many small and medium-sized enterprises characterize the Austrian industry landscape. In 2006, approximately 40% of all companies of Austria had less than 10 employees, about 80% had less than 100, and only 1.4% of all companies had more than 1,000 employees. (Austria 2006, 2006)

Based on the share of industry in the gross value added, Austria has one of the world's largest industrial sectors in 2003. Following branches have traditionally accounted for the largest share of Austria's production overall: mechanical engineering and steel work, the motor vehicle trade, the chemical, electrical and electronics industries. Nevertheless, there are new fields in which Austrian companies have also performed well, as material engineering and surface coatings, IT, biotechnology and medical technology, as well as hydraulic engineering and environmental technology, in recent years. (Austria 2006, 2006).

The Austrian industry can be classified according to Federation of Austrian Industries (IV, 2010) in following sectors (Table 3-4):

Table 3-4: Sectors of the Austrian Industry [Data according to IV, 2010]

Industrial sectors in Austria
Foundry Industry
Non-ferrous Metal Manufacture
Leather production Industry
Leather processing Industry
Electro and Electronic Industry
Wood-working Industry
Chemical Industry
Automotive Engineering
Food & Drug industry
Petrol Industry
Glass Industry
Nonmetallic minerals and ceramic industry
Paper & board processing industry
Paper manufacturing industry
Apparel Industry
Textile industry
Music and Film Industry
Machinery and Metalwork Industry
Building industry
Mining
Gas- and heat supply companies

3.2.2 Process temperatures in the Austrian Industry

An estimation of the distribution of the heat demand at different temperature levels for the Austrian industry was made from the available data in Figure 3-5. For the estimation, the total final energy consumption from the table "Distribution of energy carriers in each industrial sector in Austria 2009"[14] was used with an assumption, that the share of the heat demand is equal for all sectors, since no detailed data were found. For the distribution of the heat demand at different temperature levels over different industrial sectors, figures from Euroheat & Power (2006) from 2003 for EU 27 plus Turkey, Croatia, Iceland, Norway and Switzerland were used. Not all industrial branches from the above

[14] Table 3 from the Austrian Team Report - IEA HPP-IETS Annex 13 / 35 -Application of Industrial Heat Pumps; Task 1 – Part1

mentioned table were considered, since for a number of them no figures were available. However, the industries considered account for about 80% of the total final energy consumption.

Figure 3-5 shows, that almost half (47%) of the heat energy demand in Austria is at temperatures over 400°C. About a quarter (27%) of the heat demand is at temperatures from 100°C to 400°C and a quarter (26%) at temperatures below 100°C.

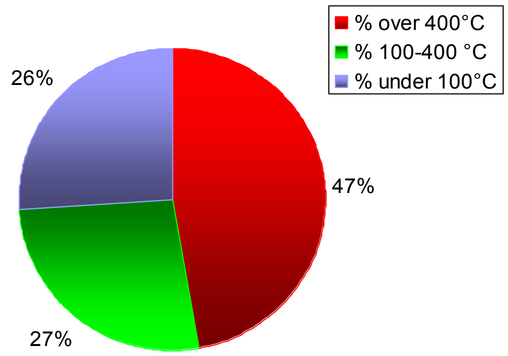

Figure 3-5: Estimation of the cumulative industrial heat demand by temperature level for selected Austrian industry branches[15] (Data according to Euroheat & Power, 2006)

The application of IHP for industrial waste heat utilization is reasonable up to 100°C or even above depending on the heat pump technology applied. This means, that the theoretical potential for the application of IHPs is about 30-40% of the overall heat demand in the industry according to the required temperature levels, including industries not considered in Figure 3-5.

In order to determine the realizable potential for the application of IHPs, it should be mentioned, that each industrial sector and each production process itself have to be regarded in detail. The operating range of thermal solar heating plants is similar to the temperature levels for the application of Industrial Heat Pumps. Various reports about the solar heating application in the industry are available in literature and have been collected to get necessary information about the process temperatures of the most significant processes in each industrial sector, which are listed in Table 3-5. As one can see in Table 3-5, there exist several different processes in the Austrian industry, which are theoretically suitable to cover their head demand by the application of IHPs.

[15] The following industry branches were not considered compared to the table 3 from the Austrian Team Report - IEA HPP-IETS Annex 13 / 35 -Application of Industrial Heat Pumps; Task 1 – Part1 "Distribution of energy carriers in each industrial sector in Austria 2009": Wood and wood products, construction industry, textiles and leather and miscellaneous.

Table 3-5: Industry sectors and processes including appropriate temperature levels for heating applications (Data according to Brunner et al., 2007, Slawitsch et al., 2007, Weiss, 2005 and Solarwärme, 2011)

Sector	Example for temperature levels of thermal processes
Food	• Preheating of substances (20-60°C), • Pasteurizing/Sterilization (70-120°C) • Boiling (100-240°C) • Distillation (40-100°C) • Drying (40-250°C) • Vaporizing (40-170°C) • Washing(30-60°C) • Substance concentration (60-70°C) • Baking (160-260°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C) • Cooling (-18-20°C)
Metal	• Galvanic (20-100°C) • Washing (30-60°C) • Drying (60-90°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C)
Paper and board	• Preheating of substances (40-80°C) • Boiling (160°C) • Drying (110-240°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C)
Textile	• Coloring (40-130°C) • Laundering (40-100°C) • Bleaching (60-100°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C)
Chemistry	• Preheating of substances (~60°C) • Boiling (95-105°C) • Distillation (110-300°C) • Thermoforming (130-160°C) • Substance concentration (125-130°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C) • Cooling (5-15°C)
Wood	• Drying (50-80°C) • Squeezing (120-180°C) • Staining (50-80°C)

Table 3-6 contains the results of a review about the required temperature levels for cooling demand in the Austrian industry in the different sectors. Particularly the sectors food and chemistry require bride temperature ranges for their cooling demand, down to -50°C. A high cooling demand signifies a theoretically high potential for waste heat utilization according to the temporary simultaneity with the heat demand.

Table 3-6: Required temperature levels for the cooling demand in Austrian Industry sectors (Data according to ETA ENERGIEBERATUNG, 2008)

Sector	Temperature levels for cooling applications
Food	-50 – 6°C
Plastics	6°C
Metal	6°C
Chemistry	-50 – 6°C
Brewery	-10°c
Dairy	-10 – 0°C
Store	-30 – 6°C

3.2.3 Overview of the Austrian industrial heat pump market

In order to give an overview of the Austrian industrial heat pump[16] market a simple online-search was performed. In the course of the online-search only a few reports of IHP applications were located, which are mostly referenced by Austrian heat pump manufactures themselves. But up to now there are not any figures of already installed industrial heat pump plants in Austria or outsells available.
However, this online-search gives an overview of Austrian IHP suppliers. The Austrian IHP market includes open cycle heat pump technologies (MVR) as well as closed heat pump technologies (compression heat pumps and sorption heat pumps). Several Austrian heat pump manufactures produce compression heat pumps for industrial applications even in series. These heat pumps are nowadays assembled for the cooling and heating in residential buildings, industrial premises, hotels, office buildings and recreational facilities and for the utilization of industrial waste heat. These heat pumps have the capability to achieve heat sink temperatures up to 65°C and are designed for heating capacity up to 700 kW, most of them using R134a as refrigerant.
Generally, it can be concluded that, the utilisation rate of IHP applications in Austria is still low. However, the Austrian industry features a relative high theoretical potential of IHP application and according to IZW (2009) the market of industrial heat pumps is rapidly growing in Austria. Especially in the field of large plants the demand rises sharply.

3.2.4 Energy prices

A rise of the energy prices is not limited to certain regions. It is worldwide observable and goes along with the demand of energy. The energy demand of Austria shows an

[16] Industrial heat pumps within this annex are defined as heat pumps in the medium and high power ranges which can be used not only for heat recovery in industrial processes, but also for heating, cooling and air-conditioning in residential, commercial and industrial buildings. The power range for the refrigerating capacity of industrial heat pumps settles between 50 and 150 kW for medium power systems and between 150kW to several MW for high power systems. This heat can deliver heat at temperatures of 100 °C and more.

increasing trend over the past decades. Together with the energy demand, the prices for the conventional energy carriers show a generally increasing trend. Table 3-7 shows the energy prices for the most common conventional energy carriers for the Austrian industry. Due to the trend of the energy prices of the conventional energy sources, it can be assumed that the usage of heat pumps gets more interesting and profitable.

Table 3-7: Energy prices (incl. VAT) for the Austrian industry from 2003 to 2009 (Data according to Austrian Energy Agency, 2010 for natural gas and Statistics Austria, 2011 for other energy carriers)

Final consumer prices for industry (incl. taxes)						
Year	Black coal [€/MWh]	Natural gas * [€/MWh]	Heavy fuel oil [€/MWh]	Gas oil [€/MWh]	Fuel oil [€/MWh]	Electricity [€/MWh]
2003	9,25	20,94	19,87	28,31	58,05	--
2004	16,45	20,52	21,40	32,17	61,11	92,52
2005	17,16	22,11	28,49	39,05	66,20	81,90
2006	17,24	29,53	33,41	44,99	72,31	87,00
2007	17,69	30,87	34,67	47,31	73,33	98,00
2008	20,36	--	45,98	43,66	78,42	105,43
2009	20,89	--	35,14	31,06	60,98	--

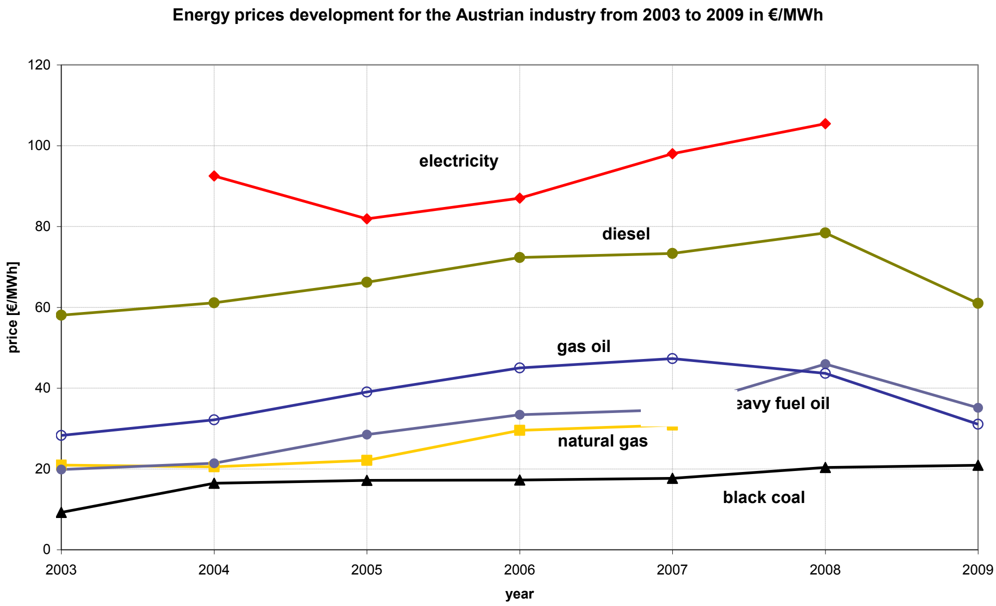

Figure 3-6: Development of energy prices (incl. VAT) for the Austrian industry from 2003 to 2009 (Data according to Austrian Energy Agency, 2010 for natural gas and Statistics Austria, 2011 for other energy carriers)

It can be seen from Figure 3-6 that, due to the global economic crisis, all energy prices, except for black coal, decreased after 2008. For 2003 and 2009 there is no data available for the electricity price. The prices of natural gas for commercial usage for 2008 and 2009 are also missing in the used sources. The prices shown are not inflation-adjusted.

3.2.5 Legal documents

This chapter gives an overview of standards as well as funding guidelines in Austria concerning the application of IHPs.

National and European Standards
The following standards are relevant in Austria for an application of an industrial heat pump plant:

- **OENORM EN 378-1** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 1: Basic requirements, definitions, classification and selection criteria"
- **OENORM EN 378-2** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 2: Design, construction, testing, marking and documentation"
- **OENORM EN 378-3** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 3: Installation site and personal protection"
- **OENORM EN 378-4** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 4: Operation, maintenance, repair and recovery"
- **OENORM EN 12263** (1999-01-01) "Refrigerating systems and heat pumps - Safety switching devices for limiting the pressure - Requirements and tests"
- **OENORM EN 12284** (2004-01-01) "Refrigerating systems and heat pumps - Valves - Requirements, testing and marking"
- **OENORM EN 12309-1** (1999-10-01) "Gas-fired absorption and adsorption air-conditioning and/or heat pump appliances with a net heat input not exceeding 70 kW - Part 1: Safety"
- **OENORM EN 12309-2** (2000-04-01) "Gas-fired absorption and adsorption air-conditioning and/or heat pump appliances with a net heat input not exceeding 70 kW - Part 2: Rational use of energy"
- **OENORM EN 13313** (2002-06-01) "Refrigerating systems and heat pumps - Competence of personnel"
- **OENORM EN 14276-1** (2006-11-01) "Pressure equipment for refrigerating systems and heat pumps - Part 1: Vessels - General requirements"
- **OENORM EN 14276-2** (2007-08-01) "Pressure equipment for refrigerating systems and heat pumps - Part 2: Piping - General requirements"
- **OENORM EN 14511-1** (2004-08-01) "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors - Heating mode - Part 1: Terms, definitions and designations"
- **OENORM EN 15316-4-2** (2005-12-01) "Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-2: Space heating generation systems, heat pump systems"
- **OENORM EN 15450** (2008-01-01) "Heating systems in buildings - Design of heat pump heating systems"
- **OENORM EN 15834** (2008-09-01) "Refrigerating systems and heat pumps - Qualification of tightness of components and joints"
- **OENORM H6021** (2003) **"**Ventilation equipment – Keeping of cleanness and hygiene"
- **OENORM H6020-2** (2007) "Ventilation equipment in clinics and hospitals – operation, maintenance, technical and hygienic control"

- **OENORM H6021** (2003) “Ventilation equipment – Keeping of cleanness and hygiene**“**
- **OENORM H6020-2** (2007) “Ventilation equipment in clinics and hospitals – operation, maintenance, technical and hygienic control**“**
- **OENORM B5019** (2007) “Hygienic design, operation, maintenance, reconstruction and supervision of drinking water equipment”

3.2.6 Funding of industrial heat pumps in Austria

National grants for the installation of an IHP can significantly reduce the payback period and consequently take an influence on the decision to invest. The Kommunalkredit Public Consulting (KPC) banking institution manages the national grant system in Austria. According to KPC (2011a) several guidelines cover the grant regulations for IHP applications:

- Heat pumps < 400kW$_{th}$ (KPC, 2011b)
  Specifications: water/brine or water/water heat pump: COP>4
  air/water heat pump: COP>3,5
  Grant ratio: max. 30% of environmentally relevant investment costs

- Heat pumps > 400kW$_{th}$ (KPC, 2011c)
  Specifications: water/brine or water/water heat pump: COP>4
  air/water heat pump: COP>3,5
  Grant ratio: max. 15% of environmentally relevant investment costs

- Efficient energy use – process-oriented measures (KPC, 2011d):
  Specifications: industrial waste heat utilisation
  Grant ratio: max. 30% of environmentally relevant investment costs

Furthermore it is possible to apply for additional regional grants according to the different federal systems in Austria.

3.3 Barriers for applications

At present no detailed information about market barriers of IHPs in Austria are found. In the course of this Annex more detailed information’s about the barriers will be ascertained form the Austrian industry. Therefore, a questionnaire was set up in order to gather and evaluate stake holder opinions, which shall be included within the final Annex report. However, from a preliminary evaluation following barriers possibly play a major role in the Austrian IHP market:

- Despite the national grant regulations for industrial heat pump applications, the economical point of view seems to be one of the most deciding barriers, which can hind the full market success in Austria. Austrian industrial companies claim for very short payback periods. It is estimated that the payback periods should be less than three years.
- Additionally, so far the confidence in the Austria’s industrial companies in the IHP-technology is not given regarding to the less experience and knowledge. So it seems to be necessary to promote the IHP-technology to the Austria’s industrial compa-

nies, e.g. by referencing to best practise cases. Because up to now only a limited number of installations is available, it seems to be necessary to refer to foreign demonstration and good practise cases at the beginning.

- From the technical point of view one barrier can be identified regarding to the temperature limits of most commercially available heat pumping units. Many applications are limited to heat sink temperatures below 65°C but as the study of the “Process temperatures in the Austrian Industry” shows, the theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps for heat sink temperatures up to 100°C.

To come up to their ecological potential, IHPs have to be commercial attractive on the market. The business success of IHPs depends on the profitability as well as on a flawless performance of the plants, which guarantee the confidence of the customers. The development of heat pump technologies for temperatures up to 100°C offers a greater application field. Also the dissemination of the advantages of IHP applications can promote the commercial success of IHPs.

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4 Canada

4.1 Industrial Energy use

4.1.1 Energy production in Canada

The energy industry contributes significantly to the Canadian economy, despite the global economic volatility and instable prices of fossil fuels observed since 2008. It accounts for 7% of Canada's gross domestic product and employs 2% of the Canadian labour force. In 2008, petroleum (including crude oil and natural gas liquids, upgraded and non-upgraded bitumen, and condensate) accounts for 39.4% and natural gas for 35.14% of domestic energy production, nuclear energy accounts for 6.13%, hydroelectricity for 7.49%, coal for 8.23% and wind for 0.07% (see Figure 4-1).

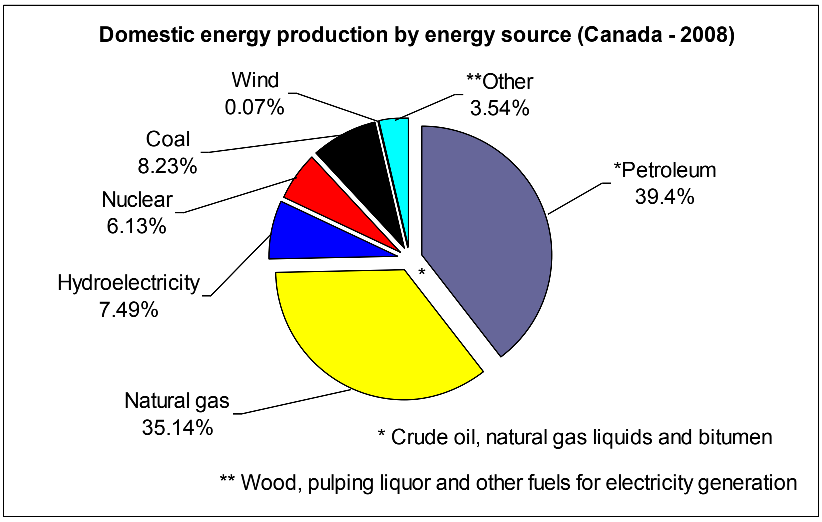

Figure 4-1: Domestic energy production by energy source – Canada 2008

4.1.2 Energy use in Canada

Canada is one of the largest consumer of energy on a per person basis in the world, consuming almost 200 GJ per capita, the equivalent of each Canadian resident using more than 5,000 litres of crude oil per year. This is approximately twice the per capita energy consumption seen in other OECD countries. 2008 total secondary energy demand (end use demand) was of approximately 11,000 PJ It is the energy used by the final consumer and represents residential (13.75%), commercial (14.04%), transportation (24.57%) and industrial (47.66%) energy demands (see Figure 4-2)

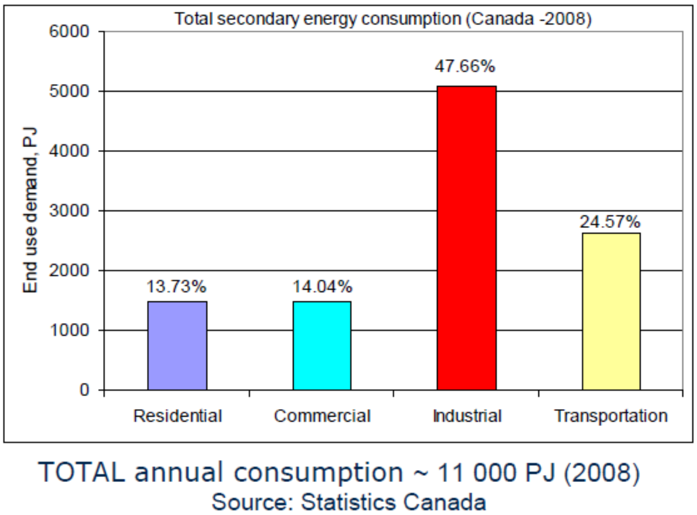

Figure 4-2: Total secondary energy consumption

4.1.3 Energy use in industry

The energy use of 14 sub-sectors of eight major Canadian manufacturing industries accounts for about 1.7 million TJ representing 65.3% of the total energy use of all Canadian manufacturing industries (2.6 million TJ). Compared to the total energy consumption, the pulp and paper sector consumes 27.6%, primary metals industries, 16% and the petroleum sector, 13.7%. Wood (3%) and food (1.2%) industries are relatively small energy consumers compared to the previous mentioned large industrial consumers (see Figure 4-3).

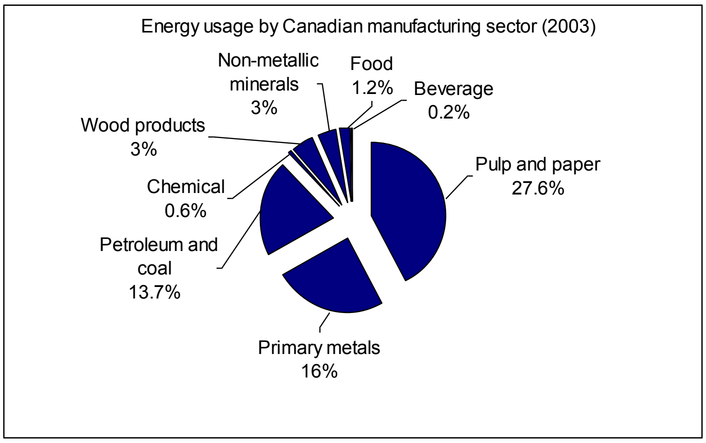

Figure 4-3: Energy use by Canadian manufacturing sectors (2003)

4.1.4 Waste heat in manufacturing industry

About 71% of the input energy is related to the environment via four classes of identifiable waste heat streams. Liquid cooling losses represent the largest class of thermal losses (553 PJ), closely followed by stack losses (524 PJ). Steam losses account for 306 PJ, and energy lost in process gases represents 290 PJ. It should be noted that “other losses” accounting for 611 PJ. However, these are normally in a form that is difficult to quantify or capture, such as radiated low-grade heat from equipment. The Figure below indicates the waste heat in 14 sub-sectors of eight major Canadian manufacturing industries:

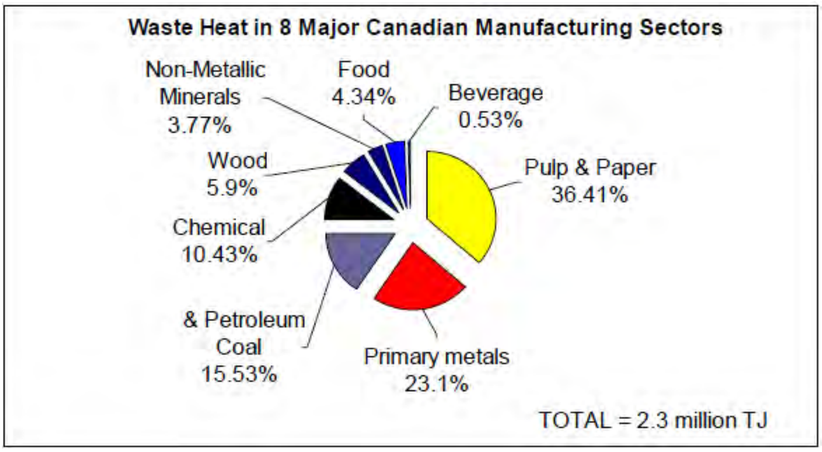

Figure 4-4: Waste Heat in 8 major Canadian Manufacturing Sectors

It shows the percentage of the total industrial waste heat that each industry sub-sector represents as a percentage of all manufacturing sector. In this Figure, not all sub-sectors of each manufacturing sector have been included. Thus, together, the selected 14 sub-sectors represent 65.3% of the manufacturing consumption, while the eight sectors account for 91.3% of the manufacturing energy usage.

More information: [1]

4.2 Market of industrial heat pumps

1994 Market Assessment

In 1994, a Canadian market assessment study [1] has investigated the industrial heat pump (IHP) potential in industries already using such heat recovery devices, as well as in processes where IHP use has been limited or non-existent. The industrial sectors already using industrial heat pumps were lumber drying, food processing (poultry, milk and cheese processing), pulp and paper production, metallurgical (iron and steel blast furnaces) and chemical production, and brewing. At that time (year end 1993), 14 chosen processes contained more than 1,900 individual plants and accounted 35% of the total Canadian industrial process heating load (Table 4-1). About 320 (17%) of these plants used industrial heat pumps. However, more than 90% (or 295 units) were found in one industry, lumber drying. In terms of current penetration, liquor distilling showed the highest level of industrial heat pumps use. The next highest levels were found in lumber drying (27%), cheese production (6%) and poultry processing (5%).

Across the 14 processes analyzed in 1994, the cumulative market penetration of industrial heat pumps under maximum scenario was estimated to be 9% by 2010 with 225 units projected to be installed. Of the total, electric closed-cycle systems were estimated to account for 70% of the potential installations, followed by mechanical vapor recompression at 19% [1].

Projected penetration under the average scenario was estimated at over 25% for four industrial processes: chlorine/soda, newsprint, pulp and specialty paper productions

For the 14 industrial processes combined, the potential to reduce industrial process heat consumption was estimated at between 5 500 – 14 600 TJ/year by 2010. Five processes were estimated to account for some 88% of the total savings: chlorine/soda production (63%), petroleum refining (7%), iron and steel blast furnaces (7%), specialty paper production (6%) and pulp production (5%) [1].

Table 4-1: Summary of 1994 industrial heat pump application in Canada [?]

Process	Number of plants	Number of IHP
Lumber drying	1087	295
Liquor distilling	24	8
Cheese production	108	7
Poultry processing	119	6
Pulp production	39	2
Milk production	179	2
Newsprint production	42	2
Iron and steel	23	0
Sugar refining	8	0
Specialty paper	28	0
Petroleum refining	33	0
Chlorine/soda production	16	0
Textile	192	0
BTX production	9	0
TOTAL	1 907	322 (17%)

Depending on the process, the potential level of energy savings per process ranged between less than 1% to 16%, with the highest levels estimated in chlorine/soda, cheese and poultry productions, and liquor distilling.

In Canada, industrial heat pumps would be reducing natural gas-based process heating energy consumption in many processes. Therefore, while they would reduce plant- and national-level emissions of all fossil-fuel based pollutants, the primary benefit would be reduced CO_2 emissions, followed by lesser reductions in SO and NOx emissions. The greatest environmental benefits from IHP use can be in processes that rely most heavily on oil and coal process heating, as pulp and paper, iron and steel, and petroleum refining [1].

During the spring 2011, a partial market assessment study of the Canadian industrial heat pump market has been performed. In order to estimate the number of industrial heat pumps existing in four Canadian provinces at the end of 2010, a simplified questionnaire has been send to several plants in some industrial sectors shown in Table 4-2. The scope was to identify the actual state and new trends of this industrial market.

Table 4-2: Industrial sectors targeted (2011)

Example of targeted industrial sectors
Lumber drying
Milk production
Cheese production
Poultry processing
Sugar refining
Pulp production
Textile
Petroleum refining

The majority of questioned plants was in Québec (eastern Canada), Ontario (central Canada) and British Columbia (western Canada), respectively. 22 plants have been identified in Manitoba (central Canada). The number of plants having responding to the questionnaire is shown in Table 4-3 by Canadian province.

Table 4-3: Number of plants that have responded to the questionnaire (2011)

Canadian province	Number of plants
Québec	132
Ontario	94
British Columbia	91
Manitoba	22
TOTAL	**339**

The number of plants with industrial heat pumps is indicated in Table 4-4. It can be seeing that only 7.67% of questioned plants use one or more industrial heat pumps for process and/or waste heat recovery.

Table 4-4: Number of industrial heat pump installed

Number of IHPs	Number of plants	%
Any	313	92.33
1	8	2.35
2	6	1.76
3	2	0.59
4	3	0.88
5	2	0.59
6	3	0.88
7	0	0.00
8	1	0.29
9	1	0.29
TOTAL	**339**	**100**

Table 4-5 shows the number of installed heat pump by industrial process. It can be seeing that 31% of them are installed in drying processes, 27% for waste heat recovery and 8% in evaporation processes.

Table 4-5: Number of installed heat pump by industrial process

Drying		**Evaporation**		**Waste heat recovery**		**Others***		**Total**
#	**%**	**#**	**%**	**#**	**%**	**#**	**%**	
8	**31**	**2**	**8**	**7**	**27**	**9**	**35**	**26**

* Others: process thermal recovery; exhausted heat recovery

Table 4-6 indicates the number of heat pumps, primary energy used as driving energy and the year of installation. The most common new installed industrial heat pumps are based on electrical closed-vapor compression cycles used especially in drying, waste heat recovery and evaporation processes. It can be also seeing that 76.9% of the industrial heat pumps have been installed after 1994, and that 92.3% of installed heat pumps use the electricity as primary energy and only 7.7% the natural gas. That means that the number of new IHPs installed between 1994 and 2010 was of 1.25/year among the 339 plants questioned.

Table 4-6: Type and date of installed industrial heat pumps

Type*	**Number**	**Primary energy**		**Year of installation**					
-	-	Electricity	Natural gas	-	-	-	-	-	-
W/W	6	6	0	1976	2000	2*2009	2 *n/a		
W/A	2	2	0	1997	2004				
A/A	7	6	1	1984	1992	2000	2001	2007	2009
A/W	1	1	0	1985					
Lumber drying	3	3	0	1979	1989	2000			
MVR	3	2	1	1985	2000	2001			
Other	4	4	0	2*2005	2*n/a	2010			
Total	**26**	**24**	**2**	-	-	-	-	-	-

* W/W: water-to-water; W/A: water-to air; A/A: air-to-air; A/W: air-to-water; MVR: mechanical vapor

The installed capacities of heat pumps listed in Table 4-6 vary between 4 to 300 tons (14 and 1050 kW) of installed cooling capacity. The compressor nominal capacity of a mechanical vapor recompression system installed in 2001 was of 257 kW.

4.3 Barriers for applications

Despite of several benefits of industrial heat pumps, as reduced energy consumption and increased capacity of heating systems, the number of this equipment installed to date is relatively low compared to the number of existing technically and economically viable opportunities. Among other reasons can be mentioned the lack of knowledge and experience with heat pump technology. Historically, technical barriers were mainly related to the availability of reliable heat pump components and the use of heat generated. Economical barriers were related to low prices of natural gas and oil versus high electricity prices. Finally, as a legal barrier, many incentives were based on product quality and/or environmental concerns *rather* than economic.

4.4 Literature

[1] IEA HPP Annex 21: Industrial Heat Pumps - Experiences, Potential and Global Environmental Benefits, IEA Heat Pump Centre,
Report No. HPP-AN21-1, April 1995

5 Denmark

5.1 Energy use in the Denmark in 2009

In 2009 Denmark had an energy consumption of 808.9 PJ, and it has been falling since 2007. From 2008 to 2009 the consumption fell by 4.0 % from 843 PJ in 2008. The share of renewable energy is 19.7 %. The electricity production based on renewable energy is 27.4 % of which wind power contributed with 18.3 %.

Table 5-1: Energy consumption in 2009

Energy carrier	**PJ**
Oil	315.6
Natural gas	165.3
Coal	168.7
Electricity	1.2
Waste heat	15.9
Renewable	142
District heat	0.2
Total	**808.9**

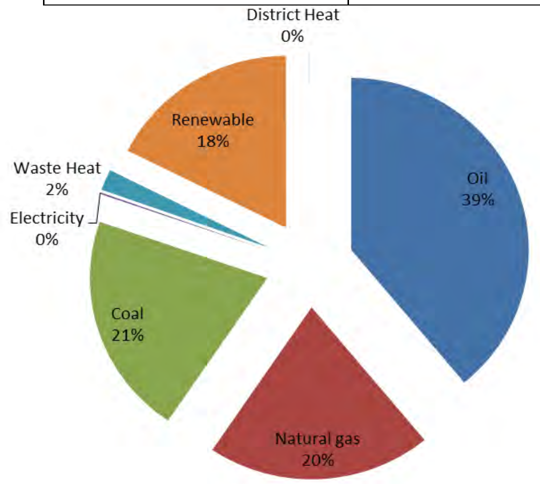

Figure 5-1: Final energy demand in Denmark in 2009 for different energy carriers [PJ]

The table depicts the net balance per energy carrier. The term 'Electricity and District Heat' does not refer to the electricity and district heat use but to the net result of import and export of electricity and district heat.

The following table presents the distribution of the total energy use across the different sectors. The energy use of energy companies relates to the conversion losses that occur during for example the production of electricity from natural gas or coal.

Table 5-2: -Energy use across sectors

Sector	PJ
Energy companies	146.6
Refining sector	44.9
Manufacturing industry	136.3
Transport	209.3
Residential	188.8
Commercial	83
Total	**808.9**

In this context the maufacturing industry comprises the following sectors: agriculture, forestry, gardening and fishing, the manufacturing industry and the building and construction sector.

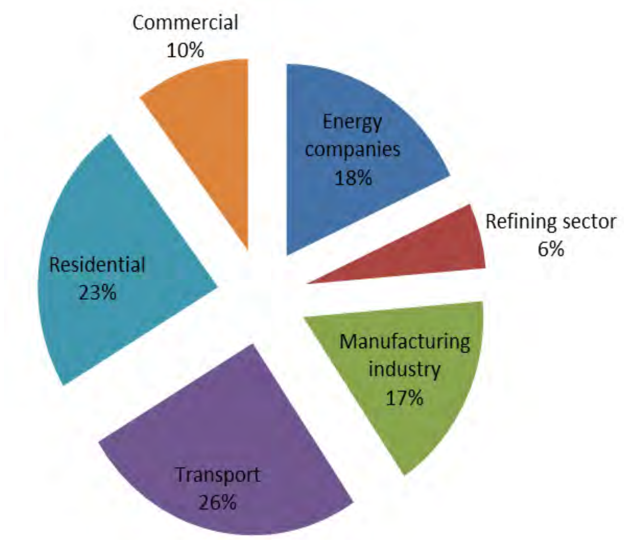

Figure 5-2: Final energy use in Denmark in 2009 for different sectors [PJ]

5.2 Energy Use in the Manufacturing Industry

The industrial energy use has been analyzed in a project from 2008 – the numbers used in this survey are from 2006. The Danish manufacturing industry used 127.2 PJ in 2006, within agriculture and fishing the consumption was 44.0 PJ, whereas the private trade and service sector used 47.6 PJ. In total, within the manufacturing industry and the trade and service sector was used 218.8 PJ.

This survey focuses on the manufacturing industry, since here is the greatest potential for large heat pumps and high temperature heat pumps.

Table 5-3: Energy use in the Danish manufacturing industry based on energy carriers in 2006 [PJ]. Wiegand og mågøe

Energy carrier	PJ
Oil	21.4
Natural gas	48.8
Coal, wood, straw	13.9
Electricity	35.8
Miscellaneous	7.1
Total	127.2

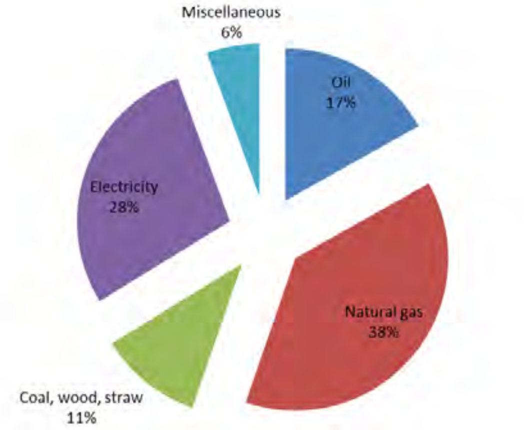

Figure 5-3: Share of industrial energy use within the different sectors

Table 5-4: Energy use in the Danish manufacturing industry based on sector and carrier

Industry sectors	**Coal**	**Rene-wable**	**Oil**	**Gas**	**Electri-city**	**District heating**	**Total**	**Share**
	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	%
Mining and quarrying	165.1	89.6	1658.0	1480.7	300.0	2.7	3696.0	**2.91**
Food, beverages and tobacco	2114.8	431.5	6997.2	12604.0	9021.0	1412.9	32581.4	**25.66**
Textile and leather	0	7.8	84.9	680.7	601.4	131.7	1506.5	**1.19**
Wood and wood products	0	2492.7	770.2	662.9	2481.0	650.0	7056.9	**5.56**
Pulp, paper and print	0	46.1	273.4	3026.5	2626.5	682.8	6655.3	**5.24**
Chemicals, medicine industry	563.8	3.4	1885.0	18016.0	5730.8	1986.8	27986.4	**22.04**
Plastic and rubber industry	0	17.463	256.0	1505.0	2551.8	154.1	4484.3	**3.53**
Metal and machinery	0	83.0	2034.4	5634.5	6782.3	1374.8	15909.0	**12.53**
Other industries	0	66.4	306.6	1044.8	2521.4	671.5	4610.6	**3.63**
Non metallic	0	0	14	1312.7	667.4	16.7	2010.9	**1.58**
Construction indus-try	10670.0	1208.1	1687.9	4323.1	2530.4	65.3	20484.8	**16.13**
Total	**13513.7**	**4446.0**	**15967.5**	**50290.7**	**35814.0**	**7149.2**	**126982.0**	**100.00**
%	**10.64**	**3.50**	**12.57**	**39.60**	**28.20**	**5.63**	**100**	

The food, beverage and tobacco industries use 25.7% of the industrial energy, whereas the medical and chemical industries use 22 %. Gas is the largest energy source in the industry and constitutes 39.6 % of the energy demand.

Table 5-5: Industrial energy use regarding sectors and application

Temperature	**Final applications**	**Fuel/FjV**	**Electricity**	**Totals**	**Share %**
		[PJ]	[PJ]	[PJ]	[%]
<70	Boiler and pipe losses	7867	0	7867	6.185575
0-120	Preheating and boiling	24592	496	25088	19.72591
40-250	Drying	15551	689	16240	12.769
40-170	Evaporation and concentra-tion	5759	0	5759	4.528121
40-100	Destillation	3755	0	3755	2.952439
300-1000	Burning/Sintering	12444	24	12468	9.803197
300-1000	Melting/Casting	2827	2458	5285	4.15543
70	Heat up to 150 °C	345	10	355	0.279125
150<	Heat above 150 °C	1187	94	1281	1.00721
NR	Transport	605	0	605	0.475693
NR	Lightning	0	2758	2758	2.168529
NR	Pumping	0	3665	3665	2.881674
NR	Refrigeration/freezing	0	3053	3053	2.400478
NR	Fans and blowers	0	6387	6387	5.021898
NR	Compressed air and process air	0	4093	4093	3.218197
NR	Size reduction	0	1599	1599	1.257243
NR	Stirring	0	709	709	0.557464
NR	Other electrical motors	0	8545	8545	6.718665
NR	Computers and electronics	0	474	474	0.372691
NR	Other electrical users	0	345	345	0.271263
50	Space heating	16436	416	16852	13.2502
	Totals	**91367**	**35815**	**127183**	**100**

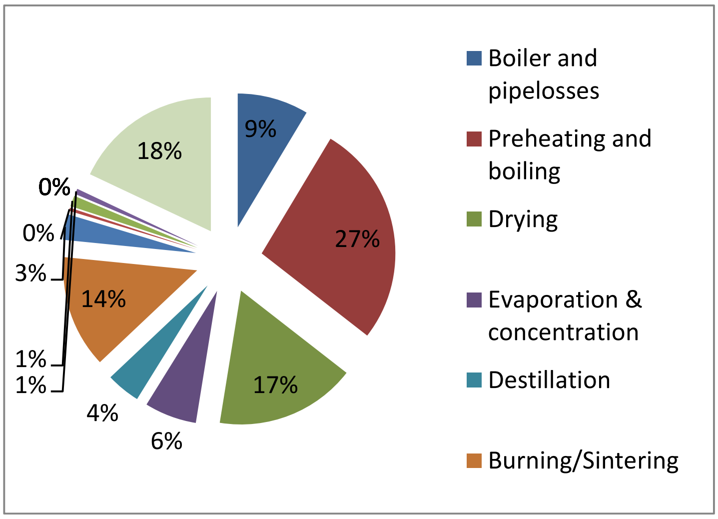

Figure 5-4: Energy use in the Danish manufacturing industry based on processes

Table 5-6: Energy use in the Danish manufacturing industry based on sectors and processes

Use	Mining	Food	Textile	Wood	Pulp and paper	Chemicals	Plastic and rubber	Metal	Other	Non metallic	Construction	Total	Share
	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	%
Boiler and pipe losses	356	3136	137	751	393	1557	341	837	224	27	296	8056	6.3
Preheating and boiling	235	7011	418	168	199	14032	202	1756	97	26	1015	25159	19.8
Drying	466	5747	186	1615	2080	1190	232	1035	115	40	2920	15626	12.3
Evaporation & concentration	2033	4025	0	0	0	478	0	0	0	0	0	6536	5.1
Destillation	0	567	0	0	0	3188	0	0	0	0	0	3755	3.0
Burning/ sintering	165	0	0	0	0	0	0	27	0	6	11930	12128	9.5
Melting/ casting	0	0	0	0	0	11	1184	1682	349	1154	905	5285	4.2
Heat up to 150 °C	0	94	32	39	0	190	0	0	0	0	0	355	0.3
Heat above 150 °C	0	586	0	58	0	0	0	281	0	128	220	1273	1.0
Transport	96	144	3	109	51	10	30	91	33	5	33	605	0.5
Lightning	9	571	78	201	295	212	194	799	294	33	72	2758	2.2
Pumping	81	1315	41	61	320	1447	84	175	38	33	69	3665	2.9
Refrigeration / freezing	0	2016	2	0	65	623	241	55	51	0	0	3053	2.4
Fans and blowers	75	1566	84	964	409	567	291	1127	486	140	677	6387	5.0
Compressed air and process air	18	596	61	386	186	1343	222	779	276	127	98	4093	3.2
Size reduction	45	290	0	47	194	53	65	2	18	7	879	1599	1.3
Stirring	0	114	0	0	54	481	42	0	0	0	19	709	0.6
Other electrical motors	69	2212	235	623	824	635	289	2096	809	120	631	8545	6.7
Computers and electronics	0	62	1	39	215	14	33	53	58	0	0	474	0.4
Other electrical users	0	0	0	0	0	0	25	298	22	0	0	345	0.3
Space heating	47	2540	227	1996	1371	2154	1010	4816	1741	164	712	16777	13.2
Totals	3696	32591	1506	7057	6655	28186	4484	15909	4611	2011	20477	127183	
	2.9	25.6	1.2	5.5	5.2	22.2	3.5	12.5	3.6	1.6	16.1	100.0	

5.3 Market Survey

Industrial demography:

From a conversional point of view, the foodstuff, metal and machine industries constitute the largest sectors within the Danish manufacturing industry. However, the chemical and medical industry exceeds the metal industry as regards use of energy. As for implementation of heat pumps, the foodstuff, chemical and medical industries are the most essential consumers of energy.

The extension of heat pumps is not huge in the Danish industry.

Challenges:

Profitability: The most important challenge is the rather low economic advantage by establishing heat pumps.

Focus on reutilization for heating: Furthermore, at great part of the focus has been on the reutilization of heat from the industry for the heating of rooms, and in this case the Danish energy tax system is a big challenge.

Knowledge: Lack of knowledge and experiences also constitutes a challenge in the industry.

5.4 Literature

1: Energistatestik 2009, Energistyrelsen (Danish Energy Agency), ISBN 978-87-7844-872-9

2: Kortlægning af erhvervslivets energiforbrug, November 2008, Energistyrelsen (Danish Energy Agency). Elaborated by: Dansk Energianalyse A/S; Viegand og Maagøe A/S

6 France

6.1 Energy in France[17]

2007 France used 154 Mtoe of Energy. The final energy consumption by fuel has been: 45% oil, 24% electricity, 20% gas and 7% renewable. The gross electricity generation was 570 TWh (2007): 77% nuclear, 12% renewable, 4% coal. The price of electricity for the industry has been 2008 one of the cheapest of Europe (6.15 € per 100 kWh).

The industry represented 2007 22% of the final energy consumption (33% transport, 27% household, 16% services and 2% agriculture).

The CO_2 emission of the French industry has been 2007 95.5 Mt of CO_2. The industry represented 24% of these emissions (34% transport, 17% energy industry, 14% residential).

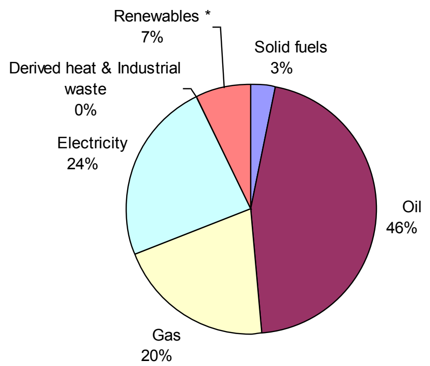

Figure 6-1: France final energy consumption by fuel 2007 (Mtoe)[18]

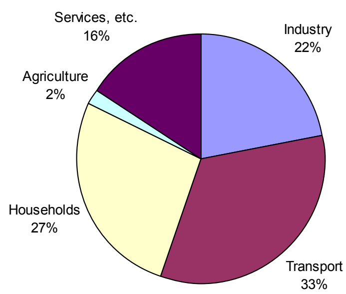

Figure 6-2: France final energy consumption by sectors 2007 (Mtoe)

[17] COMMISSARIAT GÉNÉRAL AU DÉVELOPPEMENT DURABLE - Chiffres clés de l'énergie – October 2010

[18] European Commission / ENERGY - EUROPE 2020 initiative - Energy Efficiency Plan 2011, Statistical pocketbook 2010

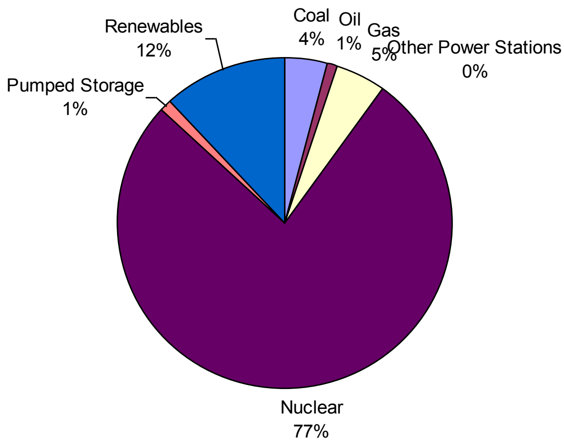

Figure 6-3: France Gross electricity generation 2007 (in TWh)

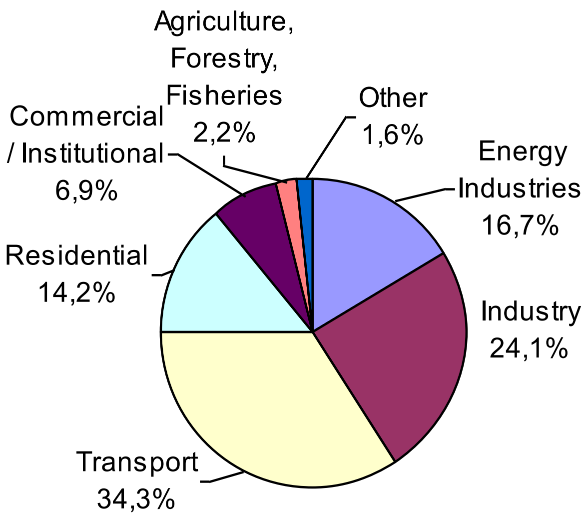

Figure 6-4: France CO_2 Emissions by sector 2007 (Mt)

6.1.1 Energy in French Industry

The industry represents 25% of the greenhouse gas emissions (24% of the total CO_2 emissions, 78% of SO_2, 44% of COV, 25% of NOx). The CO_2 emissions represent 80% of the total greenhouse gas emissions of the French industry.

The French industry represents 15% of the GDP and of the employments (3.6 for 25 millions).

The main sectors in the French industry are in 2008: 26% chemical, 17% steel, 14% Food, 13% mineral, 12% mechanical and 10% pulp and paper (two sources are presented, ADEME and EUROSTAT, the limits of the sectors are different).

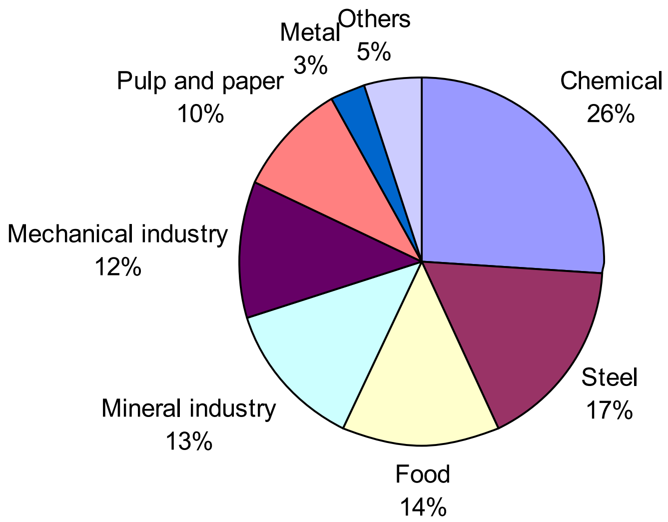

Figure 6-5: Industrial final energy consumption by sectors 2008 [19]

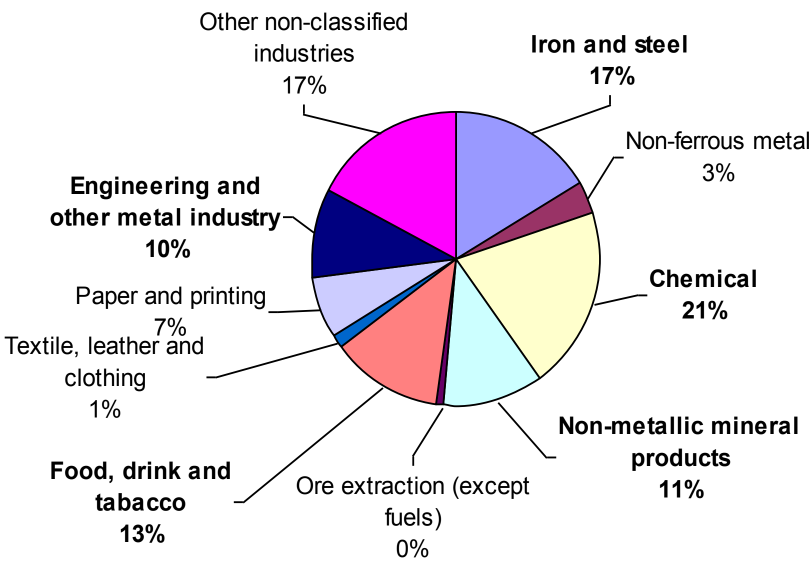

Figure 6-6: France industrial final energy consumption by sectors 2008 (Mtoe) 20

[19] Colloque Programme Energie, Vannes - France, May 29th 2009, ADEME
[20] European Commission – Eurostat - 2008

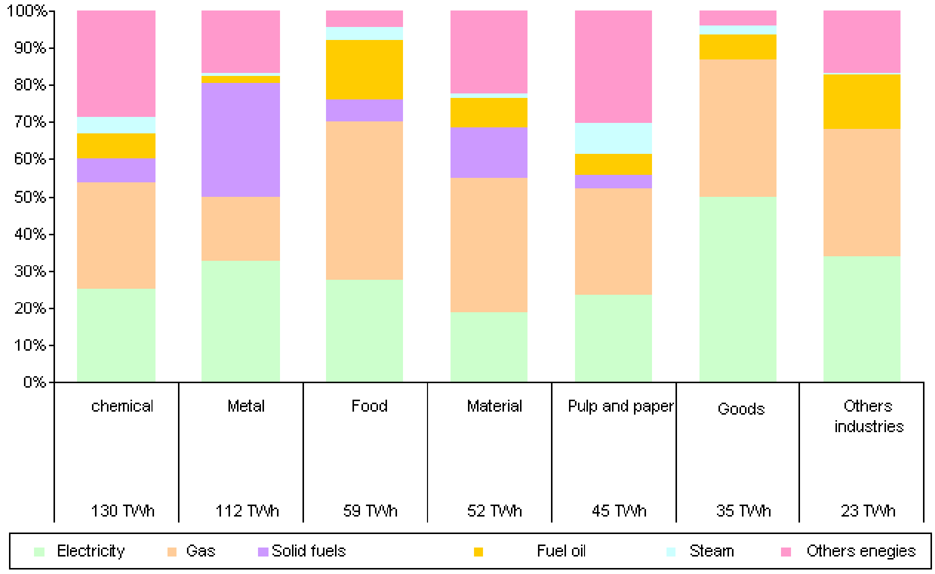

Figure 6-7: Type of energy used by industrial sectors[21]

In 2009 the energy consumption of the French industry decrease of -15.9% (-1.3% in 2008). The steel and metal industry decrease of -28.2%, the chemical industry of -10.2%, the glass industry of -15.9%, the material industry (cement, …) of -13.2% and the Pulp and paper industry of -10.1%. Only the energy consumption of food industry is stable (with +11.6% for the sugar industry).[22]

Then the electricity consumption decrease of -11% (-24% for the steel industry), the gas consumption decrease of -3.4%, fuel oil of -7.5% and coal -24% (because of the steel industry which use 70% of the coal).

The renewable energy represents 7% of the energy consumption of the industry (x2 in 10 years).

More than 70% of the energy is used to heat. In term of operation, 29% are boilers, 17% chemical reactions, 15% furnaces. The motors (motors, HVAC, Cold) represent 70% of the electrical consumption of the industry.

[21] Sources : CEREN, SESSI, AGRESTE (2010)

[22] Bilan énergétique de la France pour 2009 (Commissariat général au développement durable - Service de l'observation et des statistiques)

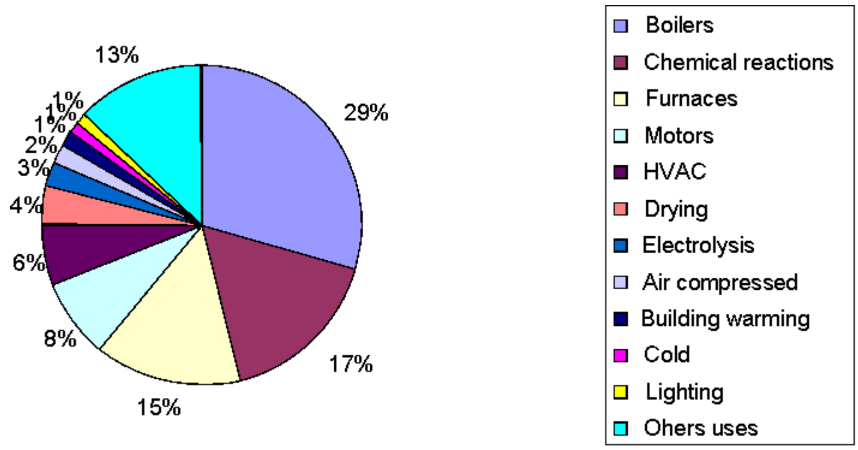

Figure 6-8: Type of uses of energy in 2007[23]

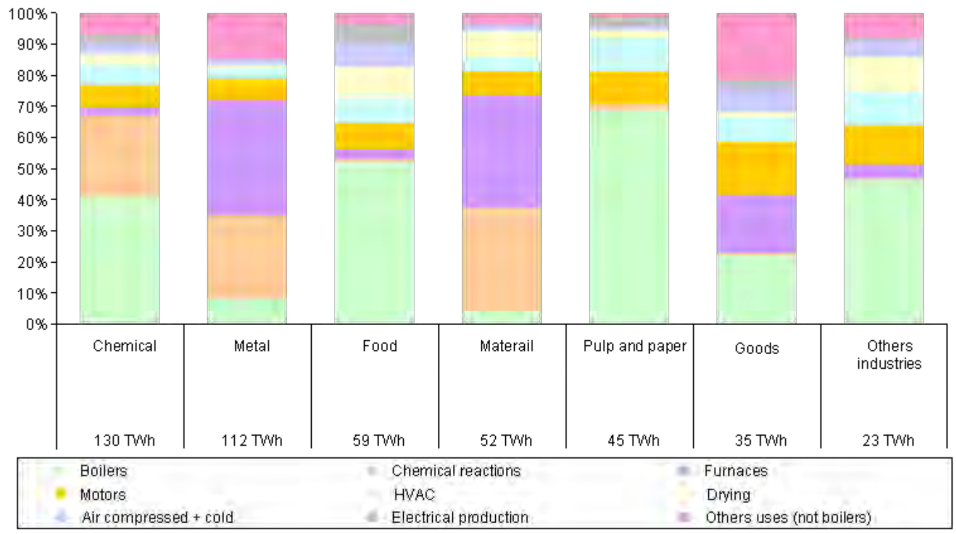

Figure 6-9: Main operations by industrial sectors[24]

6.1.2 Market assessment of industrial heat in France

This part describes the needs for heat sources and availability of cold sources.

French energy consumption analysis shows that the energy bill for the processes in the temperature range 0-200°C (all industrial sectors combined) is ten times higher than the energy bill for processes in the temperature range 0-70°C. Therefore, the development of energy efficient solutions for temperatures higher than 70°C (the limiting condensation temperature for existing industrial heat pumps), could increase potential energy savings on industrial processes by a factor of 10.

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[23] Source RTE (Operator of the French electricity transmission system.)

[24] Sources : CEREN, SESSI, AGRESTE (2010)

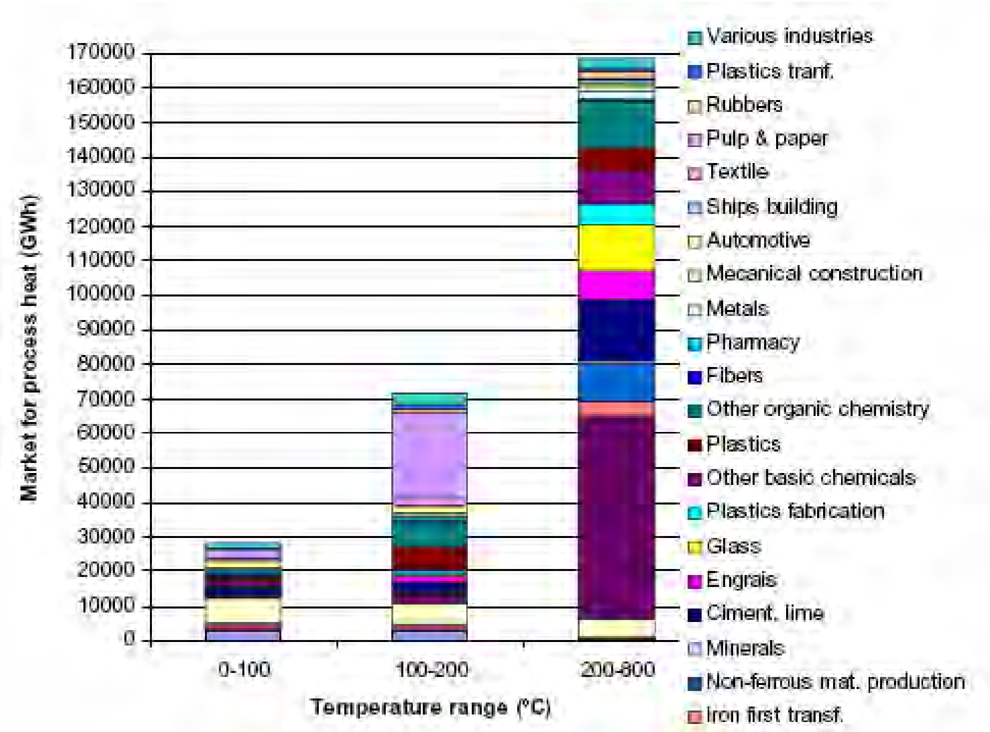

Figure 6-10: Process energy market on the 27 main industrial sectors[25]

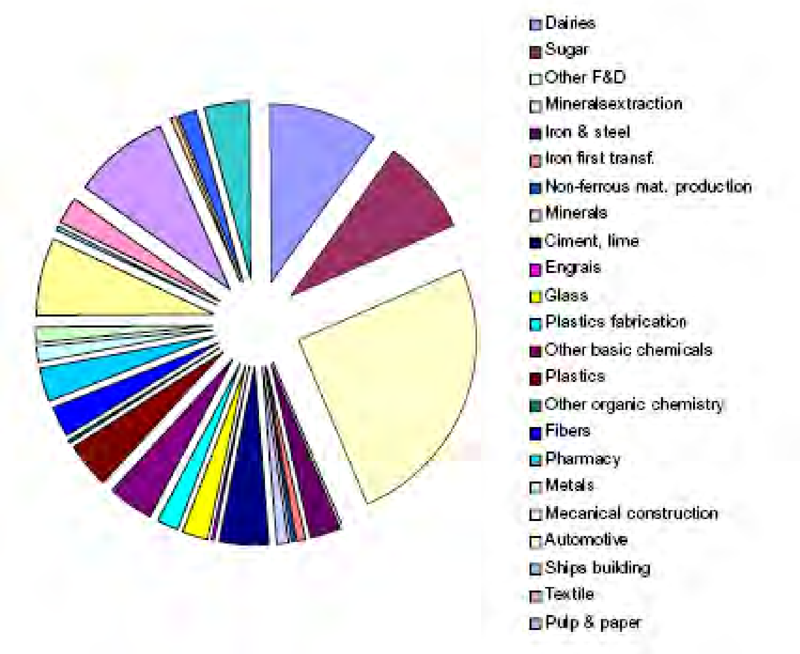

Figure 6-11: Distribution by sector of energy consumption of processes below 100°C

[25] Source : EDF-R&D (+ CEREN 2007)

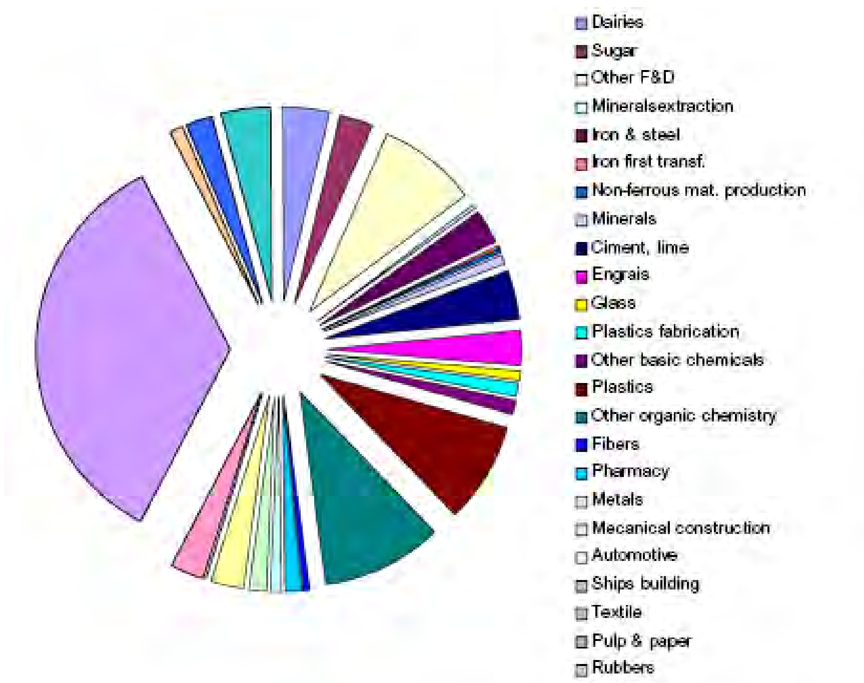

Figure 6-12: Distribution by sector of energy consumption of processes between 100°C and 200°C

By the way, the most energy consuming processes are:

- Heating of liquids and gases, very frequent between 0 and 100°C (35% of the consumption of this range) and in the food processing industry
- Drying, very frequent between 100 and 200°C (39% of the consumption in this range) and in the paper industry.

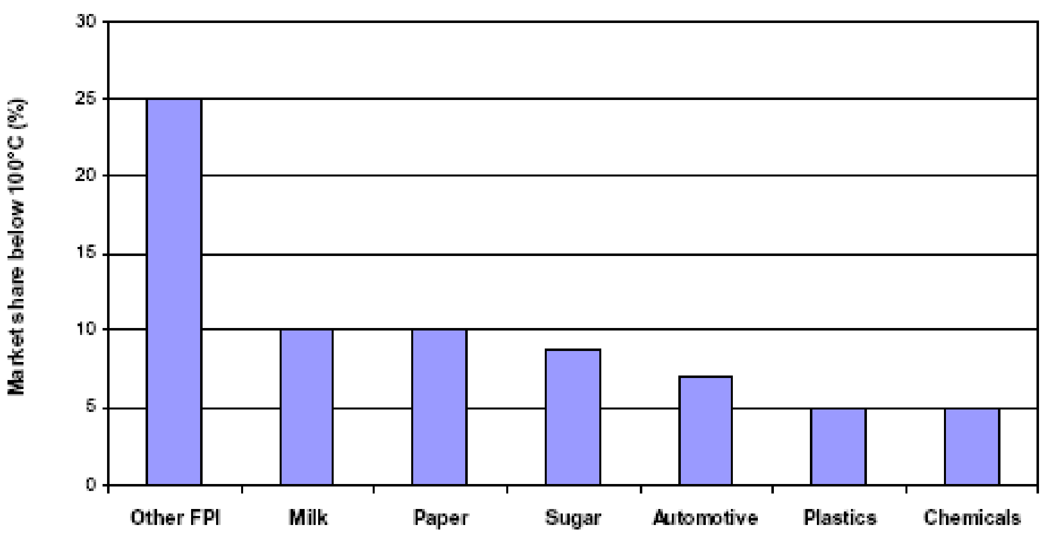

Figure 6-13: The seven sectors with the highest consumptions below 100°C

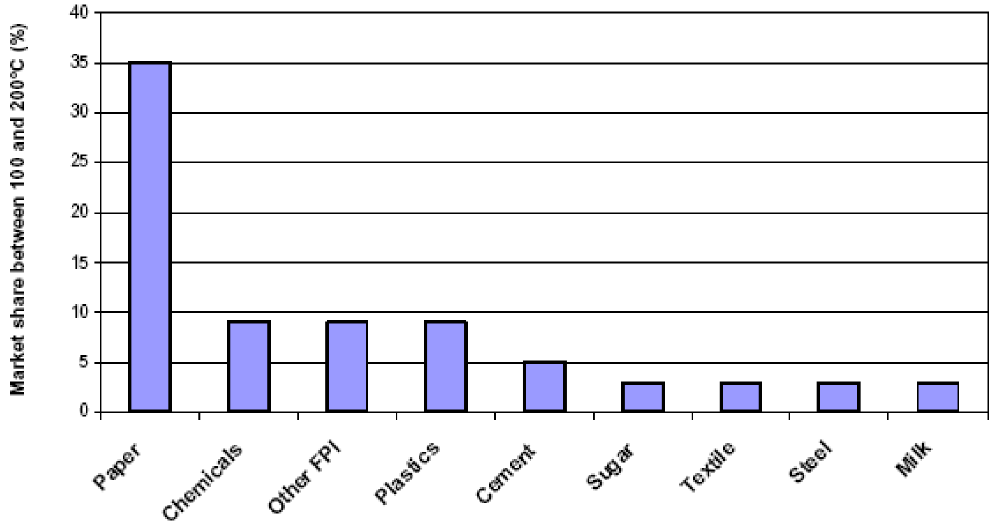

Figure 6-14: The nine main sectors for the 100°C to 200°C market

As can be seen in the figures above, in the temperature ranges 0-100°C and 100-200°C, three sectors are consuming particularly high quantities of process heat. They will be used to orientate the technological specification for a heat pump adapted to their applications:

- The food processing industry (mainly in the range 0- 100°C), including dairy and sugar;
- The basic organic chemistry industry, including manufacturing of basic plastic and elastomer materials
- The paper industry (mainly above 100°C)

These three sectors represent the respectively 64% (68%) of the total national consumption by process equipment in the temperature range 0-100°C (100-200°C).
Four other sectors consume large quantities of energy in the temperature range 100-200°C, although to a lesser extent: manufacturing of plaster, lime, cement ; automobile manufacturing ; textile industry and steelworks

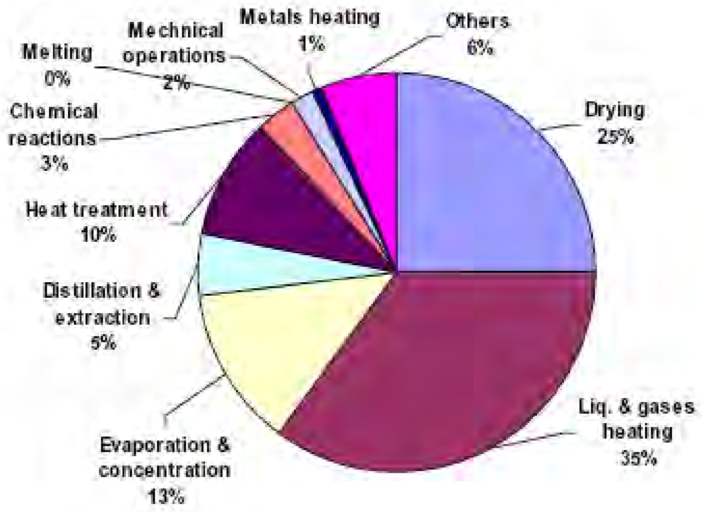

Figure 6-15: Distribution of the energy consumption on the different processes below 100°C, all sectors combined

Remarkably, each of the two temperature ranges is marked by one and possibly two major types of energy consuming operations that themselves correspond to a consumption concentration in a particular sector, despite their presence across all sectors. Thus:

- Heating of liquids accounts for 35% of energy consumption below 100°C; 47% of the energy necessary for liquid heating processes in this temperature range are consumed in the food processing industry (4.6 TWh) distributed among dairy, sugar and other food processing activities, the consumption for the dairy industry in heating of liquids being greater than consumption for all other food processing excluding sugar (see figure above).
- Drying accounts for 39% of energy consumption between 100 and 200°C; 62% of the energy necessary for drying in this temperature range is consumed in the paper sector (17 TWh), and 10% in the food processing industry (see Figure 6-16).

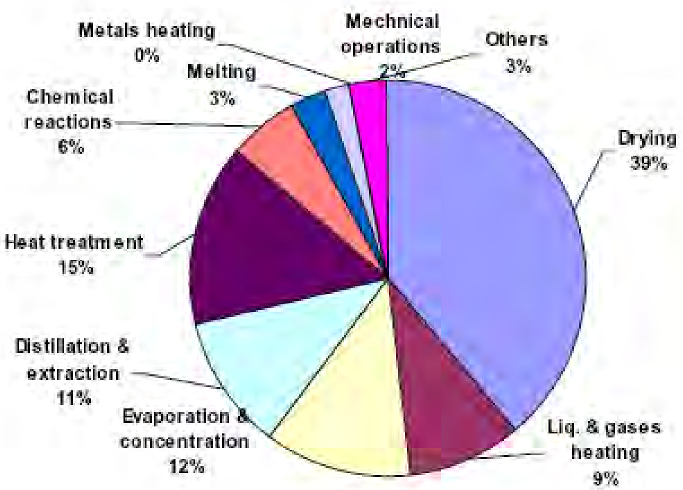

Figure 6-16: Distribution of energy consumption on the different processes between 100°C and 200°C, all sectors combined

Knowledge about consuming processes in food processing, chemicals and paper has been specified in a finer temperature range. Although the extrapolation method underestimates the number of equipment in the country and overestimates the average power per equipment, these values have validated the advantage of developing a standard heat pump for integration, substitution, make up or pre-heating for the corresponding application processes.

Key energy consuming applications for the installation of a very high temperature heat pump satisfying the two conditions (a large number of equipment and the moderate average power) are given in summary table below. Applications with a less appropriate profile composed of the number of equipment and average power, but that are still interesting due to their energy consumption have also been identified and listed in the core of this report.

It is difficult to evaluate the availability of degraded industrial heat sources that can be used by the VHT HP (Very High Temperature Heat Pump) evaporator: effluent quantities, physical and biological quality and temperatures are not well known. Nevertheless, an evaluation of the integration of a VHT HP in series on cooling units to recover heat from the cooling unit condensers, demonstrates that this solution alone could at least cover the energy consumption of the processes consuming most energy, and possibly even all process consumption, in the food processing and dairy sector.

Table 6-1: Summary of the most attractive applications of a VHT HP by temperature level

Temperature	Application	Consumption (TWh)	Number of units in France	Average unit power (MW of heat)
70 - 79°C	Dairy, pasteurisation	0.4	198	2.4
	Dairy, cleaning water	0.12	90	1.3
	Various food processing industries (FPI), heating of liquids	0.25	447	0.8
80 - 89°C	Dairy, pasteurisation	0.29	175	1.9
	Dairy, cleaning water	0.11	103	1.5
	Miscellaneous FPI, heating of liquids	0.44	438	1.6
	Miscellaneous FPI, th treatment: cooking food	0.38	521	1
	Paper, drying	0.37	276	0.8

Temperature	**Application**	**Consumption (TWh)**	**Number of units in France**	**Average unit power (MW of heat)**
90 - 99°C	Dairy, pasteurisation	0.27	182	1.1
	Miscellaneous FPI, heating of liquids	0.56	572	3.5
	Miscellaneous FPI, th treatment: cooking food	0.48	607	2.2
	Plastics, chemical reactions	0.02	101	1.6
100 - 119°C	Miscellaneous FPI, th treatment: cooking food	0.58	754	2.3
	Plastics, chemical reactions	0.16	80	4.5
	Other organic chemistry, chemical reactions	0.2	635	9
120 -139°C	Miscellaneous FPI, th treatment: cooking food	0.58	483	2.3
	Miscellaneous FPI, sterilisation, appertisation	0.92	678	3.8
	Plastics, chemical reactions: make up	0.13	55	16
	Other organic chemistry, heating of gases	0.75	274	3.3
140 - 159°C	Paper, make up drying	4.6	194	7.1
	Other organic chemistry, make up chemical reactions	0.83	1423	10.5
160 - 179°C	Other organic chemistry, make up chemical reactions	1.2	871	19
	Other organic chemistry, make up distillation	1.8	192	5.5

6.2 French Market overview

Looking at the industrial heat pump market in France, we can notice two main features:

- Open cycle heart pumps, MVR, are largely developed
- Closed cycle heat pumps are more and more used by industry, but the actual market is far to be fully developed.

Concerning MVR, a great number of installations has been realized in 80's and 90's, especially in agro-food sector. Today, most of whey concentration plants and sugar plants are equipped by MVR.

Concerning closed cycle heat pumps, the situation is different. Between the end of 80's and the beginnings of 90's some heat pumps were installed, especially for drying applications. EDF internal reports showed some existing machines in breweries and lumber drying. But most part of the potential market has not been penetrated by heat pumping technology. Today, rising of fossil energies price and increasing concerns related to CO2 emissions lead industry to discover again the energy efficiency potential of heat pumps. Several machines have been sold for recent years in different sectors, and particularly in dairies where, recovering energy at chiller condenser to valorize it at higher temperatures is becoming more and more usual.

Today, heat pumps can be found in different agro-food sectors (meat, dairy, oil, brewery) but also in cosmetic industries, PC processors plants and several other sectors. Anyway, their utilization is limited to hot water production or buildings heating. Market will be fully developed once heat pumps will be directly installed on the industrial process. The potential of this development is very high.

6.3 Barriers for applications

Three types of barriers hinder the full development of industrial heat pump market:

1. Profitability: payback period requested by French industrial customers is less than three years. Even if French electricity price is quite low, it's not easy to reach such profitability. Heat pumps are profitable when COP is high and when they're installed on a process which works all year long. For recent years, low price non conventional gas is a real barrier on heat pumps profitability.
2. Lack of knowledge: industry doesn't know heat pumps as well as boilers. Several good references are necessary before winning customer confidence.
3. Lack of specialized engineering companies: installing a heat pump on an industrial process is not easy. Heat pump is often the heart of a more complex heat recovery system including heat exchangers, secondary hydraulic loops and storage tanks. Today in France there is no engineering company special-

ized on industrial heat pump. Several manufacturers propose heat pumps for heat recovery on chillers condensers in order to produce hot water. But societies suggesting heat pump installation directly on the industrial process are almost inexistent up to now.

The three types of barriers are strictly linked: increasing profitability means more references on industrial plants, and so a growing demand and the development of specialized engineering companies able to satisfy this demand.

7 Germany

7.1 Energy use in Germany

The primary energy consumption in Germany did not change significantly in the past twenty years. Figure 7-1 illustrates this development. The minimum in 2009 is strongly related to the financial crisis that resulted in a decrease of the German GDP by 5.1 % followed by a strong recovery in 2010 /Statistisches Bundesamt 2012/.

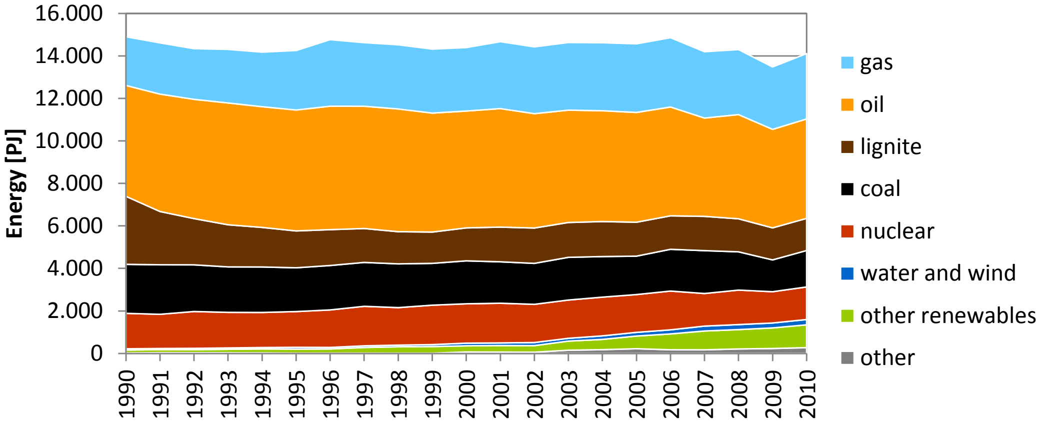

Figure 7-1: German primary energy balance per energy source /BMWi 2012/

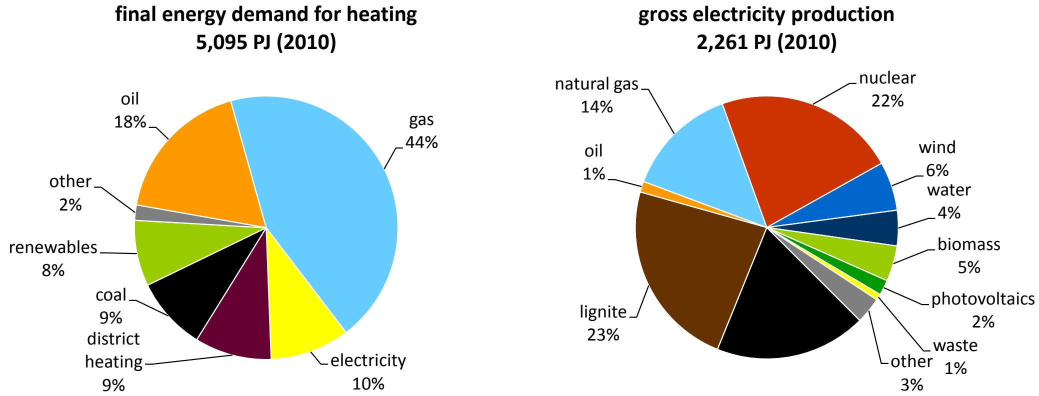

Figure 7-2: Final energy demand for heating and gross electricity by energy source in Germany /BMWi 2012/

The primary energy consumption of 14,044 PJ in 2010 was dominated by fossil energy sources. The energy mix is devided into gas (21.9 %), oil (33.3 %), lignite (10.8 %), coal (12.2 %), nuclear energy (8.8 %), water and wind energy (1.8 %), other renewables (7.6 %) and other sources (1.9 %). Figure 7-1 shows a constant increase of the renewable energy share in the last ten years.

The renewable share in final energy demand for heating has risen up to 8.1 % in 2010 but more than two thirds are covered by burning fossil fuels (Figure 7-2). In gross electricity production the share of renewable sources has risen from 7.0 % in 2000 up to

16.6 % in 2010. This led to a reduction of the specific CO_2 emissions from 623 g/kWh_{el} to 562 g/kWh_{el} /UBA 2012/.

The final energy demand in Germany can be classified in four main sectors:

- industry
- trade/services
- private households
- transport

In 2010 Germany had a final energy demand of 9,060 PJ. The shares of industry, transport and private household are of almost equal size around 28 %. Trade and services play a minor important role with a share of 15 %.

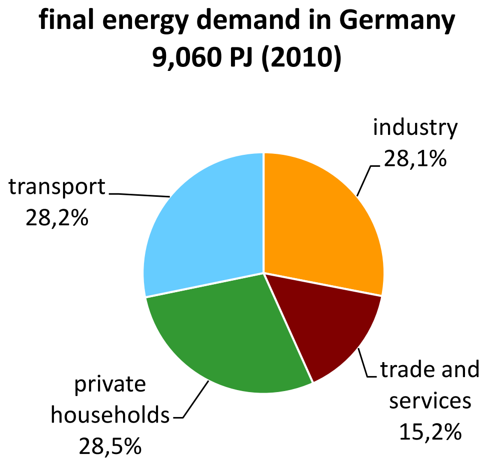

Figure 7-3: Final energy consumption in Germany by sector /BMWi 2012/

7.1.1 Final energy use in the German industry

After a decrease in the early 1990s, that was mainly caused by the collapsing industry in eastern Germany after the reunification, the final energy demand of the German industry developed constantly between 2,300 PJ and 2,600 PJ (Figure 7-4). The minimum reached in 2009 is to be seen as the effect of the financial crisis. During the last ten years the shares of renewable energies and district heat are increasing slightly, while the use of coal and oil is decreasing.

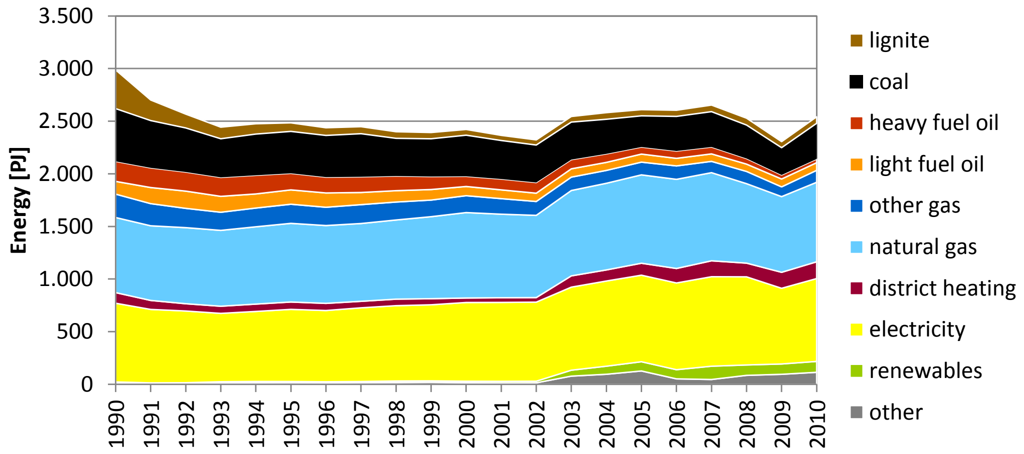

Figure 7-4: Final energy balance of the German industry from 1990 to 2010 /BMWi 2012/

In 2010 the final energy demand of the German industry has reached 2,542 PJ. The biggest share was needed in form of process heat (1,666 PJ / 65.6%), followed by mechanical energy (553 PJ / 21.7%), space heating (196 PJ / 7.7%), lighting (38 PJ / 1.5%), information and communication technology (ICT) (32 PJ / 1.3%), hot water (23 PJ / 0.9%), process cold (18 PJ / 0.7%) and climatisation (17 PJ / 0.7%). Figure 7-5 shows that heating purposes (process heat, space heating, hot water production) account for almost three quarters of the industrial final energy demand in Germany.

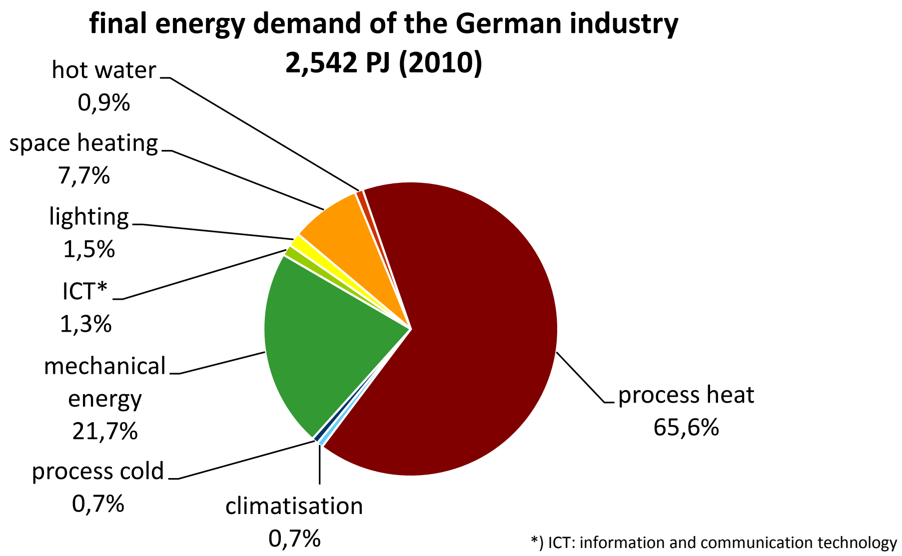

Figure 7-5: Final energy demand of the German industry in 2010 /BMWi 2012/

7.1.2 Heat demand of the German industry

The German industrial heat demand reached 1,883 PJ in 2010 (Figure 7-6). It was even more dominated by fossil fuels than the overall German heat demand (Figure 7-2). The most widely used energy source was gas (861 PJ / 45.7%) followed by coal (401 PJ /

21.3%), district heating (160 PJ / 8.5%), electricity (138 PJ / 7.3%), oil (126 PJ / 6.7%), renewables (104 PJ / 5.5%) and other sources (95 PJ / 5.0%). Although the renewable share in industrial heat production has risen slightly it is still far behind the share of renewable heat produced in private household sector (12.4 % in 2010).

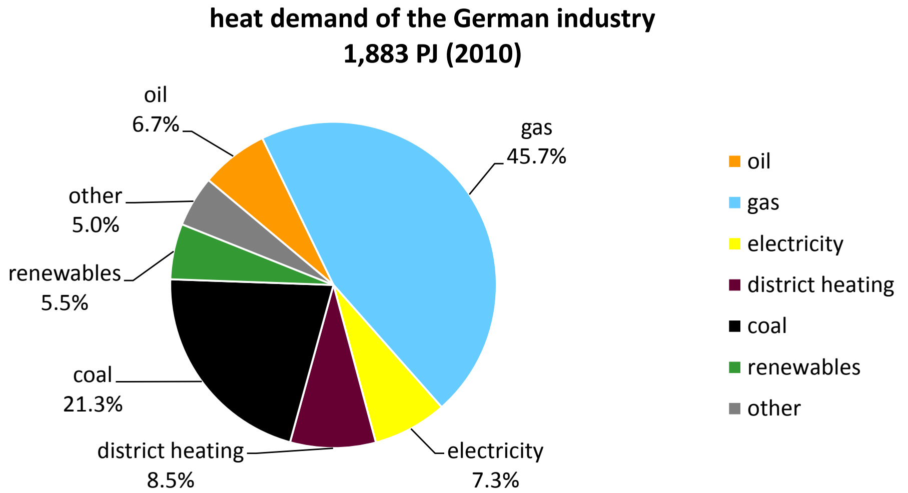

Figure 7-6: Heat demand of the German industry in 2010 by energy source /BMWi 2012/

An overview over the structure of the industrial heat demand is given in Figure 7-7. Metal production is by far the most heat consuming industrial branch followed by production of basic chemicals and food & tobacco industry. While in metal production coal is largely used for heat generation, natural gas has the biggest share in the other industrial branches.

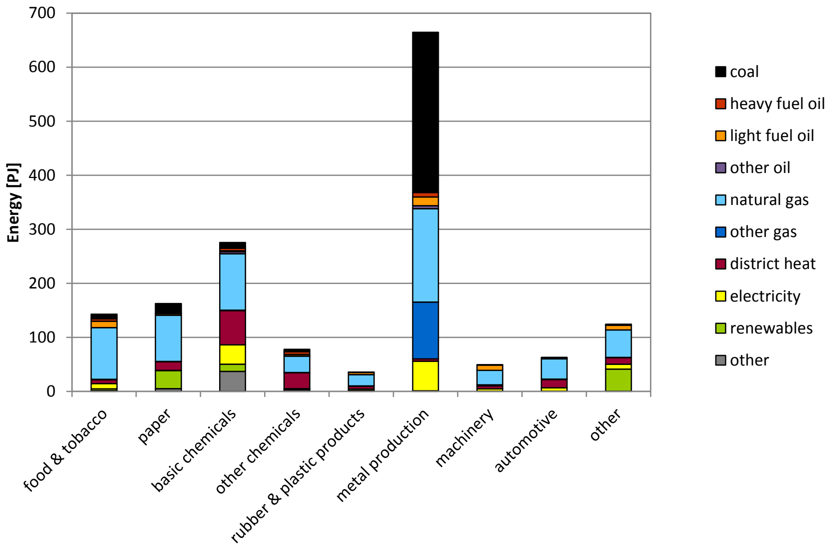

Figure 7-7: Structure of the final Energy demand for heating purposes in the German industry /AGEB 2011/

7.1.3 Industrial energy prices

As shown in Figure 7-4 the final energy demand in the German industry stayed quite constant over the last two decades. In contrast to this the energy prices for the industry have been slightly decreasing in the 1990s but started to rise in the year 2000.

Table 7-1: Development of energy prices for industry /BMWi 2012/

Final consumer prices for industry				
year	**heavy fuel oil**	**light fuel oil**	**natural gas**	**electricity**
	[ct/kWh]	[ct/kwh]	[ct/kwh]	[ct/kwh]
1991	1.04	2.07	1.47	6.91
1992	0.94	1.78	1.38	6.96
1993	0.92	1.76	1.32	7.03
1994	0.96	1.60	1.27	6.82
1995	0.97	1.52	1.27	6.74
1996	1.07	1.88	1.29	6.62
1997	1.08	1.91	1.39	6.37
1998	0.91	1.50	1.33	6.05
1999	1.07	1.96	1.27	5.34
2000	1.72	3.24	1.69	4.40
2001	1.53	2.97	2.14	4.89
2002	1.68	2.71	1.95	5.15
2003	1.70	2.81	2.16	5.79
2004	1.59	3.22	2.12	6.19
2005	2.21	4.32	2.46	6.76
2006	2.69	4.85	2.91	7.51
2007	2.62	4.77	2.77	7.95
2008	3.59	6.29	3.36	8.82
2009	2.78	4.16	3.15	10.04
2010	3.60	5.33	2.93	9.71

Table 7-1 lists the prices for the most important energy sources from 1991 to 2010. Compared to the base-year 1991 the electricity price decreased by 36.3% until 2000 and started to rise from this year on. In 2010 the average electricity price for industry was 9.71 ct/kWh, which was 40.6% higher than in 1991. The price increase for fossil fuels (heavy fuel oil, light fuel oil and natural gas) was significantly higher. In 2010 the price for natural gas was 2.93 ct/kWh (+99.7%), for light fuel oil 5.33 ct/kWh (+157.4%) and for heavy fuel oil 3.60 ct/kWh (+244.8%). In the same period of time the average cost of living in Germany increased by 42.6 %. The detailed development is shown in Figure 7-8. As energy prices are expected to further increase in the future, the market conditions for energy efficient heating technologies will further improve. For heat pumps however the electricity/gas price ratio is an important indicator for the economic feasibility. While gas prices increased faster than electricity prices in the past 10 years this ratio lead to an advantage for electrical heat pumps. This trend could be reversed in future due to the increased production of unconventional gas. This would result in an increased installation of conventional gas burners and gas driven heat pumps.

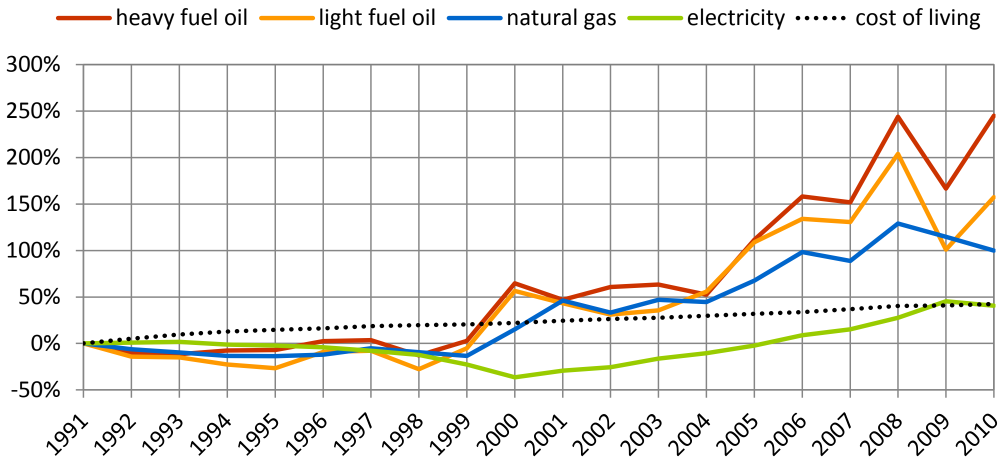

Figure 7-8: Development of energy prices for industry and general cost of living compared to the base-year 1991 /BMWi 2012/

7.2 Market overview Germany

7.2.1 German industrial sector

Although Germany is known as an industrial country with a large export of industrial products the producing sector only accounts for 24.7% (548 billion €) of the German GDP of 2,296 billion € in 2010. As shown in Figure 7-9, the service sector takes the biggest share of the German economy. Germany's export strategy and the resulting trade surplus of 128 billion € in 2010, however, are mainly driven by the producing sector.

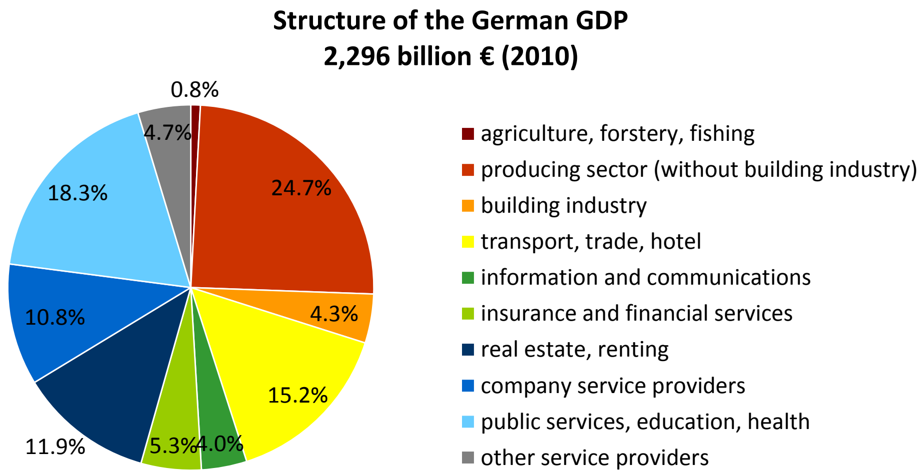

Figure 7-9: Structure of the German GDP in 2010 /Statistisches Bundesamt 2012/

The German economy is characterized by a large number of small and medium sized enterprises (SME). SMEs are defined as companies with less than 250 employees and not more than 50 million € annual turnover. All following data is taken from the year

2009, as newer statistics were not available. 99.5 % of all German enterprises fulfill the requirements of the SME definition. They account for 37.8 % of the total turnover of all German enterprises. In total SMEs employ 55.1 % of all employees in German enterprises /IfM 2011/.

7.3 Technical potential for the use of heat pumps in the German industry

The technical potential for industrial heat pumps in Germany can be derived by analyzing the heat demand of the most promising industrial sectors and the typically used processes.

Table 7-2 shows the technical potential broken down to industrial sectors and temperature levels. Data from this table is displayed in form of bar charts in Figure 7-10 Machinery, automotive, food and chemical industry show a high potential at lower temperatures up to 80 °C. These temperatures can be delivered by heat pumps using conventional refrigerants. The overall potential up to 80 °C amounts to 271.65 PJ/a, which equals 14.4 % of the industrial heat demand. When it comes to high temperature heat pumps, which operate at temperatures up to 140 °C, a great increase of the potential can be seen in food, paper and chemical industry. The technical potential for all industrial heating purposes up to 140 °C is 598.82 PJ/a. This is 31.8 % of the industrial heat demand and 23.6 % of the total final energy demand in the German industry. Figure 7-10 clearly shows a big potential for the use of high temperature heat pumps in food, chemical and paper industry. The mayor part of this potential is needed for pasteurization, sterilization, drying and thickening in the food industry, for dyeing fabrics and condensation of viscose fabrics in textile industry and for melting of polyethylene and the production of rubber in the chemical industry /Blesl et al. 2012/.

Table 7-2: Technical potential for industrial heat pumps in Germany /Blesl et al. 2012/

	hot water	**space heating**	**PH 70 °C**	**additional PH 80 °C**	**additional PH 100 °C**	**additional PH 140 °C**
	PJ/a	PJ/a	PJ/a	PJ/a	PJ/a	PJ/a
Food	7.72	21.19	8.28	8.11	15.26	84.64
Textiles	0.42	6.74	1.98	0.24	1.46	4.55
Wood	0.18	1.45	5.41	0.00	0.00	0.70
Paper	0.38	9.89	3.85	0.00	124.04	0.00
Printing	0.31	6.66	0.00	0.00	0.00	0.00
Chemicals	1.80	21.92	8.35	2.21	11.98	84.53
Plastic	0.49	8.85	14.86	0.00	0.00	0.00
Machinery	3.25	49.23	0.00	0.00	0.00	0.00
Automotive	2.28	29.70	7.15	0.00	0.00	0.03
Other	1.68	36.37	0.72	0.00	0.00	0.00
Sum	**18.51**	**192.00**	**50.58**	**10.56**	**152.74**	**174.44**

PH = process heat

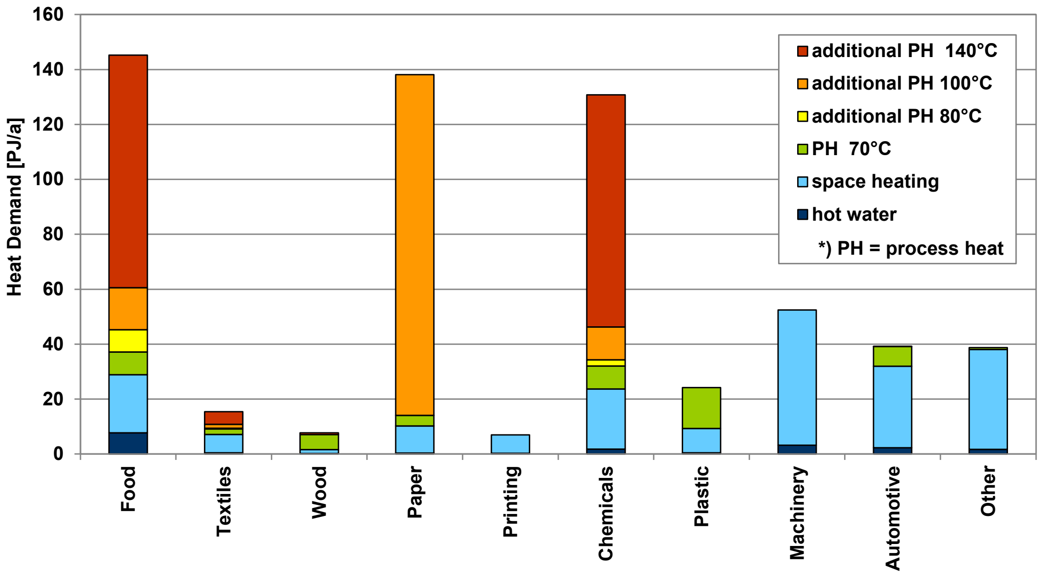

Figure 7-10: Technical potential for industrial heat pumps in Germany /Blesl et al. 2012/

7.4 German heat pump market

In Germany heat pumps are already widely used in the residential sector. Especially new buildings are often equipped with heat pumps. In 2010 612,500 heater units for residential heating were sold in Germany (Figure 7-11). Although gas fired boilers are still the most common heater type, heat pumps are increasing their market share. This lead to 51,000 sold heat pumps in 2010 and 57,000 in 2011. Half of them used ambient air as heat source.

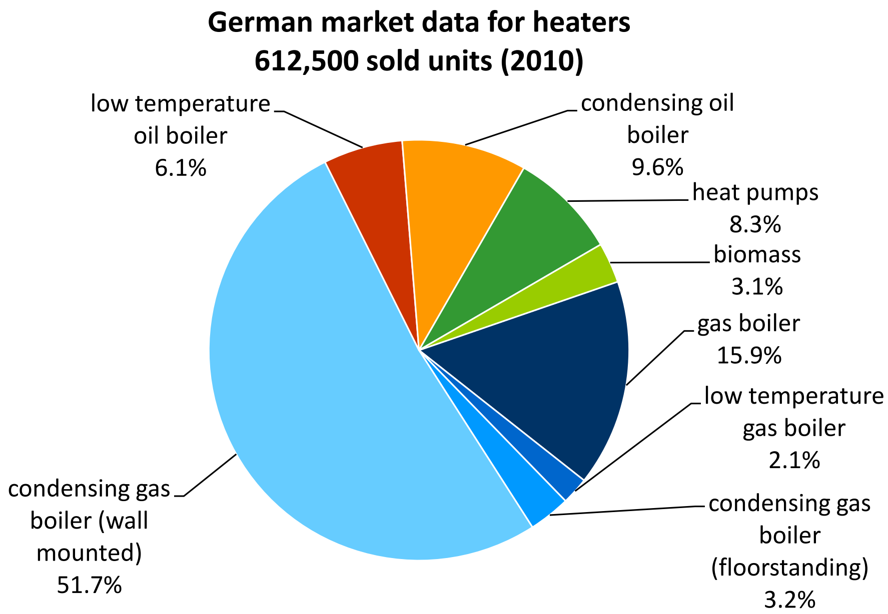

Figure 7-11: German market data for sold heater units in 2010 /BDH 2011/

Industrial heat pumps recently became available on the German market. These heat pumps not only have more power, they can also reach higher temperature levels than the models designed for the residential sector. Three different heat pump concepts using different refrigerants are available.

- Ammonia: Electrical compression heat pumps using ammonia can reach temperatures up to 90 °C.
- R245fa: Compression heat pumps using R245fa or mixtures of this refrigerant with similar properties can reach temperatures up to 100 °C.

  Current research projects aim to reach higher temperatures up to 130 °C.
- CO_2: CO2 heat pumps are especially efficient, if they are used to heat up water from a low to a high temperature level. They can reach temperatures up to 90 °C. Temperatures up to 130 °C could be available in the near future.

To distinguish the situation of heat pump planners and installers a survey has been conducted among 149 German companies. These companies were elected for the survey, if they mentioned industrial customers as well as heat pumps on their web sites. The survey was conducted in two steps. In the first step all of the 149 companies were called. Those who did not want to answer the questions on the telephone and those who could not be reached got an e-mail with information about the project and a link to a web based questionnaire. Out of 149 companies 25 filled out the questionnaire, which leads to a response rate of nearly 17 %. Figure 7-12 shows the response to the survey structured by telephone calls and e-mails.

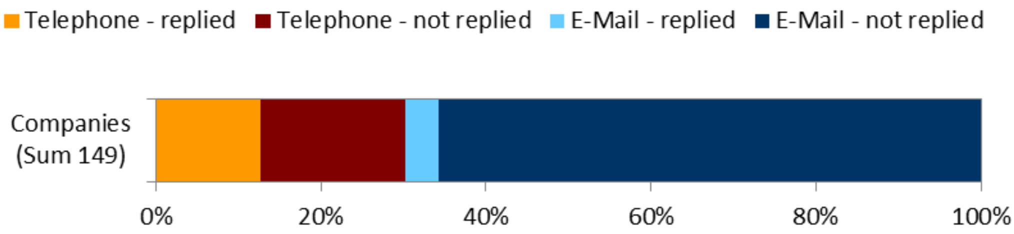

Figure 7-12: Respondents to the survey

Almost all of the respondents (96%) are experienced in planning of electrical heat pumps and 28% have experience with gas-engine heat pumps. No respondent had planned or installed a sorption heat pump.
As private households are the main application area for heat pumps most of the respondents had experience with heat pump systems for space heating (96%) and hot water production (84%). 16% had planned or installed a heat pump for process heat production. But in half of the cases the companies categorized hot water production in industrial companies as process heat.

In line with these results heat pumps are mainly applied for low temperature purposes. While 88% of the respondents had gathered experience with temperature levels of up to 55 °C, only 60 % had ever used heat pumps that could deliver up to 75°C. Only one respondent had planned ammonia heat pumps that could deliver up to 90°C.

Even though there is a large number of companies that only offer heat pump systems with small sizes of below 50 kW, 20 % of the respondents offer very large systems with more than 800 kW. Figure 7-13 shows the sizes offered by the responding companies.

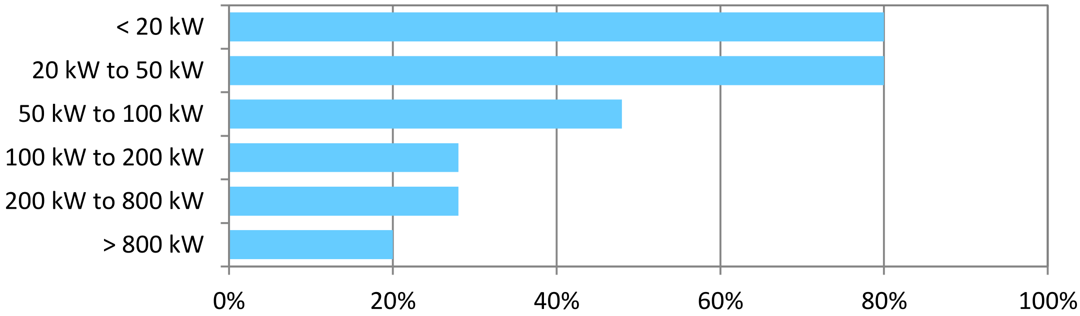

Figure 7-13: Heat pump sizes offered by the responding companies

7.5 Research and Literature

The oil price shock in the 1970s put energy research into political focus. The sudden rise of energy prices lead to a boom of energy related research. Energy research groups were founded and a large number of projects were started. Among other energy saving technologies the heat pump experienced a considerable increase of interest. Figure 7-14 shows the number of heat pump research projects that were funded by different German ministries. It also shows the amount of money invested into heat pump research from 1974 to 2011. Starting with a large number of projects in the 1970s the interest into heat pump technology peaked in the early 1980s. In 1981 funding of heat pump research reached an all-time high of 6.76 million €. With declining energy prices in the 1980s and 1990s heat pumps got out of focus. Since 2008 a growing number of heat pump research projects can be observed. Also the amount of money invested into heat pump research rose to 5.12 million € in 2011 and will continue to rise in 2012.

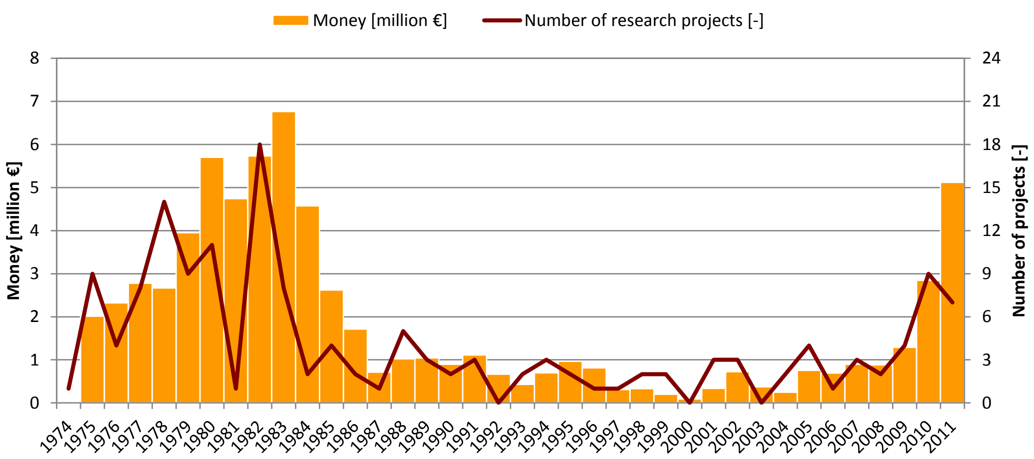

Figure 7-14: Heat pump related research projects in Germany /BMBF 2012/

To document the direct and indirect output of these research projects the amount of available literature about industrial heat pumps in German and English was analyzed. The analysis was performed by a search in the scientific search engine google scholar which can search a multitude of scientific databases. The search was performed for the terms “industrial + heat pump”, “high temperature + heat pump” and “heat pump + process heat” as well as for the German translations “Industrie + Wärmepumpe”, “Hochtemperatur + Wärmepumpe” and “Wärmepumpe + Prozesswärme”. The results of this analysis are shown in Figure 7-15 and Figure 7-16. All search terms show a rising number of publications especially since the late 1990s. In 2010 121 new publications could be found that fitted the term “Industrie Wärmepumpe”. For the English term 2350 new publications could be noted in 2010 and 2780 in 2011.

Of course the amount of available articles is overlaid with the development of the internet, but this effect should have been shrinking in the last 5 years, while a growing increase in the number of new publications can still be noted. Therefore it can be concluded that with the number of research projects also the available scientific information about heat pumps has been growing rapidly in recent years.

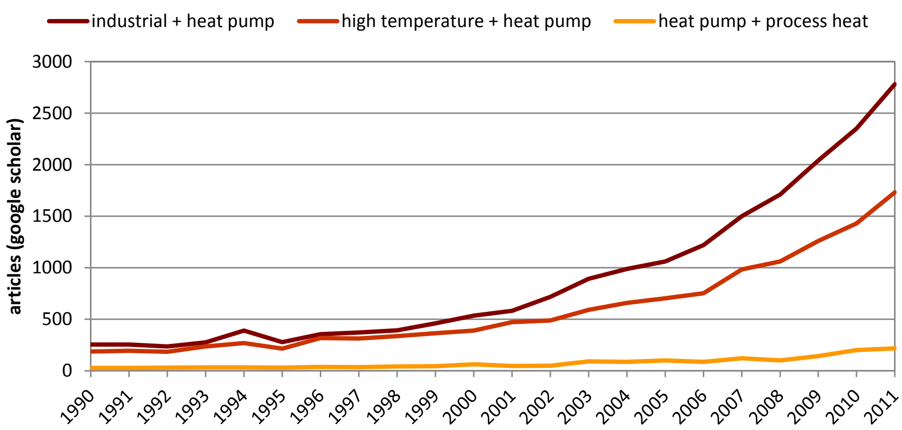

Figure 7-15: Scientific search results for industrial heat pumps (English)

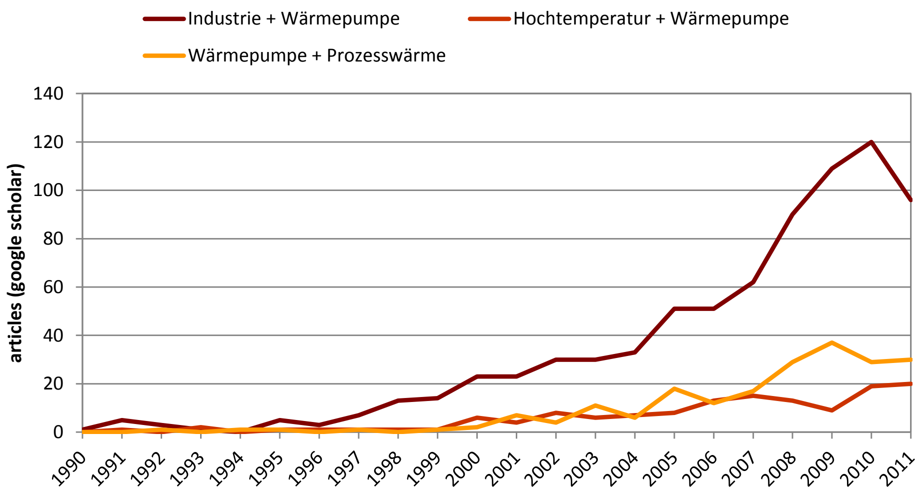

Figure 7-16: Scientific search results for industrial heat pumps (German)

7.6 Barriers for the application of heat pumps in the industry

Although heat pumps for the industrial use became available on the German market in recent years, just very few carried out applications can be found. To distinguish the reasons for this situation, application barriers were also a part of the survey mentioned in paragraph 7.4. Its results are in line with another survey from 2008 /Lambauer et al. 2008/. Four major barriers could be identified.

- Lack of knowledge:
  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.
- Long payback periods:
  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.
- Customer concerns:
  Installers named customer concerns as one of the most important barriers. They mostly prefer well proven gas or oil burner, as the heat production is a very sensible part of the factory infrastructure. As long as documented successful applications of industrial heat pumps are very rare, it will be difficult to persuade these customers to choose a heat pump.
- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump

Another reason for the poor diffusion of heat pumps into the industrial heating market can be found in the fact, that achievable temperatures were limited to 80 °C. As seen in Figure 7-10 just a little share of the industrial heat demand is needed at such low temperature levels.

7.7 Literature

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UBA, 2012 Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011. Bundesrepublik Deutschland. 2012

8 Japan

8.1 Energy use in Japan

8.1.1 Outline of Energy Situation in Japan

The primary energy consumption in Japan is 4.4% of world energy consumption. Energy supplied is highly dependent on fossil fuels such as oil, natural gas and coal. The share of fossil fuels is 84.0% of the total energy supply in 2009FY. Oil accounts for 45.8% of the primary energy supplied to Japan. Although this percentage has been declining from 77% in the peak year of 1973, the share is still the largest among all energy sources. About 96% of the energy resources supplied in Japan are imported from oversees.

Table 8-1: Primary energy supply by energy source (Japan 2009 FY)

Energy source	Primary energy [PJ]	[%]
Oil	9,866	45.8
Coal	4,452	20.7
Natural gas	3,778	17.5
Nuclear	2,465	11.4
Hydroelectricity	710	3.3
Other	280	1.3
Total	21,550	100

Other: Geothermal, Wind, Solar, Biomass, etc.

(Source: EDMC energy and economics statistics handbook, 2011)

The primary energy supplied is mainly used to produce oil products and electricity. Their shares of final energy consumption are 53.3 and 25.4 % in 2009 FY, respectively. Electricity is superior to an energy carrier. The electricity consumption has been increasing in use of heating as well as mechanical power, lighting, air conditioning and information & communication. The electrification rates are 19, 44 and 47% for industry, residential and commercial sectors, respectively.

Table 8-2: Final energy consumption by energy source (Japan 2009 FY)

Energy source	Final energy[PJ]	[%]
Oil products	7,355	53.3
Natural gas and town gas	1,351	9.8
Coal	591	4.3
Coal products	851	6.2
Electricity	3499	25.4
Other	143	1.0
Total	13,790	100

(Source: EDMC energy and economics statistics handbook, 2011)

Energy consumption in Japan can be divided into three sectors of industry, residential & commercial and transport sectors. The relative proportions of industry: commercial &

residential: transport are changed to 1.8:1.2:1 in 2009 FY from 4:1:1 at the time of the oil crises in 1970s.

Table 8-3 indicates final energy consumption by sector in 2009 FY. Although the energy demand of an industrial sector has been decreasing since 1980s, its demand is still dominant by 45.6 % of the total demand. The shares of commercial & residential and transportation sectors are 28.0 and 25.0 %, respectively.

Table 8-3: Final energy consumption by sector (Japan 2009 FY)

Sector	Final energy [PJ]	[%]
Industry	6,293	45.6
Transportation	3,451	25.0
Residential	2,161	15.7
Commercial	1,695	12.3
Non- energy	189	1.4
Total	13,790	100

(Source: EDMC energy and economics statistics handbook, 2011)

8.1.2 Energy use in the manufacturing industry

Manufacturing industry accounts for 94.3% of the industry sector. Energy consumption of manufacturing industry increased only slightly, despite the fact that its economic scale more than doubled after the first oil embargo in 1973. This is caused mainly by the improvement of energy efficiency and the structural change from the primary & secondary industry to the tertiary industry in the sector. Although four sectors of the manufacturing industry, namely iron/steel, chemical, ceramic/stone/clay and pulp/paper/processed paper continue to account for about 70% of the energy consumption of the manufacturing industry as a whole, their share is slightly declining due partly to energy saving in the industry.

Table 8-4: Energy use in the industry (Japan 2009FY)

Industry	Consumption[PJ]	[%]
[Manufacturing]	5,933	94.3
Iron & steel	1,508	(24.0)
Chemical	2,077	(33.0)
Ceramic, stone & clay	373	(5.9)
Food, beverages & tobacco	234	(3.7)
pulp, paper & processed paper	306	(4.9)
Fabricated textiles	74	(1.2)
Non-ferrous metal	131	(2.1)
Metal goods & general machine	414	(6.6)
Other	816	(13.0)
[Non-manufacturing]	360	5.7
Total	6,293	100

(Source: EDMC energy and economics statistics handbook, 2011)

Energy of the manufacturing industry is consumed for different types of use. Figure 8-1 indicates different types of use such as boiler, direct heating, cogeneration and others in the manufacturing industry. Direct heating is the largest amount of demand accounting for 56 % of the total demand. Including the amount of boiler use, both demands reach 90 % as a whole.

Iron & steel is a predominant sector to consume the direct heating energy, over 60% of the total direct heating demand. Chemical, petro-refinery and pulp/paper/processed paper sectors follow it.

As for fuel demand of the boiler, pulp/paper/processed paper and chemical sectors consume over 50% of the demand. Subsequently it is in order of steel product, oil/coal product and foodstuffs manufacturing industries.

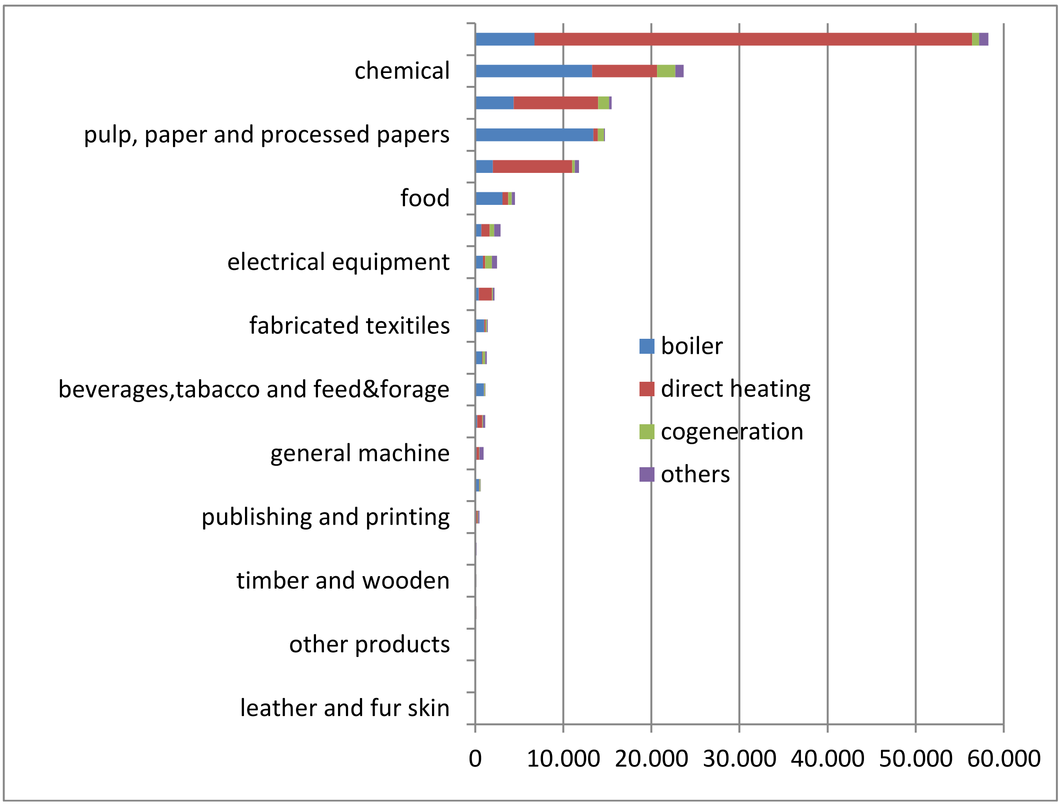

Figure 8-1: Type of energy use by sector in manufacturing industry
(million liter in oil equivalent; 2001 FY)

(Source: The structural survey of energy consumption in commerce and manufacturing, Research and Statistics Department, Ministry of Economy, Trade and Industry, 2001)

Heat produced by industrial boiler is used in various temperature ranges. Figure 8-2 shows heat demand of industrial boiler in different temperature in the manufacturing industry. Heat demands account for over 80 % in process heating over 250 °C and 17 % in the range of 150 to 200 °C, respectively. They are consumed mainly in chemical, pulp/paper/processed paper, steel and petro-refinery sectors.

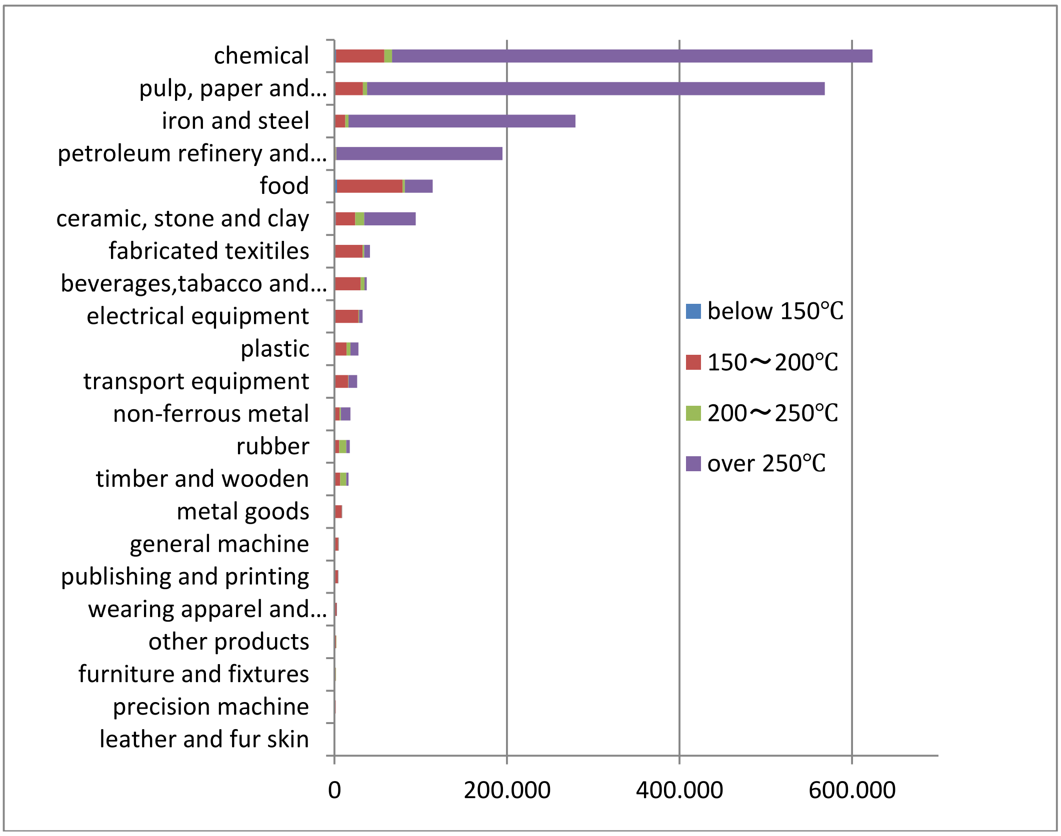

Figure 8-2: Boiler demand in different range of temperature by sector for the manufacturing industry (TJ; 2001 FY)

(Source: The structural survey of energy consumption in commerce and manufacturing, Research and Statistics Department, Ministry of Economy, Trade and Industry, 2001)

Figure 8-3 shows type of use for electricity consumption by industrial sector.

Iron & steel is a predominant sector to consume the direct heating energy, over 60% of the total direct heating demand. Chemical, petro-refinery and pulp/paper/processed paper sectors follow it.

Iron/steel, chemical, electrical equipment and pulp/paper/processed paper consume over 50% of the demand. Subsequently it is in order of steel product, oil/coal product and foodstuffs manufacturing industries.

84% of the total electricity is consumed in the power demand. Heating demand of electricity is rather small, 11% of the total electricity demand in industry. The share of electricity heating is expected to increase from the current tendency of electrification promoted by technological progress of injecting heat and industrial heat pump as well as environmental issues of preventing global warming.

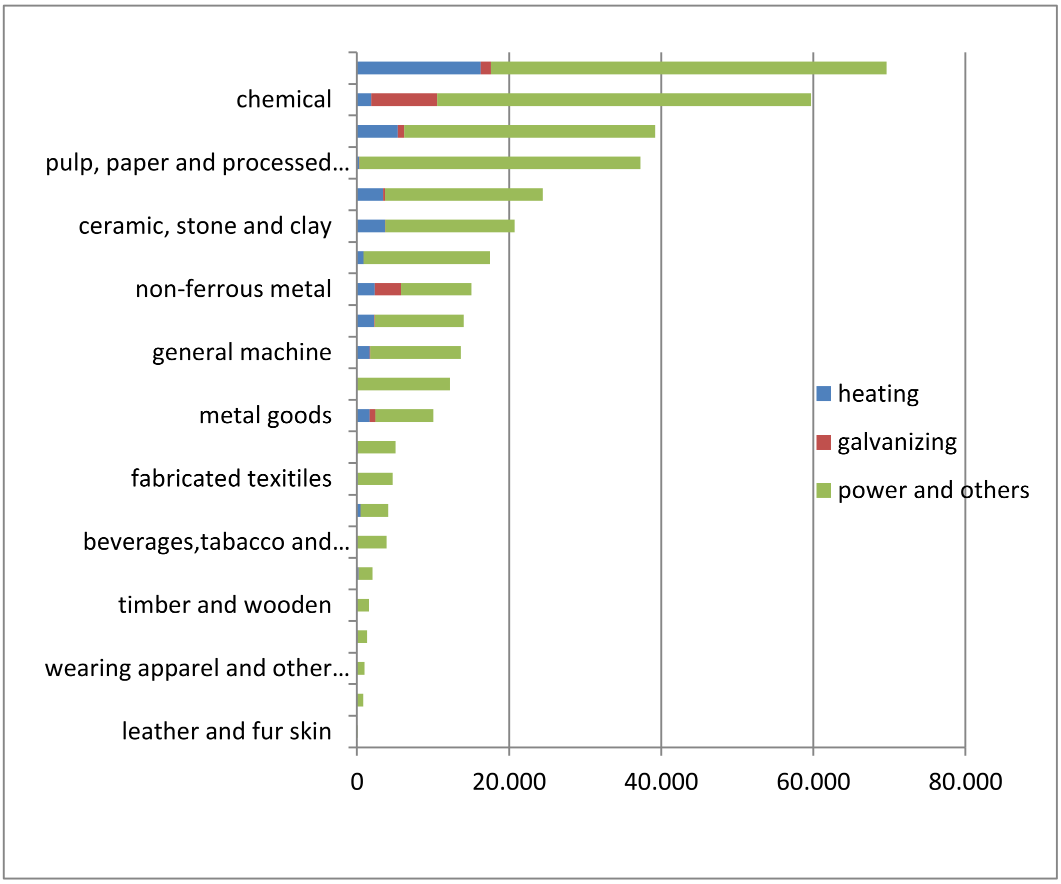

Figure 8-3: Type of electricity use by sector in the manufacturing industry (GWh; 2001 FY)

(Source: The structural survey of energy consumption in commerce and manufacturing, Research and Statistics Department, Ministry of Economy, Trade and Industry, 2001)

8.2 Japan Market overview

Heat pumps are adopted in greenhouse horticulture, hydroponic culture, plant factories and so on in Japanese prime industry. We can see improvements in quality of agricultural production, yield ratio and year-round cultivation thanks to the introduction of heat pumps. They are also used for drying process of agricultural, fishery and lumber products by cooling, dehumidification and heating function.

Cool and warm heat is used for aquaculture while a cooling seawater system is used for preservation of freshness and shipment of live fish in fishery sector. Refrigerating systems have been used for refrigerated warehouses located both at harvesting and consuming places for a long time.

Heat pumps are widely used from heating and cooling to washing in food processing plants. It is noteworthy that they have a heat-up and cool-down process repeatedly and this is the very process that heat pumps are able to show their strength and provide heat in the most effective way. We have been developing equipment that are able to produce water in suitable condition for food processing between 5 to 10 °C and around

90 °C at the same time. In addition, equipment with ability of producing around 100 °C water and steam are under development.

When it comes to air conditioners, especially air conditioners in factories, centrifugal type and high efficient heat pump chillers have been occupied much larger market share than conventional absorption chillers which use steam as heat sources. This is because technology innovation in recent years has made it possible to raise their COP. Improvements can be seen in humidifying of clean rooms and pure water heating in water production.

In machinery plants, some conventional steam-sourced systems are replaced by heat pump systems for heating in degreasing and chemical treatments. Heat pump systems with ability to heat cleaning solution and cutting liquid simultaneously have been put in practice.

Heat pumps have developed to comply with high temperatures of 120 °Celsius for coating and drying process. VRC is increasing at beer factories for molt boiling and alcohol distilling processes.

8.3 Barriers for applications

1. Higher efficiency
   Equipment with complying between 60 and 90 °C are thought to have the largest demand for industrial use and heat pump equipment are already in operation. However, heat pumps are less competitive in terms of an initial cost compared with boiler type systems. Therefore, we need to develop higher efficient equipment so that heat pumps can be competitive in terms of lifetime cost.

2. Extending adaptability for various heat sources and demands in plant
   We need to extend a temperature range of heat sources which are able to apply to daily dispatching of variable energy demand. For example, we would be able to extract refrigerated waste heat from cooling tower, high temperature heat from waste gas and heat from waste and pouring water. We need to develop an integrated technology that can extract heat from those potential heat sources by combined with heat pump systems so that we can control/adjust both the temperatures of heat source and output heat.

3. Higher temperature
   To meet requirements for higher temperatures over 100 °C, we hope to develop new technologies that produce super heated steam, pressurized water, hot air as well as new refrigerants with high condensing temperature, a new heat pump cycle and an oil-less compressor.

4. Air source heat pumps applying to old latitudes
   Although air source heat pumps are expected to be one of solutions that are available regardless of location and time, we still have room for improvements such as an application to cold latitudes and a temperature drop when defrosting.
5. Competitiveness in costs

High temperature heat pumps are more expensive than conventional air conditioning heat pumps. It is needed to reduce an initial cost by standardization, mass-production or use of simple components in accordance with temperature zones.

6. Variety of production menus
   Cool and warm heat are constantly required in relatively small scale of food processing plants. Heat sources should be spread out in those plants. We need to have production menus with small capacities for them. While many industrial sectors request the development of a high temperature heat pump which covers a wide range of temperature zones of large compressors and heat exchangers.

9 Korea

9.1 Energy consumption in Korea

9.1.1 Outline of Energy Use in Korea

The primary energy consumption of Korea is 2.3 % of world energy consumption in 2011. The total amount of the primary energy supply in Korea on 2012 is 11,669 PJ (278.7 million TOE). The total amount of energy is about 96 % of domestic energy demand is fulfilled with imported resources. Four major sources of coal, petroleum, LNG and nuclear energy occupy 96.6% of the primary energy supply in Figure 9-1.

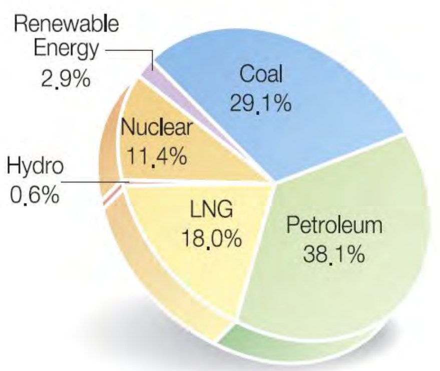

Figure 9-1: Primary energy supply by source (Korea 2012 FY)

Figure 9-2 shows the final energy consumption of Korea in 2012. Considering the fossil fuels are imported in the form of raw resources, the final energy consumption is less 25% than the primary energy, where the amount is estimated to be 8,712 PJ (208.1 million TOE). More than 60 % of coal and all the nuclear resource are converted into electric energy as a final form.

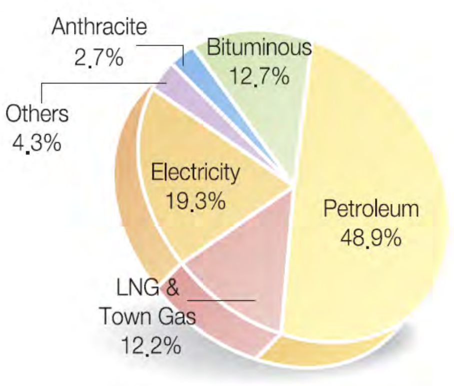

Figure 9-2: Final energy consumption (Korea 2012 FY)

Figure 9-3 shows the final energy consumption by four major sectors in Korea 2012 FY. Figure 9-4 presents annual change of energy consumption by sector. The growth of industrial sector is a major part of which portion increased from 53.7 % (1992, 2,128 PJ), 55.6 % (2002, 3,735 PJ), to 61.7 % (2012, 5,373 PJ).

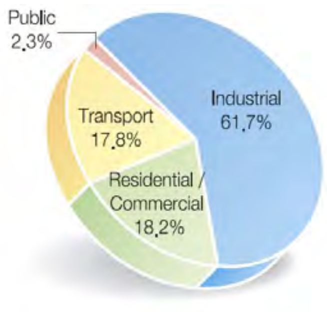

Figure 9-3: Final energy consumption by sector

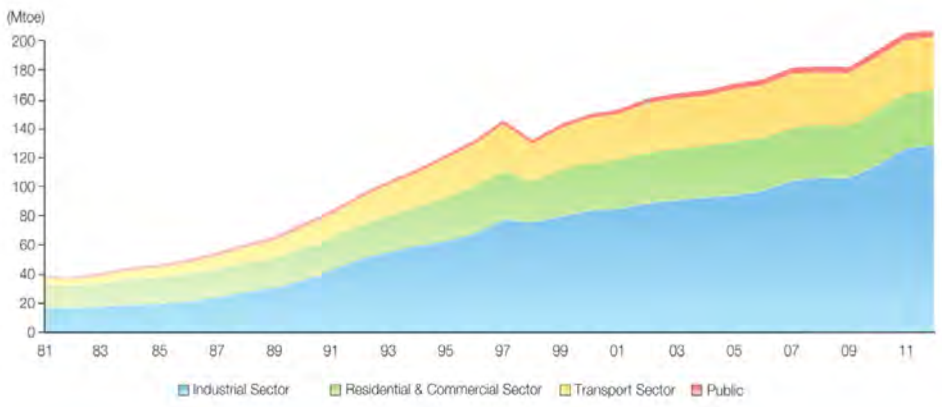

Figure 9-4: Annual history of final energy consumption by sector

(Source: 2013 Energy Info. Korea, Korea Energy Economics Institute)

Table 9-1 presents the distribution of the total energy use for the different sectors. The energy use of energy companies relates to the conversion losses that occur during for example the production of electricity from natural gas or coal. The refining sector is included in the manufacturing industry.

Table 9-1: Energy consumption by sector in 2012

Sector	PJ
Industry	5373
Residential & Commercial	1586
Transport	1555
Public & others	200
Total	8714

9.1.2 Energy use in the manufacturing industry

The Korean industry consists of four sectors; agricultural and fishery, mining, manufacturing, and construction. And 5,373 PJ of energy were consumed in 2012. Renewable energy of 243 PJ is included in the total industrial energy consumption, but is unclassified into subsectors. Excluding non-manufacturing sector, the amount is reduced as 87 %, 4,688 PJ. The balance of the different energy carriers in the manufacturing industry is shown in Table 9-2.

Table 9-2: Energy carriers of industrial sector in 2012

	Coal	Oil	LNG	Electric	Total(PJ)
Manufacturing	1,104	2,308	427	848	4,688
Food. Tobacco	1	7	29	35	73
Textile & Apparel	4	5	24	46	79
Wood & Wood Prod.	0	1	2	6	9
Pulp & Publications	0	4	18	36	58
Petro. Chemical	6	2,155	105	182	2,447
Non-Metallic	119	26	24	39	209
Iron & Steel	923	6	72	164	1,165
Non-Ferrous	0	2	10	0	13
Fabricated Metal	0	25	69	330	424
Other Manufact.	51	44	74	9	178
Other Energy	0	32	0	0	32
Non-manufacturing	199	193	0	49	243
Total	1,104	2,501	427	897	5,373

(Source: Yearbook of Energy Statistics (2013), Korea Energy Economics Institute)

The energy utilization by application in the manufacturing industry is shown inTable 9-3. The heat energy in the table includes both 69% of direct heating and 31% of indirect heating. Conversion loss was estimated about 514 PJ by subtracting total energy consumption out of the total energy supply.

Table 9-3: Energy consumption in manufacturing industry by functions in 2010

Function	PJ	[%]
Heat	1,312	29.1
Power	398	8.8
Feedstock	2,574	57.2
Miscellaneous	216	4.8
Total	4,501	100

Manufacturing industry in Korea is devided into 15 sectors. The type of energy utilization in each sector is as feedstock, by facilities, for transportation, and others. Table 9-4 is energy consumption by subsectors of manufacturing industry in 2010.

Table 9-4: Energy consumption by subsectors of manufacturing industry (Units in 100 ton in oil equivalent; 2010 FY)

Industrial sectors	Feed-stock	Facilities				Trans-port	Miscell.	Total
		IDH	DH	Power	Electro-chemical			
Food products	2	5,804	3,032	1,932	125	137	1,281	12,311
Beverage		1,236	488	400	15	8.2	213	2,359
Tobacco		169	26	69	2.2		8.8	276
Textile		2,966	3,624	2,237	68	94	1,024	10,014
Wearing apparel & fur articles		68	38	14	5.1	18	108	251
Leather, luggage & footwear	0.4	100	57	49	6.1	13	33	258
Wood and cork	0.1	1,774	465	269	84	45	147	2,783
Pulp & paper products	2.2	7,400	7,811	4,394	67	59	1,043	20,776
Printing and recorded media		32	213	91	1.6	10	119	467
Coke and refined petroleum	254,541	18,320	45,103	16,222	1.8	6.8	292	334,486
- Coke and Briquettes	0.6	2.3	6.8	12		1.1	5.6	29
- Refined petroleum product	254,540	18,318	45,096	16,210	1.8	5.6	286	334,457
Chemical products	186,485	39,095	40,181	22,589	3,175	119	18,601	310,244
- Basic Chemicals	148,346	23,396	24,745	14,925	2,773	28	13,058	227,270
- Fertilizer	0.7	110	174	219	32	12	79	626
- Rubber and Plastic	38,116	12,796	12,451	5,210	133	21	4,735	73,461
- Other chemical products	23	1,089	1,430	1,126	53	23	583	4,327
- Man-made fibers		1,704	1,309	1,109	186	35	146	4,487
Medical products		430	278	386	17	4.2	144	1,259
- Medicinal chemicals		56	78	57	6.2	0.7	19	216
- Medicaments		366	176	312	10	2.4	114	981
- Pharmaceutical goods		7.9	24	17	0.6	1.1	11	62
Rubber and Plastic	3.2	3,158	2,656	2,631	287	167	1,383	10,284
Non-metallic products	514	3,239	41,667	5,284	603	437	2,230	53,974
- Glass		2,027	4,834	965	479	15	215	8,535
- Ceramic ware	1.3	124	2,241	288	36	8.1	137	2,835
- Cement	507	921	33,800	3,589	53	351	1,627	40,848
- Other non-metallic	5.0	166	791	443	35	64	251	1,755
Basic metallic products	173,192	4,618	26,493	15,674	6,000	106	11,394	237,476
- Iron and steel	173,079	1,580	18,822	13,736	3,581	62	10,616	221,477
- Non-ferrous metals	87	2,947	6,601	1,128	1,818	22	436	13,038
- Cast	26	91	1,070	810	601	22	343	2,961
Fabricated metal products	10	641	4,632	3,336	818	367	1,902	11,706
Electronic manufracturing	0.1	4,462	12,324	9,606	1,923	68	2,962	31,346
Precision industry		14	216	277	17	26	240	790
Electric equipment		525	1,367	733	320	99	581	3,625
Other machinery and equip-ment	6.3	658	1,886	1,705	349	348	1,062	6,013
Motor vehicles	31	2,166	6,217	4,971	524	125	2,735	16,769
Other transport equipment	0.9	282	1,620	1,410	171	62	631	4,176
Furniture		24	226	285	13	24	149	721
Other manufacturing		162	461	357	71	14	417	1,481
Total	614,786	97,342	201,078	94,921	14,665	2,355	48,696	1,073,843

(Source: Energy consumption survey 2011, Korea Energy Economics Institute)

Since heat and power is mostly supplied by facilities, energy consumption by direct heat and indirect heat and power except by electrochemical facilities is shown in Figure 9-5.

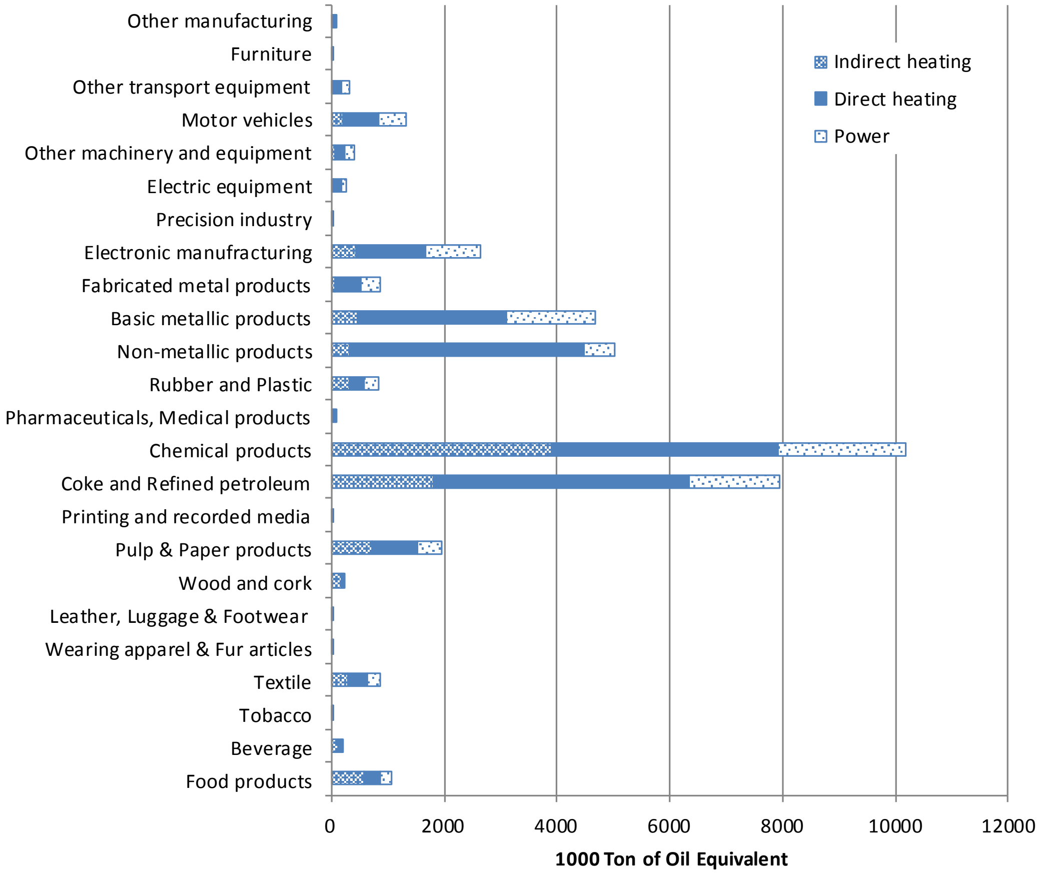

Figure 9-5: Annual history of final energy consumption by sector

9.2 Heat Pump Market of Korea

9.2.1 Market share of heat pumps

Due to its high energy-saving potential, the global heat pump market has grown rapidly in recent years. Korea strives on efforts to spread the utilization of heat pump systems, but still lags behind in market development. Table 9-5 shows the shipments of residential cooling-only air conditioners and heat pumps. As of 2010, compared to the 1.224 million cooling-only units, only 0.157 million heat pumps were sold for other applications, amounting to an 11 % market share. Various market features have contributed to the low share of heat pumps.

Table 9-5: Shipment of residential air-to-air heat pumps and cooling-only air conditioners (thousand units)

Year	Cooling only	Heat pumps
2005	1494	42
2006	1495	45
2007	1138	52
2008	1261	65
2009	1025	89
2010	1224	157

(Source: KEMCO 2011 Report)

9.2.2 Barriers for applications

From the former report on Korea market, two unique features of the Korean market are mentioned: high penetration of natural gas, and low energy prices. In 2010, the nation-wide penetration rate of natural gas in the residential sector was 72.2 %. The Seoul Special City, which is the capital and largest metropolis of Korea, had a 92.3 % penetration rate. Other major cities also have penetration rates approaching 90 %. These high numbers reflect the fact that almost every resident in the city uses natural gas, either for heating or cooling – with boilers, rather than heat pumps, taking by far the largest share.

Table 9-6 shows the retail energy prices of natural gas and electricity from IEA 2012 Key World Energy Statistics. Among the selected OECD countries, Korea has the lowest energy prices, even considering the GPD (PPP) per capita (Table 9-6). The price of electricity for domestic consumers is, for example, only 43 % of that paid by UK domestic consumers. Low energy prices make customers more sensitive to the initial cost than to the running cost. Due to Korea’s preference for floor heating, boilers are typically installed in houses for domestic hot water production. Since boilers are far cheaper than water-heating heat pumps, the payback time of a heat pump is longer than in other countries. In addition, heat pumps are usually regarded as appliances, in the same way as are air conditioners. This makes it more difficult for the concept of payback to be considered by customers.

Table 9-6: The retail prices of natural gas and electricity in OECD countries

Retail prices ($)	Finland	Germany	Ireland	Korea	New Zealand	Poland	Spain	United Kingdom
Nat. gas for industry (MWh), GCV	45.19	54.37	43.91	60.21	23.76	42.57	37.72	35.51
Nat. gas for domestic consumers (MWh), GCV	62.18	92.63	80.65	64.98	102.43	72.2	89.27	64.84
Electricity for industry (MWh)	113.64	157.23	152.39	(61.94)	73.72	121.77	148.77	127.39
Electricity for domestic consumers (MWh)	213.61	351.95	259.47	88.64	212.1	198.5	295.31	204.92

(Source: IEA 2012 Key World Energy Statistics)

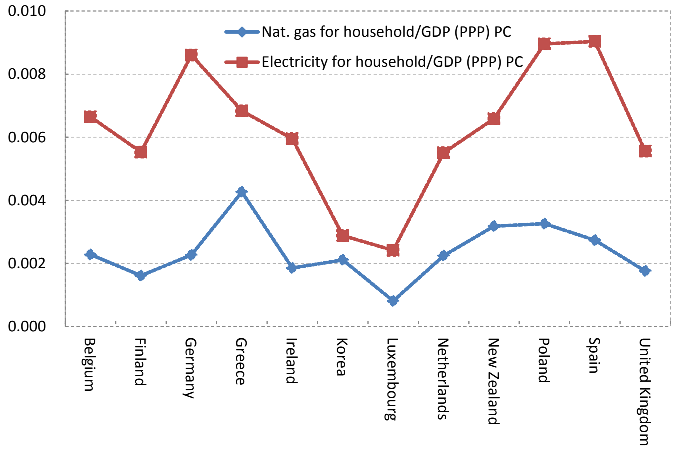

Figure 9-6: The retail prices of natural gas and electricity for domestic consumers divided by GDP (PPP) per capita

9.2.3 Potentials of heat pump applications

Despite the adverse market conditions for heat pumps, there is no doubt that they are energy-saving devices and one of the promising solutions for tackling energy problems. Although the situation is not favourable to heat pump market, some efforts to seek the possibilities to apply heat pumps to industrial applications relying on the low electricity price. Considering longer operating time of industrial heat pumps, the customers in industrial field find good economy of heat pump system.

Aside to these efforts, the Korean government supports measures to improve energy efficiency and the use of new renewable energy sources because it considers them as key players to achieve its goal of Green Growth with Low CO_2. On the government's road map to Green Energy, heat pumps were selected as one of the 15 green energy sectors to increase energy efficiency. KETEP (Korea Institute Energy Technology Evaluation and Planning) selected four heat pump systems in its Green Energy Strategy Road Map 2011, and has supported their technical development, which it hopes will create a new heat pump market in Korea.

9.3 Literature

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[2] Korea Energy Economics Institute, "Yearbook of Energy Statistics", Vol. 32, December 2013.

[3] Ministry of Knowledge Economy, "Energy Consumption Survey" – 11th Edition, 2011.

[4] M. Kim, G. Lee, B.-J. Shin, 2013, The heat pump market and its potential in Korea, IEA Heat Pump Centre Newsletter, Vol. 31, No. 4, pp. 10-12.

[5] Korea Energy Management Corporation, Annual Report 2011

[6] IEA, 2012 Key World Energy Statistics.

10 The Netherlands

Industrial processes in general need higher temperature levels. Recent developments of heat pumps focus on higher delivery temperatures of heat and a high temperature lift (difference between low (source) and high (delivery) temperature). Another trend is that industrial production processes require lower temperatures for heating. Application of heat pumps may therefore grow in the near future and contribute to further CO_2 emission reduction.

Bottle necks for this growth form the unfamiliarity with heat pumps of engineers and process designers, the complex level of integration of the installation in existing plants, the high investment costs, some experiences with unreliability in old projects, lack of references and lack of knowledge of the new higher temperature options. For successful introduction of high temperature heat pumps in industry bundling and distribution of knowledge is of importance. Process designers, engineers, consultants, contractors and end users need to be familiar with the heat pump technology, the possibilities, the advantages, good references and being aware of the do's and don'ts.

In a study by KWA commissioned by AgNL [Pennartz, 2011] the following subjects are described:

- an overview of the heat pumps options in various industrial sectors and energy consumption
- recent technological developments around industrial heat pumps after 2000
- a number of cases studies of industrial heat pumps after 2000.

10.1 Energy use in manufacturing industry

The energy balance of the Netherlands is shown in the Table 10-1 (left). The table depicts the net balance per energy carriers. Table 10-1 (right) presents the distribution of the energy use in the different sectors. The energy use of energy companies relates to the conversion losses that occur during, for example, the production of electricity from natural gas or coal. The refining sector is included in the manufacturing industry.

Table 10-1: Energy balance in the Netherlands (left) distribution of energy use (right)

Energy Carrier	PJ
Oil	1221
Natural Gas	1435
Coal	328
Electricity	88
Misc	163
Total	**3235**

Sector	PJ
Energy Companies	431
Industry	1344
Transport	500
Residential Buildings	412
Commercial Buildings	546
Total	**3233**

The main industrial sector in the Netherlands is the chemical industry located in some concentrated areas around the Rotterdam harbor. The other main industrial sectors are food industry and the greenhouse sector. Manufacturing industry used 1344 PJ in 2006.

The energy carriers that are used by industry serve different functions (heat, power, feedstock). Table 10-2 presents the energy use by these functions for the different industrial sectors. Power relates to the energy use for driving machines or lighting. Feedstock is the so-called non-energetic energy use, where the energy carrier is used to make a product, like plastics and petrol. The conversion loss refers to the losses that occur in decentralized electricity production by industry (combined heat and power).

Table 10-2: Primary Energy use in Dutch industrial sectors

	Heat (PJ)	Power (PJ)	Feedstock (PJ)	Conversion loss (PJ)	Total (PJ)
Food & drug industry	62.8	24.8	0.2	3.7	91.5
Textile industry	3.3	1.4	0	0	4.7
Paper & board industry	24.7	13.3	0	3.7	41.7
Chemical industry	261	36	455	21	773
Refining	116	9.6	0	62.1	188
Building materials	26.8	5.2	0.1	0.1	32.2
Basic metal industry	38	12.6	73.3	13.6	138
Metal products	19.0	15.9	15.5	0	50.4
Rubber & plastic products	7.7	9.4	0	0	17.3
Other	0	0	7.6	0	7.6
Total	559	128	552	105	1344

Table 10-3: Temperature levels of heat demand

Interval	Chemical + Refining (%)	Basic metal + metal products (%)	Other (%)
< 100°C	5	15	29
100-250°C	11	0	38
250-500°C	27	5	13
500-750°C	21	0	0
750-1000°C	26	10	0
> 1000°C	10	70	20

10.2 Market overview

Potentially large energy savings are possible through the application of heat pumps in the industry. Developing and dissemination of knowledge is important for successful growth of the application of heat pumps. To stimulate the application of heat pumps it is useful to analyze heat pumps which have been placed in the past and analyze how they operate in practice. Over the past 20 years there were several feasibility studies and heat pump projects supported by the TIEB and SPIRIT programs of Novem (the predecessor of RVO) which were reported upon.

Table 10-4: Overview of older heat pump projects

Factsheet	Company old/new name	location	process	Condition
	Oriental Foods	Landgraaf	Drying of Tahoe	Company closed
	Plukon	Asten Ommel	Slaughterhouse	Feasibility only
	Solphay/Dishman	Veenendaal	MDR on Aceton	End of production
	Purac Biochem	Gorinchem	MDR on lactose	End of production in NL
	Hartman/Jardin	Enschede	Garden furniture	Feasibility only
	ITB		Plastics	Feasibility only
	Quality Pack	Kampen	Crate washing	Company closed
	Beukema/Eska Graphic Board	Hoogezand	Paper drying	Feasibility only
	Huwa Bricks factory	Spijk	Brick drying	Feasibility only
	Frico	Sint Nicolaasga	Cheese evaporative drying	Company closed
	Hoogovens/Tata steel	IJmuiden	Heat Transformer	Corrosion problems
	ARCO/Lyondell	Botlek	MDR on Distillation	no data available
NL-01	Shell	Pernis	MDR on Distillation	running
NL-02	Unichema/Croda	Gouda	MDR on Distillation	running
NL-03	Hoechst	Vlissingen	MDR on Distillation	End of production in NL
NL-04	Campina	Veghel	MDR on evaporation	running
NL-05	De Graafstroom	Bleskensgraaf	MDR on evaporation	running
NL-11	Dommelsch Brewery	Dommelen	MDR on wort	running
NL-13	GPS	Nunspeet	Heating from condensor	running
NL-15	AVEBE	Ter Apelkanaal	MVR on patatoe starch	running
NL-16	Cerestar/Cargill	Sas van Gent	MVR on	replaced by new MVR
NL-17	Fapona/Berendsen	Apeldoorn	Laundry drying	running

A study has been undertaken to look into the operation of these "older" projects looking into the experiences of the companies, if there have been any changes of the design over time, whether operating & maintenance of the installation is difficult (high level of knowledge, complexity, etc.), if promised energy savings are achieved and whether there are remarks which can be defined as lessons learned.

All companies described participated in this evaluation study. Striking is that those projects described as case and feasibility studies supported by governmental subsidies (TIEB) were never realized, despite the fact that acceptable payback periods and significant energy savings were calculated in these studies. For the other projects much has changed in the past twenty years like plant closures, moving production, no demand for the product, changes in operations, etc. As a result six of the analyzed heat pumps have been removed nothing to do with any possible malfunction of the heat pumps.

Of the eleven remaining heat pumps, ten are still in use. These are eight Mechanical Vapour Recompressors (MVR), one Thermal Vapour Recompressor (TVR) and one heat pump, which uses the heat from the condenser of the refrigeration installation for process heat. Most of these are now described in new factsheets in Task 4. Only one company was not participating with new data.

Companies with a running heat pump have generally no idea why a heat pump was chosen, given the long period since the investment decision. Most of the heat pumps still run according to their original design having relatively high operating hours (5,000-8,000 hours/year) and mostly in full load. In several cases the maintenance is outsourced for reasons of complexity, high operating hours and capacity problems in the technical department. Operating the installation is generally regarded as a relatively simple. The installations have few problems and/or malfunctions. Companies have no insight on whether the system achieves its efficiency, or whether the intended energy savings have been obtained. They have no reference, given the initial situation.

- When a steam-powered evaporation process is switched to an MVR, which is electrically powered, it must be taken into account that the ratio between heat and electricity demand shifts towards electricity. This is unfavorable for the use of gas turbines, when a company has these in use.
- A point of interest for heat pump installations which processes polluted water is that the heat exchangers require relatively high-maintenance when they have to process large quantities of polluted water.
- An additional advantage of a TVR, or a MVR is that these systems reduce the emission of odors, since all vapors are condensed.

The heat pumps generally run satisfactorily, this study provides no indications to suggest that there are major risks associated with the use of heat pumps in industrial environments.

After a long period of 'silence' there seems to be renewed interest in the market since 2010, resulting in a fast increasing number of applications. A number of new Industrial Heat Pumps have been installed resulting in a long list of projects. These projects are described in fact sheets under Task 4.

10.3 Barriers and trends

Knowledge of heat pumping technologies is an important building stone in further increasing the heat efficiency of industrial processes. But knowledge is not the final piece but it's only the beginning of a whole transition process. Companies have a lot of options for energy conservation and generation and decision space, which can lead to taking no explicit decision. The challenge is to organize competition among technology solutions that leads to more explicit decision making. Decisions on applications of heat pumps are made in competition with investments on other technologies or in other parts of the industrial process.

Until recently heat in many industrial sectors has been by-product of electricity from cogeneration and therewith heat had a low economic value. Cogeneration has been a very 'hot' technological solution in the past decades for quick gains in energy conservation. Due to the strong competition from cogeneration in industry as a heat source only a few heat pumps were installed in the past 15 years, except for vapour recompression in distillation columns. In addition compression heat pumps were not suitable for temperature levels higher than 80 °C. Nowadays there a number of developments which widens the opportunities for industrial heat pumps:

- Due to the decline of the so-called spark spread, the difference in operating costs between CHP and heat pumps are considerably narrowed. It is to be expected that a lot of CHP-installations after depreciation will not be replaced. Paper and Pulp industry being an example. In those cases, there is more attention to the internal use of process heat and thus for heat pumps.
- By using other than the traditional working fluids for refrigeration and new technologies heat pumps can lift to reach 120 °C;

- Through the use of so-called "temperature glides" the heat / electricity ratio (COP) is significantly improved.
- The introduction of chillers with an additional compression step, which are perfect for the heating of hot water or cleaning process.
- The early development of acoustic and thermochemical heat pumps and heat transformers the path towards even higher temperature ranges up to 250 °C.

These technological developments do not or barely reach industry. In addition, heat pump suppliers generally have a backlog by the negative experiences in the commercial and domestic building sector.

An important aspect also is that heat pump suppliers, knowing the possibilities of alternatives, are in most cases the last link in the supply chain, where consultants and installers often lack the knowledge in finding good economic solutions. An important issue therefore is how technology suppliers, technical personnel and management, that takes the investment decision, communicate with each other. It is the experience that management is less interested in the technical side and much more in solutions for the company. Newly developed heat pump technology has been analysed in four major business cases in chemical industry. The experience gained here leads to the conclusion that more is needed than knowledge on technology only. A 'technology marketing' process is needed to be able to discuss on the same level as industrial management decision making. Knowledge, skills and competence have to be developed in that process. The approach is further discussed in Task 5.

10.4 Heat pump potential

In the Netherlands heat pumps of different types can be applied in all levels of industry ranging from bulk distillation in chemical industry to the level of milk processing at the farm or growing tomatoes in greenhouses and steam production in paper and pulp. In every application, even for domestic buildings, the approach will have to be based upon the Trias Energetica in industry a systematic approach in improving the energy efficiency of industrial processes is the onion-model developed in industrial heat technology.

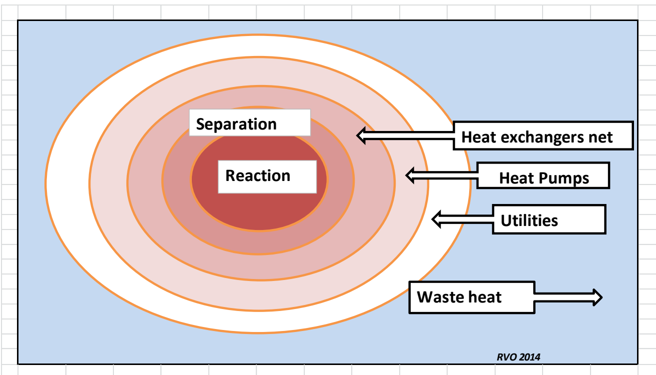

Figure 10-1: Onion model for energy efficiency improvement [Reissner, 2013]

This model will be discussed further in Task 2.

10.4.1 Chemical industry – distillation

(by D. Bruinsma and S. Spoelstra)[Bruinsma, 2011]

Distillation is the main separation technology in refineries and the chemical process industry, because of the attractive purification characteristics, the high production capacity and turndown ratio, and the straightforward design procedures. More sophisticated techniques have become state of the art to handle streams with less favorable thermodynamic properties, in particular small relative volatilities and azeotropic mixtures. The high energy demand in bulk distillation columns (1-100 MW) and the low thermodynamic efficiency (5-10%) remain the major drawbacks. A number of improvements have been developed over the years directed at reducing both operating and capital cost.

In extractive distillation (ED) a solvent or separating agent is added in order to increase the relative volatility of the components to be separated. In azeotropic extractive distillation the separating agent is used to break the azeotrope. As a consequence the reflux ratio, column diameter and reboiler duty can be reduced and/or the column height can be lower. Commercial low volatility solvents include sulfolane, triethylene glycol (TEG), NMP and NFM. The recovery cost of the solvent is an integral part of the economy of extractive distillation processes. ED is particularly effective for relative volatilities below 1.2. Industrial examples of ED processes are purification of aromatics in petro chemistry, butadiene recovery in naphtha cracking and separation of cycloparaffins from naphtha.

Instead of affecting the thermodynamics of the system also selection of the column internals is a way to increase distillation efficiency. Random and structured packings with specific surface areas from 250 up to 900 m^2/m^3 are continuously being improved with the objective to optimize stage height, pressure drop, liquid load, and turn down ratio. The main recent advancements in tray columns focus on high-capacity trays with centrifugal devices or structured packing demisters although at the cost of an increased pressure drop.

Since the 1980's dividing wall columns (DWC's) have been introduced which allow the separation of three component feeds in a single column leading to interesting reductions in both energy consumption and investment cost. Recently even more complex DWC's have been constructed to separate four component mixtures in pure products.

In contrast to improvements of the VLE or the column internals, both inside the column, a number of energy reducing measures can be considered outside the column by addressing the reboiler and condenser. These include side reboilers, dephlegmators and heat pumps. Side reboilers use waste heat at a lower temperature than the bottom reboiler and thus increase the exergetic efficiency. Dephlegmators or reflux condensers are compact heat exchangers, such as PFHE's, used to reduce energy consumption in low temperature gas separations. Heat pumps lift the temperature level of the top vapor in order to use this as the heat source for the reboiler.

Heat pumps for distillation purposes can be divided in three types: mechanically driven, heat driven and heat transformers. Mechanically driven heat pumps can be found, among others, in the following types:

- Vapor recompression heat pump (VC)

- Mechanical vapor compression heat pump - Subcritical and Trans critical (MVR)
- Thermal Vapor Recompression HP (TVR):
- Compression-resorption heat pump (CRHP)
- Absorption heat pump (AbHP) and Adsorption heat pump (AdHP)
- Thermo acoustic heat pump - linear motor driven (THP)
- Heat Integrated Distillation Column (HIDiC).

An analysis was made of distillation heat pump potential in the Netherlands, leaving out columns that do not cross the pinch and oil refinery columns. The data show that the total heat pump potential is in the order of 2.4 GW and that the average temperature lift over the column is 59 °C. These data are given in Table 10-5 (J. Cot and O.S.L. Bruinsma, Market survey, Heat pumps in bulk separation processes (2010), ECN report 7.6548.2010.0xx).

Table 10-5: Distillation in the Netherlands

Across the pinch distillation in the Netherlands

	Distillation in NL
Total $Q_{reboiler}$ (GW)	2.36
Total $Q_{condenser}$ (GW)	2.39
Average $T_{reboiler}$ (^oC)	128
Average $T_{condenser}$ (^oC)	69
Average ΔT_{column} (^oC)	59

Figure 10-2 represents the distribution of the reboiler duties in the Netherlands for columns with increasing temperature lift; only those columns that cross the pinch have been included.

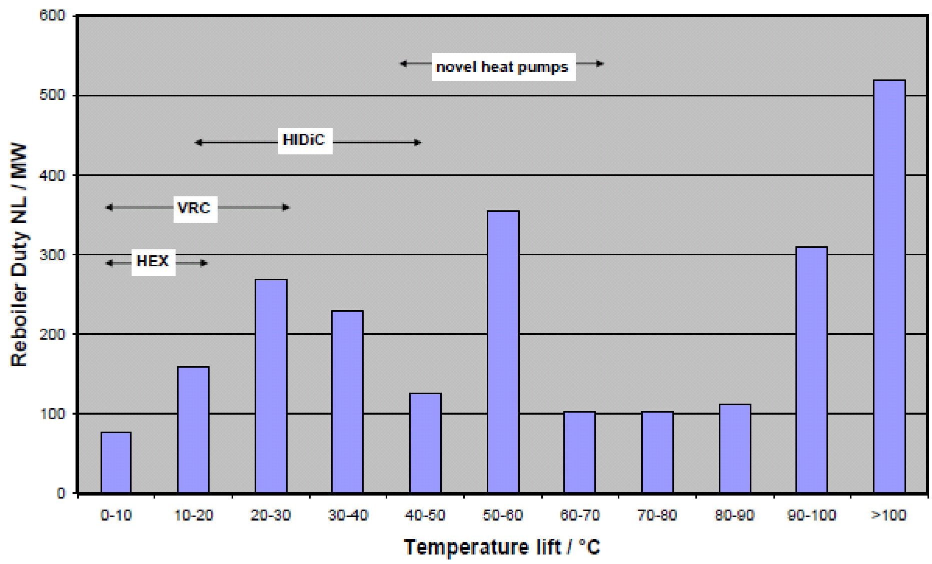

Figure 10-2: Reboiler duties for across the pinch columns in the Netherlands (2006)

In the graph four recommendation regions are identified:

- Temperature lifts below 20 °C compact heat exchangers with small ΔTHEX are crucial for the performance of the heat pump system,
- VRC's should be applied below 30 °C, which covers about 23 % of the across the pinch columns
- HIDiC's are probably interesting for temperatures in the range 15-45 °C, about 29 % of the across the pinch columns, partly overlapping with VRC but with a higher savings efficiency
- Novel heat pumps for temperature lifts of 45-70 °C, would contribute an additional 21 %.

Based on this analysis the combination of VRC, HIDiC and novel heat pumps would lead to an estimated 820 MW savings, which is almost 35 % of the reboiler duties of all across the pinch columns in the Netherlands.

10.4.2 Food industry

With an energy use of more than 62PJ in heat food industry is a large sector in Netherlands with main sub sectors: Dairy (18.0), Potatoes processing (8.7), Margarine (7.6) and Bakeries (4.8). Cooled Warehouses are a specific but important sector. Within these sectors processes like drying and cooling are the main process operations with a lot similarities in process.

Evaporators in dairy industry

The GEA handbook on Milk Powder Technology [Westergaard] states that the transforming of a liquid product into a dry powder requires means the removal of practically all water, the amount of which often exceeds the weight of the final product. During the water removal the processed product is undergoing deep changes of physical structure and appearance, starting with thin water like liquid and terminating with dry powder at the end of the process. Therefore, one single method of water removal cannot be optimal throughout the whole process, as also the product composition is different from one food product to another. In the food and dairy industry the following dehydration methods have been adopted:

- Evaporation
- Spray Drying
- Vibrating Fluid Bed Drying
- Integrated Fluid Bed Drying
- Integrated Belt Drying.

Each method should be adjusted to the properties of the processed material at each processing step. The more difficult the product, the more complex the plant.

As the development went on, the concentration was carried out in forced recirculation evaporators. In this evaporator the milk streams upwards through a number of tubes or plates. On the outside the heating medium, usually steam, is applied. The heating surface is thus increased in this system, but the evaporation surface is still limited, as the tubes and plates remain filled with product, which therefore becomes superheated in relation to the existing boiling temperature. Not until the product leaves the top of the tubes, are the vapors released and the product temperature decreases. For the separation of liquid and vapors, centrifugal separators were preferred. In order to obtain the desired degree of evaporation the product was recycled in the system. The concentration was thus controlled by the amount of concentrate discharged from the plant.

Refrigeration

An in depth study [Pennartz, 2011] has been done into the potential for heat pumps in the industrial sectors that use considerable amounts of refrigeration. Residual or waste heat available in the food sector is shown in table 1 for temperature and PJ primary energy per year. The various heat sources of the waste heat are listed in the table. Most of the waste heat is available from the condensing heat of refrigeration plants. The temperature level is between 30 °C and 40 °C. This energy source amounts to 28 PJ a year. Similarly the heat consumers have been investigated showing that 14 PJ is consumed by various processes at temperature levels between 60 °C to 110 °C. There is more residual heat available than required.

In this view, the heat demand of the food sector of 69 PJ in total can be reduced by 14 PJ by the use of high temperature add-on heat pump on refrigeration plants.

Table 10-6: Overview of available condenser heat in Dutch industry

Heat Pumps applications and potential

Sector	Total primary energy consumption (2008)	Total electrical energy consumption (2008)	Total heat (2008)	T residual heat available	Residual heat available	Delivered by:	T heat consumers	Reuse heat consumption	Consumed by:	Electricity consumption by refrigeration	Available condensing heat (T=35°C)
	PJ	PJ	PJ	°C	PJ		°C	PJ		PJprim/j	PJth/j
Sectors Industry											
Cooled warehouses	2,4	2,2	0,2	35	2,8	condensers refrigeration	80/ 60	0,1	building, water	2,0	2,8
Rubber and plastic	9,6	7,4	2,2	35	1,8	cooling tower, condenser refr	80	0,1	building, rubber	0,9	1,8
Potatoes processing	8,7	2,0	6,7	30-120	4,0	eg. steam pealing, condensers refr.	70-110	1,2	pasteurizer, dryer, blancheur	1,1	1,5
Cacoa	2,3	1,1	1,2	60- 70	0,15	cocoa milling	120	0,25	preheating air for drying	0,1	0,2
Fruit and vegetables	2,9	1,4	1,5	70-120	0,8	condenser, blancheur, sterilizer	70-90	0,5	blancheur, building	0,4	0,6
Coffee production	0,9	0,5	0,4	30,0	0,1	condensers refrigeration	70	0,1	building	0,1	0,1
Margarine, Fats and Oils	7,6	0,8	6,8	35	0,3	condensers refrigeration	80	1,0	tank storage, pipe tracing	0,2	0,3
Meat procesing	4,3	2,8	1,5	30	1,8	condensers refrigeration	70	0,25	hot water cleaning	1,3	1,8
Dairy	18,0	5,0	13,0	40-60	2,5	bruden condensate from evaporators	90	1,8	spray dryer	1,8	3,2
Soft drinks	1,0	0,5	0,5	30	0,1	cooling section pasteurizers	80	0,1	pasteurizers	0,0	0,0
Beer industry	3,9	2,0	1,9	35, 100	1,2	condenser, wort boiling	70-110	0,6	pasteurizers, wort boiling, building	0,5	0,8
Bakeries	4,8	1,8	3,0	30, 200	0,3	condensers, flue gas oven, boilers	30-70	1,0	air preheating, builing, water, dough rising	0,9	1,4
Fish processing	0,8	0,6	0,2	30,0	0,5	condensers refrigeration	80	0,1	building, hot water	0,3	0,5
Biscuits, confectionary, chocolate, icecream	2,0	0,8	1,2	30, 200	0,6	condensers refr., ovens	60-100	0,5	pasteurizers, water, cookers, storage raw materials	0,4	0,6
Other food	69	40	29,0	30-70	9,0	various	70-90	6,0	various	8,0	12,8
Total Food	**138**	**69**	**69**		**26**			**14**		**18**	**28**
Chemical industry spcialized products	10,2	4,0	6,2	various			various			0,8	1,6
Oil and gas production	40,8	10,8	30,0	90		compression gas	80		building	1,9	3,9
Chemical industry bulk	300	75	225,0	various			various			3,0	5,4
Refining	140	24	116,0	various			various			3,6	6,5
Other industry	104	16	88,0	various			various			1,3	2,6
Total Other	**595**	**130**	**465**							**11**	**20**

The feasibility of high temperature add-on heat pumps depends on an analysis of:

- Residual heat, heat demand and electricity demand
- Energy monitoring of maximum and minimum capacities, average values, operating hours.
- Apply an integral approach, evaluate the competing technologies such as high efficient hot water boilers, combined heat and power (CHP) plants. A heat pump is more flexible than a CHP, since they are available in small sizes and can operate efficiently in part load.
- Investments, replacement of heating equipment.

From a sustainable point of view: refrigeration installations should not be installed, without the use of condensing heat (such as desuperheater heat, condensing heat at 30 °C, add on with high temperature heat pump >80 °C).

10.4.3 Paper and pulp

by [De Vries, 2012]
The pulp and paper sector is with 26 PJ a significant energy user in Netherlands and currently ranks fourth in the industrial sector for its energy use. This 26 PJ is primarily used as gas to power cogeneration systems conversing this into 17 PJ's of heat. This heat is then after being used as process heat dumped into the environment as heat from drying (11 PJ), losses from conversion (4 PJ and into the waste water (2 PJ). Energy costs in paper and pulp in the Netherlands are 15 - 35% of the variable costs of production.

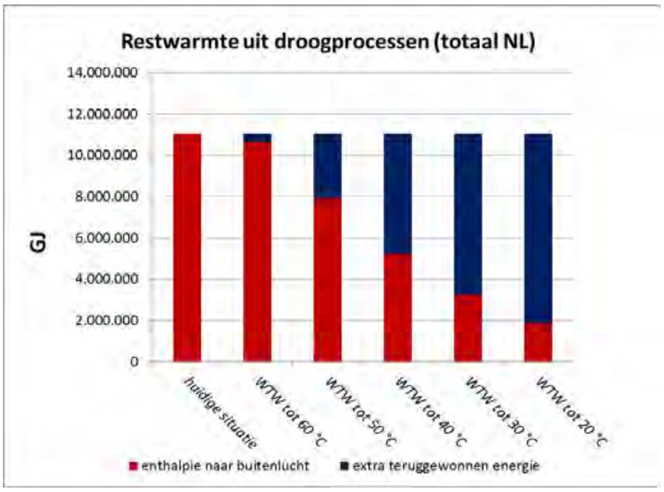

Figure 10-3: Waste heat and temperature levels in Paper and Pulp

Manufacturers have under the Multi Year Energy Agreement with the ministry of Economic Affairs constantly been working on energy efficiency for the production processes, which lead from 1990 onwards to the wide spread application of cogeneration. Several studies have been executed in the nineties of last century to find the right solution for the application of heat pumps, but due to the low costs of process heat an economical investment was not feasible. Due to the decline of the so-called spark spread, the difference in operating costs between CHP and heat pumps are considerably narrowed. It is to be expected that a lot of CHP-installations after depreciation will not be replaced. In those cases, there is more attention to the internal use of process heat and thus for heat pumps. A first R&D project has in 2013 lead to a 250kW's pilot project with a high temperature heat pump producing steam at 120 °C re-using the waste heat from the drying section. This option at this moment seems only viable for larger paper & pulp industries. According to the CEPI statistics (2012) there are in Europe some 350 paper industries of the size.

There are various possibilities to recover thermal energy from steam and waste heat in the paper drying process. These include:

- Mechanical vapor recompression and reuse of the superheated steam in the drying process;

- Use of heat pumps to recover waste heat;
- Recovering heat from the ventilation air of the drying section and using this heat for the heating of the facilities when needed.

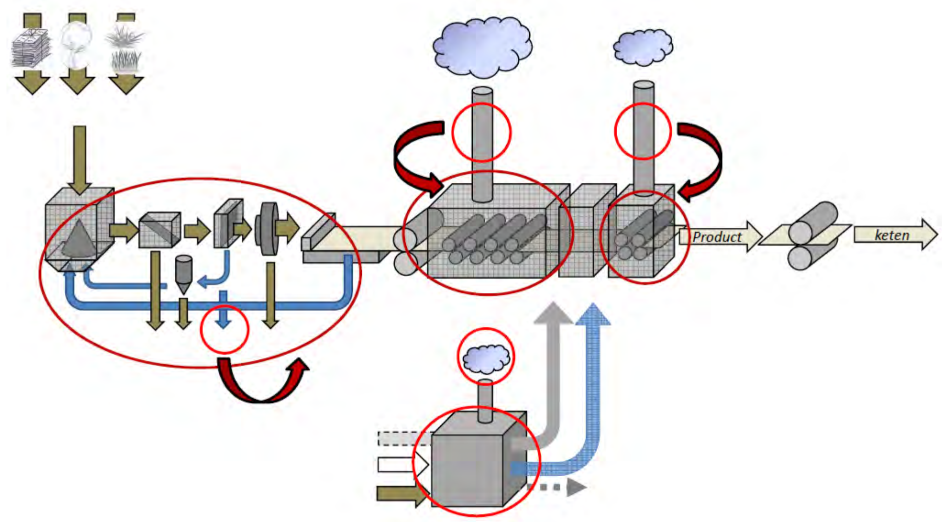

Figure 10-4: Waste heat streams that can be used (source KCPK [de Vries, 2012])

The challenge is to find the right solutions to re-use the in the process. As paper and pulp processes are rather big the best option is to re-use the heat close to where the waste heat appears.

10.4.4 Miscellaneous industrial areas

***(see www.energiezuinigebedrijventerreinen.nl*)** [Energie]

There is small success with energy conservation and the application of renewable energy at industrial areas for mixed/miscellaneous use. This is remarkable as there are many economical options for renewables and conservation. Where heat pumps in Netherlands are state of the art in commercial buildings this is not yet the case at these mixed industrial areas.

The overall energy use on existing areas with a size of 10 - 50 ha is 170 PJ which is 6% of the overall Dutch energy use. With a conservative estimate that there is potential for energy conservation of 30 – 40% this sums up to 60 PJ [6]. On the positive side is that there are good examples with new developments where renewable energy and energy conservation are basic boundary conditions to fulfill when a company considers to settle in that area. These boundary conditions are set by local governments. Of these area three examples are:

- 15 ha Kolksluis near Zijpe where heat pumps combined with a collective ATES are the main technologies
- Ecofactorij near Apeldoorn which is discussed in a factsheet under Task4
- Trompet near Heemskerk.

In the development of a new area it is of importance to develop the planning process at a very early stage and to attract companies by giving bonuses and over a long period never to depart from the goals of the planning for the area.

For existing industrial areas it is part of the renovation process which is challenging and with some small successes. Examples are given in some factsheets under Task 4.

10.4.5 Agriculture

Agriculture in Netherlands covers a large area from mushroom growth, 'bollenteelt', pig and chicken farms, dairy farming, cheese making and greenhouses. The major energy user in this segment are the greenhouses. Even for low energy growths heat pumps can give primary energy savings up to 35% [Ruiter, 2011]. In the period 2003-2013 approximately 40 growers of various crops have implemented heat pumps in their greenhouses. They comprise the following crops:

- Roses (2x)
- Tomatoes (3x);
- Orchids (Phalaenopsis) (8x);
- Freesia (2x);
- Anthurium (2x).

Recently the experience have been analyzed [Geelen, 2013] showing considerable difference with the well-established market of commercial buildings. The already installed heat pumps are 'traditional' applications. As in Paper & Pulp industry the greenhouse sector has in the past decades massively invested in cogeneration which now gets into economic problems due to negative spark spread.

By combining electric drive heat pumps with cogeneration more heat is generated and less electricity is produced for the power grid. This increases the flexibility in operational management of the energy system[26]. Heat storage as well co-producing for neighboring greenhouses and prediction of weather can lead to efficiency in management. A system is described in a factsheet.

Dairy Farmers

As an average Dairy Farms use 5,000 m^3 gas and 35,000 kWh of electricity. If all 17,500 Dairy Farms in Netherlands would adopt the ECO 200 system with heat pumps using the heat extracted from the milk storage it would give a saving up to 2PJ's. Campina Melkunie the large Dairy industry focuses strongly on these possibilities in order to get the complete chain from cow to end user of milk and cheese at a level of energy neutral. In all individual chains heat pumps are a key technology.

[26] a solution which is not possible with Paper & Pulp as these cogen systems in this sector normally are built with over capacity of heat

10.5 Manufacturers and suppliers in Netherlands

The market for industrial heat pumps is for an important part derived and developed from the market of industrial cooling and refrigeration. These manufacturers and suppliers are gradually ‘discovering’ the market of heating in industrial processes, but also in other markets. With their profound knowledge of thermodynamics they are developing and applying new innovative products in a fast growing market.

Compressor technology being the core of the technology with one main well established manufacturer Grasso from Den Bosch, part of GEA. The other manufacturers and suppliers in Netherlands use components from Grasso and other suppliers to create and build innovative and outstanding products. Some of the products are standardized and some of the suppliers make tailor made solutions. Many of these have applications in all different sectors ranging from industry to greenhouses, skating rings and commercial office buildings.

Figure 10-5: Grasso FX P heat pump

- **Grasso. Grenco** (www.grasso.nl), old established company and manufacturer of screw and piston compressors of different sizes. Factories in Den Bosch (NL) and Berlin (D). Under the GEA group also active in several industrial sectors with MVR compressors. The Dutch division is typically a department derived from refrigeration having developed the add-on heat pump for which they got the NVKL-Award in 2012, with an example project at Wiseman Dairies in UK.

- **IBK-Refrigeration** (www.ibkgroep.nl) from Houten, as the name suggests are specialists in refrigeration but at the same time supplying innovative heat pump concepts. IBK Refrigeration is part of the IBK-group. The first add-on heat pump was built at Unilever in Rotterdam (factsheet NL 08). Another interesting application is in ice skating rinks (factsheet NL 29). In a further development IBK is now involved in a pilot of e high temperature heat pump in paper and pulp industry, for which they got the NVKL-Award 2014.

Figure 10-6: NVKL-Trofee 2014

- **Energie Totaal Projecten** (ETP – www.etp.tv) from Dordrecht is a company delivering overall projects from engineering, design, financing, servicing and maintenance including performance guarantees for all sectors with larger systems. Their main markets are in commercial buildings and greenhouses. Based upon a chiller from international high standard they have developed a standardized high performance compact heat pump which is skid built. Heat pumps are standardized in sizes from 85kW to 3.8MW's. Several patents are pending on new breakthrough technologies. Example projects are under Greenhouses (NL-27).

Figure 10-7: ETP HWD-3800 skid

- **KODI** (www.kodi.nl) from Heerhugowaard started just like ETP as a consultancy and installer in commercial buildings and agriculture. Not happy with the products on the market KODI developed with a subsidy from Novem a high performance heat pump concept for greenhouses (see factsheet NL 27d). Standardized compression heat pumps based upon Grasso technology is now installed in several smaller industrial areas. KODI is also involved in projects like Kolksluis industrial area. On their site they give a long list of reference projects.

Figure 10-8: Typical KODI heat pump in Greenhouse

- **Reduses** (www.reduses.nl) from Nijkerk is part of a group of companies delivering all services from consultancy to installing, maintenance and monitoring. Installect,

GeoComfort and Instead are the partners where Installect is responsible for installation and design, GeoComfort for the ground source (innovative concept of mono-source) and Instead for the monitoring and maintenance (innovative concept where monitoring is used as benchmarking between companies and as tool for maintenance). Reduses is manufacturer of gas engine driven heat pumps up to 250 kW's. The gas engine is from Volkswagen. Reduses have their own certified lab to do performance tests.

Figure 10-9: Reduses gas engine heat pump

- **De Kleijn Energy Consultants & Engineers** (www.industrialheatpumps.nl) is a consulting company in Druten with a focus on industrial projects and tailor made innovative solutions (factsheet NL 11). Their focus on industrial heat pumps is clear with their website and the recent visit by NEDO in 2014. For RVO Kleijn is executing a communication strategy on heat pumping technologies.

- NRG-TEQ (www.nrgteq.nl) from Rosmalen is a manufacturer of heat pumps in the range from 4 – 400 kW's. Until recently NRG-TEQ was only active in domestic and commercial buildings.

It is of importance to notice that next to these Dutch companies other large companies are active in this market where the local office often developers innovative applications with components from their 'mother'. Carrier from Hazerswoude, together with French office, is such an example. Their heat pumps are rather popular in greenhouses and commercial buildings.

10.6 Literature

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Reissner, 2013	Reissner, F., Gromoll, B., Schäfer, J., Danov, V., Karl, J., 2013a. Experimental performance evaluation of new safe and environ-mentally friendly working fluids for high temperature heat pumps, European Heat Pump Summit, Nürnberg, Germany
Ruiter, 2011	Quickscan toepassing van warmtepompen voor energiebespar-ing bij teelten met een laag energiegebruik, J.A.F. de Ruiter (KE-MA), KEMA report June 2011
Westergaard	Milk Powder Technology, Evaporation and Spray Drying, ed. Vagn Westergaard, 5th Edition, GEA Process Engineering

11 Sweden

11.1 Energy use in Sweden in 2011

The overall final energy use in Sweden redistributed by energy carrier is shown in Table 11-1:

Table 11-1: Final energy use by energy carrier in Sweden in 2011 [1]

Energy carrier	**PJ**	**TWh**
Oil	386	107
Natural gas	24	6.7
Coal	55	15
Biomass	275	76
Electricity	454	126
District heating	170	47
Total	**1364**	**379**

The overall final energy use in Sweden is dominated by electricity and fossil fuels standing for a share of about one third each. Biomass has an outstanding share of 20 % and district heating stands for the remaining 12 %.

11.1.1 Energy use in the manufacturing industry

Figure 11-1 presents the distribution of the total energy use across the different sectors in Sweden including the redistribution on energy carriers for the industry sector.

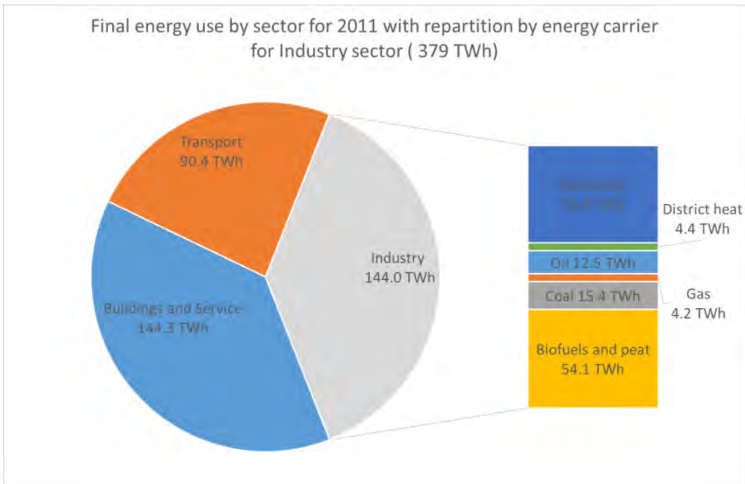

Figure 11-1: Final energy use 2011 by sector with repartition on energy carriers for the Industry sector [1].

Electricity and biofuels are the major energy carriers used in the Swedish manufacturing industry. The pulp and paper industry being one of the largest energy users mainly consumes biofuels (spent liquors to a large extent) whereas the iron and steel sector largely depend on electricity and coal (for coking processes).

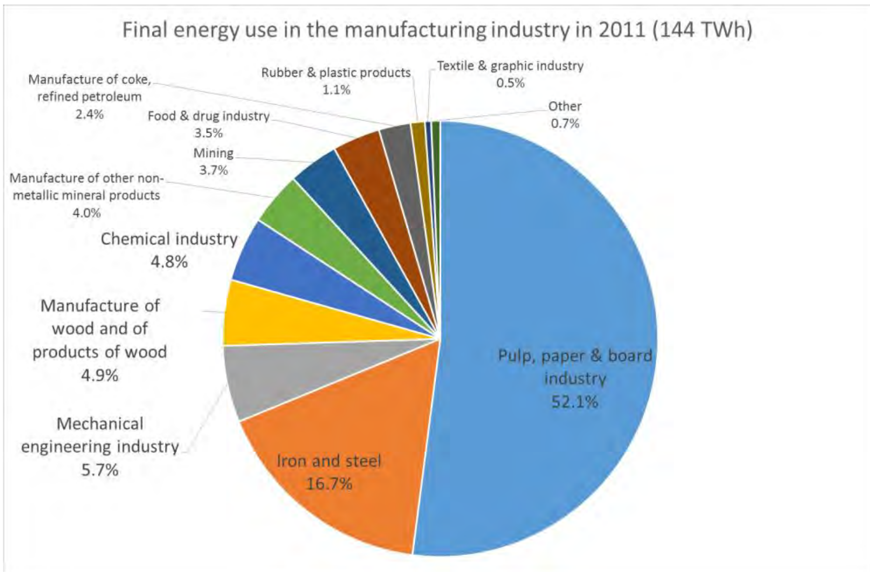

Figure 11-2: Final energy use in the different industrial sectors in 2011 (144 TWh in total) [2,3].

In Sweden the energy use in the manufacturing industry is dominated by a relative small number of sectors. The major energy user is the pulp- and paper industry standing for more than half of the total industrial energy use. The iron and steel industry is the second largest user, while the chemical, mechanical and wood manufacturing sectors are using similar amounts of energy, together standing for about 16 %. The remaining 16 % is used by the non-metallic mineral sector, food and drug sector, refinery sector and other smaller industrial sectors [1].

In Table 11-2 the energy use in the manufacturing industry is presented with fuel and electricity consumption details. Industries having a high percentage of electricity in the energy supply are less suitable for heat pump applications as there are less excess heat streams to be expected, with e.g. waste heat from electric motors being difficult to recover.

Table 11-2: Industry sector fuel and electricity use in 2011 [2,3].

Industry sector	Fuel [TWh]	Electricity [TWh]	Total [TWh]
Pulp, paper & board industry	2.1	3.3	5.4
Iron and steel	2.6	2.5	5.1
Mechanical engineering industry	0.2	0.4	0.7
Manufacture of wood and of products of wood	5.0	2.0	7.1
Chemical industry	52.5	22.6	75.1
Manufacture of other non-metallic mineral products	2.4	1.0	3.4
Mining	2.4	4.6	7.0
Food & drug industry	0.4	1.2	1.5
Manufacture of coke, refined petroleum	4.7	1.0	5.7
Rubber & plastic products	16.2	8.0	24.2
Textile & graphic industry	2.5	5.8	8.2
Other	0.4	0.6	1.0
Total	***91***	***53***	***144***

11.1.2 Market overview

A report on industrial excess heat in Sweden from 2009 presents the status of available excess heat in the different industrial sectors and the changes in excess heat delivery from 1999 to 2007. It also estimates the theoretical potentials for the different sectors. In Figure 11-3 the excess heat delivery (standard and upgraded by heat pumping) from the different industrial sectors. Due to a change in the coding system the sectors are grouped somewhat different compared to the previously presented data[27].

The amount of delivered excess heat increased by 0.8 TWh from 1999 to 2007 reaching 4.1 TWh/year. The largest supplier of excess heat is the pulp and paper sector that also increased its excess heat supply (without heat pumping) by 60 % from 1999 to 2007. Together the energy-intensive industry sectors (pulp and paper, iron and steel, petroleum refining, and chemical industry) stand for more than 90 % of all excess heat supply. Other industry sectors supply about 8% of excess heat but represent about 40% of the total number of companies supplying heat. The largest increase in heat supply of about 60% from 1999 to 2007 is seen for the wood manufacturing industry, but even the food sector increased its supply considerably (about 44%). Upgraded excess heat from low temperature heat sources by heat pumping represented about 630 GWh in 1999 but the amount delivered dropped to 265 GWh in 2007 [4].

[27] The report cited [4] uses the SNI 2002 codes while more recent data is using SNI 2007 codes.

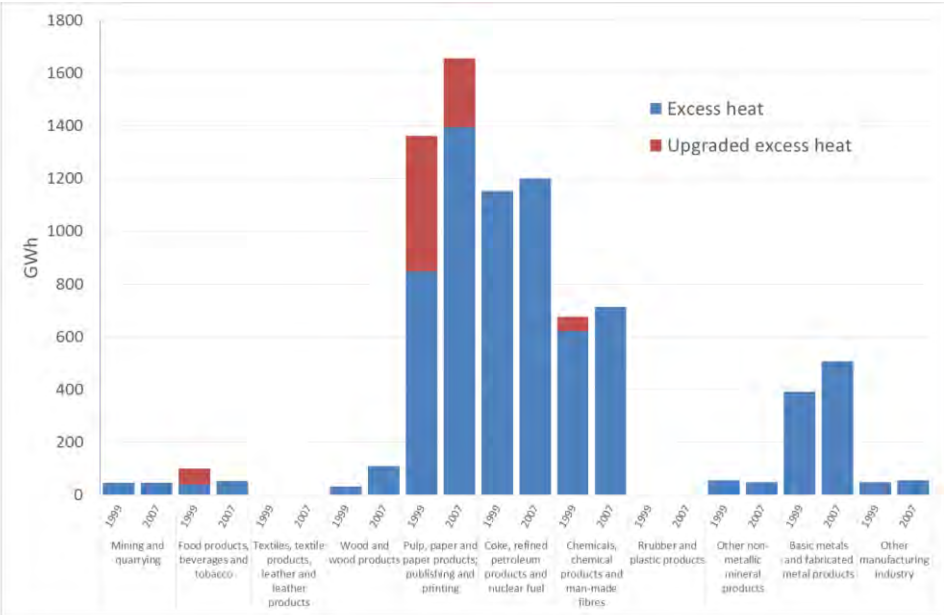

Figure 11-3. Delivered excess heat from industrial sectors in 1999 and 2007 [4].

An estimation of the potential for excess heat deliveries from the manufacturing industry sectors is presented in Table 11-3. The potential delivery estimate ranges from 6.2 to 7.9 TWh/year and is an estimated based on statistical data for the actual heat delivery as well as the industry sectors' fuel use. The calculated potential is up to 1.9 times larger than the delivered today.

The report cited here [4] discusses both the potential as well as barriers for excess heat delivery for each sector. According to the authors, a general discussion for the whole manufacturing industry sector is not possible due to varying prerequisites for the different sectors depending on their structure, location and surrounding infrastructure. A number of aspects mentioned that are relevant for industrial heat pump applications are stated in the following.

Increasing energy prices force industry to focus on energy efficiency measures and improve the profitability of heat recovery projects in general. Heat recovery from flue gases has become much more common, with biomass being used as fuel favoring the heat recovery potential due to a higher moisture content in the flue gases. The temperature level for flue gas heat recovery is rather high but even heat pump application in the lower temperature range might be considered.

Table 11-3: Excess heat delivery in 2007 and theoretical potential for manufacturing industry sectors in Sweden [4].

Industry sector	Delivered excess heat 2007 (GWh/Year)	Calculated theoretical potential of excess heat (GWh/Year)
Mining	50	250 – 300
Manufacture of food products: beverages and tobacco	61	80 – 120
Manufacture of textiles and textile products	0	0
Manufacture of wood and of products of wood	110	250 – 300
Manufacture of pulp, paper and paper products	1392	2000 – 2500
Manufacture of coke, refined petroleum products, chemicals and chemical products	1908	2500 – 3000
Manufacture of rubber and plastic products	3	10 – 20
Manufacture of other non-metallic mineral products	48	150 – 250
Manufacture of basic metals	502	900 – 1300
Other	58	100 – 140
Total	**~ 4100**	**~ 6200 - 7900**

For small scale enterprises the amount of excess heat often is rather small and heat recovery measures have not been considered yet. For district heat an increasing number of small suppliers however have a beneficial effect on the stability/reliability of the system. Considering heat pump applications, increased awareness for heat recovery have the potential to reduce the company's vulnerability with respect to changing energy prices.

11.1.3 Barriers for application

A number of barriers hindering increase excess heat delivery from the manufacturing industry are given in the cited report [4] with the ones relevant for heat pump applications are indicated here.

In particular for the small to medium size enterprises, the amount of excess heat often is considered too small or companies are not aware enough of the potential for excess heat recovery. Increasing energy prices might change this in the future.

In e.g. the wood manufacturing sector the fact that the drying equipment – representing an interesting source of heat recovery – is not running continuously is a major barrier for application. Similar problems exist in the pharmaceutical industry that is often operating batch processes with limited heat recovery potential.

The energy-intensive industry-sectors in Sweden are exposed to international competition leading to a strong strive for energy efficiency increase. Increased use of low temperature heat sources internally decreases the potential for district heat delivery but might open up for increase heat pump use. For example within the pulp and paper industry low temperature black liquor evaporation and pulp drying are applications that strive at using heat sources at lower temperature level.

11.1.4 References:

[1] Swedish Energy Agency (2013) *Energiläget 2013*, ET 2013:22, Eskilstuna, Sweden.

[2] Swedish Energy Agency (2012) *Annual Energy Balance Sheets 2010 – 2011*, EN 20 SM 1206, ISSN 1654-3688, Eskilstuna, Sweden.

[3] Swedish Energy Agency (2013) *Energy use in manufacturing industry, 2011 Final data*, EN 23 SM 1301, ISSN 1654-367X, Eskilstuna, Sweden.

[4] Cederholm, L-Å, Grönkvist, S, Saxe, M (2009) *Spillvärme från industrier och värmeåtervinning från lokaler* (Waste heat from industry and heat recovery in buildings, in Swedish), Report 2009:12, Svensk Fjärrvärme, Stockholm, Sweden.

12 Literature survey

12.1 Review of all countries

In [1] a total of 11 countries, namely France, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, the UK, the USA, and China, were surveyed to estimate CO_2 reduction potential by introducing current-technology heat pumps into the food and beverage fields. On the assumption that an electric drive compressor heat pump is used, applications at a boiler energy use end temperature of below 100 are selected as a heat pump applicable range.

As a result of this estimation, it has been concluded that the emission of 40 million tons of CO_2 per year can be reduced in all 11 countries by replacing applications at an end use temperature below 100 boiler energy in the food and beverage fields with heat pumps (with MVR in the beer brewing industry included). A total CO_2 reduction effect of 25 million t CO_2/year in the 10 countries other than China can be expected.

[1] Heat Pump & Thermal Storage Technology Center of Japan: Survey of Availability of Heat Pumps in the Food and Beverage Fields, March 2010

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Task 2:
Modeling calculation and economic models

Final Report
(20.06.2014)

Prepared by
Participants of Annex 35/13

Contents

1 Introduction

Task 2 is intended to outline how the integration of industrial heat pumps (IHP) in processes is supported by computer software, i.e. by modeling. The legal text comprises four items:

- Make SWOT analyses of available software and calculation procedures for application for different sectors.
- Analyze and update of existing models from Annex 21, where does the heat pump fit and how does it fit.
- Use the analysis of tools and findings of Task 1 to determine the gaps, needs and possibilities for new model development.
- Examine the possibilities to make software available.

During the execution of Task 2, the original legal text was slightly modified by a new activity plan:

- Database/collection of information on manufacturers of large/industrial heat pumps and their performance figures.
- Overview of software for Process Integration (PI) of industrial heat pumps.
- SWOT-analysis of integration of industrial heat pumps in industry.
- Principles for the integration of heat pumps in industry.

Unfortunately, we cannot report a complete execution of Task 2. Although the Annex 35/13 project had been prolongated by one year (mainly because of missing results from Task 2), nearly none of the deliveries could be finished as foreseen. We attribute this low interest to two facts:

- Most participants are not concerned directly with modeling and software aspects.
- The wide range of software tools with their very different scopes was largely underestimated.

Therefore, this Task 2 report expresses in some parts the Operating Agent's/ Annex Manager's view how Task 2 could be approached in a future project. The important consequence of this four years' work is to carefully reconsider the goals based on the State of the Art as well as on industrial needs if a "new Task 2" team should be constituted.

1.1 Integration of heat pumps into industrial processes: an outline of theoretical methods

Process integration (PI) methods and software tools have been compiled in numerous publications, for instance in "Process Integration Implementing Agreement within the IEA". One of its products is the comprehensive IEA Tutorial on Process Integration by T. Gundersen [1]. Software tools are discussed by the same author in Ref. [2]. Another source of general information on software tools for process integration, modeling and optimization is given by Hon Loong Lam et al. [3]. Further references are the book of L. Puigjaner and G. Heyen (eds.) [4], the overviews given by I.E. Grossmann, J.A. Caballero and H. Yeomans [5].

Design, integration and operation of industrial processes (more generally synthesis problems) have been developed since more than 3 decades starting in the early 70's at the ETH Zürich and Leeds University by B. Linnhoff and J.R. Flower [6][1]. This work and subsequent developments are known under the key words "pinch analysis". A recent detailed overview is given by the book of I. C. Kemp "Pinch Analysis and Process Integration" and the overview of F. Maréchal [8], which we use in subsequent chapters. Generally, pinch analysis allows to determine the heat recovery potential by heat exchange in complex thermal processes, or in other words, to determine the minimum energy requirement of the process.

The general solution of synthesis problems employing all kind of optimization techniques has been developed by several researchers. Numerous contributions of I.E. Grossmann and coworkers have to be noticed. Their pioneering work dates as early as 1983 [9]. A concise overview of the mathematical programming approaches to the synthesis of chemical process systems is given by I.E. Grossmann, J.A. Caballero and H. Yeomans [5] and by the book of C. Floudas "Nonlinear and Mixed-Integer Optimization, Fundamentals and Applications", see Ref. [10].

It is important to understand the difference between these general solutions and pinch analysis: In pinch analysis optimization is restricted to a simplified heat cascade model (see below), which largely reduces the optimization problem, whereas a general solution of synthesis problems means taking all process details (process units) into account. This leads to problem sizes orders of magnitude above pinch analysis. Consequently, we will briefly discuss the two groups of models, pinch analysis and (large) optimization methods separately although these differences are more and more bridged in modern software tools.

A wealth of information is available and there is no need presenting all details. Rather, emphasis is given to the integration of heat pumps into processes. We dispense with any detailed presentation of software support for the design of the heat exchanger network (HEN), i.e. we concentrate on the integration of heat pumps into processes in the sense of a specific add-on, which programs may offer or not. Nevertheless, we are aware that the design of the HEN and the integration of a heat pump are closely related to each other.

1.1.1 Pinch analysis

Subsequently we follow the comprehensive review on pinch analysis given by F. Maréchal [8], which links pinch analysis to mathematical refined optimization methods. Pinch analysis is performed in three steps:

- the definition of hot and cold streams,
- the calculation of the minimum energy requirement (MER), the so-called targeting step, in combination with a minimization of costs and
- the design of the heat exchanger network (HEN), the synthesis step.

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[1] This reference stands for the many publication of B. Linnhoff and his co-workers

Before presenting some further details, the merits of pinch analysis should be addressed:

- Pinch analysis allows a deep insight into any process. Its development was driven by detailed thermodynamic understanding of processes. Sometimes this is referred to as a holistic view. Minimum energy requirements or minimum costs are considered, as well as rules and guidelines for the design of the heat exchanger network. Nevertheless, for step three detailed knowledge and engineering judgment is required, which is augmented or supported by specific software tools.
- Pinch analysis may be considered as a mature technology and most software tools available fall into this category.

The basic idea behind the pinch analysis model is that individual hot and cold process streams are merged into fictitious hot and cold streams in order to perform a thermodynamic optimization and an optimization of costs. The thermodynamic optimization is done by the problem table algorithm, which is a specific simplification of the heat cascade model (see below). The optimization of costs is based on an approximation of the heat exchanger network (HEN). Only by these two simplifications, pinch analysis is kept rather simple. A temperature-heat load diagram can be constructed with the hot and cold composite curves (see Figure 1-1). Indicated in Figure 1-1 is the pinch, which characterizes the nearest approach between hot and cold composite curves, the so-called minimum approach temperature ΔT_{min}. The pinch is defined by pinch temperature and location. The minimum approach temperature ΔT_{min} is a parameter that determines the heat transfer between hot and cold composite curves and that is used for approximately optimizing costs: A small value of ΔT_{min} means large heat exchanger areas and hence large costs, a larger value leads to smaller areas and hence to lower costs but at the expense of thermodynamic effectiveness. Further indicated in Figure 1-1 are the resulting heating and cooling duties, also called utilities.

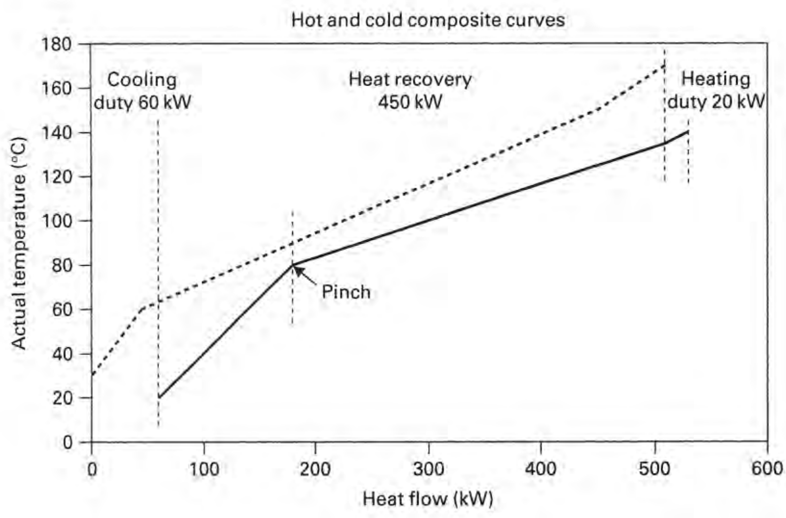

Figure 1-1: Composite curves for a four stream problem; Figure taken from Ref. [7]

In the original formulation of the pinch analysis, the integration of heat pumps is not foreseen in the targeting (optimization) step.

The design of the heat exchanger network, i.e. the synthesis step is by its nature combinatorial with a huge number of matches [8, p 184]. Pinch analysis does not follow a mathematical optimization approach, which will be discussed below, but is a sequential method mainly based on the insight gained by the thermodynamic interpretation of the pinch. More detail will be given in section 1.2.

1.1.2 Optimization Models

As early as 1983, S.A. Papoulias and I.E. Grossmann presented an optimization approach for the synthesis of total processing systems [9]. Since then, these optimization techniques were developed taking advantage of the parallel development of computer science (computers as well as numerical techniques). Significant progress has been made in optimization theory, modeling complex systems and nonlinear control with the consequence that such tools are nowadays employed routinely (I.D.L. Bogle and B.E. Ydstie, Chapter 4 of Ref. [4], p. 383). These tools are sometimes labeled **c**omputer-**a**ided **p**rocess **e**ngineering tools (CAPE). As mentioned already, a detailed overview of the present state-of the-art is given by I.E. Grossmann, J.A. Caballero and H. Yeomans [5]. Further, the book of C. Floudas [10] gives a comprehensive description of the fundamentals and the applications of nonlinear and mixed-integer optimization.

Heat pump integration has been investigated by several researchers. We mention here only the F. Maréchal group at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, which published recently several papers on this specific subject (Refs. [11], [12] and [13]). Reference [13] refers to the thesis of H.C. Becker (directed by F. Maréchal), in which a systematic methodology is presented, based on pinch analysis and process integration techniques to integrate heat pumps into industrial processes.

Generally speaking, today's comprehensive optimization methods are mature enough that heat pumps can be integrated into any process. So where is the problem? It seems that most problems origin from the fact that the integration of heat pumps is only a part of a very complex "**optimization machinery**" encountering several problems:

Mathematical problems I

The mathematical models go far beyond simple linear programming. Problems may get nonlinear and discrete (binary) variables need to be introduced, leading to programs as the mixed integer linear program (MILP) or the mixed integer nonlinear program (MINLIP). If we consider a MILP problem with m binary variables, which may take either the value 0 or 1, we have of 2^m solutions of a linear programming problem. If m is too large, combinatorial solutions are no longer feasible and specific techniques need to be applied. Nonlinear models generally suffer that convergence problems can never be excluded.

Mathematical problems II

Generally, an extremum (maximum or minimum point) can be either global (truly the highest or lowest function value) or local (the highest or lowest in a finite neighborhood). Only specific mathematical strategies, thermodynamic insight and engineering judgment can enhance the likelihood that the result of an optimization is a global minimum. This likelihood is reduced if the number of binary variables is too large for a (complete) combinatorial solution.

Problems in setting up the optimization model

In order to apply a mathematical programming techniques to design and synthesis problems, it is always necessary to postulate a superstructure of alternatives (Ref. [5, p. 5]). Or expressed in simple words: Alternatives that are not foreseen cannot be optimized. This means that the setup of superstructures is a tremendous work that needs a high degree of engineering competence, knowledge and experience. It is likely that several setups of the superstructure are needed to approach a technical solution. In addition, during the optimization it may turn out that some modification of process data ("super targeting") could further improve the optimization. Most likely, the global optimum can only be approached by an outer iteration process covering modifications of the superstructure and of process data.

Uncertainties

The mathematics must not hide the many uncertainties involved, mainly originating from estimations and predictions of costs and the definition of the optimization target itself. The solution depends on such uncertainties. Variations of costs, the optimization target or even process data enhance the possibility that several designs fulfill the requirements, i.e. variations could turn a local minimum to a global one and vice versa, especially if several local minima are close to the global minimum.

Competence needed

It is obvious that any group performing this type of optimization needs high competence in optimization mathematics as well as thermodynamic engineering. Access to large standard optimization computer programs is mandatory, which may need some specific adaption.

We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models.

Integration of heat pumps

In principle, the integration of heat pumps is no particular problem. The important question in our context is whether integration of heat pumps is already a standard in process synthesis employing detailed optimization models.

We should clarify, which possibilities exist to consider various heat pump types in a superstructure. We should elaborate whether heat pump databases are in use. However, it seems that a general heat pump database is missing and its development could be a major contribution.

1.2 Integration of Heat Pumps in Industrial Processes: general principles

1.2.1 Introduction

In this section general principles for process integration of industrial heat pumps are discussed. The text is partly based on the one presented in the IEA work “Industrial Heat Pumps Experiences, Potential and Global Environmental Benefits”, Annex 21, 1995 (Ref. [14]).

There are some parameters that are of major importance when integrating a heat pump into an industrial process:

- The industrial process. Each process is unique and consists, from an energy point of view, of heat sources and heat sinks. In order to process integrate the heat pump, applying for instance pinch analyze, it is necessary to have a good knowledge of these sources and sinks. The load and temperatures are then crucial but also other aspects as location and type of load are important from a practical point of view.
- The heat pump type. Heat pump types have different characteristics which will make them suitable in various situations. Operation temperature limitations will restrict heat pumps installations and also the choice between different types. Efficiency and type of drive energy are also crucial decision parameters.
- Energy costs. The cost of drive energy to the heat pump and the cost of the heat that is replaced determine the operation cost which is a large part of the annual cost.
- Capital costs. The investment costs associated with an installation of a heat pump derive from several parts. The heat pump itself (including auxiliaries) and the cost to install it is normally the largest part of the investment. However other parts may well be significant. The heat to the heat pump must be extracted and possibly a heat collecting system must be constructed. On the hot side of the heat pump also a distribution system might be necessary. Furthermore other changes and supplements often are necessary e.g. changes in the heat exchanger network (see below), drive energy supply and control system.

1.2.2 General Considerations and Principles of process integration of heat pumps

1.2.2.1 Basic pinch analysis concepts

In order to integrate a heat pump properly in an industrial process a good knowledge of the process is necessary. In this respect, pinch analysis is a very powerful tool, because the pinch temperature has an important physical meaning: It divides the heat sinks and sources into two separate parts, see Figure 1-2. In the part above the pinch, there is a net heat deficit, and heat must be added to the system by a hot utility. If a cold utility is applied above the pinch, it follows that the demand for the hot utility will increase by the same amount. Thus, valuable heat is just off-set by the amount of cooling added. On the other hand, in the part below the pinch, there is an excess of heat that must be removed from the system by a cold utility. Any heat added below the pinch must also be removed. Hence, in a well designed process, no cold utility should be used above the pinch and no hot utility below the pinch.

From these facts three fundamental rules can be stated:

- Do not cool a stream by utility above the pinch;
- Do not heat a stream by utility below the pinch;
- Do not transfer heat from a stream above the pinch to a stream below the pinch.

Pinch violations are said to exist if these rules are not fulfilled. Thus there are three types of pinch violations:

- Heat extraction from a heat sources above the pinch, i.e. a cooler above the pinch
- Heat supply to a heat sink below the pinch, i.e. a heater below the pinch
- Heat exchange between a heat source above the pinch and a heat sink below the pinch, i.e. heat exchanging across the pinch

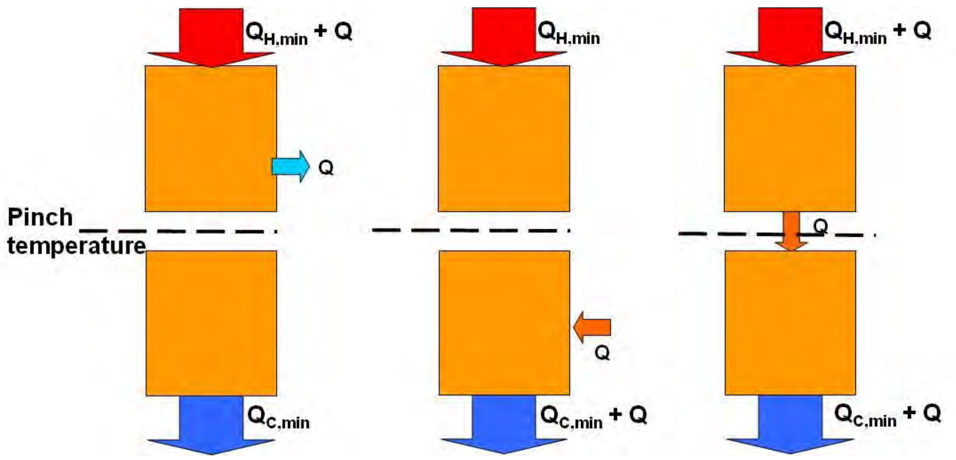

Figure 1-2: The pinch rules

1.2.2.2 Principal consequences in a theoretical situation

In a theoretical situation in an industrial process the minimum heating and cooling requirements are equal to the theoretical ones, i.e. there are no pinch violations. In this situation Figure 1-3 shows the consequences of the three principle alternatives of integrating a heat pump.

A heat pump should be integrated in such a way that the heat source is situated where there is an excess of heat (i.e., below the pinch), and the heat sink where there is a need for heat above the pinch. The heat pump is thus integrated across the pinch and both the hot and cold utility is reduced.

If the heat is extracted below the pinch and also delivered back below the pinch the consequence will be a larger cooling demand due to the net input of drive energy to the heat pump.

The third possibility is to extract heat above the pinch and also deliver it back above the pinch the hot utility will decrease by the drive energy to the heat pump. In this way hot utility can be replaced by drive energy which could be beneficial in a situation where the utility is limited of some reason.

In practice, technical and economic constraints of course limit the actual potential for heat pumping even if there are no pinch violations.

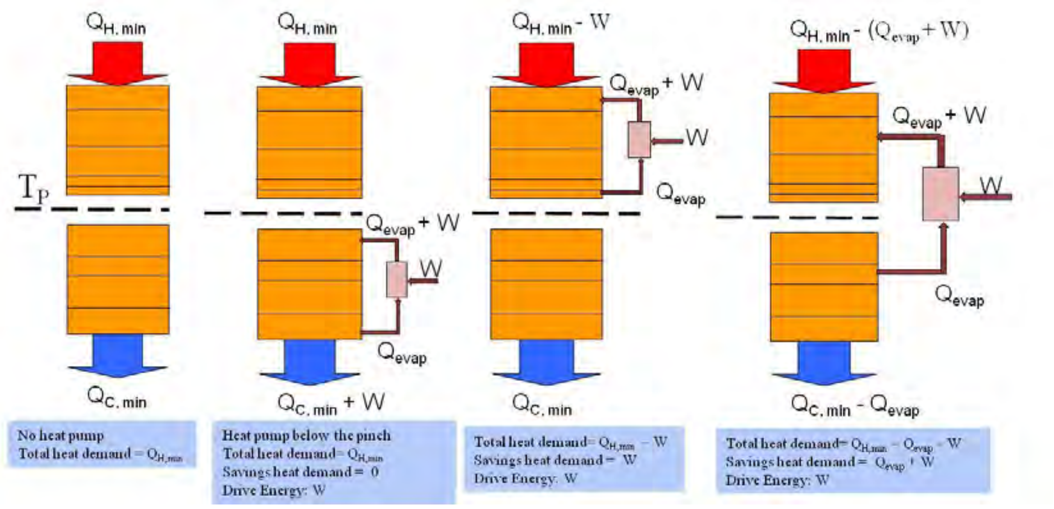

Figure 1-3: Consequences of integrating a heat pump in process without pinch violations

1.2.2.3 Principal consequences in realistic situations

In practice pinch violation exist in most processes due to various reasons, e.g. economic and practical. In these cases integration of a heat pump not necessarily has to be across the pinch in order to save energy. In principal a heat pump can eliminate pinch violations and thus reduce the energy used. Two main possibilities can be identified:

- A heat pump which utilizes the pinch violations cooling above and/or heat across the pinch (or part of them) and delivers the heat above the pinch will save hot utility. The amount is equal to the sum of the heat flow into the heat pump and the heat pump driving energy. The heat pump driving energy should of course be taken into account when a total energy balance is established. In Figure 1-4 the situation with a cooler above the pinch is shown.

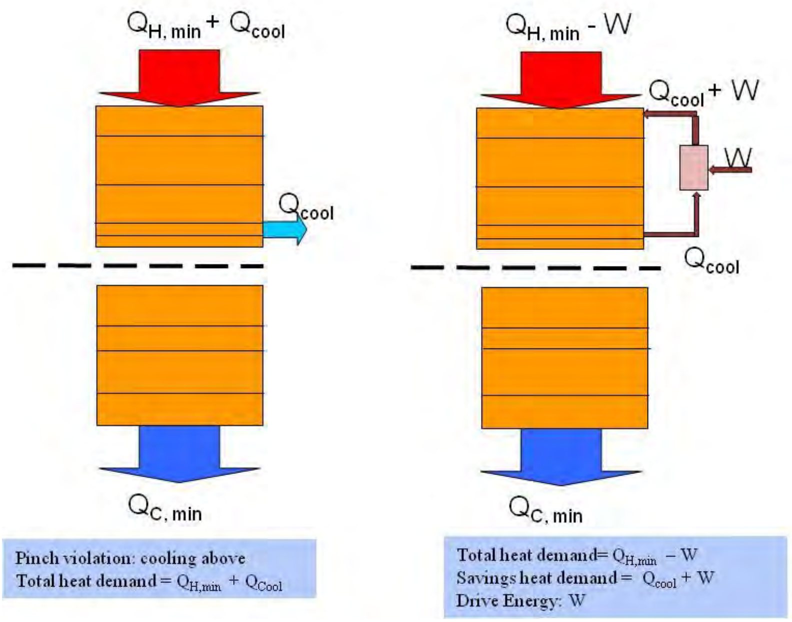

Figure 1-4: Consequences of integrating a heat pump in process in a process with a cooler above the pinch

- A heat pump, in a process with the pinch violation heating below the pinch, which extract heat and replaces this violation or part of it also saves hot utility. The amount is also in this case equal to heat flow to the heat pump and the heat pump drive energy. However in this case the drive energy needs to be cooled away. This situation is illustrated in Figure 1-5.

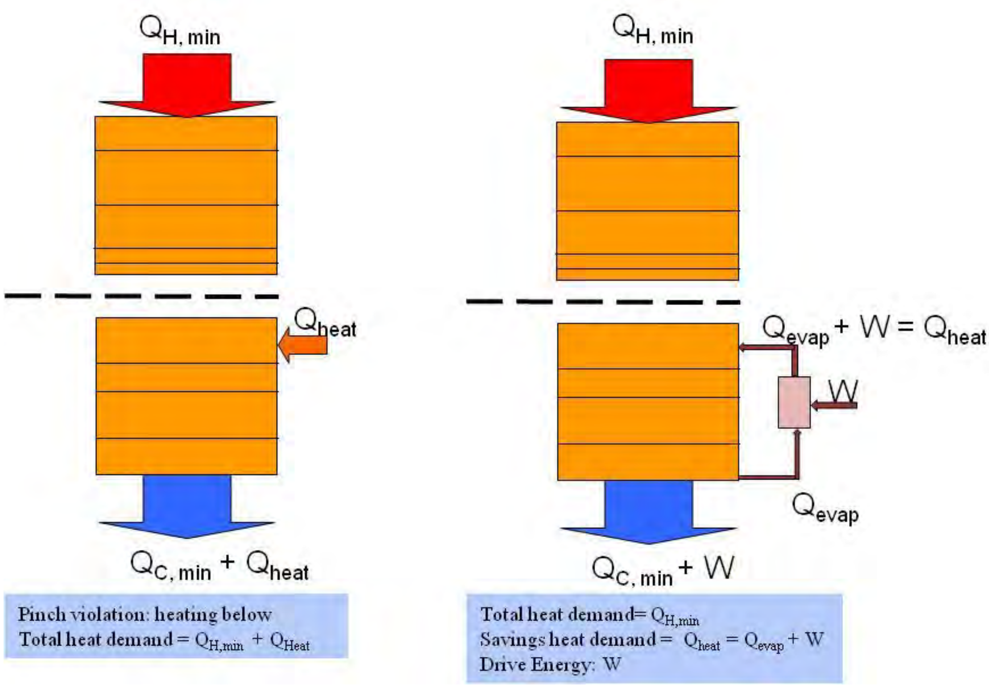

Figure 1-5: Consequences of integrating a heat pump in process in a process with a heater below the pinch

These principles show that also heat pumps not places across the pinch can save energy if pinch violations in the process exist which is the normal situation. This is in contrast to most previous published statements and opens up for more successful implementations.

1.2.2.4 Consequences on the process heat exchanger network

The consequences of integrating a heat pump into a process on the heat exchanger network can be extensive. When extracting heat to the heat pump below the pinch, the heat available for process heat exchanging might decrease. This also means that the driving force for heat exchanging decreases below the starting temperature of the heat source stream(s). This decrease in driving force means that the area needed for process heat exchanging in many cases becomes larger, and possibly that more heat exchanger units must be added. The same principals also hold for the situation above the pinch. Generally speaking, the closer in size the sink and/or source is to the theoretically maximum size at given temperature levels, the more heat exchanger network changes are necessary. The degree of these changes, however, is also dependent on the actual layout of the heat exchanger network (the location geographically and in terms of heater and cooler temperatures).

By process integrating the heat pump instead of using it from the cold utility temperature to the hot utility one, the heat pump will, in most cases, by necessity become smaller, On the other hand, this configuration may be economic as a result of the smaller temperature lift and hence higher COP.

1.3 Analysis of the Annex 21 Screening Program

1.3.1 Introduction

It has been mentioned above that the majority of software tools available for process integration fall into the pinch analysis category. Amongst these programs is the Industrial Heat Pump (IHP) screening program with the explicit objective to screen the technical and economic potential of heat pumps in various industrial processes without performing extensive and time-consuming case studies employing optimization models. The Industrial Heat Pump (IHP) screening program has been developed in the mid nineties by a group of the Chalmers Industriteknik Energiteknisk Analys (CIT-ETA) headed by T. Berntsson. Since this IHP screening program constituted a major (if not the most important) contribution to the Annex 21 Report [14, April 1995] it will be labeled subsequently as Annex 21 IHP screening program (in short screening program where not ambiguous). This model will be the starting point of our analysis of software models available.

A detailed description of the program is found in the Annex A of Ref. [14]. The intended purpose (see Ref. [14], p 41) is given as:

"The main purpose of the Annex 21 IHP screening program is to serve as a tool to allow for preliminary screening of the technical and economic potential of heat pumps in various industrial processes, based on proper integration into the process. To fulfill this purpose, a number of functions have been built into the program. These functions also make it possible to use the program as

- a database for process data

- a database for heat pump performance data
- a calculation tool to establish heat pump performance"

The pioneering idea behind the Annex 21 IHP screening program as well as its very ambitious goals and its uniqueness raised the question of today's relevance and hence lead directly to the item in the legal text of Task 2 of this Annex:

"Analyze and update of existing models from Annex 21, where does the heat pump fit and how does it fit".

Authors of the Annex 21 IHP screening program are not named explicitly. However, the presentation of the screening program within Annex 21 closely follows the publication of Wallin and Berntsson in 1994 [15], which outlines the main concept only but does not allow to fully understand the details of the screening program. Reference is made to two (at that time unpublished Papers, Refs. [16] and [17]), which were published in 1996 within the Ph. D. thesis of E. Wallin [18] as Appendices 2-5. Obviously, the original intention of the author, to publish the Appendices 2-5 in a journal has been abandoned.

Although the Annex 21 IHP screening program has been offered as an important tool for the integration of a heat pump into a process employing the pinch analysis technique, it has not been advertised or commercialized by CIT-ETA [19]. It has been made available through the IEA Heat Pump Centre (HPC) since the finalization of Annex 21 in 1997.

The Annex 21 IHP screening program has been used by several organizations but this usage is not reflected in subsequent publications. Since its finalization in 1997 the Annex 21 IHP screening program has never been modified or updated.

1.3.2 Conversion of the Annex 21 IHP screening program

During the First Annex 35/13 Meeting in 2011 [20] the update of the Annex 21 IHP screening program was discussed. The participants came to the conclusion that an update might be too lavish, expensive and time-consuming. It was agreed to check possible minor improvements and to concentrate on improved input data. Weak points were summarized by R. Nordman [21]:

- Requires detailed knowledge of both process integration and heat pump
- Outdated refrigerants' data (R12, R22, R114, HC, Steam (open type)
- Not possible to add new refrigerants (thermophysical data)
- No automatic screening possibility, user must test number of options by hand
- No transparent interaction possibility with other software (data export)
- Separate help files
- Graphical system user unfriendly
- Need new implementation which would need lots of coding although basic code is available

The new implementation suggested in the last item of the list shown above was done by the Information Center on Heat Pumps and Refrigeration (IZW): The complete Annex 21 IHP screening program (with only a few minor items missing) was converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. Details of this work are documented in two internal IZW notes [22]and [23].

Both versions, i.e. the original version from 1997 and the converted version from 2011 give in almost all situations identical results. Differences found in specific situations may be attributed to an error detected in the original screening program. Another reason for disagreements in specific situations could be a possible inconsistency between the source code used to build the executable of the original screening program and the source programs provided to IZW. This possible discrepancy could never be clarified. Two examples of the converted version are shown in **Figure 1-6** and **Figure 1-7**. All results (numbers) in the figures are identical with the original Annex 21 IHP screening program.

The conclusion from this conversion is obvious: The new, converted version is ready for any modifications, updates of data and models as well as for extensions. Parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

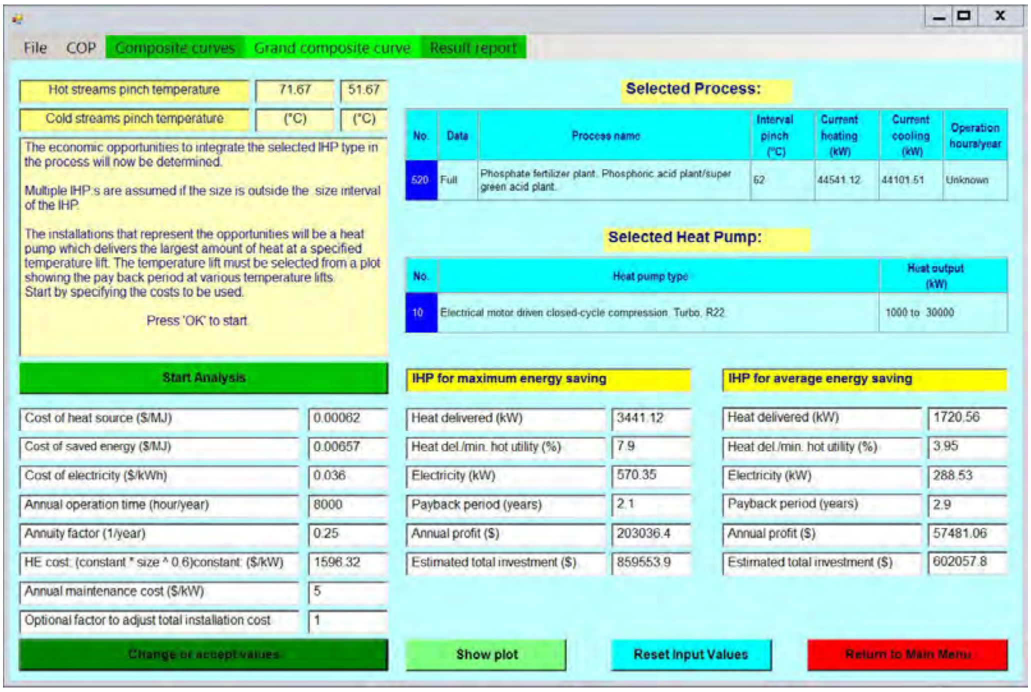

Figure 1-6: Menu item "Economic opportunities-part 1" of the revised Annex 21 IHP Screening Program (Refs. [22] and [23]); all results (numbers) are identical with the original Annex 21 IHP screening program

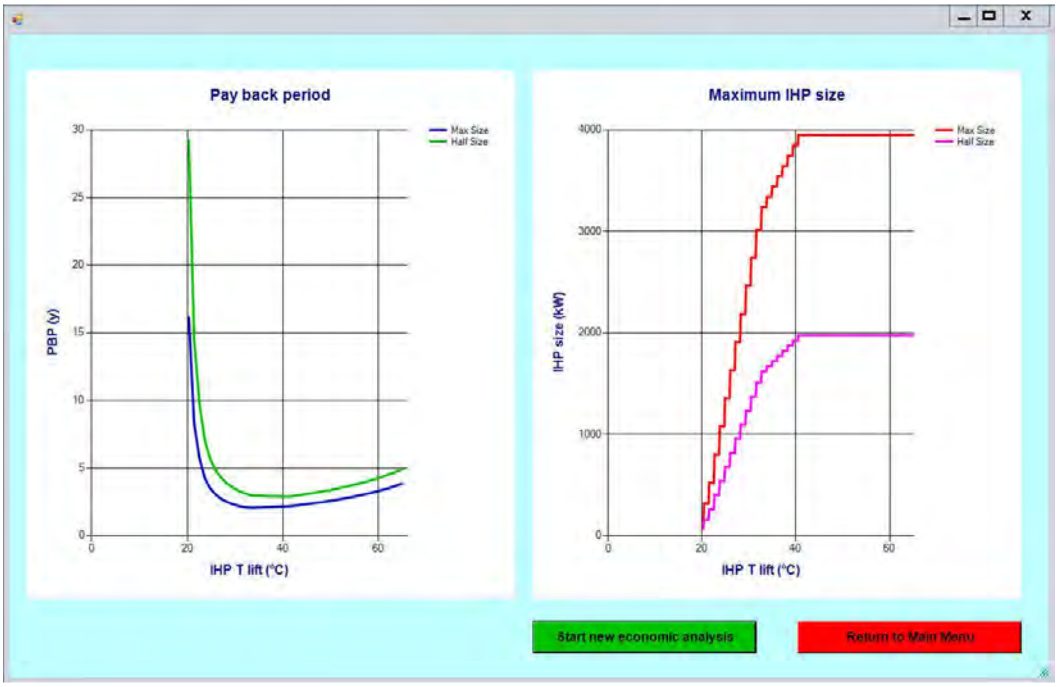

Figure 1-7: Menu item "Economic opportunities-part 2" of the revised Annex 21 IHP Screening Program (Refs. [22] and [23]); the graphs are identical with those from the original Annex 21 IHP screening program.

1.3.3 Analysis of the Annex 21 IHP screening program

Two problems make any critical analysis rather difficult, if not impossible:

- A systematic verification of the Annex 21 IHP screening program has never been published. Especially any comparison between the screening program and more sophisticated models is missing.
- The work of E. Wallin [18] gives a vast amount of details, various approximations and approaches. It is obvious that only selected models or approaches have been implemented in the screening program. Unfortunately, the information what detailed approaches have been implemented is missing. In view of the statement made above, that the screening program has not been advertised or commercialized by CIT-ETA, such a detailed description has never been intended. What is available must be considered as fair enough.

The work of Wallin is based on a very detailed thermodynamic and technical understanding of processes and heat pumps. Such a detailed understanding is also mandatory if a heat pump is to be integrated in a process employing the screening program. Its usage is a step by step optimization, guided by the experience and knowledge of the user. Besides the standard pinch analysis optimization there is no support given by further optimization methods. This approach makes the usage of the screening program rather complex and time-consuming.

It seems that the difficult usage of the screening program was one major obstacle for any updating of data and models. However, there is one compelling and convincing argument against any update of the screening program in its original form: during the execution of Task 2 it became obvious that the authors (and owners) consider this particular approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We criticise that the formulation of the corresponding item in the legal text did not take this situation into account.

Nevertheless, we should not loose sight of the database for heat pump performance data, included in the screening program. Since we have worked through all details of the screening program, we know that this database is one the largest part of the screening program. It consists of rather general parts, which need only minor modifications and of input data for heat pumps which must completely be updated (for more details see below).

1.4 A modern concept for a screening program based on pinch analysis

The proposed modern concept for a screening program based on pinch analysis considers the work of F. Maréchal and S.A. Papoulias & I.G. Grossmann. Chapter 1.4.1, "*The problem table algorithm*" follows closely F. Maréchal (Ref. [8]), whereas chapter 1.4.2 "*The transshipment model of Papoulias and Grossmann*" is a short description of this model directly taken from S.A. Papoulias and I.G. Grossmann [9, p. 709]). From these two references the concept for a new screening program based on pinch analysis has been developed. The kernel of this model has been tested through a preliminary test program (see chapter 1.4.3 "*A simple test program*").

Although many details are incorporated in the test program it is not necessary presenting all equations. Rather emphasis is put on a more general understanding of the mathematical concept. It will be shown that the resulting equations of linear programming (linear optimization) are more or less as simple as solving a linear system of equations.

As mentioned in previous chapters, the general solution of integrating heat pumps into a problem has been discussed in all aspects and has been solved for several case studies by H.C. Becker [13]. Here we analyze an approximate solution for the simultaneous optimization of heat pump, utilities and heat exchanger network (in an approximate form) by substituting the problem table algorithm of the classical pinch analysis by a simple optimization model.

1.4.1 The problem table algorithm formulated as mathematical optimization method

The original (classical) pinch analysis is using the problem table algorithm as optimization technique, which is extremely simple but also unnecessarily limiting. The problem table algorithm stands for a specific heat balance model (heat cascade model), to obtain the minimum energy requirement. The heat cascade is represented by temperature intervals obtained by the construction of composite curves, in which energy balances are performed. The standard procedures for partitioning the entire temperature range account for thermodynamic constraints in the transfer of heat, i.e. it guarantees that the second law of thermodynamics is taken into account. Temperatures of hot streams are corrected by $-\Delta T_{min}/2$ whereas cold streams are corrected by $+\Delta T_{min}/2$. The heat cascade model of the classical pinch analysis is visualized in Figure 1-8. The vector $\boldsymbol{R}$ represents the heat cascaded from higher to lower temperatures, R_1 is the cold and R_{n+1} the hot utility, i.e. the minimum energy requirement.

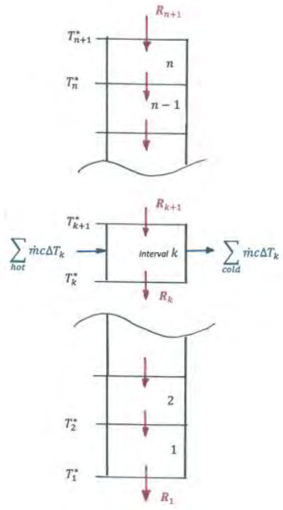

Figure 1-8: Heat cascade model underlying the classical pinch analysis; for explanations see text; corrected temperatures are labeled as T_i^*; the specific notation is given in the text

From Figure 1-8 we see that only two utilities are considered: one hot ($\equiv R_{n+1}$) and one cold ($\equiv R_1$) utility. The reason for this restriction is quite simple: This particular form of the optimization problem to obtain the minimum energy required can be carried out by hand. However, this simplicity has its prize: Only for these restrictions the optimization problem can be solved without employing optimization methods such as linear programming (linear optimization) methods. This would already be necessary if utilities in more general configurations are to be considered. In pinch analysis these restrictions are overcome by use of the grand composite curve and performing this optimization by hand, which restricts this optimization to manageable situations only.

The mathematical form of the problem table algorithm is as follows: For the independent variables $R_1, \dots, R_{n+1}$ (the heat cascaded from higher to lower temperatures), we need to maximize the function

(1) $$z = -R_{n+1}$$

subject to primary constraints

(2) $$R_k \geq 0 \qquad k = 1, \dots, n+1$$

and simultaneously subject to the additional constraints (balance of heat)

(3) $$R_{k+1} + \sum_{hot\ streams} \dot{m}\ c_p\ \Delta T_K - R_k - \sum_{cold\ streams} \dot{m}\ c_p\ \Delta T_K = 0$$

with $\dot{m}$ = mass flow rate

c_p = specific heat at constant pressure

$\Delta T_k = T^*_{k+1} - T^*_k$

For the sake of simplicity the individual stream indices have been omitted in Eq. (3). These equations formulate a rather simple problem which can be solved by standard solvers of linear programming (linear optimization).

1.4.2 The transshipment model of Papoulias and Grossmann

A transshipment model may be considered as an extension of Equations (1)-(3) in order to consider utilities in a more flexible form. Its basis is also a heat cascade model similar to the one shown in Figure 1-8. Papoulias and Grossmann write:

"The transhipment model for the heat recovery network has the hot streams and the heating utilities as sources, the temperature intervals as the immediately nodes and the cold streams and the cold utilities as the destinations. The heat flow pattern, and thus the extended equations compared with the equations (1)-(3), is as follows:

- Heat flows into a particular interval from all hot streams and heating utilities whose temperature range includes the temperature interval.
- Heat flows out of a particular interval to the cold streams and cooling utilities whose temperature range includes the temperature interval.
- Heat flows out of a particular interval to the next lower temperature interval. This heat is the residual (excess) heat that cannot be utilized in the present interval, and consequently has to flow to a lower temperature interval.
- Heat flows into a particular temperature interval from the previous interval that is at a higher temperature. This heat is the residual (excess) heat that cannot be utilized in the higher temperature interval."

The main advantage of the transshipment model in comparison to the problem table algorithm is the significantly increased flexibility to optimize complex utility configurations with arbitrary cost structures.

The authors also show how this transshipment model could be extended to treat restricted matches, i.e. pairs of hot and cold stream that are not allowed to exchange heat. Such a case cannot be treated by the classical pinch analysis.

The statement presented at the beginning of this chapter, i.e. that a transshipment model may be considered as an extension of Equations (1)-(3) can also be reversed: The problem table algorithm is included in the transhipment model as special case. This leads immediately to the question whether the substitution of the problem table algorithm by the transhipment model as a more or less general optimization method offers advantages in a modern pinch analysis programs.

One advantage is obvious: The optimization of utilities could be done by the code if the necessary information concerning utilities (temperature, mass flow rates, costs etc.) is provided to the code by a specific "Utility Window". Of course, the user could modify this optimization of utilities of the code by using the standard approach, namely by employing the grand composite curve.

We would expect that such modifications of the classic pinch analysis approach has already be realised in one or the other pinch analysis code.

The second advantage is also obvious: by a further minor extension of the classical transhipment model (see chapter 1.4.4 “The extension of the transshipment model to integrate a heat pump”), a heat pump could be included in the process by a simultaneous optimization of utilities and heat pump. This will be discussed below.

The fundamental requirements of the substitution of the problem table algorithm by a transshipment model are applicability, numerical accuracy and reliability as well as reasonable computational times. In other words, would this substitution eventually annihilate the simplicity of pinch analysis models? We would expect that the numerical effort of the optimization is negligible, since the heat cascade model itself is a thermodynamic simplification of complicated processes.

Since the transshipment model plays a dominant role in the proposed ‘modern’ pinch analysis program and since all numerical aspects need to be known in principle before a major code development is started, a numerical model was written in form of a simple test program.

1.4.3 A simple test program

A simple test program has been programmed in a rather flexible form: Up to 500 temperature intervals are allowed and ‘arbitrary’ utilities may be considered. The optimization goal can be either minimum of energy or minimum of costs. It has to be stressed that this version of the transshipment model is a test version only, which does not include a Graphical User Interface. It has been used for various very specific situations by directly modifying the code.

When applied to appropriate situations (and only for such specific situations a direct comparison can be made; see Figure 1-8), the agreement between the results of the classical pinch analysis with the problem table algorithm and the transshipment model is perfect. Compared were 4 quantities for 14 very different cases taken from the process data base included in the Annex 21 IHP screening program: pinch temperature, pinch location, hot utility and cold utility (see Figure 1-9). The computational cost of both algorithms is hardly to be measured on a modern PC.

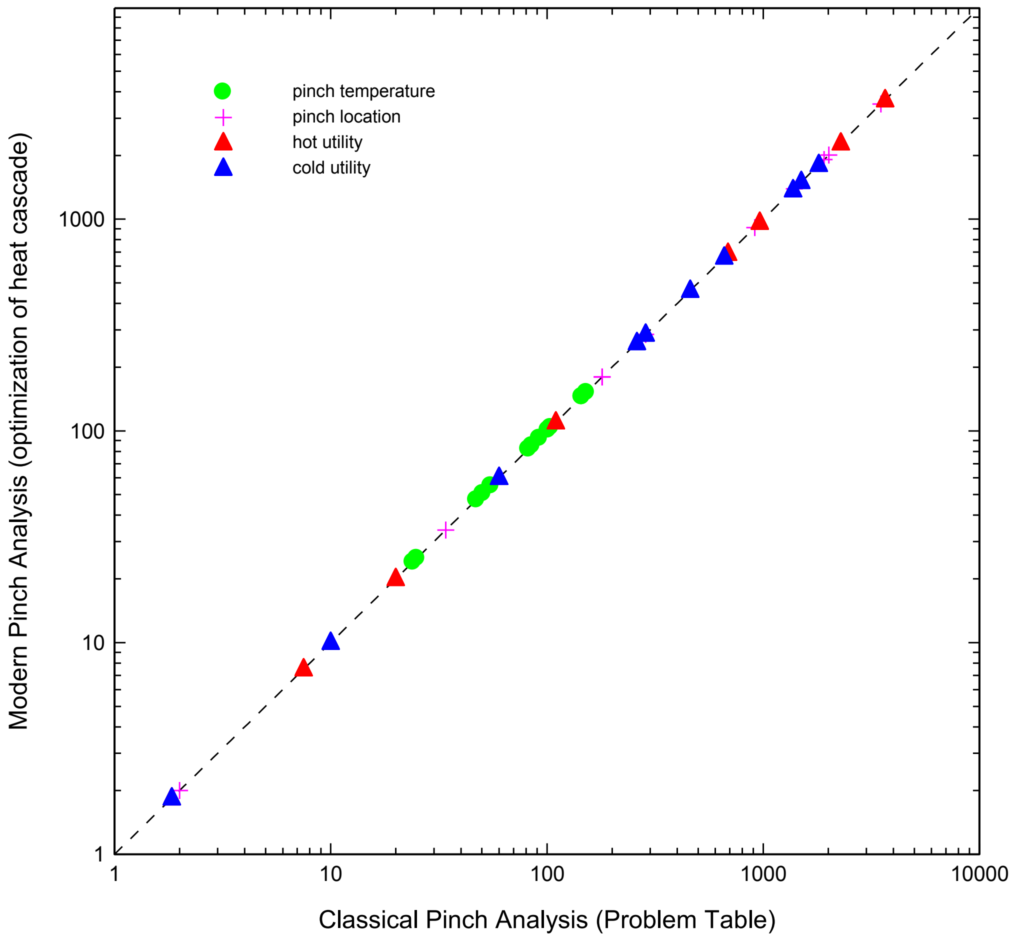

Figure 1-9: Comparison between the solution of the heat cascade model according to the classical pinch analysis based on the problem table algorithm and an optimization technique for 14 different processes; the agreement is perfect

Our proposal that that optimization of utilities could be done by a transhipment model within a pinch analysis code if the necessary information concerning utilities (temperature, mass flow rates, costs etc.) is provided to the code by a specific “Utility Window” can be realized more or less without any restrictions.

We therefore expect that such or similar extensions of the classical pinch analysis are employed in several software tools.

The further tests confirmed applicability, numerical accuracy and reliability of the transshipment algorithm as well as short computational times. These tests included rather complicated situations of utilities and their different costs, in which we doubt that an optimization performed by hand is trivial.

Consequently there are no obstacles to further follow this approach for a modern concept for a screening program based on pinch analysis

1.4.4 The extension of the transshipment model to integrate a heat pump

The consequences of integrating a heat pump into a process on the heat exchanger network have already been discussed in chapter 1.2 "*Integration of Heat Pumps in Industrial Processes: general principles*". In a heat pump heat is lifted from a low temperature level (heat source) to a higher temperature level (heat sink). For integrating a heat pump into a process both terms must additionally be taken into account in the transshipment model, i.e. in the heat cascade. The consequence of integrating a heat pump has not only been extensively discussed in the Annex 21 report, but also visualized in Figure 3.4 of Ref. [14], p. 31. As already discussed in chapter 1.2, the modification of hot and cold composite curves lead to a decrease of driving forces for heat exchanging below heat source temperatures and above heat sink temperatures, which implies that larger heat exchange areas are necessary.

For modeling it is important to recognize that the model gets nonlinear, i.e. not only the driving forces for heat exchange are affected but also the location of the pinch point.

1.4.5 The elements of the proposed modern concept for a screening program based on pinch analysis

Let us consider the heat balance equations in the form of the heat cascade as the first element of the proposed modern concept for a screening program based on pinch analysis.

The second element is the heat exchanger network. As long as we aim at developing a 'modern' screening program based on pinch analysis, we must assume that - analogous to the standard pinch analysis- the heat exchanger network is approximated by an artificial heat exchanger area A_{ex}, which depends on the minimum approach temperature ΔT_{min}. As above in the case of the heat cascade we indicate the type of mathematical dependencies only.

For a cold stream to be heated up from an initial temperature $T_{cold,in}$ to a target temperature $T_{cold,target}$ and one hot stream to be cooled down from $T_{hot,in}$ to $T_{hot,target}$, F. Maréchal gives the solution from which one can see the typical dependencies [8, p 167ff]:

$$(4) \qquad A_{ex}(\Delta T_{min}) = \frac{\dot{m}_{hot}\; c_{p,hot}}{(1-\kappa)U_{ex}} \left[\ln\left\{ \frac{(1-\kappa)\left(T_{hot,in} - T_{cold,in}\right) + \kappa\, \Delta T_{min}}{\Delta T_{min}} \right\} \right]$$

$$\text{with} \qquad \kappa = \frac{\dot{m}_{hot}\; c_{p,hot}}{\dot{m}_{hot}\; c_{p,cold}} \quad \text{and} \quad \frac{1}{U_{ex}} = \frac{1}{\alpha_{cold}} + \frac{e}{\lambda} + \frac{1}{a_{hot}}$$

$\dot{m}$ is the mass flow rate, c_p is the specific heat at constant pressure, U_{ex} is the overall heat transfer coefficient of the heat exchanger, α is the heat transfer coefficient, e the thickness of the tubes. Eq. (4) allows estimating the costs of the heat exchanger network and can easily be refined.

Clearly, this approach is an approximation. Unfortunately, we cannot say how good this approximation is since we are not aware of any systematic comparison between the costs estimated by pin analysis and from analyses based on detailed optimization. It is obvious that this approximation is only meaningful for those situations, in which the error of the approximation is far less than the actual potential of incorporating a heat pump.

Further elements of the model are:

- Development of a heat pump database to be used within the optimization process. Typical information to the database are not only source and sink temperature as well as size of heat pump but also further details of the selected hot and cold streams to which the heat pump is selected which allow to select a specific heat pump type. It has been mentioned in chapter 1.3.3 that the data base of the original Annex 21 IHP screening program is one the largest part of this program. It consists of rather general parts, which need only minor modifications. Most importantly, the input data for heat pumps must be updated.
- Development of an algorithm for selecting of a hot and cold stream (may be the selection of several hot and cold streams) to which the heat pump could be connected. This algorithm is not really clear in Wallin's thesis [18]. No attempt has been made to look deeper into this problem.
- The nonlinearity mentioned above requires an iteration that converges towards the solution. Generally, convergence can never be guaranteed per se, but in this case it is even worse since the nonlinearity has a rather nasty characteristic: Some of the functions are or get discontinuous. For instance the pinch point itself, or the size and price of a specific heat pump with a specific power range, where the full power range is realized by overlapping of individual heat pump models. In view of the extremely short computational costs in the range far below seconds per analysis, we have had in mind to apply a Monte Carlo technique with quasi-random sequences. This technique would have allowed obtaining results in a reasonable time. Of course there would have been the need (with the help of experts!) to replace this Monte Carlo technique by a more appropriate technique used in process integration later on.

The proposal to substitute the problem table algorithm by a modified transshipment model in pinch analysis in order to integrate a heat pump into a process is supported by the approach taken by K. Holiastos and V. Manousiouthakis [25] for the optimal integration of heat pumps and engines in heat exchanger networks. Heat pumps and heat engines are considered as components of the heat exchange network. Analogous to pinch analysis, which does not deal with single heat exchangers (at least not in the targeting step), individual units (e.g. heat pumps) are not dealt with. Rather, a thermodynamic approach is considered, enabling the solution of the global optimum over all network configurations. Two subnetworks are considered, whose interaction produce the optimal network: a heat exchanger subnetwork, representing the aggregate action of heat exchangers, and a heat engine and heat pump subnetwork, representing the aggregate action of power units. The heat exchanger network is modeled by a modified equation (4) taking into account that only a fraction of the hot composite stream enthalpy will be transferred to the cold composite stream. The heat engine and heat pump network is modeled by the work available (first law) and the second law: it is necessary to ensure that the total stream enthalpy change due to aggregate heat pump/engine action in the subnetwork is zero (Ref. [25], p. 8).

1.4.6 Summary

A modern concept for a screening program based on pinch analysis can be developed by substituting the original problem table algorithm of the pinch analysis by a modified transshipment model. Numerical aspects and principal feasibility have been analyzed. However, some details of this model need to be developed:

- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base.
- Development of an iteration algorithm to cope with the specific type of nonlinearity.

In principle this analysis should be very similar to the "engineering" procedure of integrating a heat pump. However, we must be aware that the approximation of the net of heat exchangers may jeopardize the whole approach if its error is too large.

1.5 Scoping analysis of existing software tools based on pinch analysis

This chapter is called 'Scoping Analysis' since neither a detailed mathematical analysis nor any detailed analysis of functionalities, user support or user friendliness can be given within this Task 2 report. However, experiences with one of the major tools, the Einstein code, and the models used for the choice of a heat pump will be reported below.

A comprehensive State of the Art review on analytical tools based on the pinch method, is given by Y. Beucher, J.-L. Peureux and A. Vuillermoz (see chapter 3). Methods of process energy integration with emphasis on pinch analysis are discussed and stakeholders from academic research laboratories and other non-academic players are listed. Although this compilation has been carried out over several years, it does not claim to be an exhaustive list, as numerous pinch analysis tools exist and new tools are released every year. Some of the tools presented in this report may even now be obsolete. Here, we only list the names of the programs treated in more detail in the report: STAR and SPRINT, Pinchlight, OSMOSE, Thermoptim, CERES, Pro_Pi, PinCH, Hint, Einstein, SuperTarget, AspenEnergyAnalyzer. The compilation is rather descriptive and more oriented towards giving potential users a first orientation. Although mathematical details have been omitted in the overview, the authors indicate what is to be expected from the theoretical point of view with regard to the integration of heat pumps:

OSMOSE: Developed by the group "energy integration of heating systems" headed by F. Maréchal of the Ecole Polytechnique Fédérale de Lausanne (EPFL). Calculation models and procedures have been developed to integrate heat pumps into an industrial process. OSMOSE is an optimisation platform, rather than a tool based on the pinch method. OSMOSE uses the mathematical programming formulation of the heat cascade and aims at calculating the flows in the utility system. This approach is the only practical approach for the heat pump integration since the flows of the hot and cold streams of the heat pump are interacting with the other heat pumps and with the other utility streams like combustion gases, cogeneration and steam cycle models. It has to be highlighted that although pinch analysis gives an explanation of the principle of the heat pumping integration, the pinch analysis is mainly targeting the heat recovery and therefore can be hardly used when it comes to calculate the optimal integration of a heat pumping systems [26].

CERES: developed by the CES (Centre d'Eco-efficacité des Systèmes or Centre for Systems Eco-Efficiency) of the Ecole Nationale Supérieure des Mines de Paris (Mines Paristech). CERES enables the pinch method, but has been further enhanced with optimisation algorithms designed to select among a number of utilities (heat pumps, turbines, etc.).

Einstein: The pinch method is involved only when designing the exchanger network, and not in the choice of utilities: the tool does not really allow for determining which utilities or combinations thereof would be optimum; it only provides the possibility for testing various energy supply scenarios and to compare them based on energy, economic or environmental criteria. The module designed for heat pump integration is not easy to use, and – at least in V2.1 – had some bugs.

1.6 Conclusions

Although the Annex 35/13 project had been prolongated by one year, mainly because of missing results from Task 2, nearly none of the deliveries could be finished as foreseen. We attribute this low interest to two facts:

- Most participants are not concerned directly with modeling and software aspects.
- The wide range of software tools with their very different scopes was largely underestimated.

The Annex 21 IHP screening program has been analyzed and converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. This new, converted version would in principle be ready for any modifications, updates of data and models as well as for extensions. However, during the execution of Task 2 it became obvious that the authors (and owners) consider this approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We simply notice that the formulation of the corresponding item in the legal text did not take this situation into account. However, parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

In order to 'update' the Annex 21 IHP screening program in the sense of a 'modern' development taking the original goals into account a proposal is made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.

- Development of a heat pump data base to be used within the simultaneous optimization. Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

This concept of integrating a heat pump into a process is ‘below’ the sophisticated methods given by H.E. Becker [13]. Presently it is impossible to state whether such a development is unprecedented, relevant and needed.

The scoping analysis of existing models shows that the difference between ‘pure’ pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Regarding the integration of heat pumps into a process, codes like OSMOSE or CERES (amongst may be others) look promising.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

The goals of Task 2 should be carefully reconsidered if a “new Task 2” team should be constituted. The State of the Art as well as industrial needs of research organizations, large companies as well as of energy consultants should be critically reviewed. We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models. This is the main reason why we propose to develop a ‘modern’ screening program ‘below’ the sophisticated methods given by H.E. Becker [13], which may be considered as a specific add-on for standard pinch analysis codes for integration of heat pumps. Nevertheless, in the whole context we consider the thesis of H.C. Becker (directed by F. Maréchal) as key reference due to the systematic methodology, based on pinch analysis and process integration techniques, to integrate heat pumps into industrial processes.

More detailed information of the programme and work on Task 2 of the Operating Agent see the IZW Internal Reports

- 01/2011: Analysis of the Annex 21 IHP Screening program [22]
- 02/2011: Upgrade of the Annex 21 IHP Screening program [23]
- 11/2012: Some thoughts regarding Annex 35/13 Task 2 report [26]
- 12/2012: Integration of heat pumps into chemical processes:
  An outline of theoretical methods [27].

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2 Austrian Team Report - Software

Within the Task 2 of the IEA HPP-IETS Annex 35/13 different software tools regarding the integration of heat pumps in production processes and there energetic and economical savings have been analysed. Due to the lack of the availability of measurement data the tools are only described theoretically without validation.

An investigation concerning available programs for the calculation and interpretation of large heat pumps and their integration into complex systems has been carried out, focusing on software solutions that can be used by industrial companies: No time-consuming model development is necessary, technical and economic aspects might be considered, relatively simple data entry, data are easy and inexpensive to collect, etc. Since the financing of the national project does not provide costs for the purchase of software licenses, the search was limited to free software. An attempt was made to obtain demo versions of the software to analyze the applicability. From this analysis a qualitative evaluation of the available software can be carried out to prove if the tools can be used for research and as well for industry. The analysis will include, among others, the following:

- For what purposes is the software suitable?
- Which heat pump technologies can be simulated?
- How flexible is the software in terms of system design?
- Is the software suitable rather for research or for planning and calculation of real systems?

Based on the experience gained, the need for the development of new or the adaptation of existing tools and models have been evaluated. In this regard also the simulation tools EES, ASPEN Plus and CoolPack have been analysed concerning the ability for proving suitable system integrations. EES (2010), ASPEN Plus (2009) and CoolPack (2014) are tools for a theoretical analysis of different heat pump cycles by means of thermodynamics, but they are not the optimum tools for the analysis of the integration of heat pumps in complex systems, as e.g. production processes by the end users or planers concerning ecological and economical criteria.

As part of this project two software tools "TOP-Energy" (2013) & "EINSTEIN" (2013) for the analysis and optimization of energy systems including the possibility of integrating heat pumps have been traced and described in more detail.

2.1 TOP Energy

The “TOP energy” (2013) software was developed by the Department of Technical Thermodynamics - RWTH Aachen University to support the analysis and optimization of energy systems. The software consists of several modules, which are attached to a common framework. The framework provides basic functionalities, such as Open / Save Project / Export, while the modules satisfy a specific engineering task.

Currently the modules eNtry for initial analysis, eSim for the simulation of Energy systems and eVariant for the comparison of different variants exist.

The TOP energy framework is a software tool, which specifies a specific application structure to carry out projects for the analysis and optimization of power engineering problems in industry. The execution of tasks is supported by implemented application modules that are controlled and monitored by the framework.

The energy oriented analyses are performed by eNtry - initial analysis and use specific questionnaires for data collection. The module checks the entered data for plausibility, calculates a number of operational energy figures and compares them with typical industry values. The results of the evaluation are presented clearly in diagrams and tables and can be exported to a report.

The optimization of energy use in the industry is determined by the simulation module eSim and the flow diagram editor, while energetic as well as economic and ecological characteristics are worked out. A comparative economic analysis for energy applications is realized with the module eValuate - variant comparison.

Two types of heat pump models are available:

- A compression heat pump is given as a component template. It is used in TOP energy as model description of a heat pump process, which is driven mechanically respectively electrically. Apart from the technical input data it is also possible to use economic data which indicate the capital- bound or the operational costs of the components. This information is used to compare the efficiency of energy system variants with the TOP Energy eValuate Module.
- The Model of an absorption chiller describes the thermal behaviour of a thermally driven heat pump. Electric auxiliary drives, for example for the solvent pump between drain and desorber are not modelled and are not included in the calculations. User input concerning capacity is required, which includes the nominal cooling capacity, power consumption (thermal) and electricity. Furthermore temperature levels can be specified for cooling, re-cooling and the thermal input. The dependencies between the temperature levels and the behaviour of the chillers are not yet implemented in this component. With an input file the characteristic of a part load behaviour for the absorption chiller can be specified, in the simplest case, there is a linear curve from 0 to 100 % of the rated power.

2.2 EINSTEIN

EINSTEIN (Expert System for an Intelligent Supply of Thermal Energy in Industry and other large-scale applications, 2013) is a tool-kit for fast and high quality thermal energy audits in industry, composed by an audit guide describing the thermal energy audit methodology and by a software tool that guides the auditor through all the audit steps.

The free, open-source software tool EINSTEIN enables the development of strategies to reduce energy consumption and operating costs in the company. In contrast to standard measures for reducing the electrical consumption in industry such as by pumps, motors, lighting achieving good results, the optimization of the thermal energy requirements is technically quite complex (Schweiger et al., 2011). The "eye of EINSTEIN" (see takes into account heat recovery, process integration and a smart combination of economic heating and cooling supply technologies.

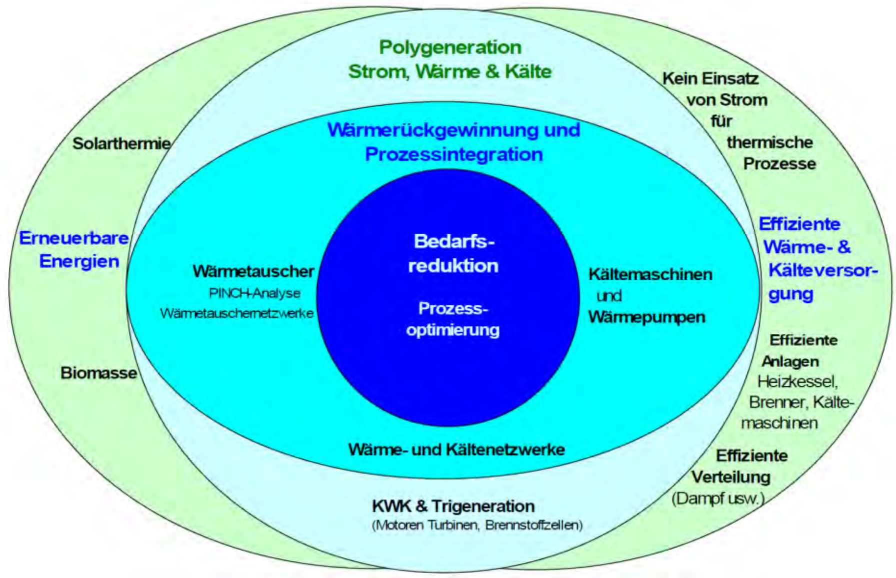

Figure 2-1*: "The eye of EINSTEIN" – holistic approach for audits of the thermal energy supply of processes (Schweiger et al., 2011)*

The software results from the Intelligent Energy Europe (IEE) project EINSTEIN with the collaboration partners: Joanneum Research (Austria), Sapienza University of Rome (Italy) and energyXperts.NET (Spain) in the framework of the IEA (International Energy Agency) - Solar Heating and Cooling and SolarPACES Programs, task 33 (Brunner et al., 2010)

EINSTEIN is a method of introducing a holistic and integrated approach to thermal energy audits for both, industrial applications as well as hospitals, office buildings and sports halls. Einstein calculates the thermal energy demand, rates savings by heat exchange using pinch analysis, points out technical alternatives for the integration of energy efficient and renewable energy systems and evaluates them. The user is guided through the entire audit process, from data collection through to the development of alternative technological solutions. The tool is aimed in particular sectors with a high proportion of low and medium temperature levels of heat, such as the food or the paper industry.

Figure 2-2: *Elements of EINSTEIN`s audit instruments (EINSTEIN, 2013)*

The software tool shows concrete results for energy and economic savings that can be achieved through a restructured or optimized heat supply system. The alternatives include all major energy- efficiency technologies (e.g. heat recovery, cogeneration, heat pumps, solar thermal and biomass).

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3 French Team Report - State of the Art Review on Analytical Tools based on the Pinch Method

3.1 Introduction

Process energy integration is intended to identify potential sources of energy recovery via heat exchange and integration of utilities in an industrial process. Historically, it has relied on the concept of Pinch Analysis.

The Pinch Method enables among other to identify potentials for the positioning of heat pumps by evaluating the operating powers and temperatures.

This review inventories tools identified as based on the Pinch Method. It does not claim to be an exhaustive list, as numerous pinch analysis tools exist and new tools are released every year. Some of the tools presented in this report may now be obsolete, since this state of the art review was carried out over several years.

3.2 Methods of process energy integration

3.2.1 Principle

The pinch analysis relies on a thermodynamic approach of the process. It involves identifying the energy flows of the process, considering only the real requirements linked to product conversion, and hence disregarding the means implemented by the industrial manufacturer to meet these needs. Once the list of streams is established, some mathematical tools can be used to identify sources of process inefficiencies and to propose corresponding upgrades.

The successive steps of the method are detailed below:

1. Definition of hot flows and cold flows. This involves defining the unitary process operations and quantifying their energy requirements. These requirements may be determined according to nature of the fluid (and specific heat), its temperature at input and output of the unit operation. A heat **source** (or hot flow) qualifies a fluid containing a certain amount of recoverable energy or that must be **cooled** to meet the process needs, and a heat **sink** (or cold flow) refers to a fluid that must be **heated** before being used in the process.
2. Construction of composite curves. Composite curves are used to establish target values of minimum energy consumption. They represent the profile of available heat sources (cold composite curve) and the profile of heating needs of the process (hot composite curve). To build these curves, the total heat availability and demand values are cumulated at various temperature intervals in the system (based on the formula $\Delta H = mC_p\Delta T$) and these enthalpy results are plotted on a diagram (T,H).
3. Identification of the pinch. The cold and hot composite curves are plotted on the same diagram (in such a way that they do not overlap). The lowest vertical gap ΔT_{min} is identified, corresponding to the minimum allowable temperature dif-

ference between the two fluids in a heat exchanger: this is the **pinch point**. The pinch ΔTmin arises from a trade-off between the cost of an exchanger providing for heat recovery internally and the cost of utilities required to meet the heating and cooling requirements of the process.

The region above the pinch (right-hand side of the graph) requires only a heat input (Q_{hmin}) to meet the process needs, while the region below the pinch (left-hand side of the curve) only requires cooling (Q_{cmin}). Thus the process should be built in such a way as to avoid any heat transfers from a hot flow above the pinch towards a cold flow below the pinch. Otherwise, the energy consumed would need to be offset by an input from a utility (hot or cold).

4. Calculation of minimum energy requirement (MER) for the process. Once the composite curves are calibrated with the pinch point, the MER corresponds to the requirements in utilities (hot and cold) not supplied by the process itself.

3.2.2 Required data

The data necessary for a pinch analysis correspond to the characteristics of the streams needing to be heated, cooled or where there is a phase change. These data generally include:

- mass flow (kg/s)
- calorific power (kJ/(kg.°C)
- temperature of available flow and temperature that it needs to reach in the process (°C)
- latent heat for phase-changing flows (kJ/kg)

3.2.3 Results

3.2.3.1 Composite curve (CC)

Building the composite curves (Figure 3-1) enables the identification of the pinch point along with a technical and economic optimisation of the potential for heat recovery via exchangers. By shifting the cold flow curve to the left or to the right, the temperature gap between the two curves (and therefore the pinch) decreases or increases respectively, which reflects that heating or cooling energy requirements decrease or increase respectively. Consequently, the energy consumption, i.e. operating costs (opex) of the facility, is proportional to the pinch. Conversely, the exchange surface area of the exchangers, i.e. capital spending costs (capex), is inversely proportional to the pinch.

Thus, depending on the selected criteria, the proposed solutions may differ.

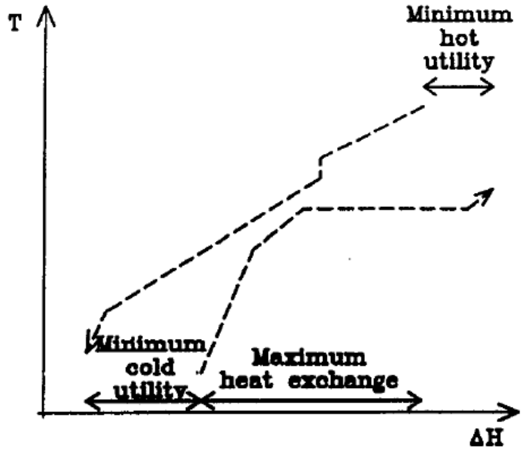

Figure 3-1: Composite curves[2]

3.2.3.2 Grand Composite Curve (GCC)

Instead of superimposing the two composite curves, it is possible to plot, for each temperature interval, the enthalpic balance, net of the interval, which provides the "grand composite curve" or GCC representing the gap between the hold and cold fluids (Figure 3-2).

The GCC is used primarily to optimise the utilities. Such optimisation is applied when several temperature levels are possible for the heating or cooling energy inputs into the process. Thus, the GCC enables an identification of opportunities for positioning heat pumps.

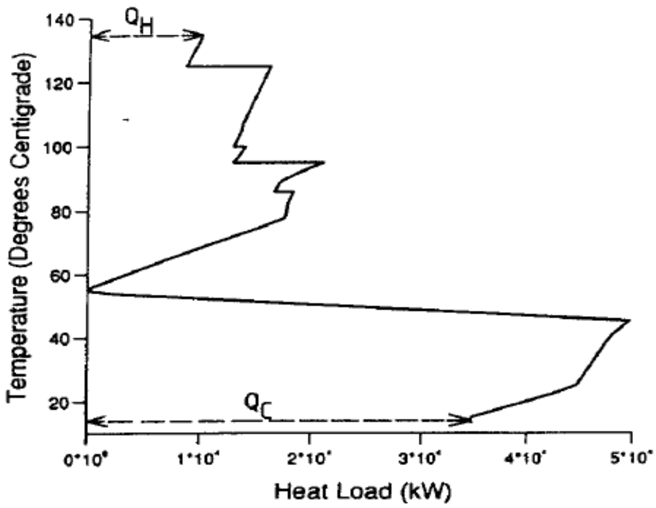

Figure 3-2: Example of Grand Composite Curve[3]

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[2] Erik WALLIN & Thore BERNTSSON, Integration of heat pumps in industrial processes, Heat Recovery Systems & CHP, vol 14, No 3, pp. 287-296, 1994

3.2.3.3 Positioning of heat pumps

Based on the pinch method, and via the data supplied by the grand composite curve, it is thus possible to optimise the positioning of utilities, and heat pumps in particular. A heat pump should be positioned through the pinch in such a way that the heat source is located below the pinch and the sink above the pinch. The presence of a pinch automatically implies the thermodynamic feasibility of a heat pump; and based on a reading of the grand composite curve, the theoretical COP of the system can be evaluated (via the condensation and evaporation temperatures). The technical and economic feasibility is however not automatic, and some tools incorporate these parameters into their calculations.

3.2.4 Benefits and drawbacks

The pinch analysis presents a number of benefits useful to enhance the energy efficiency of industrial processes.

- It provides an overall view of the industrial site under study, by optimising the recovery of often-lost energy and thus minimising energy losses in non-cooled hot flows.
- It helps adapt the utilities energy consumptions to the process requirements, unlike traditional methods which primarily address the utilities by segregating them from the manufacturing process.
- It relies on a simple graphic representation that enables the energy consumptions to be visualised and helps both the energy expert and the industrial manager to view the potential gains and the actual gains achieved in the study, thereby delivering objective analytical data.

The method however also presents a few limitations, among which the following, most frequently reported drawbacks:

- Loss of geographic information: the layout of (hot and cold) flows in the industrial site may dictate some constraints to their integration. For instance, some flows identified on the utilities side may be very remote from the production shop, which requires a very long exchanger network, thereby generating potentially non-negligible losses, or even losses higher than the energy gains identified via the pinch method. In order to remedy this problem, specific requirements (or prohibitions) should be applied when pairing some streams.
- Temporal disparity of the flow: this would be the case for instance with irregular power demands on the flows (hot and cold). This problem is frequently encountered for batch processes where energy streams are not available simultaneously and require heat storage systems to be installed. Although in some cases this difficulty may be overcome by reorganising the work schedule, this solution is however not always easy to implement for industrial managers.

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[3] Erik WALLIN & Thore BERNTSSON, Integration of heat pumps in industrial processes, Heat Recovery Systems & CHP, vol 14, No 3, pp. 287-296, 1994

- Technological difficulties linked to the process: such difficulties may be encountered in the food industry for instance where health security and bacteriological requirements are substantial. Exchanges between the various energy streams are then difficult to achieve with simple heat exchangers only.
- Lastly, the technical constraints may be compounded by economic constraints. In compliance with the IPPC (Integrated Pollution Prevention and Control) Directive, the application of process energy integration methods may prove very costly, due primarily to the substantial amount of data to be collected.

3.3 Stakeholders

A number of private companies offer off-the-shelf software programs, but research laboratories are also very actively involved in developing such tools for research purposes.

3.3.1 ACADEMIC RESEARCH LABORATORIES

3.3.1.1 University of Manchester (UK)

Presentation of research laboratory:

The University of Manchester (UMIST) and more specifically the Centre for Process Integration (CPI), is positioned as a benchmark in the field of process energy integration. Professor Bodo Linnhoff, creator of the Pinch Analysis, had developed his method within this university.

UMIST proposes several tools focussed on energy integration distributed via the Process Integration Research Consortium (PIRC). The consortium is a partnership between the University of Manchester (UMIST, School of Chemical Engineering & Analytical Science), industries (primarily from the oil industry, e.g. BP, Total, etc.) and other academic institutions.

PIRC operates on the basis of annual memberships granting access to the tools developed and to training sessions and exchange workshops.

UMIST has developed two software tools linked to the pinch method:

- SPRINT (focused on optimizing the heat exchanger network) – a detailed description is provided on page 3-44.
- STAR (focused on optimizing the utilities system of complex processes, such as petrochemical) – its major functionalities are described on page 3-44.

3.3.1.2 EPFL (Switzerland)

Presentation of the research laboratory:

EPFL or Ecole Polytechnique Fédérale de Lausanne is one of the prime engineering schools in Switzerland based in Lausanne. EPFL is the co-founder of the European Center Laboratories for Energy Efficiency Research (ECLEER), jointly with EDF and the Ecole des Mines de Paris engineering school.

Within EPFL, the *Laboratoire d'Energétique Industrielle* (LENI, or Laboratory of Industry Energy Engineering) headed by Professor Daniel Favrat, is an internationally recognized benchmark in the field of energy conversion systems (heat pumps, organic Rankine cycles, fuel cells) and of energy integration of heating systems; this latter research topic is headed by François Maréchal based on several methods, and the pinch method in particular, along with other environmental assessment methods such as LCA (life cycle analysis).

Following the retirement of Professor Favrat in the summer 2013, the LENI research teams have been reorganised. Activities related to energy integration are nevertheless continuing in a research group under the leadership of François Maréchal.

The LENI lab has developed three tools based on the pinch method:

- OSMOSE: presented on page 3-192 of this review.
- Pinchlight: web interface with the "basic" functionalities of OSMOSE, presented on page 3-191.
- PinchLENI: this tool was adapted and converted by the Hochschule Luzern to design the PinCH software; see presentation of the Hochschule Luzern for more details on page 8.

3.3.1.3 Mines Paristech (France)

Presentation of the research laboratory:

The Ecole Nationale Supérieure des Mines de Paris (Mines Paristech) is one of the most prestigious French engineering schools. Its CES (*Centre d'Eco-efficacité des Systèmes*) or Centre for Systems Eco-Efficiency, formerly CEP (*Centre Energétique et Procédés*), is a research laboratory dedicated to energy engineering, both on the generation and the consumption sides.

The CES has developed two tools based on the pinch method:

- CERES platform, presented on page 3-194.
- Thermoptim, presented on page 3-193.

3.3.1.4 Chalmers University of Technology (Sweden)

Presentation of research laboratory:

Chalmers University of Technology is one of the most renowned universities in Sweden.

The university has outsourced its corporate services via the engineering consulting firm CIT (or Chalmers Industriteknik) consisting of five subsidiaries, including in particular **CIT Industriell Energi with expertise in the field of industrial process energy integration.**

This subsidiary has developed and uses a tool called Pro_Pi presented on page 3-196.

3.3.1.5 Hochschule Luzern / Lucerne University of Applied Science & Arts (Switzerland)

Presentation of research laboratory:

The University of Lucerne is a recently founded Swiss university (1997). Among its faculties, the School of Engineering & Architecture is involved in developing the "PinCH" tool designed for applications of the pinch method and supported by Office Fédéral de l'Energie (OFEN).

PinCH uses the PinchLENI tool as a starting point, an open-source software for pinch analysis designed by the LENI lab at EPFL in the 1990s. PinCH has however been largely upgraded since then and is now entirely different from PinchLENI.

The PinCH tool developed by this university is presented on page 3-197.

3.3.1.6 Universidad de Valladolid (Spain)

Presentation of research laboratory:

The department of *Ingeniería Química y Tecnología del Medio Ambiente* of the University of Valladolid in Spain offers a curriculum in energy integration teaching the pinch method. However, this university does not seem to be recognized as a benchmark in the field.

The university has designed a tool called Hint, downloadable on line free of charge, presented on page 3-199.

3.3.1.7 University of Aalto (Finland)

Presentation of research laboratory:

Formally named Helsinki University of Technology (TKK), the University of Aalto is conducting research on energy integration within its Department of Energy Technology.

Their research activities focus on energy integration in paper-making sites, in particular integrated sites (simultaneous production of pulp and paper). Apart from the pinch method, they also use other methods of process analysis.

The university is developing a tool to visualise heat exchanger networks, called HeVi. The specific feature of this tool is to combine the conventional representation of flows in a Grid Diagram with a representation in Sankey diagrams.

This tool does not use the pinch method strictly speaking since it does not provide for modelling the exchanger network, but merely its graphic representation (although this representation is of great interest in itself). However, the tool version available on their web site dates back to 2008 and the web page has not been updated since then. Its development appears to have been stopped and the tool has no explicit documentation.

3.3.1.8 University of Waikato (New Zealand)

Presentation of research laboratory:

The University of Waikato in New Zealand has a dedicated laboratory called Industrial Energy Efficiency Division looking at the pinch method and the integration of discontinuous processes. The research work is carried out in close partnership with industries (dairy industry in particular) and involves both lab-scale and field-scale experimental trials.

The lab researchers publish frequent articles at the PRES conference (Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction).

In the context of research on the pinch method, the University of Waikato has developed an in-house application of the method; this tool has however not been released outside the university and its functionalities remain unknown (only a few screenshots are available in some of their publications).

3.3.1.9 Instituto Superior Técnico (IST) of Lisbon (Portugal)

The Technical Institute of Lisbon includes a department called Integration and Optimisation of Processes with teaching and research activities on the pinch method.

The IST is involved in the development of tools such as BatchHeat, or more recently FI²EPI on behalf of *Ferramenta Informática para Integração Energética de Processos Industriais*, developed in partnership with the Portuguese Energy Agency (ADENE). The tool exists only in a Portuguese version and we were unable to test it.

3.3.2 OTHER NON-ACADEMIC PLAYERS

3.3.2.1 AEE-Intec (Austria)

Presentation of research laboratory:

AEE – Institute for Sustainable Technologies (or AEE-Intec) is an independent Austrian research institute working in three main areas: solar heating, low-energy buildings and energy efficiency of industrial processes.

Their research focuses on energy integration of discontinuous processes (particularly in the brewery industry), size design of heat storage systems and integration of solar heating in industries.

AEE Intec develops numerous auditing tools, most of which involve the pinch method for analysis; this is the case of Einstein, a process thermal auditing tool containing a pinch method application module. Einstein is presented on page 3-199.

3.3.2.2 KBC Advanced Technology (UK)

Presentation of the company:

KBC Advanced Technology, founded in 1979, is a consulting and engineering firm dedicated to industrial processes. KBC is specialised more specifically in the oil industry but covers all energy areas (refinery, petrochemical, power generation, biofuels, etc.).

In 2002, KBC acquired Linnhoff March Ltd., an independent engineering firm created in 1983 by Professor B. Linnhoff, the founder of the pinch analysis method.

Further to the acquisition of Linnhoff March Ltd, KBC inherited the sequel tools of SuperTarget, the benchmark for applications of the pinch method that follows the Linnhoff concept to the letter. This tool is presented on page 3-202.

3.3.2.3 Aspentech (USA)

Presentation of the company:

Aspentech (abbreviated from Aspen Technology Inc.), a start-up created in 1981 at the Massachusetts Institute of Technology (MIT), has become a leader of software applications dedicated to industrial process optimisation (particularly in the chemical and petrochemical industries) and offers an extensive range of applications covering all sectors and all issues (modelling, simulation, logistics, equipment design, etc.). Their solutions address primarily the petrochemical, fine chemistry and pharmaceutical industries, but over time they tend to extend to other industrial sectors as well.

Aspentech offers an extensive range of software programs combined in the AspenONE V8 software suite, split into five categories:

- Engineering
- Petroleum Supply Chain
- Supply Chain Management
- Advanced Process Control
- Manufacturing Execution System.

The AspenEnergyAnalyzer tool (formerly known as Aspen HX-Net) fits in the first of the above software categories. This tool is presented on page 3-203.

3.3.2.4 Canmet ENERGIE (Canada)

<u>Presentation of research laboratory:</u>

Canmet ENERGIE is a laboratory affiliated to the Canadian Ministry of Natural Resources, specialised in technology development and research on clean energies. Its staff includes over 450 scientists, engineers and technicians.

The lab works in all fields related to energy – renewable energy sources, fossil fuels, energy consumption in buildings, etc. – in close collaboration with the industrial sphere. It includes among other a department dedicated to process energy integration.

In the field of process integration, Canmet ENERGIE has developed an **Integration** tool for applications of the pinch method as well as energy modelling and analysis of utilities (boilers, cooling units, air compressors, etc.).

3.3.2.5 ProSim (France)

<u>Presentation of the company:</u>

ProSim is a leader in the field of chemical engineering software, providing process simulation software programs and design & engineering services in the following industries: oil and gas, chemistry, pharmaceuticals, energy and other process industries.

The company was created in 1989, backed by a flowsheeting tool developed at Ensiacet in Toulouse (formerly called ENSIGC).

ProSim offers several software programs, among which ProSimPlus (for process modelling and simulation) and Simulis Thermodynamics (to calculate the properties of fluids and fluid mixes).

In 2010, this tool was limited to plotting composite curves, while ProSim's short-term goal was to develop a library of utilities models along with an algorithm for optimising exchanger networks. ProSim is currently developing a tool designed for energy integration, in partnership with Veolia under an ANR project (COOPERE). Their approach appears to be oriented to energy analysis, although they use the pinch method for basic analysis.

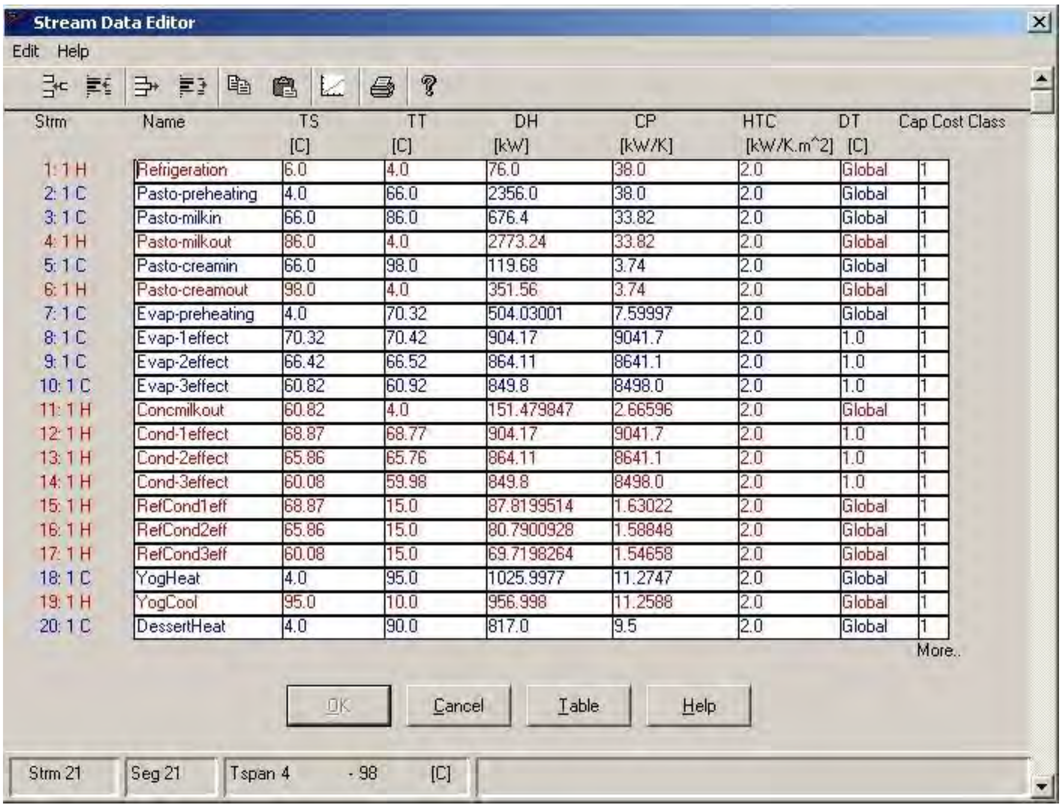
3.4 Tools

3.4.1 STAR and SPRINT

Star and Sprint are very similar and complementary tools, but used independently of each other. Figure 3-3 below shows their respective interfaces.

Figure 3-3: Comparison of interfaces in Star and Sprint

They share the basic functionalities of the pinch analysis, such as optimisation of ΔTmin, or graphic representation of composite curves and grand composite curves ("Target" menu of the interface on Figure 3-3). The curves are calculated from the chart of process flows presented in Figure 3-4) below, and their data can be exported from one tool to the other.



Strm	Name	TS [C]	TT [C]	DH [kW]	CP [kW/K]	HTC [kW/K.m^2]	DT [C]	Cap Cost Class
1: 1 H	Refrigeration	6.0	4.0	76.0	38.0	2.0	Global	1
2: 1 C	Pasto-preheating	4.0	66.0	2356.0	38.0	2.0	Global	1
3: 1 C	Pasto-milkin	66.0	86.0	676.4	33.82	2.0	Global	1
4: 1 H	Pasto-milkout	86.0	4.0	2773.24	33.82	2.0	Global	1
5: 1 C	Pasto-creamin	66.0	98.0	119.68	3.74	2.0	Global	1
6: 1 H	Pasto-creamout	98.0	4.0	351.56	3.74	2.0	Global	1
7: 1 C	Evap-preheating	4.0	70.32	504.03001	7.59997	2.0	Global	1
8: 1 C	Evap-1effect	70.32	70.42	904.17	9041.7	2.0	1.0	1
9: 1 C	Evap-2effect	66.42	66.52	864.11	8641.1	2.0	1.0	1
10: 1 C	Evap-3effect	60.82	60.92	849.8	8498.0	2.0	1.0	1
11: 1 H	Concmilkout	60.82	4.0	151.479847	2.66596	2.0	Global	1
12: 1 H	Cond-1effect	68.87	68.77	904.17	9041.7	2.0	1.0	1
13: 1 H	Cond-2effect	65.86	65.76	864.11	8641.1	2.0	1.0	1
14: 1 H	Cond-3effect	60.08	59.98	849.8	8498.0	2.0	1.0	1
15: 1 H	RefCond1eff	68.87	15.0	87.8199514	1.63022	2.0	Global	1
16: 1 H	RefCond2eff	65.86	15.0	80.7900928	1.58848	2.0	Global	1
17: 1 H	RefCond3eff	60.08	15.0	69.7198264	1.54658	2.0	Global	1
18: 1 C	YogHeat	4.0	95.0	1025.9977	11.2747	2.0	Global	1
19: 1 H	YogCool	95.0	10.0	956.998	11.2588	2.0	Global	1
20: 1 C	DessertHeat	4.0	90.0	817.0	9.5	2.0	Global	1

Figure 3-4: Chart of process flows in Star and Sprint

Beyond this, their functionalities differ:

- Sprint is designed for simulating and optimising the exchanger network between the process flows or between the process and the utilities.

- Star is designed for selecting the utilities most suitable for the process (boilers, cooling units, etc.), and conducting the analysis on a site-wide scale (design of steam network and CHP systems if any).

Both tools were developed more specifically for the oil and chemical industries, and do not include the integration of heat pumps among their functionalities.

3.4.2 Pinchlight

Pinchlight is a web interface designed to carry out a pinch analysis using a remote server. This server communicates with a multifunctional optimisation platform called Osmose which applies the pinch method to the user's data.

Figure 3-5 below shows the Pinchlight interface.

Figure 3-5: Pinchlight interface

There are 5 levels of data to be entered:

1) "General" tab to enter the general data of the analysis, e.g. cost of exchangers, of commercial energy supply, climate conditions, etc.
2) "Resources" tab to enter data on commercial energy consumptions (fuels, water).
3) "Energy Distributions" tab to list the process energy demands, e.g. steam, hot water, cooling water, etc. You can for instance define the heat requirement even if the details of the consuming process are missing.
4) "Process" tab to define the hot and cold flows of the process. A database of predefined modules facilitates the definition of flows, as shown in Figure 3-6, with the example of a pasteurisation process.
5) "Utilities" tab to list the utilities existing on the site (boiler, cooling unit, compressed air...) and their performance levels. Similarly to the Process tab, predefined modules can be used to facilitate data entry (single-stage cooling cycle, CHP with combustion turbine, etc.).

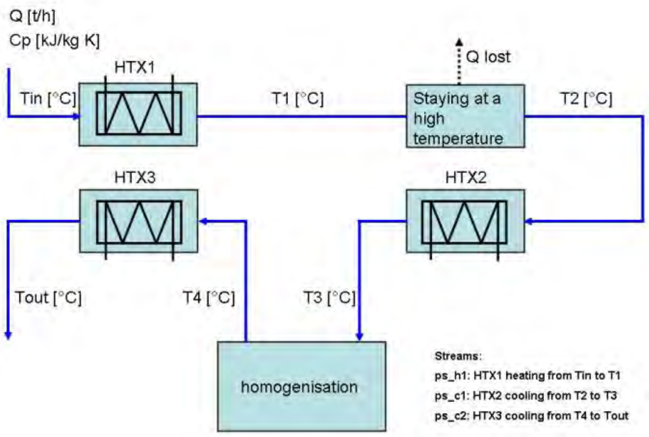


Figure 3-6: Example of a pasteurisation process

Once the data have been entered, two major types of analysis can be carried out with Pinchlight:

- "MER" analysis (Minimum Energy Requirement) for energy integration of the process, optimisation of Tmin, and determination of the minimum energy consumption requirement. This analysis further leads to a bottom-up approach to energy consumptions on the site by comparing actual consumptions (energy bills) with consumptions calculated from the process optimisation.
- "Target" analysis to optimise the utilities and exchanger network related to the process.

Pinchlight stands apart from other tools in terms of the study of utilities: on the one hand, utilities are subject to a bottom-up analysis to inform on the actual consumption against optimum consumptions. Secondly, the optimisation of the process and of utilities is simultaneous, whereas in other tools the utilities are addressed only after the process has been optimised. Another feature of interest is the modules detailing some operations and utilities.

Conversely, Pinchlight will not allow for manual plotting of the exchanger network and the tool is not really simple to use.

3.4.3 OSMOSE

OSMOSE developed by EPFL is an optimisation platform designed for applications of the pinch method (among others, the ACV method for instance can also be applied).

Calculation models and procedures have been developed so OSMOSE can be used specifically to integrate heat pumps into an industrial process.

OSMOSE enables the positioning and sizing of heat pumps in the process to be optimised. It provides for design studies to be carried out on multi-period (or discontinuous) processes by factoring in energy storage. In addition, the tool also has functionalities for multi-target optimisation.

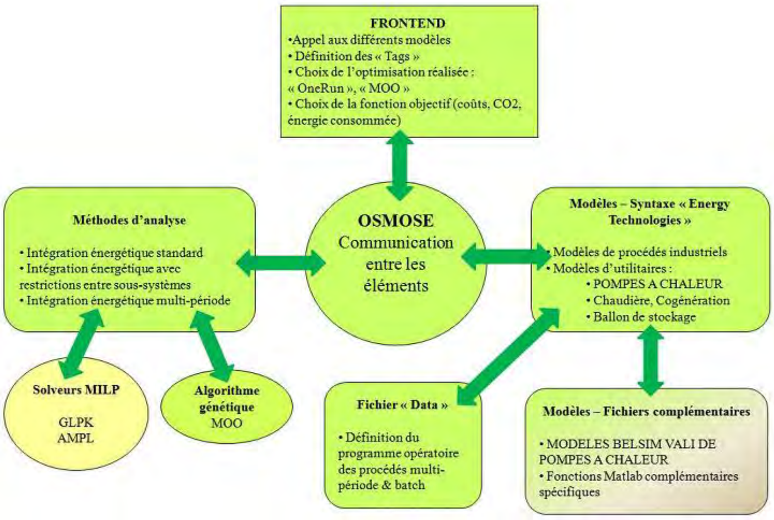


Figure 3-7: OSMOSE operating workflow

The OSMOSE platform enables discontinuous processes to be factored in and, via the multi-target optimisation function, determines the powers and temperature levels of the heat pumps to be integrated into the process. This is a highly efficient tool offering functionalities that do not exist in any other available tools.

OSMOSE however has several flaws that mitigate its qualities. Firstly, this is an optimisation platform, rather than a tool based on the pinch method; consequently, the tool is not user-friendly and learning to use it requires lengthy and complex training. In addition, it is based on many proprietary software applications (MATLAB, Belsim VALI…) whose user licensing costs are expensive.

3.4.4 Thermoptim

Thermoptim is a software package developed for the design and simulation of thermodynamic systems, in particular energy conversion processes. It consists of a diagram/flowchart editor and a simulation engine.

It provides for both an analytical and systemic approach:

- Each functional component is represented by an appropriate Thermoptim "primitive type" (vessel, process point, conversion, node, exchanger...) having its own modifiable characteristics and coupling variables.
- The full system is then modelled by assembling these primitive types via an interactive visual interface (Figure 3-8).

Once the various conversions are represented, the pinch method can be applied to the modelled system and the tool guides the user in building the exchanger network.

The primary goal of this tool is educational, hence its use is somewhat unwieldy. In addition, it is primarily suitable for energy generation systems (gas cycle turbines, Rankine cycle, etc.): while this may be overcome by building libraries of customised physical and chemical properties, it however becomes very time-consuming.

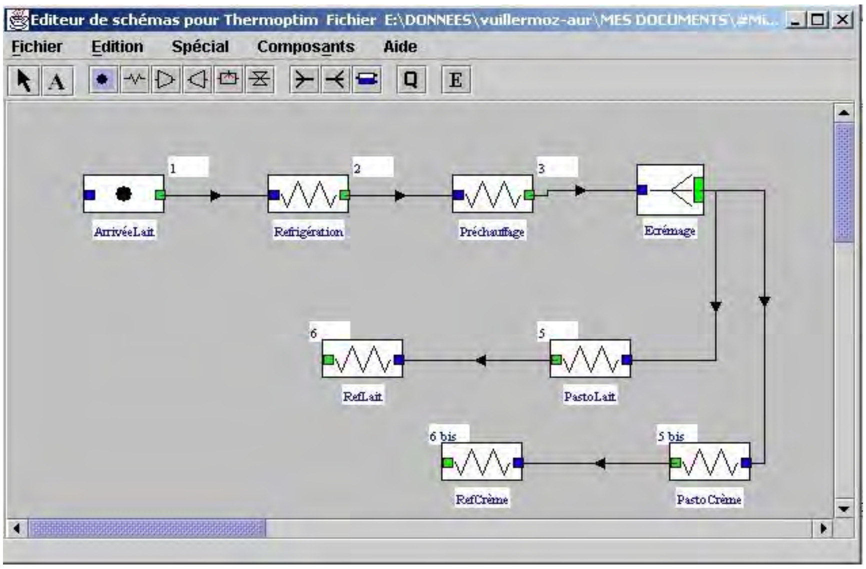


Figure 3-8: Example of modelling of a milk pasteurisation/skimming process

3.4.5 CERES

CERES is developed in the context of the ANR [French National Research Agency] project entitled "*Chemins Energétiques pour la Récupération d'Energie dans les Systèmes industriels*" involving eleven academic and industrial partners under the leadership of EDF. Its purpose is to identify strategies for the recovery and reuse of waste heat in industrial processes, and to foster the reach of innovative technologies contributing to rational energy uses.

It consists of:

- a platform designed to conduct energy integration studies,
- a library of models of industrial processes and utilities developed in Modelica language under a Dymola environment.

Note: The models library is currently developed under the Dymola environment which is a proprietary software (owned by Dassault Systems). CERES can however also operate with models developed under the free open-source OpenModelica environment.

CERES platform

The CERES platform enables **pinch method**-based studies to be carried out on energy integration. The method has been further enhanced with **optimisation algorithms** designed to select among a number of utilities (heat pumps, turbines, etc.) those that will minimise energy consumption, while factoring in the capex costs necessary to install heat exchangers, along with some environmental data.

Thus, for a given set of processes, the CERES platform allows for:

- determining the heat recovery potential and the minimum energy requirements, based on the pinch method (Figure 3-9),
- optimising the size design of utilities and exchanger network to be implemented, while minimising energy consumption and capex costs (Figure 3-10).

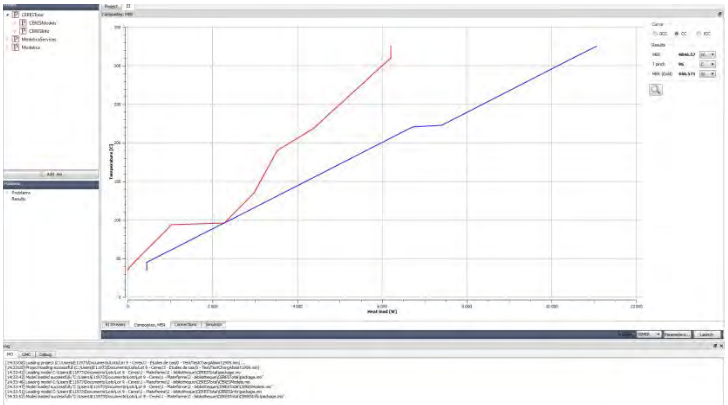


Figure 3-9: CERES platform – Composite curves and minimum energy requirement

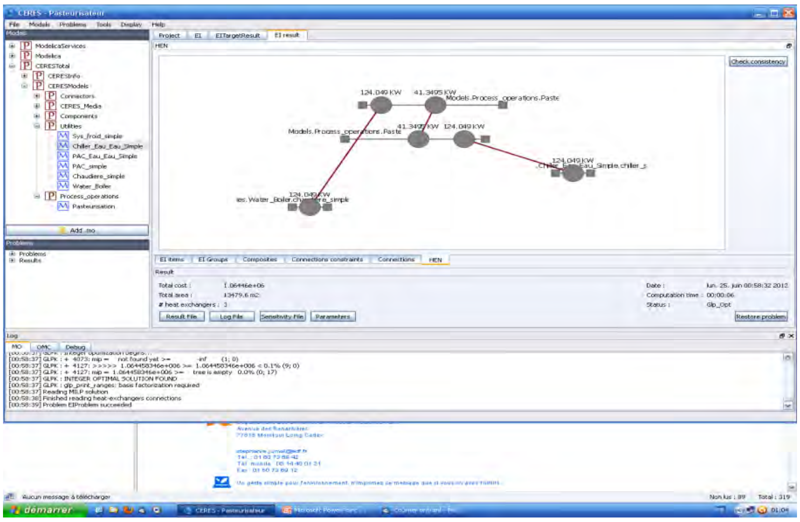


Figure 3-10: CERES platform – Optimisation and construction of utilities and exchanger network

Models library

A library of utilities and process models is currently under development in the context of the project (example shown on Figure 3-11). Table 3-1 below lists the models already developed and integrated into the platform.

Table 3-1: List of process and utilities models developed in the CERES-2 project

	Industrial processes	Utilities
Modelica models	Agri-food industry: Milk processing Pulp & Paper: Production of pulp and paper Metals: Cold machining	Exchangers and storage Compression heat pump Sorption heat pump Thermoelectricity ORC

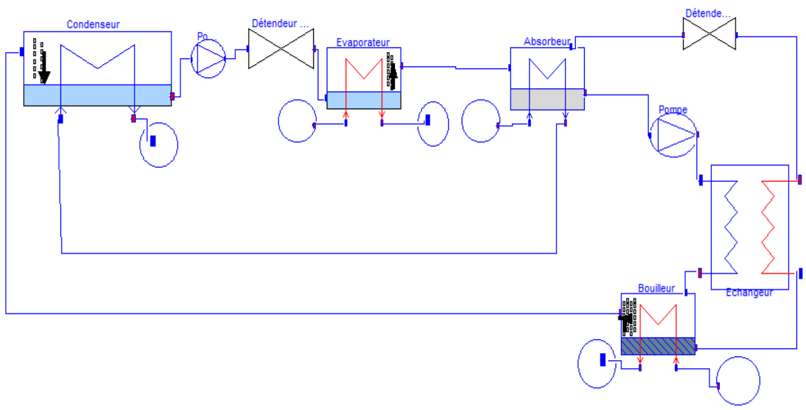


Figure 3-11: CERES library – Example of an absorption heat pump

This database of industrial processes and energy recovery and reuse technologies will be further enriched via updates and additions of new models by the users.

The CERES platform and the models library under Modelica will be available in open access once the project is completed, i.e. in mid-2014. The tool will then be free of charge with open access to everyone.

3.4.6 Pro_Pi

Pro_Pi is a tool dedicated to the pinch analysis and the construction of exchanger networks. It is formatted as a simple Excel macro (file .xls) to which are added pinch-specific functionalities (framed in red on Figure 3-12 below).

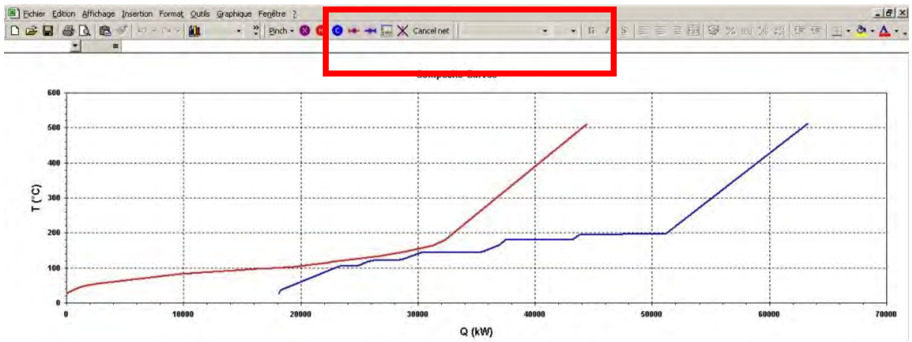


Figure 3-12: Pro_Pi interface

It also includes an interface for plotting heat exchangers.

Pro_Pi is a light-weight educational tool, usable directly under Excel. It contains the basics of pinch analysis and provides for manual plotting of an exchanger network. Modelling of utilities is rather rudimentary (quantity of heat at a given temperature), and the interface is not very user-friendly.

3.4.7 PinCH

PinCH is a tool developed by the University of Lucerne in Switzerland with support from the *Office Fédéral de l'Energie* (OFEN).

It enables the pinch method to be applied to a process or a set of processes. For each stream identified, it is possible to set the operating time frame (Figure 3-13). A Gantt diagram can thus be plotted for the process and the time parameters of the various production steps can be factored in. Based on the pinch analysis, the composite curves can then be plotted based on the Time Average Method (TAM, Figure 3-14) or based on the Time Slice Method (TSM) to account for discontinuous processes. Lastly, the tool provides the possibility for building the exchanger network for each time slice (Figure 3-15).

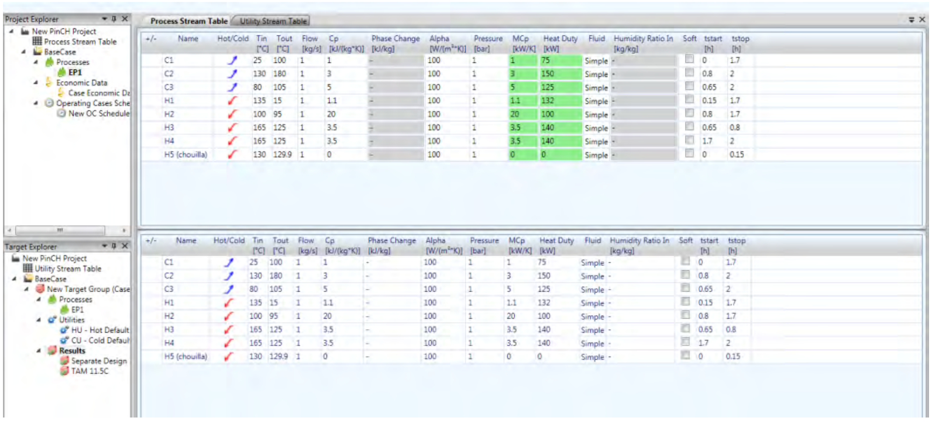


Figure 3-13: Entering flow data into PinCH

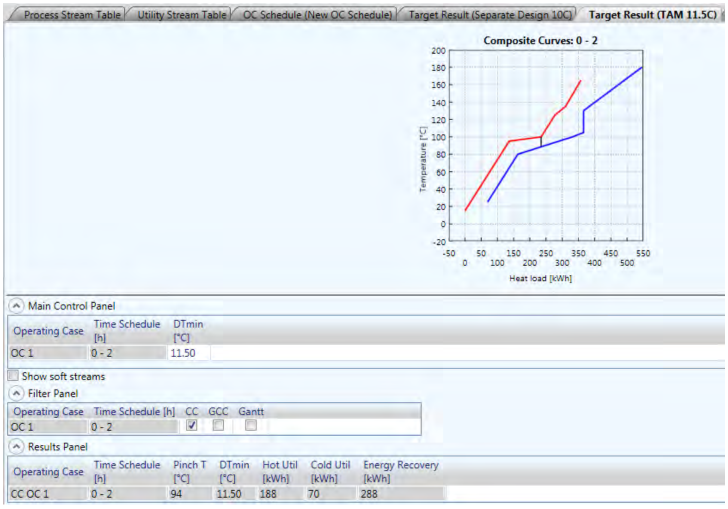


Figure 3-14: TAM analysis in PinCH

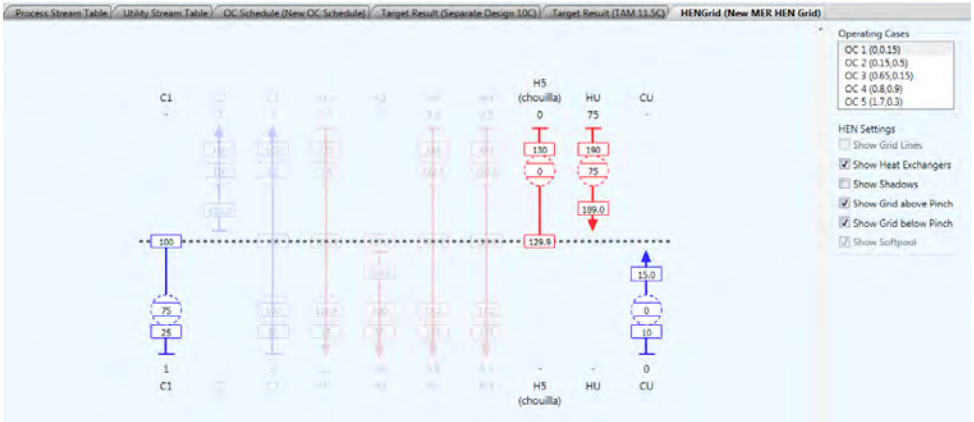


Figure 3-15: Building the exchanger network in PinCH

This software program may be ordered via a dedicated web site for a charge. The price of a single-station license is 2700 Swiss francs, i.e. EUR 2250 (in November 2012). A 10% discount is offered starting at 2 licenses and up to 25% for 5 licenses and over. It seems possible also to get lower prices if the tool is intended for research or learning purposes.

The tested version is V1.0.8.1542. This is an evaluation version where the number of flows is limited to eight. Our evaluation has however enabled us to identify the main benefits and drawbacks of this tool.

Benefits:

- Possibility for a TAM and TSM analysis.
- The exchanger cost functions can be easily parameterized.
- The license price is relatively low.
- Possibility of integrating heat pumps, MVC and motors with direct viewing on the grand composite curve.
- Parameters programmable for calculation of utilities costs.
- Where the fluid used is water, the tool automatically factors in the phase change and separates the stream accordingly.

Drawbacks:

- Non-intuitive ergonomics (subjective).
- Necessity to create a hot and cold utility meeting the MER before launching the analysis.
- In practice, it is necessary to determine a flow beyond and below the maximum and minimum temperature respectively, with enough power to meet the heating or cooling requirement respectively.
- No help function (tips, default values, etc.) to position the utilities (heat pump, motor, MVC).
- No possibility of installing an ORC or a heating/cooling pump.

PinCH provides the possibility of factoring in the timing of processes, and ultimately the developers intend to integrate the multi-period function taking storage into account.

3.4.8 Hint

Hint – for Heat INTtegration – is an educational tool directed at students and dedicated to the pinch analysis and construction of exchanger networks. Figure 3-16 shows the interface. The tool was developed at the University of Valladolid in Spain.

Apart from the composite curves and grand composite curve, HINT enables the exchanger network to be plotted and modified.

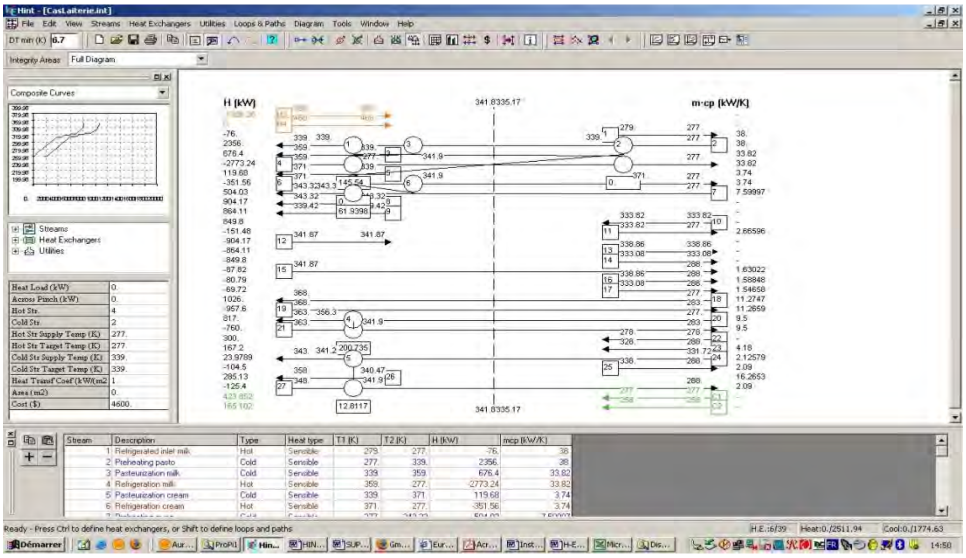


Figure 3-16: HINT interface

The HINT tool is downloadable on line free of charge. It includes the basic functionalities referring to the Linnhoff concepts, and constitutes a good resource to get familiar with the pinch method and start conducting simple studies, with a relatively easy to use interface. However, the development and related maintenance of this tool seem to have been stopped. In addition, the on-line help is very poor and a single article was published in 2008 in the journal *Education for Chemical Engineers* introducing the functionalities of the tool.

3.4.9 Einstein

Einstein means "*Expert System for an Intelligent Supply of Thermal Energy in Industry and other Large-Scale Applications*".

Einstein is primarily a tool designed for thermal audits of industrial processes offering among other functionalities an application of the pinch analysis and design of exchanger networks.

The tool is the outcome of two consecutive projects funded by the program "*Intelligent Energy Europe*":

- **Einstein I** (September 2007 - August 2009)
- **Einstein II** (July 2010 - June 2012)

Einstein provides for a methodology applied to thermal audits of processes, comprising the following steps:

- Data acquisition and process modelling: all processes must be modelled according to a generic standard model (ref. Figure 3-17) including temperature rise, steady state and cooling with possible counter-flow exchange with the in-flow.
- Validation of data consistency (consistency check).
- Reduction of energy demand via process optimisation.
- Heat recovery via exchangers: this is the step that uses the pinch method (ref. Figure 3-18). Einstein plots the composite curves, the grand composite curve, and offers a choice between manual or automatic design of the exchanger network.
- Integration of new utilities and/or renewable energy sources, in particular:
    - solar heating
    - heat pumps
    - CHP
    - high-efficiency boilers

It should be noted that the pinch method is involved only when designing the exchanger network, and not in the choice of utilities: the tool does not really allow for determining which utilities or combinations thereof would be optimum; it only provides the possibility for testing various energy supply scenarios and to compare them based on energy, economic or environmental criteria (ref. Figure 3-19).

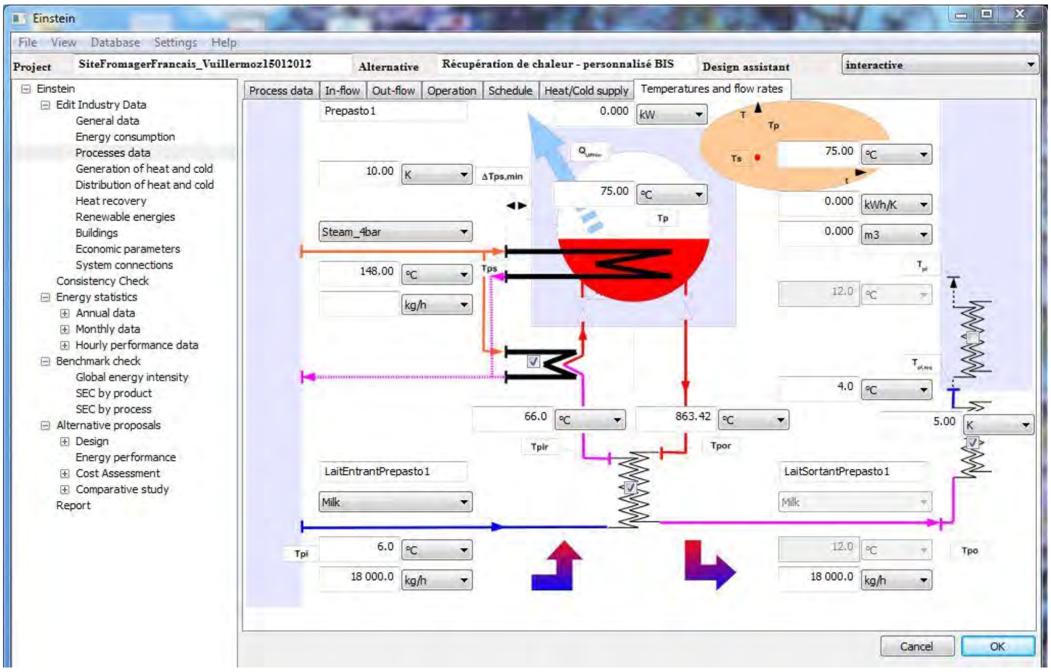


Figure 3-17: Standard model of a process

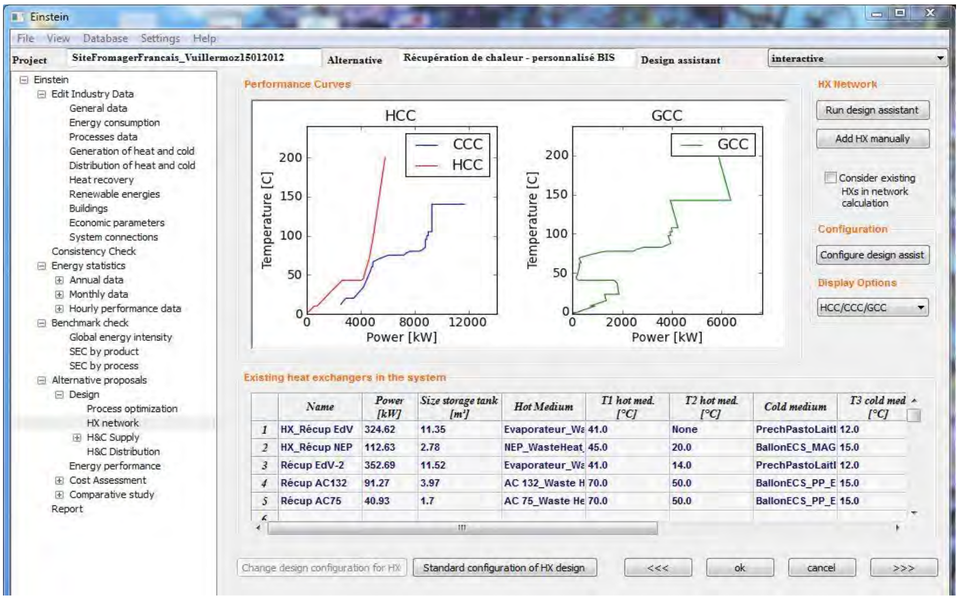


Figure 3-18: Optimisation of heat recovery via direct exchange

Figure 3-19: Comparison of various scenarios depending on primary energy consumption (top graph) and environmental impacts - CO_2, nuclear waste, water consumption (bottom graph)

The software is downloadable in free access on the Internet. The most recent available version is the V2.2; however, we tested version 2.1.

Einstein was developed jointly by several partners, among whom the following were most closely involved:

- **Energy Experts**: a German/Spanish network of engineers and energy consultants.
- **AEE Intec**: an Austrian research centre on sustainable technologies, in particular solar heating and process energy integration. AEE Intec supplied the optimisation algorithm used for automatic design of the exchanger network.

Benefits:

- This is an audit tool that is not limited only to a pinch analysis and also includes other functionalities of interest, in particular the overall consistency check.
- Manual and automatic design of the exchanger network can be easily combined.
- The representation of the exchanger network in chart format is much more legible than a “grid diagram” representation.
- All economic analyses can be customized, and it is also possible to add specific pieces of equipment (e.g. heat pumps) in the database.
- It is free of charge.

Drawbacks:

- Due to its numerous functionalities, the tool is relatively complex and requires some adaptation time.
- Hot and cold flows cannot be entered directly: the standard model must necessarily be followed in order to model a process operation, which is restrictive.
- No analysis can be launched until the “consistency check” is validated, but this can be time consuming since the tool is highly sensitive and errors are relatively difficult to decipher.
- The module designed for heat pump integration is not easy to use, and – at least in V2.1 – had some bugs.
- Since European funding has now expired, this raises the issue of the viability of the tool: i.e. who will fund developments, maintenance or training?

3.4.10 SuperTarget

SuperTarget claims to be the leading tool for industrial process energy integration and exchanger network design. Its advanced data processing functionalities provide for easy application of the pinch analysis. It is split into three specific modules:

- A “Process” module to carry out a pinch analysis on a process (direct exchange is allowed between all flows).

Among other, this module provides for thermal and economic optimisation of the minimum pinch (ΔTmin) and for the design of an exchange network. Its functionalities adjust to situations of new design and facility renovation, and its “case study manager” enables easy comparisons between several scenarios. Lastly, it is fitted with a simulator to test the sensitivity of the network in response to certain changes.

- A “Column” module to apply the pinch method to the optimisation of distillation columns.
- A “Site” module for energy integration on a site (indirect exchange between several processes via the utilities network).

This latter module provides the possibility of selecting the desired process data in the Process module. Several aggregation options may be selected, depending on whether exchanges are authorized between all flows in all processes, or only via the utilities network. In addition, this module enables an exergetic analysis to study the integration of energy generation systems (cogeneration).

It was not possible to test the Supertarget tool.

SuperTarget was developed by the founder of the pinch method and is regarded as a benchmark in the field. It is however still highly oriented to the chemical and petrochemical industries, hence its functionalities are too sophisticated, particularly for designing the exchanger network. Similarly, the utilities are unsuitable, and in particular SuperTarget does not seem to offer any heat pump integration.

3.4.11 AspenEnergyAnalyzer

AspenEnergyAnalyzer belongs to the AspenONE software suite. It is designed for applications of the pinch method in accordance with the rules defined by Linnhoff.

AspenEnergyAnalyzer provides for either manual or automatic design of the exchanger network: in the latter case, up to 5 different designs are possible, indicating that the tool most likely uses a heuristic or meta-heuristic resolution mode, and does not use any linear deterministic method.

In addition, it can differentiate between a new design and a retrofit of the exchanger network, where the purpose is to optimise only the new exchangers to be added to an existing network.

This tool proved to be very similar to SuperTarget in terms of sophisticated functionalities of optimisation and modification of the exchanger network.

3.5 Conclusions

Numerous pinch analysis tools exist for energy integration of a site, based on an analysis of composite curves and grand composite curves.

However, few among these tools enable a calculation of the economic and energy benefits of installing a heat pump. The user’s expertise is therefore required. Some tools evaluate the benefit of heat pumps and recommend their positioning and number based on energy and economic criteria.

4 Dutch Team Report - Modeling in the Netherlands

Between 1992 and 1996 the IEA HPP Annex 21 generated an overview of potential industrial heat pump applications and also developed an "Industrial Heat Pump Screening Program to determine how industrial heat pumps could be used in different applications [Geelen, 2013]. The computer program should assist potential users in assessing the opportunities to integrate industrial heat pumps (IHP) into different types of industrial processes. The program has also been designed to determine the economics of heat pumps, at least on a preliminary basis. The computer program has been developed based on pinch technology concepts. It aims to identify IHP opportunities that are consistent with fully optimized plant heat exchange systems to provide the most economic IHP designs and the lowest possible plant-wide energy consumption.

The screening program contains data on more than 100 industrial processes in five main industries: food, chemicals, petroleum refining, pulp and paper, and textiles. These data can be used directly, or modified by the user as needed, to assess site-specific IHP opportunities. The computer program also contains data on more than 50 types of IHPs. Recent analyses by the Operating Agent of Annex 13/35 concluded that an update of the screening program is not advisable as since 1997 no further work has been done on the program and the software seems to be outdated. An analysis by the Operating Agent of existing software process optimization models shows that the difference between 'pure' pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

Several of these specific heat pump models and databases have become available in the Netherlands during the work on the Annex. In order to integrate a heat pump properly in an industrial process a good knowledge of the process is necessary. In this respect, pinch analysis is a very powerful tool. Although broadly introduced into the market in the nineties in Netherlands, the use of models for process integration (i.e. pinch) and general process optimization is still limited to a fairly small number of research groups and highly specialized groups within large companies.

4.1 Industrial heat process optimization

Many tools are available to optimize industrial processes where depending on the situation there is no univocal answer to the question which tool is the best to use. It is important to be aware of the fact that the costs for measures for energy conservation are often more expensive when they are further from the core of the process. Still it is amazing that under the past decade of Multi-Year Agreements in Netherlands often cogeneration was installed as energy conservation measure, which in the end has to do with the fact that interfering with the core of the process is often considered as 'dangerous and risky' and with the fact that the Multi-Year Agreements within the policy of participating companies was a responsibility of the energy manager of the company, i.e. the utility manager, and not of the process manager.

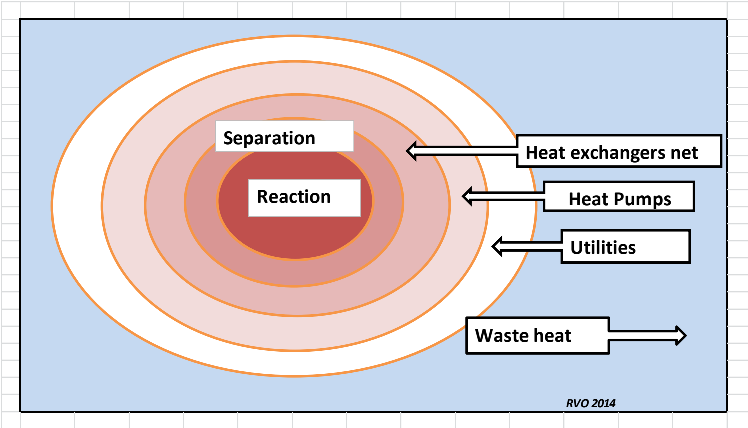


Figure 4-1: Onion model for process approach

A systematic approach in improving the energy efficiency of industrial processes is the onion-model a translation of the TRIAS-Energetica where the pre-assumption is that one should first save on energy by optimising the process and then go into thinking about the way in which the energy is exchanged within the process and then generated at the outside of the process.

The model is explained for a chemical distillation process where in the first shell the processes occurring in reactors and separators (Process) are optimized. In practice this is done by an economic optimization in which energy and other operating cost are balanced with annualized investment cost for the equipment. In distillation “Process” refers to molecular improvements such as extractive distillation as well as optimization of internals, trays and column compartments. Energy consumption can be reduced further by heat integration using heat exchangers (HEX). As heat exchangers need a driving force there is a limit to what can be achieved by heat integration. Optimization of the heat exchanger networks is done using pinch technology leading to the rule of thumb: “Do not transfer heat across the pinch temperature”. In addition the “grand composite curve” (enthalpy flow rate versus temperature) provides the minimum total cooling and heating power required for the plant. Now the temperature difference at the pinch temperature, ΔTpinch, is optimized by the economy: a higher value leads to smaller investment cost in heat exchanger area but also to increased utility cost. After heat integration has been optimized, further reduction of energy consumption can be achieved in the third shell: the heat pump (HP).

Process integration, modeling and optimization problems in chemical engineering are generally complex tasks of a considerable scale and comprehensive interactions. The application of information technology (IT) and computer software tools is essential for providing fast and, as much as possible, accurate solutions with a user-friendly interface. General purpose optimization and modeling tools overviews have been available through the years. A number of computer-based systems have been developed to support process engineers in the energy and mass balance calculations. However, due to the substantial ongoing funding needed for the continuous development, only a limited number have remained on the market. They have only been secured by a substantial number of continuous sales.

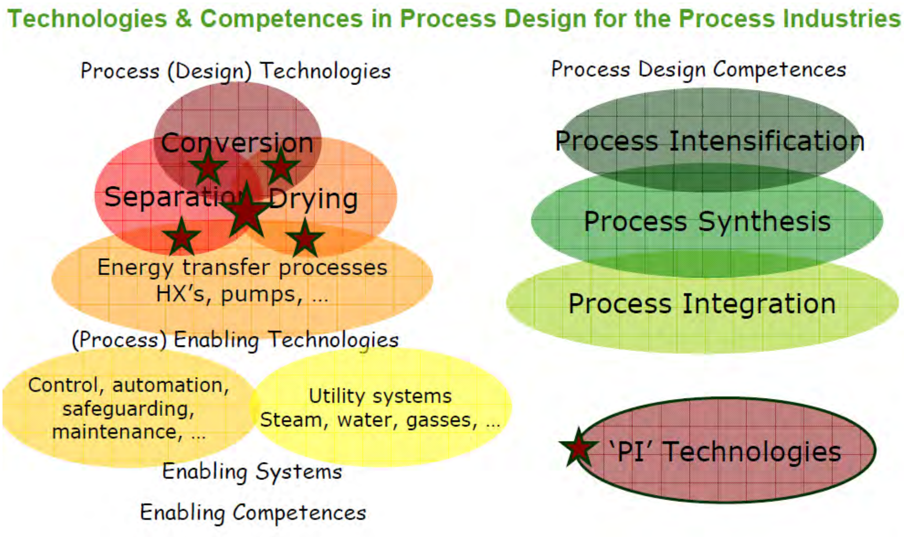


Figure 4-2: Technologies for process design in chemical industry (source TKI)

There have been a variety of efficient tools available. Each provider mainly stresses their advantages. Klemeš *et all* presented a comprehensive list of software tools that are available for the simulation of material and energy balances of chemical processing plants, which includes: (1) Aspen HYSYS (2) CHEMCAD; (3) GAMS; (4) gPROMS; (5) HEXTRAN; (6) OpenModelica; (7) PNS Solutions and S-Graph Studio; (8) PRO/II; (9) SPRINT STAR, WORK and WATER; (10) SuperTarget and (11) UniSim Design.

Computers have been changed substantially the practice of chemical engineering, allowing large advances in process modeling and simulation. The chemical engineering community has generated a rich literature about rigorous unit operation models and efficient algorithms to solve them, employing rising computational resources. Several problems, which in the past demanded a considerable occupation of engineering manpower, now can be solved by a single engineer in a fast and accurate way. Simultaneously, plant automation developments can provide a large amount of information about the process behavior in real time.

These two factors: the availability of plant data and the capacity to handle these using adequate models have opened a large field of improvements in process engineering. In a globalized world, characterized by an intensive business competition, these opportunities assume a special importance.

4.2 Available tools

By [Grift, 2011]

Tools for complex industrial processes are developed to visualize and analyze heat flows in processes to support with software the consultant in their advice on process improvements. Many of the available tools are based on graphs, diagrams and figures to easy the process of design and/or communication between experts and client.

4.2.1 Consultancy tools

Under the now long running policy of Multi-Year Agreements between industrial sectors and the Ministry of Economic Affairs, companies are benchmarked on an Energy Efficiency Index and have to make an Energy Efficiency Plan (EEP), done by an external consultant, every three years. Based upon Environmental Legislation companies, which do not participate in the program of Multi-Year Agreements, have to invest in energy efficiency measures with pay back times shorter than 5 years.

In this approach for energy conservation in industry the Netherlands Enterprise Agency (and its predecessors) have developed and used tools to facilitate the consultancy and to increase the impact by translating difficult process decisions into clearly understandable reports on management level. Some of these are:

- Energy screening
- Energy Potential Scan
- Procesintegration analyses and thermal audit (Einstein)
- Renewable energy scan

Energy analyses

An Energy Analyses which is part of the EEP consists of an energy balance, proposed measures, costs and economy and a consultancy report for decisions and an Energy Efficiency Plan for three years.

In a good Energy Analyses the heat flows and waste heat flows are mapped, not only the chimneys but also the locations in the process where the products a cooled and heated. Important to notify is the location of cooling towers and or condensers in the process. These two technologies are easily detected.

Energy Potential Scan

Energy Potential Scan is a form of participative model. Unlike traditional energy audit approach, in EPS, company and energy consultants work together to see the possibility to conserve energy. This method has been developed by Philips in Eindhoven together with Novem. There are two keys in EPS, quality and acceptance.

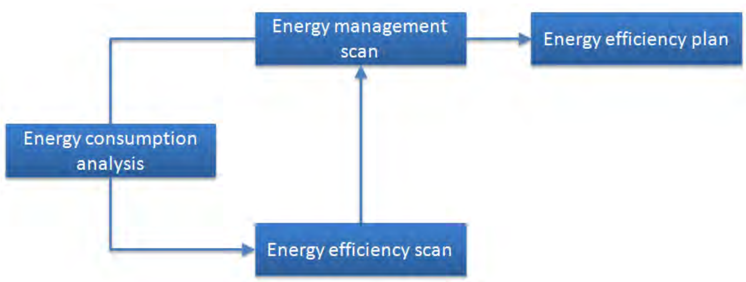


Figure 4-3: Energy Potential Scan

A key word is acceptance which created by something different from traditional energy audit where in the phase of the Energy Efficiency Scan (after the process analyses) it involves brain storming, thinking about the ideas to improve efficiency, and possible application both financially and technically. This creates commitment from management and participation of key personnel of the company.

From this very structured approach a large number of ideas are listed and discussed. The options for energy conservation a preferably developed by the company itself in an Energy Efficiency Plan.

Processintegration analyses

In a Processintegration analyses approach all heat flows for a process are mapped. For simple processes with a maximum of 20 heat flows a simple spreadsheet and pinch visualization are sufficient to develop an arrow and block diagram to engineer a heat exchanger network. For larger processes like in chemicals specialized software is needed to be able to optimize energy and economy at the same time. Based upon distances in the process between coordinates for heat, costs data and data for materials the software can propose a set of technical choices. Next to the right fit for heat exchangers the right fit for a heat pump can be calculated if the data for heat pumps are available to the program. This last boundary condition seems at this moment to be the largest problem for heat pumping technologies.

At European level it was noticed that a lot of software available for process integration analyses was not used for smaller processes as the software is often too complex or too expensive for small consultancies. Even worse is the fact that although Dutch Government thinks that process integration broadly introduced in the nineties is an accepted tool, this is not the case anymore for the larger part of industry, with exception of course for chemical industry.

In a European project a simple to use thermal audit has been developed under the name of “Einstein”. It is a freeware software tool with a report generator in Open Office.

Companies with relatively simple processes can be scanned in a few days on the potential heat integration, the internal use of waste heat, heat pumps, cogeneration and renewables like solar heat and bio-energy. The Einstein tool is still fully under development and needs as well as other software tools the right and objective information on heat pumping technologies.

Renewable Energy Scan

The Renewable Energy Scan has been developed by the Netherlands Enterprise Agency (and its predecessors) to make companies aware of the potential for applying renewable energy. This methodology is especially of interest for companies which do not have large process heat flows and can be found on many mixed industrial areas in the Netherlands.

4.2.2 Methods for Visualisation & analyse

For optimizing heat flows and to get process integration with heat exchangers and heat pumps in the first two levels of the onion the availability waste heat flows should be charted. If no data are available or if the design of the process is dated it is advised to execute when possible an extensive monitoring on the process over a certain period of time, since it is the experience (often painful) that no process runs optimally according to the design.Several methods are available for visualization of (waste) heat flows.

- Sankey diagram
- Arrows diagram
- Block diagram
- Pinch diagram
- Grassmann diagram

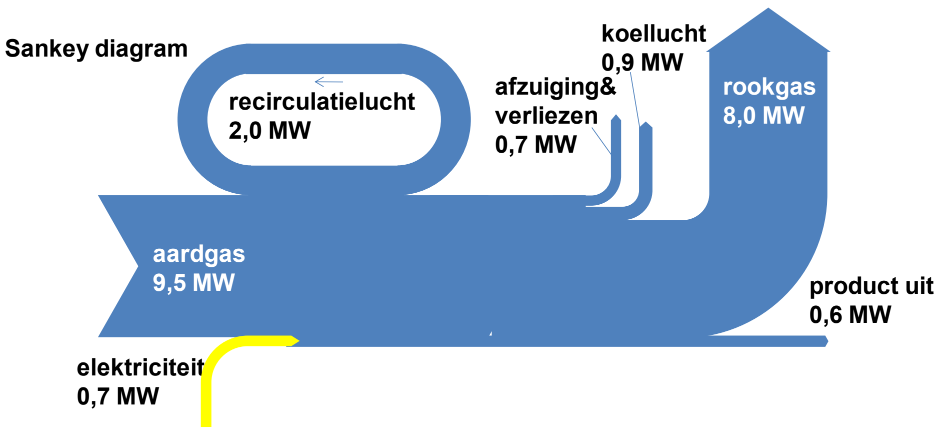


Figure 4-4: Sankeydiagram

A Sankey diagram can give insight in the energy balance on parts of the process or the complete process. The width of the arrows is a measure of the capacity of the energy flow.

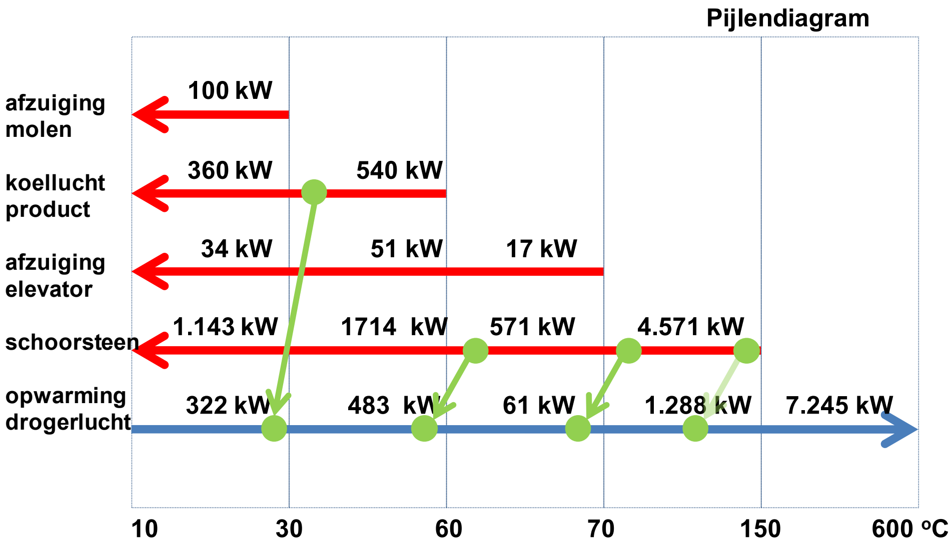


Figure 4-5: Arrows diagram

An Arrows diagram gives the heat flows at with the temperature levels. Together with the heat capacity of the flow in not too complex processes the right position for heat exchangers can be proposed. The green arrows give the potential heat exchanger between red (=hot) and cold (=blue) to be heated flows.

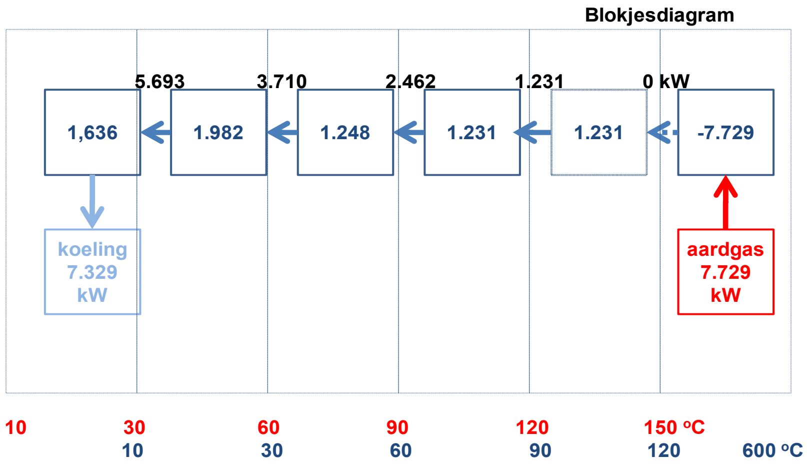


Figure 4-6: Block diagram

A block diagram is a tool to give the optimal lay out of a system of heat exchangers in a simple process. With this tool the capacity of heating and cooling can in theory be calculated. The figures in the blocks give the amount of heat residue which is available in the given temperature segment. These segments have to be placed in order to make the exchange of heat possible. The flows to be heated (blue) have to have a lower temperature than the waste heat flows (red). The block in the lowest temperature segment has to cooled by external energy. In this example only heat has to be supplied in the highest temperature segment.

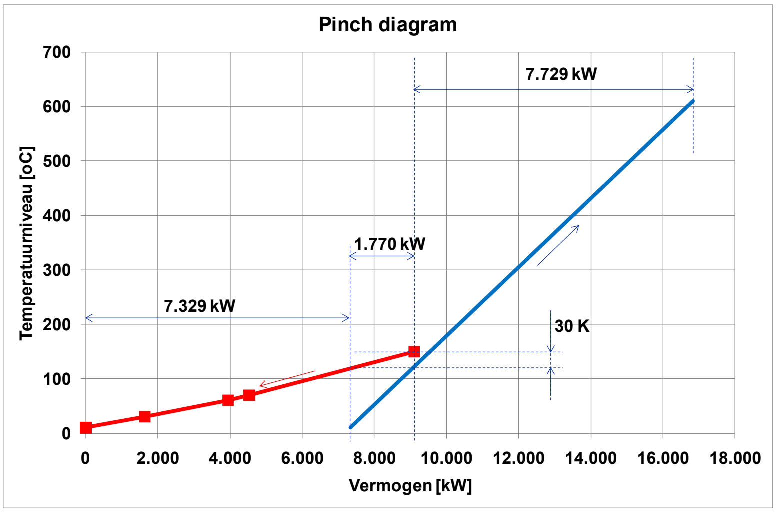


Figure 4-7: Pinch diagram

A pinch diagram gives capacities and temperatures. The process data are 'verwerkt' into a hot and cold composite curve. The hot composite curve gives all the process streams to be cooled including waste heat and the cold composite curve gives the stream to be heated. The art of engineering the process is to combine these streams in order to reduce the final heating and cooling demand of the overall process. Where the curves are closest together, i.e. the smallest temperature difference, is the so called 'pinch' (insnoering). A heat pump is only functional if the heat pump crosses this pinch. In the given example in the diagram a theoretical minimum heat is required of 7,729 kW's and cooling of 7,329 kW's, while 1,770 kW's of waste heat can be re-used in the process.

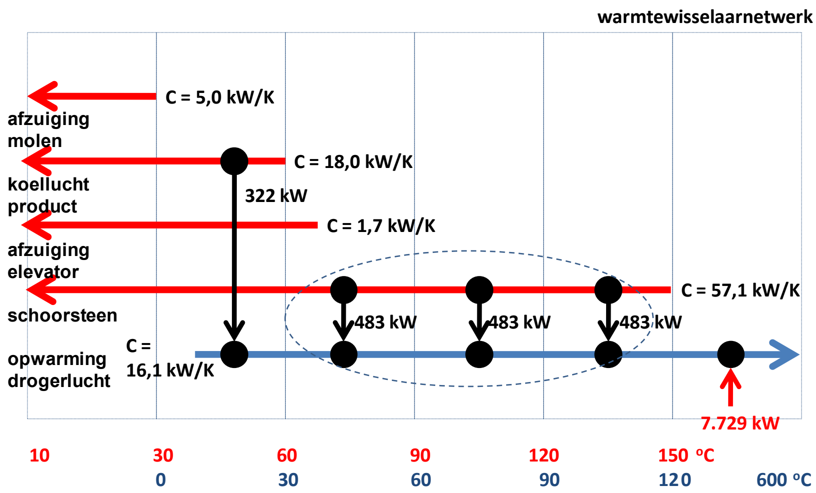


Figure 4-8: Heat exchanger Network

If the pinch temperature is known a heat exchanger plan can be engineered. For complex processes software is available to design this. For simple processes an arrows diagram can be configure the basic design of the network.

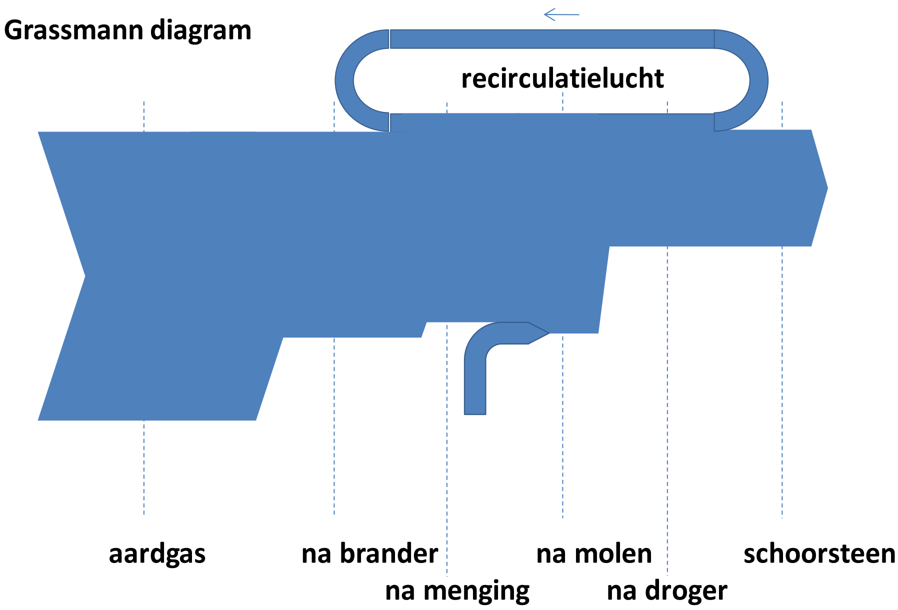


Figure 4-9: Grassman diagram

A Grassman diagram gives the exergy flows in the process. The exergy of a heat flow is a standard for the quality (temperature level) of the energy flow and a benchmark for the amount of electricity which can be generated from the flow. This is often used to analyze the optimal use of cogeneration.

4.3 Which tool fits best?

Many tools are available to optimize industrial processes where depending on the situation there is no univocal answer to the question which tool is the best to use. Several approaches for process optimisation in industry can be met with based upon the onion model as in Figure 4-1. In order of ranking:

- Process optimisation
- Process intigration
- Optimisation of Utlities
- Heat exchange with surrounding energy users

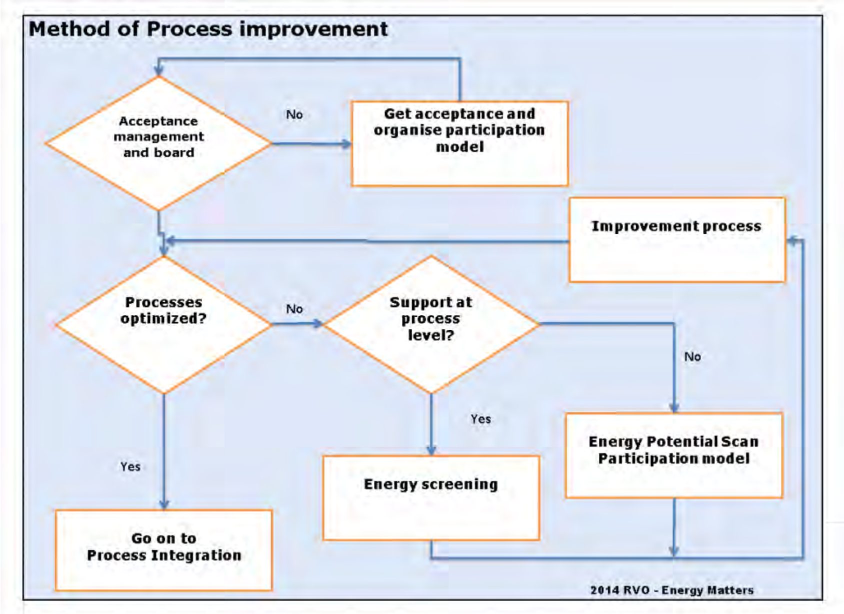


Figure 4-10: Flow diagram Improvement Process

Projects for reducing the energy use through process optimization go beyond the responsibility of the energy or utility manager alone and often have to have additional profits than only energy, like a better product or a higher yield of the production. If the project only gives reduced energy costs, the profitability is often lower than competing investments. In these kinds of projects it is of importance to create support and trust with the decision making management first, before even considering starting the project. The first phase of the project will have to focus on process mapping a improvements of the process as it is.

From the core of the original process questions can be raised as:

- Are the setpoints optimally adjusted?
- Is heat recovery already installed and optimal according to the pinch principles?
- Can temperatures be used at lower levels? Often for the easiness of installation and transport cheap steam systems are installed where only low grade heat is needed.
- Can drying processes be used by mechanical drying?
- Are heat flows mixed with degradation of heat?

Often the process (as mentioned earlier) does not run according to original design due to changes and small improvements over the years. (an interesting example is given in the factsheet on the Lips project with Doorgeest NL-18). Monitoring of the process can often already lead to large costs savings before even starting the more complex task of process integration. When it is assured that the process is optimized the task of process integration can start.

The flow diagram of the improvement process makes it clear that support and acceptance starts at management level and if the challenge can be translated to the management and board in clear and simple to understand messages the project can start. The next phase is to get participation at operational level. The Energy Potential Scan is an excellent methodology to get that result.

When the process have been basically optimized the potential for process integration can be analyzed. When not all data of the process are not already gathered in the first phase of the project, the task of data gathering must be undertaken. Monitoring of the process getting to know all mass balances, temperature levels, enthalpy levels seems to be a costly effort in time and money but will be worth every penny in the end result. The next step is to translate the data into energy-balance with costs attached (Sanky) and analyze the complexity of the process.

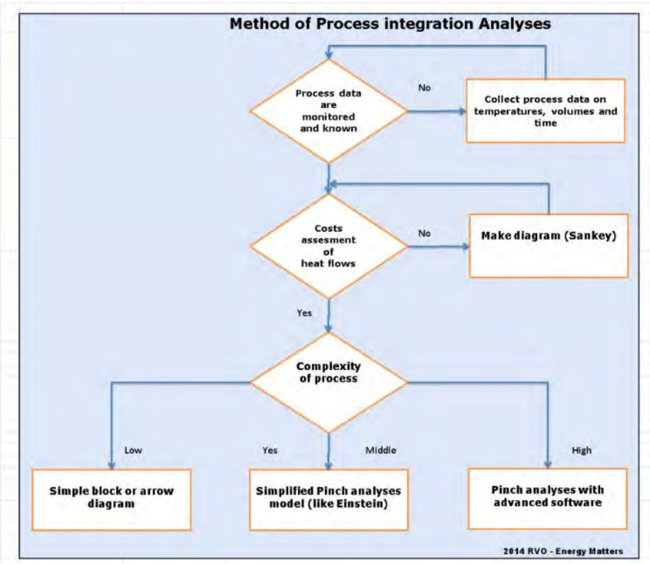


Figure 4-11: Flow diagram Integration Process

The question then raised is how many processes are suitable for process integration? In day to day practice often installers in medium sized industries are responsable for a part of the project. For cooling a refrigeration engineer is asked for. This misconception has for a long time been dominant in industry. However there are of course still a lot of smaller industrial companies can be supported with a simple block or arrow diagram. The flow diagram makes this distinction between simple and complex processes. For more complex situations Pinch software is needed to bale to calculate and design the optimal process integration. As mentioned before process integration has been broadly introduced in the nineties as tool, however it is not broadly used anymore in the larger part of industry, with exception of course for chemical industry. Therefore RVO has started togethet with the Federation of Energy Consultants (FEDEC) a series of training courses with the pinch model of 'Einstein' (see paragraph 4.4). In more complex processes a specialized consultant with advanced software steps in.

When all rational heat exchangers within the first inner circles of the process are established, the question is to optimize the utilities and to find a use for the waste heat of the process. A heat pump can be used to upgrade the waste heat over the pinch a part of the heat demand of the process. With newly developed heat pump technologies the temperature rise can be larger than originally was the case. Other possible use can be steam expansion or absorption cooling, both for the heat and cold demand of the original process. Eventually an ORC can make electricity from the waste heat if the temperature is at an acceptable level.

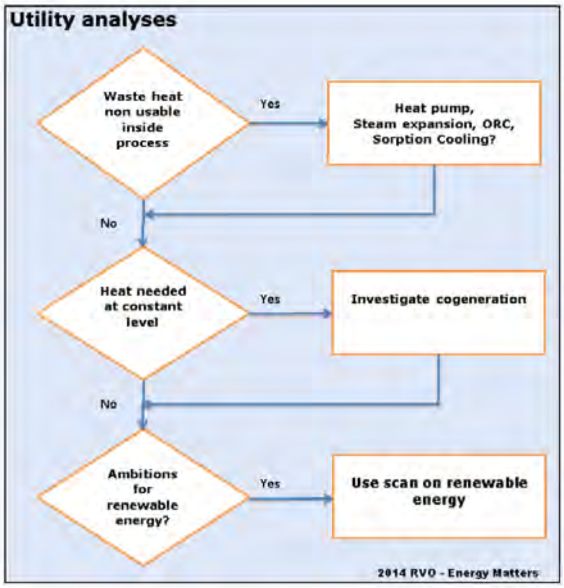


Figure 4-12: Utility Flow diagram

When there is still a constant and fair amount of heat needed for a larger part of the year cogeneration can be a serious option. However at the moment of writing the spark spread is negative, thus cogen will in almost all case be no economical option. Renewable energy options are decided on at that level where the Renewable Energy Scan as has been developed by RVO can be used. Cogeneration can also be based upon bio-energy.

When still waste heat is available a survey can be done on possible users of heat in the neighboring area where it must be closely watched that heat is not transported over too long distances with too high temperatures and transported to a heat demand with a stable demand over the year, especially in summer periods when process cooling is at its most critical. The best exergetic option for waste heat is to generate electricity with an ORC. This can be put into the grid.

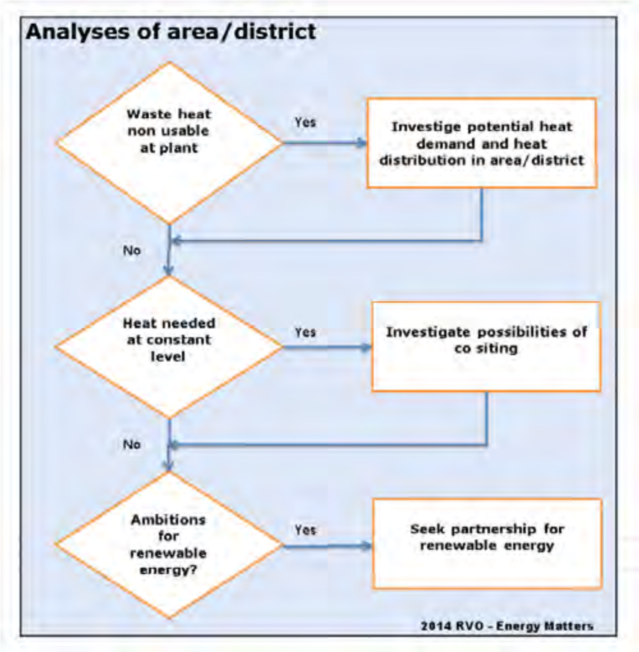


Figure 4-13: *Flow diagram for area survey*

4.4 EINSTEIN

The EINSTEIN methodology for thermal energy audit has been developed in the framework of the European (Intelligent Energy Europe - IEE).

In the follow up under EINSTEIN-II project aims to contribute to a widespread implementation of integrated energy-efficient solutions for thermal energy supply in industrial companies with a high fraction of low and medium temperature heat demand and for non-industrial users of similar demand profiles, such as hospitals, commercial centres, large office buildings, district heating and cooling networks, etc. To further optimize thermal energy supply, a holistic integral approach is required that includes the possibilities of demand reduction by heat recovery and process integration, and by an intelligent combination of existing affordable heat (and cold) supply technologies, under the given economic constraints. The follow up builds on the EINSTEIN tool kit for thermal energy auditing. This tool kit, based on an expert system software tool, guides the user through the whole procedure from auditing (preparation of visit and data acquisition), to data processing, to the elaboration, design and quantitative (energetic and economic) evaluation of alternative solutions. The tool kit, together with complementary databases, has been developed as a free and open source software project available in all the IEE project partners' languages. It uses pinch analyses as the basis is open-source software and provides the possibility for thermal energy efficiency improvements and the implementation of renewable energy within industrial processes, in different industry sectors.

The Einstein website and information (www.einstein-energy.net) claim that the methodology and Software Tool has proven in Auditing Practice (72 energy audits) that:

- The EINSTEIN methodology and tool has been successfully consolidated within the project. It has been proven that it can be applied in a great variety of different applications.
- The application of EINSTEIN compared to conventional auditing is a big help for the auditor for organizing information in a systematic and structured way and in carrying out fast feasibility analysis for a large number of possible alternative

Large Potential for Energy Efficiency An average primary energy saving potential of close to 20 %, and in some companies up to more than 60 % has been detected even under the constraint that has been applied in most audits that pay-back times should not be higher than 4 years (although this limit varied from company to company from below 2 year up to 8 years in some specific cases). If the primary energy consumption for thermal uses only is used as a reference (without electricity for lighting,

By many companies there was a positive take-up of the proposals presented (at the end of the project out of 72 companies 20 had initiated some further detail planning steps and out of them 5 already had implemented (some of) the proposed measures. The development and presentation of an attractive proposal to the company was in many other cases in-sufficient for triggering action towards a further development of detail technical issues with the objective of a real implementation of the measures.

Einstein Approach in Netherlands

In the Netherlands as in Europe it is noticable that although process integration based upon pinch analyses was broadly introduced in the nineties and should be an accepted tool, that this is not the case anymore for the larger part of industry, with exception for chemical industry. Consultants as well as energy managers within companies should therefore be trained and educated in process analyses based upon the approach described in paragraph 4.3 starting with an Energy Potential Scan and further worked out as described in the flow diagrams in Fig. 4-11.

Dependent on the complexity of the process a tool like Einstein is used or more complex tools. RVO has ordered Energy Matters after their study on which tools to use [Grift, 2011] to develop a training program together with FEDEC (Federation of Energy Consultants in Industry) based upon Einstein. The focus is to improve the availability of skilled energy auditors and energy managers and the diffusion of energy management systems and best practices. A next step will be to develop instruments to ensure availability of updated, comprehensive and usable information on energy efficiency relevant for industries. Heat pumps are one of the key technologies in this approach with models developed and described under the next paragraph.

During the process of training with Einstein bugs and small problems were discovered and are now discussed with the developers of the Einstein tool kit.

4.5 Process tools and heat pumping technology

Most of the tools discussed are focusing on heat integration and with these tools the right position and choice for a heat pump can be made. In general experienced process designers working with pinch software can easily see from the grand composite curves where heat pumps can be applied, also from the 'nose' of the curve they in general know which type of heat pump. The main problem is that it is difficult to select the right size and brand of heat pump as there is scarce information that can be directly used. A lot of information can be found on the Internet but a consultant (often highly paid) doesn't have the time available to sort out this information.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

For a heat pump to be effective there are a number issues to be considered:

- The pinch temperature and the flexibility of the plant
- The thermodynamic cycle and the heat pump efficiency
- The temperature lift required
- The enthalpy balance
- The selection and constraints of heat pump equipment
- The configuration of the system
- The available utilities
- The economy or the annualized capital cost versus the utility cost

As the target group for heat pumps is a large variety of industrial sectors several heat pump selection models have been developed and are becoming available. Three of these are discussed in the next paragraphs.

4.5.1 Mastering Heat Pumps Selection for Energy Efficient Distillation[4]

By [Kiss, 2012]

An overview on application criteria for practical systems is given in [Landolina, 2012].

Distillation still remains the most popular separation technology, in spite of claiming about 40 % of the operational costs from chemical and refining plants. Distillation has a relative low thermodynamic efficiency, requiring the input of high quality energy in the reboiler to perform the separation task. At the same time, a similar amount of heat at lower temperature is rejected in the condenser. Several heat pump concepts have been proposed to upgrade that discharged energy and reduce the consumption of valuable utilities. For example, vapor compression (VC) uses work to increase the temperature of

[4] Kiss, Flores Landaetaa, Infante Ferreirac (Mastering Heat Pumps Selection for Energy Efficient Distillation)

a fluid heat transfer media in a closed loop. Mechanical or thermal vapor recompression (MVR or TVR) use the top product as working fluid in an open cycle, reducing further the investment costs. Similarly, the structure of an internally heat integrated distillation column (HIDiC) lowers the required temperature lift, reducing the compressor work. Meanwhile compression-resorption heat pumps (CRHP) use absorption processes to enhance the heat transfer, allowing higher efficiency and wider applicability range. Average energy savings when using any of the heat pump systems in distillation range from 20 to 50%.

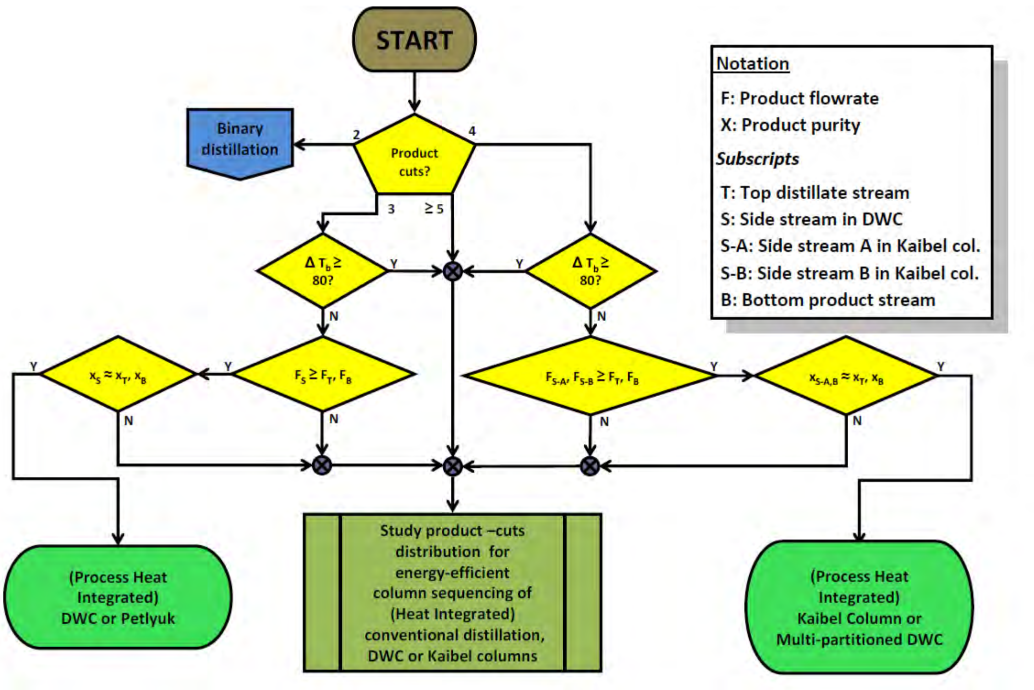


Figure 4-14: Structure

However, the energy efficient systems described in literature were evaluated for different separation tasks. Thus, their performance comparison is difficult, complicating the technology selection for other applications. To solve this problem, we developed a practical selection scheme of energy efficient distillation technologies, with a special focus on heat pumps.

Only the most promising technologies in terms of actual implementation were selected for this study: vapor compression, mechanical or thermal vapor recompression, compression-resorption and thermo-acoustic (TAHP) heat pumps, heat integrated distillation column (HIDiC), cyclic distillation (CyDist), dividing-wall column (DWC) and Kaibel distillation column. The selection criteria include the type of separation tasks, the products flow and purity specifications, the boiling point differences (ΔTb), the reboiler duty (Qreb) and its temperature level (Treb).

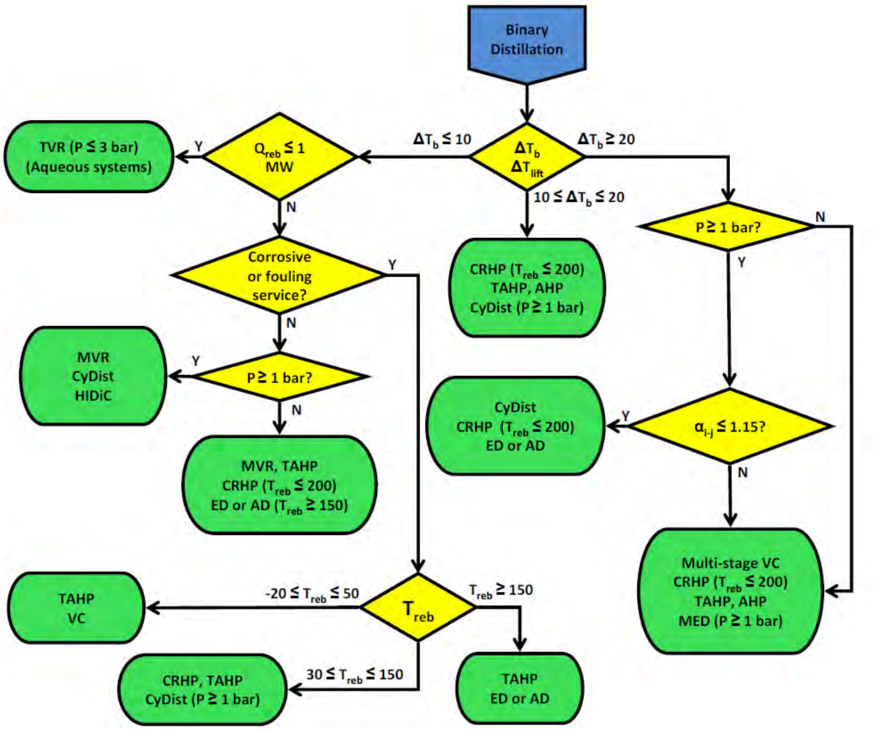


Figure 4-15:

The straight-forward selection scheme presented in this work allows the quick selection of the most suitable technology for any distillation task. Thus, the application of the proposed scheme allows considerable savings in time and resources allocated for the selection of eco-efficient separation technologies. The ultimate goal of this work is to facilitate significantly the design of energy efficient chemical processes, thus becoming a valuable tool for enhancing the sustainability of the chemical industry.

4.5.2 Heat pump models

A more general model that can be used has been developed under the Task 2 of the Annex by KWA for RVO. The challenges arose during the meetings on Annex 35 with the Dutch market consisting of consultants and institutes. The main consultants for process industries advised not to focus on process integration tools but to develop a model that could be used as an add-on to existing tools. Integrating this basic heat pump model into software models would make this model dependent on the tools. No specific new process analyses tool was deemed necessary.

The heat pump model based upon Excel would idealy be available on the Internet and could further be developed as a WIKI-approach where the market itself would fill in further details in the model and in the end applications could be hinged as factsheets to the model. This stage of development is not reached yet during the process of the Annex.

In a step by step approach the user is lead through the process filling in data from his own process.

- Find source heat with a high as possible temperature, below the pinch-temperature in the process. Determine the amount of heat available with corresponding temperature. Find out what will be the impact on the process and the existing heat integration. Determine whether it is possible to adapt the process to increase the amount and/or temperature of the source heat.
- Find process heat with a low as possible temperature but higher than the pinch-temperature. Determine the amount of process heat and temperature required.
- Determine which type of heat pump fits the process conditions that are investigated in step 1 and step 2. Heat source and heat sink temperature, power and type of process medium should be considered.
- To determine the feasibility of a heat pump, the performance of the heat pump at given process conditions should be calculated.
- When the performance of the heat pump is calculated, an indicative calculation of energy and cost savings can be performed.

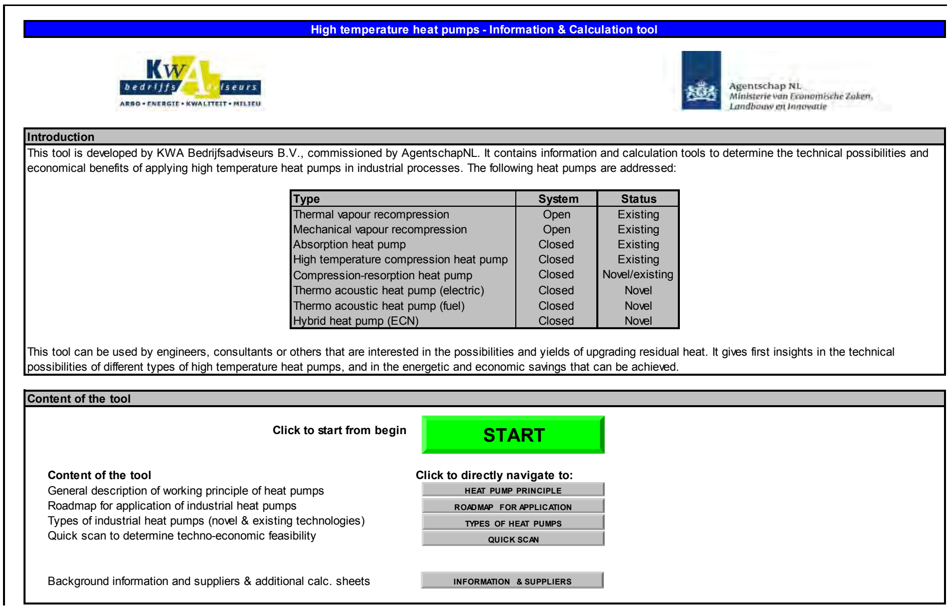


Figure 4-16: RVO - Heat pump model selection screen

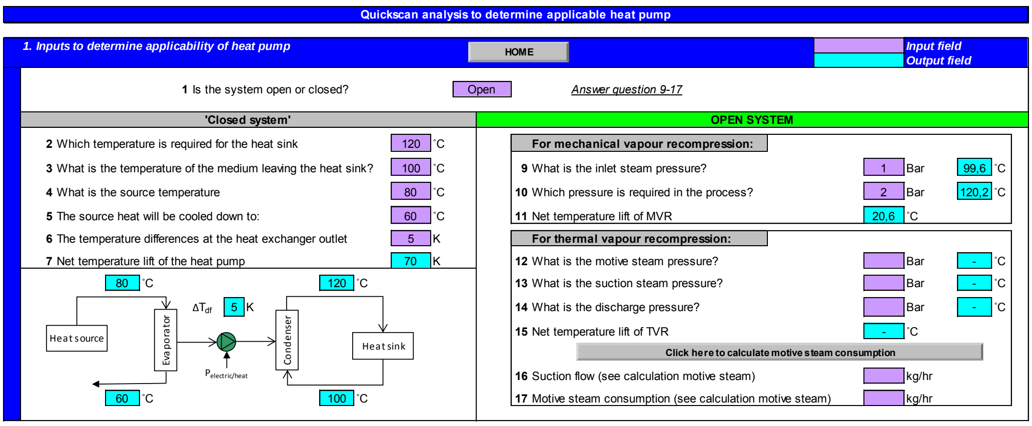


Figure 4-17: Quickscan analysis

The further development of this model will be taken up in 2014 – 2015 under a new Task 2.

4.5.3 Heat Pump Check

The Heat Pump Check is another on-line calculation tool which is developed by De Kleijn Energy Consultants & Engineers from Druten (www.industrialheatpumps.nl). The tool can help industrial companies to determine the feasibility of heat pumps for their processes. it gives a global indication of the applicability and feasibility of a heat pump. The result is a good starting point to determine if further investigation, for example by an external consultant, is useful.

SUMMARY HEAT PUMP CHECK

Industrial Heat Pumps

Input

Waste heat source		**Process**	
Heat source	: Refrigeration system	Process	: Pasteuriser
Purpose installation	: Cooling+freezing	Heated flow	: Product
Refrigerant	: Other	Temperature in	: 50 °C
Condensation temperature	: 30 °C	Temperature out	: 70 °C
Cooling capacity	: 1000 kW	Heat demand	: 1000 kW
Other data			
Current heat source	: Direct gas-fired	Electricity costs	: € 0.08 / kWh
Generation efficiency	: 85%	Fuel costs	: € 0.35 / Nm3
Running hours	: 6000 hours/year	Selection heat pump	: Largest savints
Simultaneity	: 70%	Refrigerant	: Only natural

Specifications heat pump

Heat pump type	: Mechanical heat pump with natural refrigerant Ammonia (R717)
Capacity	: 1000 kW
Electric power	: 196 kW
COPh	: 5.1

196 kW

Waste heat in 30.0 °C | 75 °C 70.0 °C Flow out

804 kW Evaporator | Condenser 1000 kW

Waste heat out | Flow in

30.0 °C 28 °C | 50.0 °C

Costs and savings

Energy savings		**Financial savings**	
Reduction fuel consumption	: 562800 Nm3 per year	Fuel savings	: € 197000 per year
Extra electricity consumption	: 823200 kWh per year	Electricity costs	: € 65900 per year
		Financial savings	: € 131100 per year
Primary energy savings	: 10404 GJ per year		
Investment costs		**Payback period**	
Heat pump	: € 370000	Investment costs	: € 432100

Figure 4-18: report generated by Heat Pump Check

4.6 Literature

Geelen, 2013 — Monitoring van (energetische) prestaties en knelpuntenanalyse WKO-systemen in de glastuinbouw, ir. C.P.J.M. Geelen en ir. K.J. Braber; Arnhem, December 2013

Grift, 2011 — Warmtetools industrie, Jan Grift, Allan Hart (Energy Matters), april 2011, Projectnumber: 11.450

Kiss, 2012 — Mastering heat pumps selection for energy efficient distillation, Kiss A. A., Flores Landaeta S. J. and Infante Ferreira C. A., (2012), Chemical Engineering Transactions, 29, 397-402

Landolina, 2012 — Strategic Research Priorities for Renewable Heating & Cooling, Cross-Cutting Technology European Technology Platform on Renewable Heating and Cooling; Many authors edited by Simone Landolina – European Renewable Energy Research Centres Agency, Manuscript completed in April 2012. Brussels, © European Union, 2012

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13

IEA Heat Pump Programme Annex 35

Task 3:

R&D Projects

Final Report

(Status: 10.06.2014)

Prepared by the

Participants of Annex 35/13

Contents

1 Summary

In **Austria**, a small number of already existing applications of heat pumps in the Austrian industry, the relevance of this topic is growing in Austria. Beside the fact that several national manufacturers already offer industrial heat pumps, there is just a focus on high-temperature heat pumps suitable for industrial applications by the Austrian R&D heat pump community. The Austrian team identify six manufacturers deliver heat pumps with a capacity up to 1 MW and with maximum heat sink temperatures < 98 °C and describe three relevant projects.

Table 1-1: R&D-Projects in Austria

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Concept for waste heat upgrade for process supply	Hybrid (absorption / compression)	Prototype	25 kW	85 °C	NH_3-$LiNO_3$ and other working pairs
Utilization of industrial waste heat for refriger-ation purposes	Absorption	Simulation	n. a.	100 °C	NH_3-H_2O and other working pairs
Upgrading flue gas condensation heat	Direct evapo-rator	Test facility for experimental analysis	n. a.	n. a.	n. a.

Canada's R&D projects have focused on recovering low-grade waste heat from relatively small- to medium-scale industrial manufacturing facilities in order to supply heat for building domestic hot water consumption and/or industrial heating purposes. The objective was to properly design, integrate and operate several types of IHPs in various energy intensive industrial processes able to provide sufficient amounts of waste heat at appropriate quality levels, flow rates and temperatures. All these projects were intended to respond to future requirements, such as a reduction of the energetic intensity of small- and medium-sized industrial processes and of environmental thermal pollution.

Table 1-2: R&D-Projects in Canada

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Thermally-driven ejector	Vapour compression	Laboratory test bench	9 kW (cooling)	10 °C	R-134a
Two-phase flow ejectors	Vapour compression	Laboratory test bench	n. a.	n. a.	n. a.
CO_2 ejector refrigeration	Ejector refriger-ation	Feasibility study, laboratory prototype	n. a.	-5 °C	CO_2
CO_2 trans-critical HP	Compression, double stage	Simulation, Laborato-ry system, monitoring project	100 kW	85 °C	CO_2
Ammonia HP	Compression, single stage	Laboratory prototype	~ 48 kW	85 °C	NH_3
	Compression, double stage	Simulation	2.7 MW	90 °C	
Cascade HP	Compression, double stage	Simulation	27.2 kW	84.6 °C	R-134a, R-1234yf
Mechanical vapour com-pression	Mechanical vapour com-pression	Test in a industrial plant	n. a.	n. a.	n. a.
Low tempera-ture drying	Compression	Laboratory-scale prototype	5.6 kW (com-pressor nomi-	n. a.	n. a.

			nal power input)		
High temperature drying	Compression	Industrial-scale prototype (2 units)	65 kW (compressor nominal power input)	n. a.	R-236fa

To have an overview of the potential and technical requirements of using heat pumps in industrial processes, two assessment reports have been published in 2013 for **Denmark**. The two reports are carried out with different approaches meaning that the results are not a 100 % comparable and conclusive. However both reports give good indications of the possibilities in industries. The first report considers excess heat of industries in general and the potential of utilization in different ways both internal and external. Technical and economical obstacles are taken into account. The focus of the second report is more specific on using heat pumps in different processes where heat is recovered and utilized in the same process. External utilization of industrial waste heat is not considered. The potential is assessed for processes with temperature requirements of up to 180 °C and categorized in temperature lifts of respectively 20 K, 40 K and 70 K. A requirement of 180° C and a temperature lift of 20 K means that the heat source is 160 °C whereas a lift of 70 K means that the source is 110 °C.

Both reports show that the majority of the potential require temperatures less than 100 °C, meaning that outlet temperatures is not a technical barrier in most cases. The assessments also show that there is some potential for heat pumps that only lifts 20 K, meaning that high COP values is possible while the heat capacities should in MW's. There is only a small potential for heat pumps with capacities less than 1 MW.

There have been a number of demonstration projects in the last couple of years implementing large scale heat pumps, which have primarily been trans-critical CO_2 or high pressure ammonia systems. At the moment research and development is also in the fields of water vapor systems and the ammonia/water hybrid process. Three demonstration projects are relevant for industrial purposes.

Table 1-3: R&D-Projects in Denmark

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Energy efficient drying with a novel turbo compressor based high temperature HP	Rotrex turbo compressor for water vapour compression	Industrial installation – timber drying	446 kW	n. a.	Steam
		Industrial installation – fish and bone meal	~2.2 MW	100 °C	Steam
Ultra high temperature hybrid HP	Hybrid (Compression / absorption)	Theoretical investigations	n. a.	180 – 250 °C	NH_3-H_2O in different mixtures
Highly efficient Thermodynamic Cycle with Isolated System Energy Charging (ISEC)	ISEC concept consists of two or more tanks. One tank is heated while the other is discharged.	Project just been initiated (duration 3 years)	n. a.	n. a.	n. a.

Since a few years, there is in **France** a renewed interest for heat pumps. Recent developments have been made to develop industrial (> 100 kW_{th}) high temperature heat pumps (> 80 °C) and very high temperature heat pumps (> 100 °C). Currently, there are only a few closed-cycle mechanical high or very high heat pumps installed in the French Industry, but interest and references are growing. The R&D activities of EDF are concentrated on three projects:

Table 1-4: R&D-Projects in France

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
AlterECO Project	VHT HP – HFC-mixture	Experimental tests in 2011 industrial experimentation in 2014	250 kW	140 °C	ECO3™
EDF/JCI	HT-HP	Experimental tests in 2010	700 kW	100 °C	R-134a R-245fa
PACO-Project	VHT WP –water Centrifugal compressor with magnetic bearings	Experimental tests 2012/13	700 kW	140 °C	Water

It is expected to install in France at least 1,500 industrial high temperature heat pumps before 2020 in spite of various commercialization barriers:

- Lack of knowledge and experience with heat pumps
- Negative perception of heat pumps due to poorly designed models early in their use
- Volatile energy prices.

The integration of heat pump can be optimized with **thermal energy storage**, with various advantages:

- The heat pump works at its nominal point
- The thermal need can be covered with a smaller heat pump, decreasing the investment.

German heat pump manufacturers and German partners of the ANNEX 35/13 identify several projects for industrial heat pumps:

Table 1-5: R&D-Projects in Germany and from German partners

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
NeatPump	High pressure compression	Projects in industry: chocolate factory, etc.	n. a.	Up to 90 °C	NH_3
n. a.	High pressure compression	Projects in industry: greenhouse, paper mill, etc.	Up to 14 MW	Up to 90 °C	NH_3
n. a.	Two stage compression	Installed in industry	n. a.	100 °C	R-134 / R-600a
Brewery	Single stage compression	Installed in industry	54 kW	120 °C	R-600a
Part cleaning system	Compression	Prototype installed in industry	~ 55 kW (at 50 Hz)	100 °C	R-245fa
thermeco$_2$	Trans-critical CO_2 HP	Installed in industry	Up to 1 MW	90 °C	CO_2

Research on new refrigerants for high temperature application is also done in Germany. The promising candidates are called LG6 and MF2.

Japan classifies industrial heat pumps into four general types: closed-cycle mechanical, open-cycle mechanical vapor recompression, open-cycle thermal vapor recompression, and closed-cycle absorption heat pumps.

CO_2 trans-critical cycle air-source heat pumps, capable of producing hot water of 90 °C with a heating capacity of 72.0 kW, have been commercialized in Japan and sold not only in Japan but also in South Korea, Taiwan, Indonesia and elsewhere. CO_2 trans-critical cycle water source heat pumps, capable of generating hot air of 100 °C with a heating capacity of 110 kW, have been also commercialized in Japan.

Table 1-6: R&D-Projects in Japan

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Dual-cycle HP water heater	Two stage compression	Commercialized	35 kW	70 °C	R-410A / R-134a
HP steam supplier (water to water)	One stage compression	Installed in industry	370 kW	120 °C	R-245fa
	Two stage compression	Installed in industry	660 kW	165 °C	R-134a / R-245fa
HP for circulating water heating	Two stage compression	Installed in industry	14 kW	90 °C	R-410A / R-134a
Waste heat recovery HP water heater	two stage centrifugal compression	Installed in industry	376 to 547 kW	90 °C	R-134a

A survey of low GWP refrigerants for high temperature heat pumps and basic analysis on their thermodynamic cycle performance is also executed in Japan, as well as the industrial application of thermal storage technologies. The latest thermal storage technologies including the ones already in practical use are explained.

More than 60 % of the total energy is consumed for the industrial application in **Korea**. A great portion of final energy in industrial field is to generate heat or provided as feedstock. So, a lot of activities have been done to improve efficiency or make advanced process in order to reduce primary energy consumption and green gas emission. The major directions of such activities are;

- Utilization of waste heat from industrial processes (reduce green gas emission and production cost) by hybridized heat source with renewables
- Production of hot water which can be directly used to the processes
- Extension of heat pump applications into advanced industrial processes formerly neglected to be a part of the processes

Under these circumstances, the application of industrial heat pump has gained much interest in these days by not only companies but also government agents.

Heat pump R&D in Korea is categorized into Energy Efficiency and Resources Program. The scope of the program is to ensure effective accomplishment of the objectives of the governments Framework Plan for the Development of Energy and Resource Technologies for the Years 2006-2015, where key parts are energy storage, heat pumps, micro

CHP, building energy, green cars, clean fuel, energy equipment, industrial process, CCS, and energy resources.

Table 1-7: R&D-Projects in Korea

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Hot water HP with waste heat	Hybrid Compression / Absorption	Prototype	30 kW	Over 90 °C	NH_3/H_2O
HP system with heat recovery from flue gas		Demonstration in a food factory	100 kW	60 °C	n. a.
Geothermal HP	Compression	Installed in industry	1000 RT	n.a.	R-410A
Double effect absorption HP for tow-temperature sewage waste heat recovery	Double effect absorption	Performance tests of the prototype	n.a.	70 °C	n.a.
Hybrid HP using solar heat	n. a.	Laboratory Tests	13 kW	n.a.	n.a.

R&D in the **Netherlands** on industrial process innovation is for a large part supported by the Ministry of Economic Affairs through the ISPT Innovation Program. Major players in this program are the Dutch process industry, TU-Delft and ECN. The focus on heat pumping technology as one of the key technologies is logical and has a long track record starting with basic research now reaching the pilot phase.

New developments in distillation heat pump technology are therefore aimed at novel heat pumps with a higher economic range and at new heat integrated configurations. In the Netherlands these developments are:

- Thermo Acoustic Heat Pump at ECN
- Compression Resorption Heat Pump at TU Delft
- Adsorption Heat Pump
- Heat Integrated Distillation Columns at TU Delft.

2 Introduction

One of the major programs of the IEA HPP IETS Annex "Application of industrial Heat Pumps" is to develop and advance heat pump technology to support industry to use its energy resources more efficiently. It involves using heat pumps in a role of both increasing the process efficiencies and recovering and reusing waste energy emitted in industrial manufacturing processes. It should foster research, development and prototype tests for more efficient and economical recovery of waste energy in industry, the identification of appropriate heat pump applications within the industrial sector and the subsequent development of heat pump technologies to meet the industrial requirements. In addition to system studies, high temperature heat pumps, including refrigerant and component developmental programs should be supported that would potentially result in enhanced performance and reduced costs.

The following R&D projects in the participating countries/organisations are of interest for the annex:

3 Austria

Despite a small number of already existing applications of heat pumps in the Austrian industry, the relevance of this topic is growing in Austria. Beside the fact that several national manufacturers already offer industrial heat pumps (see chapter 3.1), there is just a focus on high-temperature heat pumps suitable for industrial applications by the Austrian R&D heat pump community (see chapter 3.2)

3.1 Industrial heat pumping systems available in Austria

This chapter describes the current state of the art of available industrial heat pumps by Austrian manufacturers based on a screening of the Austrian heat pump market. According to this screening, customized as well as standardized compression heat pumps with heating capacities from 50 up to 1000 kW are offered by several Austrian heat pump manufacturers for waste heat recover and the use in commercial buildings. These heat pumps are usually designed for supplying temperature levels up to 60 °C and some of them up to 98 °C at a low heat sink temperature difference (10 K). Furthermore, absorption chillers are offered by an Austrian manufacturer, which allows the utilization of waste heat for industrial refrigeration purposes. Table 3-1 gives an exemplary overview of Austrian industrial heat pump manufacturer.

Table 3-1: Overview of Austrian industrial heat pump manufacturers (Status: Nov 2013) (without guarantee for completeness)

Manufacturer	Type	Capacity	Refrigerant	max. heat sink temp.
IDM-Energiesysteme GmbH	Compression	50 – 500 kW	R-134a	65 °C
OCHSNER Wärmepumpen GmbH	Compression	100 - 300 kW	„Öko1"	< 98 °C
HELIOTHERM Wärmepumpen GmbH	Compression	49 – 134 kW	R-134a	60 °C
FRIGOPOL Energieanlagen GmbH	Compression	Up to 1MW	R-717, R-723, R-236fa etc.	> 70 °C
COFELY Kältetechnik GmbH	Compression	100 - 700 kW	R-134a, R-717, etc.	< 80°C
PINK GmbH	Absorption	20 kW (cooling capacity)	NH_3/H_2O	Cooling applications

IDM Energy Systems GmbH offers their so called TERRA Max (see Figure 3-1), which is a compression heat pump working with two or three scroll compressors and R-407C or R-134a as refrigerant with a capacity range from 50 to 650 kW. This heat pump type is available for heat sink temperatures below 65 °C. [IDM, 2013]

Figure 3-1: Basic construction of the Terra Max 130 [IDM, 2013]

The company **COFELY Kältetechnik GmbH** delivers compression chillers and heat pumps for households and the industry. COFELY offers the possibility to recover the waste heat from their chillers, directly or upgraded by closed or add on-HPs (R-134a, R-717 etc.). For upgrading waste heat Cofely has a standardized R134 closed compression HP with a capacity of 150 to 700 kW for heat sink temperature up to 65 °C and heat source temperature up to 35 °C for industrial application in their portfolio, using a semi hermetically reciprocating compressor or a screw compressor for a heating capacity up to 1 MW. Furthermore, Cofely also offers R-717 compression HPs for industrial application for simultaneous heating and cooling with reciprocating compressors for a heating capacity from 50 to 750 kW and screw compressors up to about 1 MW. [Cofely, 2013]

For various applications in commercial buildings or in the industry the heat pump manufacture **OCHSNER GmbH** offers a series of heat pumps with semi-hermetic compact screw compressors with a capacity from 100 to 960 kW. For heat sink temperature levels up to 65 °C Ochsner uses R-134a, R-407C or commercial refrigerants. Additionally Ochsner also offers heat pumps for industrial applications, as e.g. the "Toppump". For high-temperature applications Ochsner offers standard industrial heat pumps, which can lift waste heat from a (external) temperature level of 40 up to 98 °C at a low temperature difference of the heat sink (5 to 10 K). As refrigerant the so called "Öko1" (by Ochsner), which is nonflammable and nontoxic, offers appropriate pressure levels at this high temperature levels. [Ochsner, 2013]

Figure 3-2: High-temperature heat pump [Ochsner, 2013]

According to the available waste heat temperature level Ochsner has two kind of this high-temperature heat pump in their portfolio, both a so called "two-stage" HP (IHWSS, see Figure 3-3) for heat source temperatures above 10°C, which is basically a cascade plant, and a "single-stage" HP (IHWS, see Figure 3-4) for heat source temperatures from 35 to 55 °C, which is designed as economizer cycle.

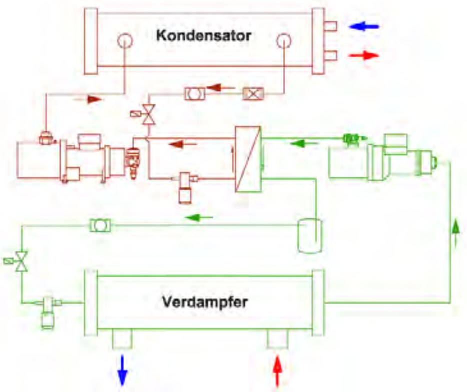


Figure 3-3: Flow scheme of the Ochsner high-temperature heat pump Type: IWHSS “two-stage” – Cascade cycle [Ochsner, 2013]

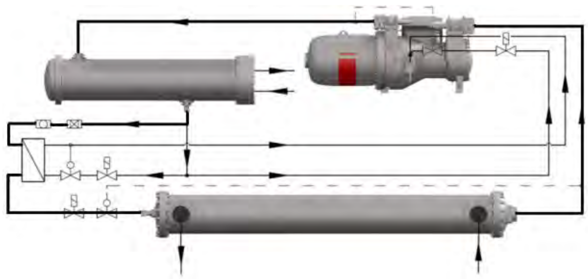


Figure 3-4: Flow scheme of the Ochsner high-temperature heat pump
Type: IWHS “sinlge-stage” – economizer cycle [Ochsner, 2013]

The Austrian heat pump manufacturer **Heliotherm Wärmepumpen GmbH** offers a standardized HP (see Figure 3-5) for application in the industrial and commercial buildings for heat sink temperatures up to 60 °C and a heating capacity up to 139 kW.

Figure 3-5: Heliotherm’s heat pump for industrial application [Heliotherm, 2013]

The Austrian company **Frigopol Energieanlagen GmbH** produces compressors and customized heat pumping systems with R-717, R-723 or other refrigerants for cooling and/or heating applications with a capacity up to 1 MW with different compressor-types. For example, Frigopol (2013) has already delivered a customized plant with 1 MW capacity working with R-236fa as refrigerant for a district heating application (see Figure 3-6). Frigopol also is involved in an innovative R&D project concerning high-temperature HPs (up to 100°C) for industrial applications (see chapter 3.2.1).

Figure 3-6: R236fa high-temperature heat pump [Frigopol, 2013]

The **PINK GmbH** offers absorption chillers (see Figure 3-7) with a cooling capacity of about 20 kW, which are driven by solar thermal or industrial waste heat (> 70°C). The actual absorption chillers from Pink are single-stage plants using ammonia/water as working pair. [Pink, 2013]

Figure 3-7: PinkChiller PC 19 [Pink, 2013]

3.2 R&D projects in Austria

A screening shows that there are some R&D projects in Austria investigating different topics of heat pumping systems suitable for industrial waste heat recovery. In this chapter three relevant projects are described. One project investigated a concept for waste heat upgrade for process heat supply (see chapter 3.2.1), one the utilization of industrial waste heat for refrigeration purposes (see chapter 3.2.2) and one for upgrading flue gas condensation heat (see chapter 3.2.3) by heat pumps.

3.2.1 Hybrid (absorption/compression) heat pumping systems

The concept of an absorption/compression-heat pump system is known since the late 19th century (Osenbrück, 1895). Due to certain technical difficulties the concept coulnd't be realized commercially in large scale up to now. In general, the system is a combination of a vapor-compression cycle and an absorption solution cycle, as shown in Figure 3-8.

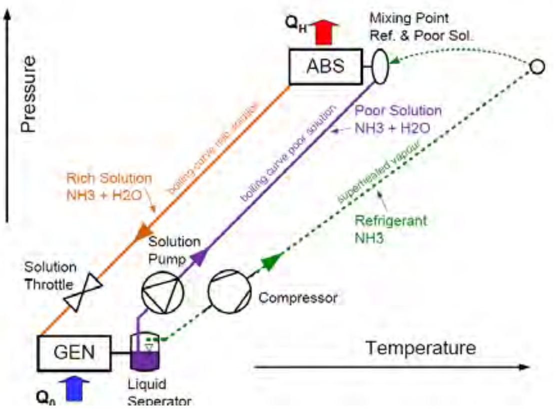


Figure 3-8: Absorption/compression- heat pump cycle in the solution field
[Moser, Zotter, Rieberer, 2011]

As shown in Figure 3-8, the refrigerant vapor from the separator at low pressure level is compressed to high pressure level by an electrically driven compressor. The high-pressure refrigerant vapor gets mixed with liquid poor solution in the Absorber (ABS) and completely absorbed by rejecting the absorption heat to the heat sink at high temperature level.

The liquid rich solution from the ABS gets expanded in a throttle to the generator (GEN) at low pressure level. Refrigerant vapor is desorbed in GEN due to heat supply from the heat source at low temperature level. The vapor is separated from the liquid poor solution in a separator afterwards. The remaining liquid poor solution at low pressure level is pumped into the ABS at high pressure level by an electrically driven solution pump, while the refrigerant vapor is compressed by the compressor.

The absorption/compression heat pump is suitable for high temperature application. Due to the use of a working pair instead of pure refrigerant, the pressure levels of absorption and desorption can be adjusted by a variation of the solution concentrations respectively changing the circulation ratio (ratio of solution mass flow to refrigerant mass flow). An absorption/compression heat pump promises several advantages in comparison to a vapor-compression heat pump:

- A high heat sink outlet temperature is possible at moderate pressure levels compared to a vapor-compression heat pump. For example temperatures above 100 °C at the heat sink can be reached with a high-pressure level below 20 bar for ammonia/water instead of a high-pressure level higher than 62 bar for pure ammonia.
- The temperature glide occurring in the generator and absorber can be varied according to the available and required external temperature glides by changing the circulation ratio. This fact offers higher coefficient of performance due to lower irreversibility in the heat exchangers (“Lorenz”-process),
- The absorption/compression heat pump is suitable for high temperature lifts, which promises a bi-generation of heat and cold.

From a technical point of view the oil-management could be an issue, if oil-lubricated compressors are used, because the working pair and the oil have to be compatible at high temperatures and arrangements for the oil return have to be considered, which are more complex than in vapor-compression heat pumps. The use of a conventional oil-lubricated compressor is limited due to high discharge temperatures and the thermal stability of the oil. At very high pressure ratios multi-stage compression has to be taken into account for higher coefficients of performance. Finally, a higher complexity of the control system results from a more complex system design.

Within the work for Annex 35 different simulation models for the “hybrid” absorption/compression-heat pump cycle have been set up for the working pair ammonia/water at the Institute of Thermal Engineering. As an example for the detailed investigation some results are shown in Figure 3-9. The coefficient of performance (COP_H, see Equation 1) and the high pressure level (p_{high}) versus the circulation ratio (f, see Equation 2) of a single stage Osenbrück-Cycle (with a solution heat exchanger, see Figure 3-10) are shown in Figure 3-9. As shown, the high-pressure level can be adjusted by the variation of the circulation ratio, which has also an influence on the COP.

$$COP_H = Q_{ABS}/(P_{Compressor} + P_{Solution\ Pump}) \qquad \text{Equation 1}$$

$$f = m_{Solution\ Pump}/\ m_{Compressor} \qquad \text{Equation 2}$$

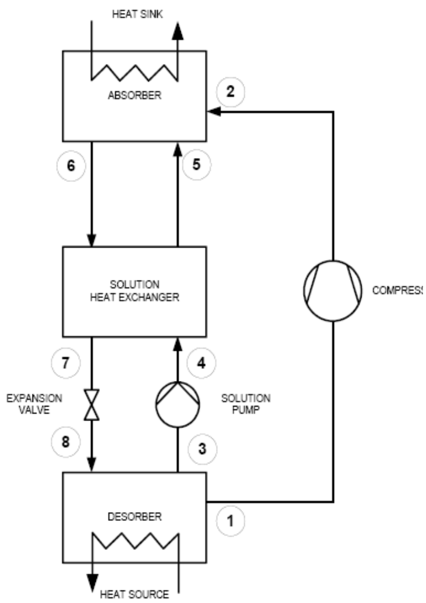


Figure 3-10: “Hybrid” heat pump cycle (Osenbrück-Cycle see

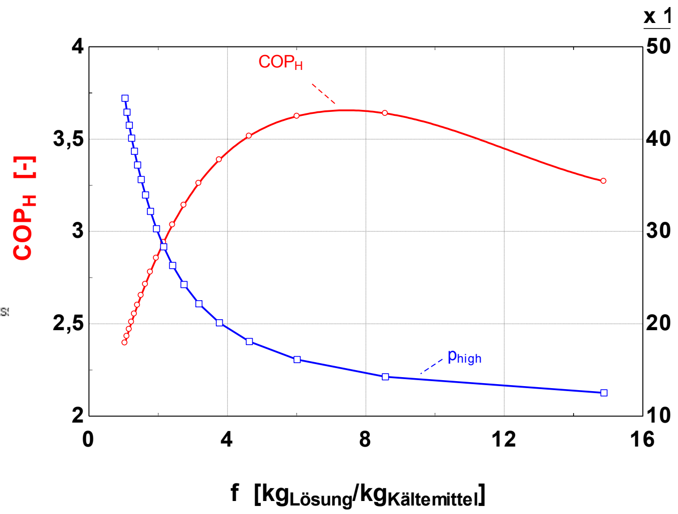


Figure 3-9: Simulation results - COP_H & p_{high} vs. f for a “hybrid” NH_3/H_2O heat pump (Osenbrück-Cycle, Figure 3-10) @ plow = 2 bar, $t_{source,ex}$ = 40°C, $t_{sink,ex}$ = 85°C

Nordtvedt, 2005) [Vehovec et al., 2013]

Recently, there are increasing research activities regarding the absorption/compression-heat pumps which are commonly known as “hybrid” heat pump system (HHP). Nevertheless there are only few suppliers for commercial available HHP. For example “Hybrid Energy AS” from Norway offers customized ammonia/water-absorption/compression-heat pumps with heating capacities of several hundred kW, shown in Figure 3-11.

Figure 3-11: Pictures of two “hybrid” heat pumps by “Hybrid Energy AS”left: 300 kW, right: 650 kW heating capacity [Nordtvedt, 2009]

Within the Austrian research project “HyPump” – financially supported by the Austrian Funding Agency “FFG” (Project-Nr. 834614) – the project partners IWT (TU Graz), AIT and Frigopol (Austrian compressor and heat pump manufacturer) develop a “hybrid” heat pump for small scale application (ca. 25 kW) consisting only standardized components, for minimizing the cost. Because the major aim of this project is to develop a high-temperature heat pump for industrial waste heat recovery, which demands low payback times to achieve a high market potential.

Within the “HyPump”-project different ammonia-based working pairs are investigated and compared to each other. Ammonia/lithium nitrate ($NH_3 - LiNO_3$) has been choosen, because of the expected pure ammonia gaseous phase in order to overcome problems with the oil-lubricated compressor and the water content in the refrigerant vapor [Hannl & Rieberer, 2014].

Further to build up a prototype, different system configurations are investigated, using e.g. variation of the working pairs and design boundaries, as well as solutions for system design problems are analyzed in detail. The actual design of the test facility is shown in Figure 3-12. [Hannl & Rieberer, 2014]

Figure 3-12: Picture of the absorption-/compression heat pump prototype @ IWT [Hannl & Rieberer, 2014]

3.2.2 Absorption heat pumping systems

Absorption heat pumping systems (AHP) are often used to utilize the waste heat for industrial refrigeration purposes as well as to upgrade the temperature level of waste heat. Besides of the process itself and its components, the choice of the working mixture plays an important role in regard to efficiency and costs of an AHP-plant.

AHP are so called thermally driven heat pumps. So AHP can be driven by waste heat at temperature levels higher than 60 °C, as e.g. from oven, air compressors etc. for cooling application on one hand and on the other hand AHP, driven for example by steam with 160°C, can upgrade the temperature level of waste heat e.g. from 60 to 90°C, as e.g. to use the flue gas condensation heat for district heating purposes.

Various working mixtures have been investigated, however, just two (NH_3/H_2O and $H_2O/LiBr$) are commercially available. As industrial refrigeration application mostly requires evaporating temperatures below 0°C, the NH_3/H_2O AHP-process is in the focus for industrial application at the Institute of Thermal Engineering (TU Graz). Figure 3-13 shows a single-stage NH_3/H_2O AHP-process in the pressure/temperature diagram.

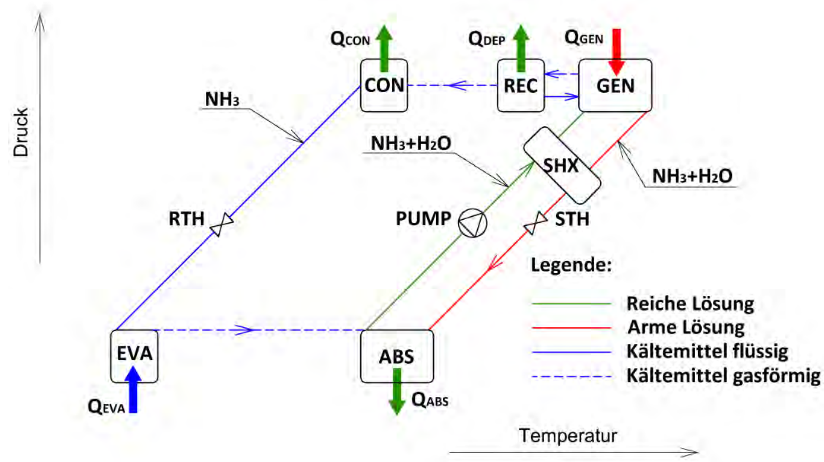


Figure 3-13: One-stage *NH_3/H_2O* AHP-process in the pressure / temperature diagram [Kotenko, 2012]

The *NH_3/H_2O* AHP process (see Figure 3-13) has been analyzed by means of thermodynamic simulation using the software program ASPEN Plus at following conditions (parameters):

- cooling water inlet/outlet temperatures of 20/25°C and 25/30°C
- cold water inlet/outlet temperatures of +2/-1°C.

The calculated values of the COP_C for cooling are shown in dependence on the hot water inlet temperature (influence the temperature of the poor solution) in Figure 3-14. Apparently, the maximum COP_C at low temperature lift (blue line) lies within the generator outlet temperature range from 80-100 °C and is about 0.69. At high temperature lift (green line) the maximum COP_C is about 0.62 and the heat at higher generator temperatures (95-100°C) is necessary. With a decrease in the waste heat temperature (down to 80-85°C), the use of the *NH_3/H_2O* AHP process is efficient only at low temperature lifts.

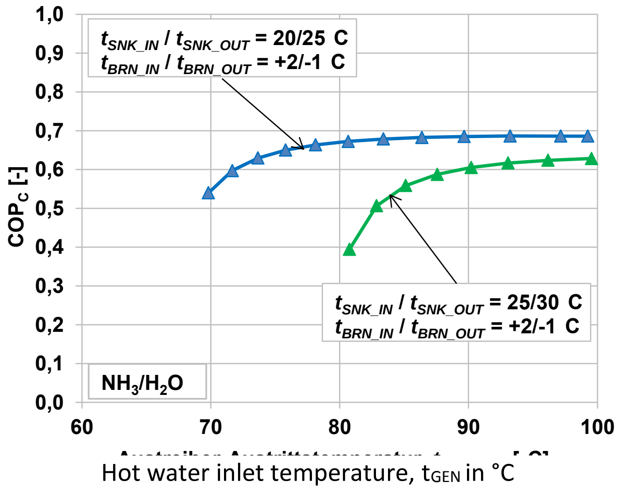


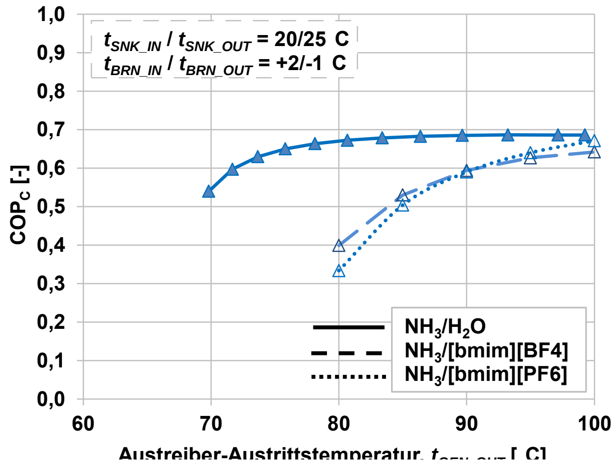
Figure 3-14: Calculated COP_C for the *NH_3/H_2O* AHP process at cooling water inlet/outlet temperatures of 20/25 °C and 25/30 °C and brine inlet/outlet temperatures of +2/-1 °C [Rieberer et al., 2012]

Ammonia/IL AHP process

In the last years, in order to overcome some drawbacks of the *NH_3/H_2O* working mixture (i.e. need of rectification) the use of ionic liquids (ILs) as absorbents has been suggested. Commonly ILs are described in the literature as substances composed entirely of ions (cations and anions) with melting points below 100 °C.

At the Institute of the Thermal Engineering (TU Graz) the *NH_3/IL* AHP process with two ionic liquids (*[bmim][BF_4]*, *[bmim][PF_6]*) has been analyzed and compared with the above described *NH_3/H_2O* AHP process.

The calculated values of the cooling COP are shown in Figure 3-15. The efficiency of the AHP process with both ILs at investigated generator temperatures is lower than that of the *NH_3/H_2O* AHP process. It can be seen, that there is a big decrease in the COP_C of the process with ILs at low generator temperatures. This occurs due to the low difference between *NH_3*-concentrations in the rich and poor solutions and, therefore, high specific solution flow rate (ratio of the flow rate of the rich solution to the flow rate of the refrigerant).



Hot water inlet temperature, t_{GEN} in °C

Figure 3-15: Comparison of the calculated cooling COP of the AHP processes with the working mixtures of NH_3/H_2O, NH_3/[bmim][BF_4] und NH_3/[bmim][PF_6] depending on the generator outlet temperature [Rieberer et al., 2012]

Generally, it can be concluded, that the investigated *NH_3/IL* AHP processes cannot beat the conventional *NH_3/H_2O* AHP process for the industrial refrigeration application using waste heat but could have a high potential for heating applications, as high

However, AHPs have a high potential for the utilization of waste heat, as e.g. from baking oven, air compressors etc. for industrial refrigeration purposes from an economical and an ecological point of view.

3.2.3 HPs for upgrading flue gas condensation heat

HPs, as well as AHPs and CHPs offer the possibility to use the condensation heat of the flue gas from e.g. power or co-generation plants by upgrading its temperature level, even thou the temperature level of the heat supply system is higher than the dew point temperature of the flue gas.

The aim of the current national project ICON (FFG-No.: 829964, project head: AIT, project partners: BIOS BIOENERGIESYSTEME GmbH, OCHSNER heat pumps GmbH, Scheuch GmbH) is to increase the heat output by flue gas condensation of biomass plants with heat pumping systems. Beside the heat recovery, systems for flue gas condensation in biomass plants are already known as a way for reducing the dust and plume of the exhaust systems, typically for 1 MW_{th} biomass power plants. In practice, the useful temperature level of e.g. districting heating systems are too high for flue gas condensation, as unfortunately the water dew point of the flue gas (50 to 60 °C) is often much lower than the heating return temperature. By integrating a heat pump, flue gas condensation can be made more efficient and available all-season. Therefore, this heat pump application in a biomass plant offers savings of approximately 10 to 15 % of the required fuel and related to that a significant reduction of emissions. Further, also the electrical power for flue gas de-vaporization can be reduced using a heat pump for the flue gas condensation. In conclusion, such a heat pump application in a biomass power plant offers a large ecological and economical potential. Within this Austrian project a heat pump using a direct evaporator and a refrigerant suitable for flue gas condensation is developed and investigated (see Figure 3-16Figure 3-16).

Figure 3-16: Test facility for experimental analysis of flue gas condensation @ AIT [Seichter et al., 2013]

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4 Canada

4.1 Introduction

Canadian industry requires about 48 % of the total country primary energy input. The annual energy used by eight major manufacturing industries, such as pulp and paper, primary metals and oil, accounts for about 1.7 million TJ representing 65 % of the total energy used by all Canadian industries [NEB, 2008]. But, up to 71 % of the energy input is released to the environment via waste heat streams such as stack emissions (combustion gases and hot air), steam, process gases and liquid effluents. The largest heat losses occur in the pulp and paper industry (36.4%) followed by primary metal manufacturing industries (23 %) [Stricker, 2006].

IEA-IETS Annex 13 / IEA-HPP Annex 35 [Annex 35, 2010] defines industrial heat pumps (IHP) as *medium and high thermal power units used for heat recovery and heat upgrading in industrial processes*. It also specifies that … *heat pump in medium … power ranges …can be used not only for heat recovery in industrial processes, but also for heating and air-conditioning of industrial buildings.*

Since industrial heat pumps can significantly reduce fossil fuel consumption and, thus, contribute to global energy conservation and industrial productivity improvement, as well as to reducing greenhouse gas emissions, Canada has initiated a number of R&D studies followed by some *field* demonstration projects. The scope was to indentify appropriate heat pumps applications for meeting future industry and environmental requirements.

Canada's R&D projects have been conducted in a specific national energetic context where prices of primary energies (electricity, natural gas, oil) are relatively low and where industrial companies are investing to improve production efficiency (profitability) rather than reducing their specific energy consumption.

In spite of this particular energetic environment, theoretical and experimental R&D work has been performed in order to improve the heat pump vapour compression cycles, particularly by using ejectors [Scott].

Moreover, because industrial waste heat in liquid form available at low-temperatures represents about 25 % of the total energy used by Canadian manufacturing industry, a number of R&D work has focused on high-temperature heat pumps able to recover heat at relatively low temperatures, generally between -5°C and 35 °C, and produce hot water at temperatures up to 85-90 °C [Minea, 2010]. In this area, the Canadian R&D projects have focused on using natural refrigerants such as carbon dioxide and ammonia, and more or less known thermodynamic cycles, as well as on developing national expertise and improving public and industry awareness.

4.2 Historical background

In the past, the IEA HPP Annex 9 project (High Temperature Industrial Heat Pumps - 1990) presented a status report on high-temperature industrial heat pumps, as well as a detailed description of R&D efforts going on at the time [Annex 9, 1990].

Later, the IEA HPP Annex 21 (Global Environmental Benefits of Industrial Heat Pumps - 1996) provided an overview of potential industrial heat pump applications [Annex 21, 1995], and identified the lack of operator and engineer experience as the main market barrier for industrial heat pumps. Other reasons that have contributed to a low level of industrial heat pump utilization were the relatively low cost of primary energies and a lack of knowledge on the potential benefits.

Prior to 1995, low-temperature industrial heat pumps were developed and implemented in Canada, especially in lumber drying and evaporation/distillation processes, and also in the food industry, including dairies, poultry, sugar refining, breweries, liquor production and fish processing [Annex 21, 1995].

Toward the end of 1993, 17 % of 14 chosen processes involving more than 1,900 individual plants were using industrial heat pumps, more than 90 % of which were in lumber drying. At the end of 2010, in 339 plants surveyed in Québec (Eastern Canada), Ontario and Manitoba (Central Canada) and British Columbia (Western Canada), 31 % of existing industrial heat pumps (26) were used for drying, 27 % for waste heat recovery and 8 % for evaporation processes with cooling capacities varying between 14 and 1,050 kW [Minea, 2010].

Today, in spite of their well known potential benefits (e.g. reduced energy consumption for heating, increased capacity of existing processes, and improved product quality and plant environmental performance), the number of industrial heat pumps (IHPs) installed in Canada is still relatively low compared to the number of existing technically and economically viable opportunities. Higher capital costs and low energy prices, as well as a lack of knowledge on the potential benefits and/or experience with industrial heat pump technology may explain this situation.

4.3 Canada's R&D projects

According to the definition of IHPs set forth in the Annex 35/13 legal text [Annex 35, 2010], over the last decade, Canada's R&D projects have focused on recovering low-grade waste heat from relatively small- to medium-scale industrial manufacturing facilities in order to supply heat for building domestic hot water consumption and/or industrial heating purposes. The objective was to properly design, integrate and operate several types of IHPs in various energy intensive industrial processes able to provide sufficient amounts of waste heat at appropriate quality levels, flow rates and temperatures.

During the last few years, two Canadian public research institutions, i.e. CANMET Energy Technology Centre (CETC) - Varennes [Scott] and Hydro-Québec Research Institute - Laboratoire des technologies de l'énergie (LTE) [Minea, 2010] have conducted a number of R&D projects on industrial heat pumps. All these projects were intended to respond to future requirements, such as a reduction of the energetic intensity of small- and medium-sized industrial processes and of environmental thermal pollution.

The LTE laboratory has worked on technologies aimed at extending the conventional limits of heat source and heat sink temperatures, respectively. The scope was to recover waste heat at temperatures as low as -5 °C, especially from liquid effluents, and supply heat at relatively high temperatures (i.e. up to 85 °C) (Figure 4.1). These technologies have been theoretically and experimentally studied because of their simplicity, which allows for faster industrial implementation, as well as their ability to efficiently contribute to the global reduction of energy costs and greenhouse gas emissions [Minea, 2011a; Minea, 2013]. Applications in small- to medium-sized industries, as well in large institutional buildings, such as hospitals, have been targeted because simultaneous heating and cooling processes are required in these settings. The scope was to adapt and/or improve a number of heat pump cycles for industrial heat recovery, demonstrate their energetic and environmental benefits, and prepare the industry for future demonstration and/or application projects.

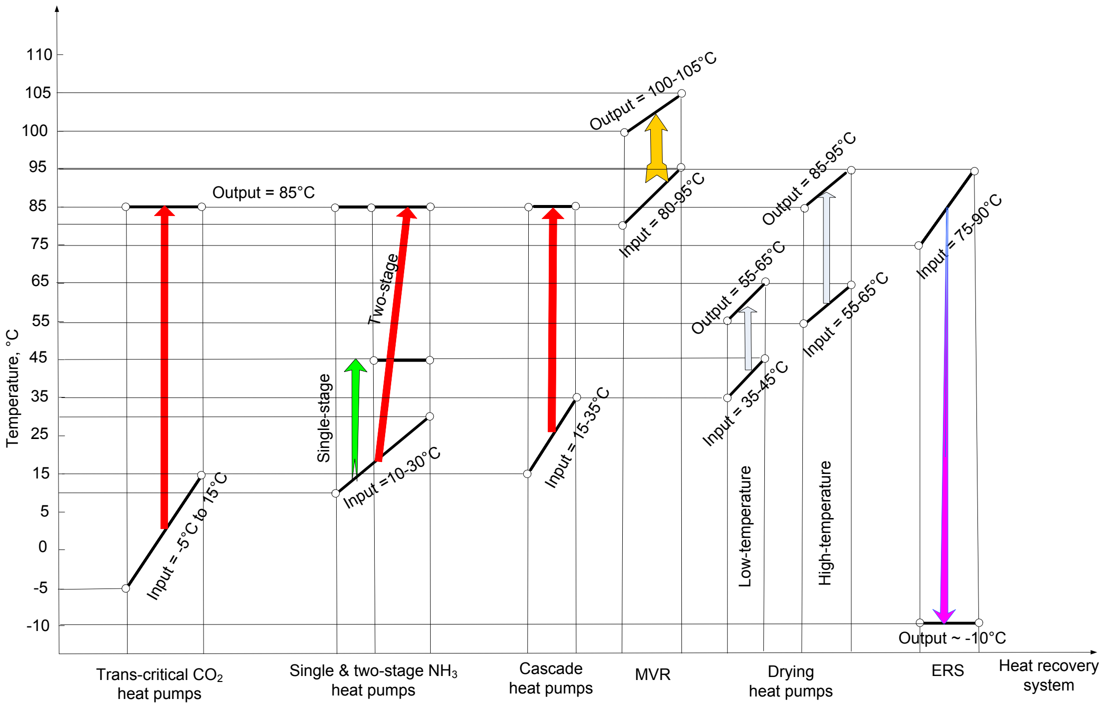


Figure 4-1: Industrial heat recovery systems studied at the LTE laboratory [Minea, 2011a; Minea, 2013]. ERS: ejector refrigeration system; Input: inlet temperature of waste heat carrier; MVR: mechanical vapour recompression; Output: output temperature of heat sink thermal carrier

On the other hand, CANMET's research laboratory focused its R&D efforts on improving the design and energy performance of ejector cooling and heat pump-ejector assisted systems [Scott]. As previously noted, primary energy prices (e.g., electricity, natural gas, oil) in Canada are today still relatively low compared with those of other industrialized countries. This reality hasn't encouraged small- and medium-sized industries to invest in heat recovery technologies such as heat pumps, even though the potential is enormous. As a consequence, Canada's R&D projects have rather focused on future energetic and climate crises by proposing efficient and reliable technical solutions to use the enormous quantities of low-grade industrial waste heat available.

4.3.1 Thermally-driven ejector heat pumps

The use of ejectors as vapor compression devices in thermally driven heat pump systems has received increased attention over the past two decades [Scott]. Unlike mechanical vapour compression heat pumps, such systems are driven by heat instead of electricity.

Ejectors are simple devices, generally used to compress a vapour stream and produce vacuum simultaneously. They have no moving parts, are relatively easy to manufacture, represent relatively inexpensive alternatives to conventional mechanical vapour compressors, and have low maintenance costs. These features can give ejector heat pumps an advantage over other thermally driven systems with comparable COPs (e.g. absorption, adsorption). However, the ejectors require primary motive steam at a relatively high pressure, mostly 7-15 bars, and their noise level can be rather high.

In traditional industrial ejector applications, water steam is used as a moving fluid to generate vacuum and cooling effects [Ashrae, 1969]. To improve the efficiency of the simple ejector cycle, more complex cycles have been investigated [Yu, 2006], as well as the integration of ejectors in vapour compression and absorption systems. Significant efforts have also been devoted to the development of solar driven ejector refrigeration systems [Pridasawas, 2008].

More recently, new research work has shown the benefits of using other moving fluids to provide more favorable operating conditions and increase system efficiency. Several HFCs (e.g. R-245fa, R-141b, R-134a and R-142b) as well as natural refrigerants (e.g. butane, propane and CO_2) [Elbel, 2011] have been considered as alternative working fluids.

A typical ejector has one inlet to admit the motive (primary) fluid (flow) and another one to admit the gas/vapour mixture to be discharged from the evaporator (Figure 4.2a) [Scott]. At the nozzle exit area, the primary stream flows at supersonic speeds at low pressure and temperature levels. This induces the secondary flow from the evaporator to pass through a converging section, resulting in the secondary stream attaining sonic flow conditions. In the constant area section (b), the supersonic primary stream and the secondary stream mix. Friction, mixing losses and shock formation in this mixing section cause the streams to be compressed and decelerate to subsonic velocities. Further compression occurs in the diffuser, after which the mixed stream flows to the condenser (c) [Ouzzane, 2003; Scott, 2008].

Such single- or multiple-stage ejector systems are designed to convert the pressure energy of the motive fluid to velocity energy in order to carry the suction fluid, and then to recompress the mixed fluid by converting velocity energy back into pressure energy. A properly designed nozzle will economically make use of high pressure fluids to compress them from a low pressure area to a higher pressure one.

Typically, ejector efficiency involves comparing energy output to energy input. Since ejectors approximate a theoretically isentropic process, their overall efficiency is expressed as a function of entrainment efficiency. The direct entrainment of a low velocity suction fluid by a motive fluid, results in an unavoidable loss of kinetic energy owing to the impact and turbulence originally present in the motive fluid. This fraction, which is successfully transmitted to the mixture through a momentum exchange, is called the "entrainment efficiency ratio" (ω), defined as the ratio of the secondary mass flow rate to the primary mass flow rate (Figure 4.2b). For any given generator and evaporator temperatures, this parameter remains constant up to a critical exit pressure (p_c^*). Above this value, the secondary stream no longer reaches supersonic speeds, and ω decreases rapidly. When the ejector is used as a compressor in heat pump systems, the stream leaving it passes through a condenser (Figure 4.3). After the condenser, the working fluid is split in two separate flows: one returns to the evaporator while the remainder is pumped to a vapour generator in order to generate the primary motive flow.

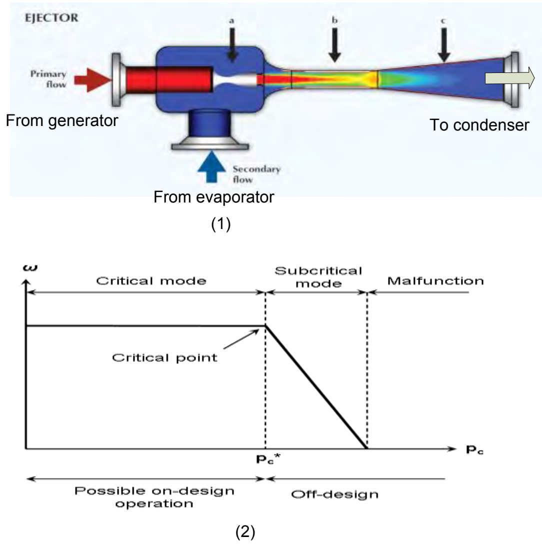


Figure 4-2: (1) Schematic representation of a single-phase, single-stage ejector; (2) typical performance curve of an ejector; p_c*- critical condenser pressure; ω- entrainment ratio [Scott]

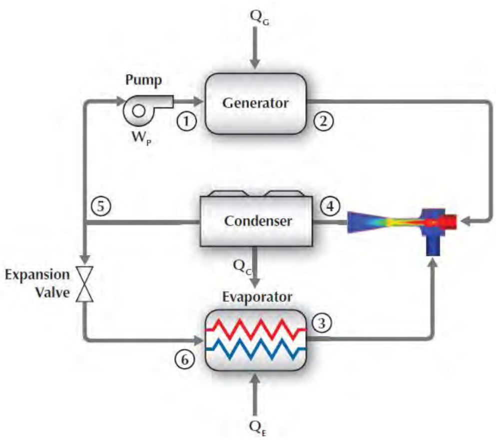


Figure 4-3: Schematic illustration of a simple ejector heat pump [Scott]

Prior to conducting experimental R&D work, the CanmetENERGY laboratory developed simulation (numerical) models of single-phase, supersonic ejectors [Ouzzane, 2003]. One-dimensional ejector models, providing a full description of the flow inside supersonic ejectors, have been developed using Computational Fluid Dynamics (CFD) methods and software [Scott, 2008].

Using the 1-D models thus developed, an ejector has been designed and built for an experimental heat pump prototype to provide cooling by using industrial waste heat and HFC-134a as a refrigerant [Scott, 2011].

The COP of thermally driven heat pumps is defined as the ratio of the useful energy produced (cooling, heating, or both) to the total energy input (thermal plus electric). The "entrainment ratio" at the critical point is representative of the highest COP attainable by the ejector heat pump, and higher entrainment ratios result in higher COPs. COPs above 0.35 have been predicted at condenser, evaporator and generator saturated temperatures of 36 °C, 15 °C and 80 °C respectively, without accounting for the motive steam boiler efficiency. The ejector heat pump COP at low temperature lifts is, therefore, of the same magnitude as for the absorption heat pump, but at much lower capital costs.

The laboratory test bench (Figure 4.4) produced up to 9 kW of cooling from the evaporator while using up to 30 kW of electricity to generate vapour as the primary moving stream. Preliminary results showed that 5 kW of cooling can be provided with a thermal COP of approximately 0.4 at condenser, evaporator and generator temperatures of 25 °C, 10 °C and 90 °C respectively [Scott].

Figure 4-4: View of CanmetENERGY's laboratory ejector test bench [Scott]

A second R&D programme conducted at CanmetENERGY investigates two-phase flow ejectors. A first experimental test bench integrates a supersonic ejector into an existing heat pump system in order to recover the expansion valve work, otherwise lost in conventional vapour compression heat pump systems. Other test benches will be built in order to better understand the operation of two-phase flow ejectors [Aidoun, 2011].

Canmet Energy's research team estimates that thermally driven heat pumps provide interesting alternatives to conventional mechanical vapour compression systems for industrial applications. Given their high reliability and their ability to be powered by industrial waste heat, ejector-based heat recovery systems offer a significant potential for future applications in any field where industrial heat pumps are used [Scott].

4.3.2 CO_2 ejector refrigeration system

Conventional cooling systems use electrically-driven compressors. However, in many countries, during the hottest periods of the year, cooling and air-conditioning systems cause a serious electrical peak load problem. On the other hand, there is relatively abundant energy, such as various types of wasted heat, solar, geothermal and biomass energy.

The thermally driven ejector technology, also known as jet pump refrigeration or ejector refrigeration, has been used in cooling applications for many years. In their present state of development these systems have a much lower COP than vapour compression systems, but offer advantages in terms of simplicity and no moving parts, and their ability to refrigerate using industrial waste heat (or solar thermal energy) as a heat source at temperatures above 35 °C and up to 75 °C.

Since 1910, ejector refrigeration cycles have been used in air conditioning applications until the development of CFC refrigerants in the 1930's. At that time, the mechanical vapour compression cycle, much more efficient than thermally driven cycles, became predominant. However, R&D work on ejector technologies continued worldwide particularly in the chemical and process industries bringing cooling capacities up to 60 MW [Eames, 1995; Shrerif, 1998; Chunnanond, 2004; Alexis, 2005].

Other applications can be found in the food processing industry where waste heat is available and ejector refrigeration systems can be used for process cooling and transport refrigeration, as well as in tri-generation power systems where they can be used in conjunction with combined heat and power systems to provide cooling.

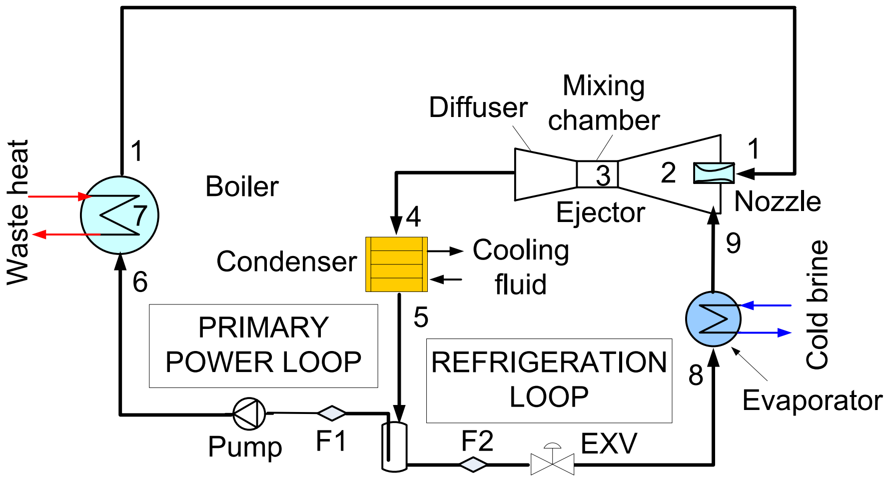
The main barriers to the widespread use of the ejector refrigeration technology include its lower COPs (± 0.3) compared to vapour compression systems and other thermally driven technologies, and the unavailability of industrial processes facilitating their application. On the other hand, the main drivers encouraging the uptake of the technology, especially in the food processing or tri-generation systems industries, are the successful demonstration of the technology benefits, the continuous increase in primary energy prices and better thermal integration in the manufacturing industry.

To increase the attractiveness of ejector refrigeration systems, R&D is still required to increase efficiency, develop alternative ejector types, such as roto-dynamic ejectors that have the potential to boost efficiency, develop ejectors that can operate with natural refrigerants other than water, such as CO_2 and hydrocarbons, to extend the range of applications below 0 °C, to enhance cycle optimisation and the integration of ejectors with conventional vapour compression and absorption systems.

A feasibility study on a CO_2 ejector refrigeration system (ERS) aimed at producing cold fluids at temperatures between 0 and approximately -5 °C by using waste heat at inlet temperatures above 35 °C has been designed and experimentally studied in Canada. A small-scale laboratory prototype using CO_2 as a working fluid was built and tested within thermal conditions simulating cold climate weathers [Minea, 2011a; Minea, 2013].

The EPS set-up (Figure 4.5) uses an ejector powered directly by thermal energy to replace the conventional mechanical compressor. The only moving part in the system is the working fluid circulation pump (see also Section 4.3.1).

The laboratory prototype consists of two loops, the power and the refrigeration loops respectively (Figure 4.5a). Within the power loop, low-grade heat is used in a boiler to evaporate a high pressure CO_2 liquid refrigerant (process 6-1) (Figure 4.6). The high pressure vapour generated, known as the primary fluid, flows through the ejector where it accelerates through the nozzle. The pressure reduction that occurs induces vapour from the evaporator, known as the secondary fluid, at state 2. The two fluids mix in the mixing chamber before entering the diffuser section where the flow decelerates and pressure recovery occurs. The mixed fluid then flows to the condenser where it is condensed, rejecting heat to the environment. A portion of the liquid exiting the condenser at state 4 is then pumped to the boiler for the completion of the power cycle. The remaining liquid is expanded through an expansion device and enters the evaporator of the refrigeration loop at state 6, as a mixture of liquid and vapour. The refrigerant evaporates in the evaporator producing a refrigeration effect, and the resulting vapour is then drawn into the ejector at state 9. The refrigerant (secondary fluid) mixes with the primary fluid in the ejector and is compressed in the diffuser section before entering the condenser at state 4. The mixed fluid condenses in the condenser, exits at state 5, and the refrigeration cycle re-starts.



(a)

(b)

Figure 4-5: Experimental set-up of the ejector refrigeration system; (a) schematic diagram; (b) view of the laboratory prototype [Minea, 2011a; Minea, 2013]

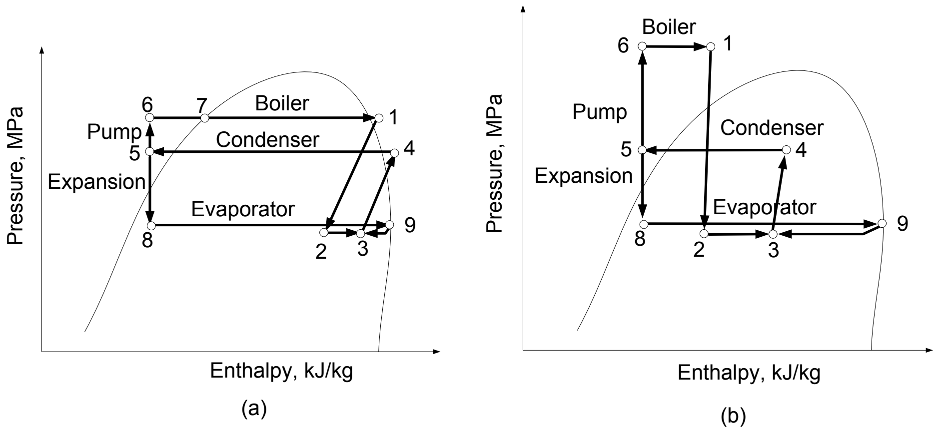


Figure 4-6: Ejector refrigeration thermodynamic cycles; (a) with a relatively low ejector inlet pressure; (b) with a much higher ejector inlet pressure [Minea, 2011a]

Table 4-1 summarizes the prototype's design parameters based on the assumption that low enough cooling fluid inlet temperatures are available in cold climates, resulting in the lowest ejector inlet pressures. This assumption leads to low ejector compression ratios (p_4 / p_3) ranging between 1.6 and 1.7.

Table 4-1: Cycle design for lowest ejector inlet pressures (see Figures 4.5 and 4.6)

State	**Pressure**	**Temperature**	**Enthalpy**	**Flow rate**
-	MPa	°C	kJ/kg	kg/s
1	6.4	25	410	0.145
4	5	15	420	0.195
5	5	15	220	0.195
6	6.4	10	220	0.145
7	6.4	12	220	0.145
8	3	-5	220	0.05
9	3	-5	435	0.05

Based on the cycle thermodynamic design at the lowest ejector inlet pressure, the boiler, evaporator and condenser design thermal capacities were 27, 11.4 and 40.7 kW respectively, with an average calculation error of 5.6% (Figure 4.6a). In this case, the system COP, defined as the ratio of the refrigeration effect to the heat input to the boiler, was 0.4, still relatively low compared to the COPs of conventional vapour compression systems, even when neglecting the energy consumption of the CO_2 liquid pump.

A 313 kW (cooling capacity) industrial-scale CO_2 ejector refrigeration machine with waste heat entering the system at 35 °C and cooling water at 20 °C has been simulated with the EES software. Using such inlet operating parameters, cold brine could be provided at 5 °C with a COP of approximately 78.4 (Figure 4.7). However, optimization work is under way by considering higher waste heat input temperatures and lower cooling fluid inlet temperatures in order to achieve much lower refrigerating temperature levels.

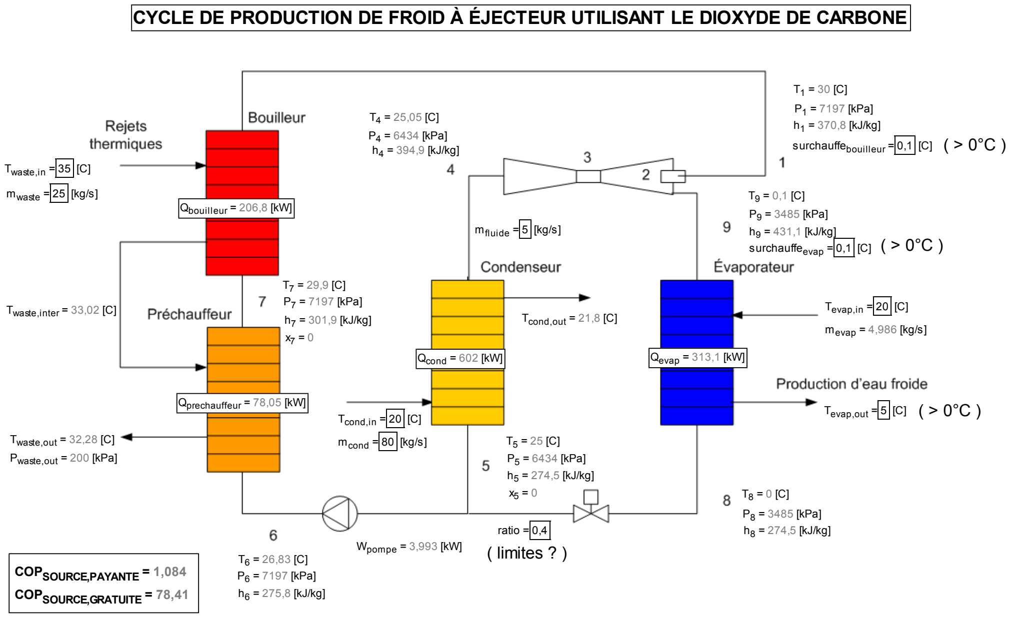


Figure 4-7: Simulation of an industrial-scale CO2 ejection refrigeration system [Richard, 2011]

4.3.3 High-temperature heat pumps

As part of the Annex 35-13 project [Annex 35, 2010], much R&D work has been done to develop/adapt and promote high-temperature heat pump applications in the Canadian small- and medium-sized manufacturing industry [8]. This section succinctly describes a number of heat recovery technologies, including high-temperature heat pumps (i.e. single- and double-stage and cascade) and mechanical vapour recompression systems, using natural (CO_2, NH_3) and low-emission (HFC-236fa, HFC-245fa, HFC-134a, HFO-1234yf) artificial refrigerants.

The principle of each technology is summarized and some of the simulation and experimental results achieved, such as operating parameters and energy performance, are provided. The data presented aim at supporting and encouraging the industry to use energy resources more efficiently by accelerating the implementation of feasible and efficient heat recovery technologies.

4.3.3.1 CO_2 trans-critical heat pumps

Industrial waste heat effluents and/or process fluids in a liquid form at temperatures between -5 °C and 25 °C are valuable heat sources for CO_2 trans-critical heat pumps in order to produce hot water (or air) at temperatures as high as 80-85 °C [Minea, 2013; Minea, 2012a].

A laboratory-scale, double-stage heat recovery system (Figure 4.8), including a pre-heating heat exchanger (as the first stage) and a 7 kW (shaft power input) CO_2 water-to-water trans-critical heat pump (as the heat recovery second stage), has been designed, built and tested [Minea, 2011; Minea, 2013; Minea, 2012a]. The pre-heating heat exchanger is required when the temperature of the industrial waste effluent (heat source) is higher than the temperature of the cold water to be heated. In this case, it recovers heat from the hotter waste heat (heat source) fluid and pre-heats the colder water (heat sink) before it enters the CO_2 heat pump. However, the pre-heating heat exchanger must be bypassed when the temperature of the waste heat source at the inlet isn't high enough to pre-heat the cold water. Consequently, the pre-heating heat exchanger is equipped with three-way motorized by-pass valves.

The heat pump refrigerating circuit contains a semi-hermetic, constant-speed CO_2 compressor, three plate heat exchangers (evaporator, gas cooler and internal heat exchanger), a low-pressure side receiver and an electronic expansion valve. A 48 kW electrical boiler supplies hot water to the evaporator simulating the industrial waste heat source. Because the scope of this study was to investigate the CO_2 trans-critical heat pump behaviour at the lowest heat source and heat sink inlet temperatures, the pre-heating heat exchanger was by-passed during all laboratory tests. After passing through or by-passing the pre-heating heat exchanger, the cold water is supplied to the once-through gas cooler at a constant flow rate, temperature and pressure. Hot water is produced at temperatures that vary with the heat source inlet temperature and flow rate. The gas cooler is connected to the hot water storage tanks by means of a closed water loop. A variable speed pump circulates the water from the bottom of the storage tanks through the gas cooler and to the top of the storage tank. In industrial field applications, energy efficiency is best under perfect hot water stratification inside the storage tanks. In a laboratory setting, as well as in the field, the hot water storage tank assembly can be easily by-passed, if required.

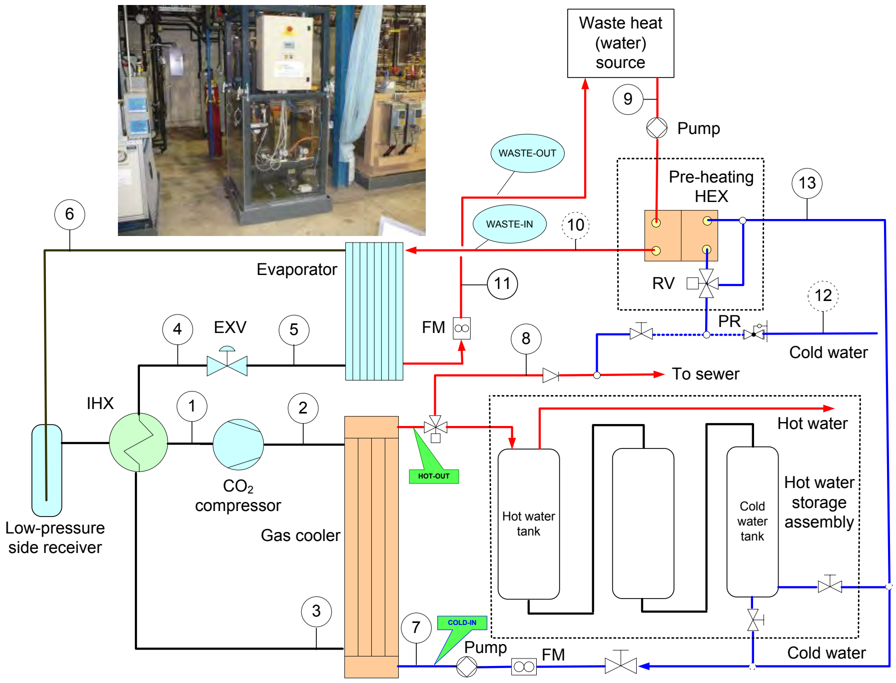


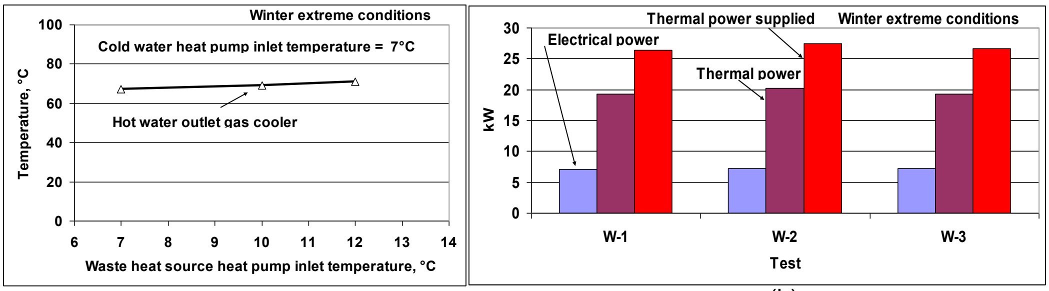
Figure 4-8: Experimental setup of the laboratory-scale, two-stage heat recovery system with a CO2 trans-critical heat pump as a second stage. EXV: expansion valve; FM: flow meter; HEX: heat exchanger; IHE: heat exchanger; PR: pressure regulator; RV: 3-way regulating valve; 1 to 13: measurement points (temperatures, pressures, flow rates) [Minea, 2011a; Minea, 2012a]

Several tests have been done under the following experimental conditions: (i) both waste heat source and heat sink fluids enter the heat pump at constant flow rates, i.e. 1 kg/s for the waste heat source water and 0.11 kg/s for the cold water; (ii) the waste heat source fluid enters the heat pump at 7 °C, 10 °C and 12 °C in the winter, and at 7 °C and 15 °C in the summer; such thermal conditions, specific for winter and summer cold weathers respectively, are considered here as “extreme”; (iii) these heat source inlet temperatures allowed for the cold water to by-pass the preheating heat exchanger; (iv) the hot water storage tank assembly is also by-passed in order to avoid water stratification issues; (v) the hot water produced is rejected to the city sewer at temperatures below 40 °C after being mixed with fresh cold water.

For higher waste heat source temperatures at the heat recovery system inlet (i.e., above 15 °C in the winter and 25 °C in the summer), the pre-heating heat exchanger can’t be by-passed. It must operate in order to preheat the cold water prior to entering the heat pump evaporator. For example, if the temperature of the waste heat fluid reaches its maximum value (45 °C) at the inlet of the two-stage heat recovery system, it will be cooled down to 38 °C prior to entering the heat pump evaporator. At the same time, the temperature of the cold water will be increased, for example, from a minimum of 7 °C (in the winter) and 17 °C (in the summer) up to 38 °C before entering the heat pump gas cooler [Minea, 2012a]. Under such operating conditions, as a first stage heat recovery device, the pre-heating heat exchanger will improve the overall energy efficiency of the entire heat recovery system.

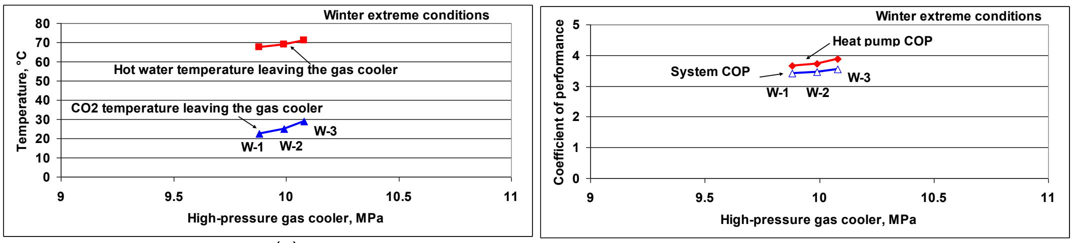
Temperatures of hot water leaving the gas cooler under “extreme” winter operating conditions are presented in Figure 4.9a. It can be seen that with cold water entering the heat pump at 7 °C, process hot water has been supplied at average temperatures of 67 °C, 69 °C and 71 °C by using waste heat water entering the heat pump evaporator at 7 °C, 10 °C and 12 °C respectively. The hot water temperatures at the gas cooler outlet increased with the waste heat source inlet temperatures as well as with the corresponding high-pressure gas cooler (compressor discharge) pressures.

The *heat pump* coefficient of performance (COP_{hp}) can be defined as the gas cooler thermal power supplied ($\dot{m}_{hot\,water}\bar{c}_p\,\Delta T_{gc}$, where $\dot{m}_{hot\,water}$ is the mass flow rate, $\bar{c}_p$ - the average specific heat of the heated water, and ΔT_{gc} - the hot water temperature increase within the heat pump gas cooler) divided by the compressor electrical power input. The *system* heating coefficient of performance (COP_{syst}) can be similarly defined as the gas cooler thermal power supplied by the gas cooler divided by the electrical input power of the compressor and waste water circulating pump. Figure 4.10b presents the heat pump (compressor only) and system (compressor plus the waste heat source circulating pump) coefficients of performance for the same “extreme” winter operating conditions. At constant cold water inlet temperatures, both *heat pump* and *system* heating coefficients of performance increase with the waste heat source inlet temperatures. During the winter, with cold water entering the heat pump at 7 °C and waste heat fluid entering the heat pump at 7 °C (test W-1), 10 °C (test W-2) and 12 °C (test W-3) respectively, the thermal power recovered was about 74 % of the total thermal power supplied during each of these tests (Figure 4.9b).



(a) (b)

Figure 4-9: Heat pump “extreme” winter operating conditions; (a) hot water temperatures at the gas cooler outlet; (b) overall energy balance [Minea, 2013; Minea, 2012a]



(a) (b)

Figure 4-10: Heat pump performance in extreme winter operating conditions; (a) CO2 and hot water temperatures at the gas cooler outlet; (b) heat pump and system coefficients of performance [Minea, 2013; Minea, 2012a]

Temperatures of both CO_2 and hot water leaving the gas cooler in the *extreme* summer operating conditions (tests S-1 and S-2) are presented in Figure 4.11a. With cold water entering the heat pump at 17 °C, hot water is supplied at 72 °C and 77 °C by using waste heat water entering the heat pump evaporator at 7 °C and 15 °C respectively. Both CO_2 vapour and hot water gas cooler outlet temperatures increase with the high-pressure gas cooler (compressor discharge) pressure. Figure 4.11b presents the heat pump (compressor only) and system (compressor plus the waste heat source circulating pump) coefficients of performance for extreme summer operating conditions. Both COPs were over 3, but *system* heating COPs were about 8.2 % lower than *heat pump* COPs. Figure 4.12a shows the hot water temperatures at the gas cooler outlet in “extreme” summer operating conditions. Under these “extreme” conditions, the thermal power recovered represented about 70 % of the total thermal power supplied by the heat pump’s gas cooler (Figure 4.12b). Over the experimental range of waste heat source and cold water inlet temperatures, the maximum thermal effectiveness of the internal heat exchanger was achieved in the winter (41.4 %) and the lowest, in the “extreme” summer operating conditions (17.5 %). This relatively low thermal effectiveness suggests that further design improvements and proper selection of the internal heat exchanger are required to enhance the overall heating performance of the system. The majority of experimental tests have been validated by a simulation model based on the EES software. An example of the results obtained is given in Figure 4.13.

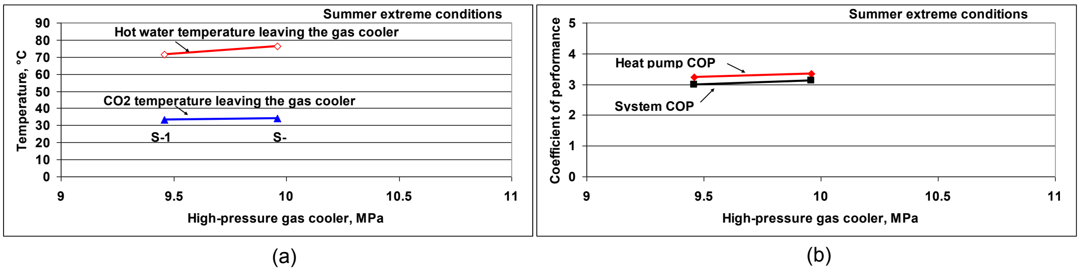


Figure 4-11: Heat pump performance in extreme summer operating conditions; (a) CO_2 and hot water temperatures at the gas cooler outlet; (b) heat pump and system coefficients of performance (COP) [Minea, 2013; Minea, 2012a]

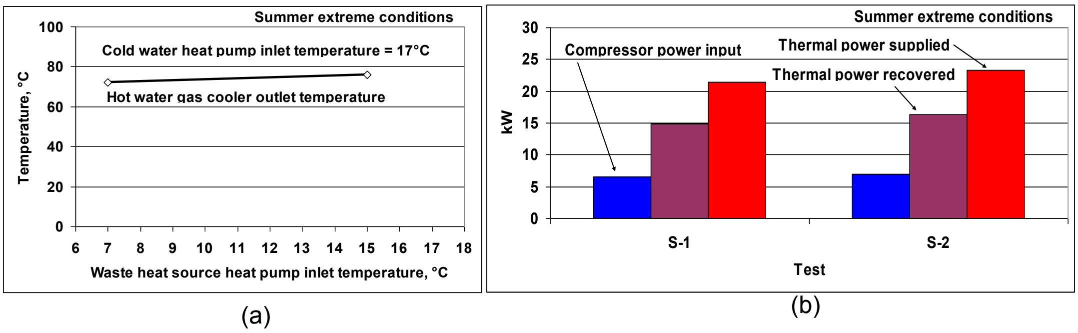


Figure 4-12: Heat pump extreme summer operating conditions; (a) hot water temperatures at the gas cooler outlet; (b) overall energy balance [Minea, 2013; Minea, 2012a]

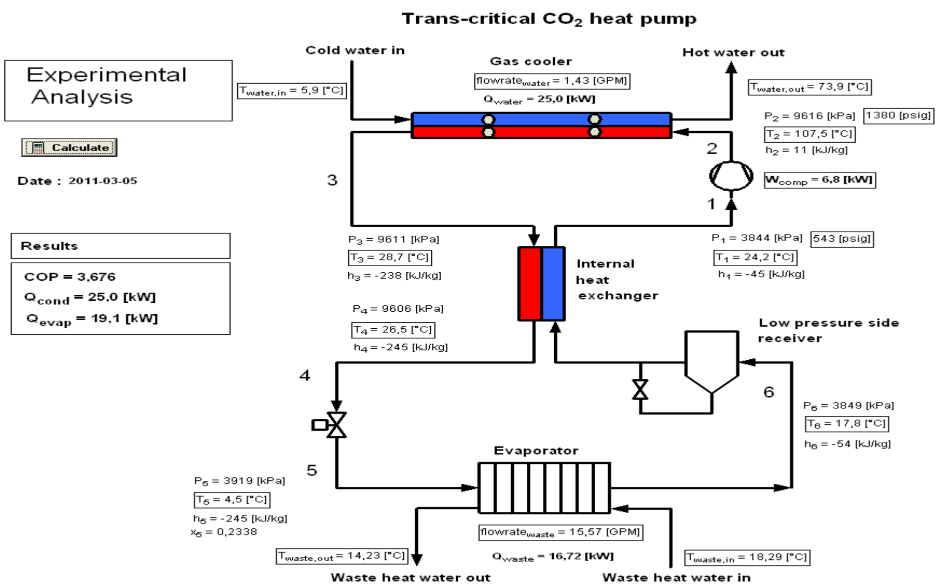


Figure 4-13: Example of trans-critical CO_2 heat pump simulation with the EES software [Richard, 2011]

Figure 4.14 schematically represents a CO_2 super-critical industrial heat pump recently implemented in a Canadian dairy plant [Minea, 2013; Marchand, 2011]. Hot water is provided at temperatures varying between 60 and 75 °C by recovering process waste heat. This IHP has been fully instrumented and an intensive monitoring project is under way. The first results are expected to be provided toward the end of 2013.

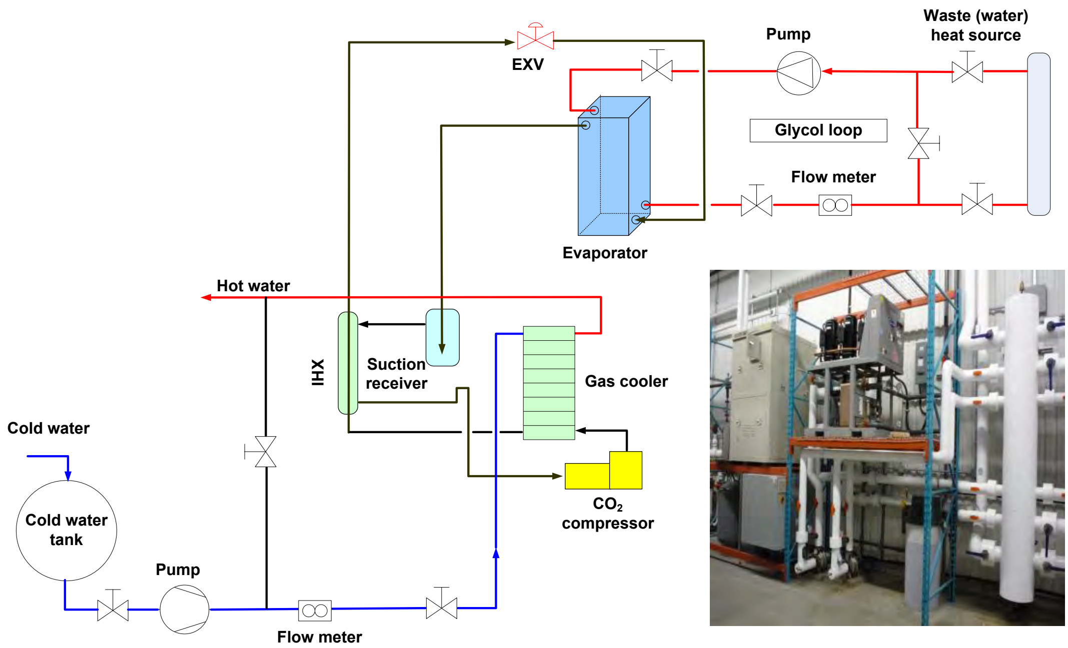


Figure 4-14: Schematic diagram of the 100 kWth CO2 trans-critical industrial heat pump implemented in a Canadian dairy plant [Minea, 2013; Marchand, 2011]

4.3.3.2 *Ammonia heat pumps*

Over the last few years, research has focused on the use of natural refrigerants to replace the synthetic ones. Among other candidates for replacement, ammonia (NH_3, R-717) is an energy efficient and cheap refrigerant with zero Ozone Depleting (ODP) and Global Warming (GWP) Potentials. In Canada, low-grade waste heat rejections at temperatures between 15 °C and 45 °C represent about 25 % of the total primary energy input of many manufacturing industries. Simultaneously, many industrial processes and domestic consumers need hot water at temperatures varying between 60 °C and 85 °C. Ammonia single- and double-stage industrial heat pumps could accomplish this task. But, even though ammonia is an appropriate refrigerant for this waste heat recovery temperature range, and in spite of its well known qualities, ammonia is still non-accepted as a natural working fluid in industrial heat pumps, especially because of its toxicity and inflammability at high concentrations in ambient air.

A single-stage 7.5 kW (compressor nominal power input) water-to-water ammonia heat pump has been designed, built and laboratory tested. The unit was installed in a mechanical room equipped with ammonia detection and discharge systems in accordance with the Canadian Refrigeration Code (Figure 4.15) [Minea, 2011a; Minea, 2013]. A 48 kW electrical boiler supplied hot water simulating the waste heat (heat source) fed into the heat pump evaporator. The condenser heat was discharged outside by an air-cooled liquid cooler.

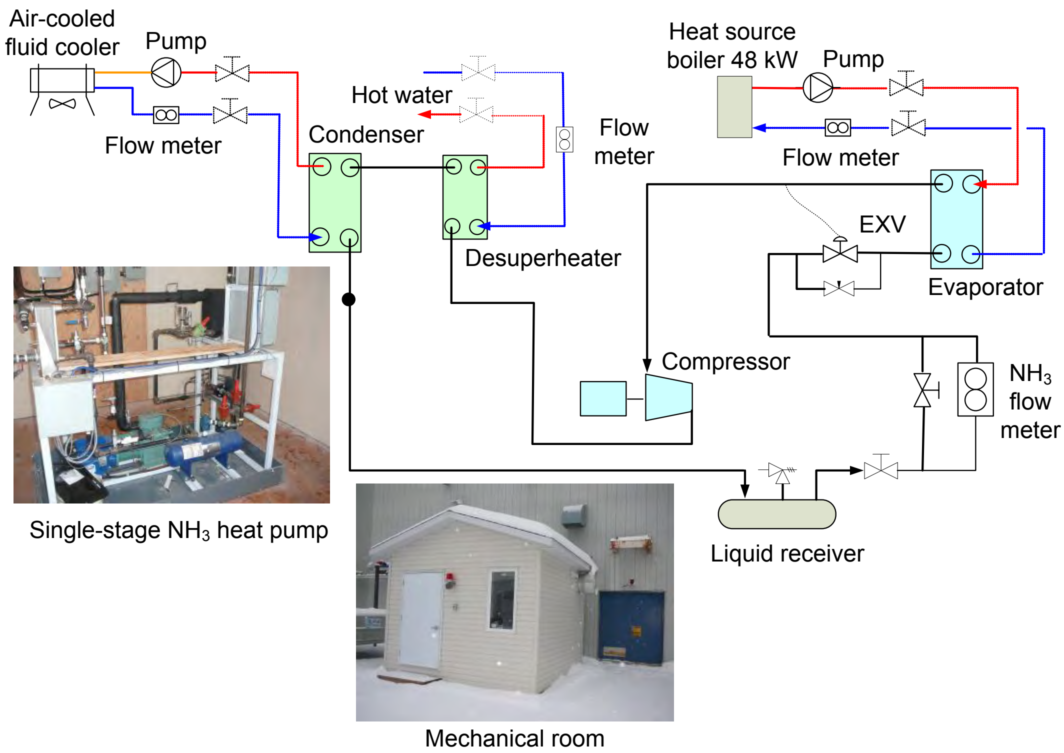


Figure 4-15: Experimental setup of the single-stage ammonia heat pump [Minea, 2011a; Minea, 2013]

The main scope of this project was to demonstrate that ammonia heat recovery heat pumps are reliable and safe in the Canadian industrial and regulatory environment, and achieve high energy performance levels. Other objectives were to encourage future R&D work, especially in the area of two-stage ammonia heat pumps, develop specific operation and maintenance skills for local technicians, promote further implementation in Canada, encourage most local manufacturers to provide ammonia heat pumps, as well as reliable detection devices, increase public confidence and promote ammonia as safe and efficient refrigerant going forward.

As can be seen in Figure 4.16a, with 1.08 kg/s of waste heat carrier fluid (water) entering the heat pump evaporator at 15 °C, the heat pump supplied 1.26 kg/s of hot water at 42 °C. At the same time, the desuperheater heated 0.19 kg/s of process/domestic hot water from 25.5 °C to 44 °C (Figure 4.16b). Based on the compressor energy consumption, the heat pump coefficient of performance was 3.84. However, it dropped to 3.46 when considering the energy consumption of the compressor and the waste heat fluid circulating pump, and to 2.85 when the energy consumption of the compressor, the waste heat fluid circulating pump (0.65 kW) and the hot water circulating pump (1.44 kW) were taken in consideration.

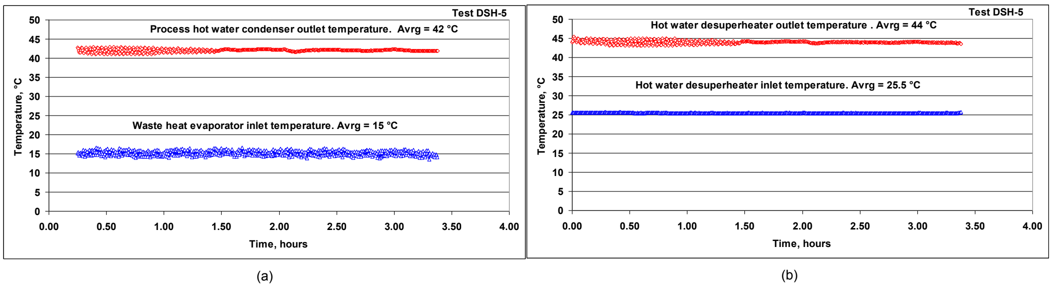


Figure 4-16: Single-stage ammonia heat pump; (a) waste heat (inlet) and process water (outlet) temperatures; (b) hot water temperatures entering and leaving the desuperheater [Minea, 2011a; Minea, 2013]

Simulation models for both single- and double-stage ammonia heat pumps have been developed using the EES software. Part of the simulation results has been experimentally validated. Figure 4.17 shows, for instance, the simulation results of a two-stage ammonia heat pump used to heat cold water from 10°C to 85 °C by desuperheating the compressor discharge ammonia vapour coming at a temperature of 90 °C from the plant's existing ammonia refrigeration system [Richard, 2011].

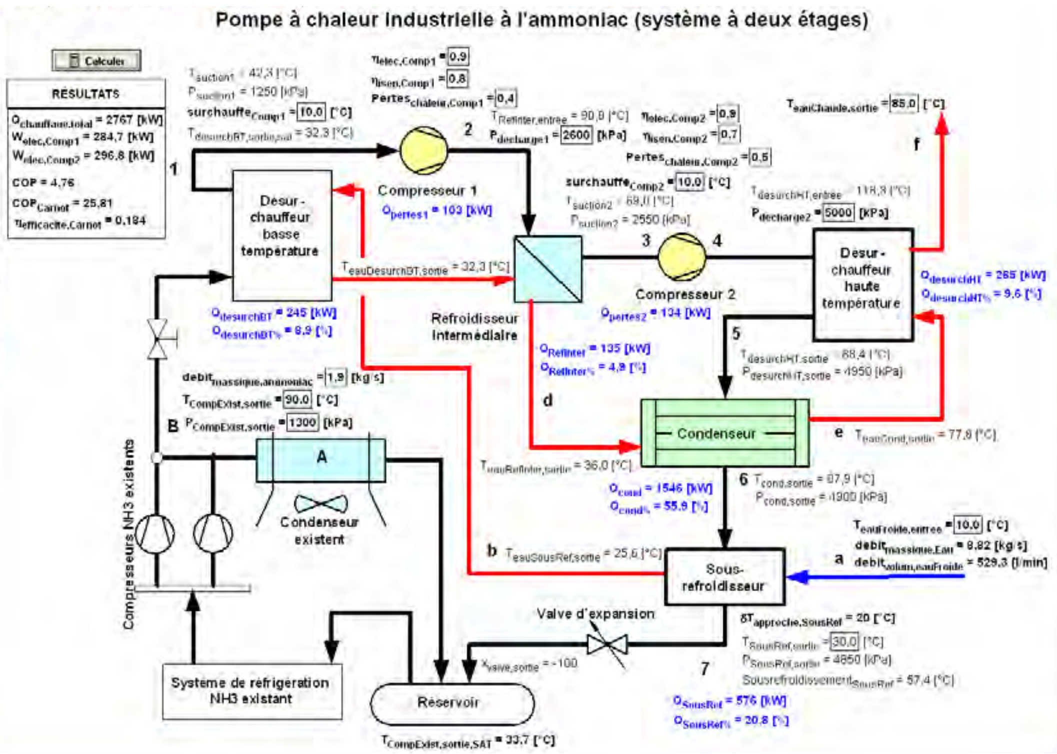


Figure 4-17: Simulation model of a double-stage ammonia heat pump [Richard, 2011]

Figure 4.18a schematically represents the diagram of a single-stage ammonia heat pump recently implemented in a new Canadian dairy plant [Gosselin, 2013]. Finally, Figure 4.18b shows an industrial double-stage ammonia heat pump implemented for recovering heat from large existing ammonia refrigeration systems [Vilter]. This implementation project is just starting and the first preliminary results are expected in December 2013.

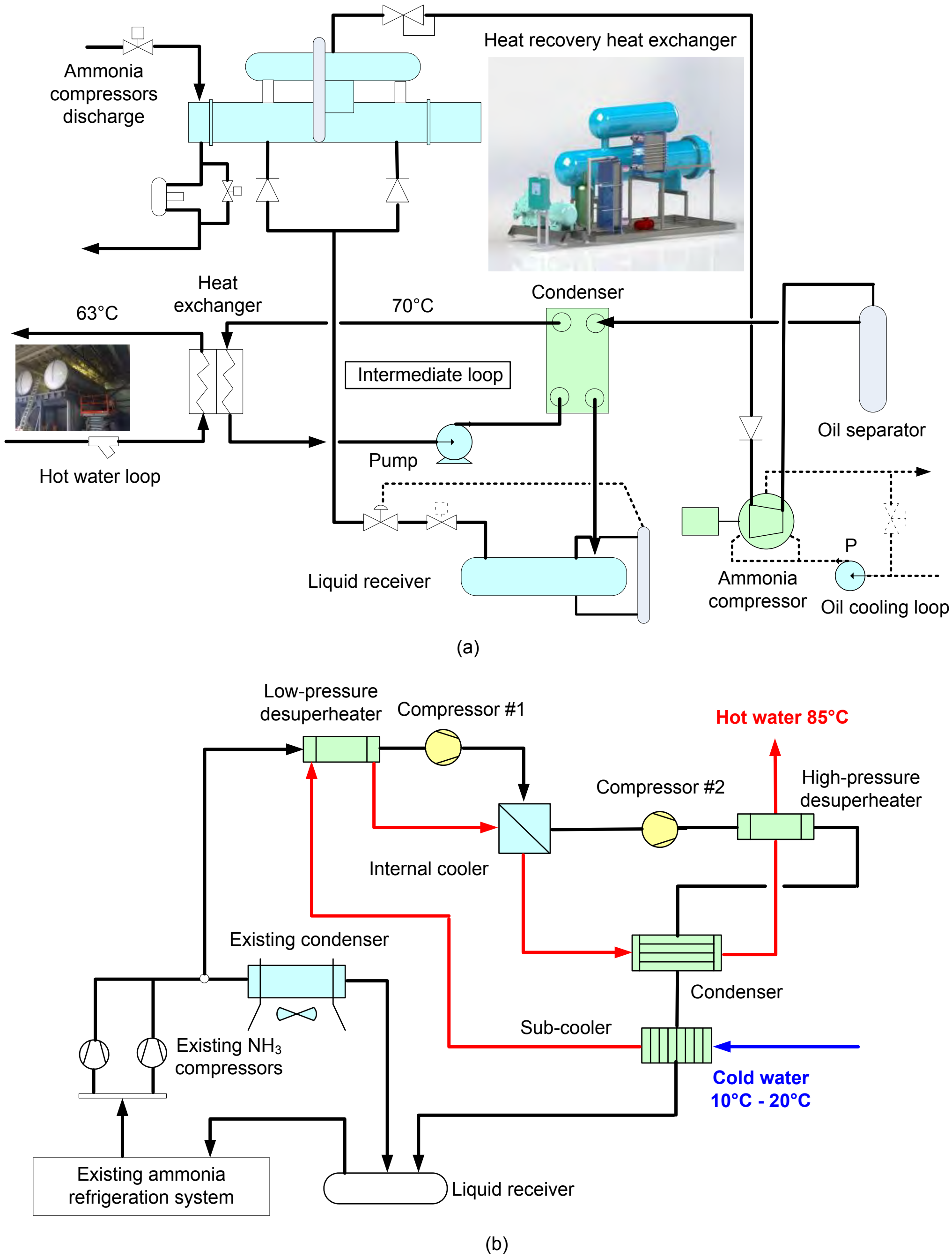


Figure 4-18: Examples of ammonia industrial heat pump applications in Canadian existing refrigeration systems; (a) single-stage application [Gosselin, 2013]; (b) double-stage application [Vilter]

4.3.3.3 Cascade heat pumps

Cascade heat pump systems have the advantage of lower pressure ratios and higher isentropic efficiencies for each stage compressor. At the same time, different combinations of working fluids can be used according to the temperature ranges of both the waste heat and heat sink sources. On the other hand, cascade heat pump systems introduce extra temperature differences in the cascade heat exchanger, greater complexity and extra control problems, and slightly reduce the overall system coefficients of performance. However, this energy performance reduction seems less critical in the context of high-temperature heat pumps recovering large quantities of *free* industrial waste heat.

Two cascade heat pump cycles have been studied in order to find the best working fluid combination, control sequences, and energy efficiency [Minea, 2011a; Minea, 2013]. The first concept (Figure 4.19) is an optimized cascade system including two closed, electrically-driven vapour compression cycles with an intermediate cascade (condenser/evaporator) heat exchanger. Compared to a standard cascade cycle, this configuration includes a liquid refrigerant pump and a vapour injection solenoid valve on the second heat pump cycle, to facilitate system start-up. At the beginning of each running cycle, the liquid pump or, alternately, the injection solenoid valve, may help remove the high-temperature refrigerant (HFC-245fa) storred inside liquid receiver #2.

The second concept (Figure 4.20) consists of two vapour compression cycles coupled by an intermediate liquid closed loop [Minea, 2011a; Minea, 2013].

Both experimental set-ups use a 48 kW electrical boiler as a waste heat source and an outdoor air-cooled liquid cooler rejecting the condensing heat via a brine (50 % water and ethylene glycol) closed-loop. They have been sized to recover waste heat (water) at temperatures varying from 10 °C to 30 °C and supply heat (process or domestic hot water) at temperatures up to 85 °C. The HFC-236fa, HFC-134a and HFO-1234yf refrigerants were successively chosen as working fluids for the first stage, and HFC-245fa, a high-temperature refrigerant, for the second stage. The main selection criteria were the thermo-physical properties and environmental impacts (ODP, GWP, etc.) of the selected refrigerants. Were selected electrically-driven reciprocating compressors of which efficiency vary between 70 % and 97 %. Because compressor capacity decreases with the evaporating temperature and the increasing pressure ratio, both compressors were equipped with automatic variable speed controllers. The electronic expansion valves were programmed to keep superheating at values varying between 5 °C and 15 °C, according to the thermal properties of each refrigerant.

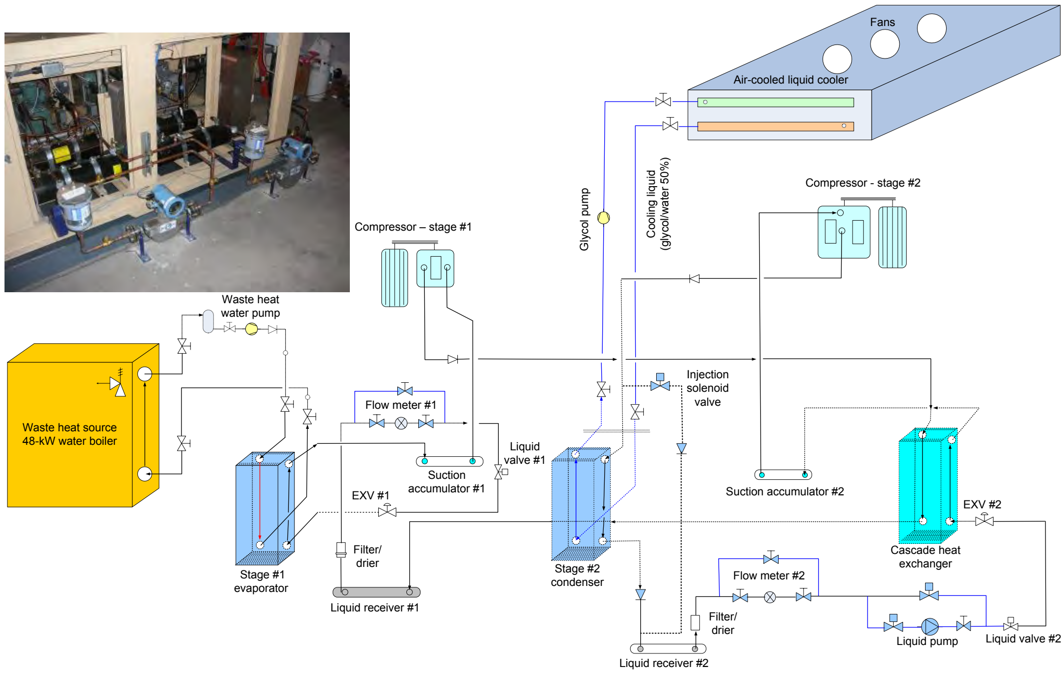


Figure 4-19: Optimized cascade heat pump prototype; EXV: expansion valve [Minea, 2011a; Minea, 2013]

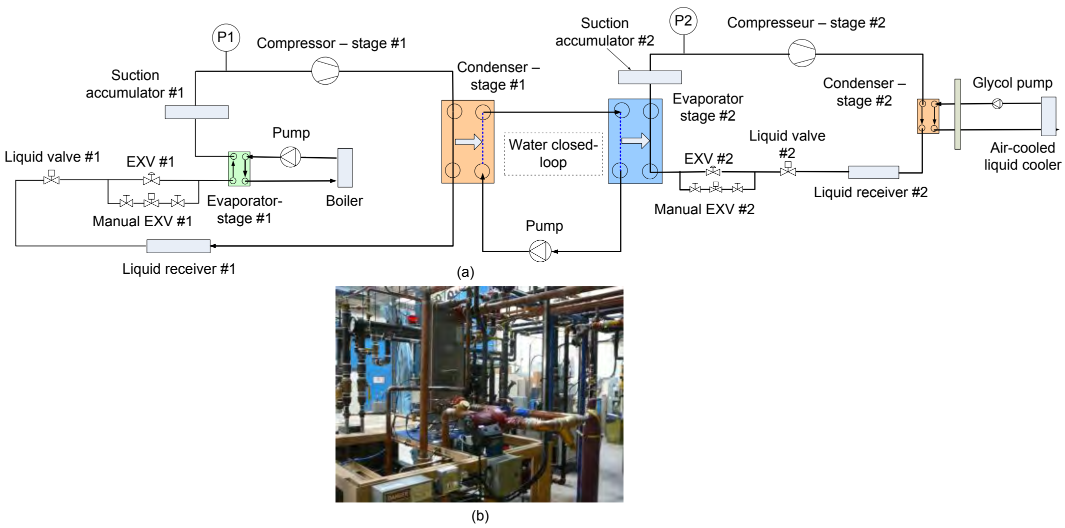


Figure 4-20: Cascade heat pump with intermediate closed-loop; (a) schematic layout; (b) view of the intermediate closed-loop; EXV: expansion valve [Minea, 2011a; Minea, 2013]

Figure 4.21 shows the simulation results for one of the laboratory experimental tests achieved with the HFO-1234yf and HFC-134a refrigerants on the first and second stage respectively. It can be seen that, by using waste heat at a 25 °C inlet temperature, hot water was provided at 84.5°C with an overall coefficient of performance of 2.08 and Carnot efficiency of only 0.34 [Richard, 2011]. However, with higher waste heat inlet temperatures, higher COPs and Carnot efficiencies were obtained.

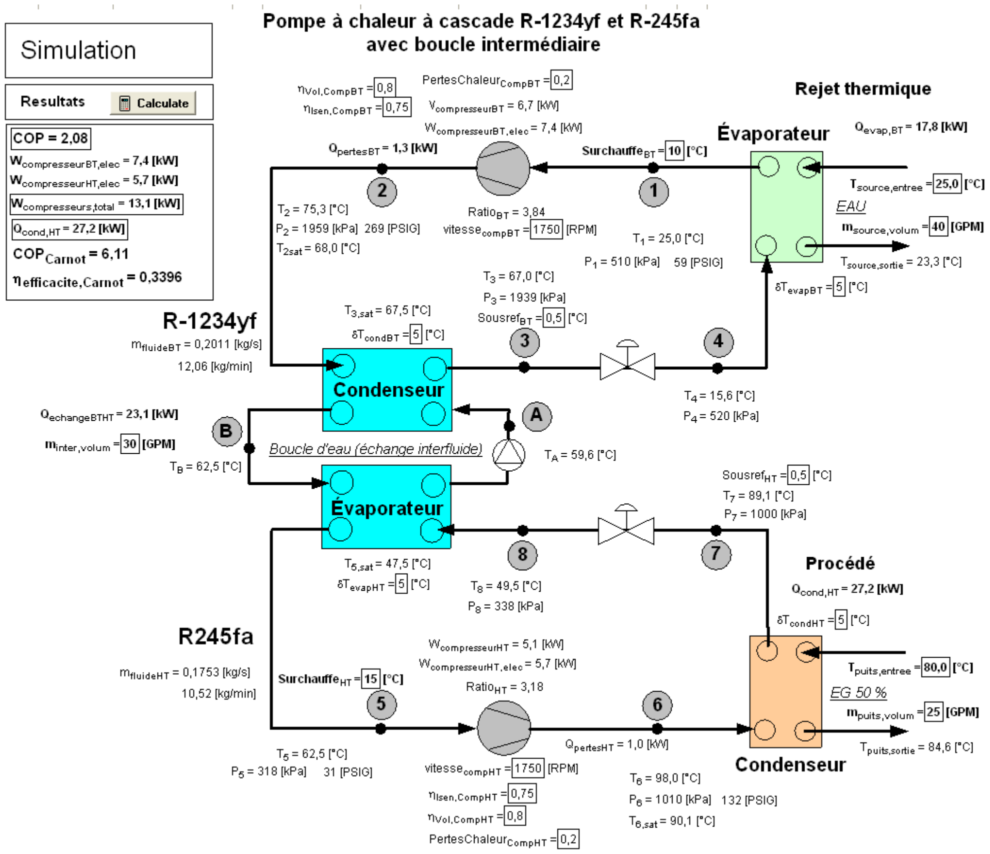


Figure 4-21: Simulation results of a cascade heat pump system with intermediate closed-loop using HFO-1234yf and HFC-134a as the first and second stage refrigerants [Richard, 2011]

For the industrial implementation of cascade heat pump systems, many practical options are available. As can be seen in Figure 4.22, the first stage in such a system may recover the waste heat rejected by an industrial ice machine in a poultry processing plant [Caddet]. The cascade heat pump is the second stage of a heat recovery system, also used to recover heat from the condensers of an existing refrigeration plant with an intermediate closed-loop. Cold water entering the system at 12 °C is heated up to 25 °C inside the pre-heating heat exchanger and then up to 63 °C with the cascade heat pump, prior to being stored inside a storage tank and/or supplied to industrial processes or other consumers.

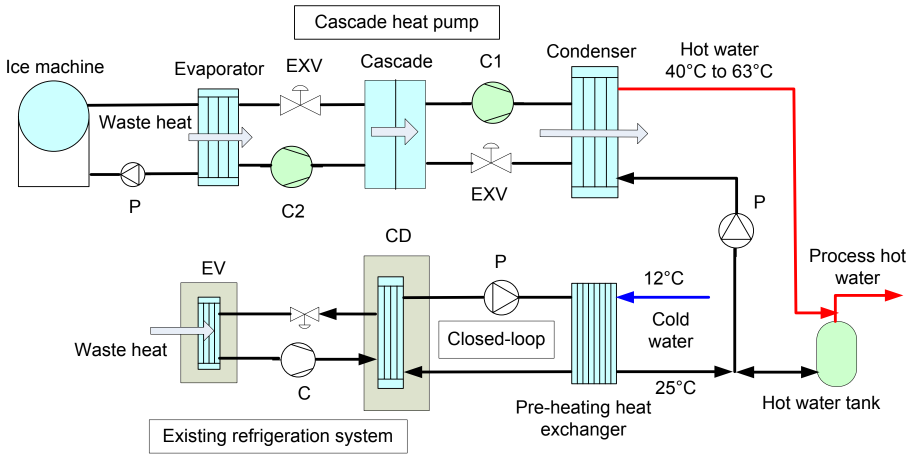


Figure 4-22: Schematic diagram of a cascade heat pump implemented in a Canadian poultry processing plant [Caddet]

4.3.3.4 Mechanical vapour recompression

In many energy intensive industrial processes, such as evaporation and distillation, low pressure steam is rejected into the atmosphere as waste heat. Among other methods, mechanical vapour recompression (MVR) semi-open thermodynamic cycles make it possible to efficiently recover this high quality (enthalpy, temperature) wasted heat. Recovering the vapour latent heat is performed by raising its pressure and temperature, and then by condensing it inside the same evaporator. To achieve this, a fast revolving, high pressure device capable of operating under vacuum (compressor or blower) is used to increase the pressure of the recovered vapour and its corresponding saturation (condensation) temperature. This way, the same vapour can used as a heating medium for the liquid or solution being concentrated by the initial evaporation or distillation process.

Selecting the compressor (centrifugal, turbo, volumetric, axial, etc.) or blower is the most important design issue. Today, centrifugal compressors are still the most common types used in MVR installations, even though the pressure ratios are restricted to approximately 2. They are usually equipped with a liquid separator in the suction line because liquid drops cause erosion, leading to lower efficiencies and possible blade failure [Annex 21, 1995].

MVR systems offer benefits such as reduced energy consumption and cooling water requirements compared to conventional steam heated evaporator systems with a similar capacity. However, higher capital costs than conventional steam heated systems, and high electrical power and voltage requirements for compressors may from an economic point of view limit the number of industrial applications. [Annex 21, 1995]

MVR systems provide very high COPs (up to 100 and even higher), being very dependent on the magnitude of the temperature lift that, generally, is - or must be - bellow 20 °C.

A mechanical vapour recompression system has been studied, improved and successfully implemented and tested in a Canadian industrial plant (Figure 4.23) [Bédard, 2002]. This MVR evaporator system is similar to a conventional steam heated, single-effect evaporator, except that the vapour released from the boiling solution is compressed by the compressor. As previously noted, the compressor raises the pressure and saturation temperature of the vapour so that it may be returned to the evaporator as a heating medium. This reduces the steam quantity required to meet the evaporative load of the overall system.

The vacuum pump maintains a pressure of about 200 mbar inside the container, which corresponds to a water boiling temperature of 60° C. The compressor (107.5 kW) increases the vapor pressure by 20 mbar and its temperature by 2 °C between the evaporating and the condensing sides. The product is continuously re-circulated from the bottom to the top of the container. Inside the heat exchanger, the compressed vapor condenses and the liquid is pumped outside. A plate heat exchanger preheats the entering product by using heat from both the condensed and concentrated product leaving the container. The compressor consumes 7.8 kWh per ton of water evaporated, while the energy required by a conventional evaporation system is of about 700 kWh per ton of water evaporated. Thus, the coefficient of performance, defined as the ratio between the thermal energy supplied divided by the electrical energy consumed, was 86. However, during system operation, about 30 kW average thermal back-up power in the form of vapor was supplied in order to keep the temperature of the product being concentrated constant. This operation increased the specific energy consumption to 9.9 kWh per ton of water evaporated and the system average COP dropped to 68. However, this last number didn't include the energy consumption of the vacuum and other circulation pumps the total electrical power of which was estimated at 60 kW) [Bédard, 2002].

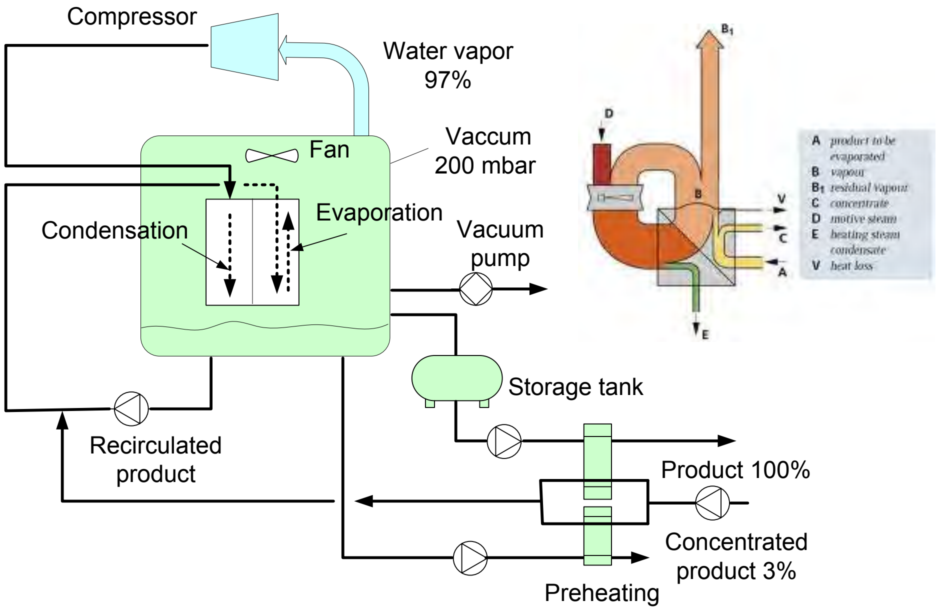


Figure 4-23: Mechanical vapour recompression system implemented in Canada [Bédard, 2002]

4.3.3.5 Heat pump-assisted wood drying

Wood drying is a complex, highly non-linear thermodynamic process. In Canada, most conventional hardwood and softwood drying kilns use fossil fuels (oil, propane, natural gas) or biomass (bark) as primary energy sources. However, most of them can be coupled with heat pumps for dehumidification drying purposes. In this case, practically all warm air loaded with moisture is discharged into the environment. The process consists in saving energy through re-heating and dehumidifying the process air. Warm dry air is led over the surface of the wood boards to be dried, and its very low relative humidity helps remove moisture from the wood. The water vapour picked up condenses on the externally finned heat transfer surface of the heat pump evaporator, and then is heated again by passing through the heat pump condenser. Heat is thus recovered from the dryer hot and humid air, and the recovered sensible and latent heat is used to reheat the dehumidified drying air. Other advantages include proper control of product moisture content, reduced energy consumption and relatively short pay-back periods for the industrial drying heat pumps. However, when compared with basic hot air convective dryers, drying heat pumps involve higher capital and maintenance costs, are more complex to operate and require qualified operators.

a) Low-temperature drying heat pump

A low-temperature laboratory-scale prototype consisting of a 13 m^3 forced-air dryer with variable-speed fans coupled to a 5.6 kW (compressor nominal power input) low-temperature heat pump (Figure 4.24) has been extensively studied for drying Canadian hardwood species through dehumidification [29, 30]. Hardwood, such as sugar maple and white and yellow birch, has relatively complex cell structures, and in Eastern Canada, their average green moisture content varies between 6 5% and 72 %. For these species, drying is an essential step in the manufacturing process (furniture, etc.). The dryer is equipped with steam and electrical backup heating coils. Steam is supplied at variable flow rates by a natural gas-fired steam boiler. The air flow rate over the lumber surface is maintained sufficiently high to provide a rapid air exchange and minimise dead spots. To ensure uniform heating and drying, the direction of the air flow is periodically reversed. The heat pump, including the compressor, blower, evaporator, condenser, subcooler, refrigeration piping and controls, is installed in a mechanical room next to the dryer. Based on the product actual moisture content, the drying schedules, as well as the heat pump hourly running times, are established prior to each drying cycle.

The heat pump compressor operating time was set in accordance with an intermittent drying schedule, as shown in Figure 4.25a [Minea, 2006; Minea, 2011b]. Both heating and dehumidification processes were controlled by the actual wet-bulb temperature of the air inside the drier. At the beginning of each drying cycle, the compressor hourly running ratio was pre-set at 100 %, and then it was continuously adjusted between 0 and 100 % in order to have the actual wet- and dry-bulb temperatures in the dryer practically equal to their setting points. Under such schedule if, for example, the compressor hourly running time was set at 60 %, it ran for 30 minutes and shut down during the next 20 minutes. After the heat pump started, the compressor running time was increased when the actual wet-bulb temperature was above the upper limit, and decreased when it was below the lower limit. Figure 4.25b shows the cumulative amount of water extracted during a typical drying cycle with yellow birch using the intermittent drying strategy shown in Figure 4.25a.

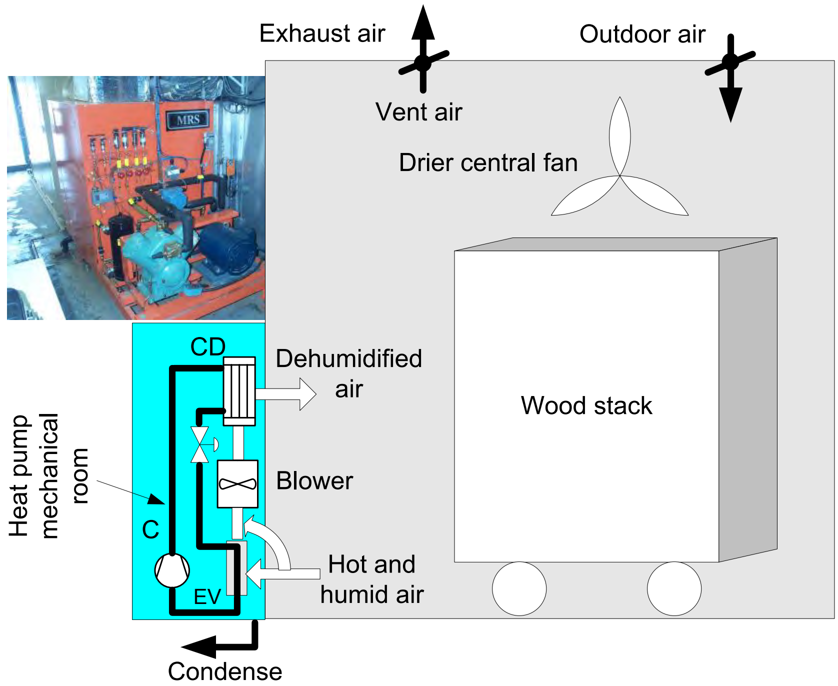


Figure 4-24: Schematic diagram of the laboratory-scale hardwood drying heat pump prototype [Minea, 2006; Minea, 2011b]; B: blower; C: compressor; CD: condenser; EXV: expansion valve; EV: evaporator; LV: liquid valve; SA: suction accumulator; SC: sub-cooler; SV: solenoid valve; VS: variable speed; A, B: air circulation direction.

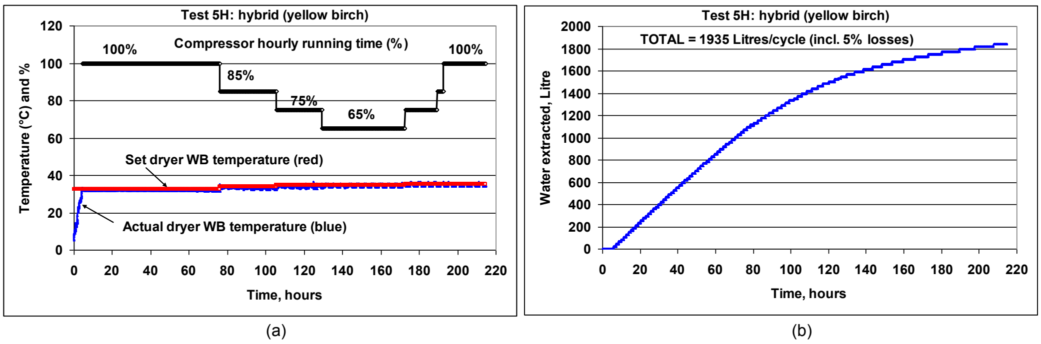


Figure 4-25: (a) Compressor hourly running profile and set value, and actual value of dryer wet-bulb (WB) temperatures; (b) cumulative amount of water extracted [Minea, 2006; Minea, 2011b]

The average dehumidification efficiency of the system, expressed in terms of the specific moisture extraction rate (SMER), which represents the ratio between the mass of water extracted and the heat pump total electrical energy consumption (compressor and blower), was 2.5 kg_{water}/kWh_{hp} above the wood fibre saturation point. On the other hand, the natural gas consumption of the same drying cycle decreased by 57.5 % as compared to the natural gas consumption of the equivalent *conventional* drying cycle. Compared to the *conventional* drying cycle using natural gas, total energy costs (electricity plus natural gas) decreased by 23 %.

b) High-temperature drying heat pump

An industrial-scale, high-temperature drying heat pump prototype, including one 354 m^3 forced-air wood dryer with steam heating coils and two high-temperature drying heat pumps (Figure 4.26) has also been studied in Canada [Minea, 2011b; Minea, 2004, Minea, 2012b]. Finished softwood lumber is produced in standard sizes, mostly for the construction industry. Softwood, such as pine, spruce and fir (coniferous species), is composed of vertical and horizontal fibre cells serving as a mechanical support and pathway for the movement of moisture. These species are generally dried at relatively high temperatures, but no higher than 115 °C, and thus high-temperature heat pumps coupled with convective dryers are required [Minea, 2011b; Minea, 2004]. An oil-fired boiler supplies steam for heating. The dryer central fans force the circulation of the indoor air. Each heat pump includes a 65 kW (nominal power input) compressor, an evaporator, a variable speed blower and electronic controls located in an adjacent mechanical room. Both remote condensers are installed inside the drying chamber. The refrigerant (HFC-236fa) is a non-toxic and non-flammable fluid, having a relatively high critical temperature compared to the highest process temperature. Expansion valves are controlled by microprocessor-based controllers that display set points and actual process temperatures.

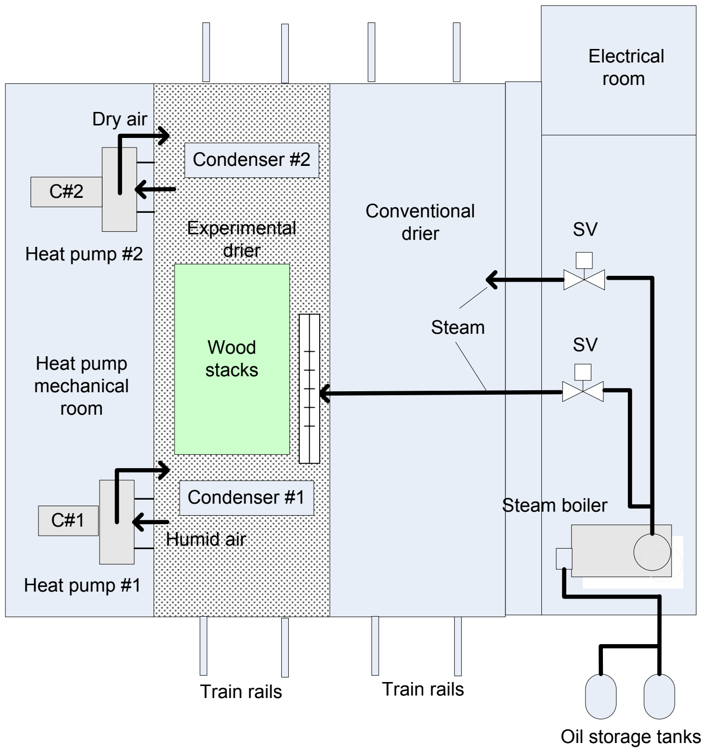


Figure 4-26: Site of the experimental industrial-scale softwood drying heat pump system [Minea, 2011b; Minea, 2004; Minea, 2012b]; C: compressor; LV: liquid valve; SA: suction accumulator; SC: sub-cooler; EXV: expansion valve; VS: variable speed; SV: solenoid valve; A, B: direction of air circulation

Based on the softwood moisture content prior to entering the drying enclosure, generally in the range of 35 % to 45 % (dry basis), optimum drying schedules were developed for each softwood species. The average coefficients of performance (COP) of both heat pumps, defined as useful thermal power output (kW) divided by electrical power input (kW), varied from 4.6 at the beginning to 3 at the end of the drying cycles. The heat pumps (compressors plus blowers) used 72 % and the dryer central fan 28% of the total energy consumption of each drying cycle. The drying time to deliver white spruce with an approximate final moisture content of 18% was about 2.5 days, while, for balsam fir, it averaged 6.3 days. Total amounts of water extracted exceeded 19,100 kg (Figure 4.27) for dried white spruce and 27,000 kg for dried balsam fir. Consequently, relatively high water extraction rates, varying between 178.8 kg_{water}/h and 313 kg_{water}/h were achieved respectively. These numbers do not include venting moisture losses (on average, 90kg_{water}/h), but account for 5% of condensed water losses. The Specific Moisture Extraction Rate (SMER) ranged from 1.46 kg_{water}/kWh (with balsam fir) to 2.52 kg_{water}/kWh (with white spruce). These values do not include the energy consumed during the pre-heating steps, nor do they include any allowance for the energy consumed by the kiln's central fan and the venting moisture losses. Finally, the energy consumed during the drying cycles with high-temperature heat pumps was between 27 % and 57 % lower than the energy consumed during the *conventional* drying cycles using oil as the sole source of energy. Also, the average reduction in specific energy costs, compared to the costs of *conventional* softwood drying cycles, was estimated at about 35 %.

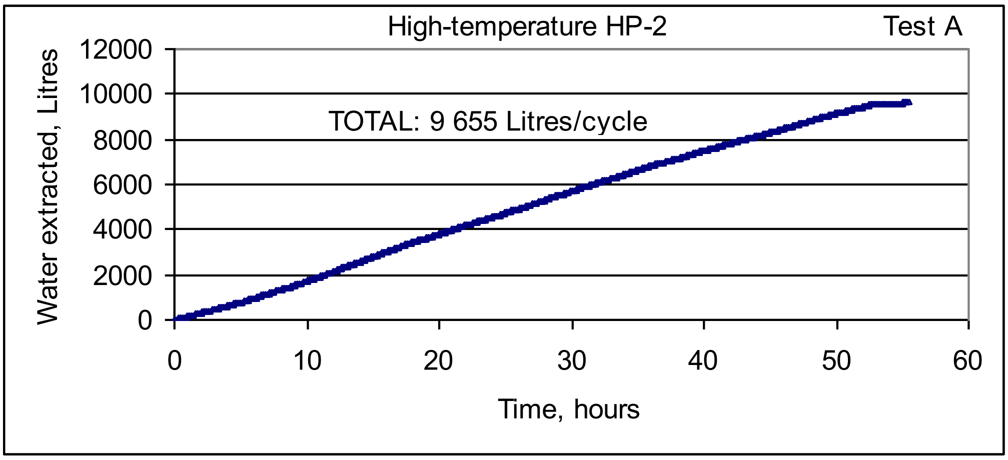


Figure 4-27: Cumulative volume of softwood water extracted by heat pump 2 only [Minea, 2011b; Minea, 2004; Minea, 2012b]

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5 Denmark

5.1 Introduction

In 2010 the Danish Commission on Climate Change Policy published a report describing the road to a Danish energy system without fossil fuels by 2050. In the political system there is consensus about the Commission's recommendations and thus, Danish energy research is to a high degree governed by these.

Figure 5-1: The Danish Commission on Climate Change Policy: "Green Energy – the Road to a Danish Energy System without Fossil Fuels. Summary of the Commission's considerations, results and recommendations", published 28 September 2010.

In the report heat pumps are attributed a significant role in the future energy supply, as a link between energy produced by electricity and utilization of excess heat. To underline the future role of heat pumps, Commission chair Katherine Richardson estimates that by 2050 between 25 % and 50 % of the district heat supply should be supplied by heat pumps. More than 60 % of the Danish households are heated by district heating.

The Refrigerant Situation

Denmark has stricter rules for use of synthetic refrigerants than most other countries. With regard to CFC and HCFC refrigerants, Denmark follows the international rules and thus, the former have been completely phased out whereas HCFCs (primarily R-22) must be phased out by 1 January 2015. As to HFC refrigerants, Denmark enforces a special rule allowing only plants with a 0.2-10 kg refrigerant filling. In practice, this means that industrial heat pumps only use natural refrigerants.

Due to this, Denmark is in a strong position worldwide particularly in relation to research, testing and experience of natural refrigerants ammonia, CO_2 and water vapour.

5.2 Ongoing R&D

In Denmark R&D on large scale heat pumps has primarily been utilized in district heating systems, with forward temperatures between 70 and 90 °C. Heat sources are typically at ambient or slightly higher temperatures and could be flue gas, surface water, thermal storages, treated sewage water etc. Technologies in focus are trans-critical CO_2, ammonia and isobutene.

Today CO_2 systems are the main choice for commercial refrigeration in Denmark and the thermodynamical properties in the trans-critical state makes CO_2 suitable in heat pumps where the medium is heated from a temperature below 40 °C up till 70-90 °C, thus making it suitable in most district heating systems.

Ammonia systems arise from industrial cooling, where the primary difference in heat pumps is higher operating pressures. Traditionally ammonia heat pumps in Denmark have been either 25 or 40 bar systems reaching a maximum temperature of 50-55 °C and 70-75 °C respectively. Today new 50 and 60 bar screw and piston compressors are being developed and demonstrated. These systems exceed 90 °C.

Isobutene is a low pressure refrigerant that can be utilized using low pressure HFC components. Isobutene systems can heat water to around 85 °C using standard low pressure components.

Heat pumps in industrial applications

Applying heat pumps in industrial processes is often much more complicated than in district heating systems. Heat production cost is what district heating is about, meaning that the fuel savings heat pumps contribute to, is of major importance causing heat pumps to be profitable. In production companies, the product is the main focus. Here energy cost is not always one of the main competitive parameters, meaning that the only benefit a heat pump provides might not be particularly important.

In industrial processes, boilers can often be difficult to convert directly to heat pumps as heat pumps are dependent on a heat source and temperature levels. In traditional systems these parameters is almost of no importance, meaning that the heat distribution systems are often build for high temperatures while heat recovery can be very difficult. This means that heat pumps in general must be built into specific processes as a heat recovery unit rather than a centralized heating system. This gets even more complex with inconsistency in timeline of heat source and demand.

Analysis of heat demands and requirements in industrial applications

To have an overview of the potential and technical requirements of using heat pumps in industrial processes, two assessment reports have been published in 2013. The two reports are carried out with different approaches meaning that the results are not a 100 % comparable and conclusive. However both reports give good indications of the possibilities in industries. The first report [Viegand, 2013] considers excess heat of industries in general and the potential of utilization in different ways both internal and external.

Technical and economical obstacles are taken into account. The most important results of the first report [Viegand, 2013] are:

- ¼ of the Danish heat demand in industrial processes require a temperature of 60 °C or less
- ½ of the Danish heat demand in industrial processes require a temperature of 100 °C or less
- ½ of the Danish heat demand in industrial processes require higher temperatures than 100 °C.

The focus of the second report is more specific on using heat pumps in different processes where heat is recovered and utilized in the same process. External utilization of industrial waste heat is not considered. The potential is assessed for processes with temperature requirements of up to 180 °C and categorized in temperature lifts of respectively 20 K, 40 K and 70 K. A requirement of 180° C and a temperature lift of 20 K means that the heat source is 160° C whereas a lift of 70 K means that the source is 110 °C. The most important results of the second report [Weel, 2013] are:

- At a temperature lift of 70 K and delivering at 180 °C, around ½ of the heat demand considered can be produced by heat pumps
- At a temperature lift of 70 K and delivering at 100 °C, 75 % of the potential is possible
- At a temperature lift of 40 K around 35 % of the potential is possible. At this temperature lift it is only a small part of the potential that require higher temperatures than 100 °C
- At a temperature lift of 20 K around 25 % of the potential is possible. At this temperature lift it is only a negligible part of the potential that require higher temperatures than 100 °C
- About 90 % of the potential (regardless of temperatures) can be covered by heat pumps with a capacity of 2 MW-heat or more.

Both reports show that the majority of the potential require temperatures less than 100 °C, meaning that outlet temperatures is not a technical barrier in most cases. The assessments also show that there is some potential for heat pumps that only lifts 20 K, meaning that high COP values is possible while the heat capacities should in MW's. There is only a small potential for heat pumps with capacities less than 1 MW.

Viegand, 2013 Analysis of utilization of industrial excess heat, Viegand & Maagøe, 2013

Weel, 2013 The potential for high temperature heat pumps in industrial application, Weel & Sandvig, 2013

5.3 Demonstration

There have been a number of demonstration projects in the last couple of years implementing large scale heat pumps, which have primarily been transcritical CO_2 or high pressure ammonia systems. At the moment research and development is also in the fields of water vapor systems and the ammonia/water hybrid process.

The following three demonstration projects are relevant for industrial purposes:

“Development of Rotrex turbo compressor for water vapor compression”

The project aims to develop a new and competitive electric water vapor compressor. The compressor is based on the Danish "Rotrex" turbo compressor, which is currently used for the compression of air. The project will develop and test a prototype using water vapor at laboratory level. There has conducted preliminary tests and calculations of the compressor, using water vapor, and it has been verified that practice and theory are consistent. There are various types of compressors on the market today that can be used for the desired applications, but they are either very expensive, limited in capacity or insufficiently reliable.

Water vapor heat pumps differ from other types of heat pumps by high efficiency and low working pressure in the temperature range of 70 to 250 °C. Today systems are often custom made, which makes them very expensive and not profitable in heating applications where other alternatives are available.

The Rotrex compressor could be integrated directly into existing steam systems as a stand alone unit or in combination with traditional heat pumps, where the water vapor compressor can boost the temperature level another 20-30 °C i.e. from 90 °C to 120 °C.

Generally, the target for this technology are industrial sectors using thermal heat in the temperature range of 50 to 200 °C - and the potential is vast.

On the following pages is a paper by Weel & Sandwig, Rotrex and DTI on using the turbo compressor for drying applications:

5.3.1 Energy efficient drying with a novel turbo compressor based high temperature heat pump

Abstract

Drying is one of the most energy intensive operations for preservation of product in many industries. One way to reduce the primary energy consumption for drying is to integrate a high-temperature heat pump to recover the latent heat in the exit stream from the drying process. Rotrex, Weel & Sandvig and DTI are developing a new high-speed radial turbo-compressor designed for steam. The compressor is derived from Rotrex suit of auto mobile turbochargers. The steam-compressor is the heart in the working cycle for a heat pump suitable for integration in a drying system. The new concept is based on a modular basis where compressors can be configured in parallel and serial to match the operational specification for the actual drying system. The COP value of the drying heat pump system typically will be between 4 and 6 depending on the actual configuration. As working medium of the heat pump, steam is selected, because of its excellent thermodynamic properties at high temperatures to meet high COP values, non toxicity and zero greenhouse potential.

Introduction

Drying is one of the most energy intensive operations in industrial processes. Drying is consuming about 20 % of the total energy consumption in industrial processes world-wide. Many efforts have already been implemented to increase the drying efficiency as super heated steam drying, improved process control etc. Integration of a heat pump in a drying process does not itself improve the drying efficiency but is a way to upgrade the exhausted heat from the dryer to usable heat for the drying process. Heat pumps so far have not been suitable for industrial processes because of temperature limitation in the delivery temperature.

Furthermore, the price development for electricity and fossil fuel (gas and oil) has in the past decade been very favorable for heat pump integration in most countries.

The performance of a heat pump can be derived from the main governing equations for a simple ideal Carnot heat pump cycle. The COP value can be expressed from the temperature of the heat source T_c and heat sink T_h which represents the highest theoretical performance of a heat pump with constant source and sink temperatures.

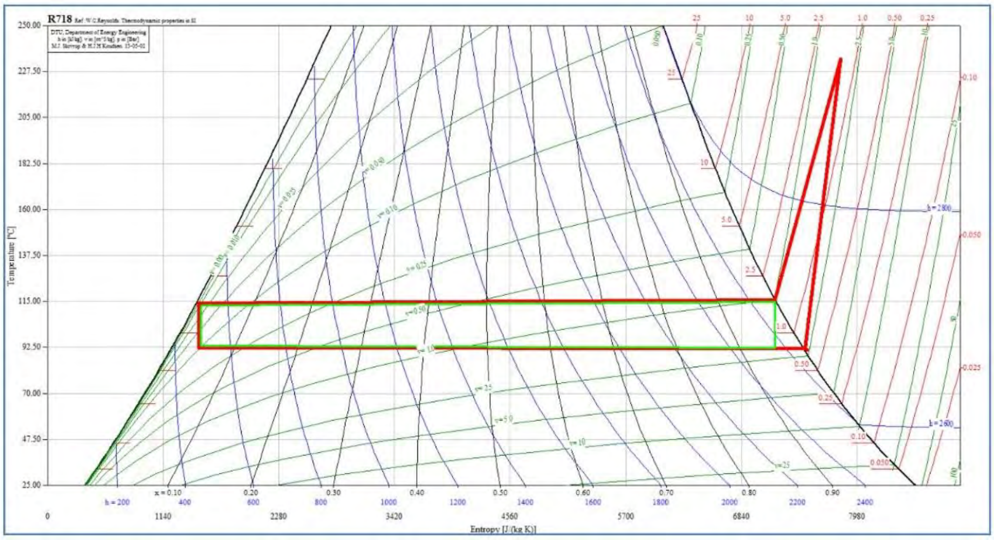


Figure 5-2: Ideal carnot cycle, Water based heat pump cycle (green) and real cycle (red) shown in TS-diagram

Typically the efficiency of a real heat pump cycle is about 0.6 - 0.75 of the theoretical values Carnot heat pump cycles when considering the actual condenser and evaporator temperatures.

$$COP_{real} = \frac{Q}{E} = 0.6 \dots 0.75 \frac{T_h}{T_h - T_c}$$

$$COP_{Carnot} = \frac{T_h}{T_h - T_c}$$

Where E is the electricity input to drive the compressor and Q is the heat delivered by condensing the water vapour from the heat pump. The COP versus temperature lift and evaporation temperature is shown in Figure 5-3. A temperature lift of 50 K will result in a COP value about 4.5 - 5. In many drying applications and other industrial processes a temperature lift of 20 - 60 is required to transform waste heat to usable heat for the dryer design. In Figure 5-3 the relationship between achievable COP-values versus temperature lifts for a heat pump is shown. As can e seen the COP-values within 4 – 8 is achievable with a temperature lift between 30 and 70 K.

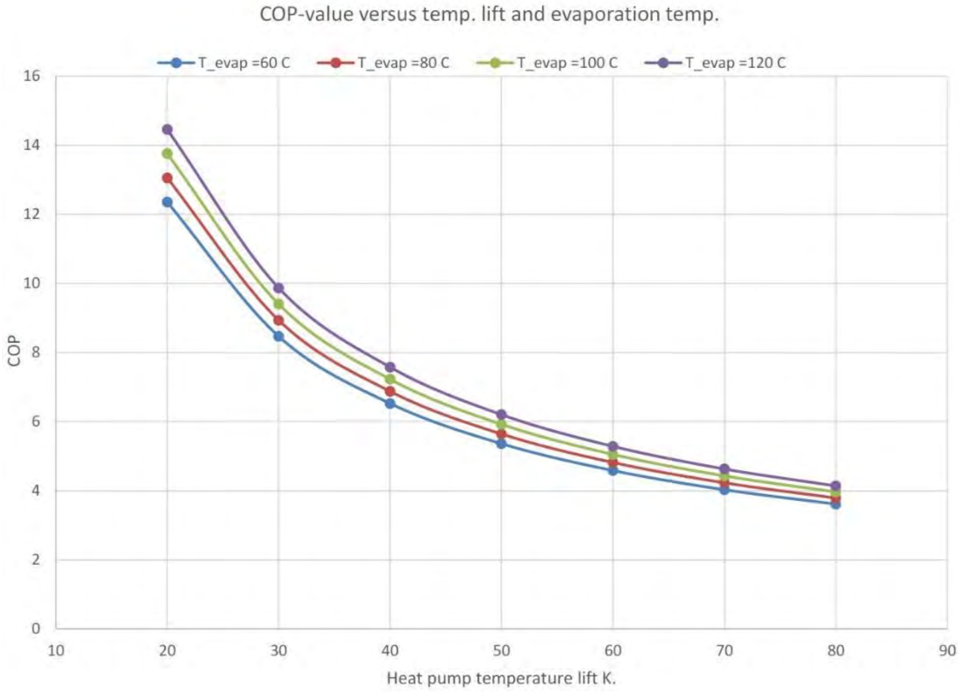


Figure 5-3: COP versus temperature lift and evaporation temperature

In many industrial applications the waste heat temperature (source temperature) is available in the range from 100 °C to 40 °C or lower and the temperature requirement for the process heating is in the range from 100 °C to 150 °C. The best heat pump to accomplish the variable source temperature and process temperature needs to have a similar temperature glide in order to minimize the exergy loss in the heat exchangers (condenser and evaporator). The Lorenz cycle heat pump introduced a temperature glide in the condenser and evaporator to reduce the exergy loss in the heat exchangers.

The COP value of the ideal Lorenz cycle is expressed by:

$$COP_{Lorenz} = \frac{T_{hm}}{T_{hm} - T_{cm}}$$

Where : T_{hm} *is the condenser temperature*

T_{cm} *is the evaporator temperature*

In Figure 5-4 a comparison of the ideal Carnot cycle and the Lorenz cycle in a T-Q diagram is shown. The Lorenz cycle is equivalent to an infinite Multi-stage Carnot Cycle. The Lorenz cycle can be approximated by using binary mixtures like ammonia-water or a trans-critical process (typical with CO_2 as the working fluid). In reality, in the high temperature range a multi-stage Carnot process with water as working medium in 2 - 3 stages achieves higher COP-value.

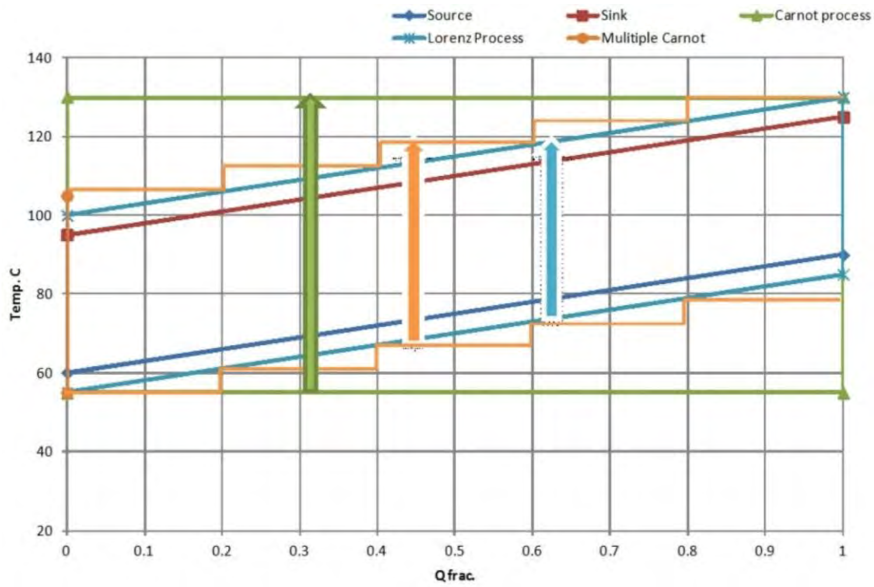


Figure 5-4: Comparison of different ideal heat pump cycles in the TQ-diagram

The main cycle and components in heat pump is shown schematic in Figure 5-18. There are only 4 key components in a heat pump: Compressor, Condenser, Expansion valve and Evaporator.

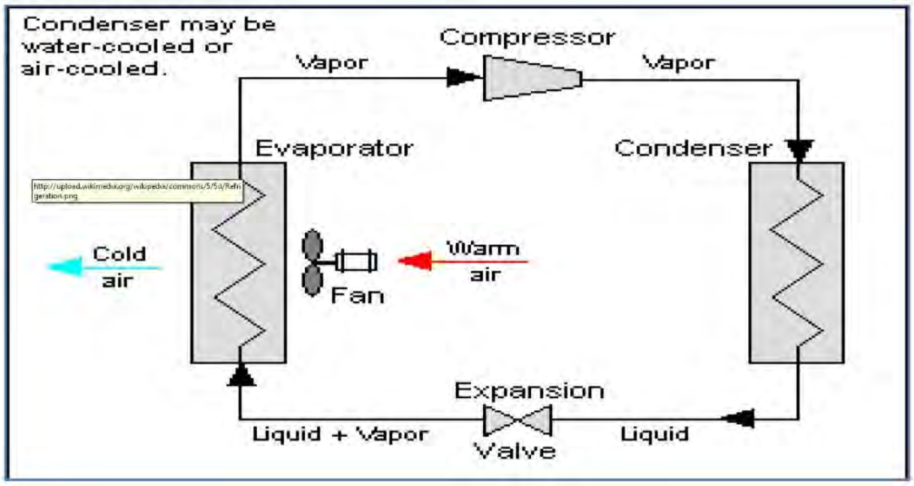


Figure 5-5: Simple schematic of the main components in the compression heat pump

In drying applications the drying temperature and the exhausted waste heat flow versus temperature will be the main governing parameters for the recoverable heat and the achievable heat pump COP value.

Existing drying systems are designed with high exergy destruction making them unsuitable for heat pump integration. New drying processes in super-heated steam have significant less exergy destruction and thereby are much more suitable for efficient heat pump integration.

A comparison of various working media for high-temperature heat pumping shows that water is the most efficient medium for condensing temperatures above 100 °C. In Figure 5-6 the COP-value for heat pumps cycles with different working fluid (water, butane, isobutane, CO_2, NH_3). For high-temperature operations it is clear that water is a superior working fluid. One drawback of water vapor is the relatively low vapor density when the evaporation temperature is below 80 °C which requires a high volumetric capacity of the heat pump compressor. Turbo compressors have very high volumetric flow rate capacity and are therefore preferable for water vapor heat pumps.

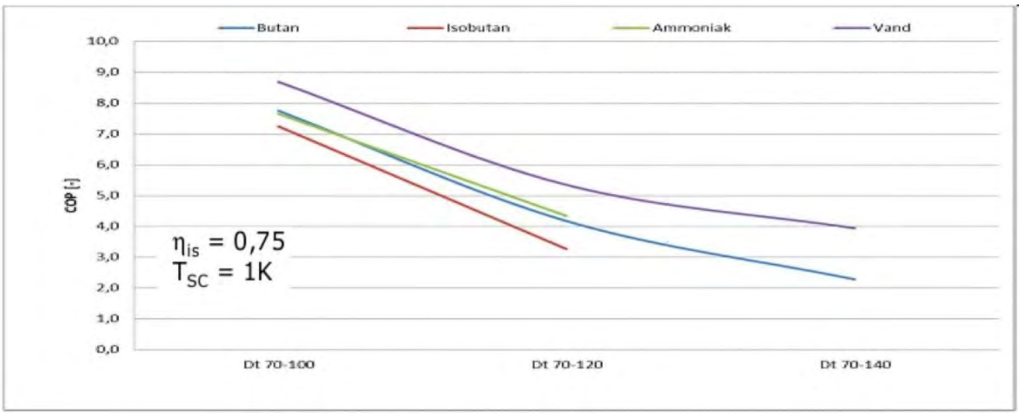


Figure 5-6: COP values of various heat pump refrigerants versus temperature lift. Evaporation temperature is 70 °C

Compressor development and test

The turbo compressor for water vapor compression is derived from Rotrex's line of automotive turbochargers. The aluminum based compressor has been replaced with a new impeller made of titanium and housing and volute are designed to meet a higher pressure ratio and high efficiency and durability. New carbon based shaft seals are implemented to prevent steam or oil leaking at the shaft, see Figure 5-7.

The compressor suction volume is about 0.28 m^3/s and the maximum pressure ratio with steam is approximately 3. A typical heat pump installation consisting of one turbo compressor unit can deliver about 450 kW heat at 130 °C when the suction pressure from the evaporator is 0.9 bar(a) (93 °C saturated steam temperature).

The Rotrex turbocharger has a unique traction geared compressor with excellent performance and approved for the automotive marked. The traction gear has a step-up ratio of 7.5 and the efficiency is 98.5 % at full load. The low-speed shaft of the traction gear is connected directly to a high speed motor (15,000 RPM) or a standard motor via a fast belt drive to assure a compressor impeller speed of up to 105,000 RPM. In Figure 5-7 and Figure 5-8 some principle drawings of the compressor assemble with traction gear, housing, impeller, volute etc. are presented.

The traction gear is lubricated by an internal oil pump which maintains a safe oil film on the traction (or friction) parts and circulates the oil through the external oil cooler.

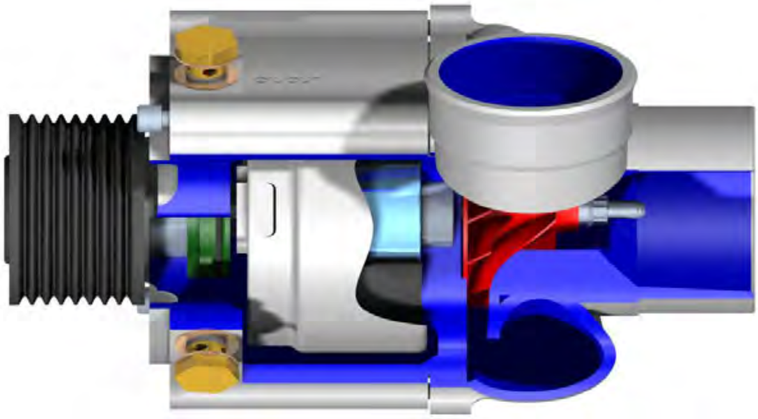


Figure 5-7: Compressor and gear

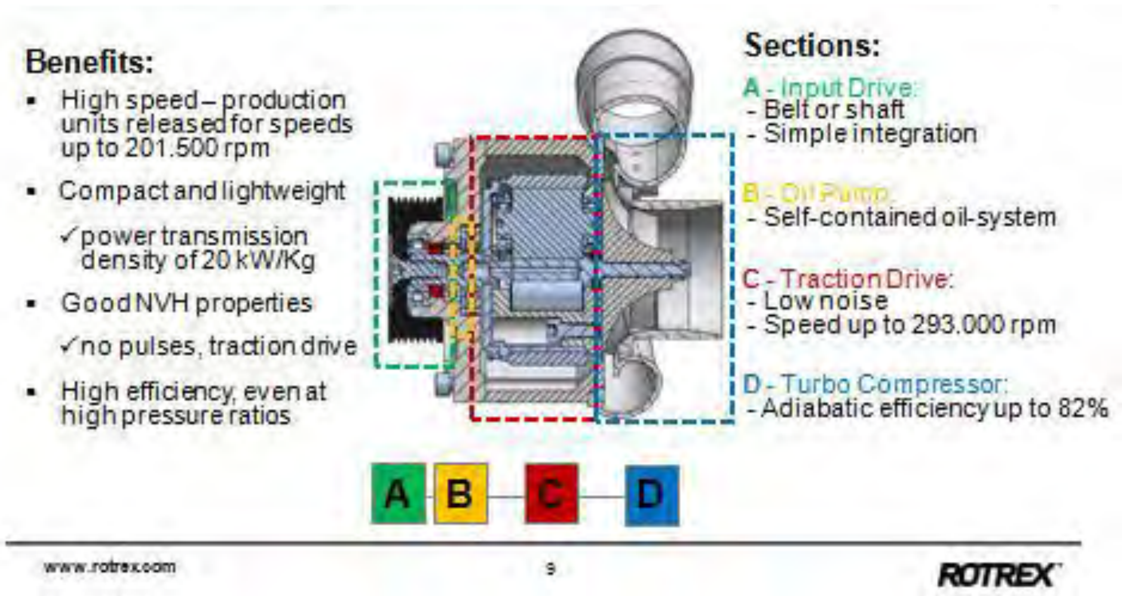


Figure 5-8: Main parts of the Rotrex compressor derived for steam compression

In Figure 5-9 the predicted performance map including the actual measured operating points are plotted during a test run on a rig installed at the production facility of Haldor Topsøe A/S in Frederikssund. The measured performance was close to the expected performance. Pictures from the test rig are shown in Figure 5-9.

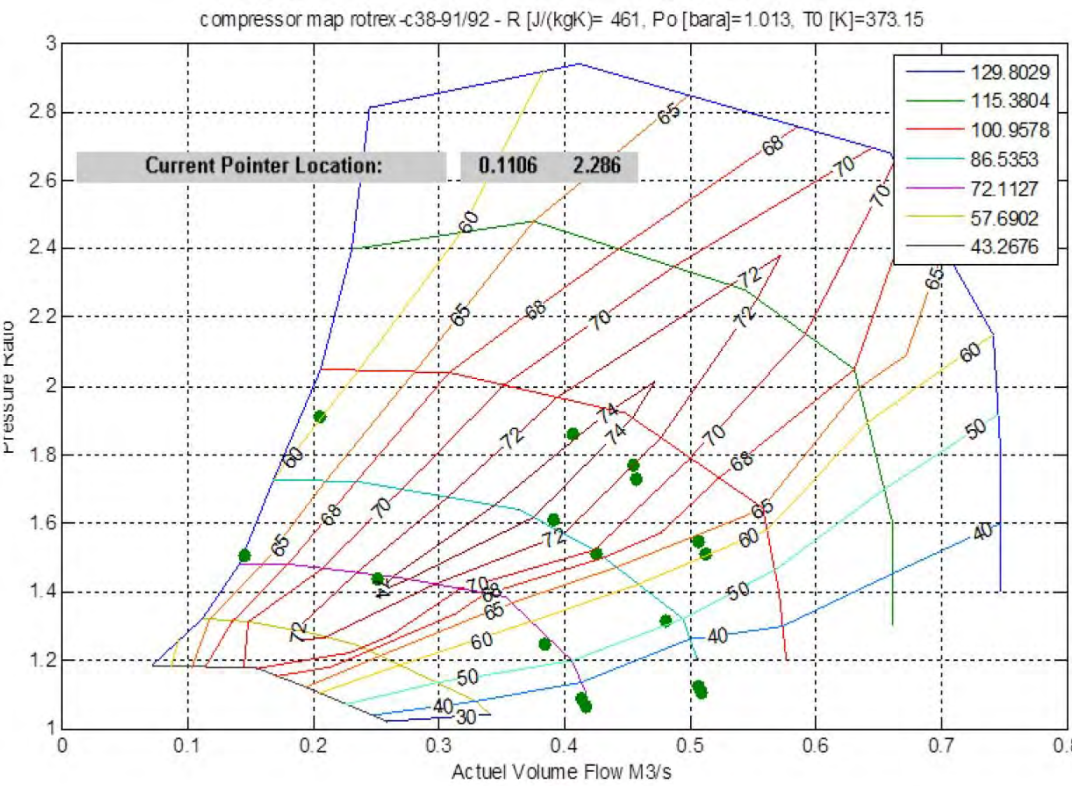


Figure 5-9: Measured operating points shown in the predicted (transformed from air to steam) compressor map

The new turbo compressor including traction gear has a very high volumetric suction capacity considering its compactness and weight of only 6 kg. For comparison a screw compressor [Mayekawa, 2002] for steam compression with a capacity of about 12,000 m^3/h has a weight of approximately 6,000 kg. The same capacity and temperature lift can be reached with 12 Rotrex turbo units arranged in a two stage (8 in 1st stage 4 in 2nd stage) parallel-serial configuration resulting in a total weight for compressors of 72 kg.

The cost of the multiunit concept of turbo compressor that can be mass produced is considerably lower than other compressor concepts with the same capacity.

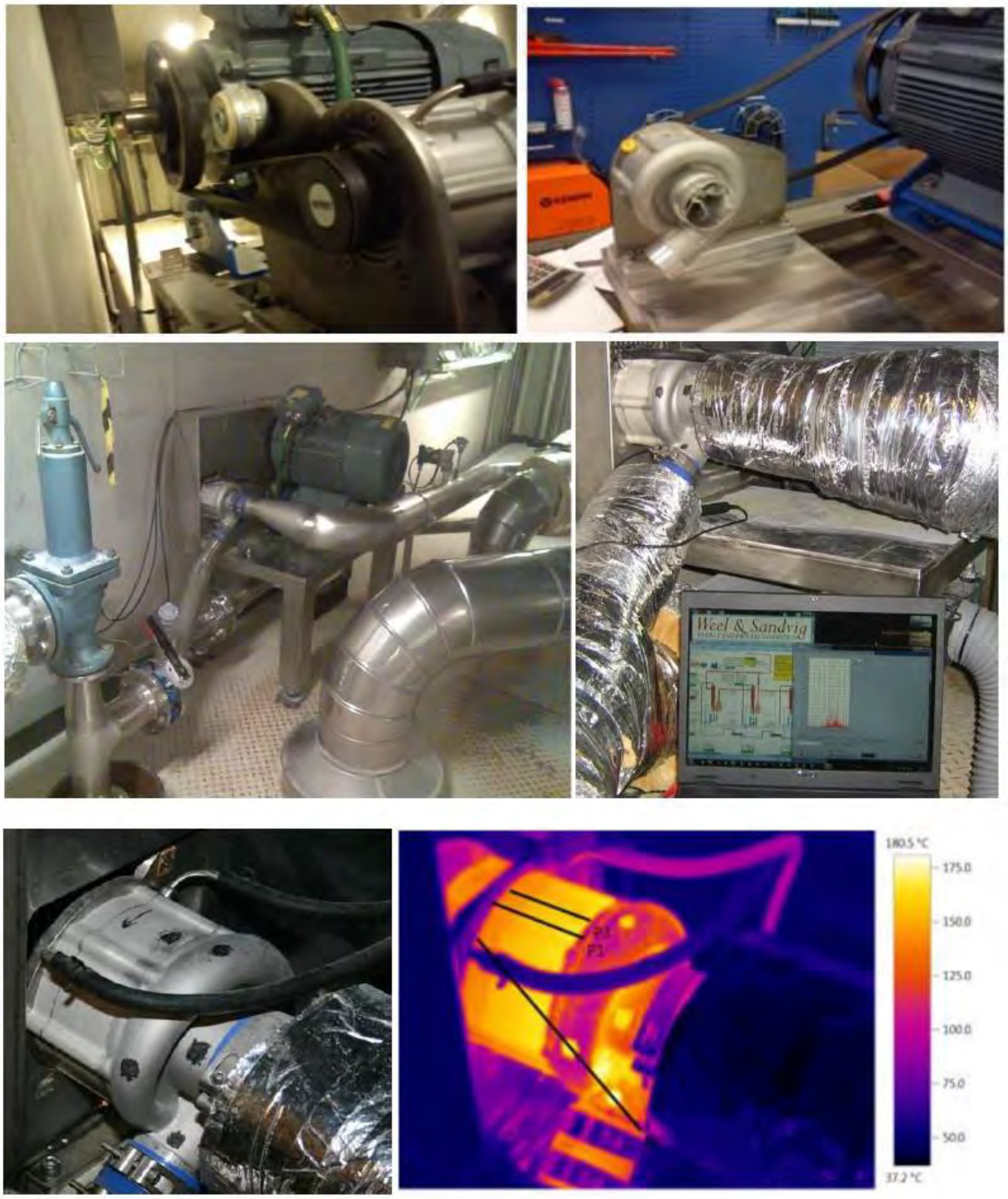


Figure 5-10: Pictures from the first heat pump test at Haldor Topsøe's production facility in Frederikssund, Denmark

Heat pump applications in the drying industry

The new heat pump concept has potential for being used in many drying applications to reduce primary energy consumption. For most drying applications a temperature lift above 40 K is required for balancing cost of investment and operational cost.

The new compressor unit developed in the project (by DTI, ROTREX, and Weel & Sandvig) is designed for a pressure ratio up to 3 which is equivalent to a temperature lift about 30 K. To accomplish a higher temperature lift a two-stage configuration with compressors arranged in a serial coupling as shown in Figure 5-11 can deliver temperature lifts between 30 and 60 K.

Figure 5-11: Compressor set up in parallel combined with serial coupling to match required capacity and pressure ratio

One possible application is timber drying. Timber is dried as a batch process with a typical drying profiler versus time as shown in Figure 5-12.

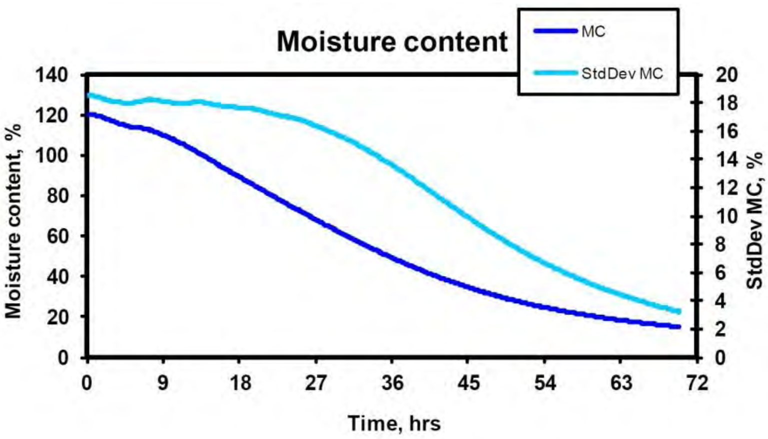


Figure 5-12: Typical drying profile for a timber drying kiln

In Figure 5-13 two options for heat pump integration in a timber drying kiln. To the left a heat pump retrofitted to a conventional “Air dryer” and (to the right) a super-heated steam kiln drying process. For the conventional kiln drying process, the heat pump circulation fan consumes about 20 kW and the compressor consumes about 84 kW when delivering 446 KW heat to the drying chamber. The total COP value is about 4. In the super-heated steam drying kiln drying concept the COP-value can reach above 7.

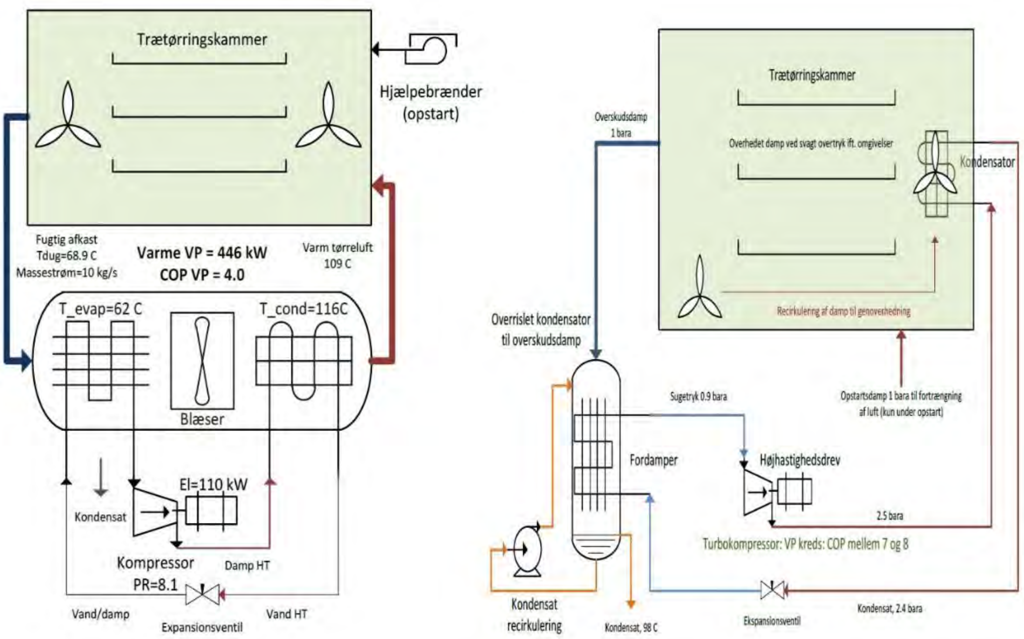


Figure 5-13: Heat pump integrated in a timber drying kiln.
Left: conventional drying and right: drying in super heated steam

Another application is a disk dryer used in fish and bone meal industry and sludge drying etc. The heat and mass balances for a heat pump integrated with a disk dryer is shown in Figure 5-14.

When integrating a heat pump with an indirect dryer it is important to reduce the amount of air in the dryer and exhaust air to a minimum in order to maintain a high dew point temperature profile at which the heat can be extracted from the exhaust stream. In addition lower air content in the exhaust implies higher heat transfer coefficient and consequently smaller heat exchanger with less pressure drop, saving power for blower.

Figure 5-15 shows the condensation temperature versus heat at 1 bara total pressure in exhaust streams from a drier evaporating 1 kg/s of water having various content of air. Almost pure water (no air content) will condense at 100 °C constant temperature. If just a small amount of air is present the condensing temperature will decline considerably. If for instance 7 % air is present, the final condensing temperature (evaporation temperature if seen from the heat pump site) will fall about 10 K and thereby requires much higher temperature lift and input of compressor power to the heat pump.

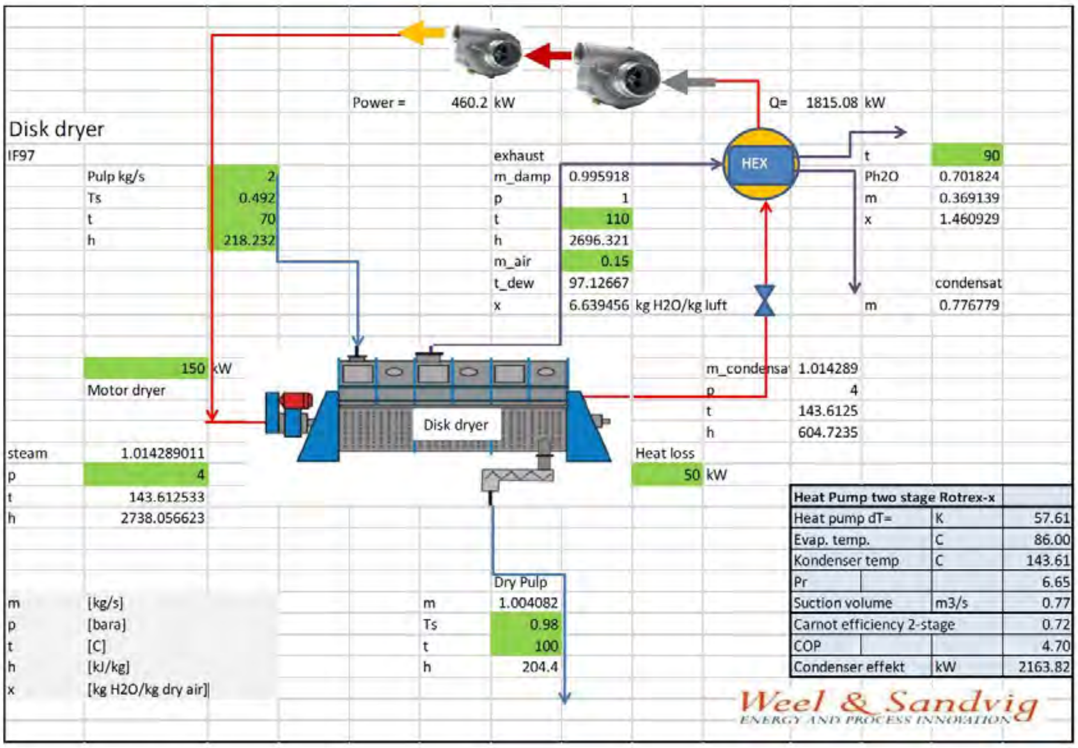


Figure 5-14: Energy and mass balance of a heat pump integrated with a typical disk dryer (fish and bone meal industry)

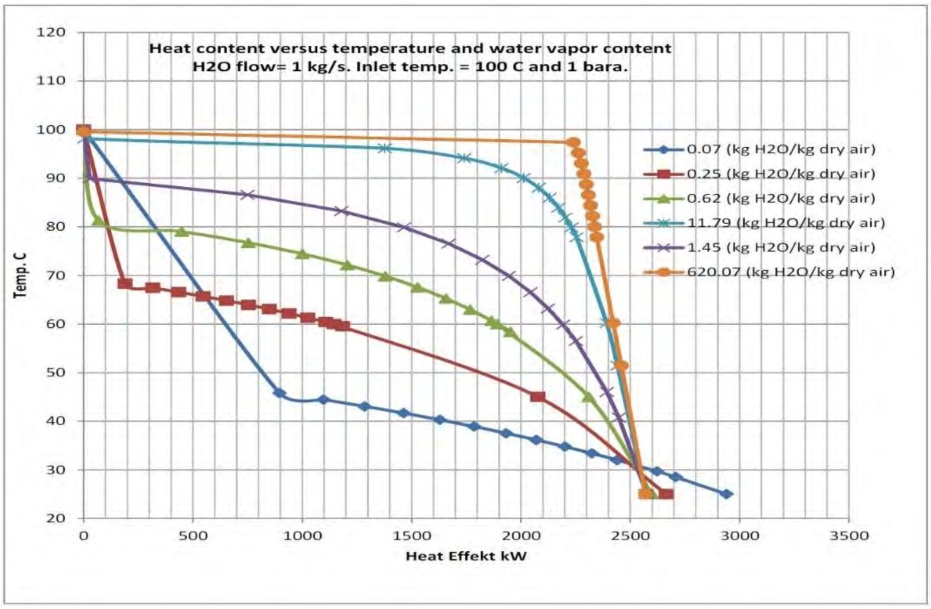


Figure 5-15: Heat content versus temperature and water vapor content

Drying of PET food in super-heated steam has been developed [Schmidt, 2012], where a heat pump has been considered, as shown in Figure 5-16.

When integrating a heat pump into a super-heated steam dryer, optimization of circulating steam flow and temperature rise and heat exchanger size has to been considered. In

Figure 5-17 is shown COP values and power uptake from the steam compressor and steam circulating fan versus logarithmic mean temperature difference in steam re-heater (dTmin= 5 K). As shown there is a minimum of total power consumption.

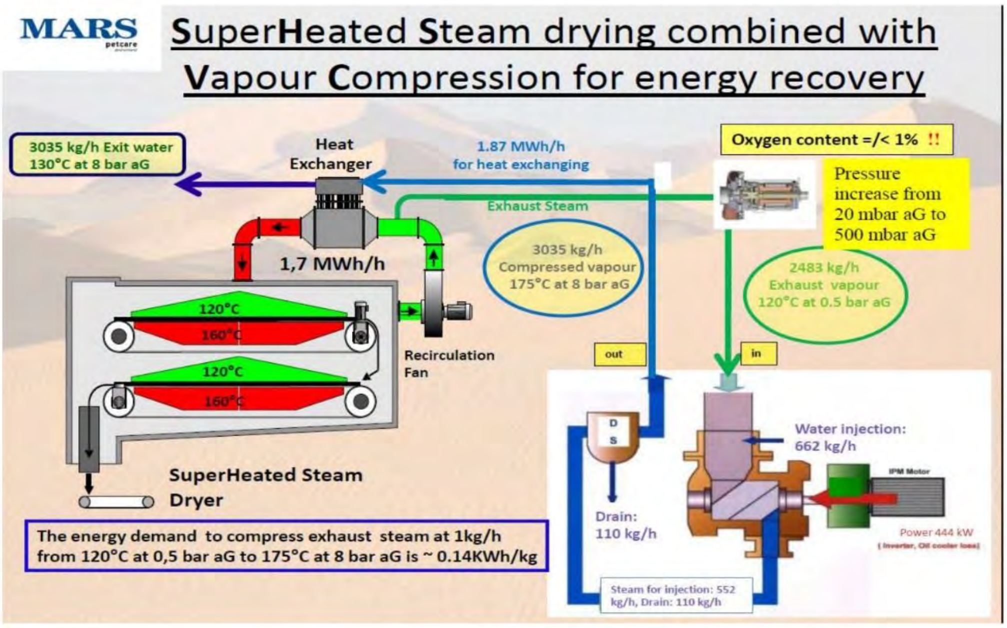


Figure 5-16: Super heated steam drying process for pet food with integrated heat pump – ref [4]

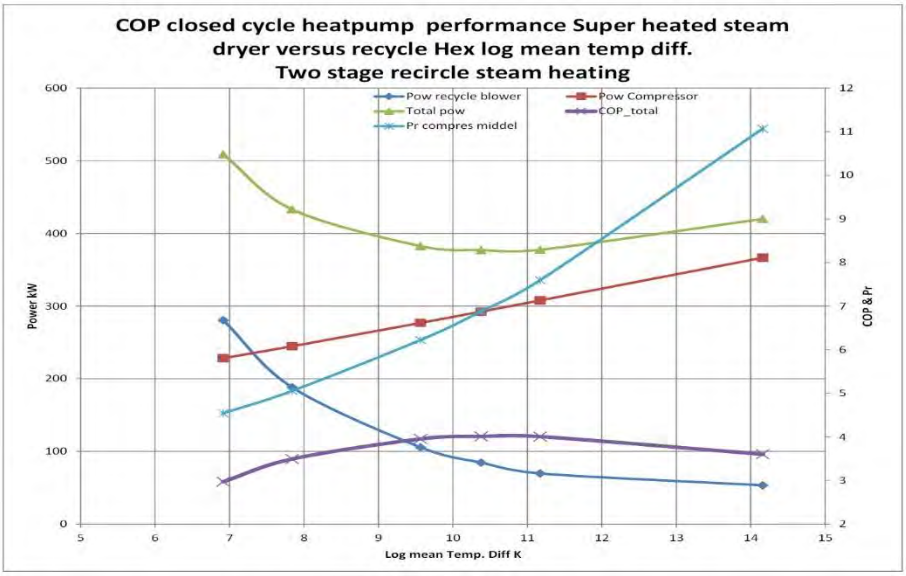


Figure 5-17: Example of optimization of a heat pump for a SHS dryer delivering 1,500 kW heat

Conclusion

We see a bright future for heat pumps in drying applications and expect this technology to provide the major energy savings and CO_2 reductions in the drying industry. Analyses have shown that the new turbo-compressor based heat pump concept can be integrated into drying applications and achieve COP-values between 4 and 7.

Mayekawa, 2002 Steam Compressor for Brewery Plant Y. Endo, Mayekawa Mfg. Co. 2002.

Schmidt, 2012 SHS AS A TECHNOLOGY PLATFORM FOR SUSTAINABLE & COMPETETIV ADVANTAGE, Taastrup 02.11.2012, Siegfried Schmidt, Mars GmbH Europe.

Weel, 2012 Industrial heat pumps for high temperatures, Mogens Weel, Jens Mikkelsen, 2012.

Weel, 2013 The potential for high temperature heat pumps in industrial application, Weel & Sandvig, 2013.

5.3.2 Development of ultra high temperature hybrid heat pump for industrial processes

Industrial scale heat pumps have until recently been limited to maximum temperatures of 75-80 °C and thereby limiting the application range. During the last years new components are available and the use of high temperature heat pumps for waste heat recovery has found its way into the market. A maximal temperature of 100°C is still the limitation for these processes based on the traditional heat pump cycles and fluids. Hybrid Energy (HE), which is a partner in this project, has reinvented a heat pump process called “the hybrid process” where the absorption and compression cycles are combined. Because of this combination it is possible to reach temperatures of 110° C with standard industrial refrigeration components. This can be done with very high efficiencies. There are currently 6 hybrid plants running in the market with more than 50,000 running hours. The process has proven to be reliable and it is possible to reach the estimated values of COP. During the EUDP project “Utilization of low grade waste heat by means of high temperature heat pumps” the Danish company Innotek was introduced to HE and the hybrid process, and has signed an agreement with HE concerning cost optimization and representative for the Danish market. The interest in Denmark has grown tremendous due to this.

The aim of the project is to increase the operating limits of the hybrid process by using the new standard components that are approved to higher pressures. By using new components the maximum temperatures can be as high as 180-250 °C. This will open new markets in the food and process industry for utilizing heat pumps to recover waste energy at a lower temperature level and bring the energy back into processes at a higher temperature level. Nearly 100 % of these processes are today heated using fossil fuels.

The project will demonstrate that it is possible to develop an efficient and reliable heat pump process for high temperatures above 180-250 °C.

The project consists of three parts

1) Theoretical and practical investigation of the hybrid heat pump process for ultra-high temperatures

2) Investigation of possible implementation into the processes at the end users in the consortium and the conduction of a general market survey
3) Demonstration at one of the end users in the consortium

The project will verify that it is possible to reach temperatures in the range of 180-250 °C based on the commercial available industrial refrigeration equipment coming to the market these years. The implementation of such high capacity systems will make it possible to lower the use of primary, nearly always fossil fuels significant in processes which are nearly impossible to day. The project will investigate where an ultra-high temperature hybrid heat pump can be a profitable tool to do this. Further ultra-high temperature heat pumps (UHTHP) will make it possible to implement more renewable energy into the food and process industry.

The hybrid process

The hybrid process is a combination of the well know vapor compression cycle and the absorption cycle using the natural refrigerants water and ammonia. The two refrigerants are flowing in the hybrid process as a mixture. When mixing the two refrigerants it is possible to reach a high temperature at moderate pressures.

As shown in Figure 5-18 the maximum achievable temperature is depending on the con-centration of the water/ammonia (H_2O/NH_3) solution.

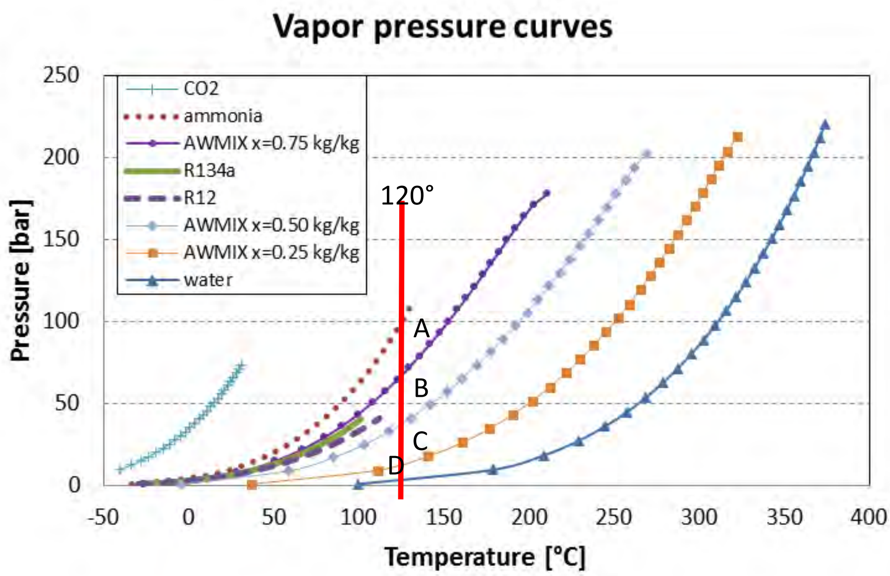


Figure 5-18: Comparison of different refrigerants the needed pressure to reach a given temperature

The figure shows the achievable temperatures for different working fluids. The red line indicates 120 °C, and it can be seen that the needed pressure in order to achieve this is highly influenced by the concentration: A: Pure NH_3 ~ 100 bar, B: 75% NH_3 ~ 65 bar, C: 50 % NH_3 ~ 35 bar and 25 % NH_3 ~ 15 bar. Using pure water the pressure is 1 bar(g).

The low operating pressure makes it possible to use standard industrial refrigeration equipment up to 110 °C, which again has a very positive impact on the competitiveness against other technologies for the same temperature level.

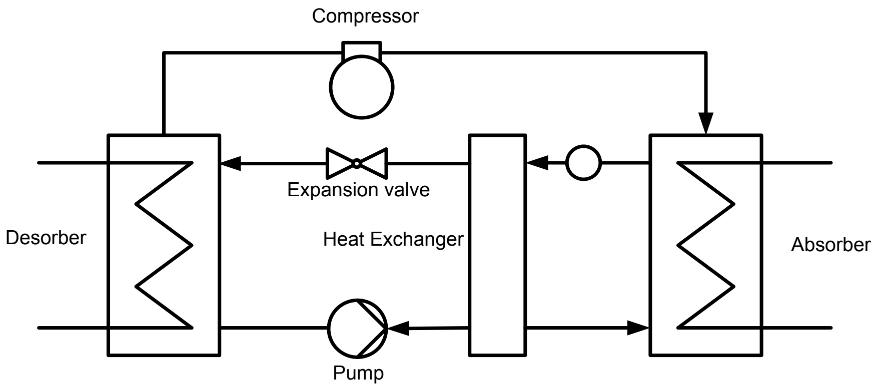


Figure 5-19: Flow diagram of hybrid process

Figure 5-19 shows a flow diagram of the hybrid process. Compared to a conventional vapor compression cycle the desorber corresponds to an evaporator and the absorber to a condenser. In the desorber heat is transferred from the heat source to the refrigerants, at low temperature (could be waste energy). In a conventional vapor compression cycle the refrigerant evaporates at a constant temperature. This is not the case for the hybrid process, where the evaporation is partial and the temperature of the refrigerants changes from the inlet to the outlet. This phenomenon is called a temperature glide.

The evaporated ammonia is compressed in a compressor to a higher temperature and pressure and the water (still liquid) from the desorber is pumped through a heat exchanger to the absorber. In the absorber the heat is rejected to a heat sink (bringing waste heat back to a process at a higher temperature). Again the heat is transferred with a temperature glide like in the desorber. In a traditional vapor compression cycle the heat in the condenser is rejected a constant temperature.

To achieve the highest COP for the process the temperature glide in the desorber and absorber should match the actual temperature profile of the heat sink and heat source. This is illustrated in Figure 5-20.

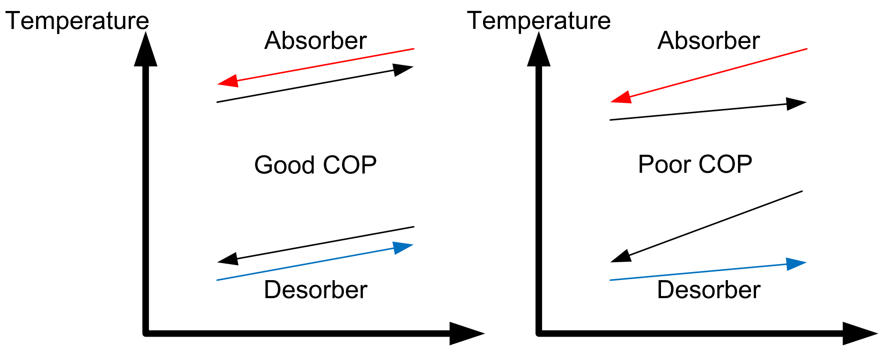


Figure 5-20: Temperature profile in absorber and desorber

5.3.3 Highly efficient Thermodynamic Cycle with Isolated System Energy Charging (ISEC)

This R&D-project has just been initiated and no experimental results are available at this time. The new concept is scheduled to be developed and demonstrated by 2016. Below is a short description of the project.

The objective is to demonstrate an improvement in the energy efficiency of heat pumps with up to 50 % by using a novel technology where heat pumps are operated with usage of storages which will reduce the average temperature level in the heat pump. The pay-back time for the investment is expected to be less than three years.

The project aims at developing and demonstrating how a high-efficiency heating unit based on the traditional thermodynamic cycle process in a heat pump can achieve an energy saving potential up to 50 % by using a newly developed “Isolated System Energy Charging” concept (ISEC). By heating one tank at a time, the condensing temperature (or evaporating temperature) of can vary according to the actual temperature of the secondary medias. This means that the condensing temperature will be only slightly higher than the medium temperature of the liquid during the heating process.

The ISEC concept consists of two or more tanks. One tank is heated while the other (which previously has been charged) is discharged. When the second tank has been discharged, the first tank is fully charged with and the system switches to discharge the first tank while the second tank is being charged. Seen from the heat source and the heat sinks perspective, the introduction of the ISEC concept does not change the conditions.

Project activities include theoretical calculation, design and construction of individual components, experimental stage and construction of actual systems during the demonstration stage.

5.4 Economy and other incentives

As mentioned elsewhere in this report, electricity is 2.5 to 3.5 times more expensive than traditional fuels for boilers, thus requiring a COP for heat pumps in this area or higher in order to be competitive in industrial applications. The initial cost of heat pumps compared to traditional heating plants is also several times higher, meaning that only heat pumps with very high COP values and many operating hours will be profitable. Because of this the most immediate applications are processes with small temperature lifts, a lot of operating hours and a steady demand meaning less complex (expensive) systems.

Although payback periods from reduced energy consumption are longer than desired in most cases, there could be other drivers. Cooperative energy policies such as reduced consumption, CO_2-foot print and so on could be met by utilizing heat pumps.

In Denmark energy consumers and providers are required to reduce energy consumption by a certain amount each year. This requirement can be met either by reducing one's own energy consumption, or by buying an excess reduction from somewhere else. E.g. three companies are each required to reduce their energy consumption by 5 MWh a year. If one of the companies finds a way to reduce energy consumption in that company by 15 MWh and the others don't reduce consumption, it is allowed for the first company to "cover" for the other two companies by splitting the excess reduction. In praxis the energy reductions (called energy savings) are traded between companies, suppliers and advisors throughout each year. The price for each MWh of "energy savings" varies depending on the buyer, availability and expectations to the market. One MWh of "energy savings" typically holds a value of between 50 and 65 Euros. For heat pumps with many operating hours (> 6,000/yr), "energy savings" will typically cover half of the investment costs meaning that this "subsidy" is essential for heat pumps in industrial applications.

"Energy savings" has no value in district heating plants as these are not part of this system. Energy consumption for residential heating is taxed and heat pumps have an advantage as tax per heat unit is considerable lower using heat pumps than other fossil fuels. This means that utilization of heat pumps in district heating systems is possible with short pay back periods as well.

6 France

6.1 Introduction

Europe is now committed on its energy policy for 2020 and further. Among other objectives, the European Union shall reduce its own CO_2 emissions and energy consumption and increase the proportion of renewable energies in its energy mix by at least 20%. Supplier obligations and white certificates were established in France in order to contribute to these energy-efficiency goals. Energy savings in the industrial sector are eligible for white certificates, as well as are the residential and commercial sectors.

Energy consumption in French industry represents 450 TWh/year. About 75% of the final energy use is for thermal purposes (furnaces, reactors, boilers, dryers etc.). The major part of that heat comes from the combustion of fossil fuels generating large CO_2 emissions. Some studies estimate that around 30% of the final energy used for thermal purposes is wasted through losses In the industrial sector, only few measures can be rewarded by white certificates in France. Most of them are obtained through boiler economizers and variable speed drives (VSD). Indeed, these two measures have high EE potential and are quite simple to implement on site. On the opposite, energy savings of more complex projects can hardly be estimated by standardized ex-ante methods and the evaluation procedure of non-standardized measures is quite slow. As a consequence, complex actions such as heat recovery on industrial processes can hardly be rewarded for the moment. However, in order to achieve energy-efficiency and CO_2 goals, actions of saving, recovering and utilizing the heat should be developed and recognized as eligible for white certificates.

The main industrial heat needs range from 60 to 140 °C and they represent about 30 TWh/year. At these temperature levels, many opportunities for heat Pump technology exist, and allow recovering low temperature heat to produce high temperature heat.

Some studies estimate that it is in theory possible to recover in flue gases between 10 % and 25% of the fuel used by thermal high temperature equipments such as boilers, furnace or dryers, which means approximately 35-85 TWh/yr for France. However, this whole potential is not entirely economically accessible. For example, some flue gases can be corrosive so that it is expensive to install a heat exchanger with a resistant material. In addition, compared to quality of products and productivity, energy savings are not a major criterion for investments in industry. EDF experienced that pure EE investments (not dedicated to the production) must generally have a payback time lower than 3 years to be accepted. Due to that strict criterion, some investments will not be "judged" as cost-effective by certain industrials so that a part of the whole potential will not be reached.

Heat pumps (HP) often require important investments. Hence, this technology will spread first and principally to sectors with the shortest payback time.

In the 80's in France, developments of high temperature heat pump started to emerge. Due to the low price of energy and high investment, it was difficult to find a good return on investment, gas boilers were preferred. Since a few years, there is a renewed interest for heat pumps. Recent developments have been made to develop industrial

(> 100 kW_{th}) high temperature heat pumps (> 80 °C) and very high temperature heat pumps (> 100 °C). Currently, there are only a few closed-cycle mechanical high or very high heat pumps installed in the French Industry, but interest and references are growing.

6.2 The French industry

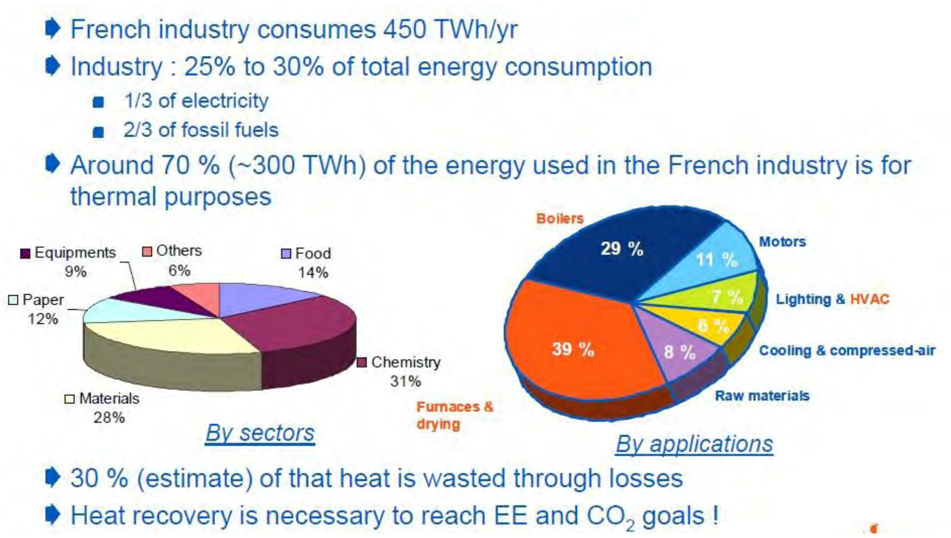


Figure 6-1: Stakes of the heat recovery in the French industry

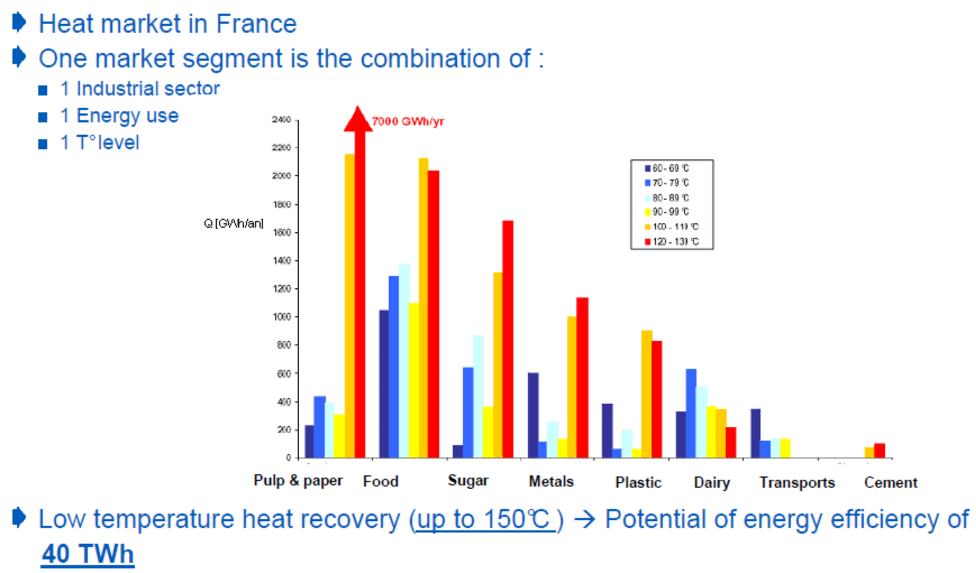
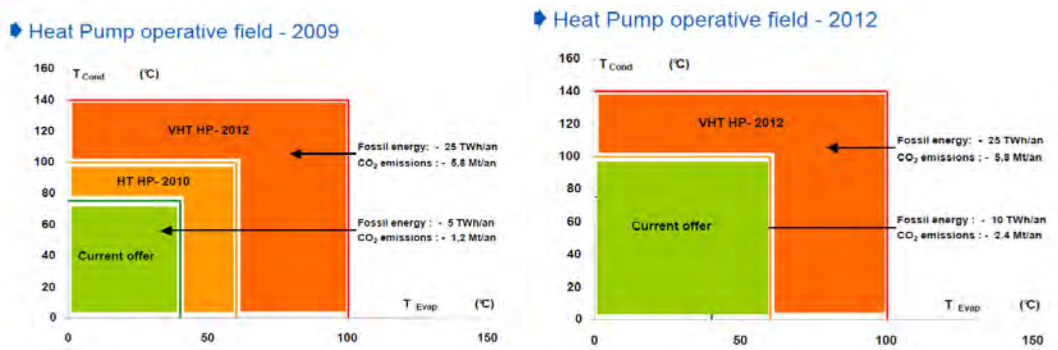


Figure 6-2: Heat market in the French industry

6.3 The temperature level

The temperature level reached by the condenser is a main parameter for heating application. Before 2009, there were no standards heat pumps able to reach a temperature above 80 °C. The identification of a huge quantity of thermal needs in the temperature range 80 – 140 °C leaded to develop systems able to heat above this temperature limit.

Figure 6-3: The evolution of the temperature level



The next figure shows the temperature levels reached by different manufacturers in 2013.

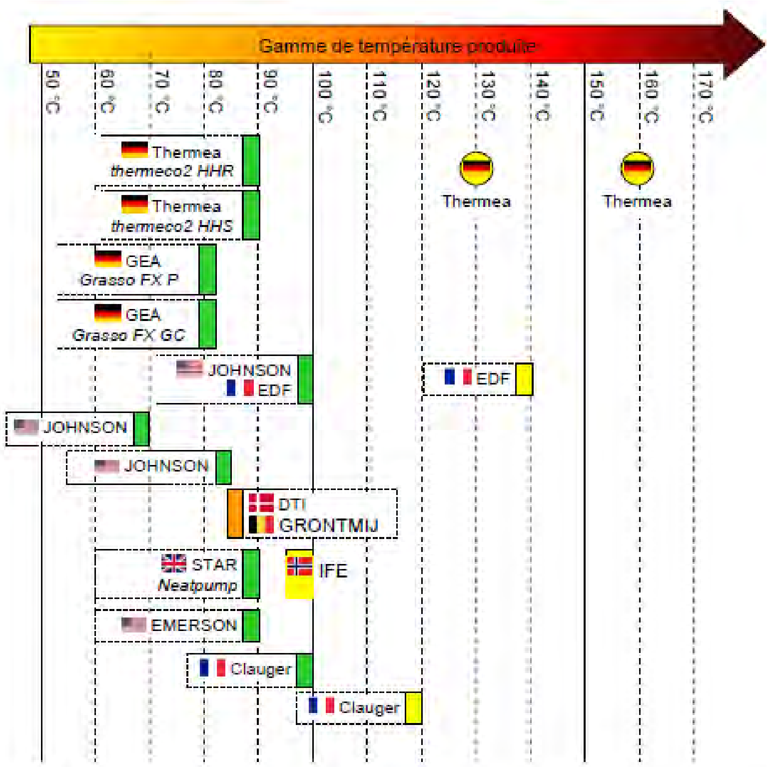


Figure 6-4: The temperature level reached by the manufacturers

The three main actors in high temperature industrial heat pumps France are: Johnson Controls (YORK), Clauger and EDF. They have a distribution and maintenance network in France.

6.4 Heat pumps in France: maturity, fluids and technology

The next chart gives details of the technology of the heat pumps developed or installed in France.

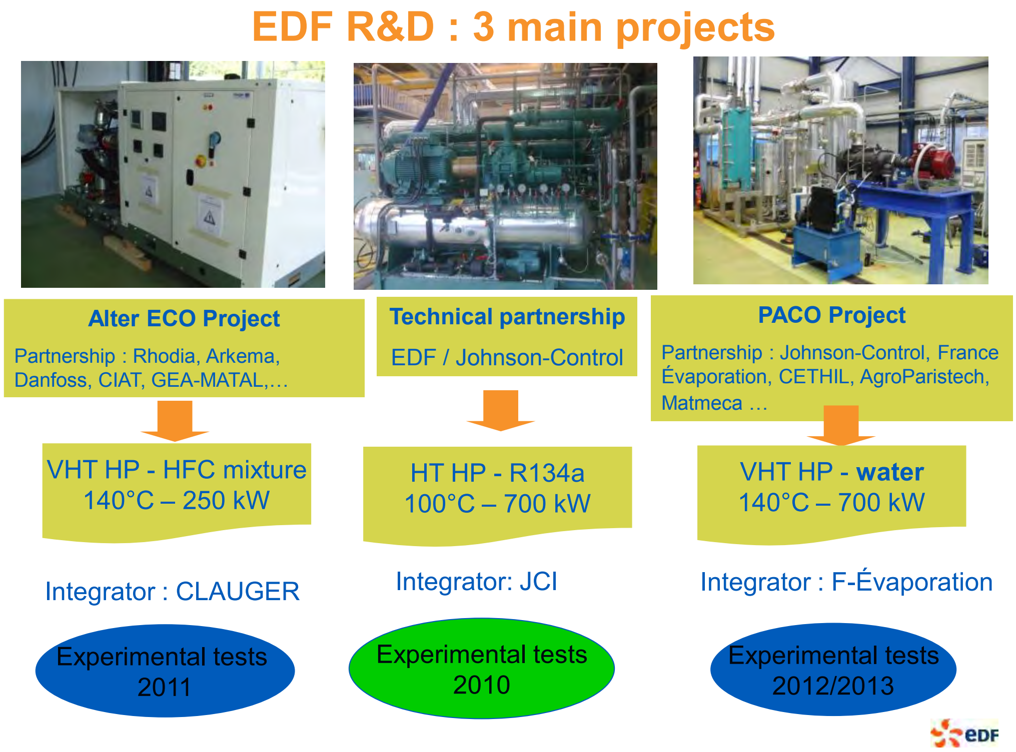
Table 6-1: Temperature, maturity and technology of industrial heat pumps in France

Temperature	Maturity	Manufacturers / Developpers	Refrigerant	Compressor technologie
Up to 70 °C	Standards	Trane GEA Clauger Ciat Carrier	R134a Ammonia	Centrifugal Screw
70 - 100 °C	Commercialized	Johnson Control/EDF	R134a R245fa	Centrifugal Screw
		Clauger	Ammonia	Screw Surcompressor on chiller condenser
		GEA Refrigeration	Ammonia	Screw
100 – 120 °C	Pre commercialized	Jonhson Control / EDF	R245fa	Centrifugal
		Clauger	Ammonia	Surcompressor on chiller condenser
120 – 140 °C	Prototype	EDF – Altereco EDF – PACO	ECO3 [1] Water	Centrifugal, Scroll
140 – 165 °C	Ø	Ø	Ø	Ø

[1] ECO3 is a mixture of HFC

6.5 EDF R&D activities

EDF is working on the development of high temperature industrial heat pumps with new working fluids to reach temperature higher than 100 °C.



6.6 Current and future activities

AlterECO Project : industrial experimentation in 2014

EDF / JCI: experimental test up to 120 °C with R-245fa

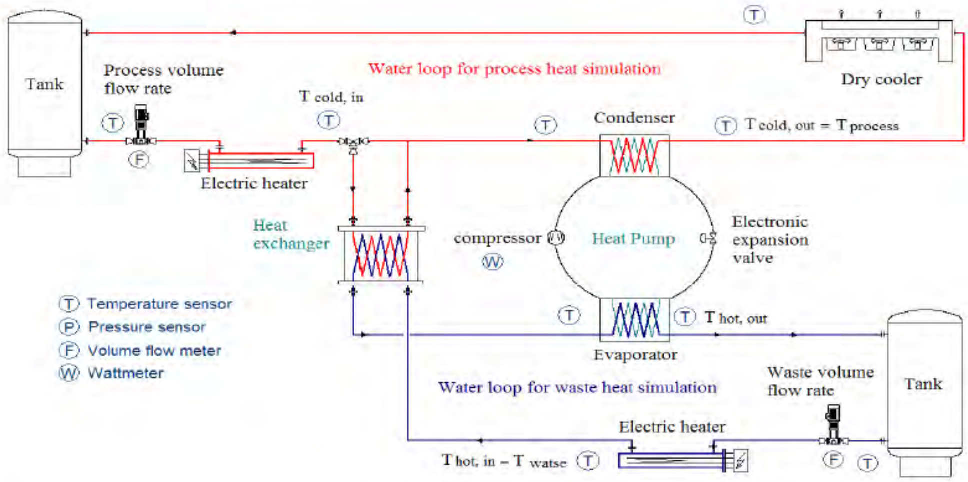
PACO Project: centrifugal compressor with magnetic bearings

6.7 Experimental test bench at EDF R&D

For machines that operate at high temperature, the EPI department of EDF R&D and Johnson Controls have developed a test bench to improve high temperature performances, made of three hydraulic loops:

- The high temperature loop (in red) allows simulating the process heat requirement. This circuit is equipped with a pump and variable capacity dry cooler. Water or pressurized water are currently used as fluid.
- The low temperature hydraulic loop (in blue) simulates the process waste heat. Water is used as fluid.

- The third loop (brown) is needed to remove heat from high temperature loop with the help of a variable capacity dry cooler. The glycolic water is usually used as fluid.



	Effluents loop		Requirements loop	
	Min	Max	Min	Max
Temperature [° C]	5	95	5	145
Flow rate [m³/h]	16	44	21	48
Storage volume [m³]	4		5	

Figure 6-5: The experimental test bench

Both high and low temperature loops include a water tank, a controlled electric heater, and a water pump with adjustable volume flow rate. Furthermore, the system includes a counter-current plate type heat exchanger for primary heat recovery before the heat pump.
Those hydraulic loops are composed with several sensors: temperature transducers PT100 (0 – 200 °C range ±0.5 K), electromagnetic flow meters (± 0.25 % in the operating range of the experimental conditions). All sensor measurements are collected at steady state conditions using a dedicated PC via convenient data acquisition software.

6.8 Technical partnership: EDF & Johnson Controls

For machines that operate at high temperature (up to 100 °C), the EPI department of EDF R&D works in partnership with Johnson Controls to improve performances of HPs (laboratory tests with fluids such as R-245fa) and promote industrial implementation.

6.8.1 Description of the heat pump

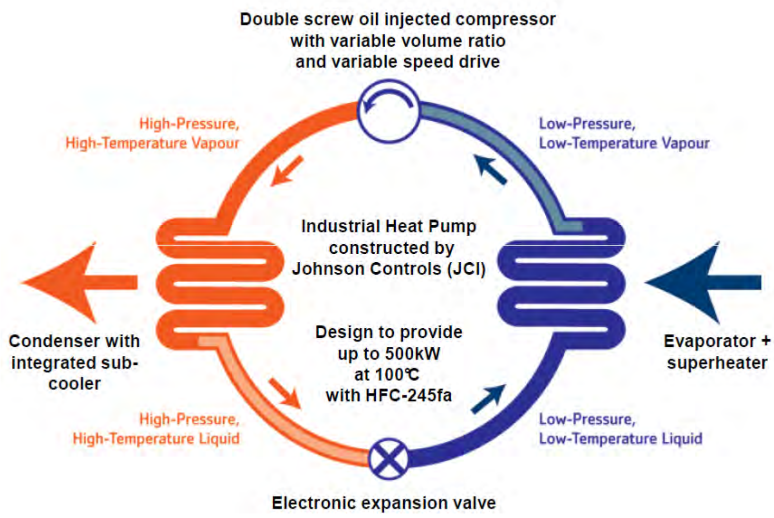


Figure 6-6: The JCI / EDF heat pump

The double screw compressor was replaced with a centrifugal compressor.

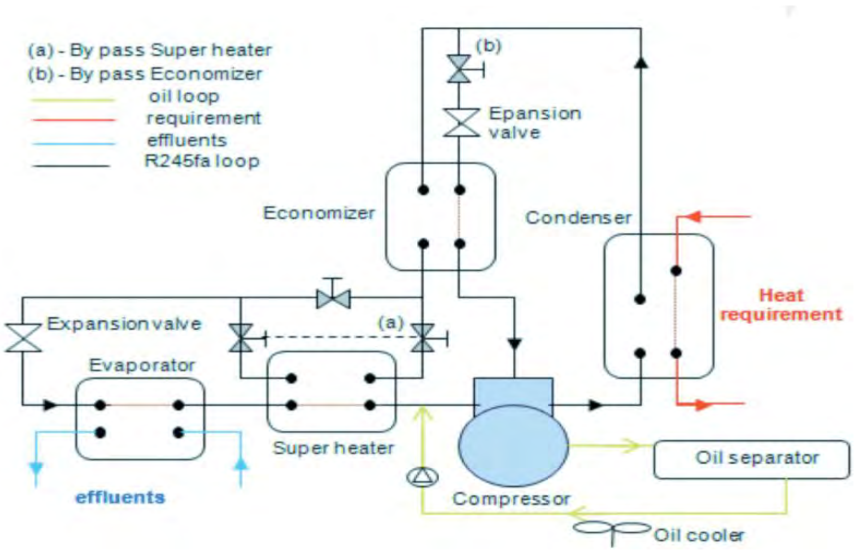


Figure 6-7: Schematic of the JCI / EDF heat pump system

Figure 6-8: Picture of the JCI/EDF heat pump

6.8.2 Results and performances

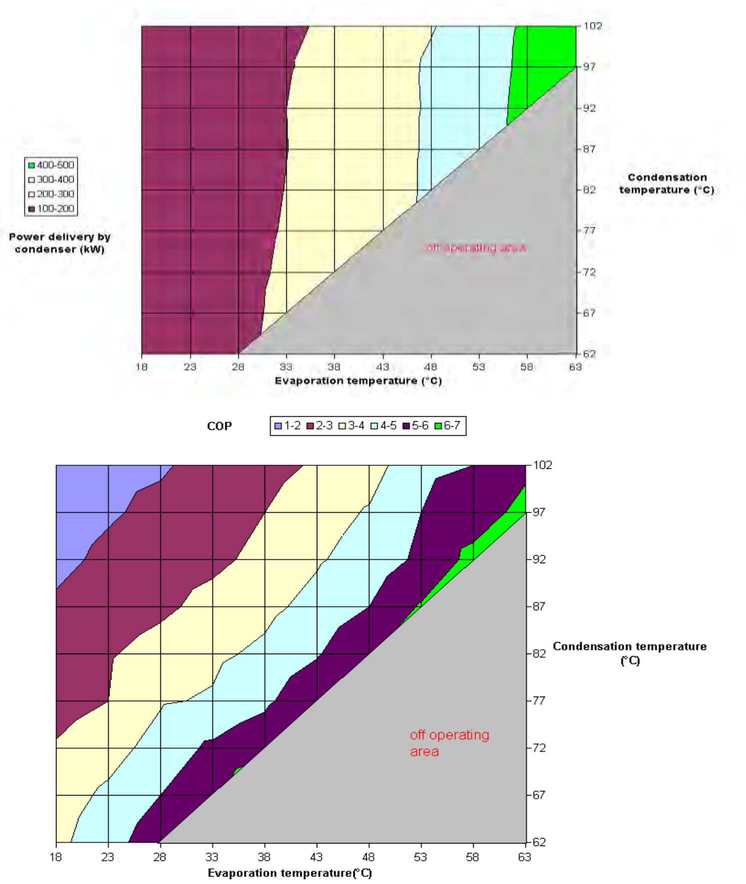


Figure 6-9: The JCI / EDF heat pump performances

6.9 Altereco project

This project includes the development and industrial testing of HPs capable of operating at 140 °C in condensation mode. The project includes a number of partners: Danfoss, Arkema, Ciat and Clauger who are studying and supplying heat exchangers, fluid, compressors, etc.
The projects leads to the publication : " Experimental results of a newly developed very high temperature industrial heat pump (140 °C) equipped with scroll compressors and working with a new blend refrigerant".
The compressor power is 75 kW. The machine performances have been characterized to demonstrate the technical feasibility. For each evaporation temperature (from 35 to 60 °C by step of 5 °C), the condensation temperature is increased by step of 5 °C from 80 up to 140 °C.
Test campaigns over 1,000 hours were carried out in industrial-like conditions to demonstrate the reliability.
The efficiency of heat recovery up to 125 °C is demonstrated. Good performances are obtained. For higher temperatures, the technological feasibility is demonstrated but some further developments have to be carried out to increase the efficiency and the economical viability: 2 stage compressors (it is designed for a given pressure ratio), expansion valve, etc.

All this demonstrates the prototype reliability and the capacity to use this newly developed machine for industrial purposes.

6.9.1 Description of the heat pump

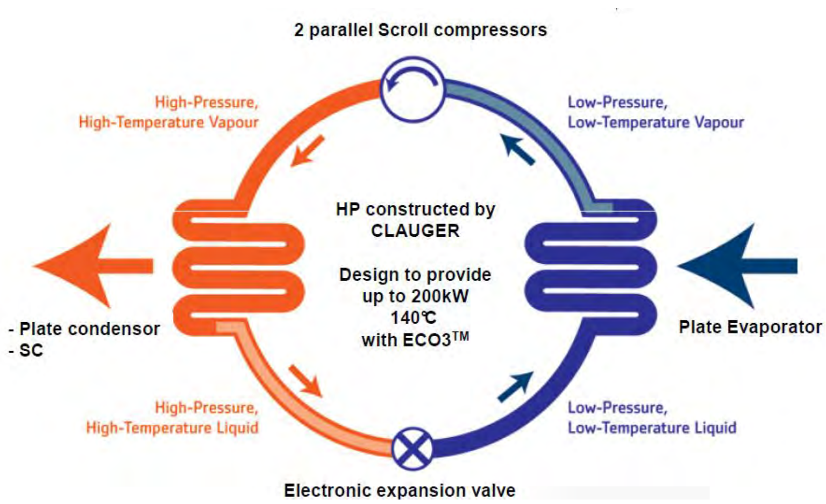


Figure 6-10: The Altereco heat pump

Technical specifications :

- Condensation temperature : 77 to 140 °C
- Evaporation temperature : 30 to 60 °C
- Compressors max power : 75 kWe
- Condenser max power : 200 kWt

Figure 6-11: Picture of the Altereco heat pump

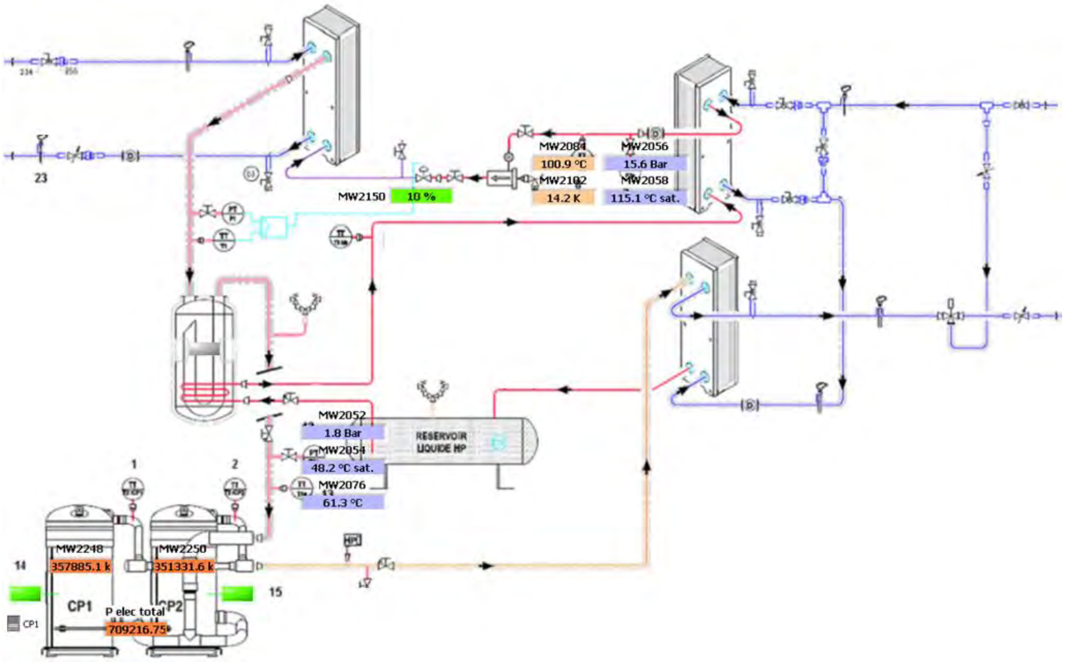


Figure 6-12: Schematic of the Altereco heat pump

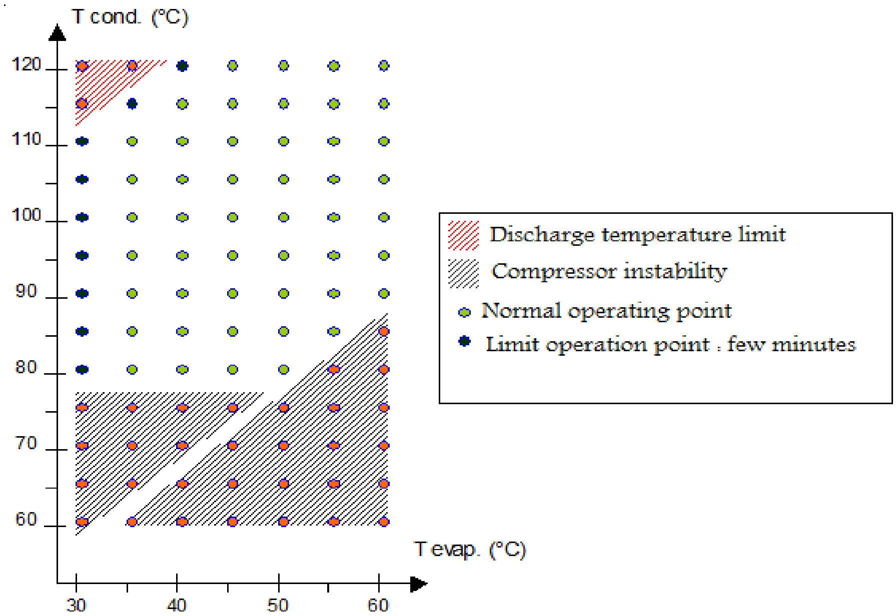
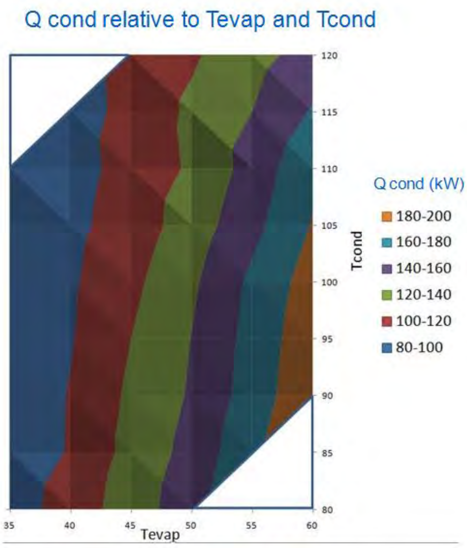
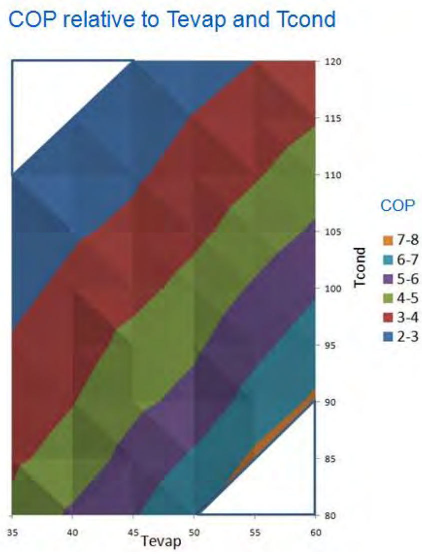


Figure 6-13: Operating points

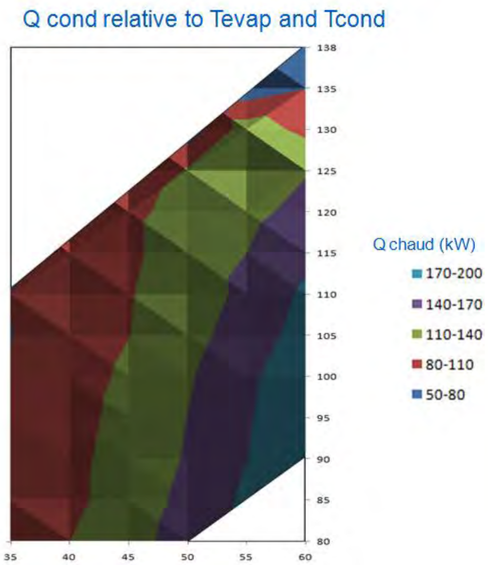
6.9.2 Results and performances

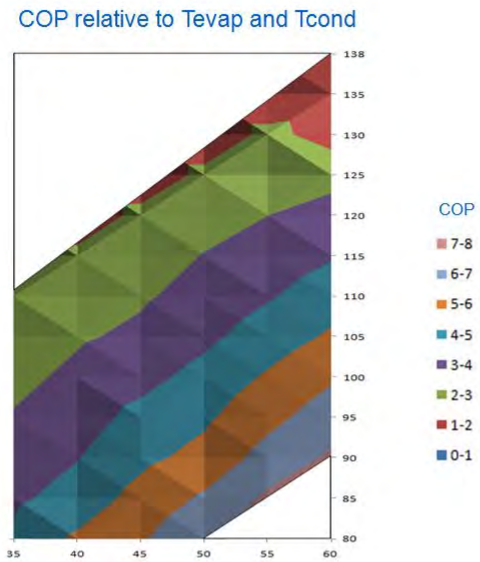
6.9.2.1 First test phase (120 °C)





6.9.2.2 Second test phase (140 °C)





6.10 PACO Project

Heat pump using water as refrigerant fluid is an interesting solution for waste heat recovery in industry. Water is non toxic, non ignitable and presents excellent thermodynamic properties, especially at high temperature. Indeed, like one can see on the following graph, COP of the different fluids decrease at a certain temperature (close to the critical temperature).

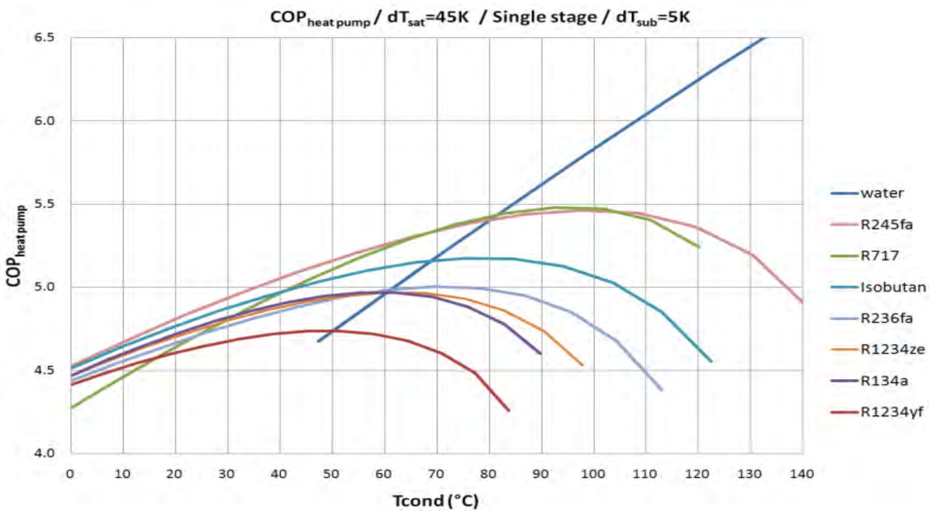


Figure 6-14: COP of different fluids vs the condensation temperature (Source: YORK)

Water HP development is complex, notably due to water vapor compression. The compression ratio of centrifugal and lobe compressors is low. It prevents gas temperature from rising more than 20 °C. For now, the only technical solution able to overcome this drawback with moderate costs is to put two lobe compressors in series. However, theses

compressors are less reliable than the others and their efficiency is low. Thus, the development of a novel water compressor is needed. Screw and centrifugal compressors on magnetic bearings seem to be the most promising technology. Discussions with the compressor manufacturers, and the numerical simulations show that the COP can be increased up to 80 % if such a compressor is integrated on a water heat pump. The price of this prototype compressor is very high, but it should decrease with the development of the market. Thus, the payoff would be guaranteed and the water heat pump would become an industrial reality.
This project, which is partly funded by the ANR, relates to the development of industrial HPs (700 kW thermal) that use water as refrigerant and are capable of operating between 100 °C and 140 °C in condensation mode. The compressors developed under this project will also be usable to apply the mechanical vapor recompression to concentration or drying applications. Johnson Controls, France Evaporation, Cethil, IMB, Agroparitech are EDF's partners for this development. The project has started in 2010. The HP prototype is under development.

Figure 6-15: Picture of the PACO project

Experimental tests have been realized up to 140 °C. At this level, technical feasibility is demonstrated but the expected performances are not reached, due to mechanical problems on the double screw compressor. A centrifugal compressor with magnetic bearings is now installed. It has been validated with air and is currently in test on the PACO heat pump with steam.

6.11 Prospects

It is expected to install in France at least 1,500 industrial high temperature heat pumps before 2020 in spite of various commercialization barriers:

- Lack of knowledge and experience with heat pumps

- Negative perception of heat pumps due to poorly designed models early in their use
- Volatile energy prices.

The population of industrial heat pumps is relatively low in all industries except lumber drying and malting. As a result, there is limited information for many industrial applications regarding proven engineering designs, actual field performance, and economics. This lack of awareness inhibits the growth of industrial heat pump installations.

There are also lingering doubts created from first generation industrial heat pumps installed in the 1970s and 1980s. Some of these early heat pump systems were improperly designed and did not perform as expected. However, a properly designed modern heat pump system will provide high reliability, often with a payback period in the range of 2 to 5 years.

Volatile energy prices are another factor that can impact the adoption of industrial heat pumps. An industrial heat pump can represent a major capital expenditure, and plant managers expect the investment to provide near term financial benefits. The financial benefits are directly tied to energy prices, and if energy prices are volatile, risk adverse decision makers may shy away from an industrial heat pump investment.

The integration of heat pump can be optimized with **thermal energy storage**, with various advantages:

- The heat pump works at its nominal point
- The thermal need can be covered with a smaller heat pump, decreasing the investment.

EDF R&D has experimental studies on this global heat recovery chain.

7 Germany

7.1 Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart

7.1.1 Advances in the development of industrial heat pumps

7.1.1.1 Emerson Climate Technologies

In cooperation with the Scottish heat pump manufacturer Star Refrigeration Emerson Climate Technologies presented the NeatPump. The NeatPump uses ammonia as working fluid since it has a high critical temperature and a high volumetric heating capacity. Emerson developed a new single screw compressor that can achieve a discharge pressure of 61.5 bar. Ammonia heat pumps with this compressor can produce heat at flow temperatures of up to 90 °C. The illustration in Figure 7-1 shows the advances being made by this new compressor technology. The ammonia NeatPump has been applied in several projects such as district heating and the generation of process heat and cooling in a chocolate factory [Pearson 2012].

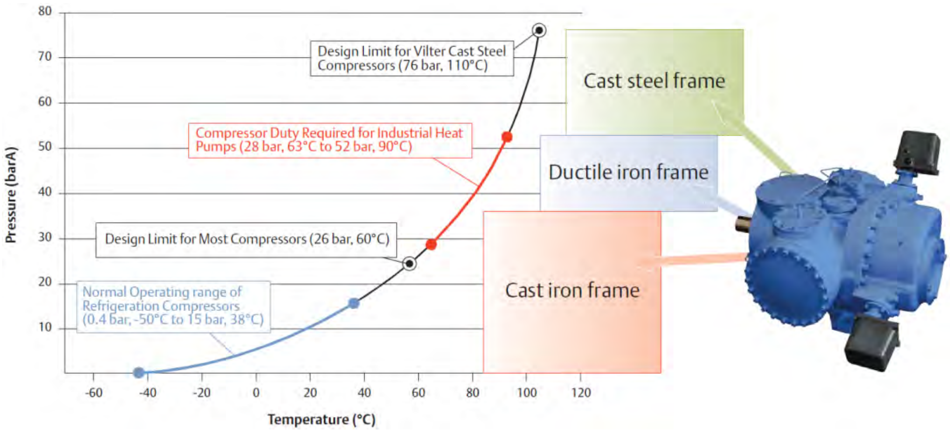


Figure 7-1: Pressure-temperature relationship and available compressor technologies [Emerson 2010]

7.1.1.2 GEA Refrigeration Technologies

GEA also developed a new compressor for high temperature ammonia heat pumps. The new double screw compressor design allows discharge pressures of up to 63 bar. This design is based on a 52 bar compressor. Compared to the standard version the new compressor was equipped with a stronger thrust bearing at the male rotor, a stronger driving shaft and other high pressure components. While the 52 bar version is limited to a maximum condensing temperature of 82 °C, the extended design can reach temperatures up to 90 °C. The compressors are available in various sizes from 165 to 2,838 kW drive power. At a source temperature of 35 °C and a sink temperature of 80 °C a heat pump using this compressor can reach a COP of 5.0 at a heating capacity of 14 MW. Ammonia heat pumps using this technology have been applied in several projects (e.g. a greenhouse, a paper mill and a production facility for galantine) [Dietrich 2012].

7.1.1.3 Thermea Energiesysteme

Thermea is a specialized manufacturer for heat pumps using the natural refrigerant CO_2. The company two series of high temperature CO_2 heat pumps. The thermeco$_2$ HHR uses a reciprocating piston compressor. It is available in different sizes from 45 to 1,000 kW heating capacity. Due to the special properties of CO_2 the maximum heat source temperature is limited to 40 °C. On the heat sink side up to 90 °C can be achieved. The thermeco2 HHS uses a screw compressor. The heating capacity of this heat pump is 1 MW. To make use of the large temperature glide CO_2 heat pumps show in the gas heat exchanger a high temperature lift on the heat sink side is preferred. Under these ideal conditions the heat pumps can achieve COPs up to 6.9. These large size CO_2 heat pumps have been successfully applied in different operating conditions such as a district heating system with river water used as heat source /Glaser 2013/.

7.1.1.4 Huber Kältetechnik (HKT)

Huber Kältetechnik has built two high temperature heat pumps using the refrigerant isobutane (R-600a). Its high critical temperature of 135 °C and the low GDP make it an interesting refrigerant for high temperature application. However, it should not be forgotten that R-600a is highly flammable.

The first heat pump is a two stage system with R-134a in the low temperature stage and R600a in the high temperature stage. With a heat source temperature of 17 °C and a heat sink temperature of 100 °C the heat pump reaches a COP of 1.7. The heat pump is now running for more than 5,000 hours.

The second example is a single stage heat pump that is used in a brewery to heat brewing water to 120 °C. The heat sink temperature is 75 °C. With a resulting temperature lift of 45 K the heat pump achieves a COP of 3.6 at a heating capacity of 54 kW [Huber 2013].

7.1.1.5 Siemens

Siemens did a screening for existing refrigerants that can be used for high temperature applications. A promising candidate was named LG6. It is already available in large quantities. The composition of this refrigerant is considered to be confidential until the research has been finished. The known properties are a critical temperature of more than 165 °C and a GWP of 1. In addition to that the refrigerant is neither toxic nor flammable. Siemens conducted several tests in a lab scale prototype of a high temperature heat pump with a heating capacity of 12 kW. Tests were carried out with heat source temperatures of up to 110 °C and heat sink temperatures up to 150 °C. So far LG6 has shown a slightly higher COP than R-245fa. Its use, however, is limited to heat sink temperatures larger than 110 °C due to its relatively low volumetric heating capacity [Reissner et al. 2013].

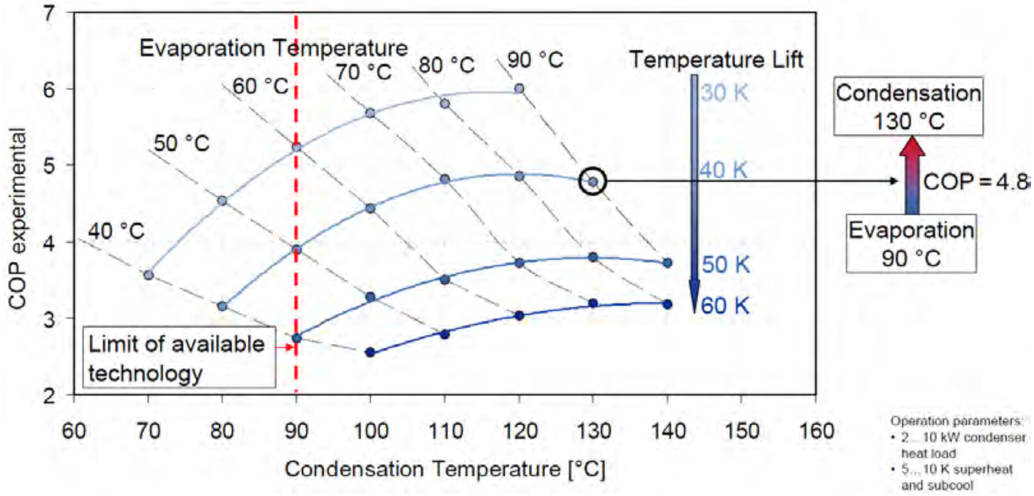


Figure 7-2: Test results for LG6 [Reissner et al. 2013]

7.1.2 Development and application of an industrial high temperature heat pump using R245fa

Within a cooperative research project the industrial plant building company Dürr Ecoclean GmbH, the heat pump manufacturer Combitherm GmbH and the institute for energy economics and the rational use of energy (IER) of the University of Stuttgart developed a high temperature heat pump, integrated it into a part cleaning system and performed an extensive testing program.

In the metal working industry many processes can be found that leave contaminations on the work piece's surface. Part cleaning systems are used to remove fats, emulsions, chips, particles and other contaminations from the work piece. Part cleaning systems can be differentiated by the degree of automation, part throughput, cleaning quality, maintenance requirements and energy consumption. However, the principle of operation is always similar. Work pieces are treated with a cleaning solution based on water or hydrocarbons. To achieve good cleaning results this solution must have a high purity. In conventional part cleaning systems contaminations accumulate in the cleaning solution. If certain purity thresholds are exceeded, the cleaning solution has to be replaced. In addition to an unavoidable down time costs for the disposal of the old cleaning solution and the purchase of the new one arise.

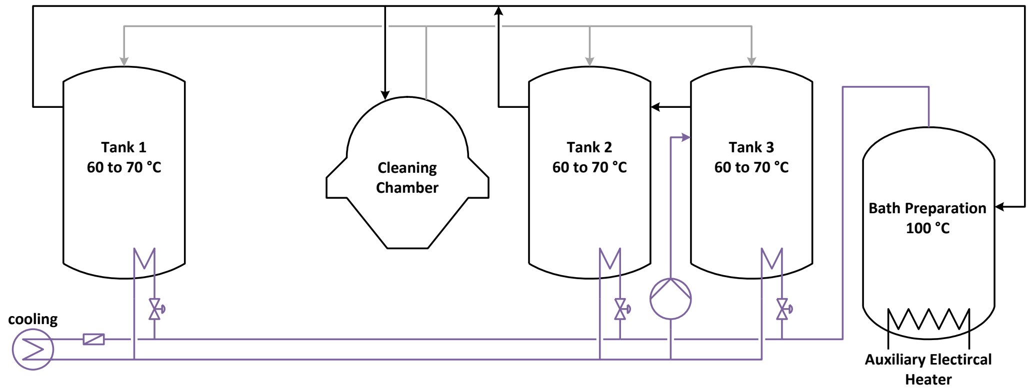


Figure 7-3: Scheme of the part cleaning system EcoCMax

Dürr Ecoclean reduced the need for regular exchanges of the cleaning solution by integrating a bath preparation unit into their part cleaning systems. Figure 7-3 shows a simplified scheme of the part cleaning system with the integrated bath preparation. In the bath preparation module heat is applied at 100 °C to evaporate the water based cleaning solution. The heat needed for this process is entirely generated by electric heaters. Contaminations that boil at higher temperatures such as oils and fats remain in the evaporator. They have to be disposed periodically. The heat content of the evaporated cleaning solution is used to heat three tanks that hold the cleaning solution at a 60 to 70 °C. In this way most of the heat can be recovered. However, if the bath preparation is operated at full load it generates more waste heat than can be recovered. In the heat controlled operation mode the bath preparation can only prepare 5 l of cleaning solution per hour. At full load up to 50 l/h can be prepared with 36 kW heat input. In this case an external cooling system needs to absorb the heat surplus. To recover this waste heat and thereby to allow the bath preparation to operate at full load without the need of external cooling a heat pump was taken into account.

Other companies took similar approaches to increase the usage time of the cleaning solution and to improve the energy efficiency of their part cleaning systems. They offer central bath preparation units that recover waste heat using mechanical vapor recompression (MVR). Those systems are of much larger size with treatment capacities of up to 1,500 l/h. The energy input for these systems is 35 Wh/l.

7.1.2.1 Development of the high temperature heat pump

In contrast to the competitive stand-alone bath preparation systems, Dürr integrated the bath preparation into the part cleaning system. Therefore operating conditions are much more volatile compared to a stand-alone bath preparation unit. Since a vapor recompression system works best at stationary operating conditions and potentially causes problems in combination with certain cleaning agents, Dürr decided to use a more flexible closed cycle compression heat pump.

To limit heat losses the condenser of the heat pump had to be integrated into the bath preparation unit. Because of the limited construction space, the heat exchanger has to be relatively small, so that a high driving temperature difference of 10 to 15 K is needed. Due to the high condensing temperature of up to 115 °C, conventional refrigerants like R-410A or R-134a could not be used. A screening of available refrigerants resulted in the choice of R-245fa because of its advantageous properties in the required temperature range. The compressor is a reciprocating piston compressor. This compressor type offers various cooling options to control the operating temperature. To find the optimal cooling solution for the compressor, three different cooling systems were installed. All three systems can be controlled individually. This is necessary since the used compressor had originally been designed for a maximum inlet temperature of 40 °C. The operating limits are shown in Figure 7-3. The condensation temperature (t_c) is plotted on the vertical axis, while the discharge temperature (t_o) is plotted on the horizontal axis. The original design limits are marked in black. Through different tests theses limits could be extended to the dashed red line. The lubricating oil used in the compressor is considered to be stable up to 130 °C, marking the maximum operating temperature. Higher temperatures lead to coking of the oil, which damages the whole heat pump system and in particular the compressor. The compressor is powered by an electric motor. Its drive power can be adjusted by means of a frequency converter.

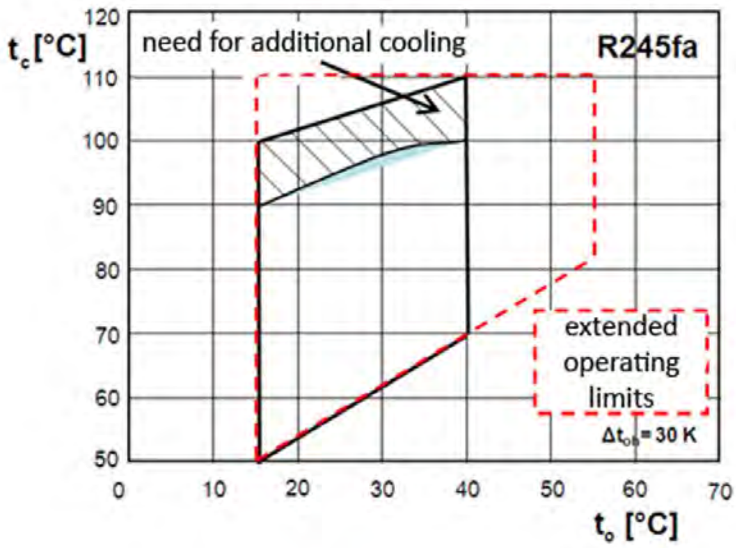


Figure 7-4: Operating limits of the reciprocating piston compressor

7.1.2.2 Integration of the high temperature heat pump

For the integration of the heat pump into the bath preparation system three variants were discussed. All three are illustrated in Figure 7-5.

- Option 1: Direct integration of the evaporator into the waste heat stream from the bath preparation unit. This option offers the highest temperatures.
- Option 2: Integration of the evaporator into tank 1. Thus the volume of the tank can be used as a buffer to create more stable operating conditions for the heat pump.
- Option 3: Integration of the evaporator into an existing filtration circuit. The external heat exchanger makes the system easier to build and to maintain. Furthermore the filtration unit in the circuit prevents particles from damaging the evaporator.

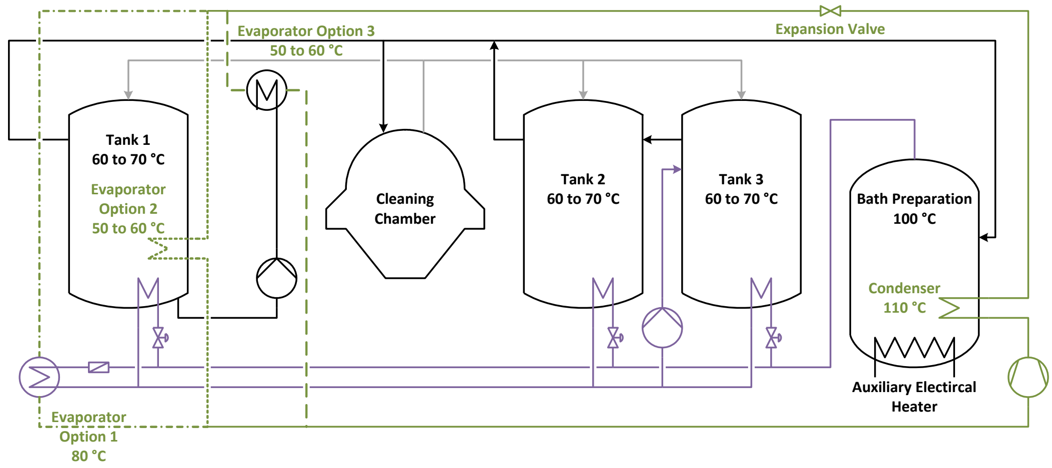


Figure 7-5: Options for the integration of the heat pump into the part cleaning system

The third option was finally implemented because it ensures the highest process reliability. In addition to that it does not require major changes in the plant design. The 36 kW electric heater remains in the bath preparation unit. Its operation, however, is now limited to the starting phase, when the water in the bath preparation unit needs to be heated up from 20 °C to 100 °C. The rest of the time the heat pump takes over the heat supply. It creates two temperature zones in tank 1 at 60 to 70 °C and in the bath preparation unit at 100 °C. In this way the cooling demand is reduced to a minimum.

7.1.2.3 Testing of the high temperature heat pump

In more than 70 series of measurement 99 values were tracked and evaluated. The system was tested in different operation modes in order to obtain a full picture of the high temperature heat pump. Since the system was tested under laboratory conditions the heat output from the cleaned parts had to be simulated by an external cooling.

The heat pumps drive power can be adjusted by means of the frequency converter. In the test runs the heat pump was run with a range of drive frequencies from 25 Hz over 50 and 60 Hz to 75 Hz. The normal operating condition would be 50 Hz.

To determine the efficiency of the high temperature heat pump its energy balance was evaluated using volume flow and temperature measurements. The measuring points are marked in Figure 7-6. The heat supply could only be measured after the bath preparation unit. Thus the heat losses of the bath preparation are included into the calculation of the coefficient of performance (COP). The COP results from the relation of heat output to electrical power consumption.

$$COP = \frac{c_p * \dot{m}_2 * \Delta T_2}{P_{el}}$$

In the test runs the heat pump reached a COP of 3.4 at a drive frequency 50 Hz. At the upper and lower end (25 Hz and 75 Hz) a COP of 3.1 was reached. In order to give information about the efficiency of the heat pump independent from the operating conditions the exergetic performance was calculated. It sets the real COP into relation to the ideal Carnot process.

$$\eta_{ex} = \frac{COP}{COP_{Carnot}} = \frac{COP}{\frac{T_{condenser}}{T_{condenser} - T_{evaporator}}}$$

The exergetic performance varies between 29.8% (25 Hz) and 32.7% (50 Hz) of the efficiency of the ideal Carnot process. Conventional heat pumps for heating purposes reach values of 40% to 50%. The results are illustrated in Figure 7-7. Regarding these results it has to be considered that the tested high temperature heat pump is only a prototype. In the final version the compressor cooling and the insulation of pipes will be improved. Furthermore it has to be kept in consideration that the calculations also include the heat losses from the bath preparation unit.

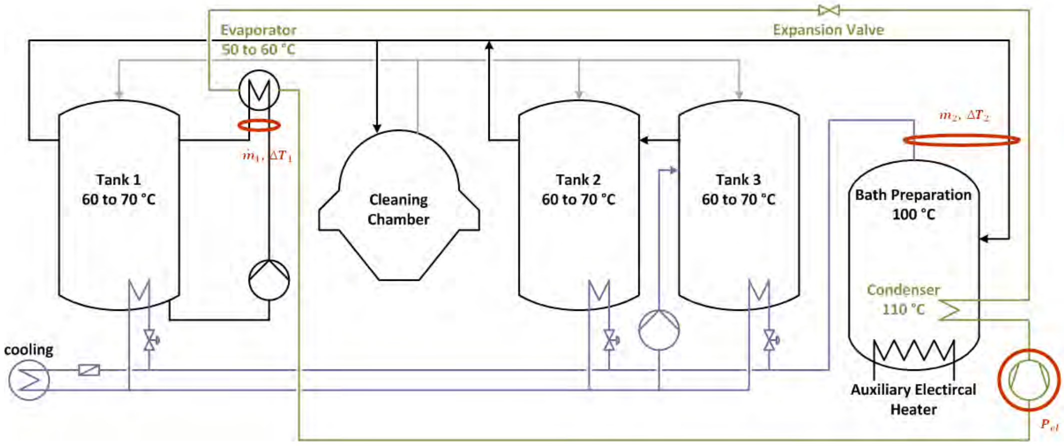


Figure 7-6: Measuring points for the calculation of the COP

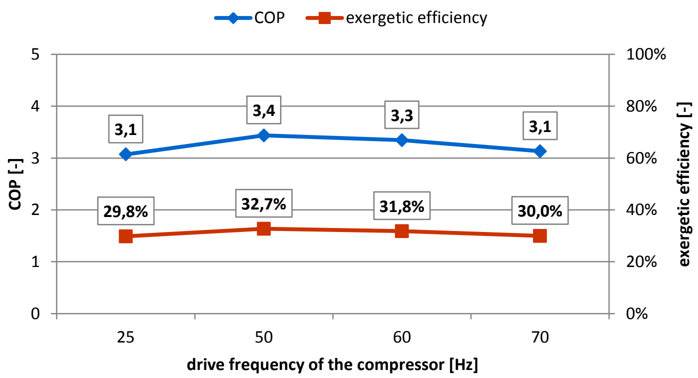


Figure 7-7: COP and exergetic efficiency of the high temperature heat pump

To determine the potential for energy efficiency measures, the thermal losses of the system were calculated. The amount of heat absorbed by the evaporator is calculated from the data of measuring point one. The sum of absorbed heat in the evaporator and drive power is the energy input flow.

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{loss}$$

$$(c_p * \dot{m}_1 * \Delta T_1 + P_{el}) - (c_p * \dot{m}_2 * \Delta T_2) = \dot{Q}_{loss}$$

The heat output of the system is 14% to 22% (25 Hz and 75 Hz) smaller than the energy input. The missing energy is rejected in form of thermal losses. These losses occur in the compressor cooling, un-insulated pipes from tank 1 to the evaporator and in the bath preparation unit. Figure 7-8 shows the gap between energy input and heat output.

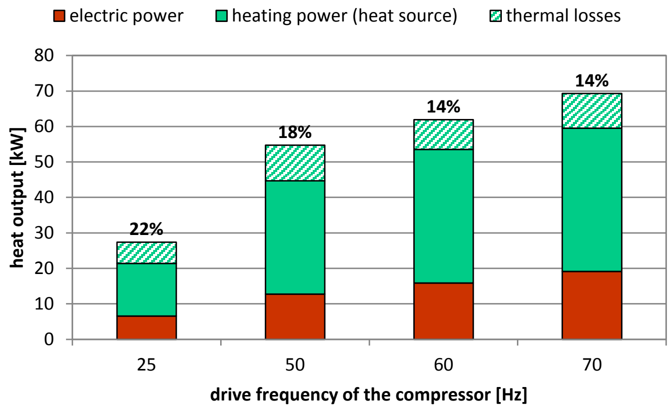


Figure 7-8: Thermal losses of the heat pump system including the bath preparation unit

If the part cleaning system is operated at maximum load, 30 kW of cooling are needed to reject the generated waste heat. After cleaning the work pieces are dried by hot air at a low pressure. To lower the air pressure in the washing chamber a vacuum pump is needed. This pump needs to be cooled with a capacity of 5.9 kW. The remaining 24 kW are the heat surplus generated by the bath preparation unit. This waste heat is now used by the high temperature heat pump to keep the bath preparation unit at 100 °C. At a drive frequency of 50 Hz the heat pump prototype only leaves 4 kW unused. Under real conditions this heat would be carried out of the system by the processed work pieces. Only in 25 Hz mode the auxiliary electrical heater would probably be needed. Figure 7-9 gives an overview of the energy flows in the part cleaning system.

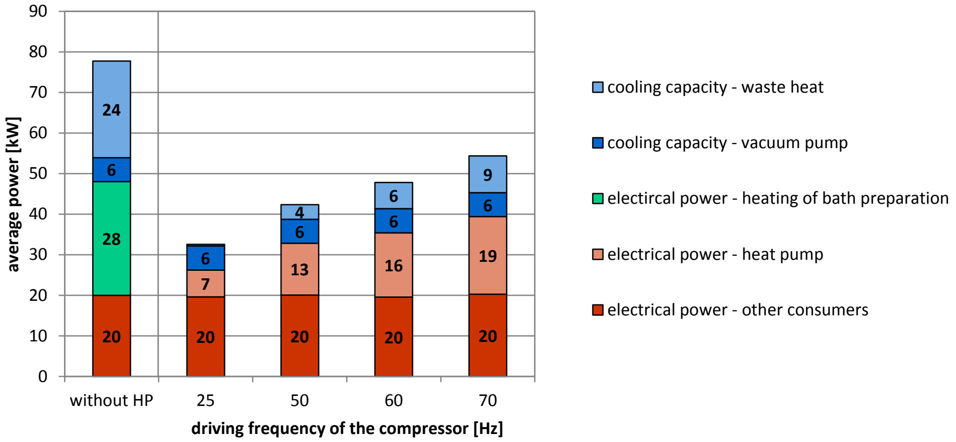


Figure 7-9: Energy balance of the part cleaning system

Beside the energy demand the bath preparation capacity is another keyfigure for the success of the heat pump system. In normal operation the part cleaning system prepares 40 l/h. With 33 l/h this value is almost reached at the lowest drive frequency at 35 Hz. At normal operation (50 Hz) 70 l of cleaning soulution are prepared per hour. The average amount of prepared cleaning solution in different operation modes is shown in Figure 7-10.

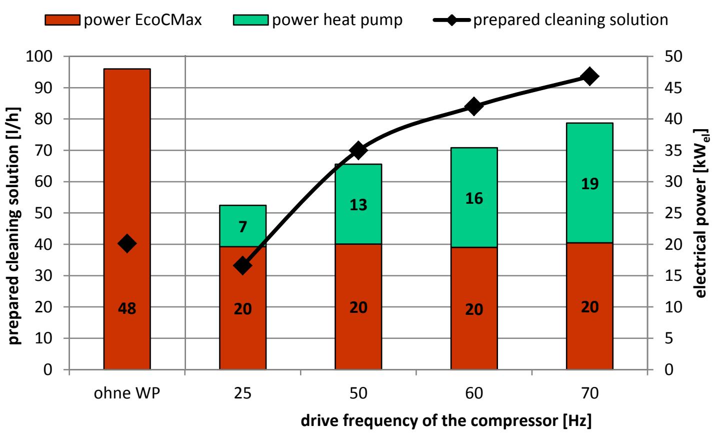


Figure 7-10: Bath preparation rate and energy consumption in different operation modes

The illustration in Figure 7-11 shows that the energy needed to prepare one liter of cleaning solution could be lowered significantly. In normal operation the heat pump system only needs 182 Wh per liter cleaning solution. The conventional system without heat recovery needs 696 Wh/l.

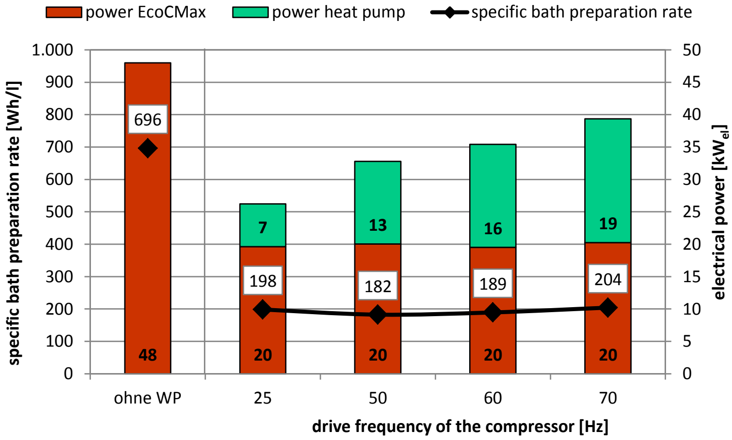


Figure 7-11: Specific bath preparation rate in different operation modes

7.1.2.4 Summary

The measurements have shown that the high temperature heat pump operates reliably. The ambitious targets in terms of energy efficiency and bath preparation rate were not only met, but exceeded. In normal operation mode at 50 Hz, the heat pump achieves a COP of 3.4. If the cooling of tank 1 is also balanced as useful cooling energy, the integrated COP is as high as 5.8. The bath preparation capacity was increased by 75%, while the energy demand was reduced by 31 %. Assuming a yearly operation time of 2,600 hours and a CO_2 emission factor of 601 g/kWh (German electricity mix) /UBA 2012/, the high temperature heat pump system saves up to 24 t CO_2 per year.

7.1.3 References

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7.2 thermea Energiesysteme

thermea. Energiesysteme GmbH is a German manufacturer of high temperature heat pumps using CO_2 as refrigerant (www.thermea.de).

These heat pumps are developed to support the heat pump application in the industry especially to supply process heat up to 90 °C in the capacity range up to 1,000 kW heating capacity.

The potential for such heat pumps is been identified in the present Annex by the University of Stuttgart. Thermea has contributed information coming from own marked considerations. To date thermea has installed first machines in Switzerland, Poland and Germany. Further information will be presented in Task 4 report "Case Studies".

7.2.1 How to come up to high supply temperatures

In contrast to low-capacity heat pumps for heating flats and single-family homes, the use of heat pumps for industrial applications requires high supply temperatures. There are two ways to meet this requirement with optimal energy efficiency. They can be deduced from the function principle of the heat pump process. As is known, heat pumps are machines that elevate calorific energy from a low temperature level to a higher usable one by the consumption of electrical energy. In the most cases, a counter-clockwise running thermodynamic vapour compression process with electrical drive is used for this (Figure 7-12).

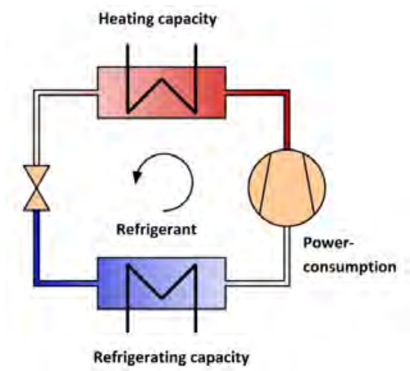

Figure 7-12: Function principle of a heat pump

At low pressure, a refrigerant absorbs heat from a heat source on a low temperature level and evaporates as a result. A compressor pumps the refrigerant vapour to a higher pressure and thus to a higher temperature at which heat is delivered to the "consumer" while the refrigerant is either isothermally liquefied or isobaric cooled. The refrigerant circuit is closed via an expansion valve.

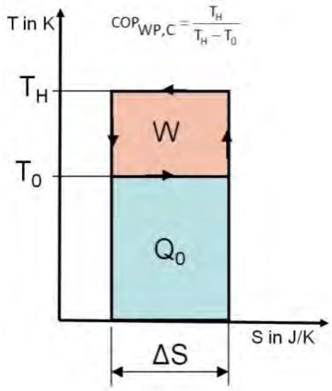

Figure 7-13: Carnot process in the T-S diagram

Figure 7-13 shows the loss-free process in the T-S chart. The $COP_{WP,C}$ (Coefficient of Performance) - which can be determined from the two temperature levels T_H und T_0 - is used for the evaluation of the energy efficiency of this process named after Carnot.

$$COP_{WP,C} = \frac{T_H}{(T_H - T_0)}$$

It can be easily seen that a high temperature level T_H can be reached with an acceptable $COP_{WP,C}$ provided the temperature T_0 is also high. This is the first method. Specific components and heat pump equipment need to be developed for the technical implementation of this high-temperature process because the operational conditions significantly differ from that in a refrigeration machine. First approaches are known from the literature. thermea is developing such a heat pump within the framework of the Annex "Industrial heat pumps" on which information will be given in due course.

A trans-critical process on the high pressure side is the second method used to reach high supply temperatures (Figure 7-14).

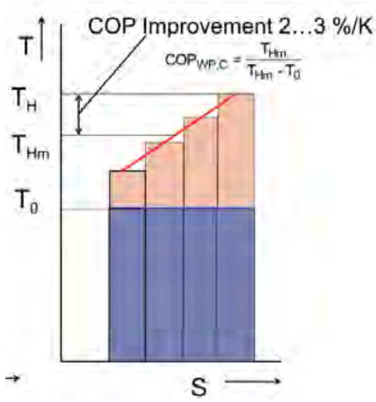

Figure 7-14: Trans-critical process on the high pressure side

The refrigerant is not liquefied on the high pressure side but the heat transfer results from cooling down of the refrigerant without phase change. Figure 3 shows that the

$COP_{WP,C}$ of the modified Carnot process can be calculated from the thermodynamic mean temperature T_{Hm}. Because T_{HM} is always below T_H, this process offers energetic advantages. The lower the heat transfer medium's inlet temperature on the high pressure side the higher is this advantage. CO_2 is predestined as a refrigerant because its critical point is advantageous for this application and it also meets the thermodynamic and ecological requirements very much.

7.2.2 CO_2 as refrigerant in high temperature heat pumps

Carbon dioxide (R744, CO_2) is a known substance used in a variety of applications, e.g. in the food industries. When used as a refrigerant the typical advantages (+) are only disturbed by a few disadvantages (-):

+ Environmental compatibility (global warming potential = 1, ozone depletion potential = 0)
+ High useful temperatures
+ High volume-based (refrigeration) capacity (compact design)
+ Low compression ratio
+ Good material compatibility
+ Availability and low cost
- High pressure level (optimal high pressure up to approx. 130 bar)
- Affectation of the respiration by CO_2 requiring safety precautions

The critical point (30.98°C; 73.78 bar) allows the above mentioned trans-critical process management on the high pressure side. That is why CO_2 is well suited for an application in high temperature heat pumps.

However it has to be taken into account that only components specifically designed for CO_2 can be used due to the pressure level. It is noteable that the range of components on the market improves more and more. The unique selling point for thermea is the access to the world's first screw compressor for high-capacity CO_2 heat pumps.

Suited applications can be deduced from the knowledge that the advantage of high supply temperatures in connection with high COP values takes effect if the warm water inlet temperature in the heat pump is relatively low. Such applications include water heating, heating of outside air, pre-heating of feed water, etc. Applications with small spread such as cooking processes at a high nearly constant temperature level are unfavourable or unsuitable for CO_2 heat pumps.

7.2.3 thermea's CO_2 heat pump series therme$_{CO_2}$

Since 2008, thermea has made great necessary research efforts based on which the heat pumps listed in Table 7-1 have been developed and launched.

Table 7-1: therme$_{CO_2}$ series CO_2 heat pumps

Type	thermeco₂ HHR CO_2	thermeco₂ HHS CO_2
Prinzip	Reciprocating Compressor	Screw Compressor
Heating capacity	30 ... 1.000 kW	1.000 kW
max. outlet temperature heating	90°C	90°C
heat source temperatures	ca. -10 ... 40°C	ca. -10 ... 40°C

Figure 7-15 shows a greatly simplified P&I diagram for the $thermeco_2$ HHR range with reciprocating compressors. This range includes 10 basic models covering a capacity range from 30 to 1,000 kW. Figure 7-16 shows one of these models.

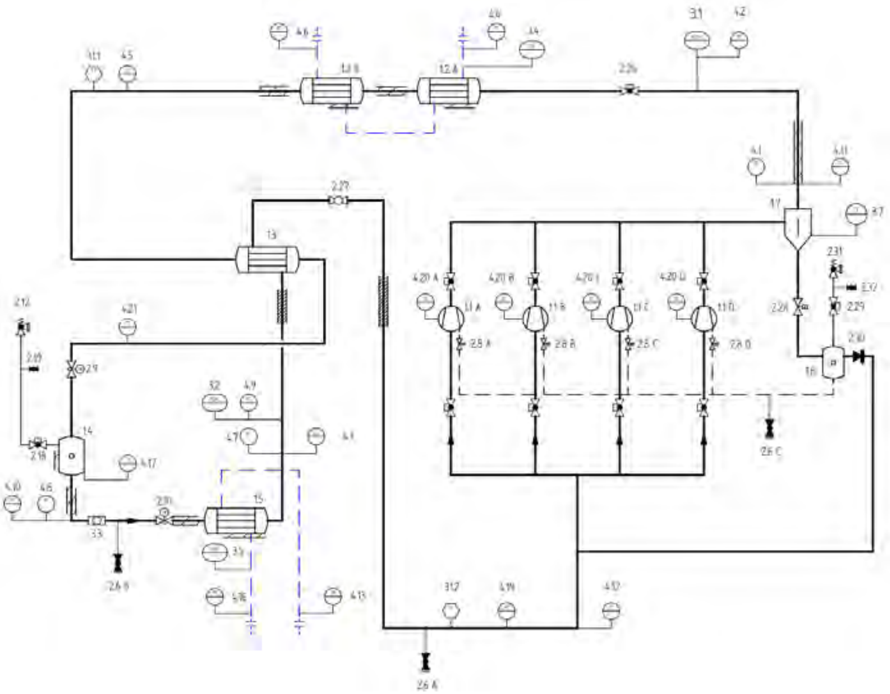

Figure 7-15: P&I diagram of the CO_2 heat pump $thermeco_2$ HHR with reciprocating compressors

Figure 7-16: One model of a CO_2 heat pump with reciprocating compressors

Usable as heat pump and for cold water/cold brine generation, the high temperature CO_2 heat pump excels by its rugged and very compact design. On a solid frame from painted sectional steel, all components are neatly arranged, completely piped internally and electrically wired to the switch cabinet. The machine is equipped with semi-hermetic reciprocating compressors and one of them can be frequency-controlled.

The trans-critical CO_2 circuit on the high pressure side is fitted with an internal heat exchanger. This heat exchanger provides a high refrigerant inlet temperature in the compressor and thus for high outlet temperatures allowing water supply temperatures up to 90 °C. This internal heat exchanger also contributes to some improvement of the COP. The refrigerant is injected to the evaporator as usual by control of the refrigerant superheating on the evaporator outlet. Additionally, a control of the high pressure is required. With the trans-critical process management, it is determined by the refrigerant amount being on the high pressure side. The refrigerant collector is installed between the high pressure control valve and the expansion valve on the medium pressure level. All heat exchangers are tube bundle apparatuses or have a coaxial design for smaller capacities.

A speed-controlled pump controls the hot water supply temperature to the adjustable set point. In the heat source circuit, also a speed-controlled pump is used to control the cold water supply temperature to a constant value.

A programmable logic controller (PLC) with convenient touch panel integrated in the switch cabinet is used for the control. Sensor and control signals can be interrogated via appropriate menu navigation. Further, the touch panel also allows the parameterisation of the heat pump (capacity, temperatures, pressures) within permissible limits. Faults or limit value violations are recorded in an alarm list.

The heat pump is equipped with all safety devices required for a safe operation as per DIN EN 378-2.

The design of the thermeco₂ HHS heat pump with the world's only available screw compressor type from GEA Refrigeration Germany is similar (Figure 7-17 and Figure 7-18). There is an additional oil supply for the compressor consisting of oil separator and oil cooler. To obtain the maximum COP possible, the heat from the oil cooler has to be included in the heat supply. The performance of the machine is controlled by the compressor speed the maximum of which is 6,000 rpm.

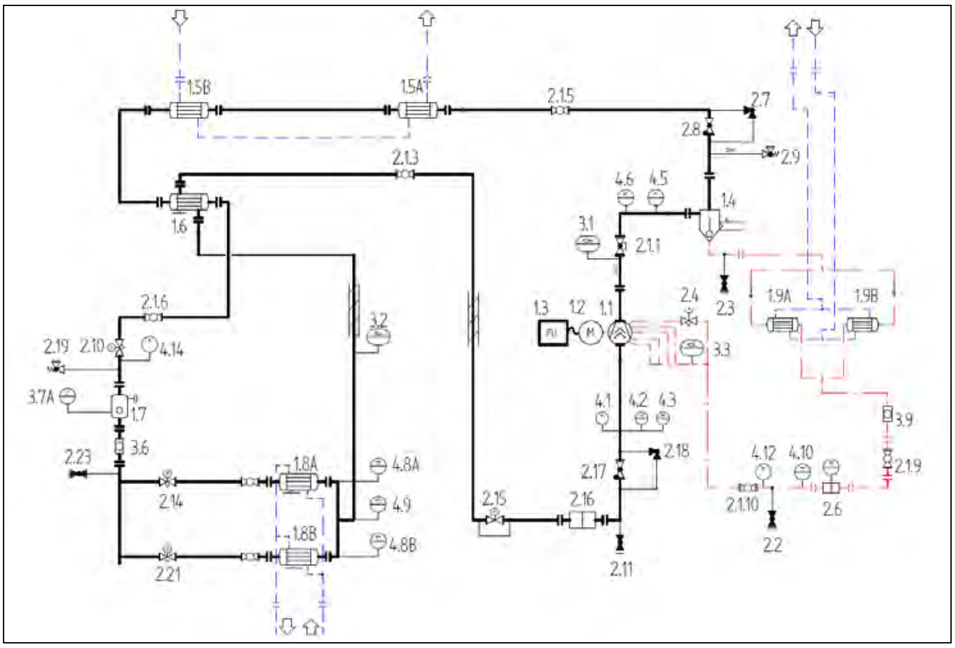

Figure 7-17: P&I diagram of the CO_2 heat pump with screw compressor

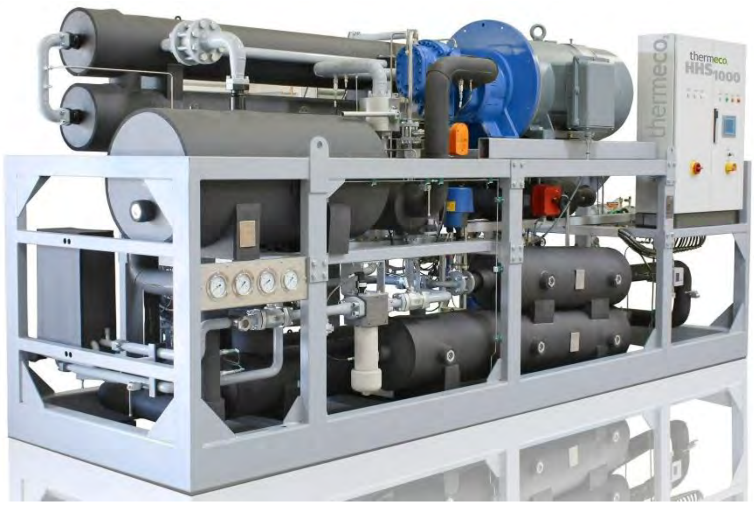

Figure 7-18: CO_2 heat pump thermeco₂ HHS with screw compressor

7.2.4 Summery

thermea. Energiesysteme GmbH has developed a series of high temperature heat pumps using CO_2 as refrigerant:

Type	thermeco₂ HHR CO_2	thermeco₂ HHS CO_2
Prinzip	Reciprocating Compressor	Screw Compressor
Heating capacity	30 ... 1.000 kW	1.000 kW
max. outlet temperature heating	90°C	90°C
heat source temperatures	ca. -10 ... 40°C	ca. -10 ... 40°C

Low return tempeatures from the consumer (warm side inlet) are important for high COP values and high supply temperatures. The thermodynamic middle temperatur is essencial for the COP of the transcritical process. Because of this temperature is lower than the condensing temperature of a theoretical comparable subcritical process the CO_2 heat pump reaches higher COP values. The lower the return temperature the higher this advantage.

Currently new compressors, heat exchangers and control devices are in development. This is the basis of further enhancements of the thermeco$_2$ heat pumps.

7.2.5 Literature

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8 Japan

8.1 Overview of industrial heat pump technology in Japan

8.1.1 Introduction

Heat pump technology is important for reducing CO_2 emissions and primary energy consumption as well as increasing amount of renewable energy usage. The expansion of industrial applications is also important for enhancing these effects further more. In particular, development and dissemination of high-temperature heat pumps for hot water supply, heating of circulating hot water, and generation of hot air and steam are necessary.

8.1.2 General types of industrial heat pumps

Industrial heat pumps are classified into four general types: closed-cycle mechanical, open-cycle mechanical vapor recompression, open-cycle thermal vapor recompression, and closed-cycle absorption heat pumps. These are shown in Figure 8-1 through Figure 8-4 respectively [DOE, 2003].

Closed-cycle mechanical heat pumps, which are the most commonly deployed in variety of industrial processes, can supply cool/hot water/air by successive compression, condensation, expansion and evaporation processes in a closed refrigerant flow loop. Closed-cycle mechanical heat pumps equip with mechanical compression to upgrade the temperature of refrigerant. Their most common compression drives are electric motors.

In industrial processes accompanying steam process, open-cycle mechanical vapor recompression heat pumps are often applied to reuse low pressure waste steam by recompression with mechanical compressors. Open-cycle thermal vapor recompression heat pumps consume energy in high-pressure motive steam to increase the pressure of waste vapor. Recently, hybrid vapor recompression systems consisting of mechanical and thermal vapor recompression have been adapted to reduce the equipment cost and power consumption of mechanical vapor recompression heat pumps [Mayekawa, 2007]. These hybrid vapor recompression systems will be explained in detail in Chapter 4 of TASK 4.

Closed-cycle absorption heat pumps consist of four types of heat exchangers, namely evaporators, absorbers, generators and condensers and generally use a mixture of Lithium Bromide and water as a working fluid. There are two types of absorption heat pumps. Type1 can increase the amount of heat more than the heat source and chill at the cold end, while Type2 can increase temperature and deliver higher-temperature heat than the heat source temperature.

Steam supply is possible via mechanical heat pumps or Type 2 absorption heat pumps, which will be explained in detail in Chapter 2 of TASK 3.

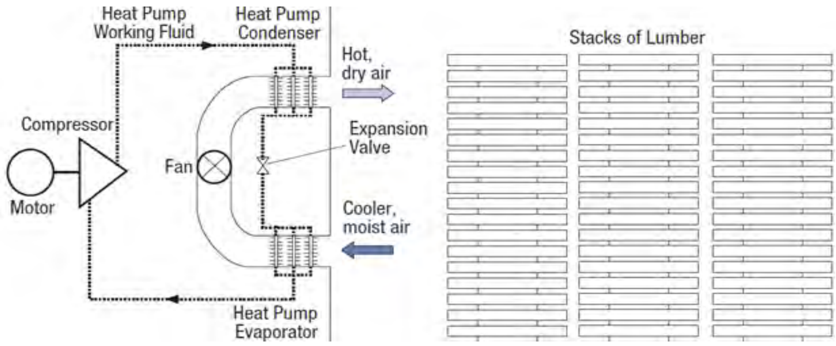


Figure 8-1: Closed-cycle mechanical heat pump [1]

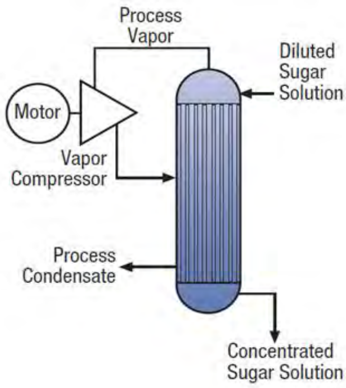


Figure 8-2: Open-cycle mechanical vapor recompression heat pump [DOE, 2003]

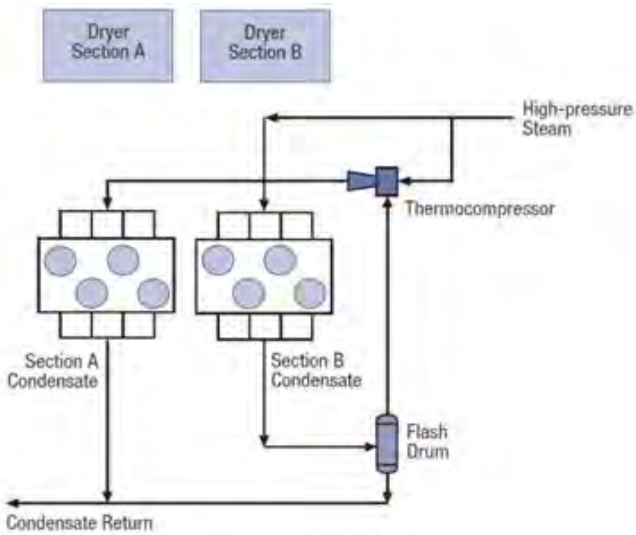


Figure 8-3: Open-cycle thermal vapor recompression heat pump [DOE, 2003]

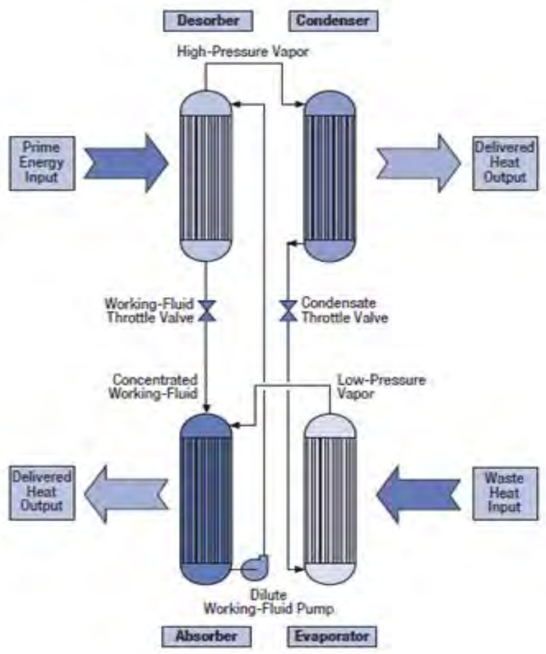


Figure 8-4: Closed-cycle absorption heat pump [DOE, 2003]

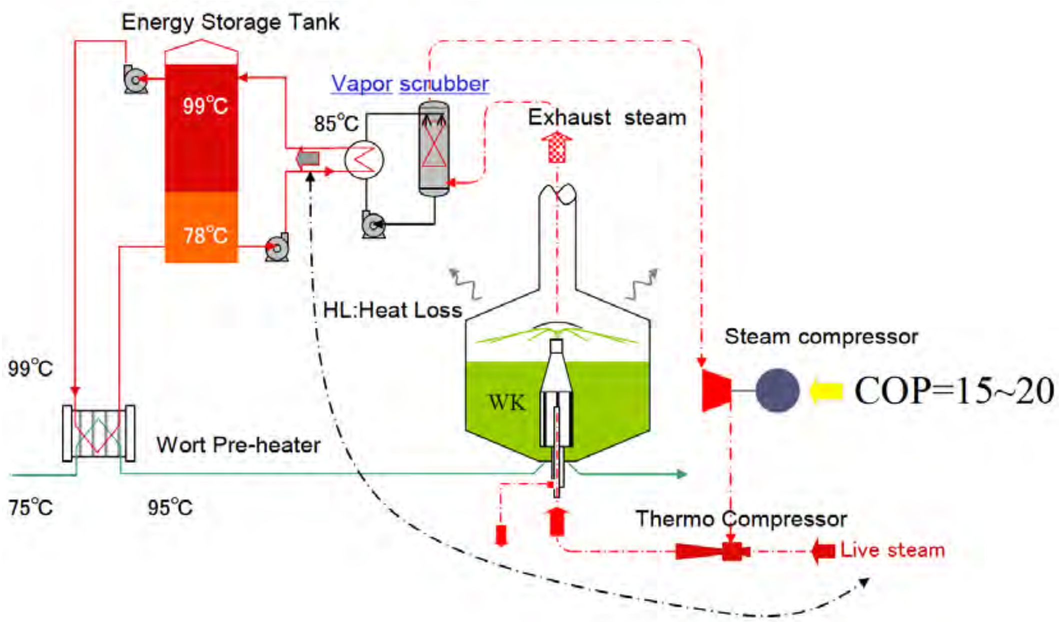


Figure 8-5: Hybrid vapor recompression System [Mayekawa, 2007]

8.1.3 Thermodynamic cycles of high-temperature heat pumps

The thermodynamic cycles of high-temperature heat pumps for hot water supply, hot air supply, heating of hot water circulation and steam generation are picked out and explained as they are most commonly deployed throughout Japan.

8.1.3.1 CO_2 transcritical cycle

CO_2 transcritical cycle air-source heat pumps, capable of producing hot water of 90 °C with a heating capacity of 72.0 kW, have been commercialized in Japan and sold not only in Japan but also in South Korea, Taiwan, Indonesia and elsewhere [Kitayama, 2011]. CO_2 transcritical cycle water source heat pumps, capable of generating hot air of 100 °C with a heating capacity of 110 kW, have been also commercialized in Japan. These heat pumps will be explained in detail in Chapter 2 of TASK 3 and Chapter 4 of TASK 4.

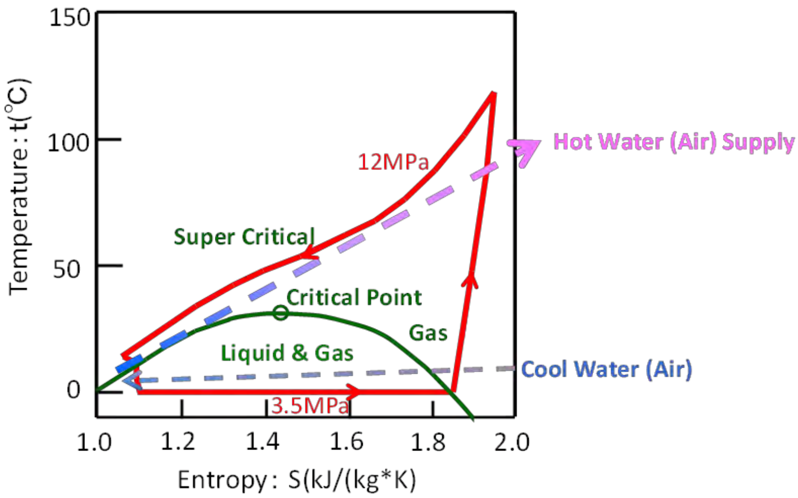


Figure 8-6: CO2 Transcritical heat pump cycle

8.1.3.2 Reverse Rankine cycle (to reheat circulating water up to between 60 and 80°C)

In many industrial processes, hot water cooled down by 5 to 10 °C in process is reheated through the heat pump cycle prior to its circulation. If a CO_2 transcritical cycle heat pump is applied to such processes, the COP generally drops. Therefore a reverse Ran-kine cycle, using HFC-134a refrigerant, is applied to reheat circulating hot water up to between 60 and 80 °C, which shows a high COP.

Figure 8-7 shows a reverse Rankine cycle with HFC-134a refrigerant and these applica-tions will be explained in detail in TASK 4.

Furthermore cascade cycle heat pump will be explained in detail in Chapter 2 of TASK 3, since a cascade heat pump cycle, which consists of the HFC-134a cycle in high-temperature side and the HFC-410A cycle in low-temperature side is also efficient as the effect of cascading.

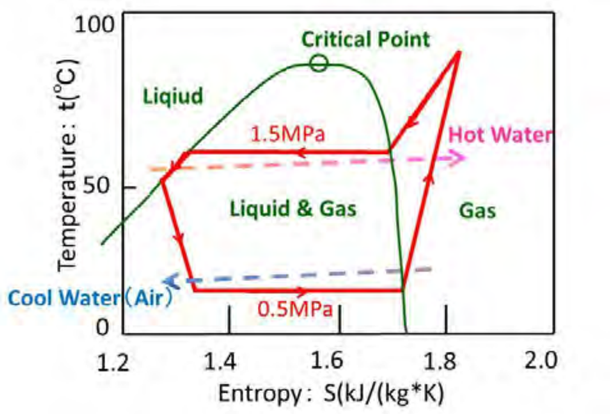


Figure 8-7: Reversed Rankine cycle (HFC-134a)

8.1.3.3 Reverse Rankine cycle (to reheat hot water up to 80 °C or over, and to generate steam of 100 °C or over)

Figure 8-8 shows a two-stage compression cycle of the refrigerant HFC-245fa. Owning to the critical temperature 150 °C or over of an HFC-245fa refrigerant, a single- or two-stage compression heat pump can be used to reheat circulating hot water to 80 °C or over and to generate steam of 100 °C or over. Heat pumps for steam generation with this compression cycle have been commercialized in Japan [4]. High pressurized hot water is generated in the heat pump unit and then evaporated in the flash tank to generate steam at a temperature of 100 to 120 °C. In order to generate steam at a temperature of 165 °C, steam is compressed by the steam compressor, and then, the pressure and temperature increase. Heat pumps for steam generation will be explained in detail in Chapter 2 of TASK 3.

It is also efficient to have the cascade cycle consist of an HFC-134a cycle for the high-temperature side and an HFC-410A cycle for the low-temperature side to reheat hot water up to 80 °C. These cascade cycle heat pumps will be explained in detail in Chapter 2 of TASK 3.

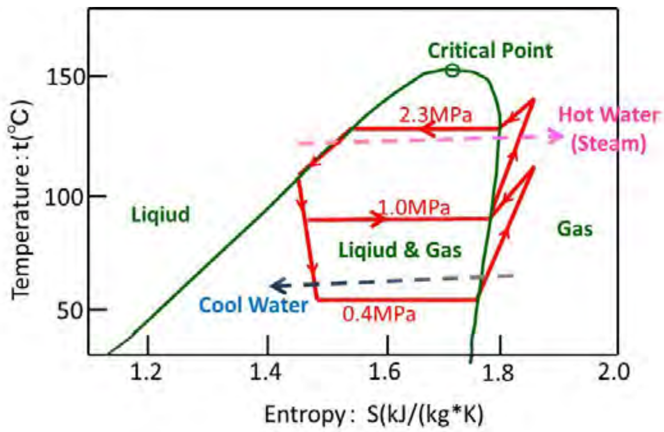


Figure 8-8: Two-stage compression reversed Rankine cycle (HFC-245fa)

8.1.4 Technologies required for industrial heat pumps

The configuration of the cycle is important to achieve a large temperature difference between the output and heat source temperatures efficiently. In addition, the technologies of compressors and refrigerants can withstand high temperatures are also important to deliver high-temperature output. These will be explained in detail in Chapter 2 of TASK 3.

Heat exchange technologies against dust and dirt are also another key issue since the industrial process fluid or industrial waste water used as a heat source for heat pumps contains dust and dirt such as oil stains, metal chips, and so forth. These will be explained in detail in TASK 4.

Refrigerants HFC-245fa and HFC-134a are suitable for generating steam or hot water of 60 °C or over. However, their downside is high GWP, indicating the necessity of low GWP refrigerants development for high-temperature heat pumps. HFO-1234ze (Z) and HFO-1234ze (E) are promising alternative materials for HFC-245fa and HFC-134a because of their compatible thermodynamic properties. Practical application for high-temperature heat pumps are expected owing to the research such as the assessing the risks related to flammability. These will be explained in detail in Chapter 3 of TASK 3.

If heat generated with heat pumps or waste heat exhausted in plants can be stored in a heat storage material, the effective use and control of the heat are enabled. Imbalance between day and night power loads is expected to improve as shown in Figure 8-9 and Figure 8-10, and waste heat is expected to be further utilized. At present, water or ice are normally used as thermal storage materials. However, thermal storage materials such as molten salt, organic material or hydrated salt can store heat over a wide temperature range from -10 to 250 °C. These thermal storage materials will be explained in detail in Chapter 4 of TASK 3.

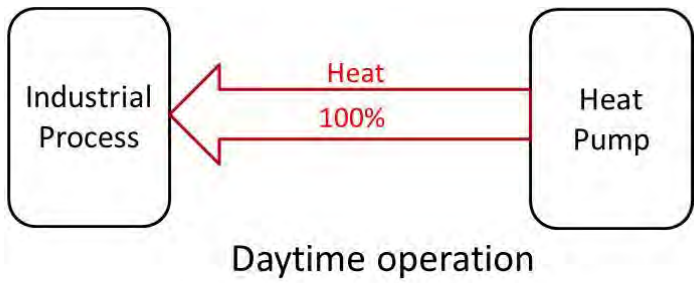


Figure 8-9: Heat pump system without thermal storage tank

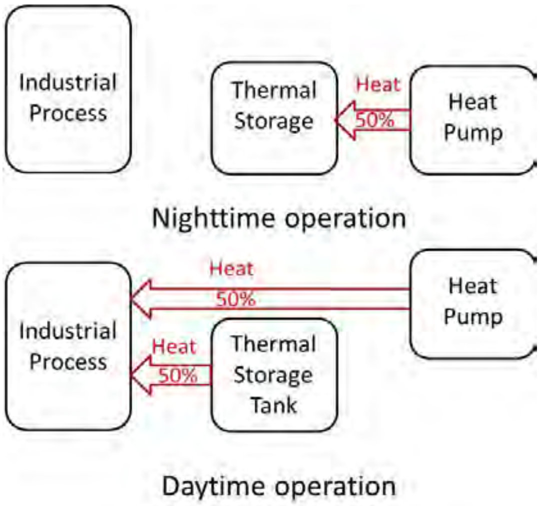


Figure 8-10: Heat pump system with thermal storage tank

8.1.5 References

DOE, 2003 US Department of Energy: "Industrial Heat Pumps for Steam and Fuel Savings", DOE/GO-102003-1735, 2003.

Mayekawa, 2007 Mayekawa manufacturing Co., "A case study application to ethanol distillation - the possibility of energy conservation and reduction of carbon dioxide emissions by vapor recompression (VRC) System", 'Electro-heat', No. 155, 2007 issue.

Kitayama, 2011 H. Kitayama, Mayekawa manufacturing co., "Current status and issues of technology transfer for industrial heat pump", 6th initiatives briefing paper, global warming symposium series, 2011.

8.2 High Temperature Heat Pump

8.2.1 DUAL-CYCLE HEAT PUMP WATER HEATER (AIR-TO-WATER)

8.2.1.1 Outline

A new industrial heat pump system was developed, which uses R-410A and R-134a in a dual cycle. This system has a coefficient of performance (COP) of 3.0 when keeping heat in the storage tank.

Since there is a strong demand to save energy and electricity in Japan, the heat pump market is expected to develop efficient thermal storage.

Adopting a dual cycle that uses two different refrigerants can greatly reduce electricity consumption to keep the heat in the storage tank. With the feature of two refrigerants in a dual cycle, this system realises stable operation under the conditions of a -20 °C outdoor temperature and a 90 °C hot water supply in cold districts. In ‘energy-saving mode’, electricity consumption can be reduced to limit the use of the heating capacity in summer.

To meet the demand for saving energy and electricity, this commercial heat pump can be used for large facilities like nursing homes, hospitals, hotels, and so on.

8.2.1.2 System flow

Figure 8-11 shows the system flow. Figure 8-12 shows the P–h diagram. This system features a dual cycle. R-410A is used for the heat source unit, and R-134a is used for the cascade unit. The heat source unit is used in the normal compression cycle. The cascade unit uses the refrigerant–refrigerant heat exchanger for the evaporator and the refrigerant–water heat exchanger for the condenser.

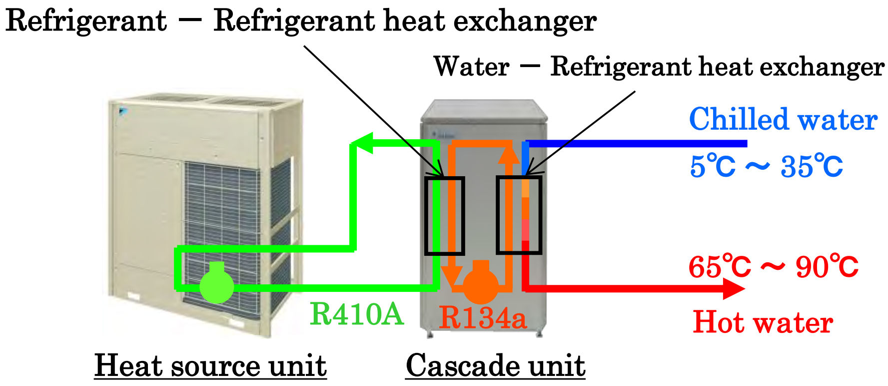


Figure 8-11: System flow

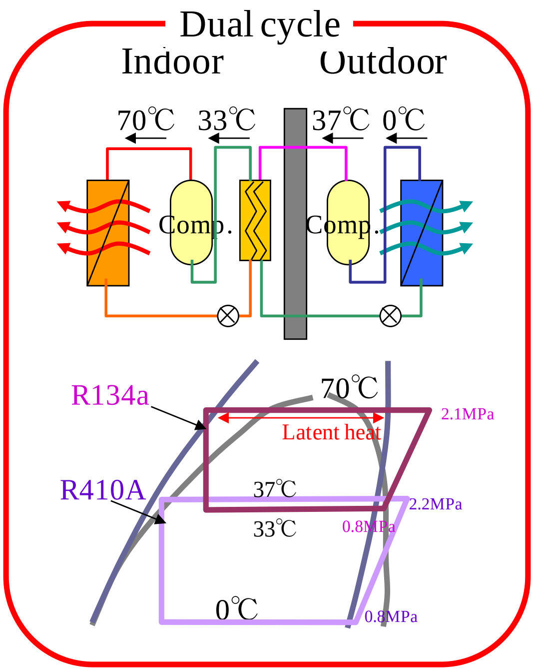


Figure 8-12: P–h diagram

8.2.1.3 System details

Figure 8-13 shows the actual developed system in practical use. Table 8-1 lists the specifications of this system. The COP hits 3.0 when reheating the hot water and keeping the hot water warm, and 4.1 when heating up the supply water, which makes it possible to reduce electricity consumption by 24%.

When the heating capacity is small in summer, electricity consumption can be reduced by changing the driving mode from normal one (maximum heating capacity of 35 kW) to energy-saving one (maximum heating capacity of 30 kW). With the demand control function, the number of operating systems can be limited, and electricity consumption can be reduced.

This system can be operated at the ambient temperature of -20 °C and the hot water supply temperature of 90 °C owing to the adaptation of a cascade cycle.

Twelve systems can be connected for a maximum hot water supply of 120 tons/day.

Since the heat source unit which absorbs the heat from the ambient air and the cascade unit which heats up the hot water have two compressors each, backup operation is still available in case one compressor is out of order.

Figure 8-13: Dual cycle heat pump water heater (Daikin: 'MEGA-Q')

Table 8-1: Specifications of dual-cycle heat pump water heater

Product name		Heat pump water heater	
Type		RLYP350B	
Configuration name		Heat source unit	Cascade unit
Ttype		RLP350B	BWLP350B
		Middle season rated	
One through	Heating capacity	35.0kW	
	COP	4.1	
	Supply water	17℃	
	Hot water	65℃	
Ambient temperature		−20℃ ～ 43℃	
Power source		3 ϕ 200V 50/60Hz	
Outward appearance		H1525mm×W1240mm× D765mm	H1525mm×W890mm× D765mm
Refrigerant		R410A	R134a

8.2.1.4 Features of components

As shown in Figure 8-14, a new four-surface heat exchanger was developed for the system. This system equips with the dual cycle. Generally, when a dual cycle is adopted, the system size is bigger. However, this system equips with a new heat exchanger, which reduces the volume of the heat exchanger and air flow resistance by adopting small-diameter tubes and reducing fin pitch.

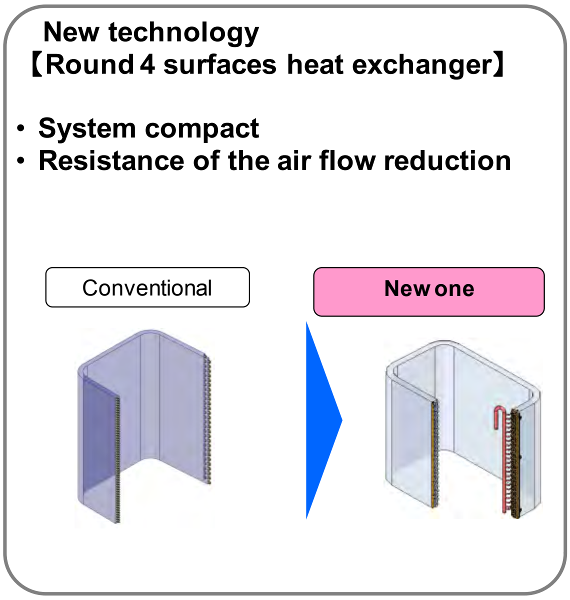


Figure 8-14: New compact heat exchanger

8.2.1.5 Example of installation

As shown in Figure 8-15, this system can be applied to open and closed tank flow systems. Remote monitoring is possible to prevent failure before occurring by connecting with the network system.

An automatic backup with multiple heat pump units and two compressors for each unit is adopted; thus, this system can escape shutdown with some trouble and continue a jury-rigged operation.

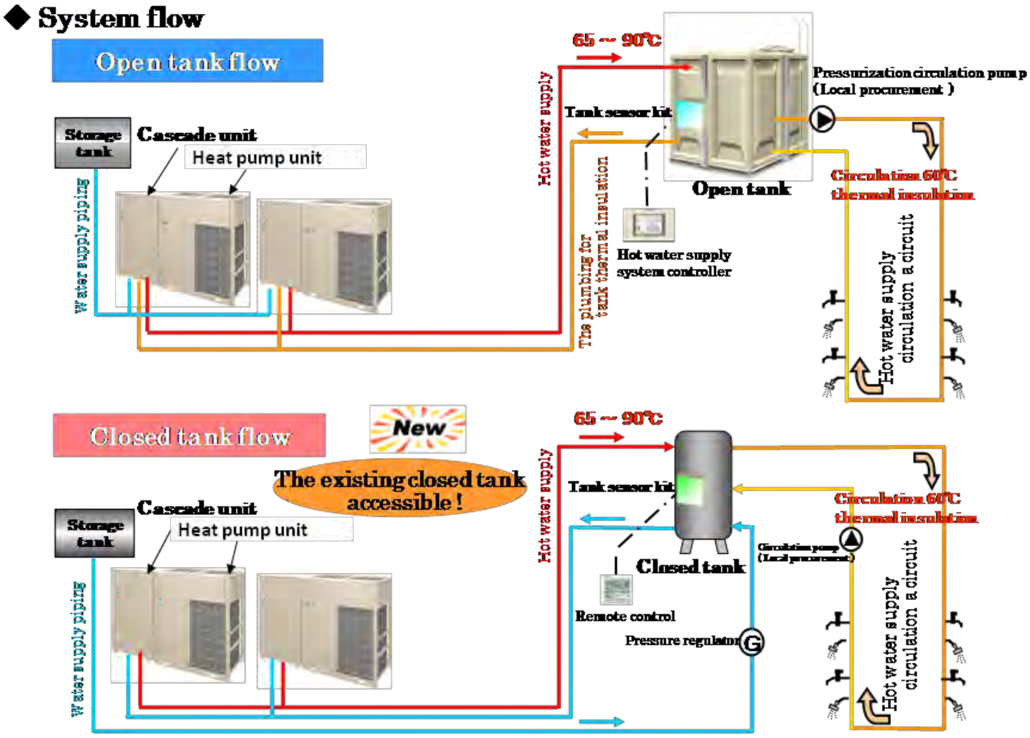


Figure 8-15: System configuration

8.2.2 CO_2HEAT PUMP AIR HEATER (WATER-TO-AIR)

8.2.2.1 Outline

Since the CO_2 refrigerant heat pump air heater adopts a transcritical cycle and uses the supercritical region of the refrigerant, this system can heat hot water to higher temperatures efficiently. Therefore, the heat pump can be replaced by the conventional systems or deployed supplementarily with the conventional systems in manufacturing processes which use combustion systems conventionally. This system has advantages over conventional industrial driers that consist of a steam boiler, heat exchanger, and dry room in terms of durability, environmental protection, maintenance, and economy.

There are many types of industrial driers: for example, a box-type air drier, a band circulation drier, a fluidized drier, and a rotational drier. A conventional drier that produces hot air uses the direct fired method but indirect heating and uses a steam boiler and an electric heater as heat sources. Other than the electric heater, these heat sources use combustion of fossil fuels.

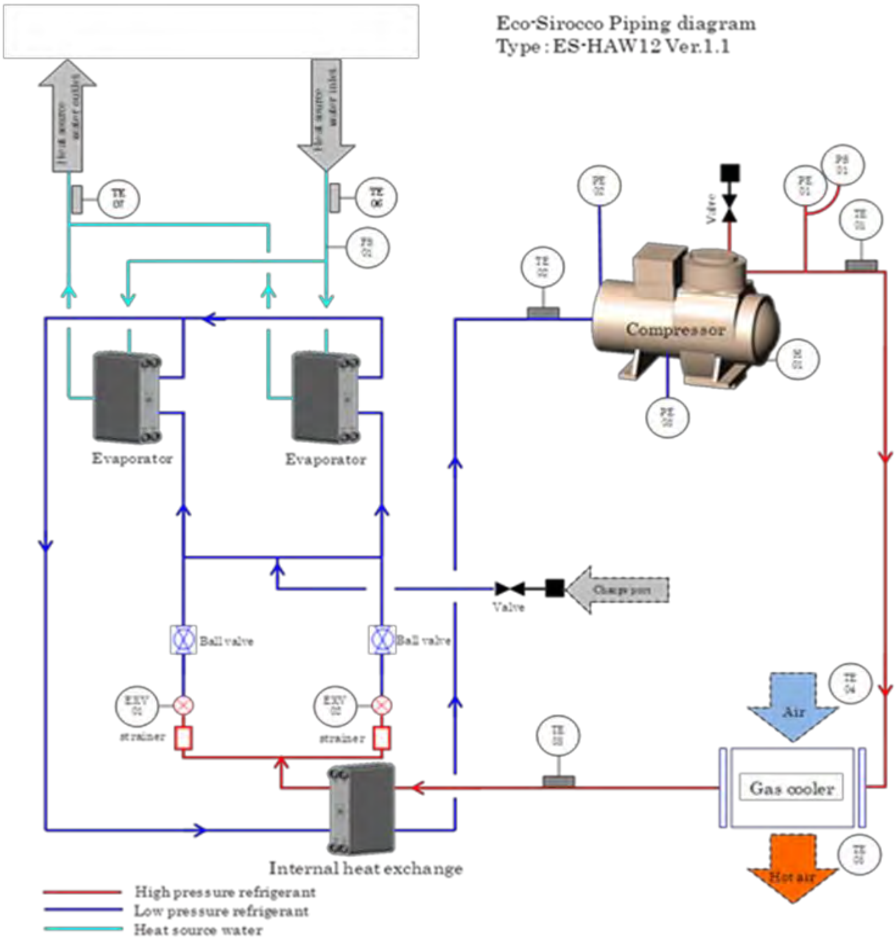
The CO_2 heat pump air heater does not use neither electricity nor direct combustion as the heat source. To widen the range of applications of the drier, it uses the supercritical region of CO_2 to efficiently heat the air to 120 °C or over.

This heat pump uses water as a heat source and can produce not only hot air but also cooling water. We can achieve further efficiency by utilising both the hot air and the cooling water simultaneously. Since the hot air is produced in the supercritical region of the CO_2 refrigerant, CO_2 emissions and energy consumption can be reduced. No NOx is produced, because this system does not take a combustion process.

8.2.2.2 System flow

Figure 8-16 shows the system flow of the CO_2 transcritical cycle. This system consists of a gas cooler, an expansion valve, a compressor, and an evaporator. Figure 8-17 shows the operating conditions of the system on the T–s diagram.

This system features the use of the supercritical region of the CO_2refrigerant. In the general compression cycle, since the two-phase region is used, the refrigerant is condensed. This is why there is a temperature limit of hot air production. However, in this system, the temperature of the refrigerant changes according to the temperature change in air to enhance the system efficiency. This kind of system for producing hot water is already commercialised under the name of Eco-Cute in Japan for residential and business uses.



Symbol	Equipment name
EXV01, EXV02	Electronic expansion valve
H01	Oil heater
PE01 ～ PE03	Pressure transmitter
TE01 ～ TE07	Resistance Temperature Detector (RTD)
FS01	Fluid sensor
PS01	Pressure switches

Figure 8-16: Flow of CO_2 heat pump air heater (Mayekawa Eco-Sirocco)

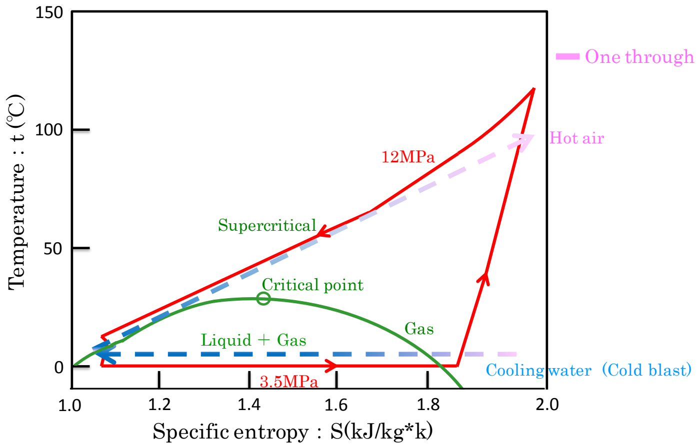


Figure 8-17: T–s diagram

8.2.2.3 System details

Figure 8-18 shows the appearance of the commercialised CO_2 heat pump air heater. Table 8-2 shows the specifications of this system: a rated heating capacity of 110 kW and a COP of 3.43. They can produce hot air up to 120 °C or over. Figure 8-19 shows the relevance between the heat source temperatures and heating capacities or COPs under the condition of ambient temperature being 20 °C.

Figure 8-18: Appearance of CO_2 heat pump air heater (Mayekawa Eco-Sirocco)

Table 8-2: Specifications of CO2 Heat Pump Air Heater
(Mayekawa Eco-Sirocco)

Performance	Heating capacity [kW]	Air temperature :	110 Inlet 20℃ (50%RH)→ Outlet 100℃
	Cooling capacity [kW]	Heat source temperature :	81 Inlet 30℃ →Outlet 25℃
	Power consumption	32	
	COPh	3.43	
	COPc	2.54	
Power source		3 φ 200V 50Hz/60Hz	
Outward appearance [mm]		W1,100×L1,600×H2,235	
Weight [kg]		1,948	
Operating temperature range	Inlet air temperature [℃]	0～50 (While driving) 0～43 (stoping)	
	Outlet air temperature [℃]	80 ～ 120	
	Air flow rate	1,500 ～ 8,000	
	Inlet heat source temperature [℃]	−5 ～ 40	
	Outlet heat source temperature [℃]	−9 ～ 35	
	Heat source flow rate [L/min]	100 ～ 330	

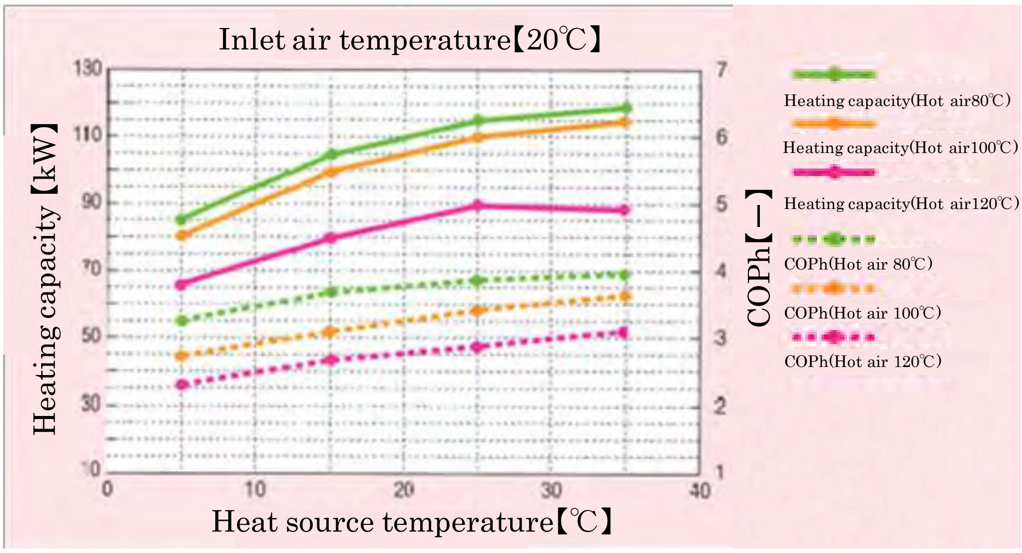


Figure 8-19: Performance Curve of CO_2 Heat Pump Air Heater (Mayekawa Eco-Sirocco)

8.2.2.4 Features of components

Figure 8-20 shows the appearance and scheme of a small CO_2 heat pump air heater produced by the Central Research Institute of Electric Power Industry. In this system, fin and tube heat exchangers are used for the air heater. In this element, air is directly heated by the supercritical CO_2 refrigerant.

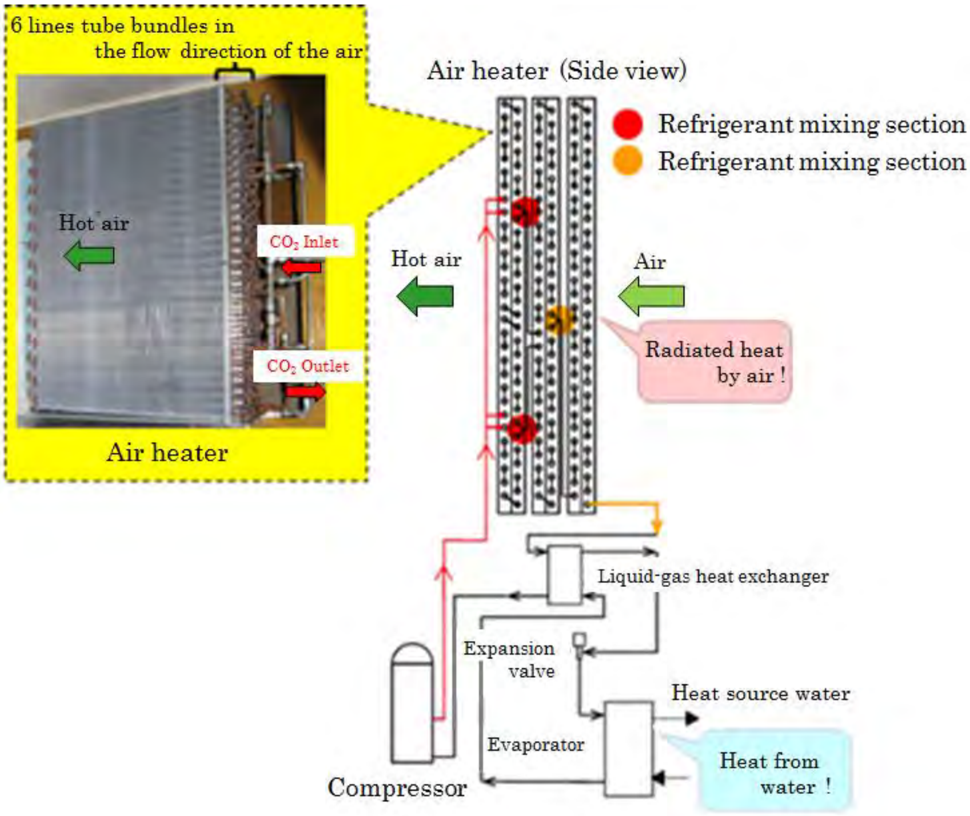


Figure 8-20: CO_2 heat pump air heater
(Central Research Institute of Electric Power Industry)

8.2.2.5 Example of installation

Figure 8-21 shows a case example installed in a laminating factory. In this factory, the CO_2 heat pump air heater is used to supply hot air for the drying process and cooling water to cool the cooling roller. With this system, the refrigerator installation is not necessary, and energy consumption for the boiler is reduced. A higher COP can be realised by simultaneous heating and cooling using one system.

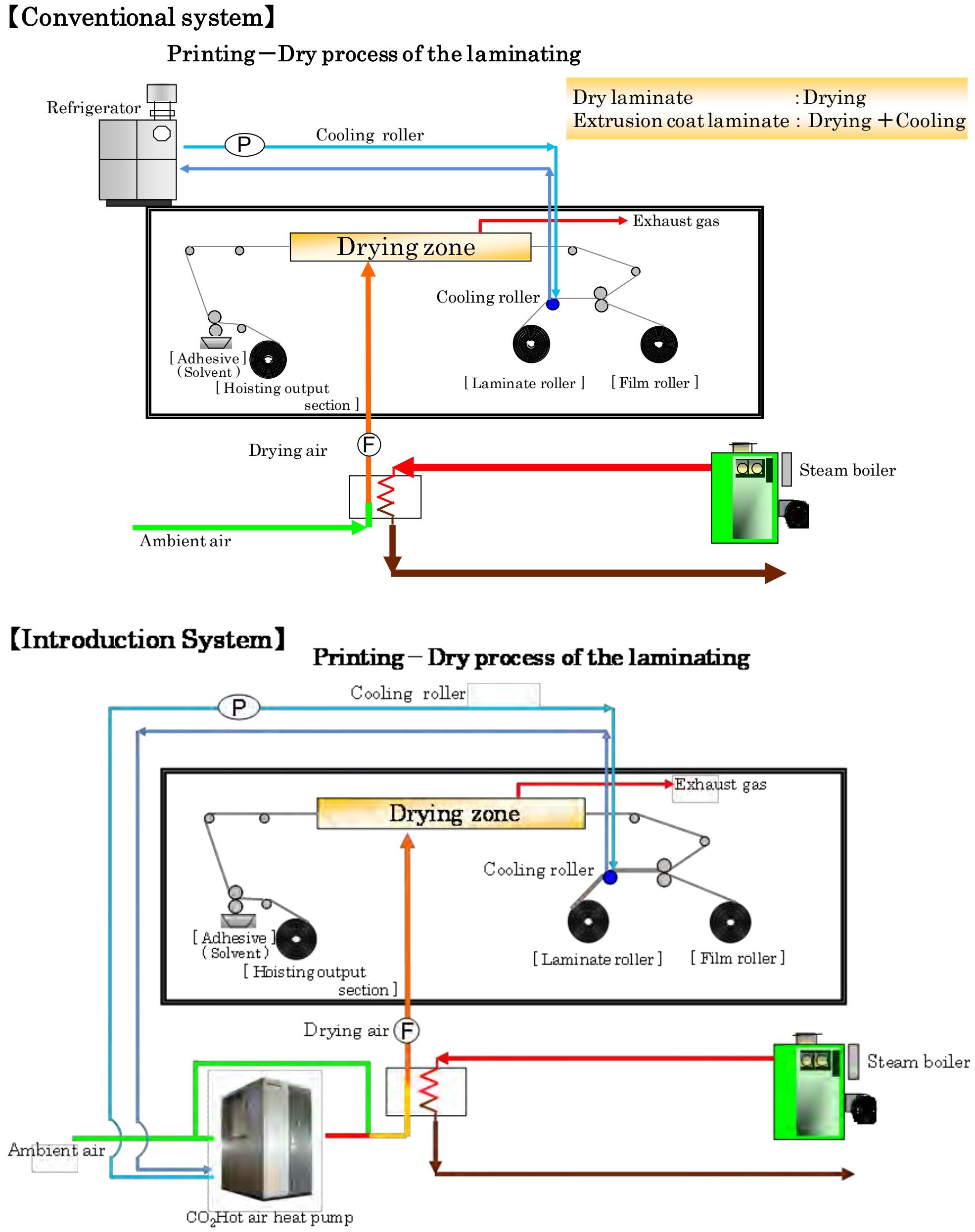


Figure 8-21: Laminating factory

Figure 8-22 shows the effect of introducing this system into the drying process. Using this system can reduce primary energy consumption by up to 46%.

Introduction effect

【The introduction effect that is anticipated by a field test】

	CO_2 emission ($t\text{-}CO_2$ / year)	Energy consumption (GJ / year)
Conventional system	147	2,900
New system	47	1,600
Reduction rate	68%	46%

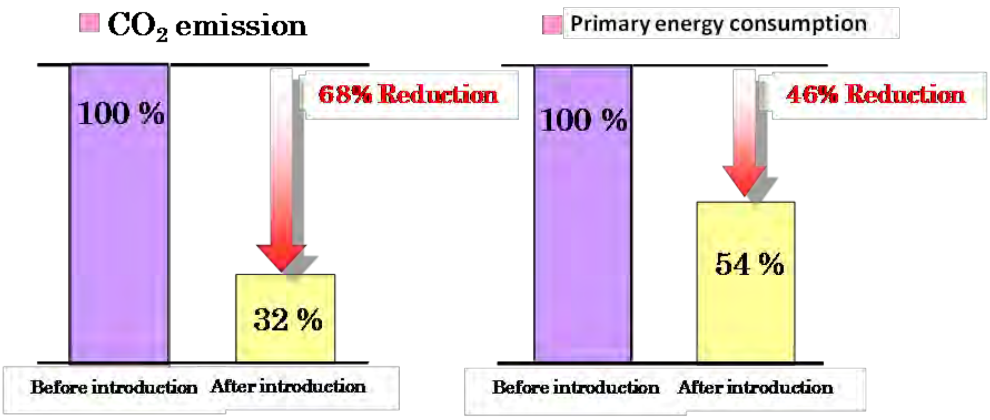


Figure 8-22: Efficiency results from adoption

8.2.3 HEAT PUMP STEAM SUPPLIER (WATER-TO-WATER)

8.2.3.1 Outline

Conventionally, a boiler is needed for 120 °C or over steam supply for processes such as sterilising, concentrating, drying, and distilling. Since there is more and more demand to save energy owing to concerns over global warming, heat pump technology, which can efficiently supply steam higher than 120 °C has a high degree of applicability.

This system realises a supply of 165 °C steam through the addition of a steam compressor and a flash tank to the vapour compression cycle.

8.2.3.2 System flow

Figure 8-23 shows the flow of this system. The flow of the heat pump to produce 120 °C steam is the same as that of the conventional heat pump. 120 °C steam is supplied from the flash tank. The refrigerant is R-245fa for SGH120, and a mixture of R-134a and R-245fa for SGH165 to achieve a good performance. For SGH165, 165 °C steam is produced by compressing 120 °C steam with a steam compressor.

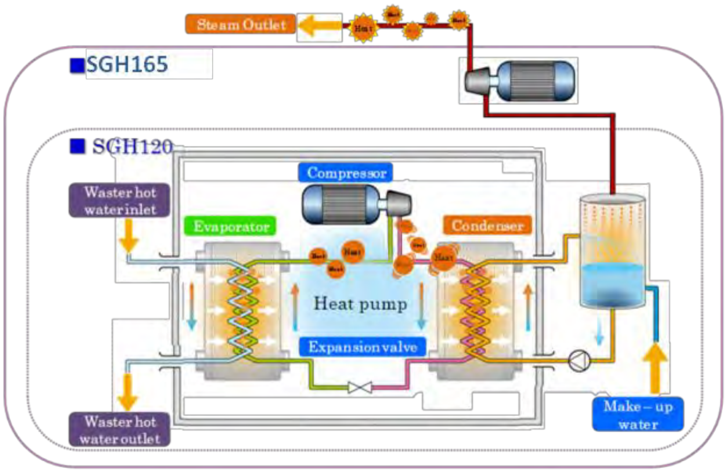


Figure 8-23: System flow (KOBELCO: SGH series)

Steam is usually produced in the central boiler room at high pressure and send to each building through a header and long piping network. Locating the heat pump steam supplier close to the process directly can reduce heat loss from the piping network.

Thus, this heat pump supplier can produce 120 °C steam for a distributed system and 165 °C steam when located close to a conventional boiler.

8.2.3.3 System details

This system is the first efficient heat pump steam supplier in the world whose steam temperature is more than 120 °C. SGH120 is a heat pump steam supplier that can produce 120 °C steam. SGH165 can produce 165 °C steam by adding a steam compressor to SGH120. Figure 8-24 shows the appearance of the commercialised systems.

In Table 8-3 their specifications are listet, which indicates SGH120 has a heating capacity of 370 kW and a COP of 3.5 and SGH 165 has a heating capacity of 660 kW and a COP of 2.5. Figure 8-25 shows COP values related to heat source temperatures.

120℃/0.1MPaG Steam supply　　165℃/0.6MPaG Steam supply

Figure 8-24: Overview of system (KOBELCO: SGH series)

Table 8-3: System specifications (KOBELCO: SGH series)

Type			SGH 120	SGH 165
Capacity	Steam pressure	MPaG	0.1	0.6
	Steam temperature	℃	120	165
	Inlet heat source water temperature	℃	65	70
	Outlet heat source water temperature	℃	60	65
	Heating capacity	kW	370	660
	Steam	t/hr	0.51	0.89
	HeatingCOP	-	3.5	2.5
Heat source water temperature range		℃	25 ~ 65	35 ~ 70
Steam pressure range		MPaG	0.0 ~ 0.1	0.2 ~ 0.8
Dimensions	Width	mm	1,200	4,300
	Depth	mm	4,850	2,950
	Height	mm	2,530	2,530
Weight	While carrying	kg	4,000	6,630
	While driving	kg	4,240	6,960

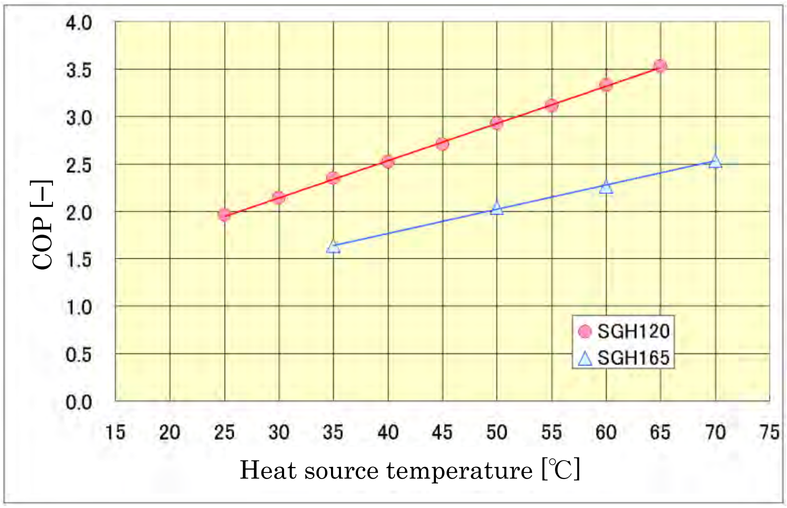


Figure 8-25: System performance (KOBELCO: SHG series)

8.2.3.4 Features of components

To comply with a compressor getting hot, a newly developed screw compressor was equipped (Figure 8-26). It is developed for high pressure and high temperature and sprays refrigerant mist into a motor for cooling down.

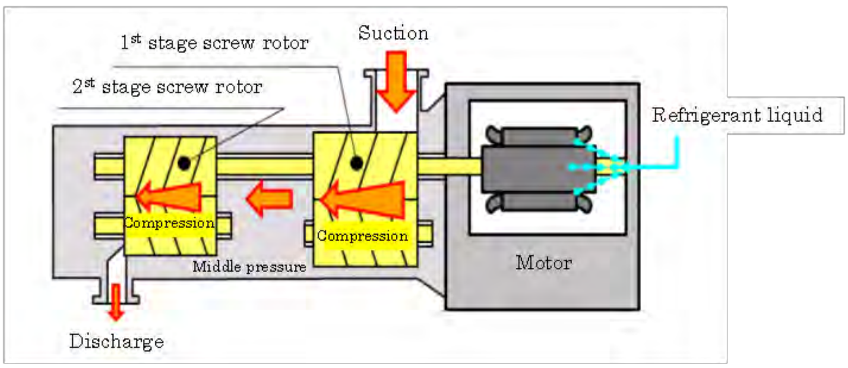


Figure 8-26: New screw compressor

8.2.3.5 Example of installation

The system was integrated in the following process (Figure 8-27). Setting the heat pump close to the process can realise a distributed heat source settlement system that uses the waste heat. With this system, piping loss can be reduced by 50 %.

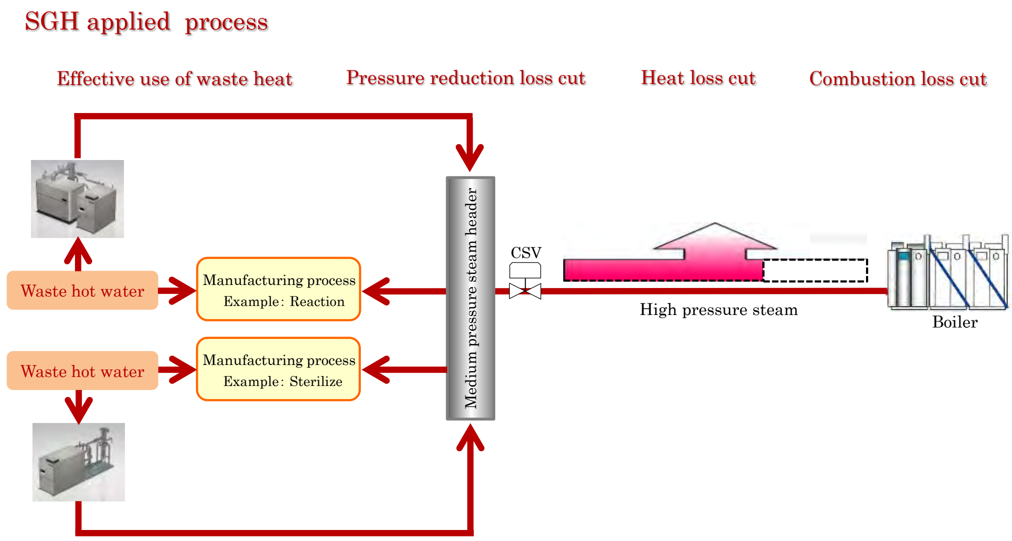


Figure 8-27: SGH-integrated process

8.2.4 HEAT PUMP FOR CIRCULATIONG WATER HEATING (AIR-TO-WATER)

8.2.4.1 Outline

Recently, heat pumps have been applied to not only air-conditioning use but also water heaters as a key technology for saving energy and reducing costs. However, the spread to the industrial market is still slow.

There are many kinds of heating processes for manufacturing, and boilers are widely used for these processes. The boiler is centralised in the power house, and steam is provided by a long piping network to the places required. This loses heat.

Many processes require hot water. Hot water that is used below 90 °C and circulated to keep the temperature of the storage tank constant has an energy demand of about 67 TJ.

Recently, industrial heat pump systems have been developed and installed. However, the market demands an efficient circulation type heat pump that is compact and easy to install. To meet this demand, a heat pump for circulation water heating has been developed for which the heat source is the air.

Generally, if a single-stage cycle is used for the air heat source heat pump, COP decreases because one compressor has to be operated with a higher pressure ratio. Particularly when hot water is circulated, the condensing pressure rises, so COP decreases with increasing hot water supply temperature.

The dual cycle was adopted to obtain 90 °C hot water outdoor the installation when hot water is circulated.

8.2.4.2 *System flow*

Figure 8-28 shows the system flow. This system adopts a dual cycle. Figure 8-29 shows the dual cycle on the temperature-specific enthalpy diagram. The dual cycle consists of two independent cycles and a middle heat exchanger that connects the two cycles. Since the heat absorbed in the lower temperature cycle is transferred to the higher temperature cycle, higher temperature heat can be produced even though the ambient air temperature for the lower temperature cycle is lower.

This system uses R-410A for the lower temperature cycle and R-134a for the higher temperature cycle, the latter of which is suitable for higher temperature use. In the dual cycle, since the refrigerant of each cycle is pressurised using a different compressor, different ambient air temperature limit, and different hot water temperature, the problem of a lower COP can be avoided to realise efficient operation.

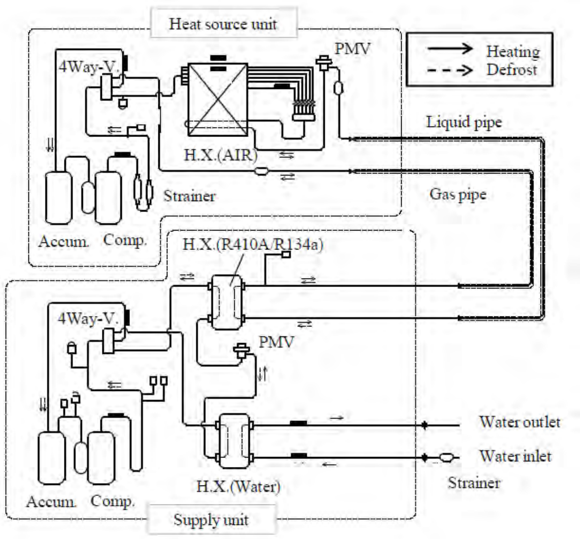


Figure 8-28: System flow

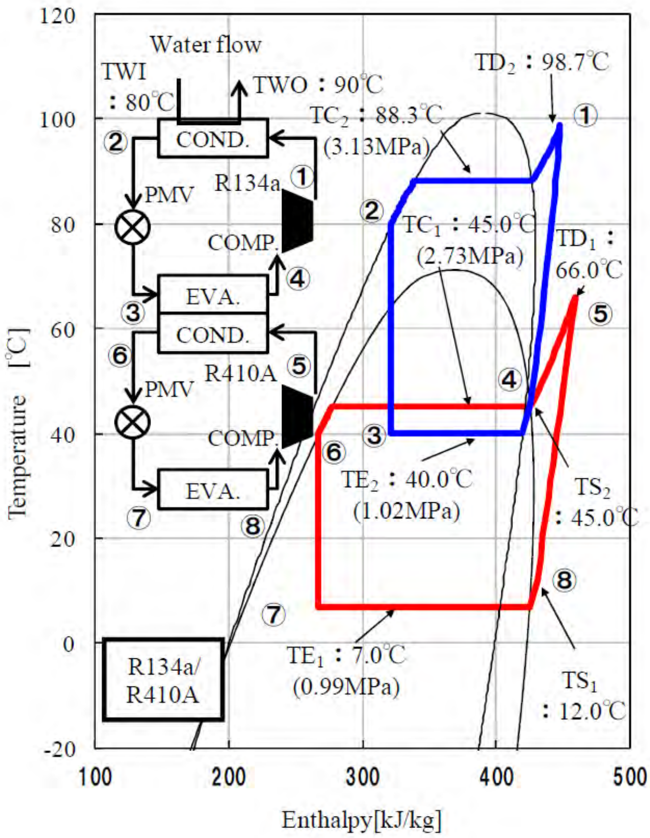


Figure 8-29: Driving conditions on specific enthalpy–temperature diagram

8.2.4.3 System details

Figure 8-30 shows the flow and overview of the system. Table 8-4 lists the specifications of this system. The system uses two units: a heat source unit that adopts the lower temperature cycle and a hot water supply unit that adopts the higher temperature cycle. Since both are connected by the refrigerant piping of R-410A, the system has many applications cases despite the variety of installation conditions.

In the heat pump unit, the refrigeration cycle and heat exchangers are optimised based on the storage type of the air-conditioning system. The heat exchangers and control method are optimised. The hot water supply unit is an indoor installation type, which is assumed to be installed near the spots where a heat-use device. This concept allows heat loss to be reduced.

This system has a dual cycle with two compressors. This increases the partial load efficiency because the load of each compressor changes depending on the ambient air temperature, hot water temperature, and heating capacity.

Figure 8-31 shows the partial load efficiency depending on the ambient air temperature. This indicates that COP can be kept higher.

As shown in Figure 8-32, the driving range of the hot water temperature was from 50 °C to 90 °C; that of the ambient air temperature was from -15 °C to 43 °C DB. A maximum of four systems can be connected in parallel.

Figure 8-30: Flow and Overview of system

Table 8-4: Specifications of system

System type	HWC-H1401S	
Unit type	Heat source unit HWC-H1401H	Supply unit HWC-H1401XH
Outward appearance (width×depth×height)	900mm×320mm×1340mm	900mm×320mm×700mm
Rated power source	3φ200V (50Hz/60Hz)	
Heating capacity	14.0 kW ※1	
COP	3.5 ※2	
Hightest hot water temperature	90℃	

*1 Conditions: Normal capacity

(Conditions: Ambient temperature dry bulb 16 °C/wet bulb 12 °C, Inlet temperature 60 °C, Outlet temperature 65 °C)

*Performance changes depending on ambient temperature and inlet temperature conditions

*2 Conditions: Ambient temperature dry bulb 25 °C/Wet bulb 21 °C, Inlet temperature 60 °C, Outlet temperature 65 °C

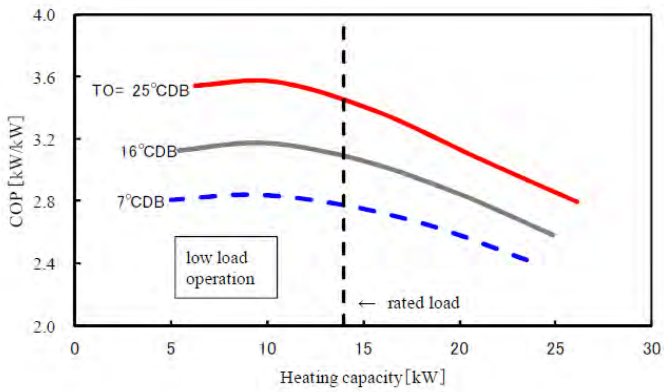


Figure 8-31: Partial load efficiency

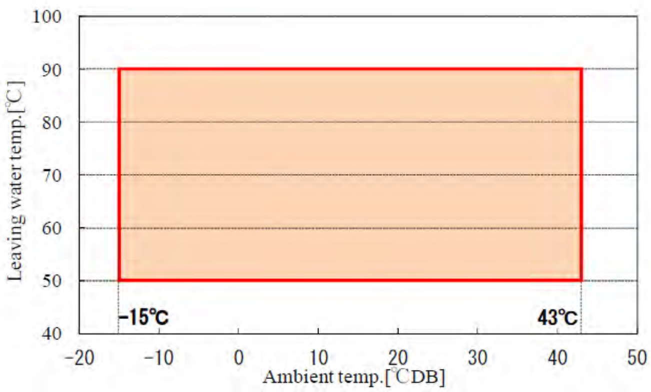


Figure 8-32: Driving range

8.2.4.4 Features of components

As shown in Figure 8-33, this system adopts two DC twin rotary compressors. The compressor for the R-134a cycle was newly developed to maintain the reliability in the higher temperature driving region than existing R-134a cycle temperature range.

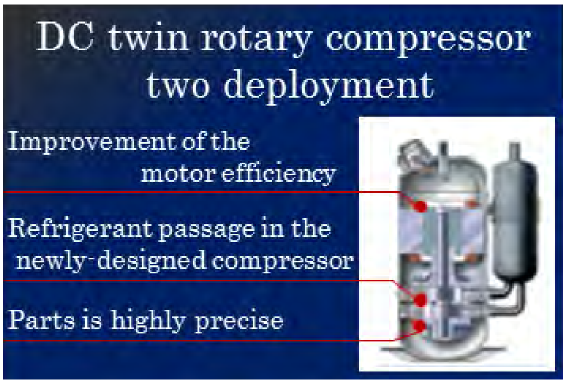


Figure 8-33: Newly developed compressor

8.2.4.5 Example of installation

Figure 8-34 shows this system being applied to washing and antirust treatment processes. This system can reduce the energy consumption by 61 % and the running cost by 65 % compared to a conventional gas boiler.

This system has several input and outputs ports for each signal assumed to be used in the factory process. As an output function, this system has non-voltage contacts that output driving and failure signals. As an input function, this system has a contact input circuit that can input the start-up, shutdown, and interlock circuit signals and an analogue input circuit that can input the auxiliary temperature, pressure, and so on as needed for industrial application.

Thus, this system has a wide range of applicability.

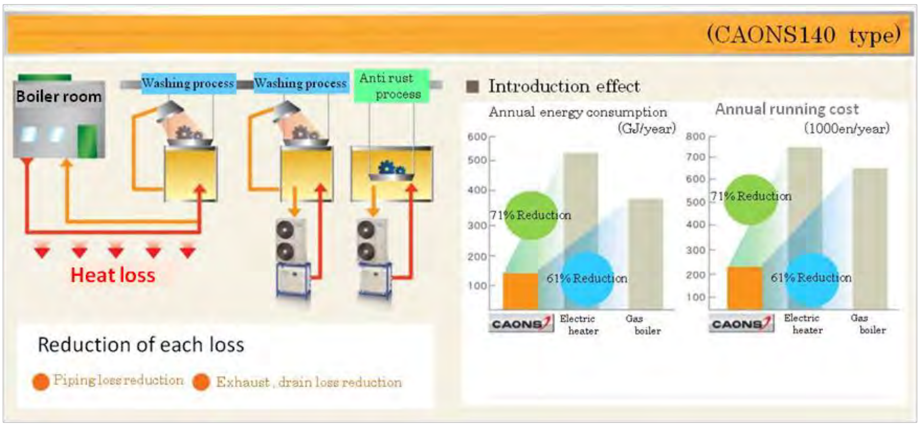


Figure 8-34: Efficiency results from adoption

8.2.5 WASTE HEAT RECOVERY HEAT PUMP WATER HEATER

8.2.5.1 Outline

A great deal of hot water is used in processes such as heating, drying, washing, and sterilizing. Most of it is produce by the boiler, which is fuelled by oil or gas. Waste heat produced in the manufacturing process is cooled down by a cooling tower.

If this waste heat can be used effectively, this will significantly contribute to saving energy and reducing CO_2 emissions. Therefore, a heat pump was applied to the hot water supply process. The waste heat recovery heat pump water heater can use waste heat with a temperature of about 10–50 °C and heat it up to 90 °C, which is supplied to processes where hot water require.

8.2.5.2 System flow

Figure 8-35 shows the system flow. This system mainly consists of an evaporator, a condenser, a compressor, an expansion valve, and an economiser. This flow is a simple single-stage cycle.

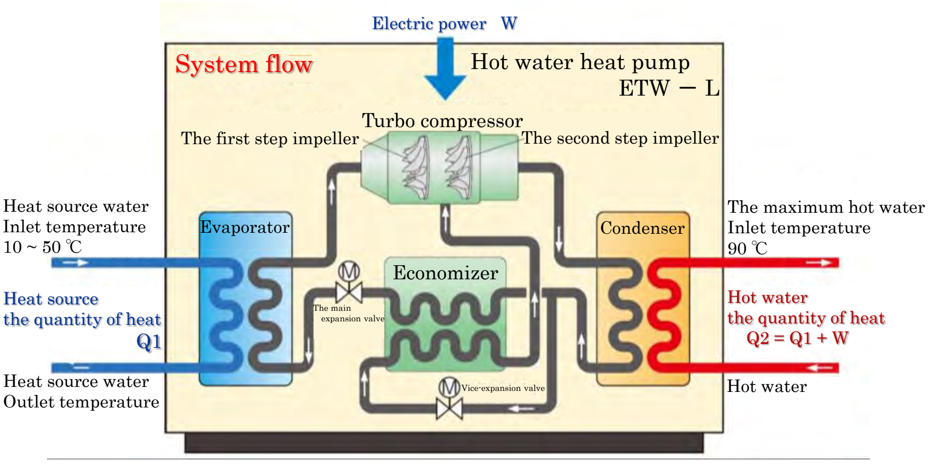


Figure 8-35: System flow

8.2.5.3 System details

Figure 8-36 shows the appearance of the system in practical use. Table 8-5 lists the specifications of this system. The heating capacity is 376–547 kW.

Figure 8-36: Appearance of system (Mitsubishi Heavy Industries: ETW-L)

Table 8-5: System specifications (Mitsubishi Heavy Industries: ETW-L)

Heat pump water heater			ETW－L		
Capacity	Heating capacity	kW	376	545	547
	Cooling capacity	kW	266	400	405
Outward appearance	Length (L)	m	1.55		
	Width (W)	m	1.2		
	Height (H)	m	2		
Weight	Basic machine mass		2500		
	Operating mass		2700		
	Oil		JOMO α68 B		
	Refrigerant		R134a		
	Holding water quantity		120		
Power source	Main power source		400V(380 ~ 440V), 50/60Hz		
	Starting current		Current value or less		
	Inverter capacity		160		
	Voltage,Frequency permission change				
Compressor	Type		MCM150L		
	Number		1		
	Electric motor output	kW	104	136	133
	Starting method		Software start with inverter		
Euaporator	Water side design pressure	Mpa(G)	1.0		
	Inlet heat source water temperature	℃	15	35	50
	Outlet heat source water temperature	℃	10	30	45
	Flow rate of heat source water	m3/h	44.3	69.3	72.9
	Nozzle diameter		100A		
	Pressure loss	kPa	18	43	48
	Drain/Air diameter		15A/15A		
Heat pump water heater			ETW－L		
Condenser	Water side design pressure	Mpa(G)	1.0		
	Inlet hot water temperature	℃	50	65	80
	Outlet hot water temperature	℃	60	75	90
	Flow rate of hot water	m^3/h	32.3	47.9	48.3
	Nozzle diameter		80A		
	Pressure loss	kPa	20	41	42
	Drain/Air diameter		15A/15A		

8.2.5.4 *Features of components*

This system uses a centrifugal compressor, as shown in Figure 8-37. To make the total unit compact, the sizes of the motor, gear, and compressor are reduced. This makes it easier to introduce this system to factories and plants as it improves operability and controllability.

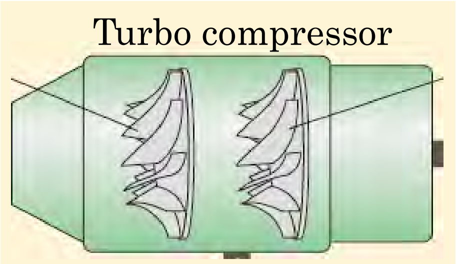


Figure 8-37: Centrifugal compressor

8.2.5.5 *Example of installation*

Figure 8-38 shows this heat pump applied to a pasteuriser. This pasteuriser is a system that sterilises outside bottles after beverages are filled. After the products are heated with a spray of hot water and then kept at a regulated temperature for some time, they are cooled down by a spray of chilled water. This process needs both heating and cooling. If the inlet and outlet temperatures of the hot and chilled water are the same, the heat quantities are also the same.

Conventionally, steam is used to heat up the storage tank, and the chiller cools it down. Simultaneous heating and cooling with this heat pump realises reductions of 58 % in CO_2 emissions and 32 % in running costs.

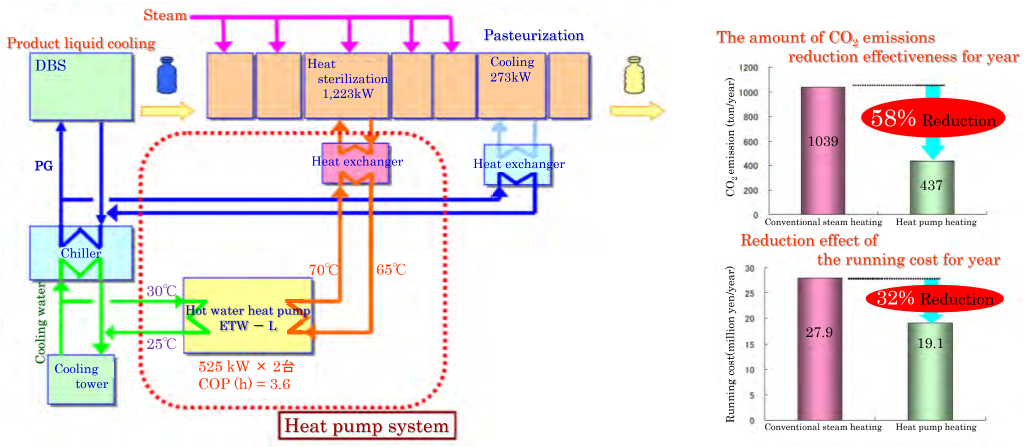


Figure 8-38: Application to pasteuriser

In food factories, humidity control is another important factor. Mechanical dehumidification, where the process air is dehumidified by chilled water from a refrigerator and then reheated, or desiccant dehumidification is normally used.

Since high-performance desiccants have been developed recently, the desiccant dehumidifier can be driven by a lower-temperature heat source supplied as hot water. For this dehumidification system, application of the heat pump water heater can save great amounts of energy. Conventionally, cooling and heating are provided separately for this dehumidification process. However, the heat pump system provides both simultaneously. This system reduces CO_2 emissions by 60 % and running costs by 50 %, as shown in Figure 8-39.

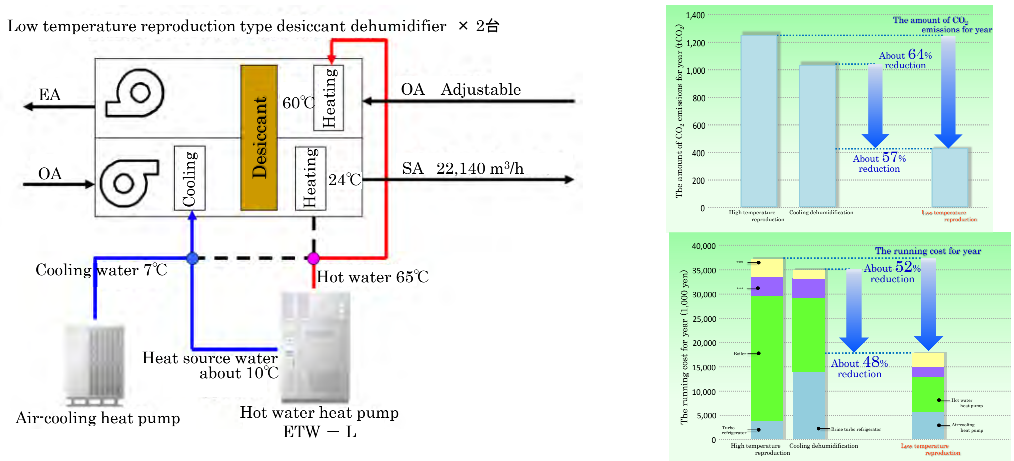


Figure 8-39: Application to desiccant dehumidifier

8.3 Survey of low GWP refrigerants for high temperature heat pumps and basic analysis on their thermodynamic cycle performance

8.3.1 Introduction

In recent years, in civilian, industry and transportation sectors, effective use of energy has been one of the most important issues in terms of greenhouse gas emission cut, the increase of energy cost, etc. Especially, in the industrial sector, introduction of heat pump technology is indispensable as a technology of using waste heat effectively.

This section examines the basic characteristics of several kinds of refrigerants, which are considered to be suitable for heat pumps to use waste heat effectively. Then, thermodynamic cycle analysis on heat pumps for hot water circulation, heat recovery and vapor generation is demonstrated.

8.3.2 Basic characteristics of refrigerants suitable for high temperature heat pump

Some development of the industrial heat pump using R-134a, R-245fa, R-744, etc. has been made recently. However, except for R-744 which is a natural refrigerant with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. At first, basic characteristics of these refrigerants are compared. Table 8-6 shows basic characteristics of R-744, R-1234yf, R-134a, R-1234ze (E), R-1234ze (Z), R-245fa and R-365mfc. In this table, T_c is the critical temperature, Pc is the critical pressure, and NBP is the normal boiling point. As for the critical temperature T_c, R-744 is the lowest, and it becomes high in order of R-1234yf, R-134a, R-1234ze (E), R-1234ze (Z), R-245fa, and R-365mfc. The transcritical cycle using R-744 and the reverse Rankine cycle using R-134a are put in practical use to generate hot water of 60 to 90 °C from water of 20 to 30 °C, the reverse Rankine cycle using R-134a is developed to reheat the circulating water between heat pump and heating load utilizing waste heat effectively. The reverse Rankine cycle using R-245fa is also developed to reheat the circulating water and to generate steam from the waste heat of 50 to 60 °C. Furthermore, zeotropic refrigerant mixture of R-245fa/R-134a was put in practical use as the working fluid of the reverse Rankine cycle for generating the steam more than 120 °C. In the above-mentioned systems put in practical use, refrigerants with high GWP values are used except for R-744. Therefore, new systems using low GWP refrigerants should be developed.

Figure 8-40 shows the saturated vapor pressure curves of R-134a, R-245fa, R-1234ze(E), R-1234ze (Z) and R-365mfc. The vapor pressures become high in order of R-134a, R-

1234ze (E), R-1234ze (Z), R-245fa, and R-365mfc at a same saturation temperature. The vapor pressure curve of R-1234ze (E) is shifted to the high temperature side a little as compared with R-134a. The vapor pressure curve of R-1234ze (Z) is very close to R-245fa. R-365mfc with the highest critical temperature T_c has the lowest vapor pressure among these refrigerants.

Figure 8-41 shows the relation between the latent heat and saturation temperatures of R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc. In a temperature region of 60 °C or less, the latent heat becomes small at the order of R1234ze (Z), R-365mfc, R-245fa, R-134a, and R-1234ze (E). At about 100 °C, the latent heat of R-245fa, R-1234ze (Z) and R-365mfc is higher than 130 kJ/kg, while that of R-134a and R-1234ze (E) decreases steeply because the critical temperatures of those refrigerants are a little higher than 100 °C.

Figure 8-42 shows the relation of volumetric refrigeration capacity and the saturation temperature. The refrigerants have the highest refrigeration capacity as follows, R-134a at 90 °C, R-1234ze (E) at 100 °C, and R-245fa and R-1234ze (Z) 140 °C respectively. The inverse Rankin cycle around 160 °C seems to be feasible using R-365mfc, while the other refrigerants are used as working fluid of the trans-critical cycle.

Table 8-6: Basic characteristics of refrigerants for high temperature heat pump applications

Refrigerant	Chemical fomula		GWP	Flamability	Tc °C	Pc MPa	NBP °C
R744	CO2	carbon dioxide	1	none	30.98	7.3773	−78.40
R1234yf	CF3CF=CH2	2,3,3,3-tetrafluoropropene	4	weak	94.7	3.382	−29.48
R134a	CF3CH2F	1,1,1,2-tetrafluoroethane	1430	none	101.06	4.0593	−26.07
R1234ze(E)	CFH=CHCF3	trans-1,3,3,3-tetrafluoropropene	6	weak	109.37	3.636	−18.96
R1234ze(Z)	CHF=CHCF3	cis-1,3,3,3-tetrafluoropropene	<10	weak	153.7	3.97	9.76
R245fa	CF3CH2CHF2	1,1,1,3,3-pentafluoropropane	1030	none	154.01	3.651	15.14
R365mfc	CF3CH2CF2CH3	1,1,1,3,3-pentafluorobutane	794	weak	186.85	3.266	40.19

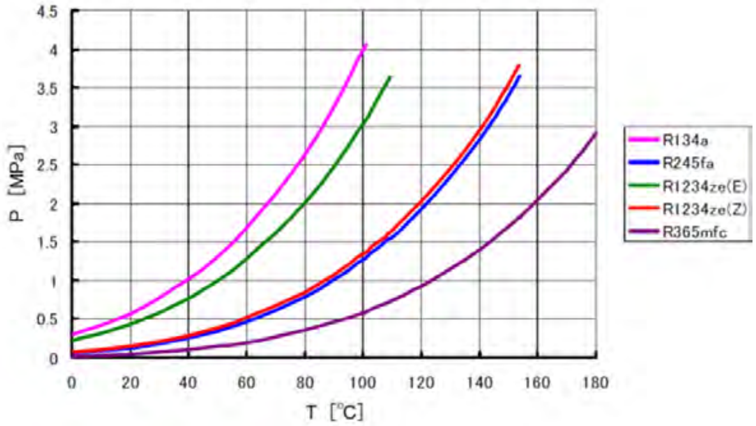


Figure 8-40: Saturated Vapor Pressure Curve

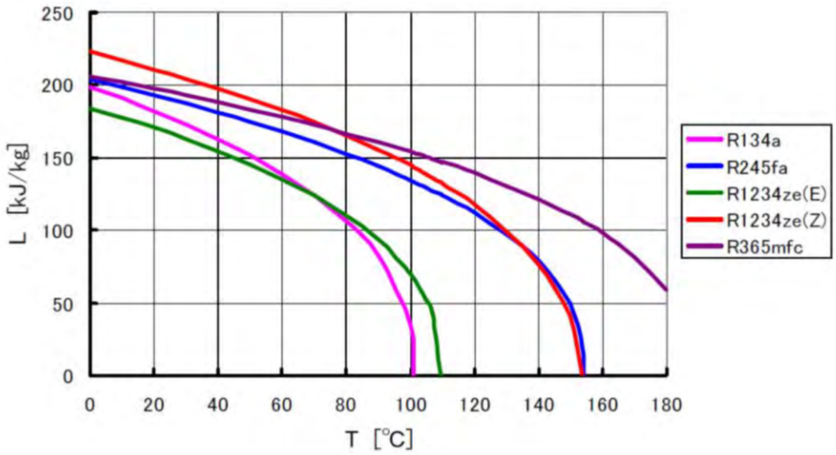


Figure 8-41: Latent heat of vaporization

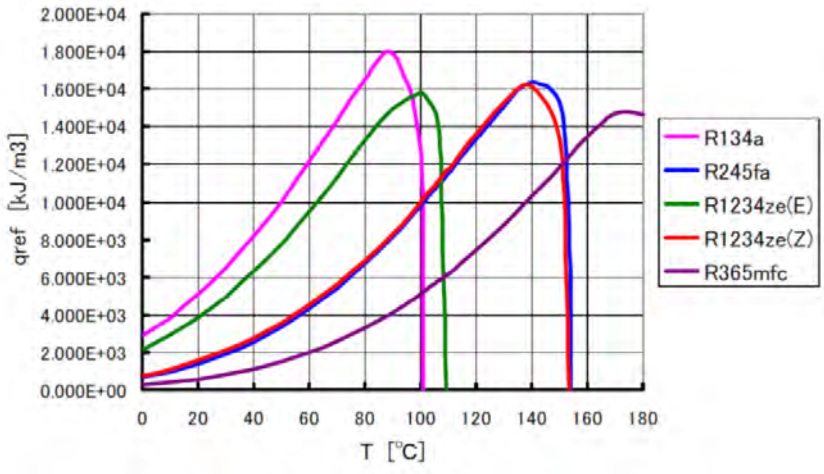


Figure 8-42: Volumetric refrigeration capacity

8.3.3 Thermodynamic analysis of cycle performance

In order to examine the possibility of introduction of heat pump as technology for effective use of waste heat, thermodynamic analysis of cycle performance is carried out under three kinds of conditions as: (case 1) reheating of circulated hot water from ambient heat source, (case 2) reheating circulated hot water from waste heat, and (case 3) steam generation using waste heat.

(Case 1) Single-stage heat pump cycle for hot water circulation

The single-stage heat pump cycle is used to reheat hot water circulating between the heat pump cycle and heating load. Thermodynamic performance of this cycle is calculated on the following condition.

- High temperature heat source

  Secondary fluid side: water returned from heating load at 60 °C is heated up to 65 °C.

  Refrigerant side: refrigerant is condensed at 67 °C and subcooled at 62 °C.
- Low temperature heat source

  Secondary fluid side: water or air at 25 °C is cooled down to 20 °C.

  Refrigerant side: refrigerant is evaporated at 18 °C and superheated up to 23 °C.
- Compressor performance

  Adiabatic efficiency: 0.92, mechanical efficiency: 0.85, electric motor: 0.9
- Refrigerants: R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc

The calculation results of cycle performances are shown in Table 8-7. As for any refrigerants, the values of COPs are 3.9 or more, and the primary energy efficiencies are 1.4 or more. The volumetric heating capacities of R-245fa, R-1234ze (Z) and R-365mfc are low although COPs of those refrigerants are slightly high as compared with R-134a and R-1234ze (E).

Table 8-7: Cycle performance of single-stage heat pump for hot water circulation

Refrigerant	Heating capacity kJ/kg	Volumetric heating capacity kJ/m^3	Suction–discharge pressure ratio	COP	Primary energy efficiency
R134a	152.95	3882	3.683	3.908	1.446
R245fa	170.23	1105.8	4.953	4.192	1.551
R1234ze(E)	140.48	2913.7	3.751	3.92	1.45
R1234ze(Z)	190.08	1284.9	4.47	4.246	1.571
R365mfc	172.78	451	5.732	4.207	1.557

Demand side electric power generation efficiency = 0.37

(Case 2) Single-stage heat pump cycle for thermal recovery from waste heat

The single-stage heat pump cycle is used to reheat hot water circulating between the heat pump cycle and heating load. The waste heat is used as low temperature heat source. Thermodynamic performance of this cycle is calculated on the following condition.

- High temperature heat source

  Secondary fluid side: water returned from heating load at 80 °C is heated up to 90 °C.

  Refrigerant side: refrigerant is condensed at 92 °C and subcooled at 87 °C.
- Low temperature heat source

  Secondary fluid side: water or air at 50 °C is cooled down to 40 °C.

  Refrigerant side: refrigerant is evaporated at 38 °C and superheated up to 43 °C.
- Compressor performance

  Adiabatic efficiency: 0.92, mechanical efficiency: 0.85, electric motor: 0.9
- Refrigerants: R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc

In Table 8-8 the calculation results of cycle performance are shown. Although the volumetric heating capacities of R-134a and R-1234ze (E) are high, the COP values and primary energy efficiencies of those refrigerants become low because their operating temperatures approach the critical temperature. Volumetric capacities of R-245fa and R-1234ze (Z) increase as compared with case (1) and the COP values of these refrigerants are comparatively high at about 3.8 or more. In the case of R-365mfc, COP is high, but volumetric heating capability is low. From a viewpoint of primary energy efficiency and volumetric heating capability, R-245fa and R-1234ze (Z) are considered to be suitable refrigerants under the present temperature condition.

Table 8-8: Cycle performance of single-stage heat pump for thermal recovery from waste heat

Refrigerant	Heating capacity kJ/kg	Volumetric heating capacity kJ/m^3	Suction–discharge pressure ratio	COP	Primary energy efficiency
R134a	111.78	5339.8	3.509	3.244	1.2
R245fa	146.89	1902.1	4.499	3.832	1.418
R1234ze(E)	109.78	4099.6	3.552	3.323	1.23
R1234ze(Z)	165.33	2131.1	4.135	3.905	1.445
R365mfc	152.84	839.8	5.15	3.89	1.439

Demand side electric power generation efficiency = 0.37

(Case 3) Single-stage heat pump cycle for thermal recovery and steam generation from waste heat

The single-stage heat pump cycle is used to generate steam from waste heat. Thermodynamic performance of this cycle is calculated on the following condition.

- High temperature heat source
  Secondary fluid side: steam at 120 °C is generated
  Refrigerant side: refrigerant is condensed at 130 °C and subcooled at 125 °C.
- Low temperature heat source
  Secondary fluid side: factory waste liquid at 100 °C is used as heat source
  Refrigerant side: refrigerant is evaporated at 90 °C and superheated up to 95 °C.
- Compressor performance
  Adiabatic efficiency: 0.92, mechanical efficiency: 0.85, electric motor: 0.9
- Refrigerants: R-245fa, R-1234ze (Z) and R-365mfc

Table 8-9 shows the calculation results of cycle performance. R-134a and R-1234ze (E) were excepted from the refrigerants for calculation, since those critical temperatures are lower than high temperature heat source temperature. COPs of R-245fa, R-1234ze (Z), and R-365mfc are 5.3 or more, and those primary energy efficiencies are also as very high as 1.9 or more. In particular, although the volumetric capability of R-365mfc is not high, its primary energy efficiency is high as 2.1.

Table 8-9: Cycle performance of single-stage heat pump for thermal recovery and steam generation from waste heat

Refrigerant	Heating capacity kJ/kg	Volumetric heating capacity kJ/m^3	Suction–discharge pressure ratio	COP	Primary energy efficiency
R245fa	109.24	5997.7	2.33	5.318	1.968
R1234ze(Z)	121.08	6279.1	2.28	5.365	1.985
R365mfc	127.84	3231	2.496	5.761	2.131

Demand side electric power generation efficiency = 0.37

8.3.4 Concluding remarks

(1) Refrigerants for high temperature heat pump

- R-1234ze (E) and R-1234yf are promising as alternative of R-134a.
- R-1234ze (Z) is promising as alternative of R-245fa.
- The alternative of R-365mfc is under research and development.

(2) Thermodynamic analysis of heat pump cycle performance

Thermodynamic analysis of cycle performance was carried out under three kinds of conditions as: (case 1) reheating of circulated hot water from ambient heat source, (case 2) reheating circulated hot water from waste heat, and (case 3) steam generation using waste heat. In the present analysis, five kinds of refrigerants R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc are selected as objectives of calculation. From a viewpoint of volumetric heating capacity and primary energy efficiency, it can be judged as follows.

- In case 1, R-134a is the most suitable refrigerant. However, R-1234ze (E) is the promising one because of its low GWP.
- In case 2, R-245fa and R-1234ze (Z) are suitable refrigerants.
- In case 3, R-245fa and R-1234ze (Z) are suitable refrigerants. Although the volumetric heating capacity of R-365mfc is about half lower than R-245fa and R-1234ze (Z), its primary energy efficiency is the highest.

In order to select the combination of cycle and refrigerant, which is suitable for given heat source and sink condition, thermodynamic performance analysis of pure and mixed refrigerants should be carried out not only for single stage heat pump cycle, but also for two stage and cascade heat pump cycles.

8.4 Industrial Application of Thermal Storage Technologies

Thermal storage technologies make it more convenient to transfer and use thermal energy anywhere and anytime by storing thermal energy including industrial cold energy and waste energy.

Since the Great East Japan Earthquake occurred in 2011, the power load leveling has become one of the major issues to tackle in Japan. Thermal storage technologies, which can use energy stored at night, are in particular expected to gain importance in industrial applications in the future to address this issue. This is because thermal storage technologies bring various advantages such as lower electricity prices by taking a less expensive option for night-time consumption which an electricity tariff offers, and contract amperage reduction in response to reduced installed capacity. In addition, combined systems of thermal storage technologies and heat pumps, which use renewable energy, are expected to attract attention since they can level power load, conserve energy and reduce CO_2 emission at the same time.

The latest thermal storage technologies including the ones already in practical use are explained below sorted by temperature ranges.

8.4.1 Ice slurry made from trehalose aqueous solution

Trehalose ($C_{12}H_{22}O_{11}$: Molecular weight = 342) is a relatively inexpensive natural carbohydrate that can be synthesized from starch. It is widely used as a food additive.

I. Application: Ice slurry made from trehalose aqueous solution can be utilized for cold storage of foods such as vegetables and fruit in a wide temperature range below 0 °C.

II. Characteristics: Ice slurry has a high fluidity and is excellent at absorbing heat. As shown in Figure 8-43: Freezing point of trehalose aqueous solution [Kawanami, 2011, its temperature change against concentration change is extremely small, which is very important for cold storage of food. Moreover its freezing point in the same concentration as propylene glycol (PG), an existing refrigerant for cold storage of food, is higher than that of PG. It will help raise refrigerator evaporation temperature and lead to coefficient of performance (COP) improvement.

III. Latent heat: Estimated at approximately 210 kJ/kg

IV. Combined system with heat pump, example of installation: It is used for making ice and hot water at night and cooling milk with ice during daytime.

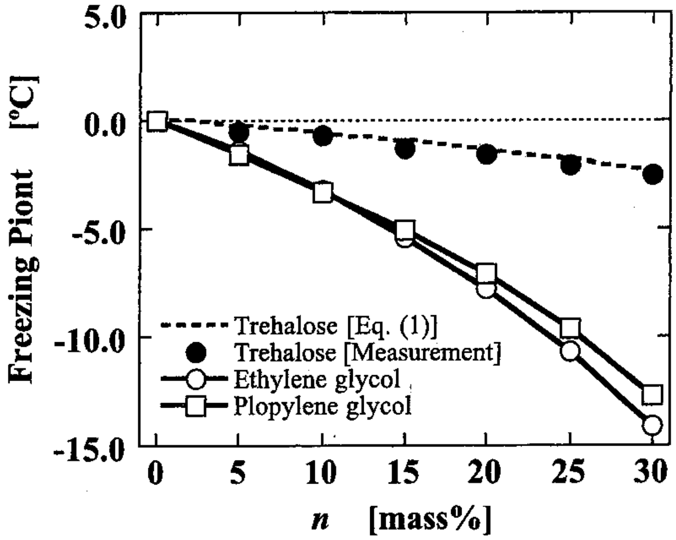


Figure 8-43: Freezing point of trehalose aqueous solution [Kawanami, 2011]

Kawanami, 2011 T. Kawanami, K. Togashi, K. Fumoto, S. Hirano, S. Hirasawa, Physical Properties and Heat Transfer Characteristics of an Environmentally Neutral Ice Slurry, Japan J. of Thermophysical Properties, Vol. 25, No. 2 (2011) p. 89-94 (in Japanese)

8.4.2 Tetra-n-butyl ammonium bromide (TBAB) hydrate slurry

i. Application: Air conditioning at a components factory (already in practical use)

ii. Characteristics: TBAB hydrate slurry changes a phase in the temperature range of air conditioning. As shown in Figure 8-44 at a concentration from 13 wt.% to 20 wt.%, its solidification temperature is from 5 °C to 8 °C, which is suitable for air-conditioning. Moreover based on the conditions of the concentration, two types of TBAB hydrate slurry can be produced. Type 1 hydrate slurry has a better function in fluidity.

iii. Latent heat: Table 8-10 shows the latent heat of Type 1 and Type 2 hydrate slurry. The difference between Type 1 and Type 2 is very small.

Table 8-10: Latent heat of TBAB hydrate crystals

	Oyama et al. [Oyama,2005]	Takao [Takao, 2002]
Type 1 (kJ/kg)	193.18	193
Type 2 (kJ/kg)	199.59	205

Oyama, 2005 H. Oyama, et al., Fluid Phase Equilibria, 234 (2005) 131-135

Takao, 2002 S. Takao, Japanese Journal of Multiphase Flow, Vol.16, No. 4 (2002) 412-414 (in Japanese)

iv. Combined system with heat pump, potential of installation: They have not been in practical use yet. However, if a heat pump can supply cold water at approximately 5 °C, it will be possible to combine the slurry with a heat pump.

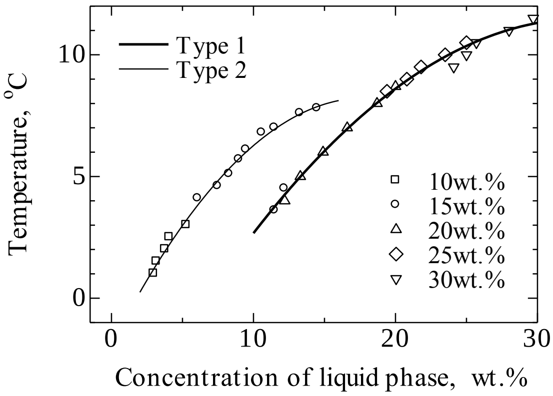
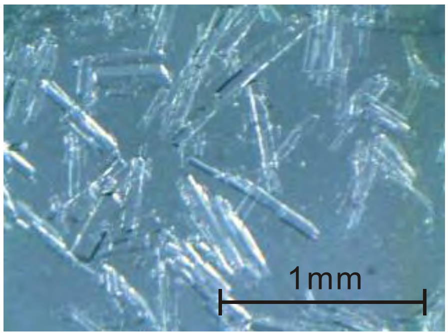
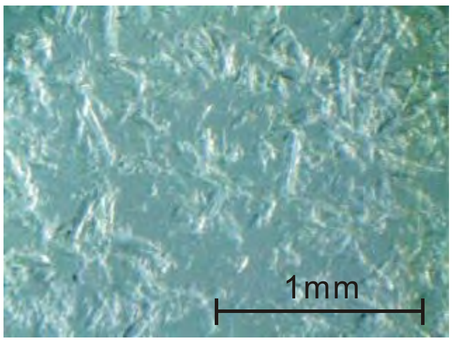


Figure 8-44: Relationship between hydrate slurry solution concentration and temperature [Kumano, 2006]

Kumano, 2006 H. Kumano, A. Saito, S. Okawa, Y. Goto, Study on Fundamental Characteristics of TBAB Hydrate Slurry, Trans. of JSME, Ser. B Vol. 72, No. 724, 2006, 3089-3095 (in Japanese)



(a) Type 1 hydrate



(b) Type 2 hydrate

Figure 8-45: Photographs of TBAB hydrate slurry [Kumano, 2012]

Kumano, 2012 H. Kumano, T. Hirata, Y. Hagiwara, F. Tamura, Effects of Storage on Flow and Heat Transfer Characteristics of Ice Slurry, Int. Journal of Refrigeration, Vol. 35, No. 1, 2012, 122-129

8.4.3 Paraffin slurry

(a) Ice slurry: produced by nanoemulsion with water as a continuous phase and tetradecane as a dispersed phase.

i. Application: Air conditioning at factories

ii. Characteristics: Paraffin slurry has fluidity and changes a phase at around 5.9 °C, which is very suitable for air conditioning. Table 8-11 shows the physical properties of tetradecane and Table 8-12 shows the nanoemulsion composition ratio. As shown in Table 8-12, two types of non-ionic surfactant (Span 80, Tween 120) are mixed for the emulsion.

iii. Latent heat: Table 8-13 shows the thermophysical properties of the nanoemulsion.

iv. Combined system with heat pump, example of installation: They have not been in practical use yet.

Table 8-11: Physical properties of tetradecane [Fumoto, 2011]

Properties	Tetradecane
Melting point (°C)	5.9
Latent heat (kJ/kg)	229.1
Specific heat (kJ/(kg・K))	1.80 (Solid), 2.14 (Liquid)
Density (kg/m³)	810 (Solid), 770 (Liquid)
Viscosity (mPa・s)	2.47

Table 8-12: Composition ratio of nanoemulsion [Fumoto, 2011]

Tetradecane (wt%)	Surfactant (Span 80, Tween 120) (wt%)	Water (wt%)
10.0	8.0	82.0
20.0	8.0	72.0

Table 8-13: Thermophysical properties of nanoemulsion [Fumoto, 2011]

Tetradecane (wt%)	Thermal conductivity W/(m K)	Viscosity (mPa・s)
10.0	0.578 (at 28.1°C)	2.16
20.0		3.24

Fumoto, 2011 K. Fumoto, M. Kawaji, T. Kawanami, Thermophysical Property Measurements of Tetradecane Nanoemulsion Density and

Thermal Conductivity, Japan J. of Thermophysical Properties, Vol. 25, No. 2 (2011) 83-88 (in Japanese)

(b) CALGRIP (trademark pending product of JSR Corporation)

i. Characteristics: CALGRIP stabilizes paraffin with a special olefin-based thermoplastic elastomer. Its latent heat storage capacity has been increased by 40 % to 100 % compared to paraffin-based latent storage material. As shown in Figure 8-46, even when it is being melted, it retains in a gel state. Various forms are available in accordance with practical application. In fact, products having melting points of 4 °C, 9 °C, 18 °C, 25 °C and 80 °C have already been developed.

ii. Combined system with heat pump, example of installation: They have not been in practical use yet.

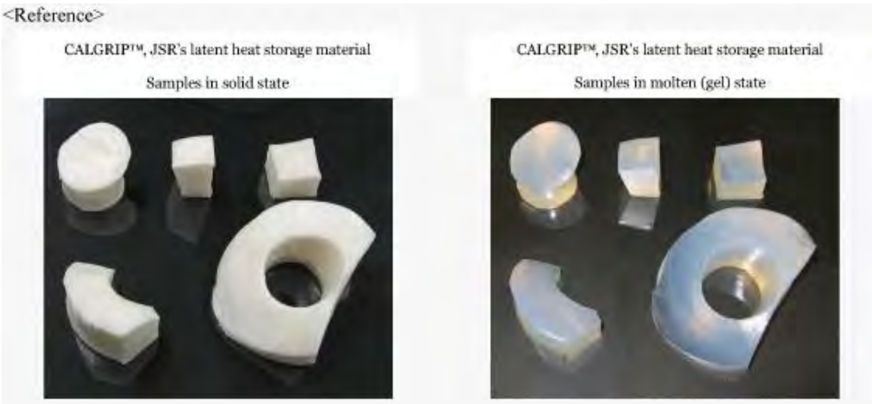


Figure 8-46: States of solidification and melting of CALGRIP [jsr]

jsr www.jsr.co.jp/news/0000086.shtml

8.4.4 Sodium acetate trihydrate: $CH_3COONa \cdot 3H_2O$

i. Application: Thermal storage for solar water heating or efficient utilization of factory waste heat of 60 °C

ii. Characteristics: Sodium acetate trihydrate changes a phase at around 60 °C and is used as a food additive.

Latent heat:

iii. Table 8-14 shows the melting point and latent heat of sodium acetate trihydrate.

iv. Combined system with heat pump, example of installation: They have not been in practical use yet.

Table 8-14: Melting point and latent heat of sodium acetate trihydrate

Melting point (°C)	58.8
Latent heat (kJ/kg)	247-255

8.4.5 Erythritol: ($HOCH_2[CH(OH)_2]_2CH_2OH$) and Mannitol: ($HOCH_2(CHOH)_4CH_2OH$)

Both are harmless polyhydric alcohol and sugar alcohol.

i. Application: Efficient use of waste heat at factories

   Erythritol and mannitol can efficiently use low-temperature waste gas below 200°C, which means most of the waste gas at factories. If the heat is not directly exchanged, durable capsules need to be developed. Latent heat: Table 8-15 shows the thermophysical properties of erythritol and mannitol.

ii. Combined system with heat pump, example of installation: They have not been in practical use yet.

Table 8-15: Thermophysical properties of erythritol and mannitol [Horibe, 2011]

Properties	Erythritol	Mannitol
Melting point (°C)	118	166.5
Latent heat (kJ/kg)	320	303.7
Thermal conductivity (W/(m K))	0.34 (at 120°C)	0.42 (at 170°C)
Density (kg/m^3)	1300 (at 137°C)	1386 (at 200°C)

Horibe, 2011 A. Horibe, J.Yu, N. Haruki, A. Kaneda, A. Machida, M. Kato, Melting Characteristics of Mixtures of Two Kinds of Latent Heat Storage Material, Japan J. of Thermophysical Properties, Vol. 25, No. 3 (2011) 136-142 (in Japanese)

8.4.6 Other thermal technologies

Figure 8-47 shows the relationship between melting point and latent heat for molten salt, organic material and hydrate, which are expected to be utilized as thermal materials. Erythritol and mannitol are also shown for reference.

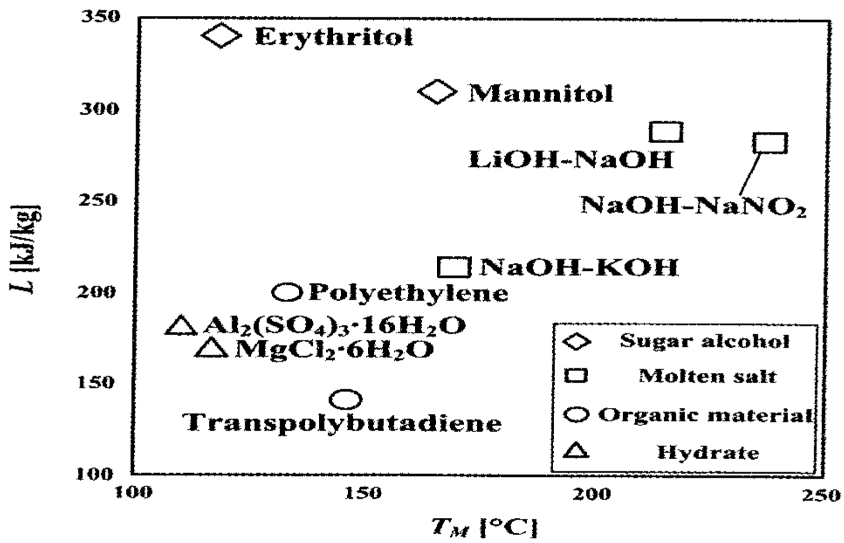


Figure 8-47: Relationship between melting point and latent heat (Horibe, 2011]

Horibe, 2011 A. Horibe, J. Yu, N. Haruki, A. Kaneda, A. Machida, M. Kato, Melting Characteristics of Mixtures of Two Kinds of Latent Heat Storage Material, Japan J. of Thermophysical Properties, Vol. 25, No. 3 (2011)

9 Korea

9.1 R&D Background of industrial heat pumps

More than 60 % of the total energy is consumed for the industrial application in Korea. A great portion of final energy in industrial field is to generate heat or provided as feed-stock. So, a lot of activities have been done to improve efficiency or make advanced process in order to reduce primary energy consumption and green gas emission. The major directions of such activities are;

- Utilization of waste heat from industrial processes (reduce green gas emission and production cost) by hybridized heat source with renewables
- Production of hot water which can be directly used to the processes
- Extension of heat pump applications into advanced industrial processes formerly neglected to be a part of the processes

Under these circumstances, the application of industrial heat pump has gained much interest in these days by not only companies but also government agents.

The global heat pump market has been increased rapidly. More interest has been given to energy efficiency increase as one of the solution to urgent problems of energy cost and environmental effect. So far, the main fields of heat pump market have been heating/cooling system and hot water generation system. Therefore the researches and policies of government have been focused on these topics. It is true that the interest on industrial heat pump featuring high temperature operation range has gained relatively low interest. Furthermore, the retail energy prices of Korea have been maintained at low level. This makes the manufacturers less sensitive to the energy cost of the product. So the manufacturers pose inactive stance on the investment of energy efficiency facilities rather than productivity increase facilities.

There are well established test standards and installation guides for the heat pump for heating and cooling. And major manufacturers dominate that market with well-modularized, mass-produced products. However, the install scene for industrial heat pump has its unique requirements. So, system design and installation should be done to cover these things. It is true that industrial heat pump has weak points in standardization and mass production. This, further makes not only the manufacturers, but also installer and engineers to have much higher technical level ever before.

Despite of all of these adverse features of industrial heat pump, the confronting issues like global warming, the climate change convention, surging of energy prices, depletion of fossil fuel, and so on, have changed the working situation in industrial market, and the manufacturers have begun to consider adopting devices or facilities which are environmentally benign requiring less primary energy. Industrial heat pump has become one of the best solutions for the manufacturers.

The benefits of adopting heat pump in industrial process are

- Heat pump is one of the most optimum solutions to recycle waste heat of industrial processes

- Application of industrial heat pump can contribute to the reduction in green gas emission
- Since heat pump can use energy from air, sea water, underground water, or any other low temperature heat resources, the additional heat out of the total produced heat is classified as renewable energy

In the Korean hot water heat pump market, 50-60 °C hot water generation systems occupy most of the market share. In order to be applied to industrial process, the generation temperature should be increased up to 90 °C or above. And since heat pump systems also produce chilled water while producing hot water owing to their thermodynamic nature, process design considering both heating and cooling resources is required to maximize energy savings with heat pump. The concept of energy network has risen under this circumstance.

9.2 R&D programs of Korea

Energy R&D in Korea is supported largely by the Ministry of Trade, Industry and Energy (MOTIE). As a key operating agent, Korea Institute of Energy Technology Evaluation and Planning (KETEP) is running four major categories of Energy Efficiency and Resource Program, New and Renewable Energy Program, Power and Electricity Technology Program, Nuclear Power Program.

Heat pump R&D in Korea is categorized into Energy Efficiency and Resources Program. The scope of the program is to ensure effective accomplishment of the objectives of the governments Framework Plan for the Development of Energy and Resource Technologies for the Years 2006-2015, where key parts are energy storage, heat pumps, micro CHP, building energy, green cars, clean fuel, energy equipment, industrial process, CCS, and energy resources.

Heat pump technologies were categorized in the national roadmaps in Korea listed below.

- Environmental Energy Core Technology in National Technical Roadmap (NTRM) (2002)
- Environmental Energy Area in Innovative Technology Five-Year Master Plan (2004)
- Energy Efficient Technology of Unutilized Energy Applications in Energy Technology Ten-Year Roadmap by the Ministry of Commerce, Industry and Energy (MOCIE, a former MOTIE) (2004)
- The Seven-Runners Program for massive energy consuming equipment by MOCIE (2006)
- Korean National Green Energy Strategic Roadmap by MOTIE

1st roadmap (2009)	Solar power, Wind power, Fuel cell, IGCC, CCS, Energy storage, Electric power-IT convergence, LED, Nuclear power, Micro CHP, Green car, Superconductivity, Heat pump, Building energy

2nd roadmap (2011)	Solar power, Wind power, Fuel cell, Biofuels, CCS, High efficiency lightings, Clean fuels, Energy storage, Clean fossil fuel power, Smart grid, Nuclear power, Green car, Building energy, Heat pump, IGCC

9.3 Heat pump R&D cases

In this section, the R&D cases related with industrial heat pumps which have started or finished within the last 3 years are presented. In Korea, heat pump R&Ds are still bias to HVAC&R area, however, some researches that have potentials extended as hybrid heat source applications were introduced.

9.3.1 Development of a 30 kW grade compression/absorption heat pump producing high temperature hot water with waste heat

This application is to secure design and control technologies of compression-absorption hybrid heat pump that produces high-temperature water by using NH_3/H_2O mixture as a natural refrigerant. The goal is to develop a prototype of 30 kW class heat pump which produces hot water over 90 °C using waste heat of 50 °C from manufacturing process.

Although vapor compression cycle and absorption cycle are applied widely, there are limits for these cycles. The limitations come from various reasons like confined temperature increase, inflexible driving range, limited capacity control, degradation of heat exchange efficiency by large temperature difference between pure refrigerant and secondary fluid during condensation or evaporation, low coefficient of performance(COP) of absorption cycle, and other physical restrictions. In order to solve these weaknesses and shortcomings of current cycles, hybrid cycle that combines vapor compression and absorption cycle was proposed and a lot of researches are in progress.

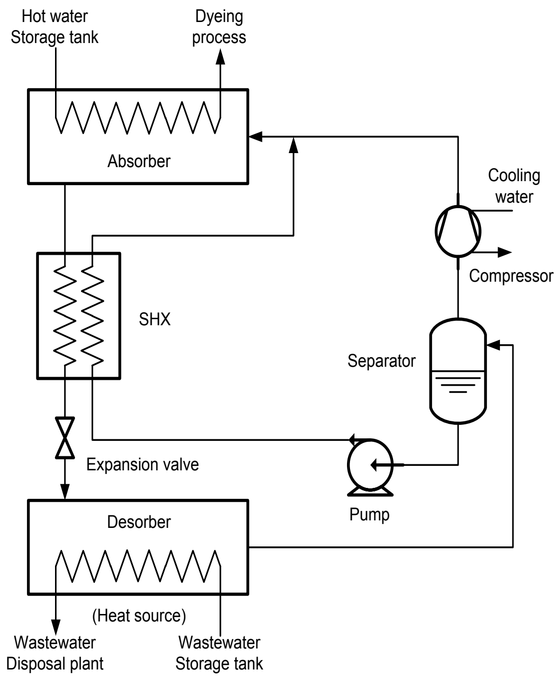


Figure 9-1: Schematic diagram of simplified compression/absorption heat pump system

A project was performed by a collaboration of a research center (Korea Institute of Energy Research: KIER) and a company (Shinsung Engineering). Through this collaboration, vapor compression/solution pumping system designed exclusively for prototype hybrid cycle including vapor-liquid rectifier design. The performance evaluation was initiated by steady-state performance simulation program, transient characteristics and control variables deduction, NH_3/H_2O concentration analysis. During the experimental evaluation, a variety of research activities for peripherals were carried out. After a long period of the optimization of each part, a prototype of 30 kW grade hybrid heat pump was produced with COP_H = 3.5 and hot water over 92 °C. This improved energy consumption efficiency 17 % compare to existing boiler when the efficiency of boiler was considered as 90 %.

Expected application area of this newly developed system is commercial facilities such as Sauna and Jjimjilbang (Korean-style dry sauna) where large capacity of heating and hot-water supply is required. This system is also applicable with connection to the facilities that generate a large amount of waste heat (ex. cogeneration plants) and can be utilized to district heating facilities in participating in a new town energy supply chain design. In an industrial complex, a large quantity of waste heat can be collected in order to utilize it as hot process water or heat source for air-conditioners for factories.

Figure 9-2: Prototype of a compression/absorption heat pump system

9.3.2 Demonstration of a high-temperature heat pump system with heat recovery from flue gases

This system effectively collects waste heat from low-temperature flue gases and utilizes this as heat source for high-temperature heat pump system that generates process hot water. The purpose of this system is to increase thermal efficiency of overall industrial boiler through exhaust gas heat recovery and heat pump.

Industrial factories and cogeneration plants produce high-temperature industrial process water by from boiler. In boiler, a large volume of flue gases under 250 °C that contain steam is discharged and thermal loss of boiler is mainly due to this exhaust gas. Therefore, many manufacturers install waste heat recovery system up to hot water of 85~90 °C and use it in preheating process to raise air temperature or boiler supply water. In case of using natural gases as a fuel, they contain few corrosives such as sulfur so manufactures can decrease the exhaust gas temperature below 60 °C under this point condensation of flue gases occurs. That means recovering more energy from latent heat of steam inside exhaust gas by lowering the temperature of exhaust gas, and water of 35~55 °C would be produced by latent heat recovery.

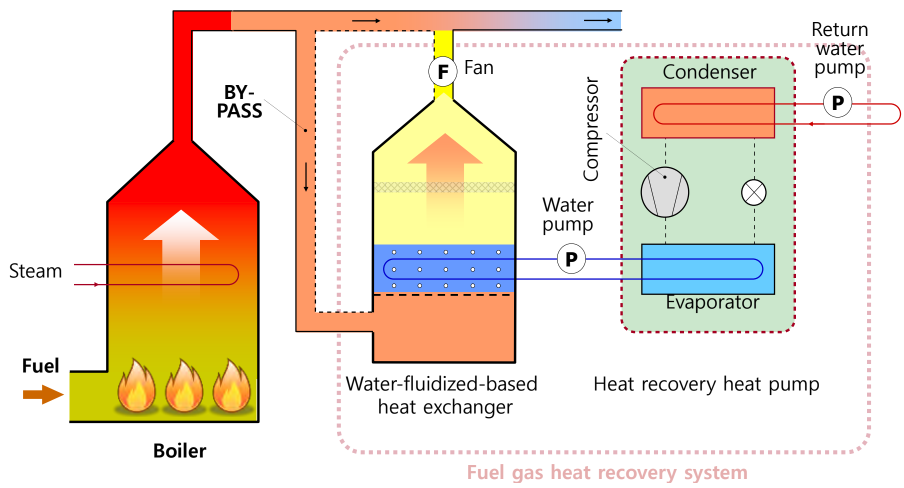


Figure 9-3: Schematic of heat pump system with flue gas heat recovery

Methane (CH_4), the main component of natural gas, generates water of 1.61 kg per cubic meter after combustion. Therefore, by collecting latent heat through condensation of all the steam inside combustion product to water, it is possible to collect additional heat of 868 kcal per cubic meter. At this point, condensing temperature of steam in exhaust gas varies from 50 °C to 60 °C depending on its excess air ratio.

In order to efficiently use recovered heat through above process, heat pump can be used. According to Korea Energy Management Corporation (KEMCO), about 40 thousands of industrial/heating boilers are installed in Korea. In addition, it is known that cogeneration plants using oil, natural gas, coal and other energy sources generate energy about 2,760 MW. However, the amount of waste heat energy inside of the exhaust gases from the plants has not been found yet.

A heat pump system with heat recovery from exhaust gas in order to utilize waste energy was installed in a food factory and its performance verification was carried out through demonstration operation. In this application, condensation heat recovery unit was installed to recover total heat of exhaust gas and its performance verification was carried out. Moreover, in connection with this heat recovery unit, a 30RT class high-temperature heat pump system was designed and produced. Demonstration operation started from winter season of 2012 and featured over 100 kW heating capacity and COP larger than 3.0. Furthermore, overall thermal efficiency of combined boiler and high-temperature heat pump system increased more than 8.2 % compare to conventional hot water boiler.

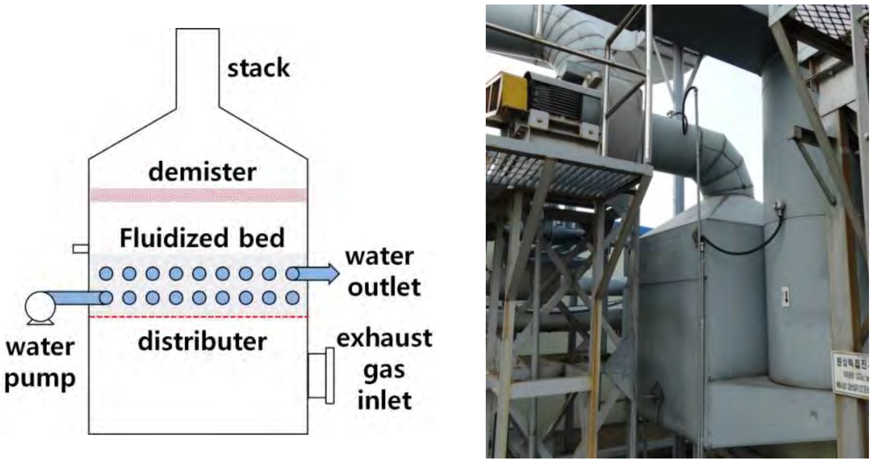


Figure 9-4: Schematic diagram of water-fluidized bed heat recovery system and its installation scene

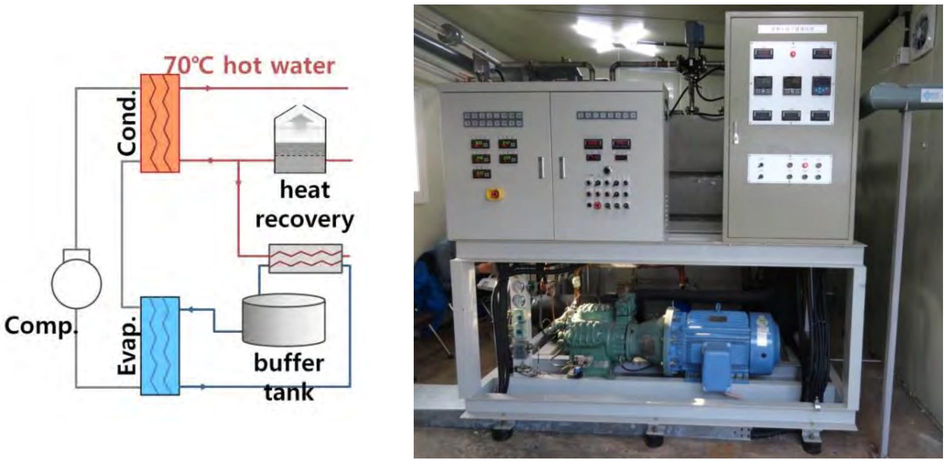


Figure 9-5: Schematic diagram of heat pump system and its installation scene

9.3.3 High-temperature heat pump for commercial drying process

Drying process is essential to various industrial fields such as chemical process, textile, paper manufacture, lumber production, electronics, wastes and other fields and it consumes a large amount of energy which takes over 7 % (6,356 thousands TOE) of industrial field energy consumption in Korea. In companies which have drying facilities use over 30% of their fuel consumption in dryer. Therefore, development of energy saving technology in this area will have great influence. The efficiency of conventional air-heating dryer is only about 30-50 %, however, the efficiency of optimally designed air-heating dryer can be raised up to 60-80 % which will remarkably contribute energy savings.

Application areas of heat pump are drying process (agricultural product, marine product, industrial product, etc.), high-temperature application field, exhaust heat recovery and other areas. Energy saving effect from heat pump complex dryer is estimated about 572 thousands TOE annually.

9.3.4 Geothermal heat pump system using R410A centrifugal compressor

Geothermal source has near constant temperature year-round which is different to the temperature of the surface of the earth or the atmosphere. Through summer season, temperature of geothermal source is usually lower than that of the atmosphere. So with coolant circulation it is possible to narrow operating temperature range of a heat pump which results in higher system efficiency (COP) compared to the conventional heat releasing method with cooling tower. Inversely, in winter season, temperature of geothermal source is usually higher than that of the atmosphere so it provides better heat source compare to air-source heat pump system which also brings enhanced efficiency.

For wide application of geothermal heat pump system in future, efficiency (COP) and capacity enhancement are necessary along with reduction in initial investment cost. So, research on enhancement of geothermal heat pump system was carried out that adopted centrifugal compressor which is easy to be scaled up and has higher efficiency compare to displacement-type compressor such as scroll or screw compressor which are applied to current geothermal heat pump. Trend for designing environment-friendly/high-efficiency refrigeration cycle with centrifugal compressor of 100 RT grade which was connected with high speed motor and oil-less bearing is actively attempted by leading companies such as Danfoss-Turbocor. In Korea, responding activity was needed for domestic market by developing centrifugal compressor technologies.

In this project, a 100 RT grade geothermal heat pump with oil-less centrifugal compressor was developed. The test run was performed at the central machinery room of KAIST in Daejeon after the installation of open and closed type geothermal system to the air-conditioning devices. By applying inverter-driven motor and gas bearing to a high speed rotor of centrifugal compressor, the developed oil-less centrifugal compressor has price competitiveness for mass production. In case of open type geothermal system, as underground water is used for heat source of heat pump, wide-Gap plate heat exchanger that strongly endures contamination was first developed and applied.

The key technologies are geothermal heat pump cycle design, high pressure aerodynamic design, high speed rotor design, oil-less bearing development, wide-Gap plate heat exchanger design, mold and product development of wide-Gap plate heat exchanger, etc. In addition, core element design technology of geothermal turbo heat pump was developed and reference on a 100 RT grade geothermal system was secured through field test. Moreover, technologies for production, operation and performance evaluation of centrifugal compression heat pump system were established. Other technologies were also secured such as oil-less gas bearing manufacture and test/evaluation, inverter-driven high speed motor design and production, heat exchange technology for fluids that have high viscosity or fouling is concerned. Heat pump system from this project showed heating COP of 4.1 and cooling COP of 6.9.

Expected benefits with heat supply system using geothermal source are environmental improvement (energy saving, reducing CO_2 emission, etc.), new and renewable energy utilization and so on. Because of those positive effects, this system is applicable to air-conditioning system for building and green house complex air-conditioning and heat supply. A 100RT grade heat pump unit with centrifugal compression technology is expected to be highly competitive where screw compressor types are currently dominant in the market. Moreover, by developing wide-gap plate heat exchanger technology, it will be simple to use underground water, high viscosity fluid or highly contaminated heat source directly.

With this improved efficiency of heat pump system, payback period become shorter so that the rapid penetration of geothermal air-conditioning system is expected. The 100RT grade high efficiency centrifugal compression technology can be applied widely such as heat pump systems and chillers that utilize other heat source and air-conditioning system for high efficiency/environment-friendly buildings.

9.3.5 Double effect absorption heat pump development for low-temperature sewage waste heat recovery

In order to obtain heat from unused low-temperature heat (sewage treatment temperature lower than 20 °C) in absorption heat pump for heating in winter season, and to make hot water up to temperature level of 70 °C, a double effect absorption heat pump system needs to be introduced which has double evaporation-absorption process. Under low temperature heat source, COP becomes low because system only utilizes half of its refrigerant capacity which takes heat from low-temperature heat source. In such a case, system can form double effect cycle that renews refrigerant by condensing it and yields COP of 1.6. The development of such technology can be applicable to wide range of temperature level for absorption heat pump cycle.

Core technologies are double evaporation-absorption cycle that raise heat rejection temperature by accepting low-temperature heat source and double effect double absorption heat pump technology to increases COP.

The developed system make it possible to utilize unused low-temperature energy by applying a heat pump with absorption cycle which was conventionally used for air cooling facility that releases low-temperature heat which is slightly hotter than the atmosphere. In addition, by a prototype demonstration of absorption cycle that was already been patented but difficult to commercialize, it was possible to utilize unused energy. The target performance was checked through the performance test of the prototype and this development of absorption cycle technology enlarges the operational temperature range of absorption heat pump cycle.

9.3.6 Development of hybrid water source heat pump using solar heat

In this project, a hybrid heat pump using solar heat was built with 4 solar collectors which were connected in the form of 2 rows by 2 columns providing 30 % of heat demand of evaporator and the number of PCM module was 220. A single heat pump system showed cooling capacity of 10.5 kW and cooling COP over 3.2 when cold supply water flow rate and temperature was 50 lpm (liter per minute) and 18 °C respectively. Heating capacity was 13 kW and heating COP was over 3.0 when hot supply water flow rate and temperature was 40 lpm and 18 °C respectively.

At the test of PCM which is inside the solar heat storage tank, the temperature difference of evaporator was much smaller at mode 1 which uses latent heat of PCM than that of evaporator at mode 2 which doesn't. When comparing the reaching time to the temperature level of 7 °C, mode 2 take 30 minutes and mode 1 with PCM takes 200 minutes (about 3 hours) which is feasible for heat pump operation.

When operating hybrid heat pump using solar heat until 3 P.M. with high solar radiation, heating capacity over 13 kW and COP over 3.3 were achieved. The capacity and COP decreases after 3 P.M.

Henceforth, a hybrid heat pump system that utilizes solar heat as a heat source for evaporator is expected to become competitive product that can save a large amount of energy.

9.3.7 Demonstration of a geothermal heat pump system and ground heat exchangers which are installed to the substructure of buildings

The introduction of geothermal air-conditioning system in Korea was relatively late compare to the developed country but the government has invested a lot of money on this and the number of demonstration cases has been increasing. As ground heat exchangers take more than 50% of the installation cost of geothermal air-conditioning facilities, research and development is required in order to lower installation cost and improve performance. Technological problems are listed below that disturb rapid propagation of geothermal heat pump system using ground heat exchanger which is installed to the substructure of buildings

1. Lack of data for standard design of ground heat exchanger and system
2. Lack of construction methods that consider geological structure and climate condition of Korea
3. Lack of data for capacity calculation method and construction cost of ground heat exchanger
4. Lack of demonstration data to prove reliability overall system and ground heat exchanger

Therefore, performance analysis, system performance evaluation, design data and construction standard establishment and other researches are required for ground heat exchanger which is installed to the substructure of buildings.

Ground heat exchanger which is installed to the substructure of buildings can be divided into two type that are energy pile and energy slab. Energy pile can be utilized as ground heat exchanger by inserting U-tube, double U-tube, W-tube or coil-shaped pipe inside of empty space in concrete or steel pile. Energy slab can also be utilized as ground heat exchanger by installing heat exchanger horizontally to the foundation slab under the building. Installation cost of ground heat exchanger for large buildings is low because these buildings already have many piles so this method fits to Korea where a lot of skyscrapers and apartment exist.

Through this project, a 58RT grade energy pile/energy slab demonstration plant was built and data collection and performance test for demonstration plant were carried out for a year. An energy pile/energy slab design program was also developed. Construction and design standard were established for energy pile/energy slab geothermal air-conditioning system which save 9 % of construction cost compare to vertical closed type.

The developed technology is expected to be applied for buildings in downtown (installation of vertical type heat exchanger is incapable due to narrow space), buildings in reclaimed land (energy pile/energy slab), apartment complexes and buildings (reduction in installation cost of geothermal air-conditioning system).

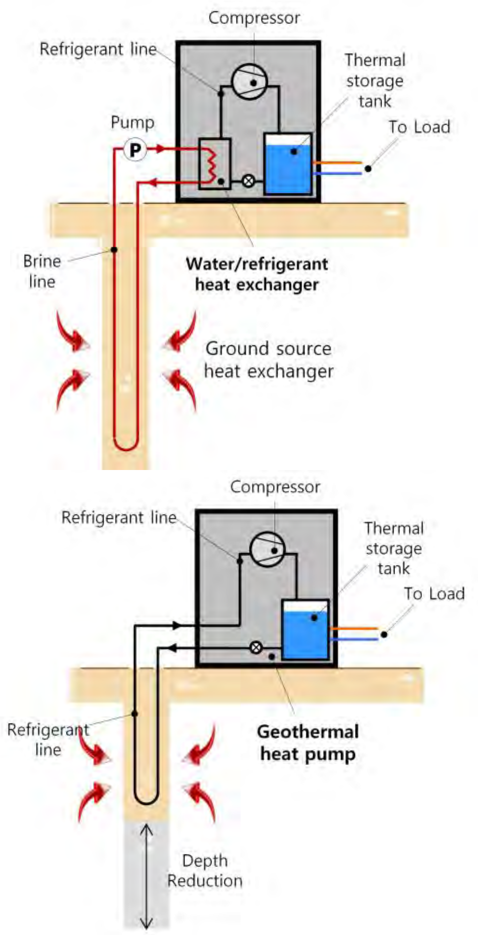
9.3.8 Technology development for vertical closed type direct exchange (DX) geothermal heat pump system

Among renewable energies, the demand for thermal energy utilization has been kept increasing. Among geothermal air-conditioning market, the installation of geothermal heat pump in building sector is popular but that of residential scale geothermal heat pump is still delayed because of the economic feasibility and construction ability. This project developed technologies for the direct exchange geothermal heat exchanger that connects underground loop with refrigerant loop which is different from conventional system that has 3 loops (refrigerant, indoor, and underground water circulation) Through this construction, refrigerant flows directly to underground where direct heat exchange occurs and this method is highly efficient because underground circulation pumps are not necessary.

Direct exchange(DX) geothermal heat pump technology does not use water/refrigerant heat exchanger but installs refrigerant circulation coil into the underground so as to gain heat directly from geothermal source and this method is expected to show excellent performance compare to conventional vertical closed type system which uses HDPE material U-tube. For the DX system, design factor, heat recovery and heat release theory were developed. In addition, researches for source technology were carried out through performance test and performance evaluation for the commercialization in Korea.

Research development details are followings. Basic specification was determined for the installation of direct exchange geothermal heat exchanger and an installation procedure for this was developed. It proceeded through two times of constructions. The performance test was done for DX underground heat exchanger which was connected to a 3RT grade geothermal heat pump system and 100 hours continuous operation was carried out. Using performance indices that were obtained from performance test, long-term driving performance was predicted. In addition, a program was developed that can analyses direct exchange geothermal heat exchanger in connection with TRNSYS which is commercial program. With the result of geothermal heat exchanger development, a guideline for construction method was made and arranged in order to make use of it.

Developed technologies can be applicable for air-conditioning system in residential and small buildings. They can also be applied to large buildings if modularized and distributed. These can be applicable to renewable heat energy propagation business in connection with 'Renewable Heat Obligation (RHO)' in Korea and to single house in connection with 'One Million Green Homes Program'. Therefore small business-oriented market is expected to form.



(a) Conventional GSHP (b) DX GSHP

Figure 9-6: Comparison of a conventional HDPE GSHP and a DX GSHP

10 The Netherlands

R&D in the Netherlands on industrial process innovation is for a large part supported by the Ministry of Economic Affairs through the ISPT Innovation Program. Major players in this program are the Dutch process industry, TU-Delft and ECN. The focus on heat pumping technology as one of the key technologies is logical and has a long track record starting with basic research now reaching the pilot phase.

More than 80% of the total energy use within the Dutch industry consists of the need of heat in the form of steam at different pressure levels and for firing furnaces. The total industrial heat use (530 PJ/year) together with exothermic heat from chemical reactions is eventually released to the ambient atmosphere through cooling water, cooling towers, flue gasses, and other heat losses. We call this heat loss 'Industrial waste heat'. A first, most logical, solution to this waste heat problem is to reuse the heat within the same process through process integration or at the same site. In an ideal process that will be within the process unit otherwise technology will have to be applied to transform the heat coming out of the process to a common carrier. This being high pressure steam or electricity generated by a high temperature heat pump or an ORC.

European R&D and the goals set are defined by the European Technology Platform on Renewable Heating and Cooling (RHC-Platform) in their recent Strategic Research and Innovation Agenda for Renewable Heating and Cooling. Industrial heat pumps are an important part in that strategy. The report is presented to the European Commission as advice on which technology to support.

In this chapter ISPT and RCH are discussed followed by a general description of research ande development projects. Please note that for confidentiality reasons, exact details of the process and the control and design alternatives for these projects are not provided and only described in general terms.

10.1 TKI- ISPT Innovation Program

Mid 2012, ISPT founded its Topconsortium Knowlegde and Innovation for Processing (TKI-ISPT) This TKI connects the chemistry, agriculture and food, energy, and biobased economy sectors.

The TKI Processing takes care of the innovation contracts for:

Topsector energy	Energy reduction in the industry (EBI) and Biorefinery
Topsector chemistry	Process Technology
AgriFood	Sustainable Manufacturing
BioBased Economy	TKI-ISPT executes the biorefinery part for the innovation contracts of the topsectors

DSTI (Dutch Separation Technology Institute) is a partnership in which industry, universities and knowledge institutes work closely together to develop breakthrough technologies for application in different sectors of the process industry. “Together we can take bigger steps, have more impact, and share the risks”.

So far, 45 companies from the Food, Pharmaceutical, Oil and Gas, Chemical and Process Water Industries and 8 knowledge centers, have joined DSTI. The estimated budget is EUR 65 million for the next 5 years. The research program covers all aspects from (fundamental) knowledge generation to technology implementation.

The program contributes to the process industry’s sustainability objectives in terms of product value, efficiency, energy savings, and the reduction of emissions through the generation and application of new knowledge in collaborative development and demonstration programs.

TKI-ISPT has been working on translating the plans of the innovation contracts into a coherent set of activities. These activities are executed within 14 cross-sectoral clusters of which for interest for heat pumps:

- Energy Efficient Bulk Liquid Separation
- Drying and Dewatering
- Utilities & Optimal Use of Heat
- Process Intensification
- Sustainable Business Models
- Maintenance

From PPP-ISPT and the TKI Action-program 2012 several projects are running which will be finalized leading to pilot projects 2014/2015, with the focus on the application of newly developed prototype heat pumps in chemical industry and paper and pulp.

- Utilities and optimal use of heat

This cluster aims to:

- reduce (fossil) energy use for the production and use of industrial heat;
- improve competitiveness of stakeholders by reduction of energy costs;
- create new market possibilities for equipment manufacturers;
- improve the energy efficiency of industrial processes.

The estimated energy saving potential equals 100 PJ/year. The use of heat within industry is responsible for more than 80 % of the final energetic energy use. Heat is used for heating feedstock, enable reactions, and to drive separation processes. The required temperature level spans a broad range, depending on the specific process. At the same time, large quantities of waste heat are released to the ambient atmosphere that cannot be reused in an economical way.

- *Reuse of waste heat:*

The recovery and reuse of industrial waste heat is hindered by technological and economic barriers. Several possible paths can be envisioned that start from economical heat recovery of waste heat. Next, waste heat can be converted into process heat, process cold or power. Finally, heat storage and distribution can be realized.

All activities carried out within this cluster are related to:

- Technology scouting
- Feasibility studies
- Research & Development
- Dissemination.

The main bulk separation processes within chemical and refining industry are distillation, absorption/desorption, and crystallization. The thermodynamic efficiency of these processes is usually very low (<10 %). Environmental implications and increasing energy costs demand improvement of energy efficiencies. Significant reductions in energy consumption are expected by using innovative heat pump concepts for removal and supply of heat from/to a separation process. The efficiency of e.g. distillation systems can be increased by heat integration of reboiler and condenser using high lift high temperature heat pump concepts.

10.2 European Technology Platform on Renewable Heating and Cooling (RHC-Platform)

RHC-Platform has produced the present Strategic Research and Innovation Agenda for Renewable Heating and Cooling [Landolina, 2013].

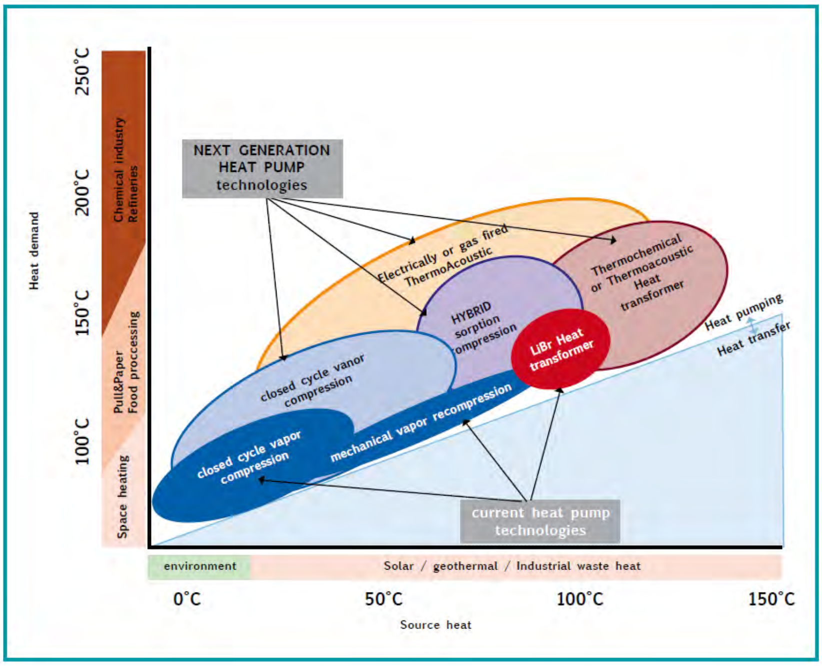


Figure 10-1: Heat pump technologies and their operating temperatures

Figure 10-1 plots the driving temperature ("source heat") against the delivered temperature ("heat demand") for various heat pump technologies. Current vapour compression systems deliver heat at a maximum temperature of ~80°C. New vapour compression systems should use low GWP synthetic refrigerants or natural refrigerants (such as butane or water) to reach temperatures of up to 150°C. Components and materials should be developed to achieve temperature lifts of up to 70 K. The use of water as the working medium allows the heat pump to be integrated into industrial heating processes. Alternative concepts such as heat transformers are interesting when a heat source of more than 90°C is available. Current systems use thermally-driven compression to upgrade waste heat from 100°C to 140°C. Reversible solid sorption reactions, such as the reaction of salts and ammonia are applicable for heat transformation at temperature levels up to 250°C. Similarly, thermoacoustic systems can accept a range of driving temperatures and output heat also in a wide temperature range. A hybrid system can be created by adding mechanical compression as driving input to a heat transformer, allowing for use of low temperature waste heat and still generating temperature lifts of up to 100 K.

A broader range of operating temperatures and higher temperature lifts are needed to increase the application potential and the energy saving potential that heat pumps offer. The end users' demands extend beyond the required temperature and cost of the system to topics such as the toxicity & flammability of the working medium and the reliability of the system. No single heat pump technology can cover this entire range of demands, meaning different heat pump technologies should be developed in parallel. The main objective is the exploration of alternative thermodynamic cycles for heat-pumping and heat transforming for different industrial applications, with the goal to increase the operating window of industrial heat pumps so that they can deliver heat at medium pressure steam levels (app. 200°C).

Not only will these improvements allow larger energy savings, but they will also unlock the benefits of economies of scale for the European heat pump industry.

The Figure above shows four types of technology that can potentially overcome the aforementioned limitations in terms of temperature range and lift. Not only these improvements will allow larger energy savings, but simultaneously it will unlock the benefits of economies of scale for the European heat pump industry. Apart from their operating temperatures, these technologies have different levels of maturity. They form a chain of new heat pump technologies in which the mechanical vapour compression systems with new working fluids are the next generation to be tested at a small scale in real applications for higher delivery temperatures. The salt-ammonia sorption and thermoacoustic heat transformers are in the development stage of laboratory prototypes, proofing the concept of the system. The hybrid sorption-compression systems and gas fired thermoacoustic heat pumps are in the stage of proofing the principle.

Conventional heat pumps provide limited temperature lift. Therefore heat pumps are required, which can operate at the temperature levels of the column and provide the desired temperature lift between condenser and reboiler. These heat pumps are presently not commercially available and therefore need to be developed. The project covers the theoretical and experimental verification of the performance of innovative heat pumps integrated in a separation process. Presently three innovative heat pumps are identified, but early on in the project an assessment is made whether additional systems should be considered. The three heat pump concepts to be covered in the program and their main technological challenges are the following:

1) Thermo acoustic heat pumps: achieve the required efficiency with a design integrated within a separation process.

2) Thermochemical heat pumps: identify the proper solid/vapor combination and ensure stability and continuous heat supply.
3) Compression-resorption heat pumps: manufacture compressors that can operate under “wet” conditions. The project is setup in two phases: Phase 1: Feasibility and heat pump selection Phase 2: Testing model heat-pump systems under reference operation conditions

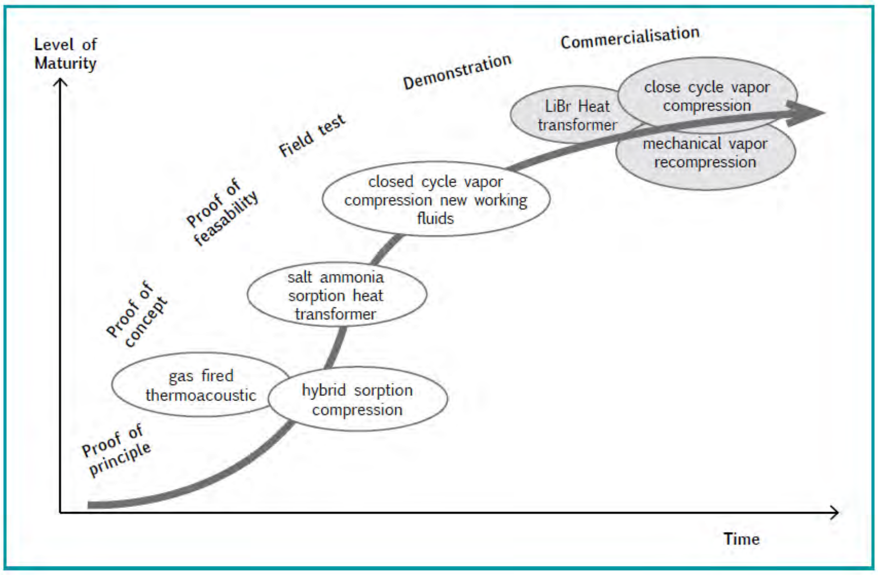


Figure 10-2: Development stages of new concepts for industrial heat pumps (source: RHC-Platform)

In their advise to the Commission the RHC Platform [EU, 2013] have proposed:

	Research and Innovation Priorities	Predominant type of activity	Impact
CCT.12	Enhanced industrial compression heat pumps	Development	By 2020
CCT.13	Process integration, optimisation and control of industrial heat pumps	Demonstration	By 2020
CCT.14	Improvements in Underground Thermal Energy Storage (UTES)	Demonstration	By 2020
CCT.15	Improvement of sorption cooling from renewable energy sources	Development	By 2025
CCT.16	New concepts for industrial heat pumps	Research	By 2030

CCT.12	Enhanced industrial compression heat pumps
Objective	Development of advanced compression refrigeration cycles based on novel working fluids for use in medium temperature industrial applications (condensation temperatures up to 150 °C and evaporation temperatures up to 100 °C). Applications of these novel heat pumps include process heat generation as well as waste heat recovery in industrial processes yielding substantial increases in energy efficiency. R&D topics to be addressed in this context comprise: • new working media (low GWP, non-inflammable) or natural refrigerants (water), • improved compressors and lubrication methods for high evaporating temperatures (up to 100°C), • heat exchangers with improved design for direct using of condensing gases (flue gas, exhaust air, drying processes, etc.).
State-of-the-art	Current vapour compression systems deliver heat at a maximum temperature of ~80 °C.
Targets	• Carnot efficiency of at least 0.35 • At least 2 demonstration projects should be realised by 2020. • Condensation temperatures up to 150°C • Temperature lift up to 60 K • Energy saving up to 30% • Cost target heat pump unit: 200 to 300 Euro/kW
Type of activity	20% Research / 60% Development / 20% Demonstration

CCT.13	Process integration, optimisation and control of industrial heat pumps
Objective	Development and demonstration of electrically and thermally driven heat pumps in individual industrial applications as well as in combination with district heating and cooling networks including thermal energy storage. R&D topics to be addressed comprise: • classification of processes (temperature levels, time-based energy demand, etc.), • process integration of industrial heat pumps (control and hydraulic design), • impact of heat pumps on existing process (dynamic behaviour), • selection of components (refrigerant, compressor, heat exchangers etc.) for the process identified,
State-of-the-art	First prototypes of compression heat pumps with evaporation temperatures of up to 40°C and condensation temperatures of up to 80°C are available but still need to be demonstrated. First prototypes of absorption heat pumps using new working pairs without crystallisation effects are available, but not demonstrated yet in real-life operating conditions.
Targets	• 5 lighthouse projects with a capacity of minimum 1 MWth implemented by 2020 • Compression heat pump: minim sCOP of 5, energy savings of at least 30% • Absorption heat pump: minimum sCOP of 1.5; energy savings of at least 50% • Cost target on system level for electrically driven heat pumps (unit plus installation): 400 to 500 Euro/kW
Type of activity	30% Development / 70% Demonstration

CCT.16	New concepts for industrial heat pumps
Objective	A broader range of operating temperatures and higher temperature lifts are needed to increase the application potential and the energy saving potential that heat pumps offer. The end users' demands extend beyond the required temperature and cost of the system to topics such as the toxicity & flammability of the working medium and the reliability of the system. No single heat pump technology can cover this entire range of demands, meaning different heat pump technologies should be developed in parallel. The main objective is the exploration of alternative thermodynamic cycles for heat-pumping and heat transforming for different industrial applications, with the goal to increase the operating window of industrial heat pumps so that they can deliver heat at medium pressure steam levels (app. 200°C). Not only will these improvements allow larger energy savings, but they will also unlock the benefits of economies of scale for the European heat pump industry.
State-of-the-art	The efficiency of any heat pump system increases as the temperature difference, or "lift", decreases between heat source and destination. Efficiently providing heat for industry at temperatures higher than 90°C with heat pumps is difficult. Industrial heat pumps (for heating purposes) currently consist of closed cycle vapour compression, open cycle mechanical vapour recompression and Lithium Bromide (LiBr) heat transformers.
Targets	• Delivery temperature up to 200°C • Temperature lift ≥ 70 K • Energy output compared to current technology ≥ 20%
Type of activity	70% Research / 30% Development

10.3 Technological developments

Before 2005, heat pumps were merely refrigeration plants where pressures are increased to deliver condensing heat at temperatures of 35°C up to 50°C. This operation range also depends on the evaporation temperature, efficiency and pressure ratio. The refrigeration compressors have a design pressure of 25 bar. This is also a limit for higher condensing temperatures. The large manufacturers of industrial refrigeration in the Netherlands, i.e. GEA-Grenco with their seat in Den Bosch and IBK from Houten, have discovered this new market of high temperature applications and already executed projects (see factsheets in chapter 4). A large application potential of industrial heat pumps is still not used because of these limited supply temperatures of about 100°C of commercially available heat pumps. If these supply temperatures could be increased, more industrial processes could be improved in their energy efficiency. The main reason for the limited temperatures has been the absence of adequate working fluids [Reissner, 2013].

10.3.1 CO_2 – Heat Pump

Beginning of 2000 the refrigeration industry is introducing CO_2 again as refrigerant and secondary refrigerant. CO_2 is a natural refrigerant without ozone depletion potential and with a low global warming potential. It is therefore a sustainable alternative for the synthetic refrigerants such as the HFC types.

Since CO_2 is a high pressure refrigerant, the refrigeration industry had to develop equipment with design pressures up to 45 bar. It is this development that has led to the construction of 50 bar industrial compressors. Using these compressors with ammonia or HFC like R134a as refrigerant, high temperature heat pumps (HT heat pumps) can be produced for industrial purposes. Condensation heat at temperatures up to 80°C can be delivered in a large variation of capacities with good efficiency.

HT heat pumps are also executed with CO_2 as refrigerant in a transcritical cycle. Larger units for water heating from 10° up to 70°C are available in a range up to 120 kW running with any heat source and can even produce cooled water (8°C). Essential is that the CO_2 at condensing pressure can be strongly cooled in order to maintain a sufficient efficiency. This is possible by a process flow that starts to heat up at e.g. 15°C. The COP of CO_2 can be higher than ammonia in case of high temperatures differences. Compressor sizes for these high pressures are however limited available.

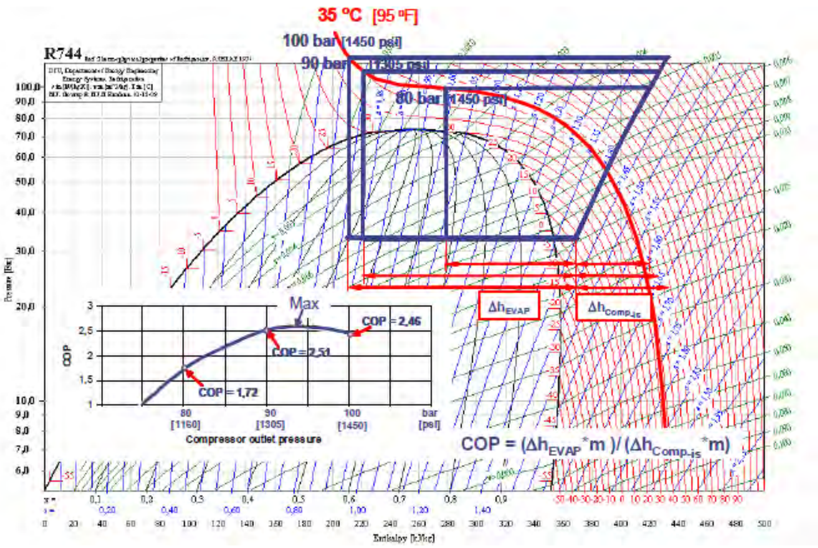


Figure 10-3: Efficiency of the CO_2 heat pump cycle, depending upon the discharge pressure [source HPC]

10.3.2 n-Butane heat pump

With the search into natural refrigerants for heat pumps the refrigerant, n-butane is regarded as a proper medium in high temperature heat pumps with condensing temperatures up to 120°C. These temperatures can be reached in standard 25 bar compressors. This type of HT heat pump is based on conventional, reliable refrigeration design with special safety attention and features for safety. Several feasibility studies have been carried out in industry and refrigeration contractors nowadays offer the HT heat pumps.

The feasibility studies show the technical and economical implications that arise when integrating the n-butane heat pump in existing installation. To integrate a heat pump it is necessary to redesign the original process and thus the equipment (heat exchangers, process layout). This should clearly be a task for manufacturers and suppliers of process equipment.

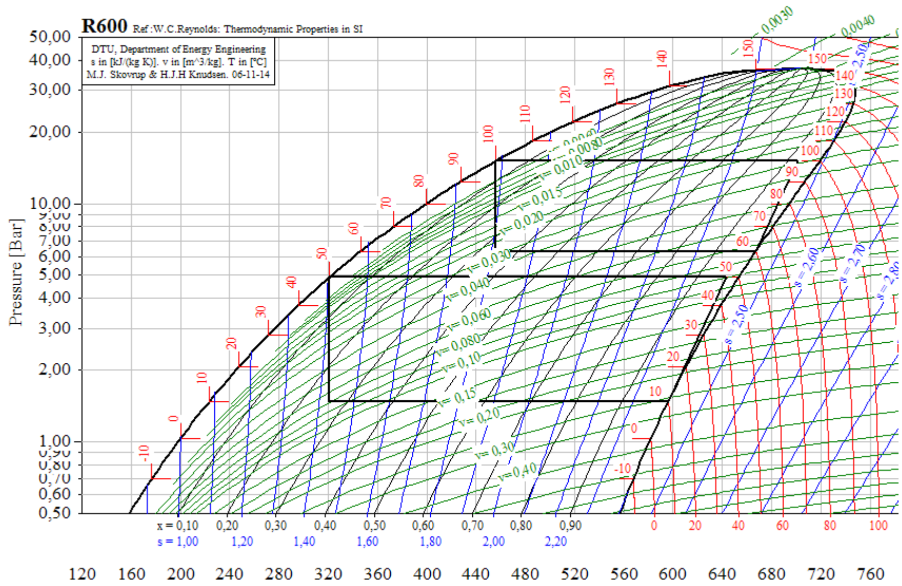


Figure 10-4: n-Butane heat pump cycle (at 60/100°C: COP=7.1 and at10/50°C: COP=6.8) (source GEA-Grenco)

As can be seen in Figure 10.4, the n-butane gas is compressed in the gas-liquid area of the n-butane Mollier (log p-h) diagram. Therefore it is necessary to preheat the suction gasses before they enter the compressor. This can be executed in heat exchangers that simultaneously heats up the suction gas and cools down the liquid after condensation. This is a regular design aspect in refrigeration installations.

10.3.3 New refrigerants

An interesting paper is presented at the 11th Heat Pump Conference in Montreal 2014 [Reissner, 2013], where it is stated that an ideal working fluid should be non-flammable, non-toxic and should have a low GWP, no ODP and a high critical temperature. Four ideal working fluids are identified: LG6, MF2, R1233zd and R1336mzz.

Table 10-1: Properties of ideal working fluids for high temperature use [Reissner, 2013]

Working fluid	T_{crit} [°C]	Flammable or toxic	ODP	GWP
R1233zd	166	no	0.0003	6
R1336mzz	171	no	0	9
LG6	>165	no	0	1
MF2	>145	no	0	<10

Important producers of these new working fluids with high condensation temperatures and low GWP are Honeywell, Siemens en Dupont. First pilots are reported of.

Interesting is the development of LG6 by Siemens showing a temperature lift of 50K with an experimental COP of 4.8.

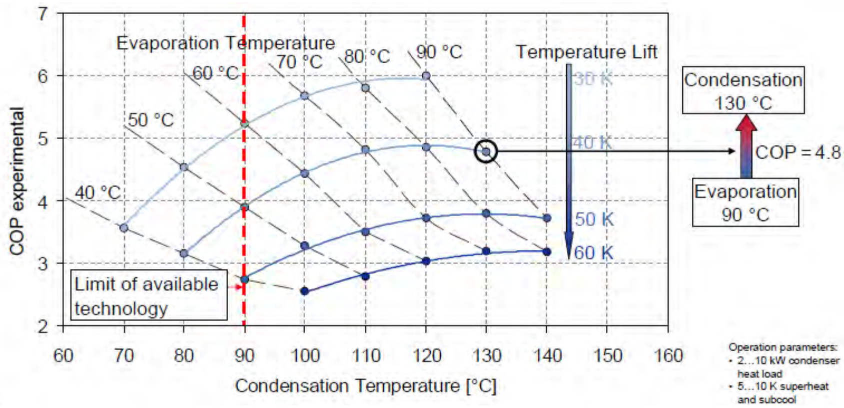


Figure 10-5: LG6 Siemens

At a presentation Dupont even claims better results with DR2.

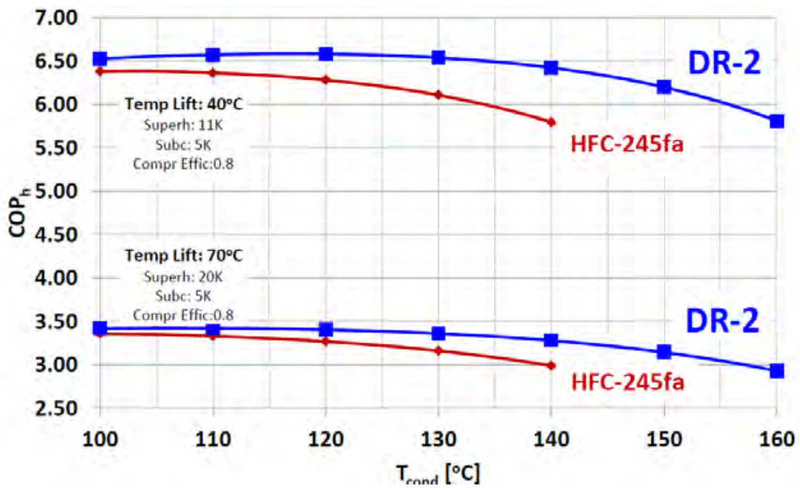


Figure 10-6: DR-2 Dupont

Solstice™ L41 from Honeywell is based upon R-32 as an alternative for R-410a and already used by several heat pump manufacturers, the largest application being by Friotherm in the district heating heat pump in Drammen (Oslo). R-1234yf will be applied by ETP in the Netherlands.

R-410A Alternatives

Refrigerant Supplier	Designation	Composition	(Mass%)	GWP	ASHRAE Class	Thermo Performance* Capacity	Efficiency
Arkema	ARM-70a	R-32/R-134a/R-1234yf	(50/10/40)	482	A2L	-15%	3%
Daikin	D2Y-60	R-32/R-1234yf	(40/60)	272	A2L	-20%	2%
DuPont	DR-5	R-32/R-1234yf	(72.5/27.5)	490	A2L	0%	1%
Honeywell	L-41a	R-32/R-1234yf/R-1234ze(E)	(73/15/12)	494	A2L	-6%	2%
Honeywell	L-41b	R-32/R-1234ze(E)	(73/27)	494	A2L	-9%	2%
Mexichem	HPR1D	R-32/R-744/R-1234ze(E)	(60/6/34)	407	A2L	-1%	0%
Daikin/National	R-32	R-32	(100)	675	A2L	8%	1%
National	R-32/R-134a	R-32/R-134a	(95/5)	713	A2L	5%	1%
National	R-32/R-152a	R-32/R-152a	(95/5)	647	A2L	3%	1%

* Relative to R-410A 4C ET / 38C CT

10.4 Running R&D Projects

An analysis was made of distillation heat pump potential in the Netherlands, leaving out columns that do not cross the pinch and oil refinery columns. The data show that the total heat pump potential is in the order of 2.4 GW and that the average temperature lift over the column is 59 °C.

Conventional heat pump cycles are driven by compressors or blowers depending on the required volumetric capacity and pressure ratio or temperature lift. The economic range for the VRC configuration driven by a compression heat pump is limited to columns with a temperature difference of about 300 °C. The heat pump which has to meet these requirements has to operate in a temperature window of 100 to 250 °C. The required temperature lift should be in the order of 50-100 °C. The heat pumps that are available nowadays are not able to fulfill both requirements.

New developments in distillation heat pump technology are therefore aimed at novel heat pumps with a higher economic range and at new heat integrated configurations. In the Netherlands these developments are:

- Thermo Acoustic Heat Pump at ECN
- Compression Resorption Heat Pump at TU Delft
- Adsorption Heat Pump
- Heat Integrated Distillation Columns at TU Delft

10.4.1 Thermo Acoustic Heat Pump

Heat transformers can be applied in cases where waste heat is available at sufficient high temperatures (> 90-100 °C). The advantage of these concepts is that they don't require additional energy to drive the system. Typical efficiencies are 25-30 %, meaning that this fraction of the waste heat can be reused in the process. Disadvantage of a heat transformer is that the other part of the waste heat still needs to be cooled to the ambient atmosphere. The general concept of a heat transformer is depicted in Figure 10.7 below.

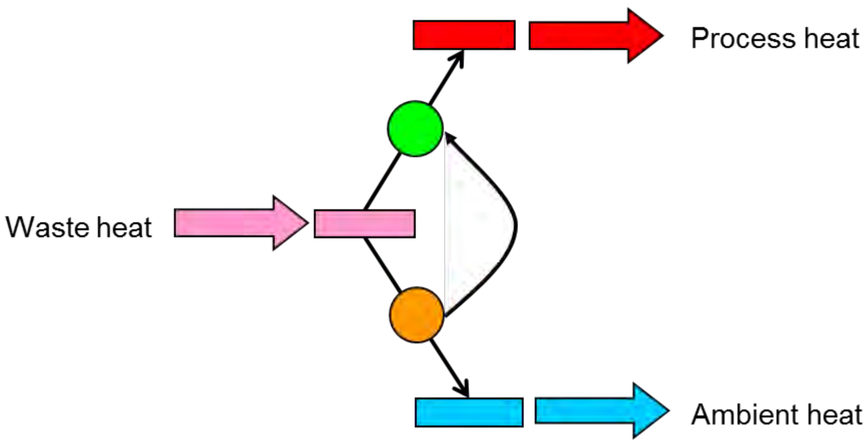


Figure 10-7: Thermodynamic concept of a heat transformer

Two technological principles are being applied at ECN to realise this heat transformer. These principles are based on thermoacoustics and thermochemistry.

Thermo Acoustic Heat Transformer

Thermoacoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts. Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology.

When thermal energy is converted into acoustic energy, this is referred to as a thermo-acoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the reverse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as depicted in Figure 10.8.

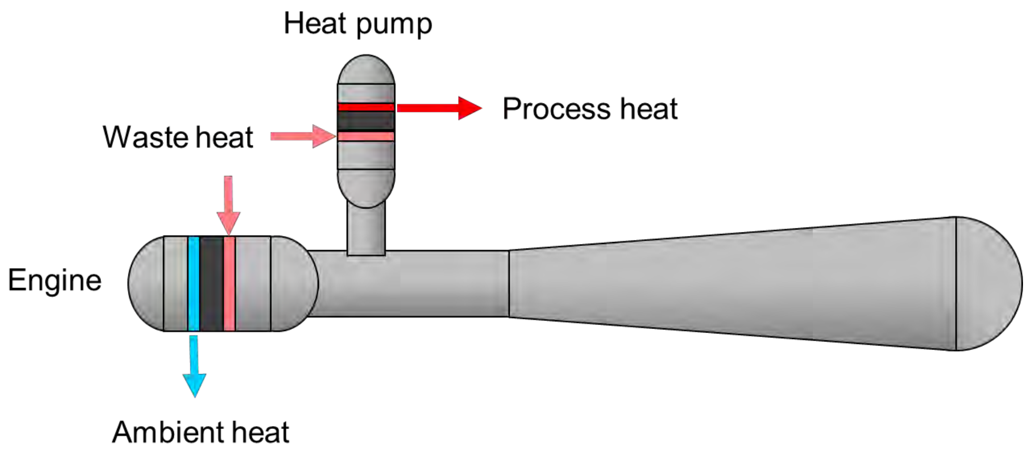


Figure 10-8: TA heat transformer

The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site. The picture below gives an experimental setup of a 10 kW system

Figure 10-9: Thermo acoustic heat transformer at ECN

Thermochemical heat transformer

Thermochemical heat pumps use the heat released/dissipated during ad/desorption of gas in solids to create a heat pump cycle. This process consists of an alternating cycle consisting of a discharge phase and a regeneration phase, in which the solids are generating heat during adsorption of the gas, respectively require heat to release the adsorbed gas from the solid.

The system operates at three temperature levels. These temperature levels are the waste heat temperature, the ambient temperature and the temperature of the upgraded heat. The system consists of two reactors, each containing a different salt. For this specific system use is made of lithium chloride as low temperature salt (LTS) and magnesium chloride as the high temperature salt (HTS). Ammonia vapour is exchanged between these two salts. Industrial waste heat is used to free the ammonia from the LTS. The ammonia flows, driven by the pressure difference between the two reactors, to the HTS and reacts with the HTS. This exothermic reaction delivers heat at high temperature. During the regeneration step the ambient temperature cools the LTS and the waste heat heats the HTS. The ammonia vapour flows back to the LTS under these conditions. The scheme below shows the implementation of such a system in an industrial process. Both the LTS and HTS reactor vessel are built in twofold in order to achieve a continuous system. A switching control system determines whether the above pair of reactor vessel are loading (regenerating) or discharging. The other vessels are running in the reverse process.

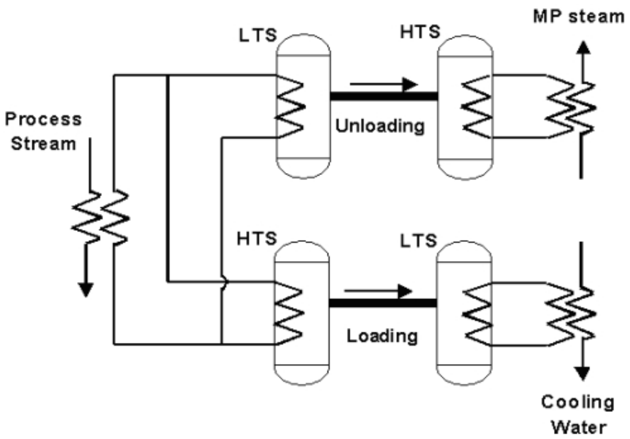


Figure 10-10: Thermochemical heat pump transformer

Figure 10-11: Thermochemical heat pump component testing

Figure 10.11 shows picture of a reactor element that is used to measure the heat uptake and release by the salt during cycling experiments. Lab-scale experiments have shown that the required operating temperature and temperature lift can be achieved. Business cases have been evaluated with industrial end-users from the chemical & refining industry which show positive economic results. Important requirement is the power density which is the main challenge.

10.4.2 Hybrid Systems

Thermochemical heat transformer

This system is an extension of a regular thermochemical heat pump. The extension consists of a compressor that adds flexibility to the system with respect to operating temperatures, and more important, enables to use of lower temperature waste heat than the system without compressor.

The final requirements for this application are:

- Driven by a compressor and waste heat in the temperature range 50 - 150°C;
- Delivering process heat in the temperature range up to 250°C, with process heat temperature at least 50°C higher than the waste heat temperature;
- System efficiency (process heat out/waste heat in) >25 %, depending on operating temperatures, (average) Electrical COP > 5;

Figure 10.12 depicts the thermodynamic concept (right side) of this hybrid concept and a picture of the setup (left) that has been used to test a compressor under batch type operating conditions.

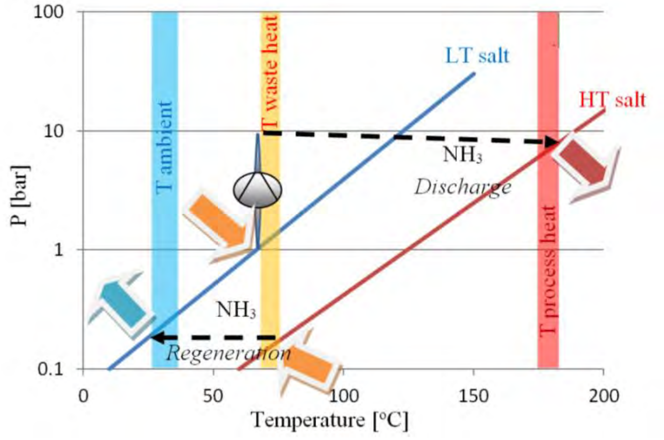


Figure 10-12: Hybrid Thermochemical-compression heat pump testing

Compression Resorption Heat Pump

Usually, heat pumps work best if the heat added or extracted at a constant temperature. However, several applications exist where the temperature of the streams will change as heat is added or extracted. The temperature difference over the glide leads to an extra exergy loss over the heat exchanger, unless the working fluid of the heat pump has the same glide. This principle is applied in the Compression Resorption (CR) heat pump. In the CR heat pump the working fluid is a zeotropic mixture, usually ammonia-water. The composition of this mixture is adjusted until the glide of the working fluid optimally matches the glide at the process stream.

The cycle can be designed to show a temperature glide in the resorber that corresponds to the temperature glide of the industrial waste flow that has to be heated. For specific operating conditions the cycle performance is significantly better than for the vapour compression cycle. The main problem of the cycle is the compressor that has to be suitable for oil-free wet compression and still show acceptable isentropic efficiencies. Hybrid Energy solves this problem by separating the liquid and vapour and compress these separately. A higher efficiency could be obtained if a compressor would be available that could compress the mixture. These compressors must be suitable for high compression ratios and for simultaneously compress vapour and increase the liquid pressure. The compressor should further be not sensible to liquid carry over.

The main goal of the developments at the Technical University of Delft is a wet compressor that is suitable for operation in compression resorption heat pumps.

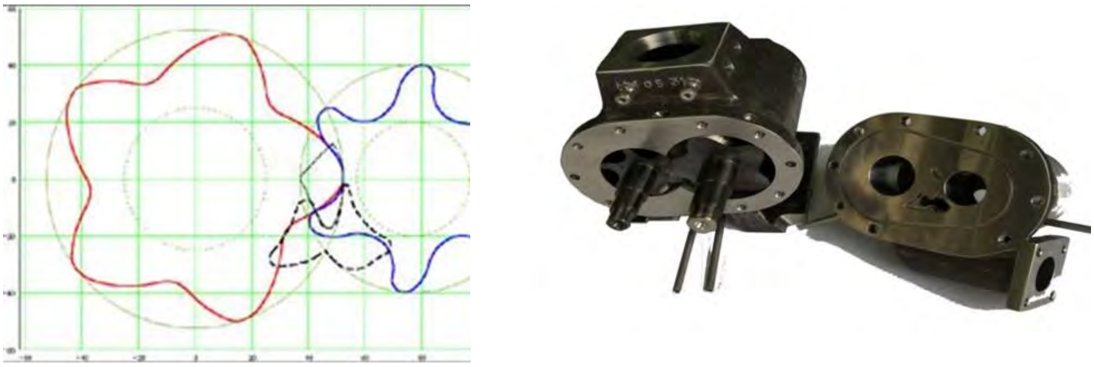


Figure 10-13: Principle of compression and prototype of compressor

In addition, large efforts have been put into the development of new multichannel re/absorbers that would be much more compact compared to conventional heat exchangers.

10.4.3 Electrically and gas fired thermoacoustic systems

The working principle of TA heat pumps has been described above. Since TA systems use a noble gas as working medium, these systems can be applied in a wide range of temperatures unlike regular compression or sorption heat pumps. Using this property of TA systems, ECN is developing two types of heat pumps, with two different drivers: mechanically and gas-fired.

A 10 kW mechanically driven system has been developed by ECN and Bronswerk Heat Transfer and is shown in Figure 10.14. This system is presently tested and subject of another paper at this conference.

Figure 10-14: *Electrically driven thermoacoustic system*

A thermoacoustic system can also be driven by high temperature heat, for example generated by a gas burner. Biggest challenge here is to transfer the heat from a gas burner to the thermoacoustic system. Figure 10.15 below shows the thermodynamic represention of this system (left) and a picture of an experimental thermoacoustic engine that is heated by hot flue gasses.

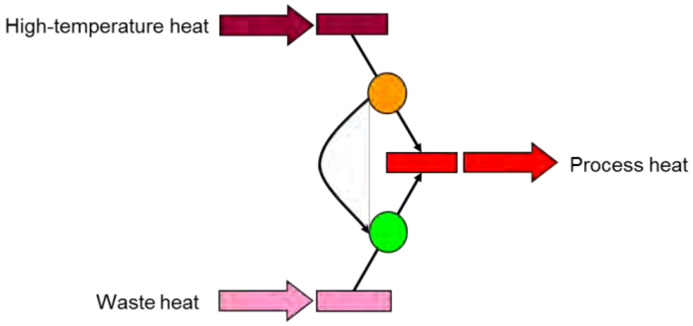


Figure 10-15: Thermodynamic scheme for gas-fired TA heat pump (left) and photo of the engine part

Both systems have virtually no limits with respect to operating temperature, other than the structural integrity limits of the pressurized resonator. In addition, large temperature lifts can be generated which means that these general concepts can be applied in a large variety of applications.

10.4.4 Minichannel heat exchangers for compression resorption heat pumps

Current separation processes within chemical and refining consume large amounts of energy. Increasing rising energy costs demand improvement of energy efficiencies. Significant reductions in energy consumption are expected by using innovative heat pump concepts for removal and supply of heat from/to a separation process. The research should lead to a fully integrated system consisting of traditional distillation and novel heat pump technology.

The amount of heat transferred will be determined by measuring mass flow, temperature and pressure at in- and outlets of a mini channel test section. From this data and the use of a fluid properties library, heat and mass transfer coefficients can be determined. Also the pressure drop can be measured.

Goals of the project are achieving high heat transfer rates and large surface area to volume ratios. This should lead to reduced investment cost and an optimized heat pump system.

Mini channel test setup 4 diameters from 0.5 to 2 mm, 5 lengths each one 6 mm tube as a reference.

Figure 10-16: Mini channel heat exchanger

10.5 Heat Integrated Distillation Columns

A large part of the work is undertaken by TU-Delft and partially published in a paper for the 10th Heat Pump Conference in Tokyo. It concerns the integration of heat pump technology in a distillation column.

In certain cases it is possible to split the process into two parts. An example is a distillation column where the rectifier and stripping section can be split from each other and exchange heat. In order to exchange heat the rectification section has to work at higher temperature and therefore higher pressure than the stripping section. This is reached by placing a compressor between the top of the stripping section and an expansion valve at the bottom of the rectification section. Possible advantage compared to compression-resorption heat pumps is the lack of one temperature driving force. The operating principle of a HIDiC is shown in Figure 10.17.

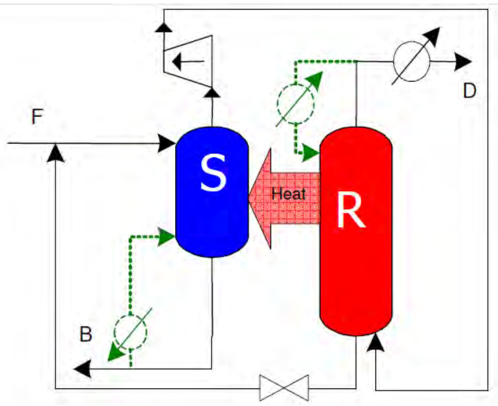


Figure 10-17: Scheme

Vapour from the top of the stripping section is compressed and directed to the rectifier. In the rectifier the vapour condenses, creating an internal reflux that is returned to the top of the stripper. The heat of condensation is used to evaporate the liquid at the stripper side. Usually the reboiler duty can be close to zero and a small external reflux is required at the top of the rectifier in order to produce the required distillate purity.

Optimization of the pressure ratio for a constant separation task is based on the balance between the compressor power cost and investment cost for compressor and HIDiC column. The HIDiC configuration can reduce the utility cost compared with the VRC with an additional 25-35% and the total annualized cost with 10-20%.

A simulation study on the existing plant was undertaken by Delft University of Technology focusing on enhancing thermodynamic efficiency of energy intensive distillation columns by internal heat integration. In the simulation study, taking propylene/propane splitter as base case, an internally heat integrated distillation column (HIDiC), offers significant potential for energy saving compared to energy requirements associated with operation of conventional and heat-pump assisted distillation columns. The rectification section of a propylene/propane splitter contains usually two times more stages than the stripping section, implying a number of heat coupling possibilities, which appears to be strongly influencing the thermal efficiency of the HIDiC. The configuration with the stripping section stages thermally interconnected with the same number of stages in the upper part of the rectification section emerged as the most efficient configuration, allowing a reduction in energy use in the range 30 to 40 % compared with a state of the art heat-pump assisted column, depending on the trade-off between the operating compression ratio and the heat transfer area requirement, the latter one being the key limiting factor.

In general, a distinctive feature of HIDiC is the fact that it combines advantages of direct vapour recompression and adiabatic operation at a significantly reduced total column height and therefore may be considered as an example of a most compact, and with respect to thermal energy conservation potential, an ultimate design of a distillation column.

10.6 Literature

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