IEA
OECD
heat pump programme

Annex 24

Operating Agent:

Sweden

Ab-Sorption Machines For Heating and Cooling in Future Energy Systems

Final report from Annex 24 of the IEA Heat Pump Programme

Ab-Sorption Machines

For Heating and Cooling in Future Energy Systems

Annex 24

By:

GASTEC NV
P.O. Box 137, NL-7300 AC Apeldoorn
The Netherlands

NOVEM
Catharijnesingel 59, 3511 GG Utrecht
P.O. Box 8242, 3503 RE Utrecht
The Netherlands

Institute for Energy Technology
Energy Systems Department
P.O. Box 40, 2027 Kjeller, Norway

Royal Institute of Technology
Department of Chemical Engineering and Technology
Division of Transport Phenomena
Sweden

Swedish Council for Building Research
P.O. Box 12866
112 98 Stockholm , Sweden

Swedish Energy Administration
Division of Electricity production
Box 310, 63104 Eskilstuna
Sweden

Oak Ridge National Laboratory
600 Maryland Ave.,SW, Suite 306W
Washington DC 20024, USA

Waterman Gore, Mechanical and Electrical Engineers
Versailles Court, 3 Paris Garden, London SE1 4ND
United Kingdom

ETSU
Harwell, Oxfordshire OX11 0RA
United Kingdom

IEA Heat Pump Centre
Swentiboldstraat 21
Sittard, The Netherlands

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IEA Heat Pump Centre
Swentiboldstraat 21, 6137 AE Sittard
PO Box 17, 6130 AA Sittard
The Netherlands
Phone:+31-46-4202 236
Fax:+31-46-4510 389
E-mail hpc@heatpumpcentre.org
Internet http://www.heatpumpcentre.org

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International Energy Agency

The IEA was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among its participating countries to increase energy security through energy conservation, utilisation of alternative energy sources, and research and development on energy technologies.

IEA Heat Pump Programme

Set up by the IEA in 1978, the IEA Heat Pump Programme carries out a strategy to accelerate the development of heat pumps, and to stimulate their use in all applications where they can reduce energy consumption for the benefit of the environment. Under this programme, participants from different countries collaborate in specific heat pump projects known as Annexes.

IEA Heat Pump Centre

The IEA Heat Pump Centre (HPC), itself an Annex, is the focal point for the heat pump related activities of the International Energy Agency (IEA).
Using the network of its National Teams, along with links with other organisations, the HPC works towards the aims of the programme by providing a world wide information exchange service. The functions of the HPC include:

- collecting, analysing and disseminating heat pump-related technical, market, regulatory, and environmental information;
- fostering international co-operation in research and development;
- facilitating contacts and information exchange among heat pump policy makers in governments and utilities, and those involved in research, development, design, manufacture, regulation, marketing, and application of heat pumps. The HPC publishes the quarterly journal *"IEA Heat Pump Centre Newsletter"*, organises *workshops,* maintains an *Internet site*, and conducts *analysis studies* on selected heat pump topics.

For further information about the HPC and its products, and for enquiries on heat pump issues in general, contact the HPC at the following address:

IEA Heat Pump Centre
Operated by Novem (the Netherlands Agency for Energy and the Environment),
PO Box 17, 6130 AA Sittard, the Netherlands
Phone: +31-46-4202 236
Fax: +31-46-4510 389
E-mail: hpc@heatpumpcentre.org
Internet: http://www.heatpumpcentre.org

Foreword

Rational use of energy, improvement of energy efficiency and reduction of environmental pollution are today priority objectives on the way to creating a sustainable global energy system. Fossil fuels are contributing to greenhouse gas emissions like carbon dioxide, methane and nitrous oxide (CO_2, CH_4 and N_2O). Of these, carbon dioxide is currently thought to account for more then 50% of the greenhouse effect, and most anthropogenic CO_2-emissions are due to the commercial burning of fossil fuels. Combustion of fossil fuels also contributes to acid rain (e.g. SO_x and NO_x). At a conference held from 1-11 December 1997 in Kyoto, Japan, the Parties to the UN Framework Convention on Climate Change agreed to an historic Protocol to reduce greenhouse gas emissions to protect the environment. Furthermore, the world is facing new challenges in terms of electricity utility deregulation, as well as increases in electrical energy and demand costs. All these complex issues challenge today's HVAC industry to consider alternatives to traditional mechanical refrigeration and heat pump equipment.

Sorption machines have gained increased interest in the recent years. Sorption systems are not only viewed as environmentally friendly alternative to CFC-, HFC- or HCFC-based technology, but also as energy-efficient cooling and heating methods when installed in a properly designed system. Sorption systems can use almost any heat source, including a wide variety of fuels, and waste heat from industrial processes, incineration plants, cogeneration systems, power plants and solar energy. However, the market penetration of these systems has not been in areas were they really offer distinct advantages in terms of reduced environmental impact and primary energy savings.

This report provides end-users, manufacturers, consultants, policy-makers and utilities with information on sorption heat pumping technologies. The report includes descriptions of available and future technology, reviews applications in different market segments, marketing influences, R&D and the outlook for future opportunities and developments. The report also provides appendices with information on manufacturers, thermodynamics of sorption systems, performance of sorption systems, brief description of competing technologies, and case studies.

We trust that the report provides useful information for all target groups involved in the promotion, manufacture, installation and use of sorption technology. Our aim is that it will assist in further promoting the technology, and will help to direct future efforts to areas where the technology can be deployed on a wider scale, and hence contribute to sound global energy systems for the 21st century.

Acknowledgements

The authors acknowledge the efforts of the Operating Agent in initiating the task, and for organising the start-up and the initial work of the Annex. All contributions and engagement in the Annex by the participating countries, companies and organisations are also appreciated.

Patti Garland
Svein Grandum
Magnus Gustafsson
Onno Kleefkens
Carel van Lange
Robert Tozer

Contents

Executive Summary

Technical report

Appendices

Glossary and Abbreviations

Absorption	Of one fluid by another. The basis of most of the technology discussed here.
*Ad*sorption	Solid sorption.
AHP	Absorption heat pump.
AHT	Absorption heat transformer.
BTA	Benzatriazole (a corrosion inhibitor).
Carnot	An ideal (perfect) thermodynamic cycle.
CCHP	Combined cooling, heating and power.
CFC	Chlorofluorocarbon. The most common type of refrigerant, now being phased out because of its impact on ozone depletion.
CHP	Combined heat and power.
CH_4	Chemical symbol for methane (a naturally-generated greenhouse gas).
COP	Coefficient of performance (of a heating or cooling system).
CO_2	Carbon dioxide. The principal greenhouse gas.
Desiccant	Technical term for a solid sorber.
GAX	Generator absorber heat exchanger.
GWP	Global warming potential.
HBr	Hydrogen bromide (a corrosion inhibitor).
HCFC	Hydrochlorofluorocarbon. An alternative refrigerant to CFC, with lower ODP than CFC.
HFC	Hydrofluorocarbon. An alternative refrigerant, replacing CFC and HCFCin many countrues, without ODP.
HP	Heat pump.
H_2O	Chemical symbol for water.
LiBr	Chemical symbol for lithium bromide (widely used with water as working pair).
NH_3	Chemical symbol for ammonia (widely used as a working pair with water).
N_2O, NO_x	Oxides of nitrogen (greenhouse gases).
ODP	Ozone depletion potential.
pH	The scale of measurement of acidity/alkalinity.
PTX	Pressure/temperature concentration (diagram).
SE/DL	Single-effect, double-lift (absorption cycle).
Sorption	Generic term for absorption and *ad*sorption.
SO_x	Oxides of sulphur (greenhouse gases).
TEWI	Total equivalent warming impact.
Thermodynamics	The science or engineering of heat flow.
Working pair	The mixture circulating in an absorption machine. (The two most common working pairs are water/LiBr and ammonia/water)
Zeolite	A solid sorber.

Nomenclature

B	Thermal exergy (kW)
E	Number of multiple effects
r	Heat of evaporation (kJ/kg)
L, l	No of Lifts, Heat of solution (kJ/kg)
N	Number
Q	Heat (kW)
S, s	No of stages, Entropy (kJ/kg)
T	Absolute temperature (K)
	Thermodynamic ratio
	Efficiency
θ	Angle

Subscripts

a	absorber
c	condenser
cc	cooling cycle
dc	driving cycle
e	evaporator
g	generator
h	high
i	intermediate
l	low
sc	solution circuit

Part One

Executive Summary

1. Introduction

The title of Annex 24, "Ab-sorption machines for heating and cooling in future energy systems" focuses attention on the technology of the known absorption cycles. However, the splitting of the word "absorption" into 'ab-sorption' (with a hyphen), emphasises that a broader view is taken, embracing all sorption technologies. The title also spells out the prime functions of the machine (to cool and heat), and of the Annex (to look into the future of this technology). Furthermore, the objectives of the Annex state that an understanding of actual systems is needed to appreciate the market barriers to the adoption of sorption technologies, and when they benefit the environment. Finally, recommendations are made regarding policies and R&D, to enable these technologies to be better assisted by market pull, especially when they offer environmental benefits.

After this Executive Summary and a brief introductory chapter, Chapter 2, Sorption Technologies for Heating and Cooling in Future Energy Systems, reviews the main types of sorption systems. They are summarised in Table 2.4 on page 32. Chapter 3, Market Segmentation, then considers the major segments of the market including residential, commercial/institutional and industrial, and the types of sorption hardware most suitable to each.

2. Applications

The highly important residential and commercial/institutional markets are mostly concerned with air-conditioning of buildings, which is dealt with. More applications are identified and discussed for the industrial market, including refrigeration, food-storage cooling, process cooling, and process heating at various temperature ranges from hot water for hand-washing to high-temperature (greater than 130°C).

Heating demand catered for by furnaces is not directly considered, since it has no direct applicability to heat pumping or other absorption technologies due to the very high temperatures involved (several hundred degrees Celsius). The waste heat may, however, be of interest to run absorption chillers, if a suitable cooling demand has to be met. Flue-gas cleaning (which is generally mandatory) is the simplest and most direct method of recovering what would otherwise be waste heat, mostly vented to the atmosphere via cooling towers. Cooling tower water is a source of lower-temperature waste heat which may be of great interest.

Other interesting industrial applications are absorption cooling or heating combined with co-generation, desiccant cooling, gas turbine inlet air cooling, combining absorption chillers with district heating systems, direct-fired absorption heat pumps (AHPs), and a closed greenhouse concept being developed for that economically important sector in the Netherlands. In all such applications of sorption (or any other) technology, it is emphasised that proper system design is essential to gain real benefits.

Industry (including agriculture) accounts on average for 20 – 50% of the total energy consumption in the countries participating in Annex 24, so technologies such as heat pumps in general, and sorption systems using waste heat for cooling in particular, would have great potential for saving primary energy (fossil fuel) and reducing its adverse impact on global warming and environmental pollution.

3. System suitability

Most of the sorption market at this time comprises direct-fired absorption chillers, or hot water or steam absorption chillers indirectly driven by direct-fired boilers. Throughout the report, this category of absorption chillers is referred to generically as 'direct-fired'. Absorption chillers constitute most of the sorption market; in addition, this report covers absorption (reversible) heat pumps, absorption heat transformers, compression-absorption heat pumps, and *ad*sorption chillers and heat pumps. *Ad*sorption systems together with desiccant systems are also addressed.

After the review of systems and markets in the earlier chapters, Chapter 4, Factors Affecting the Market, considers economic, environmental and policy issues. The geographical make-up of the world sorption market is then reviewed, followed by a number of practical operating and control considerations. These include vacuum requirements, crystallisation, corrosion, maintenance, health and safety etc. Possible crystallisation and corrosion problems are still major concerns of some users, but with proper attention by producers, system designers, installers and maintainers are shown not to be problematic in practice. The lack of trained maintenance people is a major concern.

A brief survey of R&D activities is given in Chapter 5.

4. Future opportunities

In Chapter 6, Future Opportunities, an analysis of the market factors shows that the market pull favours sorption technologies in different ways. Direct-fired absorption chillers are installed in areas where there is lack of mains electricity, or restrictions on using it to power electric-driven mechanical compression chillers. A chart has been compiled (Figure 6.1, page 65) to illustrate the different market pull factors. It shows, in decreasing order of market pull, the following technologies:

- Direct-fired or boiler-driven absorption chillers; and
- Absorption chillers driven by waste heat, heat recovery or combined heat and power (CHP) systems.

Far less prominent are:
- Absorption heat pumps; then
- Absorption heat transformers; and finally
- *Ad*sorption chillers.

The chart shows that *environmental benefit is inversely proportional to the market pull and share of sorption technologies.* The main market barriers are considered to be the relatively high first costs of absorption plant, and the lack of knowledge of sorption technology by technicians, engineers and professionals.

In practice, different technologies are found to be most suitable for different countries, mainly depending on their energy infrastructure and particularly on how the country's electricity is produced. An energy infrastructure based mainly on coal-fired generation should favour sorption or other non-electric systems over compression systems. On the other side of the spectrum are countries that have a more renewable energy basis, which should favour electric-driven systems. The history of generation shows that energy production generally improves over time, which affects the benefits sorption technology can offer. Recommendations are made regarding policies to promote sorption technology (where it is environmentally beneficial), and with regard to future R&D.

5. Conclusions

In Chapter 7, Conclusions, it is emphasised that the application of sorption technology is not in all cases the best choice for the environment.

Detailed conclusions are that:

- Encouragement should be given to absorption and *ad*sorption chillers using waste heat, heat recovery or applied heat;
- Sorption chillers applied to CHP systems have an existing market pull, and benefit the environment. However, the overall efficiency has to be relatively high with respect to each nation's power production, throughout the life of the system;
- Absorption heat pumps (including reversible heat pumps) will be available on the market in the short term, and due to their environmental benefits should be strongly supported, unless electric heat pumps are more beneficial, as occurs in countries with a high proportion of hydroelectricity and even gas energy;
- Absorption heat transformers and compression-absorption heat pumps offer excellent environmental benefits for industry. However, the latter are likely to have more market pull in the medium or long term; and
- Direct-fired chillers should be phased out whenever they do not prove to be environmentally beneficial.

6. Recommendations

Chapter 8 concludes the main body of the report with Recommendations for Future Work. Technically, it is suggested that the main emphasis of such work could be on sorption applications of waste heat / heat recovery and process heat, but other factors need equal or greater attention. They include the study of the effect of existing taxes and economic incentives, and formulation of recommendation for such measures; system capital cost reduction studies; the closer study of environmental benefits and new potential markets; and the need to assemble a representative portfolio of Case Studies and Demonstration Projects. Details of future work still have to be resolved regarding objectives, work plan, time-scales, budget and participation.

Seven Appendices conclude the report. Appendices 1 and 2 list National Contacts for the Annex, and Manufacturers of Sorption Equipment. Appendices 3, 4 and 5 briefly review the absorption heat pump cycle; sorption thermodynamics; and competing technology, i.e. the electrically-driven mechanical compression cycle.

Appendix 6 reviews 12 Case Studies, each demonstrating some new technology or novel application(s) of interest. Further information is available in the references indicated. Appendix 7 lists useful website addresses, which are followed by lists of References and Bibliography. Lists of Figures and Tables conclude the report.

7. Other work of the Annex

In concluding this Executive Summary it should be said that Annex 24 has produced or contributed to a number of works. They are:

- Workshop Proceedings I (Maastricht, 1997), Report No. HPP-AN 24-1 [1];
- Workshop Proceedings II (Tokyo, 1998), Report No. HPP-AN 24-2 [2];
- Workshop Proceedings III (San Francisco and Turin) – in preparation [3];
- An Annex 24 homepage; http://www.ket.kth.se/Avdelningar/ts/annex24/index.htm
- "An Introduction to Absorption Cooling", Good Practice Guide No 256, DETR, UK [4];
- "Pressure Systems Regulations Applied to Absorption Machines", ETSU, UK [5]; and
- This Final Report, which concludes the work of Annex 24. As outlined above, and discussed in detail on the following pages, it reviews ab-sorption technology and potential applications, and summarises experience, technical development and country-specific issues.

Part Two

Technical Report

1. Introduction

1.1 Background

Heat pumping technologies are currently very concerned with new environmental regulations. The role of chlorofluorocarbons (CFCs) in ozone depletion is well recognised. The effectiveness of other compounds in contributing to global warming on a molecule-by-molecule basis is typically measured relative to CO_2, and is referred to as the compound's global warming potential (GWP). Impact assessment of CFC alternatives on global warming must not only include direct-emission effects based on GWP, but indirect, energy-related CO_2 emissions. The sum of the direct and indirect emissions associated with a particular gas has been defined as its total equivalent warming impact (TEWI).

CFCs are also known to be greenhouse gases that may contribute to global warming. CFCs have been rigorously evaluated for their ozone depletion potential (ODP), but are now also characterised by their GWP. Of future concern in global warming scenarios are not only the CFCs but also the hydrofluorocarbons (HFCs) and other compounds scheduled to replace CFCs. More recently, the Parties to the UN Framework Convention on Climate Change agreed to an historic Protocol to reduce greenhouse gas emissions to protect the environment.

The status of sorption technology (absorption and *ad*sorption) varies significantly by region and from country to country. The market share is greatly affected by issues such as the energy situation, climatic conditions, infrastructure, national priorities and incentive programmes. These priorities play an important role in the current and future market for sorption systems. However, in most countries utilisation of waste heat, heat recovery, peak demand shaving and co-generation have been the major factors that have influenced the market pull of the technology. Sorption systems are considered as promising solutions for environmental protection, energy cascading and waste heat utilisation. With the increasing cost and scarcity of fossil fuels, and the growing concern about environment protection, the particular features of sorption systems have made them more attractive in a number of applications.

During the life of the Annex, important improvements have been proposed for compression systems (the natural alternative to absorption systems). This shows that compression technologies have made a step forward. However, due to the reluctance of the market and of legislative bodies in the US and Europe, the introduction of natural refrigerants is not going well.

1.2 Annex objectives and scope

Annex 24 aimed at further increasing and promoting the use of sorption systems, i.e. absorption systems, *ad*sorption systems and compression/sorption systems, for heating and cooling in a future energy-efficient and environmentally-acceptable energy system. The work of the Annex focused on gaining a better understanding of the market opportunities for sorption systems in a global context. It also examined how different factors (e.g. economic, political, environmental and knowledge) will affect the market pull and application of such systems. The Annex also discusses the future for sorption technology.

The Annex was used to develop guidelines to encourage more application-oriented R&D activities, that can attract the participation of industry, utilities, manufacturers and government bodies, provided there are environmental benefits. Further recommendations and support were given to the setting up of case studies and demonstration projects. The Annex aimed at finding the reasons for the lack of implementation of sorption technology for heating and cooling. The main objectives were to systemise knowledge of the utilisation of sorption machines and ongoing activities, in order to increase the competitiveness of the technology. In addition, the obstacles to using the technology were identified and means to overcome them were examined.

The activity was carried out in close co-operation with manufacturers, utilities, users, government representatives and organisations involved in the dissemination of energy technologies. The Annex 24 work has resulted in the establishment and initiation of case studies and demonstration projects (which, however, are still partially developed) related to potential fields of application.

The following objectives have been emphasised:

- To investigate the present industrial and non-industrial applications of sorption technology for heating and cooling;
- To list and evaluate ongoing national research programmes concerning sorption technology;
- To identify technical, economic, environmental and political obstacles to the introduction of sorption technology, and to find ways to overcome the obstacles;
- To clarify environmental and political issues that will strengthen or weaken sorption technology in relation to competing technologies;
- To heighten awareness of the applications where sorption technology can be a sound choice in terms of primary energy savings and environmental benefits; and
- To broaden the information base, to assist further deployment and development of sorption technology.

Task-shared activities:
Each participant nominated an individual and a substitute to assist in conducting the work proposed under this task. Each participant has (on a task-sharing basis) provided data on the current state-of-the-art and application of sorption technology in the participant's own country. They have also performed the necessary analyses to enable them to allow for the country's financial, political and environmental factors that affect the implementation of sorption technology for heating and cooling, based on the methodology and framework established by the Operating Agent. Each participant has also contributed relevant information, work with case studies and related activities that are specified in the work programme of this task.

The intention was that Annex 24 would provide a common platform, where government and utility personnel concerned with energy efficiency, energy services and application engineers would work together towards the wider deployment of sorption heat pumps and continued development of the technology. It was considered important that development work was directed toward market possibilities with good potential for serial production, in order to assess new technologies timeously.

In conducting the various Annex 24 assessments, the participating countries have performed various tasks including:

- Preparing a detailed state-of-the art report;
- Estimating potential and applications for sorption systems;
- Conducting case studies;
- Setting up demonstration projects; and
- Illustrating opportunities for the use of sorption technology.

As a result of these task-shared efforts, the Annex has produced four main products and some minor ones that can be used by the various national teams, utilities, end-users and government bodies to assess and facilitate the development and applications of ab-sorption systems. They are:

- Workshop Proceedings I (Maastricht, 1997), Report No. HPP-AN 24-1 [1];
- Workshop Proceedings II (Tokyo, 1998), Report No. HPP-AN 24-2 [2];
- Workshop Proceedings III (San Francisco and Turin) – in preparation [3];
- An Annex 24 homepage; http://www.ket.kth.se/Avdelningar/ts/annex24/index.htm
- "An Introduction to Sorption Cooling", Good Practice Guide No 256, DETR, UK [4];
- "Pressure Systems Regulations Applied to Sorption Machines", ETSU, UK [5]; and
- This Final Report, which outlines ab-sorption technology and potential applications and summarises experience, technical development and country-specific issues.

1.3 Report structure

The main body of this report is structured as follows:
Chapter 2 – Sorption Technologies for Heating and Cooling presents an overview of sorption technology, including different types of systems and their principles of operation.
Chapter 3 – Market Segmentation gives an overview and discusses the market segmentation for sorption technology applications, including residential, commercial, industrial and others.
Chapter 4 – Factors Affecting the Market describes and discusses marketing influences on sorption technology applications (e.g. economic, environmental and policies). It also presents an overview of the world market, and summarises operating experiences with sorption technology in different applications.
Chapter 5 – Research and Development presents R&D programmes on sorption technology, priority areas and national activities.
Chapter 6 – Future Opportunities discusses future prospects for sorption technology and the worldwide market pull versus market share and environmental benefits.
Chapter 7 – Conclusions presents the overall conclusions of the Annex.
Chapter 8 – Recommendations for Future Work presents recommendations for future Annex activities. Areas for continued efforts towards more widespread deployment of sorption technology are prioritised, where the environmental benefits and energy efficiency can be sustained.

In addition:
Appendix 1 – National Contacts provides information on national contact persons in the countries that participated in Annex 24.
Appendix 2 - Manufacturers gives a summary of the major sorption equipment manufacturers worldwide. Contact information is provided, together with a short summary of equipment that they provide.

Appendix 3 – The Sorption Heat Pump Cycle provides a summary of sorption system performance.
Appendix 4 – Sorption Thermodynamics gives an introduction to the fundamental thermodynamics of sorption systems.
Appendix 5 – Competing Technologies briefly reviews the main technology that is considered as an alternative to sorption technology, namely electric-driven mechanical compression.
Appendix 6 – Case Studies provides detailed information about selected case studies and demonstration projects. A brief description of the installations is given, together with a summary of the economic, energy and environmental benefits.
Appendix 7 – Useful Website Addresses gives additional sources of information for sorption technology, including material published by the participating countries, information about pressure systems regulations, relevant documents and literature.

1.4 Intended readership

The report is intended to be read as an internal document by the members of Annex 24. Additionally, it should find a wider readership. Specifically, it should be of interest to everyone interested in the future of ab-sorption technology, and competing technologies such as electrically-driven mechanical compression, including politicians, consultants, engineers and technicians with an interest in sorption technology and applications.

In this Part Two and the relevant Appendices, it is assumed that the readership is technical, but not necessarily specialised in ab-sorption technologies. For those not so specialised, a Glossary of technical terms and a summary of the more common abbreviations was given immediately preceding the Executive Summary.

2. Sorption Technologies for Heating and Cooling

Sorption technology in its various manifestations is a technology that delivers cooling or heating at several temperature levels. It covers the same working temperature range as mechanical compression systems, chillers, refrigeration machines and heat pumps. The working principle of a sorption system is similar to that of a mechanical compression system. A low-pressure vaporising liquid extracts heat at a low temperature (cooling). Then the vapour is compressed to a higher pressure, and condenses at a higher temperature (heating). After this, the pressure of the liquid is reduced, and the cycle recommences from the beginning.

The obvious way of compressing a vapour is to use a mechanically-driven compressor. This requires moving parts such as a compressor and a prime mover, or an electric motor to drive the compressor.

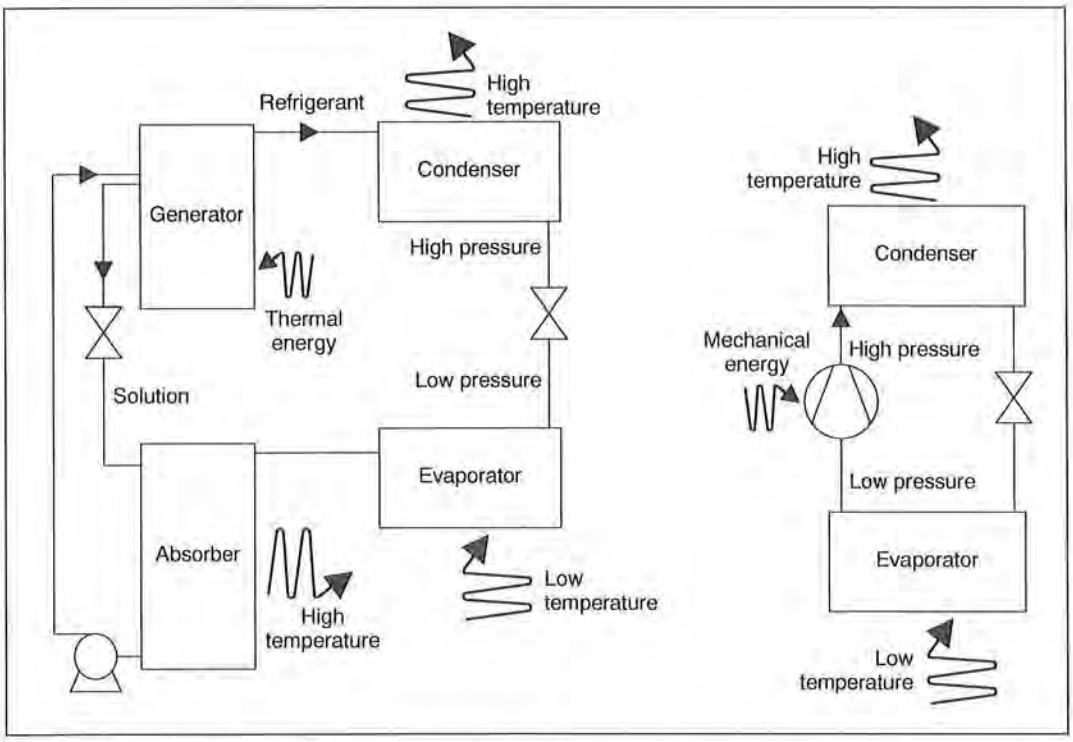


Figure 2.1 *(a) Absorption system, and (b) Mechanical compression system.*

The alternative method of compression, avoiding most of the moving parts, is to use a heat-driven compression cycle. The sorption cycle is the most widely applied example of this. Although the common feature of vapour compression in both cycles (mechanical compression and sorption) helps initially to understand sorption cycles, they should not be grouped together simplistically as having the same overall principles, because the driving energies employed are very different. For sorption systems there is a better approach based on sorption principles that enables an adequate thermodynamic analysis [6].

Sorption cycles are based on the fact that the boiling point of a mixture is higher than the corresponding boiling point of a pure liquid. The sorption system therefore always works with a mixture, i.e. a working pair of liquids, consisting of a volatile liquid (refrigerant) and an absorbent. The most common working pairs are water (refrigerant)/lithium bromide (absorbent), and ammonia (refrigerant)/water (absorbent). Appendices 3 and 4 give further information on the cycle and thermodynamics of sorption systems.

Here are various types of sorption cycles:
- Absorption chiller;
- Absorption heat pump (AHP Type I);
- Absorption heat transformer (AHP Type II);
- Compression/absorption heat pump;
- Solid sorption systems; and
- Desiccant systems.

2.1 Absorption chillers

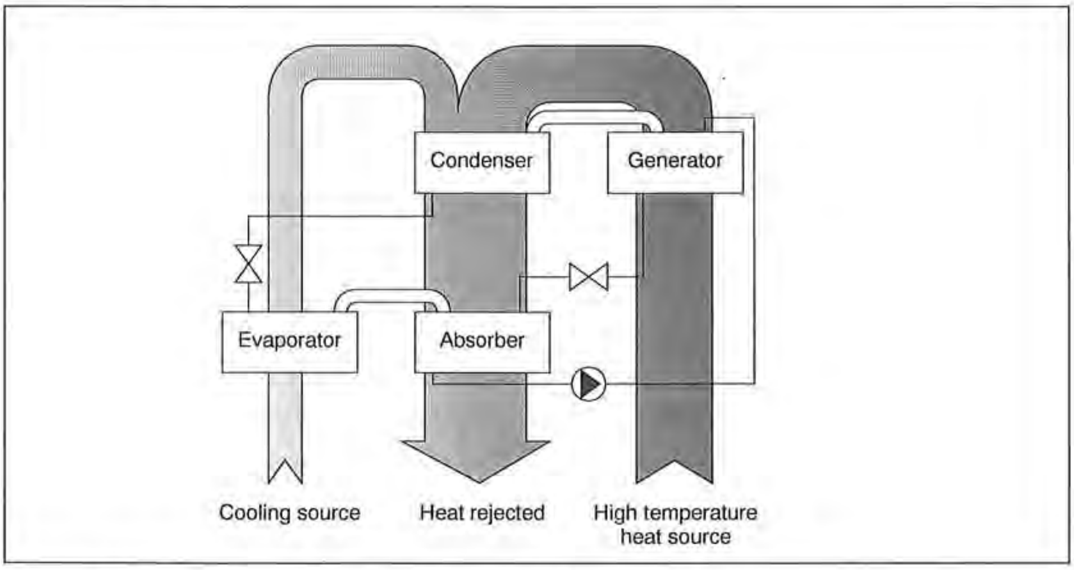


Figure 2.2 *Heat flows in an absorption chiller.*

For chillers, the heat extracted at a low temperature, or in other words 'cooling', is the main yield of the system. As described above and in Appendices 3 and 4, a sorption machine for heating and/or cooling is based on a vapour compression cycle in which compression takes place by a sorption–desorption process.

One of the two main types of absorption chillers is normally applied, mostly depending on the required cooling temperature:
- For cooling temperature > 5°C, a water/LiBr absorption machine is most frequently used, which must be water-cooled.
- An ammonia/water machine can be used for cooling temperature < 5°C. It can be either air- or water-cooled.

In the water/LiBr machine, water is the refrigerant, and cooling is based on the evaporation of water at very low pressures. Since water freezes below 0°C, at this level the chilling temperature meets a physical limit. LiBr is soluble in water if the LiBr mass fraction of the mixture is less than about 70%. Crystallisation of the LiBr will occur at higher concentrations, requiring repair of the machine. This sets a maximum to the temperature of the absorber. Poor control of temperature or a fast change of conditions may cause crystallisation. Appropriate controls will prevent problems. [See also Section 4.3.3 Crystallisation.] In order to supply sufficiently low temperatures to the absorber at high outside air temperatures, cooling towers are used. Water/LiBr chillers are used for air-conditioning.

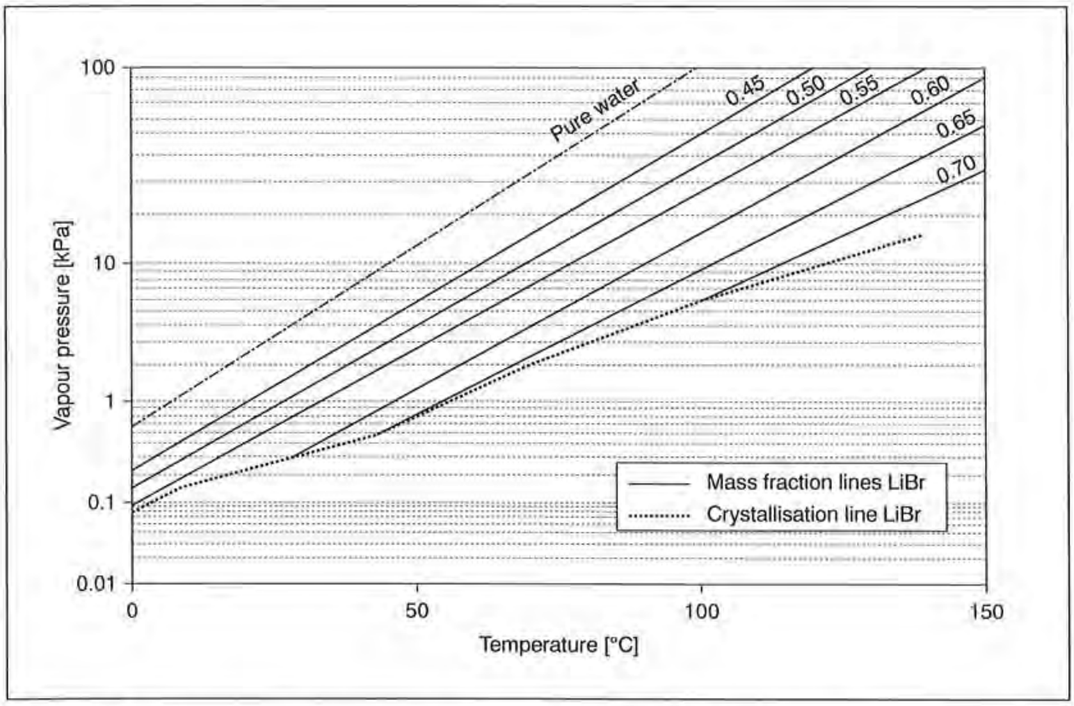


Figure 2.3 *Pressure – Temperature diagram of a water/LiBr system.*

In the ammonia/water machines, ammonia (NH_3) is the refrigerant. This offers opportunities to provide refrigeration at temperatures down to –60°C. Unlike LiBr, water has a vapour pressure of itself. This means that in the generator, besides ammonia vapour, a certain amount of water vapour will also be present. In the evaporator, this will lead to problems, because the ammonia will evaporate more easily than the water. This results in an accumulation of water in the evaporator, spoiling the chilling process. To prevent this, an extra device called a rectifier is added to the system to separate the water content from the vapour flow coming from the generator. This rectifier cools the vapour produced in the generator, therefore demanding more heat. In this way, rectification reduces the COP. Despite the rectification, a small fraction of water will still remain in the vapour. To prevent it accumulating in the evaporator, there always has to be a flow of non-evaporated fluid (liquid) from the evaporator to the absorber. Ammonia is soluble in water at all concentrations so crystallisation, as occurs in water/LiBr machines, will not occur. Consequently, at equal chilling temperatures, a higher absorber temperature is possible compared to water/LiBr chillers. Therefore, dry air coolers can be applied.

2.1.1 Overview of chillers

Table 2.1 gives a rough indication of the properties of the most common chiller types.

Table 2.1 Overview of standard chiller types.

Working pair	System	Driven/fired by (not direct)	Cooling capacity [kW]	COP
H_2O/LiBr	Single-effect absorption	Steam, water	40 – 6,000	0.7
H_2O/LiBr	Single-effect absorption	Gas, oil	40 – 6,000	0.6
H_2O/LiBr	Double-effect absorption	Steam	70 – 6,000	1.2
H_2O/LiBr	Double-effect absorption	Gas,oil	5 – 6,000	1.0
NH_3/H_2O	Single-effect absorption	Gas	10 – 100	0.5
NH_3/H_2O	GAX	Gas	10 – 100	0.7
H_2O/Silica gel	Double-alternating adsorption	Water	70 – 350	≤0.6
H_2O/Silica gel	Double-alternating adsorption	Gas	70 – 350	≤0.5

2.1.2 Single-effect chillers

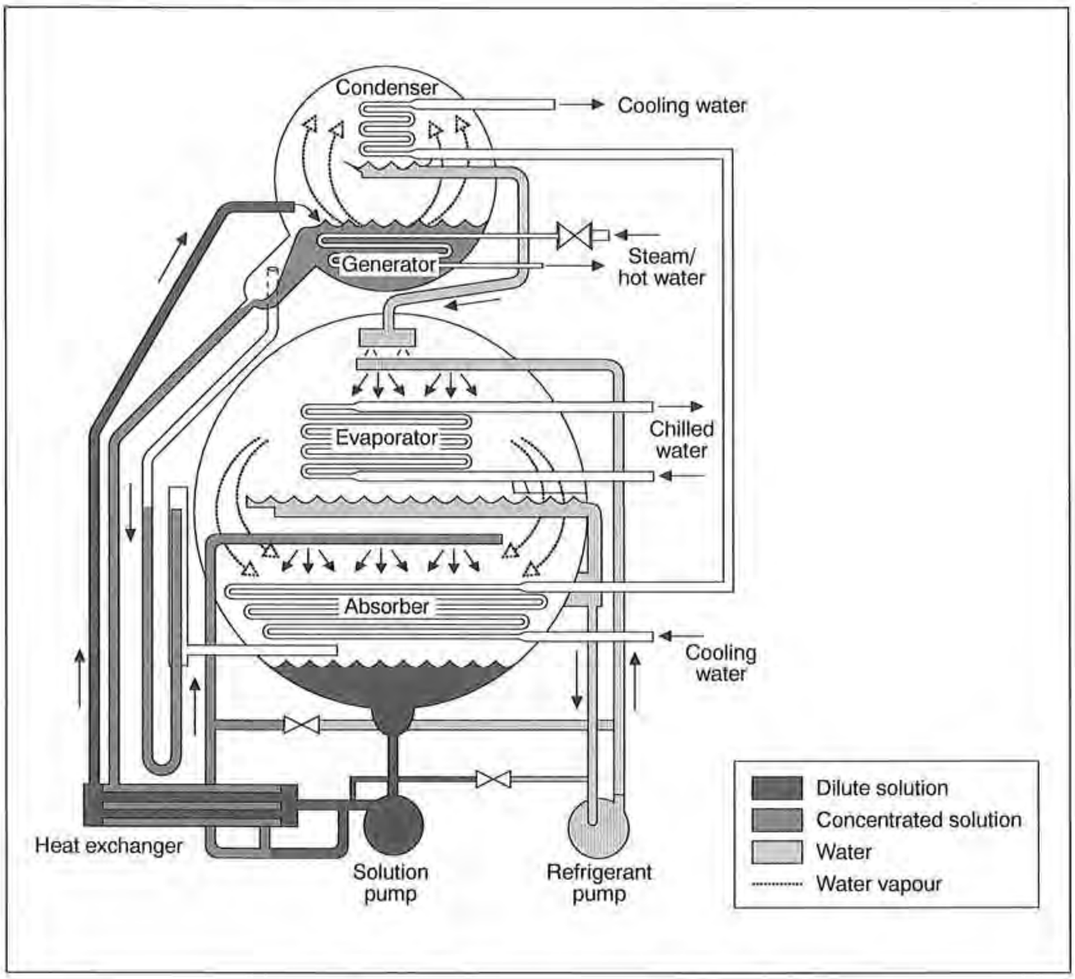


Figure 2.4 Single-effect absorption chiller. (Courtesy York)

The single-effect absorption chiller works in fundamentally the same way as the vapour compression system, except that the compressor is replaced with a solution circuit that absorbs the vapour at the low pressure and desorbs it at the higher pressure. The term 'single-effect' comes from the observation that the heat is used once by a single generator. Thermodynamic restrictions in the system dictate that the cooling capacity for ideal and real systems is always less than the heat input (see Appendix 4). The generator requires both the heat of evaporation (r) and the heat of solution (l) to be supplied. However, the evaporator can only exchange the heat of evaporation (r). For an ideal cycles this is indicated as:

$$COP = \frac{Q_e}{Q_g} = \frac{r}{r + l} \tag{1}$$

In absorption refrigeration, an absorber, generator, pump and recuperative heat exchanger replace the compressor. Like mechanical refrigeration, the cycle 'begins' when high-pressure liquid refrigerant from the condenser passes through a metering device into the lower pressure evaporator, and collects in the evaporator pan or sump.

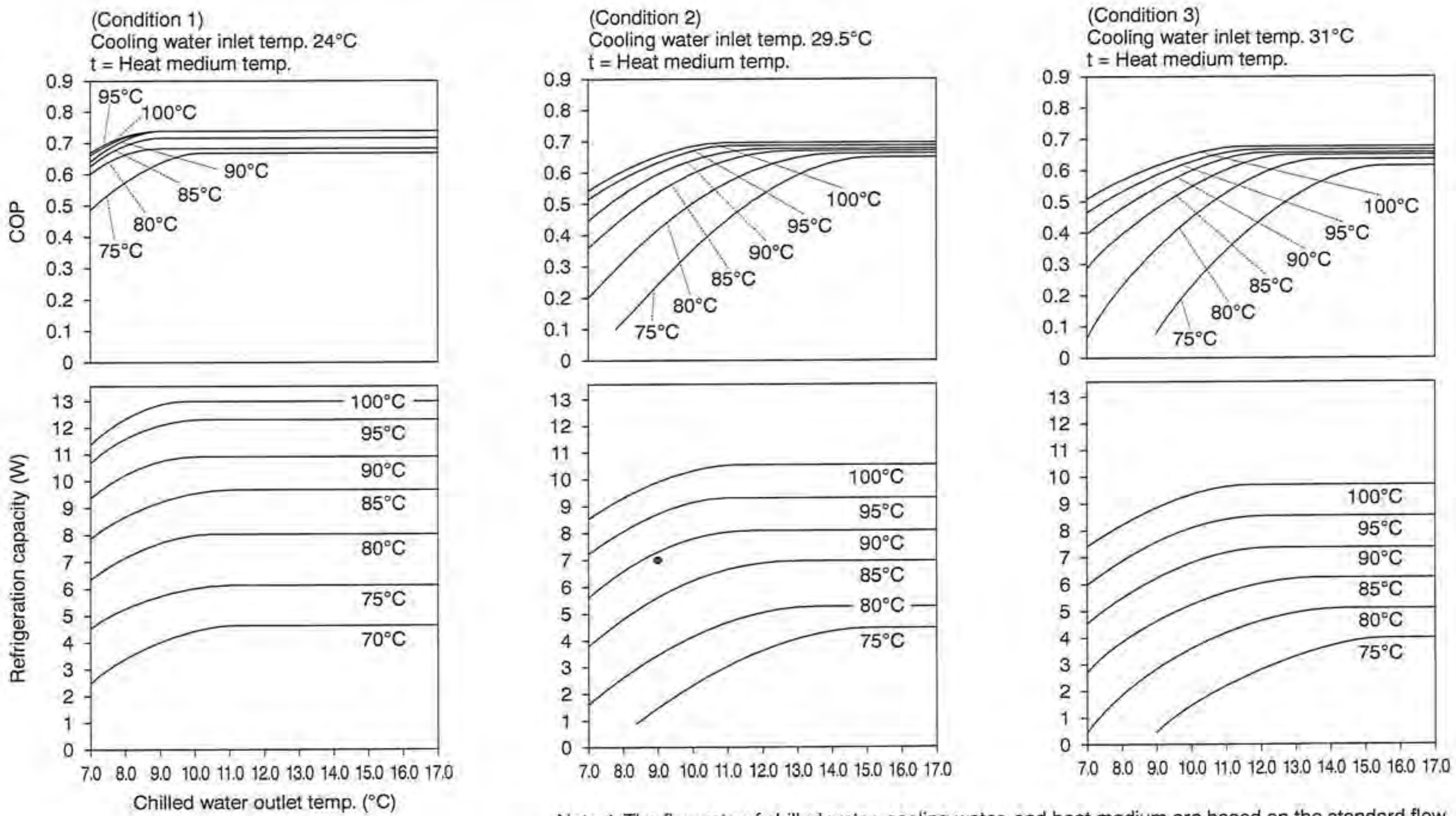
The 'flashing' that occurs at the entrance to the evaporator cools the remaining liquid refrigerant. Similarly, the transfer of heat from the comparatively warm system water to the now cool refrigerant causes the latter to evaporate, and the resulting refrigerant vapour migrates to the lower-pressure absorber. There, it is absorbed by a lithium bromide solution. This process not only creates a low-pressure area that draws a continuous flow of refrigerant vapour from the evaporator to the absorber. It also causes the vapour to condense as it releases the heat of vaporisation picked up in the evaporator. This heat – along with the heat of dilution produced as the refrigerant condensate mixes with the absorbent – is transferred to the cooling water and released in the cooling tower.

Of course, assimilating refrigerant dilutes the lithium-bromide solution and reduces its affinity for refrigerant vapour. To sustain the refrigeration cycle, the solution must be regenerated. This is accomplished by constantly pumping dilute solution from the absorber to the generator, where the addition of heat boils the refrigerant from the absorbent. Once the refrigerant is removed, the concentrated lithium-bromide solution returns to the absorber, ready to resume the absorption process.

The refrigerant vapour produced in the generator migrates to the condenser, where the refrigerant returns to its liquid state as the cooling water picks up the heat of vaporisation carried by the vapour. The liquid refrigerant's return to the metering device completes the cycle.

The concentration change in the absorber and desorber is accompanied by a change in the saturation temperature. In the desorber, this 'temperature glide' acts to absorb heat that would ideally be used for vapour generation. In the absorber, more heat is lost than would be incurred from the absorption process alone. To reduce these energy losses, a recuperative solution heat exchanger is placed between the desorber and absorber.

One major difference between absorption and vapour compression machines is in the fluids used. In most cases, a vapour compression machine uses a pure refrigerant. In an absorption machine, the refrigerant can be pure, as in water/LiBr or ammonia/sodium thiocyanate systems, or it can be a binary mixture, as in the ammonia/water system. For binary mixtures, the condensation stage is a two-part process, where most of the absorbent is recovered in a



Note 1. The flow rate of chilled water, cooling water, and heat medium are based on the standard flow.
2. Temperatures described in the performance curve are heat medium inlet temperatures.
3. The "•" mark is the rating point.

Figure 2.5 *Capacity and COP of a single-effect hot-water-driven lithium bromide chiller. (from Yazaki manual and service report [7])* rectifier and the refrigerant is liquefied in the condenser. Heat from the rectifier is rejected to the same sink as that from the condenser. The refrigerant still contains a small amount of absorbent that has some effect on the operating temperature of the evaporator.

Indications of the performance of sorption chillers are given in the figures below. Note that there can be significant variations, reflecting the many design possibilities of sorption machines.

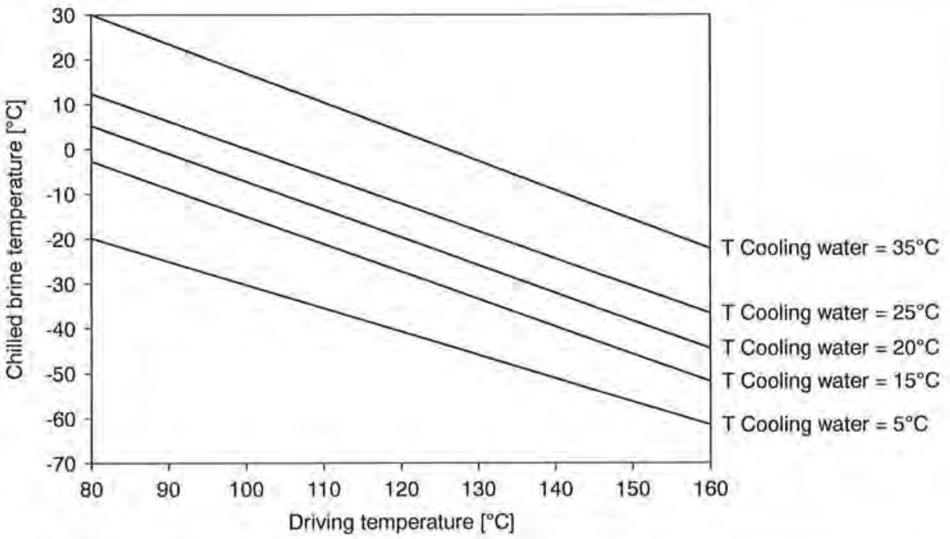


Figure 2.6 *Chilled water temperature related to driving and cooling water temperatures for ammonia/water machine, single-effect.*

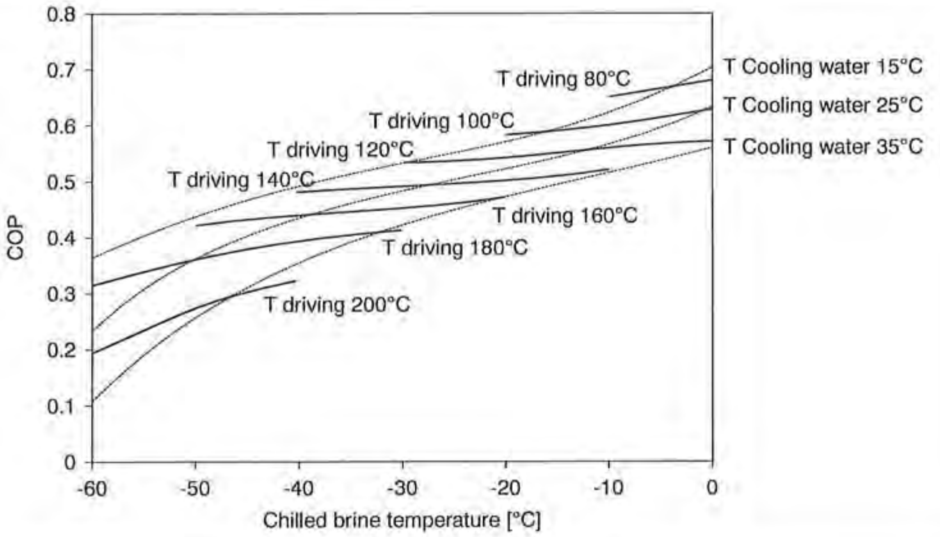


Figure 2.7 *Overview of performance of ammonia/water absorption chillers.*

2.1.3 Double-effect chillers (Type I)

A number of different configurations can produce a double-effect cycle. Their principle is based on the fact that the cooling capacity depends primarily on the amount of refrigerant that is vaporised in the evaporator. By reusing the waste heat from either the condensation or absorption stages, more refrigerant can be desorbed from the solution. One limitation of the single-effect cycle is that it cannot take advantage of the higher exergy (availability) of high-temperature heat sources to achieve a higher COP. The COP is mainly influenced by the ratio of refrigerant to solution absolute temperatures (at the same pressure), i.e. chilled water to condenser water absolute temperatures (see Appendix 4). However, in this case a double-effect cycle can be used.

The easiest way to think of a double-effect cycle is to think of it as two single-effect cycles stacked one on top of the other. The top cycle is driven either directly by a natural gas or oil burner, or indirectly by steam. Heat is added to the generator of the top cycle (primary generator), which generates refrigerant vapour at a relatively higher temperature and pressure. The vapour is then condensed at this higher temperature and pressure, and the heat of condensation is used to drive the generator of the lower cycle (secondary generator), which is at a lower temperature.

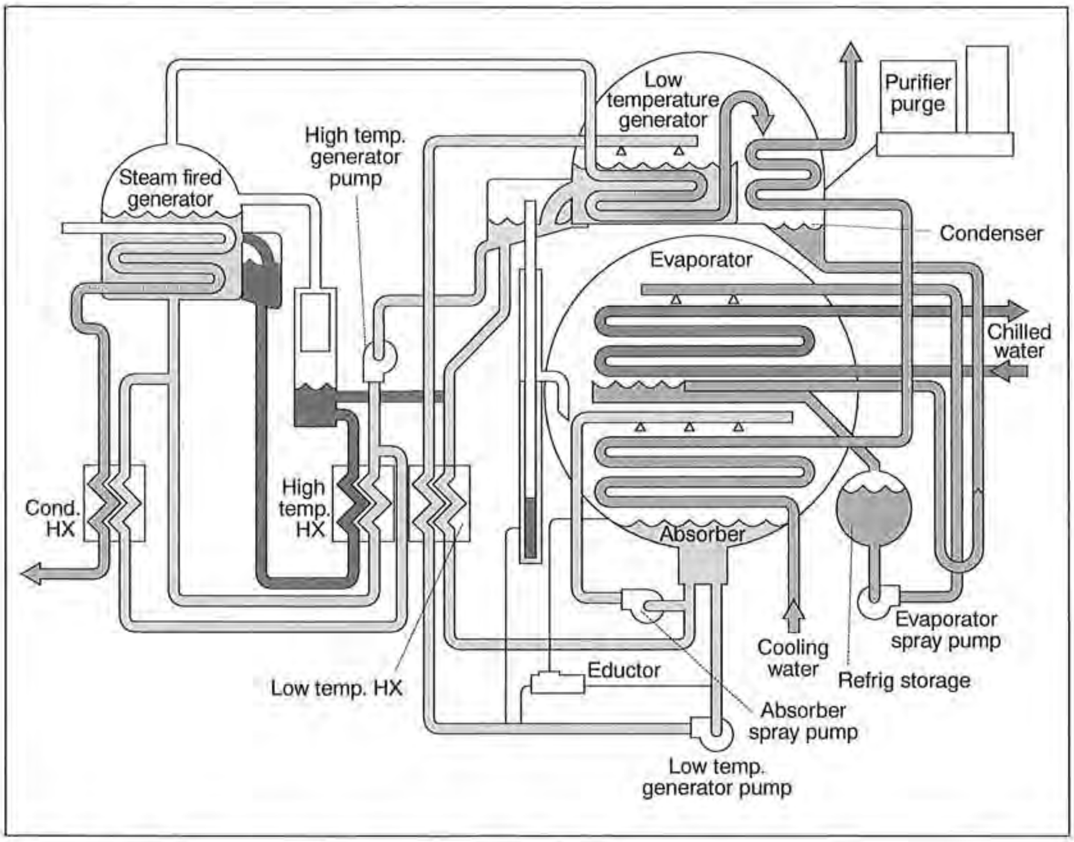


Figure 2.8 Double-effect absorption chiller. (Courtesy Trane)

In the double-effect machine, the generator receives heat of evaporation (r) and heat of solution (l), but only the condenser heat (r) is used for the lower cycle. Although heat is used twice (double-effect), only part can be utilised. The combined effect on *COP*, based on ideal cycle formulation and real cycle single-effect *COP* is:

$$COP = \frac{Q_e}{Q_g} = \frac{r}{r+l} + \left(\frac{r}{r+l}\right)^2 \approx 0.7 + 0.7^2 = 1.2 \tag{2}$$

It should be noted that up to about 10 years ago, all double-effect machines were referred to as double-stage. Older manufacturers' literature still refers to stages, though updates are changing to 'effects'. The reason for the change was the development of designs employing two evaporator temperatures, or heating the generator in two stages. It was more correct to designate these as two-stage, while those where the residual heat of an absorber or condenser is used to drive another lower temperature sub-cycle are referred to as two-effect – or more.

2.1.4 Triple-effect chillers (Type I)

There are also a number of advanced cycles such as half-effect, resorption cycle absorption, power, and triple-effect cycles. These technologies are, however, still in development or at experimental stages. The triple-effect cycle is currently being worked on by several leading absorption equipment manufacturers. A gas-fired cooling COP in the order of 1.5 is expected.

A triple-effect system has considerably more arrangement possibilities. Its *COP* approximates to

$$COP = 0.7 + 0.7^2 + 0.7^3 = 1.55 \tag{3}$$

Basically, it uses the heat three times in the same way as the double-effect cycle.

2.1.5 Multiple-effect chillers.

If the concept of triple-effect cycles is extended to a further number of cycles, the COP equation becomes a geometric series:

$$COP = 0.7 + 0.7^2 + 0.7^3 + \ldots + 0.7^N = 0.7\,\frac{1-0.7^N}{1-0.7} \tag{4}$$

If the number of effects (N) tends to infinity:

$$COP \approx \frac{0.7}{1-0.7} = 2.3 \tag{5}$$

It would therefore be reasonable to assume that the upper limit of the COP for real multiple-effect chillers will be in the range of 2 to 3. In addition, Appendix 4 demonstrates that for ideal cycles, absorption cycles with an infinite number of effects have an equivalent COP to the reverse Carnot cycle of mechanical compression systems.

2.2 Absorption heat pumps, Type I

An absorption heat pump is a device exactly similar to an absorption chiller. The only difference is the naming of the heat flows it operates on. Where a chiller provides cooling, a heat pump takes heat from a low-temperature heat source. Where a chiller reject heat, a heat pump provides heating. In this case heating is the main yield of the system. Although the principles of the chiller and the heat pump are the same, the appliance has to be designed for this application due to the required temperature levels.

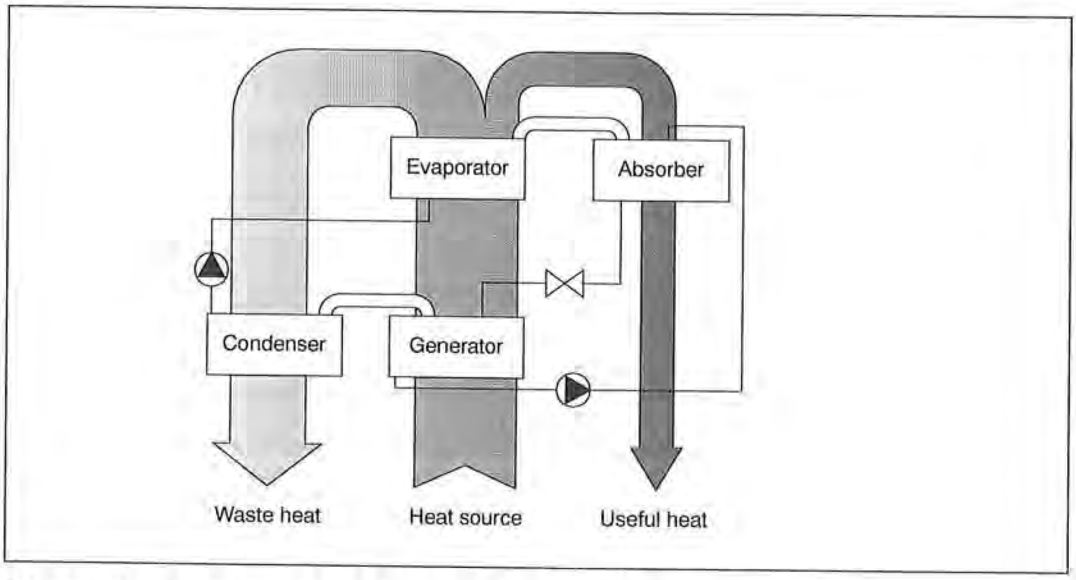


Figure 2.9 *Heat flows in an absorption heat transformer.*

2.2.1 Overview of absorption heat pumps

Table 2.2 gives an indication of the applied sorption heat pumps.

Table 2.2 *Overview of standard absorption heat pump prototypes.*

Working pair	System	Fired by	Heating capacity (kW)	COP
NH_3 / H_2O	Single-effect	Gas	3 – 40	1.4
NH_3 / H_2O	GAX	Gas	250	1.5

2.2.2 The absorption heat pump cycle

In the absorption heat pump cycle, heat is lifted from a low temperature level (T_L) in the evaporator, to a medium temperature level (T_M) in the absorber and condenser. This is achieved by supplying heat at a high temperature level in the desorber or generator (T_H).

There are three main parameters of interest. The COP determines the amount of heat that can be delivered in relation to the heat supplied. Second is the possible temperature lift that can be achieved at the three temperature levels, and third is the maximum possible temperature level at which heat can be delivered. A limiting factor is the risk of crystallisation. The concentration, and therefore the temperature in the desorber, is limited by this risk. Crystallisation can occur when cooling the liquid, as mentioned in Section 2.1, and further discussed in Section 4.3.3 and Appendix 4.

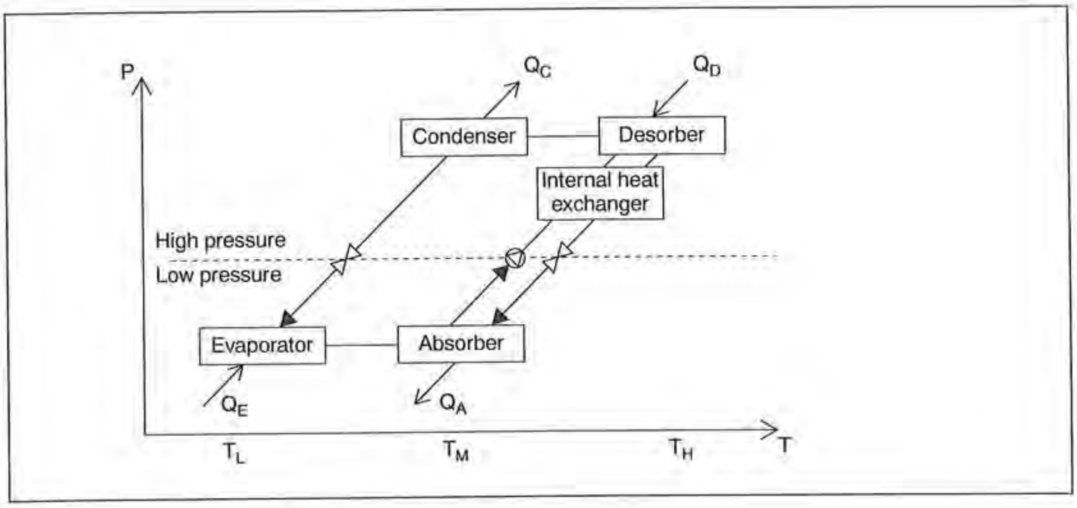


Figure 2.10 *Absorption heat pump cycle.*

In Table 2.3 these parameters are shown for two working fluids: the well-demonstrated water/LiBr and the suggested Alkitrate^{TM}.

Table 2.3 *Working pair parameters.*

Working pair	COP*	Max. temperature lift (°C)	Max. delivery temperature (°C)
H_2O/LiBr	1.6 – 1.7	30	100
Alkitrate ^{TM}	1.6 – 1.7	50	200
NH_3/H_2O	1.5 – 1.6	60	60

* If direct-fired, the COP is about 10% lower because the boiler efficiency is included in the COP

From the table, it is clear that the absorption heat pump with water/LiBr can only be used for heat demands below 100°C, due to the limit of the delivery temperature. This significantly limits the use of the cycle for industrial applications. New cycles and working media have been proposed to solve this problem.

For low-temperature applications in residential and commercial buildings, as well as greenhouses and some industrial sectors, these low temperatures are quite adequate.
Thus absorption heat pumps can be used in that sector, and have already been demonstrated in some cases (see Section 3.4.4). In the short term, smaller-sized systems will be available for single-family houses.

The possible temperature lift is nearly constant over the whole operating temperature range. A rough rule of thumb for the working pair water/LiBr, on the necessary high temperature level and possible temperature lift, is:

$$(T_H - T_M) > 2\,(T_M - T_L) \qquad (6)$$

As discussed in reference [8], the limit for an ideal single-effect sorption heat pump is:

$$T_H \; T_L = T_M^2 \tag{7}$$

The ideal COP [9, 10] is:

$$COP = 1 + \frac{T_L}{T_M} = 1 + \frac{T_M}{T_H} \tag{8}$$

2.3 Absorption heat pump, Type II (heat transformer)

In the heat transformer cycle (see Figure 2.11), heat is supplied at a medium temperature level (T_M) in the evaporator and desorber. One part of this heat is transformed to a high temperature level (T_H) (absorber), and the other discharged at a low temperature (T_L) (condenser).

The heat transformer is useful for recovering industrial waste heat at a medium temperature level, and replacing primary heat.

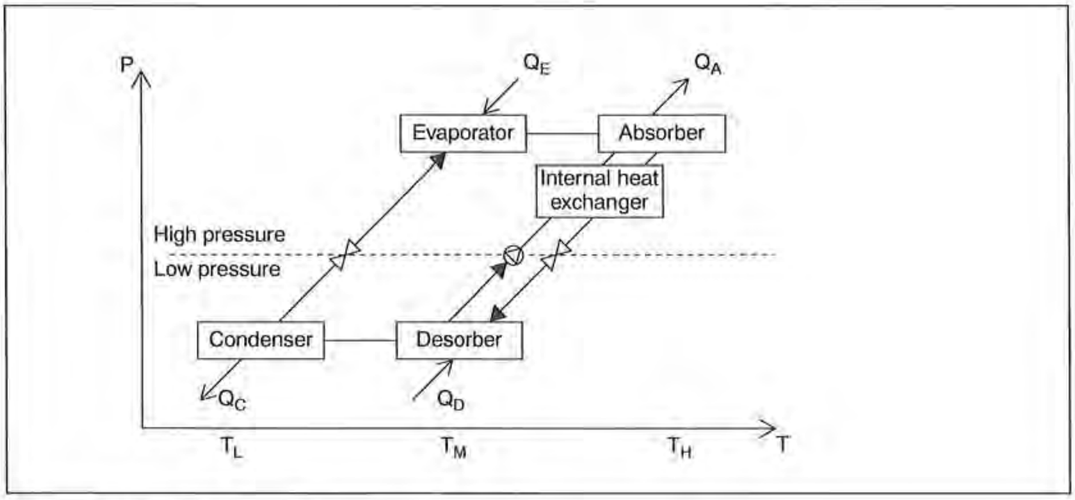


Figure 2.11 *Heat transformer.*

For industrial applications, water/LiBr is the only working pair in use today.

As in the case of the absorption heat pump, there are three parameters of major interest. The COP, which determines the relation between delivered heat at a high temperature and recovered heat at a medium temperature, is typically 0.45 – 0.49. Thus nearly half the waste heat can be transformed to a high and useful temperature level. The maximum operating temperature is 150°C, which implies that low-pressure steam can be produced. The possible temperature lift is determined by:

$$(T_H - T_M) < 0.8 \, (T_M - T_L) \tag{9}$$

Since the low-temperature level is determined by the surrounding ambient conditions, the temperature lift is directly proportional to the medium-temperature level, i.e. the waste heat temperature.

For an ideal single-lift sorption heat transformer, the limit is:

$$T_H T_L = T_M^2 \tag{10}$$

The ideal *COP* results as the reciprocal of the heat pump equation (8)

$$COP = \frac{1}{1 + \frac{T_L}{T_M}} = \frac{1}{1 + \frac{T_M}{T_H}} \tag{11}$$

Heat transformers using the suggested working fluid Alkitrate^{TM} can theoretically operate up to 250°C, with a maximum temperature lift of 70°C. This opens up the possibility of applications in process heating in the medium-temperature range.

2.4 GAX

At a small difference between the temperatures of the condenser and the evaporator, the temperature of the hottest part of the absorber will be higher than the temperature of the coldest part of the generator. This gives the possibility of transporting heat from the absorber to the generator by a **G**enerator **A**bsorber heat e**X**changer. The external power required by the generator will be reduced and so the efficiency of the machine is improved.

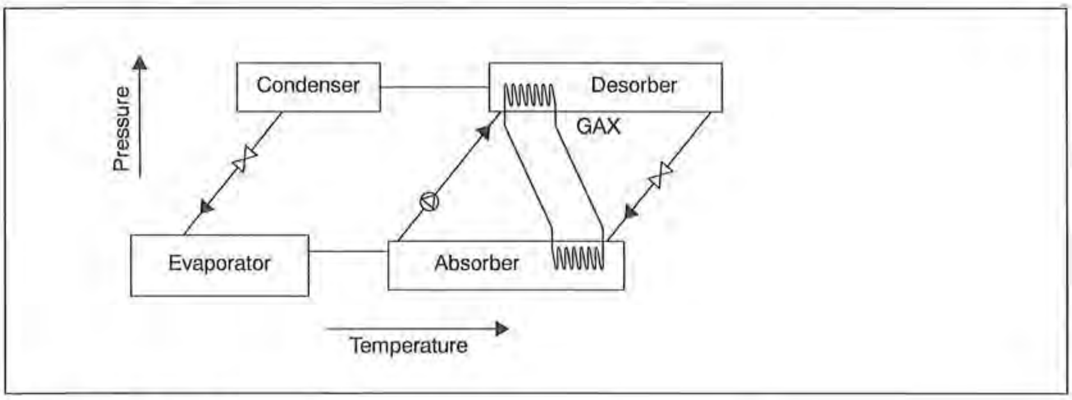


Figure 2.12 *GAX.*

2.5 Combined compression and absorption systems

A compression-absorption heat pump (i.e. compression-resorption heat pump), Figure 2.13, consists of a solution circuit incorporated in a vapour compression heat pump. The advantage of this system is the higher temperature of the heat delivery.

In an absorption-compression heat pump (Figure 2.14) the compressor is incorporated in an absorption heat pump cycle. The compressor is used as a 'temperature booster', bringing high temperature applications within reach by higher pressure in the absorber or lower pressure in the evaporator.

Systems consisting of separate compression and sorption heat pump cycles, which enable energy tariff optimisation, are explicitly not discussed here.

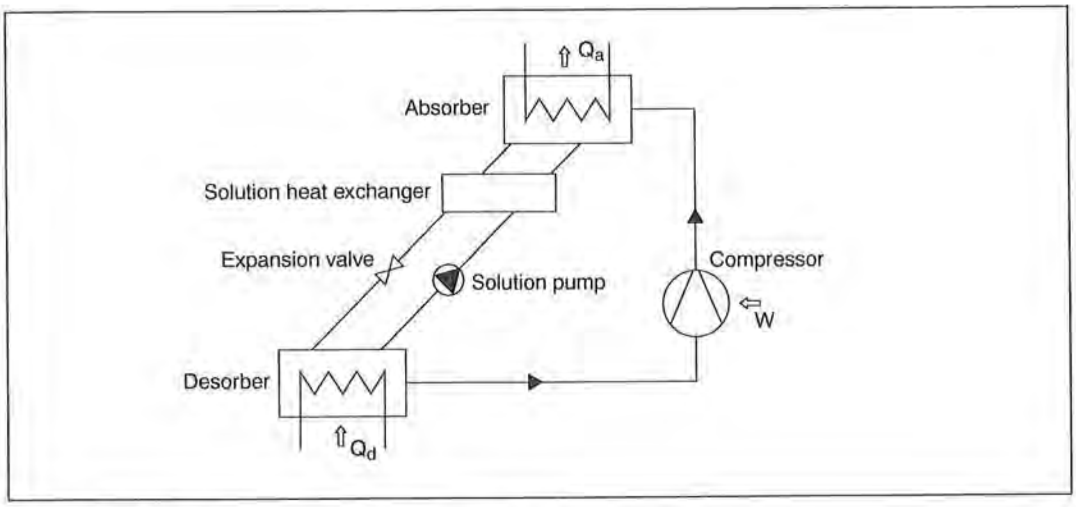


Figure 2.13 *Compression–absorption system.*

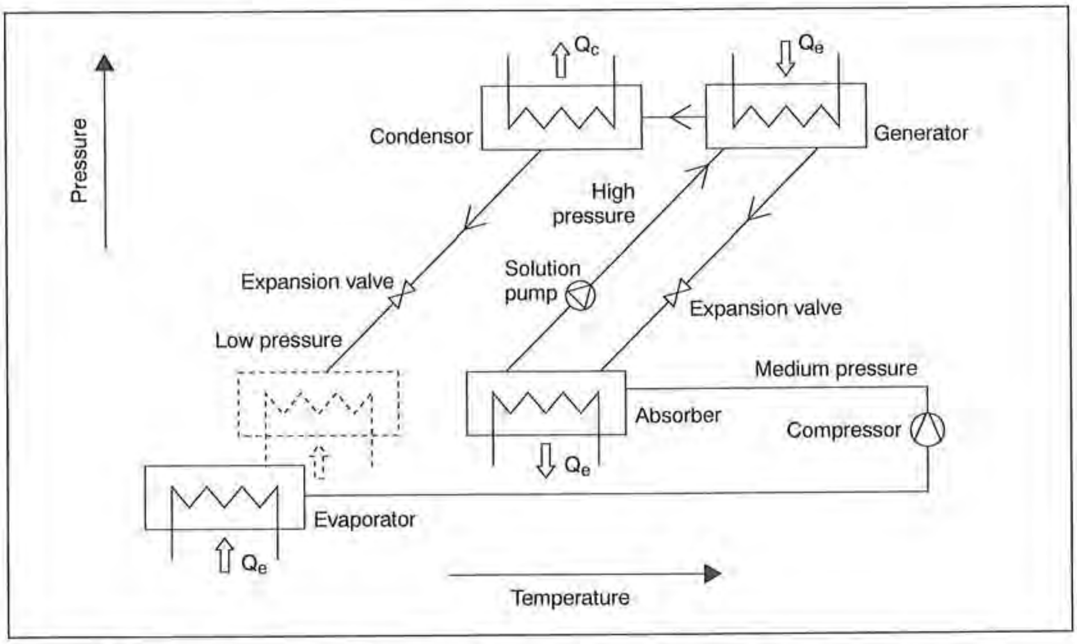


Figure 2.14 *Absorption–compression heat pump with lowered evaporator pressure.*

2.5.1 Compression–absorption

In the compression–absorption system shown in Figure 2.13 above, the evaporation of the working pair solution in the desorber is incomplete. The solution can circulate between the desorber and the absorber with the use of a solution pump. If all of the solution is circulated by the solution pump, the cycle is called the Osenbrück cycle. When all of the solution is circulated through the compressor, avoiding the use of a solution pump, the cycle is called a 'total wet compression cycle'. The total range of variation between these two cycles can be used.

Experimental set-ups for these systems up to now have mainly used the working pair ammonia and water. The presence of a mixture of ammonia and water in the absorber dramatically decreases the saturated vapour pressure compared to pure ammonia at the same temperature. This means high heat sink temperatures can be obtained without excessive compressor loads and high pressure devices.

An additional thermodynamic effect that improves the cycle compared to a vapour compression cycle is the presence of temperature glide in the non-azeotropic mixture of ammonia and water. By varying the circulation ratio between the compressor and the circulation pump, the variation in mixture concentration can be controlled. In this way, the temperature glide of the solution inside the machine can be matched to the temperature glides of the heat sink and heat source fluids. With this, the irreversibilities of exchanging heat can be reduced. In addition, variations in concentration of the working fluid mixture can be used for capacity control [11].

2.5.2 Absorption–compression

In the absorption–compression system, the compressor is incorporated in the absorption process to boost the absorption cycle. In the Figures 2.15, 16, 17 and 18 some examples of the cycles are given.

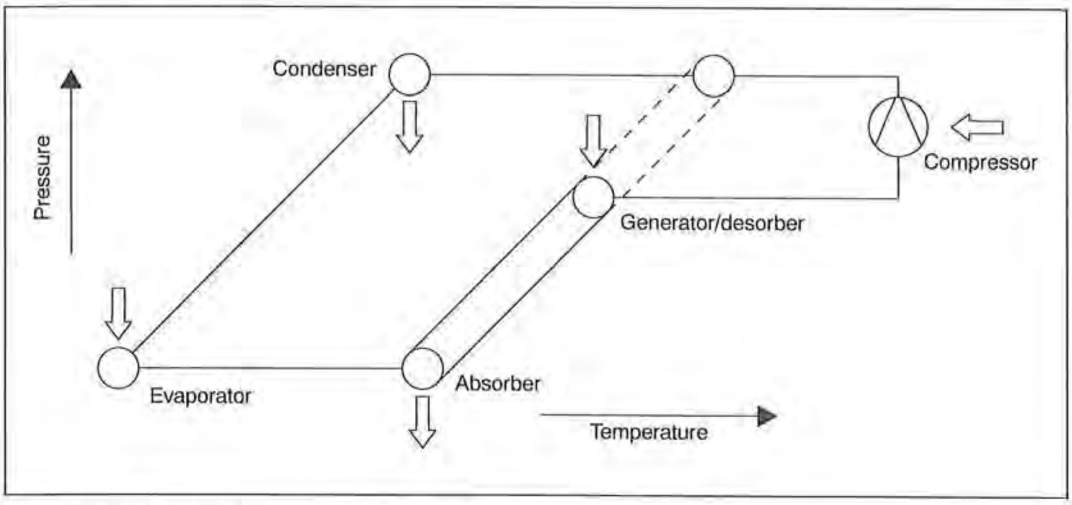


Figure 2.15 Heat pump with boosted condenser pressure.

In the cycle given in Figure 2.15, the compressor is boosting the pressure of the condenser. If the condenser pressure is kept unchanged, the generator pressure and therefore the generator temperature level can be lowered. This will allow the utilisation of waste heat.

In the cycle of Figure 2.16, a compressor is boosting the pressure of the absorber. This has the same effect as lowering the pressure of the evaporator. By lowering the pressure of the evaporator, the temperature of evaporation is lowered. This heat pump can act at lower temperatures of the sink.

In the cycle of Figure 2.17, the compressor is boosting up the pressure of the condenser. This has the same effect as lowering the pressure and the temperature of the generator. At an

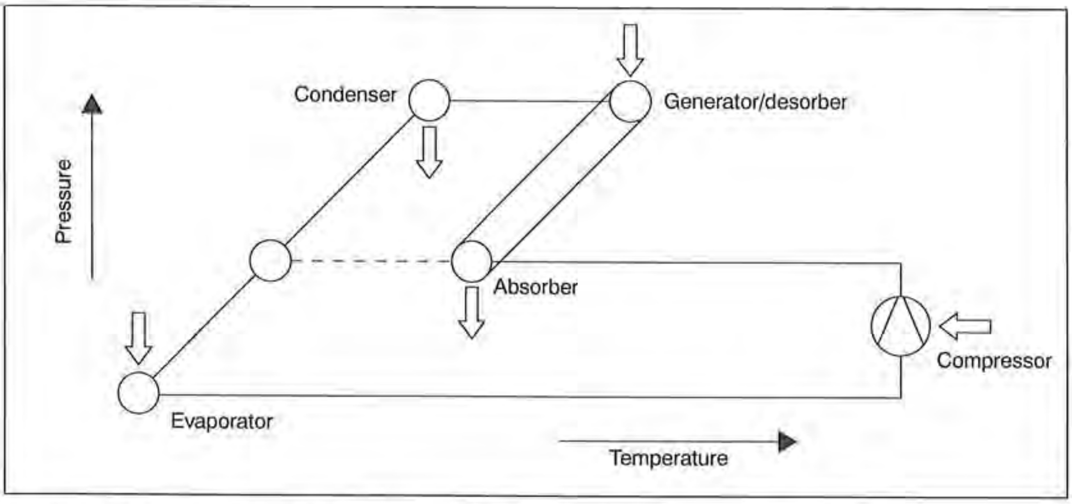


Figure 2.16 *Heat pump with boosted absorber pressure.*

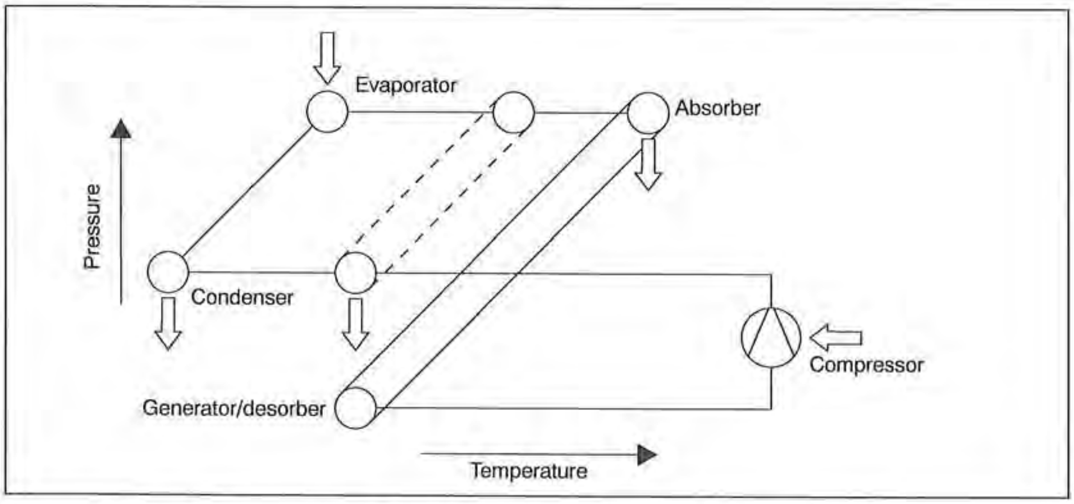


Figure 2.17 *Heat transformer with boosted condenser pressure.*

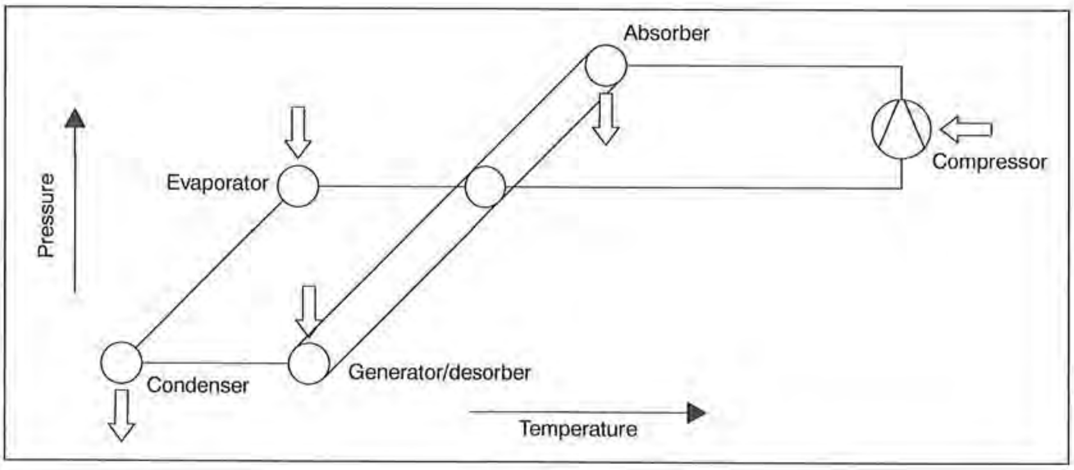


Figure 2.18 *Heat transformer with boosted absorber pressure.*

equal temperature of the generator, the temperature of the absorber will be increased. This gives a higher temperature of the heat produced by the absorber.

In Figure 2.18, a compressor is boosting the pressure of the absorber. This gives a higher temperature of the absorber, but also a lower temperature of the evaporator, the generator and the condenser.

The systems outlined above show how a system can be tailored to the required temperatures of the absorption system and the available temperatures of the process.

2.6 Solid sorption systems

Instead of absorption of refrigerant in an absorbing solution, it is also possible to *ad*sorb refrigerant into a solid. Sorption to a solid is called *ad*sorption. Typical examples of working pairs are water/silica gel, water/zeolite, ammonia/activated carbon, methanol/activated carbon etc. In absorption machines the ability to circulate the absorbing fluid between absorber and desorber results into a continuous loop. In *ad*sorption machines the solid sorber has to be alternately cooled and heated to be able to *ad*sorb and desorb. The loop is therefore by nature cyclic with time.

To create a more uniform cooling effect, two or more cycles can be connected to each other. This way there is always a sorber available to *ad*sorb the vapour of the evaporator. Another advantage is the following:

Each cycle's loop energy is needed to heat the sorber to a level where the refrigerant is released from the sorber. This energy does not contribute to the cooling effect of the *ad*sorption machine. Using multiple sorbers makes it possible for the different sorbers to exchange heat with one another, reducing the auxiliary energy needed to heat the sorbers, and improving the efficiency of the complete cycle. Much research has been put into optimising this principle.

2.7 Desiccant systems

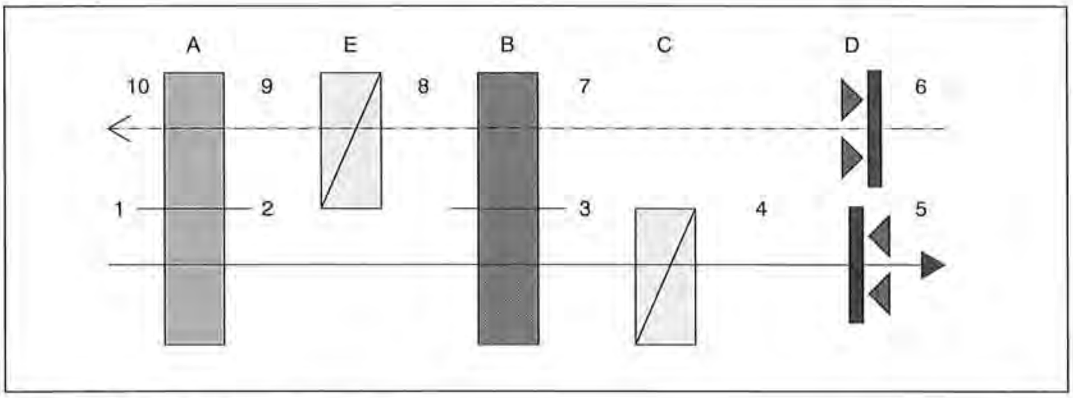


Figure 2.19 *Desiccant system.*

All sorption systems described above are closed cycles. Contrary to this, desiccant systems are open cycles. Hot humid air passes a sorber, which extracts humidity directly from the air (see Figure 2.19, Section A 1 – 2). Because of this, the temperature of the air flow rises. After cooling the air flow down to the exhaust air temperature (Section B 2 – 3) water is sprayed into the air flow (Section D 4 – 5). Evaporation of the water causes the air temperature to drop, thus creating a cooling effect. After the sorption process, the sorber is regenerated by heating the desiccant, e.g. by hot air, steam or flue gases (Section E 8 – 9). This cycle is called Desiccative Evaporative Cooling (DEC)

2.8 Overview of sorption systems

The table below gives a summary of the properties of the most widely used sorption systems.

Table 2.4 *Properties of the most widely applied sorption systems.*

	Absorption heat pump	**Absorption chiller**	**Absorption heat transformer**
Temperature ranges and COP (cooling)	**Water/LiBr** *Heating*: < 40°C *Driving*: 70 – 130°C *Source*: > 5°C *COP*: 1.7	**Water/LiBr** *Chilling*: > 5°C *Driving*: 70 – 130°C *Rejecting*: 20 – 40°C *COP*: Single 0.7 Double 1.2	**Water/LiBr** *Rejection*: 20 – 40°C *Heating*: < 130°C *Driving*: 60 – 100°C *COP*: 0.45
	NH_3/water *Heating*: < 60°C *Driving*: 80 – 200°C *Source*: –15 to +5°C *COP*: 1.5	**NH_3/water** *Chilling*: -60 – +10°C *Driving*: 80 – 200°C *Rejecting*: 20 – 50°C *COP* $\leq$ 0.6	
Advantages	Practically no moving parts	Practically no moving parts	Practically no moving parts
	Simple construction	Simple construction	Simple construction
	Good partial load behaviour if solution management system is provided	Good partial load behaviour if solution management system is provided	Good partial load behaviour if solution management system is provided
	Low noise	Low noise	Low noise
Disadvantages	Slow starting	Slow starting	Slow starting
	Corrosion at higher temperatures	Corrosion at higher temperatures	Corrosion at higher temperatures

Compression – absorption heat pump	**Adsorption heat pump / chiller**	**Desiccant evaporative cooling system**
NH_3/water *Source*: 20 – 50°C *Driving*: electric *Heating*: 80 – 120°C	**Water/silica gel** *Chilling*: > 5°C *Heating*: < 35°C *Driving*: 60 – 80°C *COP*: *single*: 0.4 – 0.6 **Water/Zeolite** *chilling*: > 5°C *heating*: < 40°C *driving*: 70 – 130°C COP *single*: 0.5 – 0.6	**Air/desiccant** *Chilling*: > 18°C *Heat rejection*: < 30°C *Driving*: 50 – 70°C *COP*: 0.6 – 1.0
High temperature lift Cycle efficiency	No moving parts Low driving temperatures Low noise	Easy regulation of temperature and humidity
Still demonstration	Batch process Exchange of heat between sorption packages Cyclic intermittent nature, operates with variable temperatures	Chilled air limited to 18°C Ventilation system has to be well balanced

3. Market Segmentation

The choice of heating or cooling systems in different market segments depends on several considerations. Climatic conditions, the energy grid and the availability of competing technologies are important and in some cases dominant factors.

Sorption technology can be applied in a wide range of applications for refrigeration, cooling, heating and dehumidification in industry. Economic considerations in comparison to competing technologies, and the availability of technology are the major factors in these market segments.

Within this chapter, the various market segments will be discussed.

3.1 Residential

In the residential sector, the type of internal climate control is dependent on the external climatic conditions. In large parts of the USA, Japan, and southern Europe a need for comfort cooling dominates the market, while in other regions colder conditions dictate a need for heating.

Another important factor that has been reported is the distribution system for heat and cold, as well as the temperature in the system. In large parts of northern Europe, hydronic systems are predominant. These water distribution systems work with temperatures typically around 50 – 80°C. An increasing trend to lower temperature (30 – 50°C) for mainly under-floor heating systems is penetrating the market for newly-built houses.

In the USA and Japan, where comfort cooling has penetrated a larger part of the market, air distribution systems are mostly used. In these areas, cooling equipment is generally powered by electricity. During the oil crisis of 1973-74, great effort was made by the Japanese government and industry to develop efficient absorption chillers. This has led to markets in the neighbouring countries, as discussed in Section 3.2 below.

The following Tables present an overview of the typical heating and cooling demand in residential and commercial/institutional buildings. The status of the building stock, and its average heating and cooling demand requirements is presented in Table 3.1. The evolution of the building stock in the participating Annex 24 countries can also be inferred. The comparison is made for the years 1991 and 1996. The total number of buildings shown includes single and multi-family houses as well as commercial/institutional buildings. The evolution of the building stock in the participating Annex 24 countries can also be inferred. As indicated by Table 3.1, the construction rate of new buildings was in the order of 1–2% in most countries. It is usually greater in the residential sector. These figures may also give an indication of the market for sorption heat pumping systems. Table 3.2 shows the heating demands (including hot water) and cooling demands for existing and new buildings in the residential sectors, in megawatts/year.

Table 3.1 *Building stock.*[1]

Country	Population (million people)	Total building Stock (1996)	Total building stock (1991)	Average new buildings/year 1991-1996
USA	263.06	101,000,000	91,200,000	1,960,000
UK	58.61	26,801,000	22,700,000	820,200
Japan	125.57	43,480,000	38,900,000	916,000
Sweden[2]	8.84	4,043,000	4,040,000	13,000
Netherlands	15.45	6,217,000	5,710,000	101,400
Norway	4.36	1,550,000	1,450,000	20,000
Italy[3]	57.27	25,400,000	24,800,000	120,000
Canada	29.61	10,586,000	10,200,000	77,600

Table 3.2 *Heating and cooling demands.*

Country	Single family houses Heating		Multi-family houses Heating		Single family houses Cooling		Multi-family houses Cooling	
	New	Existing	New	Existing	New	Existing	New	Existing
USA	20.4	23.8	9.8	14.7	2.93	2.90	1.055	1.553
UK	17.7	21.5	9	12	-	-	-	-
Japan	7.4	7.4	7.4	7.4	0.4	0.4	0.4	0.4
Sweden[3]	0.13	0.15	0.12	0.19	-	-	-	-
Netherlands	8.7	20.8	6.7	12.1	-	-	-	-
Norway [1, 3]	0.1	0.14	0.1	0.14	-	-	-	-
Italy[4]	6	-	36	-	4	-	24	-
Canada	29	34.6	-	24.7	0.19	0.185	-	0.118

Notes to Tables 3.1 and 3.2:

1. The total number of buildings includes single- and multi-family houses as well as commercial/institutional buildings.
2. Only residential sector.
3. Multi-family houses pertaining to number of buildings rather than number of households.
4. Demands of multi-family houses pertaining to entire buildings rather than individual households.

The possibilities for sorption technologies in these market segments depend on existing market boundary conditions, and the traditional and new technologies dominant in the market. Section 4.1 describes the economic, environmental and policy influences on the sorption market.

Technologies used and/or available in the residential sector to cover the demand for heating and cooling are:

- Gas boilers;
- High-efficiency gas boilers;

- Electric-driven compression heat pumps;
- Oil-fired boilers;
- District heating;
- Electric resistance heating;
- Solar energy;
- Small gas-fired CHP;
- Ammonia/water heat pumps; and
- Diffusion absorption heat pumps.

In Europe, especially, there is a noticeable trend towards new houses with low-temperature, low-energy demands and a small capacity for space heating. The demand for capacity for water heating is nominally larger (10 – 15 kW) than the base load for space heating (1 – 4 kW). Due to legislation dealing with the minimum temperatures for water heating, this market is extremely difficult for 'conventional' heat pumps. Sorption systems may be able to satisfy this demand.

3.1.1 Residential sorption hardware

Single-effect direct-fired absorption technology uses ammonia as the refrigerant and water as the absorbent. The air-cooled absorption chiller can operate at gas-fired cooling COPs of 0.60. They are available in 11, 14.5 and 18 kW models. The temperature for chilled water leaving the evaporator is typically 7°C.

In Japan, a 5 kW residential double-effect LiBr absorption air conditioner is on the market.

In the Netherlands and in Germany, a 3 kW residential space heating diffusion absorption heat pump is being demonstrated.

3.2 Commercial/institutional

The commercial market includes buildings such as hotels, office buildings, warehouses, supermarkets, retail outlets, quick-service restaurants, institutions such as hospitals, nursing homes, and schools, as well as factories and other industrial facilities. Table 3.1 presented the total building stock in the various Annex 24 member countries including the commercial market.

It should be noted that 85% of the 8,600 absorption chillers over 350 kW (100 TR) are installed in the Far East [12]. An estimated 30% are installed in Japan, 35% in China, and 20% in Korea. In that region, absorption systems have mainly been used as large centralised air-conditioning systems, district heating and cooling systems, and co-generation systems. Absorption chillers are dominant in the Korean market compared to their compressor-driven alternatives. A large part of the Korean market is catered for by direct gas-fired chillers, with capacities up to 1,050 kW (300 TR). Absorption chillers in China have been popular since the 1970s. Steam-powered single-effect and double-effect chillers have been supplied by local producers. Products have been available in China mainly from Japan. Direct-fired chillers are becoming popular, but are held back by the limited gas piping networks in China. A traditional shortage of electric power generation has in the past placed emphasis on strict limitation of electricity use for such purposes as air conditioning. This has been to the advantage for steam-driven absorption chillers, or those directly fired by oil or gas. There are markets in Taiwan, Hong Kong, Malaysia, Thailand, Singapore, Indonesia, and the Philippines. Taiwan's market has expanded quite well, due to the fact that a high chiller demand has been created by the expansion of semiconductor and personal computer production. In the Middle East, there is a potential for direct-fired units in such countries as Iran, which also lacks electricity infrastructure.

Technologies used and/or available to satisfy the demand are:
Heating:
- Gas boilers;
- High-efficiency condensing boilers;
- Electric-driven compression heat pumps;
- CHP;
- District heating; and
- Solar energy.

Cooling:
- Compression cooling;
- Natural cooling and venting;
- Desiccant cooling; and
- Ground-water cooling.

3.2.1 Commercial/institutional sorption hardware

Single-effect heat-driven absorption chillers are typically driven with hot water or low-pressure steam. Several manufacturers have chillers with refrigeration capacities of 350 kW (100 TR) to 5,000 kW (1,500 TR). Chillers with smaller or larger capacities are available. Typical COPs for large single-effect chillers are 0.7.

Double-effect heat-driven absorption chillers typically use medium-pressure steam at around 8 bar gauge, or hot water at around 170°C. Typical operating COPs are 1.1 to 1.2. Their capacities range from 350 to 6,000 kW of refrigeration. In such applications, the temperature for chilled water leaving the evaporator is generally between 5°C and 15°C.

Double-effect direct-fired absorption chillers are typically fired with natural gas or fuel oil, and many have dual-fuel capability. Typical full-load COPs are about 1.0. Their capacities range from 70 to 9,000 kW of refrigeration. These systems are also available as chiller/heaters (boiler mode, not heat pump), which can provide separate or simultaneous cooling, heating and/or hot water.

The minimum and maximum limits of capacity are established by design considerations for pump lubrication (which are somewhat flexible) and the refrigerant freezing point (0°C). Evaporator approach temperature, solution concentration and safety limitations also influence the chilled water temperature leaving the evaporator. Though it might be advantageous to install these chillers outdoors to minimise the building space required, they are seldom installed outdoors in practice. This decision is influenced by the freezing point of the refrigerant. If the chiller is installed outdoors, the installer must provide a means to prevent the temperature of the ambient air immediately surrounding the chiller from falling below the freezing point.

Desiccant systems are normally heat-driven systems that control humidity levels directly, enabling users to separate humidity control from temperature control. These systems are ideally suited for sites requiring low humidity levels, or those with high dehumidification loads, such as supermarkets, health spas, hotels, offices, hospitals and medical facilities. They also provide precise control of humidity where it is essential to the manufacturing process. By incorporating a desiccant dehumidification system with a conventional electricity supply system, the cooling equipment can operate more efficiently, and the system's air-handling equipment can be downsized. The overall effect is to reduce the electric power consumption, typically at peak rates, while incurring only a limited first-cost premium for the sorption system. It should be said that desiccant systems have not been considered in depth within the context of Annex 24.

Combination-fuel plants can easily be justified if electricity demand and peak load charges are high. In such installations, the absorption chiller operates during peak periods to avoid the high cost of electricity, while the electric-driven chiller runs during off-peak periods (when electricity costs are low) to take advantage of its higher thermal efficiency. Absorption chillers can also be operated as base load units, running in conjunction with electric systems as peak-load chillers, or they can be hooked up to co-generation systems utilising steam as the driving heat source to run the chiller. Several models include heat recovery options, reusing heat and improving efficiency.

3.3 Industrial

Industry accounts on average for 20 – 50% of the total energy consumption in the participating countries. As a result, technologies such as heat pumps in general, and sorption systems using waste heat for cooling in particular, would have great potential for saving primary energy (fossil fuel) and reducing the environmental impact.

When one talks about industrial heat pumps and chillers, we should be referring to refrigeration machines that satisfy two basic criteria [13, 14, 15, 16]:

- The heat pump/chiller should be large enough to be 'of industrial economy of scale' and the heating/cooling output is normally in the range 100 kW up to 10 MW; and
- The heat pump/chiller system should involve an industrial process stream, either as heat source (cooling) or heat sink (heating), or both (heating and cooling simultaneously).

In comparison to non-industrial heat pumps and chillers that are normally of a heating or cooling output below 100 kW, units installed in industrial systems may satisfy the following criteria:

- Long annual operating hours;
- High COPs due to relatively small temperature lifts and/or high temperature levels;
- Waste heat production and heat demand usually occur at the same time (but not always); and
- Relatively low investment costs per kilowatt of installed heating or cooling capacity, due to large units and short distances between heat source and heat sink.

The industrial sector usually has rather strict financial criteria for any investment. For cooling, there are few alternatives, since cooling can only be obtained using a heat pumping cycle. Sorption chillers could be competitive with electrically-driven compression systems, especially if waste heat can be used. As for heat pumps which could provide heating, there are more possible alternatives, including boilers with much lower first costs. Heat pumps, therefore, have to attract the decision-maker by low payback periods, usually of less than five years, in order to be chosen. The relatively high capital costs of sorption systems may be an obstacle in many cases, unless their energy-saving potential is sufficiently high. If the sorption system can fulfil more than one function at a time, such as heating, cooling and heat/cold storage within the same industrial unit, it will become more attractive.

The environmental benefits of utilising waste heat from industrial processes are a major advantage, and are seen as a stronger attraction when fossil fuel emissions have to be considered.

Sorption systems can cover a wide range of temperatures, and thus cater for a large part of the demand for heating and cooling in industry. Heat pumps or chillers of the absorption type can typically provide a combination of cooling and heating at the same time. An important consideration is that the installation of heat pumps in industry should always be done after thorough design, in which the heat pump is integrated into the process with proper tools for process-integration by exergy- and pinch-analyses [17].

Industrial processes discarding waste heat at temperatures suitable for either absorption chillers or absorption heat transformers are of particular interest. Chemical plants, petroleum refineries and pulp and paper mills have possibilities of producing waste heat, and cooling/heating demands in the right temperature region to make use of it, e.g. distillation processes for absorption heat transformers (AHTs). In addition, the pulp and paper and food industries are interesting for the high-temperature approach of the compression/absorption heat pump. Excess heat from industries such as metallurgical could also be used for residential/commercial cooling in surrounding areas. So far, sorption machines for cooling purposes have been the dominant ones.

Two typical cases for heat pump applications are:
- *Low-temperature applications (manufacturing industry)*
  Heat source: +20 to +60°C
  Heat sink +60 to +100°C
- *High-temperature applications (process industry)*
  Heat source +50 to +110°C
  Heat sink +120 to +140°C

For absorption heat pumps, a higher temperature heat source is required to drive the cycle.

Typical temperature ranges for cooling applications are given in the sections following.

In this section the focus has been on the demands for heating and cooling in industrial processes. Comfort cooling and heating of rooms outside the production area have not been considered, but possibilities obviously exist. The work performed in the IEA Heat Pump Programme's Annex 21: "Industrial Heat Pumps" [18] considers only the heating role of the heat pump systems.

Technically, the industry is segmented by temperature demand levels, and may be described by the industries which are served at each level. The production procedures and product spectrum differ slightly from one country to another, but are here generalised for simplification. Detailed information on individual countries can be found in the IEA Heat Pump Centre Report "International Heat Pump Status and Policy Review" [19].

3.3.1 Refrigeration

The temperature demand might be rather low (cryogenic), for example < –40°C in the gas processing industry when dealing with the condensation of light hydrocarbon components. Such processes are continuous, and mostly use cascade refrigeration systems. The cooling demands are rather large for each plant, typically amounting to several megawatts.

The dominant application for refrigeration is food preservation, typically at temperatures of –40°C to 0°C. Typical food industry sectors are meat, fish and ice cream. It is common to use central refrigeration systems, with the possibility of part-load operation. Freezing tunnels are often used to rapidly lower the temperature of the product, while storage rooms keep the product at an appropriate temperature to avoid bacterial degradation. Refrigeration systems have to operate 24 hours a day as long as there are products to be preserved. The size varies widely from one plant to another, from a few kilowatts up to several megawatts.

State-of-the-art technologies used for refrigeration are electric- or engine-driven compression machines using ammonia as the refrigerant.

3.3.2 Food-storage cooling

Agricultural products which should remain unfrozen but at low temperature to reduce bacterial activity are kept at temperatures between 0°C and +10°C. If there is a simultaneous demand for freezing and cooling, a central refrigeration system is often used to provide the appropriate temperatures. Typical food industry sectors are meat, fish, dairy, eggs, fruit and vegetables, and flowers. The cooling demand is usually continuous, and varies from a few kilowatts in one plant up to several megawatts in another.

State-of-the-art technologies used for cooling are again electric- or engine-driven compression machines with ammonia as the refrigerant. Other working fluids, such as HCFC22 and HFC134a are also used.

3.3.3 Process cooling

Process cooling here includes all industrial processes which have a demand for cooling in order to obtain the desired product. The temperature level may vary from far below 0°C up to more than 100°C, depending on the type of industrial process. In order to apply a heat pump/chiller correctly, knowledge of pinch-point technology is required [17]. Where the hot stream and cold stream do not overlap, external cooling and heating are required. Where the streams overlap, heat exchangers between the streams should be used. Below the pinch-point temperature, where the streams do not overlap, there is a net demand for cooling, while above the pinch-point, where the streams do not overlap, there is a net demand for heating. Therefore, the heat pumping process should be implemented with heat extraction from below the pinch-point and heat release above the pinch-point.

Typical cooling temperatures and cooling demand for some important industry sectors are:

• Food:	+2 to +60°C	A few kW up to several MW
• Chemical:	+10 to +60°C	Hundreds of kW up to several MW
• Pulp and paper:	+30 to +60°C	Hundreds of kW up to several MW
• Petroleum Refineries	+75 to +130°C	Several MW

State-of-the-art technologies used for cooling are:

- Air coolers, if temperatures for cooling are needed at a level higher than the outside ambient temperature;
- Water coolers, if temperatures for cooling are needed at a level higher than the source, groundwater at +10°C or river water at +25 to +30°C (max);
- Electric- or engine-driven compression machines with ammonia as refrigerant. Other media, like HCFC 22 and HFC 134a, are also used as refrigerant; and
- Heat pumps, if the heat extracted by cooling can be used above the pinch [17].

3.3.4 Hot water for washing/cleaning

Many industrial sectors have a high demand for hot water, which is consumed in washing operations within the factory. Maintaining proper hygiene is the main reason for the amount of heated water used. The food industry dominates this demand. Hot water is required at various temperatures, depending on what it is used for. Legislation on temperature requirements varies from one country to another. Especially in some European countries, minimum temperature requirements are in force, to avoid the risk of Legionnaire's Disease.

Typical temperature requirements are:

• Hand-washing:	+45 to +60°C
• Normal equipment cleaning:	+55 to +70°C
• Sterilisation:	+80 to +90°C

When the industrial process is properly designed, heat recovery through direct heat exchanging can be performed in a cost-effective way. The recovery of condenser heat from cooling operations at lower temperatures is also relevant. Accumulation tanks are common, since washing operations are mainly concentrated around periods when there is little or no production.

Typical state-of-the-art technologies used for heating are (if direct heat recovery is not used):

- Gas/fuel boilers
- Electric- or engine-driven heat pumps for moderate temperatures;
- High-efficiency gas condensing boilers;
- CHP; and
- In some industrial sectors, solar energy.

Low-pressure steam (3-12 bar) is widely used for low-temperature heat demands if steam is available for process heating. This gives 'easy and cheap' heat at high exergetic losses.

3.3.5 Process heating at low temperature (< 90°C)

Food industry processes are common in this temperature range. In IEA Annex 21 [18] it was found that 40% of the reported cases had temperature demands between 60°C and 80°C, and 60% below 80°C. The pulp and paper industry has heating demands for evaporation and drying which are partly in this temperature range. The textile industry has heating demands for drying partly in the range.

The following list shows some processes with typical temperature demands below 90°C. Temperatures vary from one plant to another.

- Evaporation processes (food): +50 to +90°C
- Pasteurisation: +72 (+95°C for high-temp. pasteurisation)
- Drying processes (food): +50 to +90°C
- Drying processes (pulp + paper): +50 to +90°C (could be up to +120°C)
- Drying processes (wood): +70 to +90°C

Evaporation and drying processes are highly energy-consuming, with demands varying from a few hundred kilowatts up to several megawatts.

Typical state-of-the-art technologies are:
- Electric- or engine-driven compression heat pumps for moderate temperatures;
- Gas- or oil-fired boilers; and
- Mechanical vapour recompression (MVR) systems for evaporation processes.

Hot water or low-pressure steam are usually used as heat carriers.

3.3.6 Process heating at medium temperature (+90 to +130°C)

Typical processes are at chemical plants, petroleum refineries, pulp and paper mills and some textile mills. In some cases the food industry is represented, such as for boiling and autoclaving processes. Evaporation and drying processes described above for the low-temperature region are also often in the medium-temperature range.

The following processes are special:
- Drying (textiles): +90 to +120°C
- Dyeing (textiles): +90 to +100°C
- Steaming (textiles): +100 to +130°C
- Distillation (chemical and refineries): +90 to +130°C

Typical state-of-the-art technologies are:
- Gas- and oil-fired boilers; and
- Mechanical vapour recompression (MVR) systems for distillation processes.

Hot water or low- and medium-pressure steam are usually used as heat carriers.

3.3.7 Process heating at high temperature (> 130°C)

Typical processes are found in chemical plants, petroleum refineries and in some cases also in pulp and paper mills. It is particularly the heating demand for boilers in distillation processes which are included in this category. In some food industry sectors, drying up to +200°C occurs. Heating demand catered for by furnaces is not considered here, since it does not have any applicability to heat pumping technologies due to the very high temperatures involved (several hundred degrees Celsius). The waste heat could, however, be of interest to run absorption chillers, if a suitable cooling demand has to be met.

Typical state-of-the-art technologies are:
- Gas- and oil-fired boilers

Low- and medium-pressure steam are usually used as heat carriers.

From the above, it can be seen that there is potential for using absorption machines in industry. They offer the possibility of using recovered waste heat, and simultaneous heating and cooling, and therefore opportunities for important environmental benefits.

3.4 Others

This section includes applications of sorption technology that have good potential for energy savings, and reduction of negative environmental impact, but that are normally not considered under industrial or commercial applications. The different technologies are first briefly described, then demonstrated by a particular application or with reference to other installations or sources of information.

3.4.1 Flue gas cleaning and heat recovery

Absorption heat pumps can use waste heat from flue gas condensation in incineration plants for solid wastes and fossil-fuel-fired combustion plants. Condensation has in many applications proved to be an efficient way of cleaning flue gases (e.g. to remove Hg, HF, heavy metals and HCl) and at the same time provide waste heat (of approximately 45 – 55°C) that can be used by absorption heat pumps. Using a heat pump, low-temperature heat is converted into high-temperature heat, which can be used directly, for example in a district heating plant. The driving energy for an absorption heat pump is steam or hot water that can be obtained from the incineration plant or from electric power generation. The market pull for this type of application has normally been emission requirements and taxes on fossil-fuel combustion processes, together with tax refunds for SO_2 removal from flue gases.

A good example of this type of application is the waste incineration heating plant at Graab in Gothenburg, Sweden. The flue gases drive the AHP, and use the cooling water for condensing the flue gases as the low-temperature heat source. The heat output from the AHP is used for district heating, as described more fully in Appendix 6, Case Study No 7.

3.4.2 Co-generation applications

Co-generation means the simultaneous production of electricity and heat. A cogeneration plant consists of the following main components:

- Engine (gas engine or gas turbine);
- Alternator;
- Heat recovery system;
- Electric equipment; and
- Hydraulic interconnection (to the end user).

The primary energy – in most cases natural gas, but alternatives include biogases, sewage gas, landfill gas, coke gas, LPG and gases from the chemical industry – is transformed by the engine into mechanical and thermal energy. The alternator, which is connected to the engine, produces electricity which is used by the operator or sold to the electric utility. Efficiency of electricity production can reach 40% or more. Although co-generation plants are available which achieve total efficiencies of up to 90%, special care should be given to the quality of the total energy produced, i.e. to the exergy efficiency.

Combined cooling, heating and power production

Co-generation systems are not limited to production of heat (steam or hot water) and power (CHP). Many systems have also been developed that deliver chilled water for space-conditioning. Lower-temperature (ammonia/water) systems are also used for process refrigeration. Typically, the co-generation system uses either an absorption chiller or a desiccant to provide space cooling. Cooling can be an important output for co-generation systems serving building applications, as heat recovery could otherwise be limited to the heating season.

For buildings, and industries requiring cold water for air conditioning, co-generation heat can be used to drive absorption chillers. These combined cooling, heating and power (CCHP) production systems are an optimal way to compensate for the differences in thermal demand between winter and summer. Absorption chillers are available from 70 to 5,000 kW refrigeration output per unit. Most of the chillers are used for air-conditioning (above 5°C), and operate with water/LiBr. If temperatures below about 5°C are required, chillers based on ammonia/water are available. These chillers allow cooling temperatures of down to –60°C, which are often required in the chemical industry. Absorption chillers can be operated without considerable losses at 20% of their nominal output, providing they are designed for this purpose.

Cooling system cogeneration designs are most often:

- Gas engine with a single-effect hot-water-driven absorption chiller;
- Gas turbine with a double-effect steam-driven absorption chiller.

An example of a CCHP installation is shown in Figure 3.1.

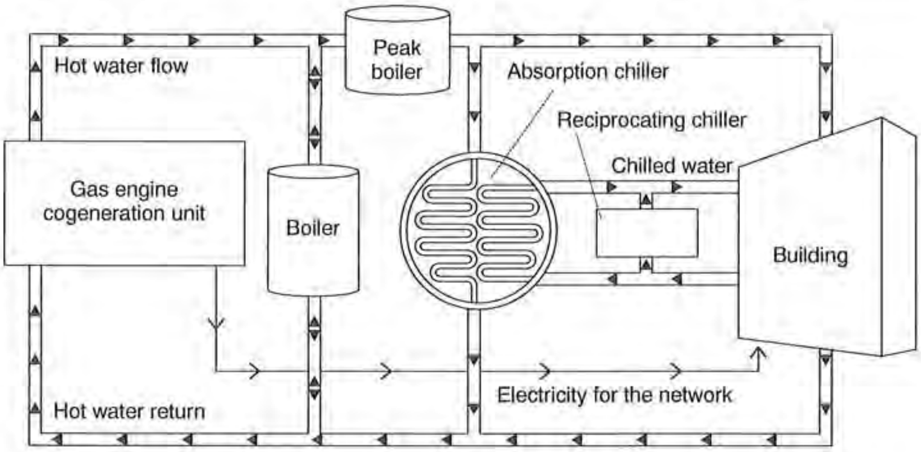


Figure 3.1 *Example of CCHP installation. (Courtesy Jenbacher 2000)*

If an absorption chiller is being considered as an addition to a co-generation installation, it is important to perform an independent analysis of the economics, compared to mechanical compression chillers. This analysis is necessary to determine the proper value for recovered heat. While an absorption chiller can be an effective component of a co-generation system, it is essential that the value of the heat used in that chiller is properly determined. There are different approaches to value the cost of heat and electricity. See e.g. reference [6] for a detailed discussion.

3.4.3 Desiccant cooling

More recently, desiccant cooling has been installed as a component of a co-generation system. Desiccants use heat to produce a cooling effect, but unlike an absorption chiller they do not address the sensible cooling load. Desiccants simply operate by removing the water vapour from the air, thus reducing the latent cooling load and, in the process, increasing air temperature. Desiccant cooling can also be combined with absorption or mechanical chillers if additional sensible cooling is required.

Desiccants can be particularly interesting in situations such as supermarkets, where high water vapour levels make up a significant part of the cooling load. In such cases, desiccants can reduce the total mechanical cooling load, so chillers can be downsized to lower capital costs.

Both liquid and solid desiccants are available. When the desiccant is saturated with water, it has to be recharged. When included in a co-generation system, the heat required for recharging the desiccant can be recovered from the engine. While recovered heat can be used for recharging, it is also possible to use conventional burners to recharge the desiccant, and the cost of heat should be compared to more conventional recharging techniques.

3.4.4 Gas turbine inlet air cooling (GTIAC)

Combustion turbines are constant-volume machines. At a given shaft speed they always move the same volume of air, but the power output of the turbine depends on the mass flow of air through it. Consequently, in summer when the air is less dense, the mass flow is reduced and there is a drop in power output from the turbine. By cooling the inlet air to the turbine, the air mass flow is increased, resulting in higher output and improved efficiency. There is, however, a limit to the degree of inlet air-cooling that can safely be accomplished. If the temperature is allowed to fall too low, ice can form, with the risk of this ice flaking off and doing mechanical damage to the compressor blades. This phenomenon can occur even when the inlet air temperature is above freezing, because suction at the turbine inlet creates a low-pressure 'cool zone' at the bell-mouth. Traditionally, both mechanical compression chillers and absorption-type evaporative coolers have been used to cool combustion turbine inlet air.

Various systems have been employed successfully for combustion turbine inlet air cooling. They range from mechanical compression chillers, to absorption chillers which utilise waste heat for the chilling process. Sanyo factory literature [20] provides some information about GTIAC using absorption chillers. Thermal storage systems have also been successfully applied to turbine systems. These use relatively small chiller plants, running off peak, to make ice or cold brine solutions which are stored in an insulated tank and used to cool the inlet air during periods of peak power demand. Such systems have proved to be a cost-effective way to overcome power loss during periods of peak demand.

3.4.5 Absorption chillers with district heating systems

A district heating system (DHS) can be utilised to supply heat, whereby absorption chillers can produce chilled water to supply a secondary district cooling system (DCS). During summer, DHSs have a low load. So production of chilled water by means of hot-water-driven absorption chillers is a good way to improve the efficiency of the DHS. The two main solutions available are:

- Integration of single-effect absorption chillers in a hot water network with a temperature up to about 100°C; and
- Integration of double-effect chillers in a steam or superheated water network.

A prerequisite for such systems is that surplus heat is available, and that it can be distributed to the DHS at low cost. This makes it a variant of district cooling, as the cold is produced locally and subsequently distributed in minor circuits.

Normally the temperatures in the DHS are reduced in summer due to lower heating loads. The return temperature can be down to 60°C. The combination of DHS with absorption chillers has to be optimised to fit the overall system. The temperature levels on the district heating side, the customer's temperature demand and the distribution temperatures from the chillers are all important parameters. In a DHS based on waste heat from e.g. waste incineration or industrial processes, the cost of the heat may be zero, or at least very low.

However, low supply temperatures decrease the capacity of the chiller. There are practical bottom limits for the operation of the absorption chiller, but new types of chillers have been developed to use low-temperature waste heat which is available on the market. For more information, see Appendix 6, Case Study No 6.

An example of absorption cooling based on district heating may be found in Gothenburg, Sweden. The concept is called 'ready cooling' and is based on the surplus heat in the DHS being used in rather large absorption chillers. From these chillers, which are placed at or near large customers, the local network for cold water can be installed for the distribution of cold to several customers, so avoiding distributing chilled water round the scheme.

3.4.6 Direct-fired absorption heat pumps

Absorption heat pumps are not widely used in industry. Some have been used to recover heat from refuse incineration plants, notably in Sweden and Denmark. Current systems with water/LiBr as the working pair achieve an output temperature of 100°C and a temperature lift of 55°C. The COP typically ranges from 1.2 to 1.4. The new generation of advanced absorption heat pump systems will have higher output temperatures (up to 260°C) and higher temperature lifts [20].

3.4.7 Greenhouses

In the Netherlands, greenhouses are a major economic and energy-intensive sector, which is responsible for about 5% of the Dutch gross national product (GNP). Primary energy consumption is 140 PJ a year, which is 7% of the total energy used in the Netherlands. More than 80% of this energy is used for heating the greenhouses, by gas boilers and gas-fired CHP.

Using gas heat pumps in this sector, it becomes possible to optimally integrate heating, cooling, CO_2 production and moisture control, thus considerably reducing the energy demands. Demonstration projects are now being realised, as discussed in Appendix 6, Case Study No 5 [21].

If this application proves to be viable, the poor availability of gas heat pumps will become a major obstacle. If only 1% of the total Dutch greenhouse area were to be heated by gas heat pumps (1% = 100 hectare) then 100 MW of heat pump capacity would have to be installed. This would be a real challenge for the industry.

4. Factors Affecting the Market

4.1 Market influences

The factors that determine the impact of sorption systems, discussed in this chapter, are primarily economic, environmental and policy. The present most important impediment in many cases is that sorption systems are not economically viable. Heating and cooling requirements in the various countries are determined by the climatic conditions that prevail. Also, the infrastructure and heat and cold distribution systems have an impact on the technical feasibility of the system.

4.1.1 Economic

When a multi-source production-to-end-user energy supply exists, it is generally agreed that the economics of the heating or cooling systems are the primary driver for the installation of sorption systems. Although first cost is often the deciding factor against installing sorption, a better approach is a life-cycle cost analysis. The simple payback period required for sorption to be considered competitive ranges from very short-term to a couple of years for domestic and commercial applications, and a maximum of five years for industry.

In life-cycle cost analyses, the relative prices of gas and electricity will drive the payback period for a particular installation. The absolute difference in energy costs is useful for comparing the payback periods for installations in different countries. The comparison of this parameter reveals a very important factor in the chillers and heat pumps market situation, and provides insight into the future prospects for development and implementation of alternative systems. Figures 4.1, 4.2, and 4.3 show end-user energy prices for fuels in homes, commercial/institutional buildings, and in industry for the Annex 24 countries in 1996.

The discrepancies in energy prices between the different countries are due mainly to national factors such as natural resources, energy and environmental taxes, infrastructure (power supply and distribution system), government subsidies, and demand. It is quite apparent from the figures that electricity prices in Japan are substantially higher than in the other countries.

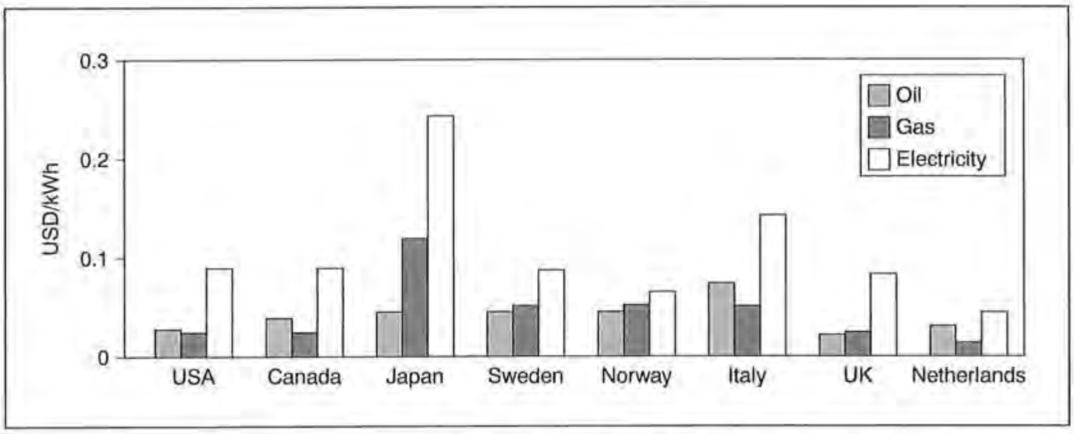


Figure 4.1 *End-user energy prices for different fuels in homes in US$/kWh.*

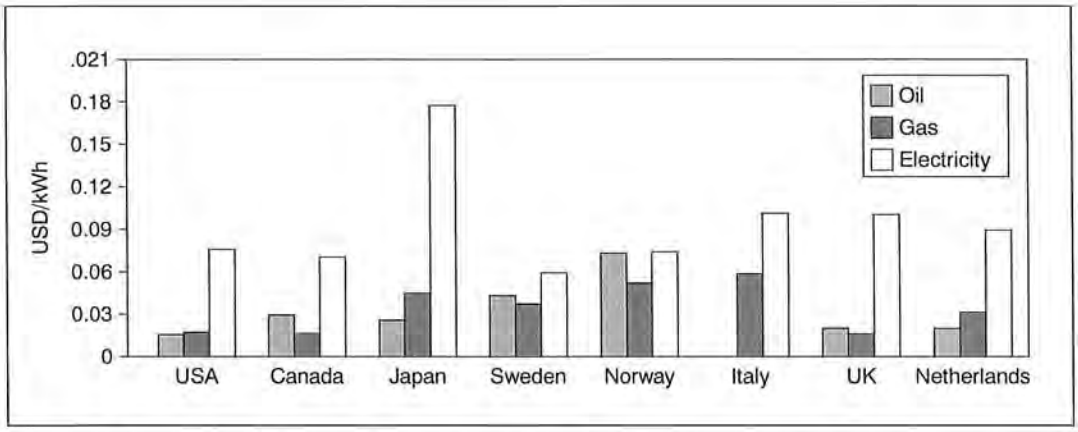


Figure 4.2 *End-user energy prices for different fuels in commercial/institutional buildings in US$/kWh.*

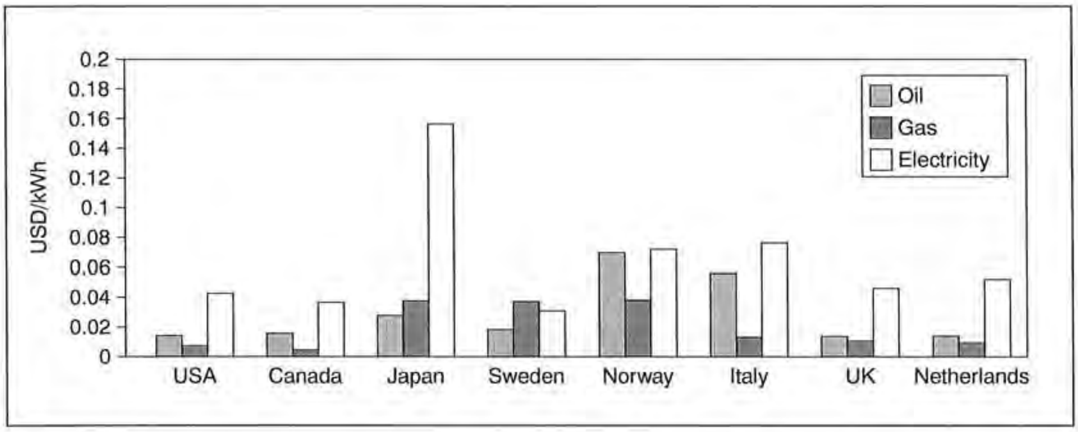


Figure 4.3 *End-user energy prices for different fuels in industry in US$/kWh.*

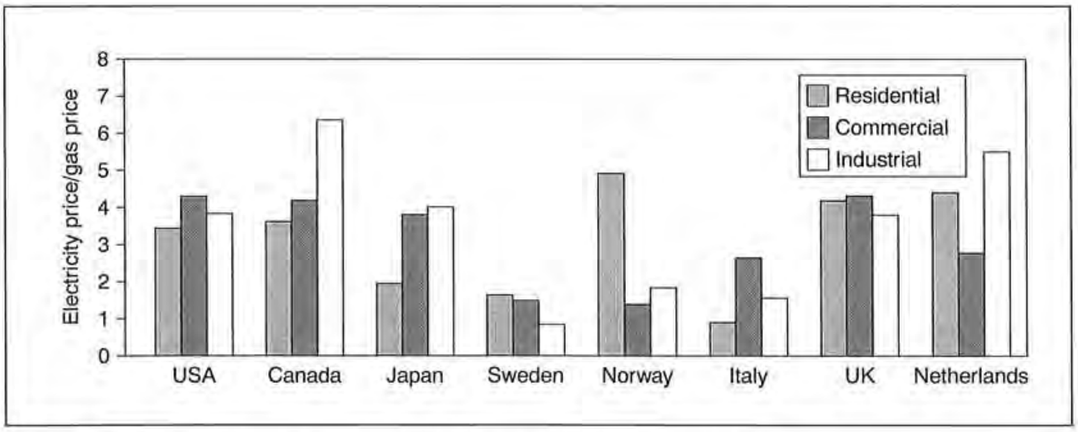


Figure 4.4 *Energy price ratios (electricity price/gas price) 1996.*

There is potential for sorption systems to save on operating costs in countries where electricity prices are high compared to natural gas. In Figure 4.4, average energy price ratios (electricity/gas) are given for the same countries in 1996.

The data of Figure 4.4 are useful in showing the market potential among the Annex participants. However, they should be interpreted with care, since the energy ratios are based on average energy prices. Industrial tariffs and energy prices are normally much lower than the average values upon which these ratios are based. For example, the figures do not indicate the advantages obtained by using gas instead of electricity during peak-demand periods. Many countries have utility rates that are based on the time of use or time of year, and some include a demand charge. Sorption may run at off-peak periods, and one could store heat or cold in an accumulator. In another example, a building energy manager may run an electric-driven system in parallel with an absorption system, and alternate base loads when the economics dictate. Consequently, in each particular case, one should assess the overall economics for different systems, although the values given are a good indication of the potential.

It should also be noted that absolute energy costs should be considered when comparing the potential for sorption from one country to another. For instance, Japan and the UK have similar energy price ratios in the commercial market, but energy costs in Japan are two to three times higher than they are in the UK. Therefore, for the same running hours and capacity, the cost savings in Japan are three times more, and the payback period is three times less.

In general, heating demand has decreased in new buildings thanks to more energy-efficient materials and construction methods. However, at the same time the internal heat loads have normally increased, due to use of more electronic equipment. For residential buildings in the United States and Japan, both space cooling and space heating are normally required, and air is the predominant medium of distribution. This is generally also the case in southern Europe, whereas in northern Europe space heating is dominant. Distribution systems in northern Europe are predominantly of the hydronic type.

For commercial buildings, on the other hand, there is generally a cooling demand in all countries. However, the distribution medium for space heating and cooling in commercial buildings in the United States is normally air. Even in northern Europe, there is generally a substantial cooling demand in commercial/institutional buildings. The distribution systems are normally of the hydronic type for space heating, and both air and water are used for space cooling. During the oil crisis of 1973-74, great effort was made by the Japanese government and industry to develop efficient absorption chillers. This led to markets in the neighbouring countries. In Asia, absorption systems have mainly been used as large centralised air-conditioning systems, district heating and cooling systems and co-generation systems. As stated in the last chapter, some 85% of the 8,600 absorption chillers over 100 TR are installed in the Far East [12].

The higher first cost of sorption compared to electric machines of equivalent capacity could be overcome by using gas. Favourable energy prices and the involvement of gas utilities and governments, and industry-sponsored R&D, will reduce the first cost and life cycle costs associated with sorption installations.

Although integration of absorption heat pumps into industrial processes has a long tradition in many countries, economic constraints are often difficult. Most decisions appear to be based on first cost rather than on life-cycle costing. The routine performance of life-cycle cost analyses would increase the use of absorption machines in industrial applications.

Rational use of thermal energy (i.e. primary energy savings) as well as the effective use of waste heat continues to increase significantly. Since thermal energy is used as the driving energy in sorption systems, almost any source of energy can be used: domestic fuels, solar energy, waste heat from industrial processes, heat from cogeneration plants, waste heat from power plants etc. Peak energy usage adds cost in the design of mains power plant, which must run on part load outside of peak hours.

4.1.2 Environmental

Carbon dioxide is currently thought to be responsible for more than 50% of the greenhouse effect. The potential of sorption systems for reducing CO_2 emission in the conversion of primary energy to electrical power and refrigeration is strongly dependent on parameters like the conversion method, the efficiency of the power station and the COP of the chiller. For example, a typical electric centrifugal chiller has a COP of 5.4 (0.65 kW/ton) while a state-of-the-art electric-driven centrifugal chiller may have a COP of 7.2 (0.49 kW/ton) or less. At an average carbon dioxide emission rate for electricity of 655 g/kWh generated, an absorption chiller would have to have a gas COP of 1.8 to produce the same carbon dioxide emissions as the 5.4 COP centrifugal chiller, and a gas COP of 2.6 to equal the 7.2 COP centrifugal chiller. Considering coal-fired plants only, with an emission rate of 1,114 g/kWh of power, the absorption chiller needs a gas COP of 1.05 to produce the same carbon dioxide emission as the 5.4 COP centrifugal chiller, and 1.5 to produce the same as the 7.2 COP centrifugal chiller.

Absorption is not as favourable with respect to CO_2 emissions when compared to an electric centrifugal chiller whose primary energy source is cleaner than coal [22]. A speculative calculation carried out on multiple-effect chillers found that only the quadruple-effect direct-fired absorption chiller could compete on a TEWI basis with centrifugal chillers for a wide range of operating hours [23].

Only CO_2 is considered above in relation to primary energy, but there are other emissions such as NO_x, SO_2, CH_4, particulate solids, nuclear waste, etc, which also have to be considered.

Table 4.1. shows the primary energy mix in percentage of total for electricity generation in the countries reviewed in this report. The data are given for 1995–1996.

Table 4.1 *Primary energy mix (percentage of total) for electricity generation in the participating countries [22].*

Country	Oil	Gas	Coal	Nuclear	Hydropower	Others	Total [TWh]
USA	2.6	13.2	52.7	19.6	9.6	2.3	3,652
UK	4.0	23.6	42.4	27.3	1.0	1.7	346
Japan	21.0	20.2	18.2	30.1	8.0	2.4	1,003
Sweden	2.7	0.4	2.1	47.2	45.9	1.7	148
Netherlands	4.6	55.6	31.6	4.9	0.1	3.2	85
Norway	0	0.3	0.2	0	99.2	0.3	104
Italy	48.9	21.0	10.6	0	17.6	2.0	239
Canada	1.6	2.9	16.2	16.3	62.4	0.7	571

As can be seen from Table 4.1, the production mix differs significantly for the various countries. In Norway about 99% of the electricity is produced by hydropower, whereas in Italy and the Netherlands more than 80% of the electricity is generated from fossil fuel (oil, gas and coal) combustion. The UK and Japan also use substantial amounts of fossil fuel for electricity production. In Sweden about 90% is produced from nuclear and hydropower. Canada also has a large proportion of electricity produced by hydropower (about 62%).

To calculate the energy conservation which can be achieved by using thermally-driven absorption systems compared to electric-driven systems, the efficiency of power generation is crucial. However, to calculate the reduction in CO_2 emissions it is important to know the effects of the primary energy mix for power generation. Three types of power generation have zero CO_2 emissions:

- Renewables, like solar, wind and hydropower;
- Nuclear; and
- Bio-energy.

Although the burning of bio-energy produces CO_2 emissions, it is generally accepted that these emissions are part of the short CO_2 cycle, and can therefore be considered as zero-emissions for the environment. In the burning of municipal waste, calculating the balance is somewhat more difficult. Waste from municipalities consists largely of materials from the short-life cycle, while only a small part (the plastics) is from the long-life carbon cycle. Nuclear energy is technically a zero CO_2-emitter and must also be considered as such in technical calculations for the greenhouse effect of heat pump alternatives. In public perception, however, nuclear energy is an environmental threat, due to its waste products and operating risks.

As energy conservation and the reduction of CO_2 emissions do not have a linear relationship, for detailed calculation a policy decision has to be made to be able to choose between systems. An approximation of the CO_2 emissions from electricity generation and their relative efficiency is shown in Table 4.2. The data are given for 1995–1996.

Table 4.2 *Approximate CO_2 emissions and efficiency of electricity generation.*

Country	**kg CO_2/kWh$_{el}$**	**Efficiency %**
USA	0.58	35
UK	0.52	36
Japan	0.39	39
Sweden	0.06	40[1]
Netherlands	0.64	42
Norway	0.00	85[2]
Italy	0.55	39
Canada	0.18	50

1 Oil- and gas-fired plants (1.7% of 1996 production)

2 Of hydro-electric plant, which is the bulk

From an environmental standpoint, considering primary energy requirements only, today's absorption machines should only be promoted for use with integrated energy systems such as waste heat or CHP. Conditions under which there is an environmental benefit for CHP requires high total and electric CHP efficiencies, good absorption COP, and relatively low efficiency of mains electricity generation. Direct-fired absorption chillers require more primary energy than compression systems. Although direct-fired absorption chillers offer lower running costs, they consume more primary energy. With current single- and double-effect absorption chillers, the benefit to the environment is in reduced ozone depletion potential (ODP). However, if vapour compression systems use zero-ODP refrigerants, which are readily available, there is no TEWI benefit [22].

The CFC ban, and eventual HCFC ban, will be of positive benefit to alternative technologies such as absorption. New HFC refrigerants can adequately replace some CFCs (R134a for R12) but their global warming potential is not zero. On the other hand, ammonia is environmentally clean, its ODP is zero, and so is its global warming potential (GWP). Its atmospheric life is about two weeks, compared with tens of years for other refrigerants. The principal objection to ammonia in residential and commercial applications is the opposition of designers and policy-makers [23]. For industrial applications, ammonia has long been accepted, and designers are experienced in building such units. Also, new natural refrigerants such as CO_2 are being looked at with great interest, and would have a promising future in many applications.

4.1.3 Policies

Policies that promote the use of sorption technologies are immature or ineffective. Governments should be encouraging technologies with beneficial environmental impact, with a longer-term view to economic sustainability. Energy policy should create the necessary conditions for the efficient use of energy, and the cost-effective supply of energy with a low negative impact on health, the environment and the climate, and facilitate transformation into an ecologically-sustainable society. Jurisdiction over energy conservation, promotion programmes and utility incentive schemes play an important role in the deployment of sorption systems. In addition the infrastructure, waste-handling systems and political willingness to develop and promote new technologies are important aspects.

Policies such as electricity deregulation are affecting the market forces for electric as well as gas- and oil-fired equipment. Some countries (e.g. Norway) are seeing a drop in electricity rates with deregulation, thus reducing the driving forces for energy efficiency measures in general and for sorption technology in particular. Some other countries (e.g. the USA) are seeing electricity prices escalate during peak periods in the deregulated market. In response, consumers are installing parallel gas- and electric-driven systems, and are using demand-side management techniques to choose which system (gas or electric) it would be more economical to run at a particular period.

4.2 The world market

In order to consider the world market, sorption machines have been classified into the following categories, so that an easy correlation can be made with the environmental impact of each technology. Indications are given of their market share in terms of their cooling or heating capacity rather than in terms of units [1, 2, 3, 12]

Market share % capacity

• Absorption chillers, direct-fired or with direct-fired boilers	more than 90 %
• Absorption chillers, driven by waste heat and CHP	less than 10 %
• *Ad*sorption chillers	less than 0.5%
• Absorption heat pumps, direct-driven	less than 0.1 %
• Absorption heat transformers (also AHPs), driven by waste heat	less than 0.1%

The world market of sorption machines mainly consists of direct-fired absorption chillers, or chillers driven with boilers. Both single- and double-effect machines, either direct-fired or indirectly driven with direct-fired boilers, are included in this category. They include water/LiBr and ammonia/water machines, both small size and larger purpose-built industrial types.

It should be stated that the formal task of Annex 24 did not include a detailed world market study of sorption technology. However, the group took upon itself the task of obtaining sufficient information as a general market overview to comment on the actual state of the art, and future opportunities. The figures that follow are not definitive but considered indicative. Further information is available from BSRIA (UK).

The water/LiBr absorption chiller market is strongest in Asia, followed by the USA and Europe. The following schedule indicates the market share as a percentage of chillers. However, chiller sizes in Asia and in the USA are larger than those generally installed in Europe.

Market share % chillers

• Japan	41 %
• China	34 %
• Korea	12%
• USA	5 %
• India	3 %
• Europe	3 %
• Rest of the world	3 %

The main reason why direct-fired and boiler-driven chillers have the highest market share is solely due to difficulties with the electricity supply for electric-driven chillers. In Japan there is a policy of diversification of energy, and in China, Korea and India there is a lack of electricity infrastructure. To a lesser degree, the USA shares this problem, though the main driving forces there are the electricity tariffs, which vary considerably from zone to zone. Europe tends to use smaller-capacity machines and has focused more on waste heat, heat recovery and CHP applications. However, the electric infrastructure problem is also present.

There are two main categories of ammonia absorption chillers: packaged 18kW air-cooled units, and industrial types. The small packaged chillers which are used for residential and light commercial applications have a world market of approximately 4,000 units per year, of which around half are sold in Europe and a quarter in the USA. Despite the relatively high numbers, this represents less than 4% of the installed cooling capacity of the larger water/LiBr chillers.

The industrial types of ammonia absorption chiller are bespoke machines applied mainly to industrial processes. There are probably not more that 100 such units installed worldwide.

Absorption heat pumps (AHPs) and absorption heat transformers (AHTs) compete mainly with boilers and, due to the big differences in initial plant costs, have very low market penetration. An estimated 100 AHPs and 30 AHTs have been installed worldwide over the last 20 years.

*Ad*sorption chillers are seeing the most rapid growth, but from a small base. Although this is a relatively new technology which has emerged only during the last years, about 130 units are already installed, with cooling capacities ranging from 70 to 600 kW. Their attractive feature is that although they have less thermodynamic efficiency, due to their cycling nature, they can be driven with lower hot water temperatures than most conventional absorption chillers. This makes them better able to cope with low waste heat temperatures, which favours their marketing possibilities. Their competition comes from a new series of absorption chillers that use counter-current heat exchangers in the generator and absorber, and can equally achieve lower hot water temperatures, and a higher COP. However, the first cost of these will determine their success in the market place.

Last but not least, the technology of the diffusion-type absorption refrigerator should not be forgotten. These use the ammonia/water mixture combined with hydrogen to achieve difference of partial pressures within the unit. Although the COPs are very low, they are very popular due to their silent operation in hotel rooms, caravans and mobile homes, and in remote locations. They were described by the late Professor Alefeld as the "Sorption success of the 20th Century", at the International Sorption Heat Pump Conference at New Orleans in 1994. He also posed the awkward question: "What will be the sorption success story of the 21st Century?"

4.3 Operating experiences and control considerations

4.3.1 Introduction

This section summarises some important factors to consider when contemplating sorption systems. The experiences reported and control measures highlighted refer to water/LiBr chillers, heat pumps and heat transformers, as described in the different sections. However, the majority of concerns and reports are related to absorption chillers, since the number of heat pump installations is very limited. Information on operating experiences has been worked on by all the participants, using private communications, technical visits to installations, discussions with manufacturers etc.

The section is organised so that a description of potential problems and control measures is first briefly given. Subsequently, reported practical operating experiences are summarised in relation to the given problem. The experiences given are a summary of worldwide experiences related to that particular issue. The issues dealt with are:

- Vacuum requirements;
- Crystallisation;
- Corrosion;
- Maintenance;
- Health and safety; and
- Miscellaneous.

4.3.2 Vacuum requirements

General

The vacuum levels associated with water/LiBr absorption are high, and the sensitivity of the technology to leaks is therefore also very high. Absorption machines are sensitive to leaks both because air in the machine reduces performance, and because of corrosion considerations. Pumping out the air and other gases from the vapour space initially attains the low pressures needed in the absorption system. Gases dissolved in the mixture (water/LiBr) are also removed naturally if a long enough time is allowed. Both some water vapour and unwanted gases are removed during the evacuation process. The amount of water vapour that is removed is very small, so does not influence the absorption cycle.

One effect of inert gases in such a machine is to reduce the performance of both the condenser and the absorber. The absorber is the most critical component in this context. Another important effect of these gases is that they reduce the effect of the evaporator due to their partial pressure. This increases the pressure at which the refrigerant (water) in the evaporator is forced to boil (at a higher temperature). This results in a loss of cooling capacity.

Different manufacturers use somewhat different methods to purge the system:

- A direct method is to simply evacuate the vapour space periodically with a vacuum pump;
- Palladium cells, which form a semi-permeable membrane in the system; and
- Ejector pumps, which use the existing solution pump to collect the gas.

In most designs, the operator must periodically purge the gas collection vessel with a vacuum pump. This is preferred over pumping the entire vapour space of the machine, since the gas is concentrated and can be removed quickly and easily. However, different manufacturers have come up with their own solutions. One example is a system which knows when the purge tank is full, automatically empties its contents and alerts the operator if the unit is purging too frequently [24]. Most purging systems utilise a palladium cell, but still require periodic manual purging. The palladium cell only removes hydrogen automatically. Manual purging is still needed to eliminate other non-condensables. The frequency at which purging of non-condensables has to be carried out is a sign of the chemical health (stability) within the chiller, i.e. there is only low and controlled corrosion.

Air leaks into the system can also cause unacceptable corrosion problems due to oxygen. For this reason, a water/LiBr absorption machine must be essentially hermetic in design. As mentioned above, other non-absorbable gases such as hydrogen can cause poor performance. The corrosion chemistry at work in an absorption machine causes low-level, continuous production of hydrogen gas. Hydrogen is essentially inert, non-absorbable in the temperature range of interest and has very low solubility in both liquid water and water/LiBr solutions. Consequently, the hydrogen produced accumulates in the vapour space of the absorption machine. The hydrogen gas has a tendency to migrate from the high-pressure side to the low-pressure side, due to the influence of pressure on solubility.

In oil-lubricated pumps, the water vapour tends to condense in the exhaust stages of the pump and to end up in the oil sump. The water tends to reduce the effectiveness of lubrication, and will harm the pump if the condition is allowed to persist. Careful observation of the oil is necessary. When discoloration occurs, the oil must be replaced. To reduce or eliminate water condensation in the pump oil, a trap should be employed to remove the water before it gets to the pump.

Operating experience
Problems reported with leakage are normally related to corrosion. The purging procedure is not normally considered a problem, although there are a few reported incidents of air leakage due to poor gaskets and valves. The experiences reported are for absorption chillers and heat pumps. The latest machines available on the market, and found in new installations, show good results in this respect, and purging can be less frequent.

Some reports indicated that the time required for purging stated by the manufacturer turned out in reality to be much less. This suggests that the manufacturers have effectively solved the problems of leakage and purging in recent years.

4.3.3 Crystallisation

General
Considerable work has been done by absorption machine manufacturers to perfect controls that provide trouble-free operation for the user. With the exception for crystallisation, water/LiBr absorption machines are today inherently stable and self-starting. However, because of possible problems with crystallisation, a number of controls are generally provided to deal with this issue. Unchecked inward air leakage causes absorber effectiveness to deteriorate. Conventional controls sense chilled water temperature rising, and call for increased heat input to the desorber. This, in turn, tends to concentrate the salt solution, and in extremes can cause crystallisation.

One approach to avoiding crystallisation is to ensure that the solution mass fraction never rises above some limiting value. As long as the machine stays in the expected operating temperature range, this restriction is enough to guarantee the absence of crystals. An indirect method of inferring the concentration is used by some manufacturers, based on a known initial charge of solution with known LiBr mass fraction. The refrigerant level in the evaporator is monitored, and when it is too high, it is inferred that the solution is too highly concentrated. This scheme is relatively simple to automate and can be implemented using widely available level-sensing transducers.

Some manufacturers also fit automatic decrystallisation controls, so that in the unlikely event of a problem caused by extreme conditions, the problem is automatically corrected.

Operating experience
Fear of crystallisation in water/LiBr absorption chillers is the biggest misconception of the technology. Although such crystallisation was a major problem in the 1970s and 1980s, it has been practically overcome since the introduction of modern controls. The main exception is possible power failure interrupting shut-down cycles. Very few actual reports of crystallisation have been found, and it is normally not considered a problem with the new generation of absorption machines. However, there are some reports by maintenance people that the newer double-effect chillers, even though better equipped to prevent crystallisation, are expensive and time-consuming to repair. This underlines the importance of not only dealing with crystallisation prevention, but also with ways to rapidly and economically remedy the problem.

However, the main reasons for crystallisation reported are [25]:

- Interruption of shut-down cycles due to power failure or poor controls;
- Insufficient purging of non-condensables, together with unreliable controls; and
- Poor control of cooling tower water temperature and of steam valves.

The following designs are also likely to generate crystallisation problems:

- Designs that require step loads to ramp cooling on and off, instead of using buffer tanks; and
- Improper combination of absorption with mechanical compression chillers that have a quicker response.

4.3.4 Corrosion

General

In the presence of dissolved oxygen, water/LiBr is highly aggressive to many metals including carbon steel and copper. However, in the hermetic environment inside the absorption machine, very little oxygen is present and corrosion rates are much slower. For the temperature range of a typical single-effect unit, carbon steel and copper are the preferred materials of construction. Over the operating life of a machine, significant corrosion can still occur, and care must be taken to minimise its effects. The primary measures available are:

- pH control; and
- Use of corrosion inhibitors.

Corrosion of steel or copper in the presence of an electrolyte is a multi-stage oxidation-reduction reaction. The oxidation potential of the solution is a strong function of the pH value. By controlling the solution to be only slightly basic, the hydroxyl radicals are in excess, and this tends to cause oxide formation directly on the solid surface – *passivation of the metal*. However, over time, alkalinity tends to increase as hydrogen gas is formed, so it is preferable to keep the pH close to neutral. pH control in a water/LiBr absorption machine can be achieved by adding small amounts of HBr to achieve the desired pH.

Corrosion inhibitors provide complementary reduction in corrosion rates. Various anti-corrosion additives have been tested over the years, including lithium chromate, lithium molybdate and lithium nitrate. These salts are added to the water/LiBr solution in amounts of the order of 1% by weight. They reduce corrosion rates, apparently by reacting with the metal surface and forming a relatively stable oxide coating (passivation). Lithium chromate was the preferred choice for many years, but its toxicity has reduced its usage. Lithium molybdate is somewhat less effective, but has been found to provide adequate machine life in many applications. In addition, Benzatriazole (BTA) has been tested as a corrosion inhibitor (at approximately 2.4 g/l). It has been found to work very well. Many machines also use nitrogen-based inhibitors.

High-temperature applications, including some components in double-effect machines, require special materials to maintain long life. Copper-nickel (CuNi) alloys resist corrosion at high temperatures better than copper, and are customarily used. If copper tubes are used, especially in the absorber to which oxygen tends to migrate, the oxygen will react quite rapidly with the copper surfaces to form copper oxide, which is soluble in water/LiBr solutions. This results in pitting and corrosion of the copper tubes. Although CuNi alloys are more expensive, they are also preferred when the external environment is corrosive, such as when seawater is used as a coolant. A major design issue is also to minimise the electro-chemical potential between the tubes and the tube sheet. Stainless steels often exhibit pitting and corrosion cracking in the presence of high-temperature water/LiBr solutions. Seals in water/LiBr systems are normally not an issue, since common rubber products are compatible.

Operating experience
Corrosion is, together with crystallisation, perceived as the major issue in absorption chillers and heat pumps, though corrosion has not been reported as a significant problem in most cases. However, there are a few older reports (before or up to 1990) where severe corrosion problems were reported with absorption heat pump installations. This was due to air leakage and lack of corrosion inhibitors.

Corrosion is normally caused by:
- Allowing units to sit on site for extended periods before commissioning, or unattended;
- Accidental drilling or damage;
- Use of a large number of ball valves; or
- Lack of understanding by maintenance personnel of the need to ensure that the machine is always kept air-tight.

The new generation of absorption machines is very safe as regards corrosion, but there may be some differences between manufacturers. In some cases poor manufacturing control of units sourced worldwide, e.g. porous welds (leaks), have been reported. Some problems have also been reported relating to pitting and corrosion cracking of the generator and absorber heat exchanger tubes.

4.3.5 Maintenance

General
Normal maintenance for water/LiBr technology includes:
- Periodic purging of non-absorbable gases;
- Periodic addition of octyl alcohol (additive that increases the mass transfer process in the absorber, and hence increases overall absorber performance);
- Periodic addition of corrosion inhibitor;
- Periodic addition of pH buffer; and
- Monitoring of the water/LiBr solution.

The appropriate period for performing these tasks depends on a number of variables, including the size of the machine and the type of purging system, and is generally specified by the manufacturer of the machine. The basic procedures are quite simple, and can be performed by trained technicians. The necessary chemicals are relatively inexpensive, and readily available from suppliers.

Along with the maintenance procedures, an assessment of cycle performance against norms should be made on a regular basis to help anticipate any potential problems. The ultimate failure mode of a water/LiBr absorption machine is usually corrosion-induced. For long life, attention must be paid to avoiding air leakage into the machine, and to ensuring that the corrosion inhibition regime is strictly followed.

If the vacuum must be broken for any reason, it is important to fill the vapour space with nitrogen or other inert gas to avoid introducing oxygen. Moreover, long-term shutdown of charged machines should involve pressurising the vapour space with nitrogen to a pressure above atmospheric, so that any leakage that does occur does not introduce oxygen.

Regular sampling of the water/LiBr solution is important, in order to check the concentration, the inhibitors and other components (e.g. corrosion products!). Suggested intervals for testing are once a year for comfort cooling applications, and twice a year for units in continuous service (i.e. heating and cooling). Analysis of refrigerant water is normally also suggested. In addition, attention must be paid to any fouling of heat exchanger tubes, and the tubes must be cleaned occasionally. Circulating water quality (steam/hot water and cooling) must be free from scale-forming chemicals to ensure machine longevity. These considerations apply to both absorption chillers and absorption heat pumps.

Operating experience
In some cases it has been reported that maintenance and site training are insufficient or even lacking. Clients are unhappy with maintenance companies and with their advice, and some are unable to recommend maintenance companies for absorption machines. The lack of skilled technicians outside absorption manufacturers and distributors has sometimes been pointed out as an important issue.

The need for trained technicians, who understand the importance of maintenance procedures for absorption chillers, must be emphasised. In the majority of installations where the maintenance is carried out rigorously by skilled people, excellent operating experience is reported.

The main areas within maintenance that require attention and understanding are:
- Purging operations;
- Corrosion control;
- Cooling water treatment to avoid corrosion and scaling; and
- Safety links.

Experience shows that an absorption machine that is running needs less than one hour per week of maintenance and service, and often no more than a cursory inspection.

4.3.6 Health and safety

This aspect mainly applies to ammonia/water systems. In addition, with water/LiBr systems, attention should be paid to the handling of additives, e.g. corrosion inhibitors, pH buffers and heat transfer additives. These chemicals are used in small amounts, but they may be toxic, carcinogenic or in some other way harmful to health. There are, to date, no reported accidents (causing injury to humans or severe damage to property) involving water/LiBr absorption systems. This is obviously related to the machine construction, the use of a safe refrigerant (water) and advanced control systems.

The potentially toxic and hazardous chemicals are anhydrous LiBr salt, aqueous salt solutions, corrosion inhibitors and additives such as n-octanol. Both anhydrous LiBr salt and aqueous salt solutions may be harmful if inhaled, ingested (swallowed) or absorbed through the skin. Large doses of lithium compounds have been shown to cause dizziness, prostration and kidney damage if sodium intake is limited. Also, bromoderma (bromide rashes resembling acne), and furanculosis often result from long periods of inhalation.

Corrosion inhibitors such as LiOH and Li-molybdate are also lithium compounds that can in large doses cause dizziness, prostration, kidney damage, apathy and even death. Moreover, LiOH is a strong base and its solution is very caustic. Certain chromium salts such as lithium chromate and sodium chromate are no longer used as corrosion inhibitors because chromium is carcinogenic.

Alcohol additives that are used in some machines are harmful if swallowed or absorbed through the skin. They can cause eye and skin irritation, and may cause allergic skin reactions.

Another very important issue that needs to be addressed is the pressures systems regulations, see e.g. reference [5]. It is important to consider proper system design so as to prevent danger. Precise guidance can not be given, as the regulations normally do not impose detailed requirements. Only general guidelines to ensure safety can be identified.

4.3.7 Other aspects

Some general issues that may need considering are:

- Compliance with European standards (when required) is not necessarily achieved by manufacturing standards;
- Machines may be international hybrids, which can make components difficult to source or stock;
- Low-load applications can cause control hunting, which is worse with oversized machines;
- Poor manufacturing quality control from some units sourced worldwide, e.g. porous welds (leaks);
- Foaming of the absorbent solution;
- Low-frequency noise from burners of absorption chillers;
- Temperature rise in plant rooms (solved by lagging of absorption machines);
- Lack of education and training of consultants, technicians etc;
- Project management; and
- Lack of education and training of maintenance personnel.

5. Research and Development

This chapter gives a brief summary of recently-reported R&D activities in sorption technologies, reviewed worldwide. Some of these activities are still ongoing. The information is taken from the Thermie-report to The European Commission DG XVII: "Absorption Cooling and Heat Pump Technologies in Europe – Present Status and Future Trends" [27]; Proceedings of the International Sorption Heat Pump Conference in Munich, Germany in 1999 [28] and from Country Reports in this IEA Heat Pump Programme, Annex 24 [29]. Further details can be found in these reports.

The activities described are categorised as follows:
- Absorption chillers for cooling and refrigeration;
- Absorption heat pumps and heat transformers;
- Co-generation systems;
- Compression/absorption systems;
- Solid sorption;
- Fundamental studies; and
- Miscellaneous.

5.1 Absorption chillers for cooling and refrigeration

In many countries absorption R&D activities are promoted, with the object of reducing electricity peaks and utilising waste heat more effectively. Various types of single-effect chillers have been investigated, as well as others with double-effect and with two-stages. There seems to be interest in cycles which can use low-temperature waste heat to supply cooling both for air-conditioning and refrigeration.

Systems that can improve life-cycle costs by delivering high-efficiency and competitive first costs, together with reduced emissions and load-levelling for gas and electricity supply, are being researched in many countries, including the USA, Japan, China and Korea. There is also R&D on natural-gas-fired absorption machines for combined cooling and heating which can provide hot water, space heating and comfort cooling in residential and commercial buildings by applying new and advanced components.

Interesting results from the UK for a combined ejector and single-effect absorption chiller show improved COP with limited increase in first cost.

The GAX cycle is receiving serious attention in many countries, where the targets are mentioned as $COP_{cooling} = 0.7$ and $COP_{heating} = 1.45$.

Efforts are being made to reduce the manufacturing cost of direct-fired, double-effect absorption systems. Compact systems seem to be attracting attention.

Multi-effect and multi-stage absorption cycles are being researched in several places. The USA has R&D activity on a triple-effect chiller based on a dual-loop cycle, and also on a direct-condenser-coupled cycle. R&D in other countries is also ongoing.

5.2 Absorption heat pumps and heat transformers

There are many absorption heat pump (AHP) projects reported, for residential/commercial and industrial applications. The work is more on demonstration than on R&D, since the technology still does not have sufficient market pull, so most needs to be demonstrated. Cost-effective double-effect as well as single-stage and double-stage AHPs are being researched in Germany. An interesting French-German collaborative project is ongoing, on a triple-effect cascade sorption heat pump system to generate heat at 180°C and cooling at 0°C. This uses a high-temperature thermo-chemical solid/gas cycle on top of a double-effect liquid/gas absorption cycle. A project on AHPs in Dutch greenhouses has shown economic feasibility, due to the consumption of CO_2 by the crop [21]. New working fluids, inhibitors and additives for single- and multi-stage AHPs, reaching temperatures of 160 – 180°C have been investigated.

The activity on absorption heat transformers (AHTs) has been basically on industrial waste heat recovery at or below 100°C, for high-temperature applications. An interesting concept for reducing electricity consumption for the circulation pumps has been tested using self-circulation systems in Sweden. A double-lift AHT cycle has been researched in Germany, in order to produce and regenerate steam from 80°C to 140°C, for subsequent expansion in a steam turbine.

5.3 Co-generation systems

The status of R&D activity described here is for absorption systems combined with combined heat and power (CHP) stations.

A key issue has been to recover heat in an effective way, either for external cooling or for gas turbine inlet air cooling, which will increase the overall efficiency of the CHP plant. The USA, Japan and the UK among other countries have been active in improving the power station's and CHP performance.

A high-performance double-effect absorption chiller is reported from Japan, showing higher efficiency of waste heat recovery.

In The Netherlands, the USA and Spain, co-generation and absorption refrigeration systems with cooling far below freezing point (–30°C is the lowest) have been tested recently. In the USA, development of CHP systems for buildings has expanded.

5.4 Compression/absorption systems

This section describes the status for both integrated compression/absorption cycles as well as for connected compression and absorption systems working as two separate cycles.

For integrated compression and absorption cycles, the most common approach has been the classical Osenbrück cycle, where a solution circuit is added to a standard vapour compression cycle. Recent R&D activities have been focusing on industrial waste heat recovery and high-temperature applications, due to the effective temperature lift that this cycle can give. Also, systems providing both heating and cooling simultaneously are found to be very feasible, for example in industrial processes. The common challenge of a suitable compressor device has been investigated, both for oil-lubricated and oil-free systems. There is still a need for more practical operational experience before valuable conclusions can be drawn. First-cost effectiveness has also been a key issue, for the compressor device, the solution pump and the heat exchangers. Compact systems also seem to be a promising option for this type of heat pump. R&D is being performed in Germany, The Netherlands, the UK, Sweden, Norway and Spain.

Absorption systems containing compressor devices to boost the temperature have been researched to a smaller extent. R&D activity has been reported from Japan, Germany and the USA. Interesting concepts for lowering the evaporation temperature by means of a compressor are reported by several sources in Japan.

The combination of separate compression and absorption cycles working in a single energy supply system is common in countries like Japan and the USA. Effective use of waste heat from an engine in an engine-driven compression system to power an absorption system has been reported, focusing on a novel absorption cycle and compact components.

5.5 Solid sorption

The number of fully developed *ad*sorption products is relatively small. In the past, one group in the USA developed a carbon/ammonia reversible heat pump for domestic use, but the de-regulation of energy prices in the USA prevented commercialisation. In Europe, there has been some development on a domestic heat pump using a zeolite/water pair. Silica gel/water chillers for commercial use, that can be driven by waste heat at less than 100°C, have been marketed in Japan. On the research front, there are many groups across the world investigating a range of *ad*sorption technologies for heat pumping. In France, some work has been done on regenerative zeolite/water systems and on absorption–*ad*sorption combinations. In the UK there are several projects on ammonia/carbon machines, including work on novel carbon materials and cycles. In Germany there is continuing work on metal hydride heat pumps.

There are many other research activities, too numerous to mention individually, for example in Italy, China, Belarus, Canada and the USA. If they have a common focus, it is on the improvement of heat transfer needed to reduce the size and cost of equipment, as well as to improve energy efficiency. Key applications are domestic heat pumping, commercial heating and cooling, and the provision of cooling from waste heat or CHP [30].

5.6 Fundamental studies

Basic research activities, which promote better component and system performance, introduce new working pairs or give a better understanding of absorption cycles, are included in this category.

On a worldwide basis, considerable work has been done to investigate basic aspects of absorption technology. At the last International Sorption Heat Pump Conference (1999) in Munich [28], around 40 papers out of 90 dealt with fundamental topics.

5.6.3 Heat and mass transfer

For liquid sorbent systems, heat and mass transfer enhancement are being thoroughly investigated. Both falling-film and bubble-type heat exchangers with various heat and mass transfer enhancement techniques, especially for absorbers, have attracted attention, aimed at improving their overall efficiency. This research seems also to be motivated by interest in developing compact heat exchanger units with lower first costs. In addition, the effect of additives in both ammonia/water and water/LiBr absorption systems is being studied with great interest, particularly with respect to heat and mass transfer enhancement. Utilising the phenomenon of Marangoni convection would contribute to more effective heat exchanger devices.

For solid sorption systems, there is some activity on heat transfer enhancement techniques, such as new *ad*sorbents and proper surface design, as well as minimisation of the thermal resistance between the heat exchanger wall and the *ad*sorber bed. Actions in the direction of compact, low-weight systems are attractive, especially for the automotive/transport sector.

5.6.4 Working pairs

In the case of liquid sorption systems, alternatives to the traditional ammonia/water and water/LiBr pairs are being continuously researched. Working pairs with reduced problems of water freezing and LiBr crystallisation seem to be attractive, as are pairs which can overcome the present limitations of ammonia/water rectification. Also, pairs with benefits like increased absorber and condenser temperature are being researched. Much work still has to be done in order to challenge the position of the two established working pairs, since thermodynamically they are not that far from that of the ideal mixture for ideal cycles.

For solid sorption systems, studies on new materials which can utilise waste heat at a lower temperature than the zeolite/water pair, and with COP values higher than the zeolite/water pair at equal temperature are interesting.

5.6.3 Thermodynamic models

In order to understand the basis of sorption cycles better, and how their design can be optimised to obtain more energy-effective processes, fundamental cycle studies are being performed worldwide. The great freedom of cycle arrangements that sorption technology allows, is always attractive for thoroughly basic studies. Better utilisation of exergy has been studied by several researchers recently. Also, work is still ongoing regarding the fundamentals of sorption thermodynamics, in France, Germany and the UK.

5.7 Miscellaneous

Solar cooling, automotive systems and desiccant systems are included in this brief section. Development of solar cooling systems is still attractive to some research groups, at least to demonstrate how the technology can be utilised under certain favourable circumstances. Studies of sorption technology in automotive systems have been performed both for *ad*sorption and absorption systems. Waste heat recovery from exhaust gases for absorption refrigeration has shown considerable energy saving in a Dutch project. *Ad*sorption systems which can operate at lower waste heat temperature levels to suit the automotive vehicles of the future, such as with low-consumption combustion engines and fuel cells, have been researched in the USA.

R&D activity on desiccant systems has been moderate. Studies on combined evaporative and desiccant cooling, and heat recovery with a new desiccant product are some of the few.

6. Future Opportunities

This chapter describes the present situations for different regions, under different conditions, and at different development stages of the present energy supply system. From this it can be seen how changes influence the market, and their environmental effects. This then enables a view to be taken on future opportunities for sorption technology.

An understanding of the worldwide market driving forces is necessary[1]. In order of decreasing importance these were perceived to be:

1) Cooling and heating requirements (the need), which determine the type of plant, temperature requirements (climate-related) and possible market;
2) Technology available, i.e. supplied in sufficient quantity and quality by installers and known about by end-users and/or consultants;
3) Economics, including life-cycle costs, but mainly capital costs of plant and of electric infrastructure for electrically-driven mechanical chillers. The dominant requirement for simple payback periods is very short-term up to a couple of years for commercial systems, and a maximum of five years for industry and energy suppliers;
4) Environmental issues, including legislation by governmental bodies and accepted policy by aware companies ('early adopters' in marketing terms); and
5) Policies which can influence forces 1), 2), 3) and 4) above. Technologies should be encouraged which have beneficial environmental impact, and are economically viable in the longer-term.

Driving forces 1) and 2) determine the market for specific types of units. Given this, then item 3) Economics becomes the main driving force. The tariff structure for energy, dictated largely by the type of electricity production, has an impact on the economics of sorption as well as most of the competing technologies. Many other reasons such as lack of electric infrastructure are also economic driving forces, due to the cost of making electricity available in the short term.

Market driving forces, however, can be in opposition to best environmental practice, which is for most governments a guideline for their policies. These policies are based not only on the need for energy conservation, but more and more on the need for restriction of harmful greenhouse gas emissions[2].

The environmental impact has been analysed within the economic context (i.e. market pull) of the main available sorption technologies. As, especially for chillers, sorption technology competes mainly with electrically-driven mechanical chillers, the environmental impact is dictated by the type of electricity generation. The boilers referred to are standard (not condensing type).

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[1] In this report market driving forces are those forces which are a benefit or a barrier in the pull mechanism on the sales of sorption technology in competition with other technologies in open competing markets.

[2] In some countries with a relatively low electric efficiency the emission of CO_2 is also rather low compared to countries with a high electric efficiency. Therefore energy conservation does not always have the same impact as reduction in CO_2-emissions.

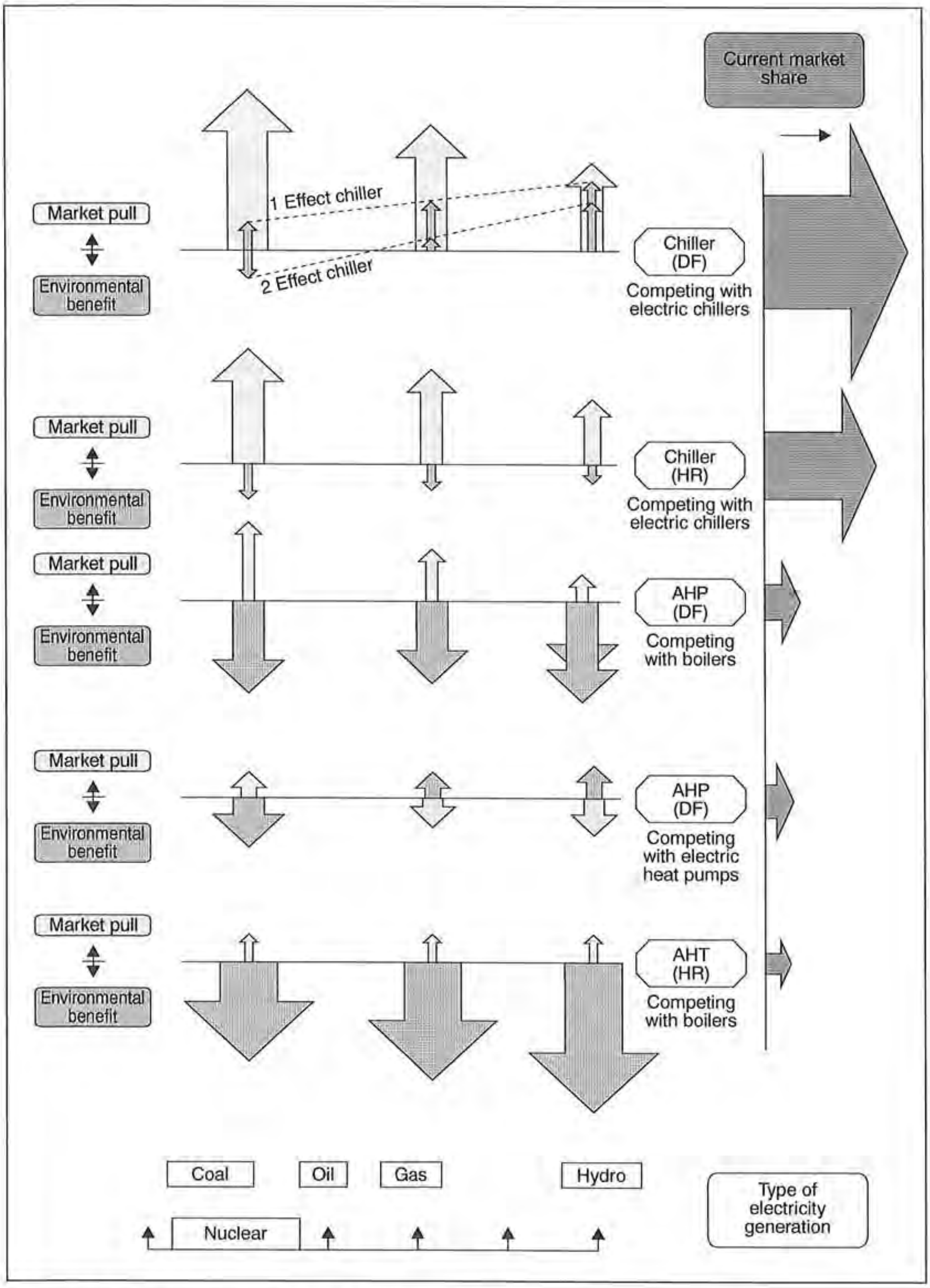

Figure 6.1 *Sorption market and environment.**

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* The area of the arrows (current market share, market pull, environmental benefit) indicate the relative magnitude of the variables. The length and width of the arrows does not provide any additional information.

Market pull in relation to the environmental impact is visualised in the graph of Figure 6.1, which gives indications for the main sorption technologies in terms of the type of electricity production of a hypothetical generic country:

- Absorption chillers, direct-fired or indirectly driven via boilers, competing with electric chillers;
- Absorption chillers, driven by waste heat and CHP (includes *ad*sorption chillers), competing with electric chillers;
- Absorption heat pumps, direct-driven, competing with direct-fired boilers;
- Absorption heat pumps, direct-driven, competing with electric heat pumps; and
- Absorption heat transformers (also AHPs), driven by waste heat, competing with direct-fired boilers.

The electricity production of each country is represented in terms of hydroelectric, natural gas, oil and coal. Nuclear energy is indicated, but with the option of allocating over a wide range of technologies, depending on the decision of each reader as to how he wants to interpret its environmental impact. The graph is a tool for future speculation, as the market and environmental impact on sorption technology of modifying or improving the electricity production of a country can be seen.

The graph makes a direct correlation for electricity generation, between its environmental benefit and cost. In general terms, hydroelectricity is environmentally clean and cheap, whereas coal generation is the opposite. Renewable energy costs are currently still high. However, they are the most environmentally beneficial power production technology. Therefore, renewable energy requires a slightly different representation on the graph, as it will tend to increase the electric energy costs, and so increase the market pull for sorption technology. That is why, in terms of market pull, renewable energy is on the left of the graph (left of coal). However, in terms of the environmental impact it is equivalent to hydroelectric energy, and in this case should be to the right of the graph.

6.1 Interpretation of the graph

Chillers (direct-fired)

Some large Asian countries have coal- or oil-fired power stations, as a result of which direct-gas-fired absorption chillers have a market pull due to the relative prices of fuel. In many cases there are also serious electrical infrastructure limitations. By using absorption chillers, there is also a short-term environmental benefit, as they replace electric chillers powered by these inefficient power stations. In the longer term, however, as the electric infrastructure and efficiency improve, the market pull will reduce and the environmental benefits will disappear. Direct-fired sorption chillers will then have a negative effect on the environment.

Developing multiple-effect chillers cannot correct this, as the COP will always be lower or at best equal to that of an electrically-driven mechanical compression system, as was explained in Chapter 2. In addition, Appendix 4 demonstrates that for ideal cycles, absorption cycles with an infinite number of effects have an equivalent COP to the reverse Carnot cycle of mechanical compression systems. When carrying out comparisons of direct-fired absorption and electrically-driven mechanical compression chillers, it is very important to compare chillers with the same heat rejection method (i.e. air-cooled or water-cooled) as their COPs vary notably in terms of the heat rejection temperature.

Chillers (heat-recovery)
This group of chillers uses hot water or steam from heat recovery or CHP[3]. In using recovered heat from industrial processes to drive the sorption chillers, there will be an environmental benefit in displacing electric chillers. The use of this type of chiller should be promoted strongly for industrial processes and other cooling applications. However, if the absorption chiller is driven by heat from a CHP system, there will not always be an environmental benefit compared to using electric-driven chillers. Their relative impact is very much related to the electric efficiency of the grid compared to that of the CHP system. Future developments will have to be taken into consideration when making choices. More optimistic results are obtained if the overall CHP–absorption system is considered, as absorption chillers have the potential to enable the CHP system to generate more electricity with lower emissions. The relative magnitudes represented on the graph can vary depending on the view taken with regard to the value of the heat recovered. If the heat recovered is considered as waste heat (with no real value), then it will have a lower market pull and higher environmental benefit. The graph illustrates general tendencies for a wide range of heat recovery applications, and a range of interpretations. However, resolving these issues was found to be too complex to achieve within the program of Annex 24, and must be tackled in future work.

*Ad*sorption chillers and desiccant systems are also within this category, as they are driven by low-temperature hot water. *Ad*sorption chillers applied to heat recovery applications have less market pull than direct-fired chillers, but they can produce environmental benefits. The reduced market pull is more associated with the costs of integrating technologies, than the costs of the chillers. Important future opportunities are to be found throughout industry for applications to heat recovery.

Absorption heat pumps
Absorption heat pumps compete both with boilers and electric heat pumps, so both competing technologies were indicated. The double arrow indicated for the environmental benefits within hydroelectric production depends on the type of fuel used for the boilers. As electricity production depends on the types of fuels with an available infrastructure countrywide, it has been assumed that this same fuel is used for the competing boilers. Hence there is a difference of market pull and environmental benefits for each type of generation technology. The same concept applies later to AHTs. Absorption heat pumps have a considerable environmental benefit providing they are competing with fuel-fired boilers. However, in countries with highly efficient and/or clean electricity production, it is better to consider electric-driven heat pumps. For example a country like Canada, which has a cold climate and low electricity costs with relatively low emissions, is better off using electric-driven heat pumps rather than GAX AHPs. Italy and Spain both have cheap natural gas, electricity infrastructural problems, warm and cold climates, so absorption cooling is attractive. This makes them potential markets for dual-purpose (heating and cooling) AHPs. There are important future opportunities in residential and commercial applications, with minor opportunities (though larger plant sizes) within industry. On the other hand, in countries with an extensive gas infrastructure, like most of northern Europe, absorption heat pumps (if available) may have an increased market pull on economic grounds, while based on the high efficiency of electricity production in these countries, electric heat pumps should be favoured.

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[3] CHP by definition does not produce waste heat. Both the electricity and heat produces are the "products" of the system.

Absorption heat transformers

Absorption heat transformers have the best environmental benefits. However, they suffer from lack of market pull due to their high costs relative to boilers. The future applications of this technology are seen to be within industry [3, 30, 31].

Compression-absorption heat pumps

Not represented on the graph are the compression-absorption (hybrid) electric-driven heat pumps, which can achieve higher temperatures than standard electric heat pumps. If we regard this type of high-temperature heat pump as operating in a heat sink temperature region which it is not possible for electric heat pumps to achieve (due to the phasing out of CFC114), boilers would be the competing technology. These are particularly interesting in countries with mostly hydroelectric generation such as Norway, as electricity prices are very low, and sometimes even cheaper than gas and oil. Also, within industrial companies where co-generation is already installed, it is possible to expand on industrial production using the low-cost electricity for driving the CHP. Such systems have a good market pull together with excellent environmental benefits, when competing with boilers. When electricity is produced from gas, there are also good environmental benefits and an attractive market pull.

A summary of the world would indicate several regions:

- *Asia*: Lack of electric infrastructure drives direct-fired absorption chillers;
- *The USA*: High electricity costs drive direct-fired and boiler-driven absorption chillers;
- *Scandinavia/Canada*: Clean and cheap electricity, and cold climates drive electric heat pumps. Expansion may require the use of combined-cycle gas turbines (CCGT) and marketing for heat recovery absorption chillers;
- *Northern Europe*: Potential for AHPs in existing gas infrastructures;
- *Central/South Europe*: Market for chillers with recovered heat; and
- *Rest of the world*: Extremely low market penetration to date.

The most significant finding of the graph is that, for sorption technology overall, *there is an inverse relationship between the environmental benefit and the market pull (and market share).*

7. Conclusions

The Annex concluded that sorption technology offers real opportunities for environmental and economic benefits, provided the best-suited technology is applied to each country. Avoid generalised statements that they are always economically and environmentally beneficial. In some cases they are beneficial, and in others they are not. This depends mainly on the type of energy sources available, and the efficiency of generation of mains electricity.

In economic terms, the main driving force for the adoption of sorption technology is identified as first costs. Unfortunately, the graph of Figure 6.1, developed under the Annex, indicated an inverse relationship between market pull/penetration and environmental benefits. To promote sorption technology via its environmental benefits, it is advisable to place economic values on the environmental benefits. This can be done via government policies and taxes, e.g. carbon taxes. In the remainder of this chapter, conclusions relating to the different types of absorption machine are individually discussed.

7.1 Absorption chillers

Direct-fired absorption chillers can be economically competitive, but generally consume more primary energy than competing technologies. It is therefore preferable to apply absorption chillers to heat recovery applications at lower heat source temperatures[4]. In fact, single-effect chillers have been launched on the market recently which have been designed for lower high-temperature heat source temperatures than conventional absorption chillers. Together with heat recovery applications and CHP, these systems have an important market pull and offer environmental benefits in the short term. In the longer term, heat recovery 'only' installations are preferred, as CHP systems have the risk of being outperformed by better efficiency of central electricity generation. This development depends on the pace of replacement of existing by renewable and less CO_2-emitting generation systems. The concepts of using heat recovery, waste heat and heat supplied from CHP systems to drive sorption systems need further work. The issues to be resolved are the cost to be allocated to different qualities and categories of heat (i.e. waste, recovered and from CHP), together with the scope of system to be analysed (i.e. the chiller only, part or entire system).

7.2 Absorption heat pumps

Absorption heat pumps (AHPs) have significant environmental benefits when competing with gas-fired boilers. For residential as well as commercial buildings in colder climates, they can become the future method of heating and cooling for the existing building stock which is connected to the gas-grid. Their economic case can be improved if they combine heating with cooling, so that they become absorption heat pump/chillers (see also Annex 25). In this way the market pull is provided in conjunction with the environmental benefits, in both the short and medium term.

For the residential sector, smaller AHPs are needed to service the future market for new buildings, as the heat demand for this type of building is decreasing. The only way to deliver heat with available AHPs is to combine the heat demand of groups of buildings or apartment blocks.

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[4] As the main thermodynamic losses are between the combustion process and the generator, it is better to supply heat near to the required temperatures (to avoid irreversibilities)

In the greenhouse sector AHPs are a viable solution to cover the low-temperature heat demand, as the AHP is able to deliver other utility needs, like cooling and dehumidification as well. For industry, the AHP seems to be viable only with low-temperature heat demands.

7.3 Absorption heat transformers

Absorption heat transformers (AHTs), normally applied in industry, are driven by waste heat. They offer the best environmental benefit, together with AHPs if the latter are also using waste heat. However, bespoke applications reduce the scope for marketing and increase the engineering costs. In addition, heat transformers have not been very successful in industrial applications, because of the changing nature of heat demands, and the difficulty of dealing effectively with partial loads. In static applications, with waste incineration plants delivering base load, heat transformers can be applied successfully. A long-term future is seen for these machines.

7.4 Compression-absorption heat pumps

Compression-absorption heat pumps are one of the most promising new developments for increasing the output temperature of heat pumps. The main market potential is in high-temperature applications in industry, when vapour compression cannot meet the requirements, especially in countries with cheap electricity (e.g hydro-electricity as in Norway). Although these units are not commercially available yet, it is thought that they could have better opportunities than absorption heat transformers.

7.5 *Ad*sorption systems

*Ad*sorption systems have lower thermodynamic efficiencies (lower COPs) than absorption systems. Their main advantage is that they can be driven by a lower temperature heat source, which makes them applicable to a wider range of waste heat applications than the majority of absorption systems. They also have some other technical advantages (simpler, potential for wider range of applications and compact units, no levelling requirements). If costs are low enough, they could compete with small-scale absorption heat pumps. Their other possible applications include transport refrigeration and cooling, and food preservation in remote areas (e.g. solar cooling). Also, vehicle air conditioning is a possibility.

7.6 Research and development (R&D)

R&D for sorption technology should focus on the above developments, but the reduction of capital costs rather than the improvement of COPs should be the main focus. There is probably more potential in enhancing the thermodynamic efficiency of a single-effect absorption chiller by improving the efficiency of its heat exchangers, rather than by trying to improve the COP with complicated and hence costly multiple-effect cycle systems.

For sorption chillers, R&D should focus on:
- Reducing costs (life-cycle costs and capital costs) of integrated systems; and
- Increasing the efficiency of generators at lower driving temperatures.

In the residential sector, sorption heat pumps tend to compete mainly with boilers, so R&D should focus on:

- Decreasing the size, to be able to reduce capital costs;
- Using the same unit for cooling and heating; and
- Increasing the temperature level, to be able to deliver hot water.

Both absorption and *ad*sorption systems should be considered for residential and light commercial applications.

For industrial countries, the compression-absorption heat pump is of particular interest. It will have a market pull in these countries, for which R&D can be recommended.

8. Recommendations for Future Work

Future work should mainly focus on the applications of sorption machines to heat recovery, waste heat or process heat. With regard to CHP, work should be carried out to establish the benefits of applying absorption systems, and promoting their use when they are environmentally beneficial. Absorption chillers used with waste heat applications and CHP are an available technology that already has considerable market pull, though not as much as direct-fired chillers. This is an aspect where a future Annex could obtain some really useful results, that could be applied to the existing market in the short- and medium-term. Within this field the following work could be investigated and carried out:

8.1 Waste heat / heat recovery / process heat

Waste heat is heat that is not required by the process, and would otherwise only be dissipated to the environment, e.g. the heat recovered in flue-gas cleaning. Recovery of such heat normally requires that some system parameters have to be modified, so as to provide heat at a useful temperature, e.g. chiller condenser heat to produce domestic hot water. Process heat is necessarily produced and consumed as part of an integral system, e.g. CHP heat. The principles need further work in terms of concept, applications, practicality, cost and environmental impact. The term 'heat recovery' describes and groups all of these.

8.2 Taxes or economic incentives

Taxes such as CO_2 taxes, or exemption from energy levies for heat recovery are recommended, with further economic incentives when the systems include absorption chillers. Due to the inverse relationship between market pull/penetration and environmental benefits, there is need to investigate how a monetary value can best be placed on the environmental benefits. This should include a review of incentive schemes in place in participating countries, together with an assessment of their effectiveness. It is also necessary to decide how such schemes can be specifically managed, e.g. via policies and taxes (carbon taxes).

8.3 System capital cost reduction studies

Absorption chillers used for heat recovery suffer from the drawback of higher capital costs to recover the heat compared to electrically-driven machines. This puts absorption systems used in such situations at a clear disadvantage, as can be seen from the relative world market penetration of this technology. Thermo-economic optimisation enables objective functions including system capital costs to be minimised. Heat recovery, CHP and absorption systems are key candidates for this type of optimisation, as most products (industrial process, engines-turbines, and absorption chillers) were developed as stand-alone plant. For instance, absorption chillers were designed originally for steam at 1 bar gauge, but now require lower temperatures to suit a wider range of applications. A new approach is required, whereby an integrated view of the overall system design is taken. There is a manufacturer of absorption chillers which produces low hot water temperature chillers with higher COPs than *ad*sorption chillers. This type of technology should be encouraged, as it makes overall heat recovery systems with sorption schemes more efficient.

8.4 Environmental benefits

It is important not to promote the technology blindly, but to understand fully the situation of competing technologies, both in economic and environmental terms for each particular country. Future projections should be made for each country in terms of its national production of electricity, because the national efficiencies are constantly improving with the introduction of newer technologies. The same considerations apply to competing electric-driven mechanical compression chillers or heat pumps. For this reason, a robust methodology will be developed, allowing each country to evaluate the environmental impact, and report on it. It will be assessed over the life of a system, to provide the most realistic picture. It will also serve to predict future tendencies, and the life expectancy of the new emerging technologies.

8.5 New potential markets

It is desirable to investigate other markets, especially in industry, where heat recovery opportunities for sorption systems have had low penetration, probably due to reliability concerns. This is very much the case in industrial process industries, financial institutions, and food retailing, where downtime is very costly. It is proposed to review the reliability requirements of these markets, and to establish criteria for designing suitable systems. Participating countries would be able to concentrate on these applications as case studies. This requires a detailed review of the applications in each country, especially in industry.

8.6 Good demonstration projects

To implement the first five recommendations, it will be necessary to form a collection of good-practice case studies. It will be necessary to hold extensive workshops in industry, with the relevant process engineers rather than site energy managers. A new website should be used for dissemination of information, as well as to invite industry to participate. It is recommended to use the multiple shell layer concept, starting optimisation from the core process, then working towards the intermediate stages before analysing the energy supplies to the overall system.

Details of future work still have to be resolved regarding objectives, work plan, time-scales, budget, participants, and operating agent.

Appendices

Appendix 1: National Contacts, IEA Annex 24

Canada

CANMET Energy Diversification Research Laboratory
Energy Diversification Research Laboratory
Natural Resources Canada
Post Office Box 4800
1615 Lionel-Boulet Boulevard Varennes
Quebec, Canada J3X 1S6.
Contact Person: Daniel Giguere
Phone: +1 450 652 5015
Fax: +1 450 652 5177
E-mail: dgiguere@nrcan.gc.ca

Italy

ItalGas
L.Go Regio Parco No. 11
10152 Torino
Italy
Contact Person: Franco Canci
Phone: +39 011 239 4865
Fax: +39 011 239 4889
E-mail: itgstuit.italgas@italgas.inet.it

Japan

Heat Pump & Thermal Storage Technology Center of Japan
F Bldg. 6F
1-28-5, Nihonbashi Kakigara-cho,
Chiyoda-ku, Tokyo 103-0014
Japan
Contact Person: Takeshi Yoshii
Phone: +81 3 5643 2401
Fax: +81 3 5641 4501
E-mail: li@host2.hptcj-unet.ocn.ne.jp

Norway

Institute for Energy Technology
Energy Systems Department
P.O. Box 40, 2027 Kjeller
Norway.
Contact Person: Svein Grandum
Phone: +47 63 806378
Fax: +47 63 812905
E-mail: Svein.Grandum@ife.no

Sweden (OA)

Royal Institute of Technology
Department of Chemical Engineering and Technology
Division of Transport Phenomena, Stockholm,
Sweden.
Contact Person: Professor Fredrik Setterwall
Phone: +46 8 790 6719
Fax: +46 8 10 52 28
E-mail: setter@ket.kth.se

Swedish Energy Administration
Department of Power Technologies
Box 310
63104 Eskilstuna
Sweden.
Contact Person: Magnus Gustafsson
Phone: +46 16 544 2106
Fax: + 46 16 544 2116
E-mail: magnus.gustafsson@stem.se

The Netherlands

GASTEC NV
P.O. Box 137
NL-7300 AC Apeldoorn
The Netherlands.
Contact Person: Harry Hondeman
Phone: +31 55 5393 347
Fax: +31 55 5393 223
E-mail: hmn@mailhost.gastec.nl

NOVEM
Catharijnesingel 59, 3511 GG Utrecht
P.O. Box 8242, 3503 RE UTRECHT
The Netherlands.
Contact Person: Onno Kleefkens
Phone: +31 30 2393 449
Fax: +31 30 2316 491
E-mail: o.kleefkens@novem.nl

United Kingdom

Waterman Gore
Mechanical and Electrical Engineers
Versailles Court
3 Paris Garden
London SE1 4ND
UK.
Contact Person: Robert Tozer
Phone: +44 20 7928 7799
Fax: +44 20 7620 2993
E-mail: r.m.tozer@waterman-group.co.uk

ETSU
Harwell
Oxfordshire
OX11 0RA
UK.
Contact Person: Jeremy Tait
Phone: +44 1235 432361
Fax: +44 1235 432144
E-mail: jeremy.tait@aeat.co.uk

United States

Oak Ridge National Laboratory
600 Maryland Ave.,SW, Suite 306W
Washington DC 20024
USA.
Contact Person: Patti Garland
Phone: +1 202 479 0292
Fax: +1 202 479 0575
E-mail: pwe@ornl.gov

International

IEA Heat Pump Centre
P.O. Box 17
6130 AA Sittard,
The Netherlands.
Contact Person: Jos Bouma
Phone: +31 46 4202 236
Fax: +31 46 4510 389
E-mail: hpc@heatpumpcentre.org

Appendix 2: Manufacturers of Sorption Equipment*

(*Water/LiBr equipment unless otherwise stated.)

Japan

Daikin Industries Ltd, 1-1Nishihitotsuya, Settsu-City, Osaka 566, Japan
http://www.nni.nikkei.co.jp
Direct gas-fired NH_3/H_2O absorption refrigeration plants
(License: Deutsche Babcock Borsig AG)
Absorption chillers (H_2O/LiBr)

Ebara Corporation, 11-1 Haneda Asahi-cho, Ota-ku, Tokyo 144, Japan
http://www.ebara.co.jp/
Double-effect absorption chillers
(300 – 2,000 kW)
Single-effect absorption chillers
(300 – 5,000 kW)

Hitachi Ltd, 6 Kanada – Surugadai 4-chome, Chiyoda-ku, Tokyo 101, Japan
http://www.hitachi.co.jp/
Steam-fired, double-effect absorption chillers
(400 – 6,000 kW)
Steam-fired, single-effect absorption chillers
(100 – 5,000 kW)
Direct-fired double-effect absorption chiller/heater
(70 – 5,000 kW)

Kawasaki, Japan
Direct-fired, double-effect absorption chiller/heater
(350 – 5000 kW)
Hot water absorption chiller
(350 – 5000 kW)
Steam absorption chiller, double effect
(350 – 5000 kW)

Mitsubitsi Heavy Industries Ltd, 5-1 Marunouchi 2-chome, Chiyoda-ku, Tokyo, Japan
Direct-fired, double-effect absorption chiller/heater
(350 – 5000 kW)
Hot water absorption chiller
(350 – 5000 kW)
Steam absorption chiller, double effect
(350 – 5000 kW)

Mycom Tokyo Overseas Planning Department
Phone: + 81 3 3642 8088 Fax: + 81 3 3643 70 94
*Ad*sorption type refrigeration machine using water/silica gel

Nishiyodo-kucho, Japan
Adsorption chillers

Sanyo Electric Co., 1-1-1, Sakata Oizumi-Machi, Ora-Gun, Gunma, Japan
http://kuchosys.sanyo.co.jp
Direct-fired, double-effect absorption chiller/heater (double) (350 – 5300 kW)
Hot water absorption chiller
(100 – 1900 kW)
Steam absorption chiller, double effect
(350 – 5300 kW)
Absorption heat pumps

Yazaki Corporation, 1370 Koyasu-cho, Hamamatsu-shi, Shizuoka 435-8575, Japan
http://www.yazaki.com
Water-driven, single-effect absorption chillers
(15 – 180 kW)
Direct-fired, double-effect absorption chiller/heater
(30 – 700 kW)

The Netherlands

Colibri bv, Tentstraat 5a, 6291 BC Vaals, The Netherlands
http://www.colibri-stork.nl
Ammonia/water absorption chillers and heat pumps

Stork Ketels bv , PO Box 20, 7550 GB Hengelo, The Netherlands
Industrial ammonia units

USA

Broad, North American Office, 1 World Trade Center Suite, 7929 NYC 10048, USA
http://www.broad.com
Direct-fired absorption chiller-heater
(350 – 9,350 kW)

Carrier Corporation, P.O. Box 4808, Syracuse, N.Y. 13221 USA
http://www.carrier.com
Direct-fired double-effect absorption chiller/heaters
(2,000 – 12,500 kW)
Indirect-driven single-effect absorption chiller
(350 to 2,400 kW)
Double-effect absorption chiller
(350 to 6,000 kW)

Dunham-Bush, Dunham-Bush Inc, 101 Burgess Road, Harrisburg, VA 22801, USA
Direct-fired, double-effect chiller
(350 – 2,800 kW)
Indirect-driven, double-effect chiller
(350 – 5,000 kW)
Indirect-driven, single-effect chiller
(350 – 5,000 kW)

Energy Concepts Co., 627 Ridgely Avenue, STE 3, Annapolis, MD 21401-0106, USA
http://members.aol.com/enerconcep
Ammonia/water absorption chillers

LG Machinery, Overseas sales network, 604 Albion Avenue, Schaumburg, IL 60193, USA
http://www.lgmach.com/eng/air01.htm
Absorption chillers (direct-fired and hot water/steam-driven (single + double-effect)
(354 - 700 kW)
Chiller - heaters
(180 – 5,000 kW)

McQuay International, Chiller Products Group, P.O. Box 2510, Staunton, VA 24402, USA
http://www.mcquay.com
Direct-fired, double-effect chiller-heater

(70 – 5,400 kW)
Indirect-driven, double-effect chiller (70 – 5,400 kW)

Robur Corporation, 2300 Lynch Road, P.O. Box 3792, Evansville, IN 4771, USA
http://www.robur.com
Direct-fired, single-effect ammonia / water chiller-heater
(10 – 20 kW)
Direct-fired, single-effect ammonia / water chiller
(10 – 20 kW)
Direct-fired, single-effect ammonia / water chiller, GAX
(10 – 20 kW)

The Trane Company, 3600 Pammel Creek Road, La Crosse, WI 54601-7599, USA
http://www.trane.com
Direct-fired, double-effect chiller
(300 – 4,000 kW)
Direct-fired, double-effect chiller-heater
(350 – 4,000 kW)
Indirect-driven, double-effect chiller
(1,400 – 4,000 kW)
Indirect-driven, single-effect chiller
(350 – 6,000 kW)

York International Corp, 631 South Richland Avenue,York, PA 17403. USA
http://www.york.com.
Direct-fired, double-effect chiller-heater
(400 – 5,500 kW)
Indirect-driven, double-effect chiller
(900 – 5,500 kW)
Single-effect chiller
(400 – 5,000 kW)

China

Broad Air Conditioning Co Ltd, Broad City, Changsha, Hunan 410001, China
Fax: +86 731 443 7505. Broad@public.cs.hn.cn, http://www.broad.com
Direct-fired double-effect chiller-heaters
(116 – 9304 kW)
Steam-driven double-effect absorption chiller
(116 – 9304 kW)
Direct-fired chiller-heater-cooling tower packaged unit
(116 – 872 kW)

Dalian Sanyo Refrigeration Co, Ltd, 31 Economical Technology Development Zone, Dalian, Liaoning,116600, China. Fax: +86 411 731 6276
Steam-driven double-effect absorption chillers
(281 – 4466 kW)
Hot-water-driven absorption chiller
(1126 - 4220 kW)
Direct-fired double-effect chiller-heaters
(352– 5274 kW)
Direct-fired chiller-heater-cooling tower packaged unit
(70 – 281 kW)

Guangdong Lifeng Air-conditioner Co Ltd, 836 East Dongfeng Road, Guangzhou Guangdong 510080, China. Fax: +86 20 8760 5329
Steam-driven double-effect absorption chillers
(350 – 3500 kW)
Direct-fired double-effect chiller-heaters
(350 – 3500 kW)

Jiangsu Shuangliang Group Corporation, Ligang Town, Jiangyin, Jiangsu 214444 China
Fax: +86 510 663 1333. Xxzx.sl@public.wx.js.cn, http://shuangliang.com.cn
Direct-fired double-effect chiller-heaters
(233– 5234 kW)
Steam-driven double-effect absorption chillers
(291 – 5234 kW)
Hot-water-driven absorption chiller
(350 - 4650 kW)

Kaifeng General Machinery Factory, 43 Xinmenguan Street, Kaifeng, Henan 475003 China.
Fax: +86 378 595 7788
Direct-fired double-effect chiller-heaters
(240– 3500 kW)
Steam-driven double-effect absorption chillers
(300– 3600 kW)

Kuenshan Lithium Bromide Refrigerating Machinery, Zhoushi Town, Kuenshan,
Jiangsu 215314, China. Tel: +86 520 762 1151
Direct-fired double-effect chiller-heaters
Steam-driven single-effect absorption chillers
Steam-driven double-effect absorption chillers
Hot-water-driven absorption chiller

Qingdao LG – Tonghe Air Conditioning Equipment Co Ltd, Tonghe Street, Pingdu City,
Qingdao, Shandong 266706, China. Fax: +86 532 731 207. Tonghe@public.qd.sd.cn
Direct-fired double-effect chiller-heaters
(176 – 4036 kW)
Steam-driven double-effect absorption chillers
(351– 4036 kW)

Shanghai First Refrigerating Machinery Works, 1199 Jiang Pu Road Shanghai 200092
China. Fax: +86 21 6541 6170
Steam-driven single-effect absorption chillers
Steam-driven double-effect absorption chillers

Shanghai Pudong Lithium Bromide Refrigerating Machinery, Gugao Road, Pudong,
Shanghai 201209, China. Fax: +86 21 5863 3702
Steam-driven double-effect absorption chillers
(291– 4071 kW)
Direct-fired double-effect chiller-heaters
(233 – 4071 kW)

Shanghai Senma Group Air-conditioner Co Ltd, Beisong Road, Maqiao Town, Minghang,
Shanghai 201111, China. Fax: +86 21 6409 2506
Direct-fired double-effect chiller-heaters
(58 – 3489 kW)
Steam-driven double-effect absorption chillers
(349– 3489 kW)
Hot-water-driven absorption chiller
(349– 2908 kW)

Shanghai Takuma Thermal Energy System Co Ltd, 716 Ping Liang Road, 4F Shanghai,
200082, China. Fax: +86 21 6546 9467
Direct-fired double-effect chiller-heaters
(106 – 352 kW)
Steam-driven double-effect chiller-heaters
(106 – 176 kW)

Shanghai Worldbest Refrigeration & Air Conditioning Equipment Co Ltd, 1958 North Zhongshan Road, 7F Shanghai 200063, China. Fax: +86 21 6203 2496. Swai@uninet.com.cn
Direct-fired double-effect chiller-heaters
(350 – 3500 kW)
Direct-fired chiller-heater-cooling tower packaged unit
(106 – 352 kW)

Shanghai Yi Leng Carrier Air Conditioning Equipment Co, Ltd, 1200 Jiang Pu Road Shanghai 200092, China. Fax: +86 21 6512 9357. E-mail: YLCB@PUBLICL.STA.NET.CN
Steam-driven double-effect absorption chillers
(352 – 5980 kW)
Direct-fired double-effect chiller-heaters
(475 – 3516 kW)
Steam-driven single-effect absorption chiller
(334 - 4853 kW)
Hot-water-driven absorption chiller
(211 - 4853 kW)

Yantai Ebara Air Conditioning Equipment Co Ltd, 80 Xishan Rd, Yantai, Shandong 264000, China. Fax: +86 535 664 8315
Steam-driven double-effect absorption chillers
(545– 5274 kW)
Direct-fired double-effect chiller-heaters
(527 – 2451 kW)

Zhejiang Lianfeng Group Co Ltd, 24 Lianfeng Rd., Shangyu, Zhejiang 312300, China Fax:+86.575.201.2719. Public@lianfeng.com http://www.lianfeng.com
Direct-fired double-effect chiller-heaters
(233– 5234 kW)
Steam-driven /hot-water-driven single-effect absorption chillers
Steam-driven double-effect absorption chillers

France

Entropie SA, 17 Rue Thiers – BP 6103, 78176 St Germain en Laye Cedex, France
http://www.entropie.com
Low hot-water temperature-driven absorption chillers
(300 kW – 6,000 kW)

Germany

AWT Absorptions-und Wärmetechnik GmbH, Gennaer Strasse 76, D-58642, Iserlohn, Germany. Phone: +49 2374 138 23, Fax: +49 2374 152 96
Direct-gas-fired ammonia absorption heat pumps
(22 and 40 kW)

Hans Guntner GmbH & Co (Borsig System), Miraustraße 54, D-13509 Berlin,
Germany
http://www.guentner.de
Ammonia/water absorption chillers

India

Thermax Ltd, Absorption cooling division, Chinchwad, Pune 411019, India
http://indiabuildnet.com/3006/thermax_1.html
Direct-fired. double-effect chiller-heaters
(300 – 1,800 kW)
Single-effect absorption chillers
(300 – 4,000 kW)
Double-effect absorption chillers
(300 – 4,000 kW)

Korea

Bumyang Air Conditioning Co., Ltd., 689-4, Guemjeong-dong, Gunpo, Kyunggi-do,
435-050, Korea
Phone: +82 343 452 5701, Fax: +82 343 453 8176, e-mail: george2@unitel.co.kr
http://www.bac.co.kr/
Absorption chillers/heaters

Daewoo Carrier Corporation, 981-11 Jangdeck-dong, Kwangsan-gu, Kwangjoo 506-251,
Korea
Phone: +82-62-951-9100, Fax: +82 62 951 9870
http://carrier.co.kr/main_e.htm
Absorption chillers

Hyundai Heavy Industries Co. Ltd., 1, Cheonha-dong, Dong-gu, Ulsan, 682-792, Korea
Phone: +82 52 230 3371/7, Fax: +82 52 230 3467
http://www.hhi.co.kr/korea/plant/product/airconditioning/main.html
Absorption chillers/heaters

Kuyungwon-Century Co. Ltd. 222-22 Naedong, Ojung-ku Buchun-si, 421-160 Naedong
Republic of Korea
Double-effect steam absorption chillers
(280 – 5,300 kW)
Direct-fired double-effect absorption chiller – heaters
(70 – 5,300 kW)

Kyungdong Boiler Co., Ltd., 437, Sekyo-dong, Pyungtaek, Kyunggi-do 450-100
Phone: +82 333 652 6564, Fax: +82 333 652 6566
http://www.kita.or.kr/catalog/kyungdong/
Absorption chiller-heater
(110 – 350 kW)

LG Cable Ltd., 200, Dangjung-dong, Gunpo-si, Kyounggi-do, 435-712, Korea
Phone: +82 31 450 3390, Fax: +82 31 450 3077, E-mail: chals@ofmail.mach.lg.co.kr,
http://www.lgmach.com/eng/air01.htm
Double-effect, direct-fired chiller-heater
(180 - 5300 kW)
Double-effect, steam-driven chiller
(350 - 5300 kW)
Single-effect, steam-driven chiller
(350 - 7100 kW)
Single-effect, hot-water-driven chiller
(350 - 3600 kW)
Custom-built units

Mando Machinery, Korea

Samsung Heavy Industries Co., Ltd., 40-1, Woongnam-dong, Changwon, Kyungnam
641-290, Korea. Phone: +82 551 260 6000; Fax: +82 551 260 8310
Absorption chillers

Samwon Machinery Co., Ltd., 639-19, Deungchon-dong, Kanseo-gu, Seoul 157-030, Korea
Phone: +82 2 3661 8872, Fax: +82 2 3663 1352
Absorption chillers/heaters

Appendix 3: The Absorption Heat Pump Cycle

A3.1 Single-stage water/LiBr absorption machines (single-effect)

As an example, the cycle for the working pair water/lithium bromide (LiBr) is described. The basic principles of the ammonia/water cycle are the same, with the exception of rectification requirements.

The boiling point[1] of a solution of LiBr and water is higher than that of pure water, given that the pressure in both cases is equal. The higher the concentration of the solution, the higher the boiling point of the solution compared to that of the pure water. This also means that the saturated vapour pressure above pure water is higher than the saturated vapour pressure above the solution of LiBr and water at equal temperature.

The evaporator

Water can boil at very low temperatures, even at temperatures about 0°C, provided that the pressure is low enough (near vacuum). A closed vessel in which water and vapour are at equilibrium at e.g. 4°C has an absolute pressure of 8 millibar. The water in this vessel will start boiling when heat of a temperature above 4°C is added to it. The vapour coming from the boiling water will increase the vapour pressure, and therefore the boiling temperature, until again there is an equilibrium between vapour and liquid. Only if the vapour is taken away can the water keep on boiling at 4°C. This can be achieved by connecting an absorber to the evaporating vessel.

The absorber

As mentioned in Chapter 2, the saturated vapour pressure above the concentrated water/LiBr solution is lower than the saturation pressure of pure water. This means that the vapour from the boiling evaporator will flow to the absorber. Since the resulting pressure in the absorber will still be higher than the saturation pressure of the solution, there will be a flow of vapour to the solution. In other words, there will be absorption. Heat effects occurring with absorption are the release of latent heat of condensation of the absorbed vapour, and heat which releases when water is mixed into the solution (heat of solution). Both heat flows cause an increase in temperature of the solution, thus reducing the driving force for absorption. The process will even stop if due to temperature rise the saturated pressure above the solution becomes equal to that of the evaporator. Therefore, to keep the process running, heat has to be withdrawn from the absorber, at e.g. 40°C.

Another effect of the absorption of water vapour is that the solution in the absorber becomes less concentrated. This also reduces the driving force for absorption and would eventually stop the absorption process. To make a continuous cycle, a device has to be added to reconcentrate the solution.

---

[1] A boiling point is a situation in which solution and vapour are at equilibrium. An increase in temperature would directly lead to boiling and an increase in pressure. A decrease in temperature would lead to condensation and a decrease in pressure.

The concentrator (desorber, generator)
From the absorber, lean solution is transferred to the concentrator, usually referred to as the generator or desorber. There the solution is heated to above its boiling temperature, so releasing water vapour and concentrating the remaining solution. The concentrated solution is fed back to the absorber. The heat which has to be added to the generator consists of latent heat of evaporation and heat of solution. The three main possible ways of heating the generator are direct-fired, steam-driven and hot-water-driven. Besides using fossil fuel to drive the sorption process it also offers the possibility of using waste heat for the purpose.

Since the temperature of the generator is higher than that of the absorber, the pressure in the generator is also higher. Therefore, to transfer lean solution from the absorber to the generator, a pump is needed to overcome the pressure difference between the two. The vapour produced in the generator has a higher pressure than the vapour absorbed in the absorber. If the absorption cycle as a whole is considered as a black box, it is a heat-driven vapour compression device.

The condenser
As in a mechanical compression-driven heat pump cycle, the compressed vapour condenses in the condenser, releasing heat at e.g. 40°C. After this the pressure of the condensate is reduced, then it is fed to the evaporator, thus closing the cycle.

A3.2 Energy balance

The following figures give an indication of the energy flows occurring in the sorption heat pump cycle. As shown in Figure A3.1, the magnitude of the internal heat flow has important repercussions on the cycle efficiency. Figure A3.2 shows the energy flows in a solution heat exchanger.

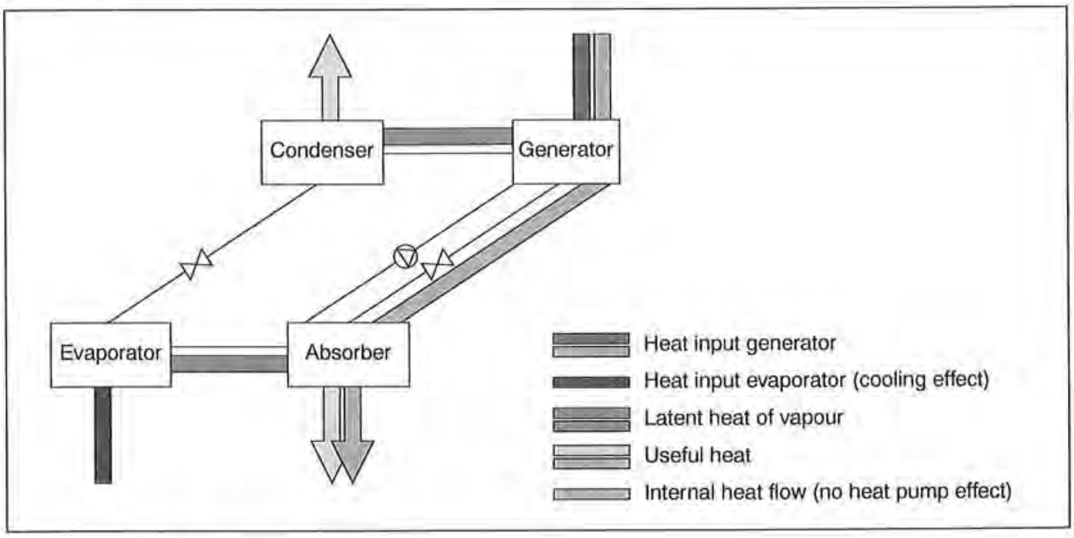

Figure A3.1 *The energy flows.*

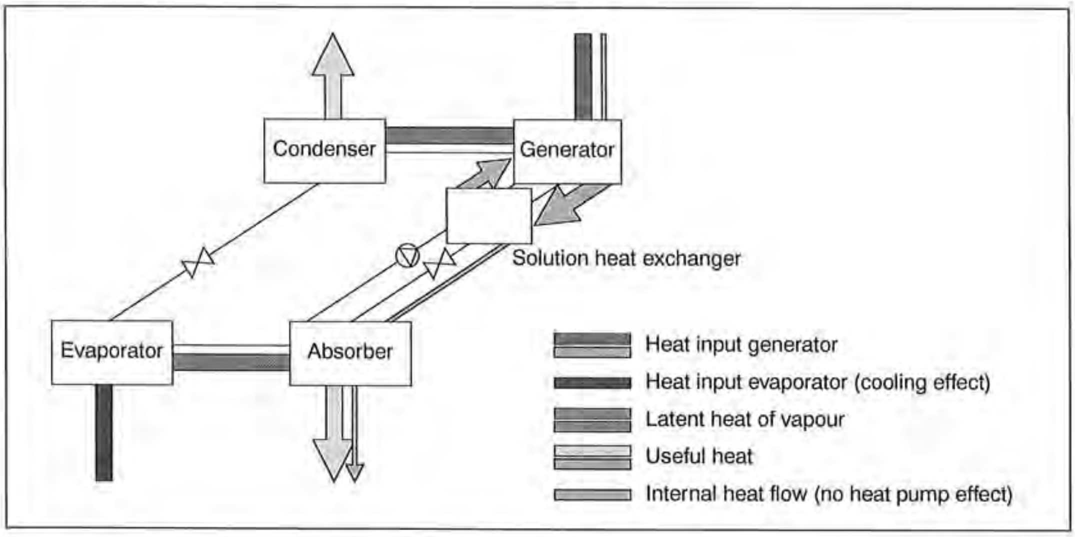

Figure A3.2 *The energy flows with a solution heat exchanger.*

Appendix 4: Sorption Thermodynamics

A4.1 Introduction

Although the thermodynamic description is related to absorption chiller cycles, the summary at the end of this Appendix provides the thermodynamic equations and results for absorption heat pumps (AHPs) and absorption heat transformers (AHTs). Absorption cycles operate on the principle of refrigerant being absorbed by a chemical solution, normally water/LiBr or ammonia/water.

It is assumed that the reader is familiar with the basic absorption cycle. However, for clarity a chiller schematic is shown in Figure A4.1. The top part of the unit is the driving cycle, where heat is supplied to the generator to boil off refrigerant that is condensed in the condenser. It also concentrates the solution (say water/LiBr) and supplies it via the solution heat exchanger to the cooling sub-cycle (evaporator and absorber), so enabling it to absorb more refrigerant. The main heat exchanges with the environment are:

- High-temperature heat source: generator (i.e. steam, hot water, combustion);
- Medium-temperature heat sink: absorber and condenser (i.e. cooling tower condenser water); and
- Low-temperature heat source: evaporator (chilled water).

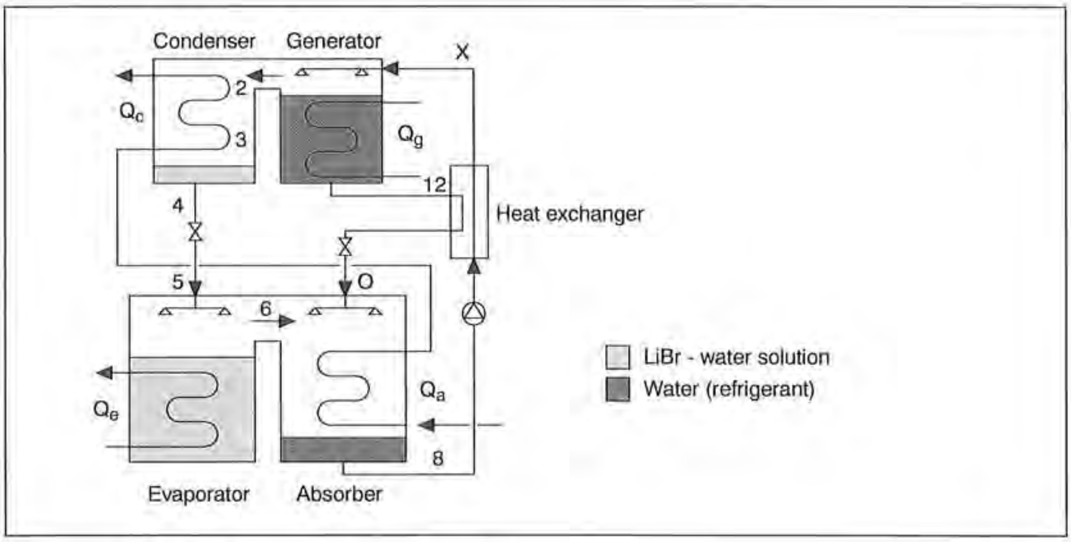

Figure A4.1 *Single-stage absorption chiller.*

The cycle is represented on the pressure-temperature concentration (PTX) diagram in Figure A4.2. The horizontal line indicates solution temperature, and the line inclined at 45° represents the pure refrigerant (water). From this line the vertical saturation pressure axis values are determined. The constant concentration lines commence from the refrigerant line and indicate percentage of LiBr. A very similar representation can be done on the Dühring diagram, which uses different scales: ln(P) and (–1/T). Two circuits (refrigerant and solution) can be identified on the PTX diagram: the left-hand side anti-clockwise quadrilateral (refrigerant circuit), and the right-hand side clockwise quadrilateral (solution circuit). It should be noted that each of the evaporation and condensation points indicates two phases: saturated liquid and vapour.

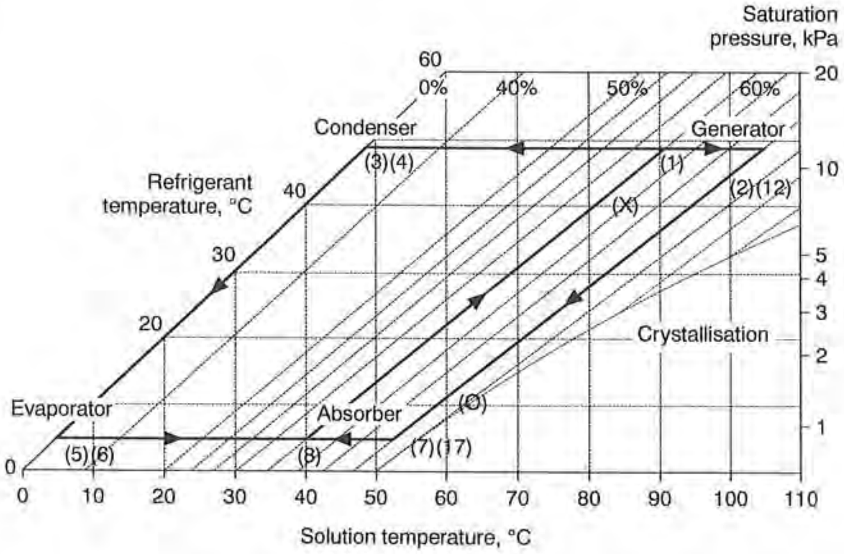

Figure A4.2 Single-effect absorption cycle on PTX diagram.

A4.2 Heat-driven cooling cycles

Absorption cycles can be associated with heat-driven cooling cycles, such as the case of a heat-driven power cycle that drives a mechanical compression refrigeration system described by Herold et al [25], as indicated in Figure A4.3.

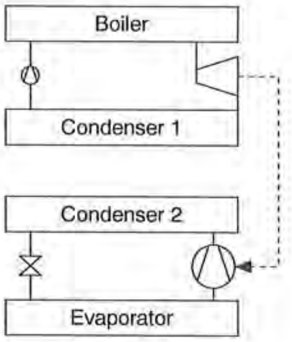

Figure A4.3 Driving and cooling cycles.

Heat is supplied from a high-temperature heat source (generator or boiler) and from a low-temperature heat source (evaporator), and all this heat is released to a medium-temperature heat sink (absorber and condenser). The heat flows of a generalised absorption cycle are indicated in the following Figure A4.4.

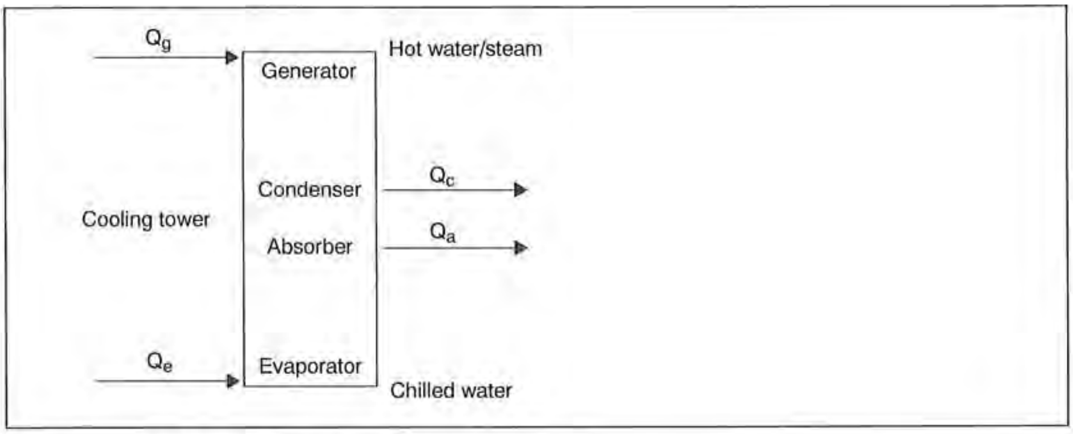

Figure A4.4 *Heat flows of an absorption cycle.*

Although absorption chillers require small pumps to circulate/recirculate solution and refrigerant, for ideal cycles these can be considered negligible. By applying the first law of thermodynamics to the above:

$$Q_e + Q_g = Q_a + Q_c \tag{1}$$

If the second law of thermodynamics is applied, the total generation of entropy will be zero as we are analysing an ideal cycle.

$$\frac{Q_e}{T_e} + \frac{Q_g}{T_g} = \frac{Q_a}{T_a} + \frac{Q_c}{T_c} \tag{2}$$

If the following assumptions are made, which are further explained later, then the evaporator heat will be equal to the condenser heat [9, 10, 30]:

1) Saturated liquid specific heat is negligible;
2) Heat of evaporation is constant;
3) Refrigerant expansion is isotropic; and
4) Superheated vapour specific heat is negligible.

$$Q_e = Q_c \tag{3}$$

By combining equations (1) and (3) the absorber heat will be equal to the generator heat.

$$Q_a = Q_g \tag{4}$$

If the above 3 equations are combined, the following COP equation is derived in terms of the four temperatures involved, as shown by Kumar and Devotta [31]:

$$COP = \frac{Q_e}{Q_g} = \frac{\dfrac{1}{T_a} - \dfrac{1}{T_g}}{\dfrac{1}{T_e} - \dfrac{1}{T_c}} = \frac{T_g - T_a}{T_g} \frac{T_e}{T_c - T_e} \frac{T_c}{T_a} \tag{5}$$

A way adopted by many authors [25, 32, 33, 34, 35] has been to assume that the absorber and condenser share the same temperature. By doing this, the previous equation simplifies to the following:

$$COP = \frac{T_g - T_{ac}}{T_g} \frac{T_e}{T_{ac} - T_e} \tag{6}$$

This expression also indicates the COP as the product of the driving sub-cycle efficiency and the cooling sub-cycle COP if Carnot expressions are considered.

The two COP expressions derived above in terms of three and four temperatures are applicable to ideal heat-driven cooling cycles where the driving and cooling sub-cycles are independent of each other. This is the case for motor-driven compression systems and absorption GAX cycles (see later). For single and multiple cycles there is no such independence between the driving and cooling sub-cycles, and further restrictions on temperatures are required and imposed.

A4.3 Ideal cycle

There is general agreement [25, 36, 37, 38] that the ideal absorption cycle comprises two ideal Carnot cycles, one driving and the other a cooling cycle.

Figure A4.5 represents a general heat-driven cooling cycle schematically, as indicated in Figure A4.3. Figure A5 shows the heat flows and thermal sources and sinks involved. The higher horizontal lines indicate higher temperatures. Heat is supplied from a high-temperature heat source (driving energy) and from a low-temperature heat source (cooling), and both of these are released at ambient conditions (cooling tower). An analogy with the absorption cycle can be made, as similar thermal exchanges occur. However, although the principles apply, the thermodynamics of these driving and cooling cycles cannot be blindly applied to absorption cycles. The main reasons for this are that no mechanical work interacts between the absorption driving and cooling sub-cycles, and more importantly, the same fluid and mass flow rate of refrigerant circulates in both sub-cycles, which imposes certain thermodynamic constraints for single and multiple ideal cycles.

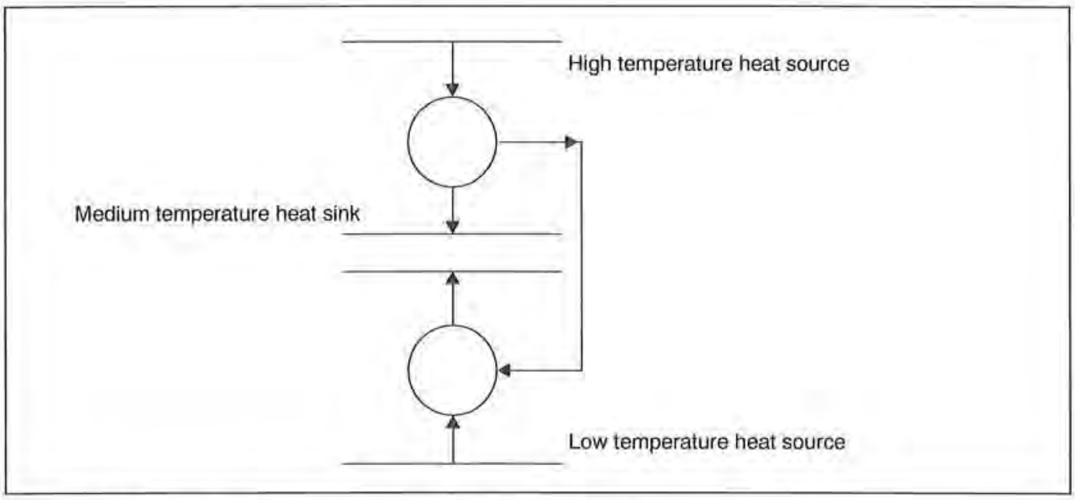

Figure A4.5 Driving and cooling cycle representation.

The driving cycle is constituted by the generator and condenser. Its purpose is to firstly produce refrigerant, and secondly to prepare the solution so that it can absorb refrigerant in the cooling cycle. The cooling cycle, which is constituted by the absorber and evaporator, absorbs the refrigerant producing the cooling effect and dilutes the solution before returning it to the driving cycle. The product of the driving cycle is the heat of solution, which is what is used by the cooling cycle. The heat of solution will be later referred to in a more generalised way as exergy of solution (chemical exergy). Carnot cycles were originally conceived prior to the concept of exergy as producing work or using it to drive a reverse Carnot cycle. Exergy is a more generalised concept of work, which therefore makes these ideal driving and cooling sub-cycles found in absorption systems very similar to Carnot cycles [39].

Absorption cycles can be correctly represented on T-S diagrams, as they are best suited to represent ideal driving and cooling cycles (Carnot cycles). Due consideration should also be given to what is going to be represented on the T-S diagram. For this, it is necessary to split the refrigerant into two parts:

1) The part that circulates throughout the main processes (generator, condenser, evaporator and absorber), which is what will be represented on the T-S diagram.

2) The other part, which is diluted in the solution and only circulates between the generator and absorber via the solution heat exchanger. It only experiences changes of temperature (and pressure) and is of minor thermodynamic importance if the solution heat exchanger area is sufficiently (infinitely) large. Therefore, this part of the refrigerant has no influence on the heat balance of the cycle, and will not be considered further.

To represent the absorption cycle on the T-S diagram, use will be made of the extended T-S diagrams developed by Eber [40]. A brief description of these extended diagrams will be given, but further details should be sought from the references [40, 41]. A real absorption cycle (water/LiBr) is indicated in Figure A4.6 where the extended T-S diagram for that mixture has been used.

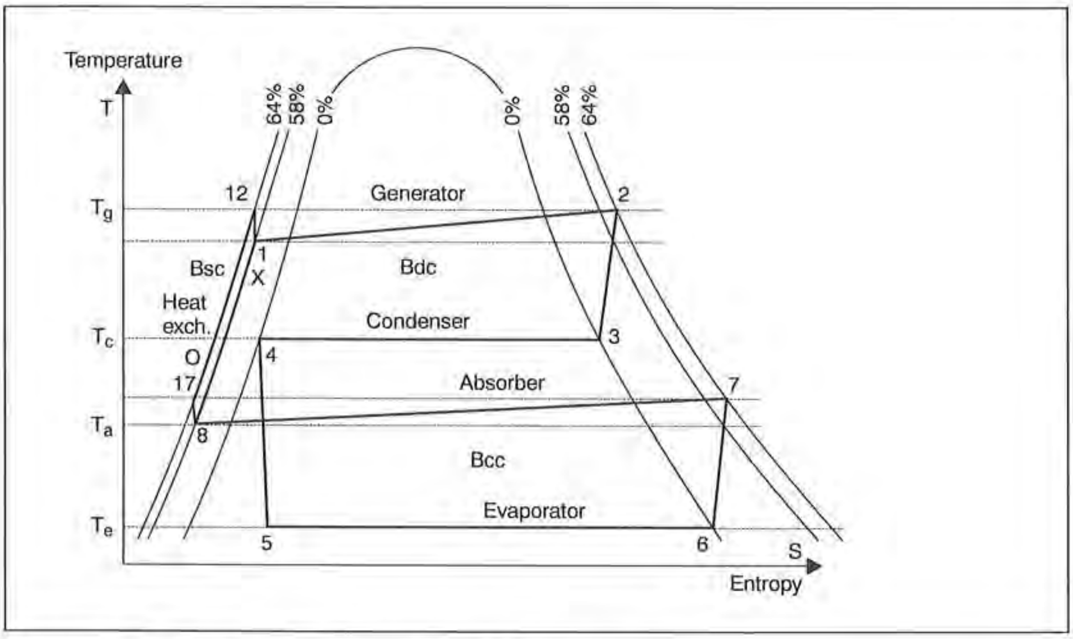

Figure A4.6 *Real absorption cycle on T-S diagram.*

Due to their different vapour pressures, no equilibrium can exist between a pure refrigerant and the solution. Therefore, the refrigerant molecules in the solution are considered, and the solution is considered indirectly. The extended curves in the vapour region (right of saturated vapour line, indicated 58% and 64%) consider the refrigerant vapour pressure to be in equilibrium with the solution. The extended curves in the liquid region (left of the saturated liquid line, indicated 58% and 64%) consider the states of liquid refrigerant in the solution. The horizontal difference between the extended liquid and vapour lines indicates the difference of entropy required to reversibly expel 1 kg of refrigerant from a very large quantity of solution, i.e. generator heat.

Further details of the processes are available [30], but a brief description follows. From this and previous Figures, the refrigeration circuit can be identified as:
1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – X – 1

The processes in the refrigerant circuit are:
1 – 2: Heating and evaporation of refrigerant introduced into the generator. The heat is equal to the sum of the heat of evaporation plus the heat of solution.
2 – 3: Cooling of the superheated vapour produced in the generator, at constant pressure down to the saturation temperature T_c.
3 – 4: Condensation;
4 – 5: Isenthalpic expansion of the refrigerant from condensation to evaporation temperature;
5 – 6: Evaporation;
6 – 7: Isobaric heating (at constant pressure) of saturated vapour refrigerant to superheated vapour; and
7 – 8: Absorption of the superheated vapour (of state 7) where both the heat of solution and the heat of evaporation are liberated.

A minimum number of 12 idealising assumptions are required to obtain an ideal absorption cycle, and further details are available [6]. Assumptions 1) to 4) were also described in the previous section.

A summary of the assumptions follows:

1) Saturated liquid specific heat is negligible: The specific heat of the saturated liquid refrigerant along the lower boundary line is equal to zero. The implication of this is that the saturated liquid line is vertical on the T-S diagram.

2) Heat of evaporation is constant: The heat of evaporation is constant and independent of the temperature. This defines the saturated vapour line as a hyperbola on the T-S diagram.

3) Refrigerant expansion is isotropic: If this process changes from isenthalpic to isotropic, it becomes vertical on the T-S diagram (process 4-5).

4) Superheated vapour specific heat is negligible: The specific heat at constant pressure of the superheated vapour is equal to zero. Therefore, the isobaric heating and cooling of vapour is represented as vertical lines on the T-S diagram.

5) Heat of solution varies only with concentration: The heat of solution l only depends on the composition of the solution and is not influenced by the temperature. Therefore, a family of hyperbolic curves will be derived for each solution concentration.

6) Solution specific heat is negligible: Therefore, both cooling and heating processes of the solution will be indicated by vertical lines on the T-S diagram.

7) Heat exchanger area is infinitely large: If the solution heat exchanger is sufficiently large, there is no sensible heating and cooling in the generator and absorber.

8) Solution circulation is infinitely high: Therefore, the concentrations of the strong and weak solutions converge.

9) Entropy of solution mixing is negligible with respect to the evaporation heat: This means that the mixing of solution will tend to be reversible.

10) Refrigerant vapour is an ideal gas: Which means that it complies with the properties of ideal gases.

11) There is no absorbent vapour pressure: Therefore, only the refrigerant will depart from the solution in the generator, and rectification is not necessary.

12) The solution pump work is considered to be negligible.

Once these changes have been implemented the ideal cycle is obtained as indicated in Figure A4.7 below:

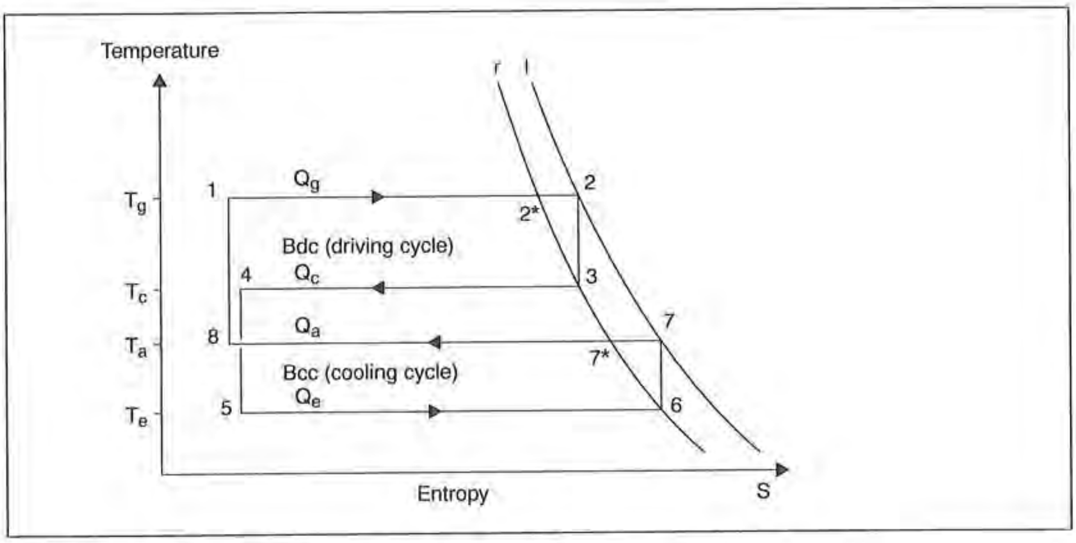

Figure A4.7 *Ideal absorption cycle on T-S diagram.*

The differences of entropy in the driving and cooling cycles are:

$$\Delta S_{dc} = \frac{r}{T_c} = \frac{r + l}{T_g} \tag{7}$$

$$\Delta S_{cc} = \frac{r}{T_e} = \frac{r + l}{T_a} \tag{8}$$

If both of these equations are combined:

$$\frac{r}{r+l} = \frac{T_e}{T_a} = \frac{T_c}{T_g} \tag{9}$$

If the areas of the driving and cooling cycles are calculated:

$$Area_{dc} = \frac{r}{T_c}(T_g - T_c) = r\left(\frac{T_g}{T_c} - 1\right) \tag{10}$$

$$Area_{cc} = \frac{r}{T_e}(T_a - T_e) = r\left(\frac{T_a}{T_e} - 1\right) \tag{11}$$

Given the relationship of temperatures of equation (9), the areas necessarily have to be equal. In both models the driving cycle area is equal to the cooling cycle area. In fact, if the indicated assumptions are made, it is impossible to construct an ideal absorption cycle whereby this condition is not satisfied.

From the above, the following temperature relationship was derived [6, 9, 10]:

$$T_g T_e = T_a T_c \tag{12}$$

It is a well-known fact that the ideal COP of a single-effect absorption chiller can never exceed unity. This can be seen by examining the COP equation, which is expressed in terms of the refrigerant evaporation heat (*r*), and the heat of solution (*l*) [42]. The COP could approach unity for low heats of solution, but it can never reach or exceed unity.

$$COP = \frac{r}{r+l} \tag{13}$$

Despite this, the COP expressions in terms of temperature equations (4) and (5) offer the degree of freedom to the temperatures so that a COP in excess of unity can be calculated for an ideal cycle. For example, with $T_e = 5°C$, $T_{ac} = 40°C$ and $T_g = 100°C$, a COP of 1.28 results, which cannot be correct for an ideal single-effect absorption chiller. Therefore, equations (5) and (6) are not correct for single and multiple absorption cycles, although they are correct for motor-driven compression systems and GAX cycles.

In real cycles, there is no such freedom to randomly select these three or four temperatures. Once the evaporator, absorber and condenser temperatures are selected, certain generator temperatures will result (from the PTX diagram), depending on the solution mixture. All of this would suggest that, for ideal absorption cycles, the temperatures cannot be randomly chosen.

The problem with equations (5) and (6) is that they are over-specified and require a further restriction. This is provided by the temperature relationship equation (12) similarly as occurs in real cycles. Once equation (12) is substituted into equation (5) the following COP is derived:

$$COP = \frac{T_e}{T_a} = \frac{T_c}{T_g} = \alpha \tag{14}$$

This equation states that the COP depends on how far the solution concentration is from the pure refrigerant.

An interesting analysis can now be made with the Dühring equations (determined pragmatically) that states temperature relationships at constant pressure in terms of two mixture-related constants A and B. The constants A and B are derived for real mixtures, and from the ideal equations stated, it is now possible to derive the ideal values of these constants: A = 0 and B = 1/α. Further information is available [6].

$$T_a = A + BT_e \tag{15}$$

An interesting correlation of temperature relations with respect to ideal chemical properties is found for absorption cycles:

$$\frac{l}{r} = \frac{T_a - T_e}{T_e} \tag{16}$$

For ideal absorption cycles, the temperature lift to the evaporator absolute temperature has the same ratio as the heat of solution to evaporator heat.

The product of the driving cycle is the heat of solution, which is transported to the cooling cycle. The driving cycle prepares the solution by concentrating it (water/LiBr) and making it so that the refrigerant is more attracted to it. Once the concentrated solution reaches the cooling cycle (absorber and evaporator), the absorber can then carry out its job adequately by absorbing the refrigerant into it. Once the solution is diluted and less able to absorb more refrigerant, it is circulated from the cooling cycle (absorber and evaporator) back to the driving cycle (generator and condenser) so that the solution can be re-prepared. It is clear from this that the product of the driving cycle, which is used by the cooling cycle, is the heat of solution, which is best expressed as the exergy of solution as shown by LeGoff and others [6, 43].

$$B_{dc} = B_{cc} = l \tag{17}$$

The absorption COP can be expressed as the product of the driving sub-cycle (generator and condenser) efficiency by the sub-cooling cycle (absorber and evaporator) COP. This is valid because both sub-cycles are complete (Carnot) cycles themselves. The equation derived by Alefeld and Radermacher [32] is:

$$COP = COP_{cc}\eta_{dc} = \frac{T_e}{T_a - T_e}\,\frac{T_g - T_c}{T_g} \tag{18}$$

Although this equation is different from the COP equation (5) derived from the 1st and 2nd laws, once the temperature relationship equation (12) is substituted into it, the same COP equation (14) is derived [6, 10].

A4.4 Multiple-effect cycles

Working with the principles described above, and assuming that the heat sources and sink temperatures within each constituting cycle of a double-effect system are infinitely close, the COPs for double-effect cycles can be derived. It should be noted that the same equations are derived regardless of whether the absorber heat or the condenser heat of the high-temperature cycle is used to drive the low-temperature cycle.

$$COP = \alpha + \alpha^2 \tag{19}$$

A higher generator temperature is required as per the following temperature relationship equation:

$$T_g T_e^2 = T_c T_a^2 \tag{20}$$

In a similar way for triple-effect, the ideal COP and temperature relationships are derived. Again these results are independent of whether condenser or absorber heat is used to drive lower-temperature cycles.

$$COP = \alpha + \alpha^2 + \alpha^3 \tag{21}$$

$$T_g T_e^3 = T_c T_a^3 \tag{22}$$

A4.5 Comparison with mechanical compression systems (reverse Carnot cycle)

Equation (21) for *N* effects can be expressed as the sum of a geometrical series:

$$COP = \alpha + \alpha^2 + \alpha^3 + ... + \alpha^N = \alpha \frac{1 - \alpha^N}{1 - \alpha} \tag{23}$$

If the number of effects (*N*) tends to infinity:

$$COP = \alpha + \alpha^2 + \alpha^3 + ... + \alpha^\infty = \frac{\alpha}{1 - \alpha} \tag{24}$$

If this equation is expressed in terms of absolute temperatures, the reverse cycle of Carnot is derived.

$$COP = \frac{\alpha}{1 - \alpha} = \frac{T_e/T_a}{1 - T_e/T_a} = \frac{T_e}{T_a - T_e} \tag{25}$$

This means that the ideal mechanical compression cycle (reverse Carnot cycle) has the same COP as an ideal absorption cycle with infinite effects.

The generator/desorber (T_g) of a sorption cycle with infinite effects (*N* tends to infinity) will require a driving energy of infinitely high temperature.

$$T_g T_e^N = T_c T_a^N \tag{26}$$

or

$$T_g = T_c \frac{T_a^N}{T_e^N} = \frac{T_c}{\alpha^N} \tag{27}$$

As the denominator is always less than zero, the generator temperature will tend to infinity for infinite effects (*N*).

A4.6 PTX diagram for ideal multiple-effect cycles

Pressure/temperature concentration (PTX) diagrams are used extensively to represent real cycles operating with the binary mixture of water/LiBr. If the solution flow rate were infinite, such as is stipulated in the theoretical assumptions of ideal cycles, the two processes at constant concentrations in the heat exchanger would merge, and the ideal absorption cycle would be represented by a single quadrilateral.

Figure A4.8 represents three ideal triple-effect cycles with infinite solution flow. The three cycles correspond to cycles utilising 1) condenser heat, 2) absorber heat and 3) condenser and absorber heat to drive the lower temperature cycles [6].

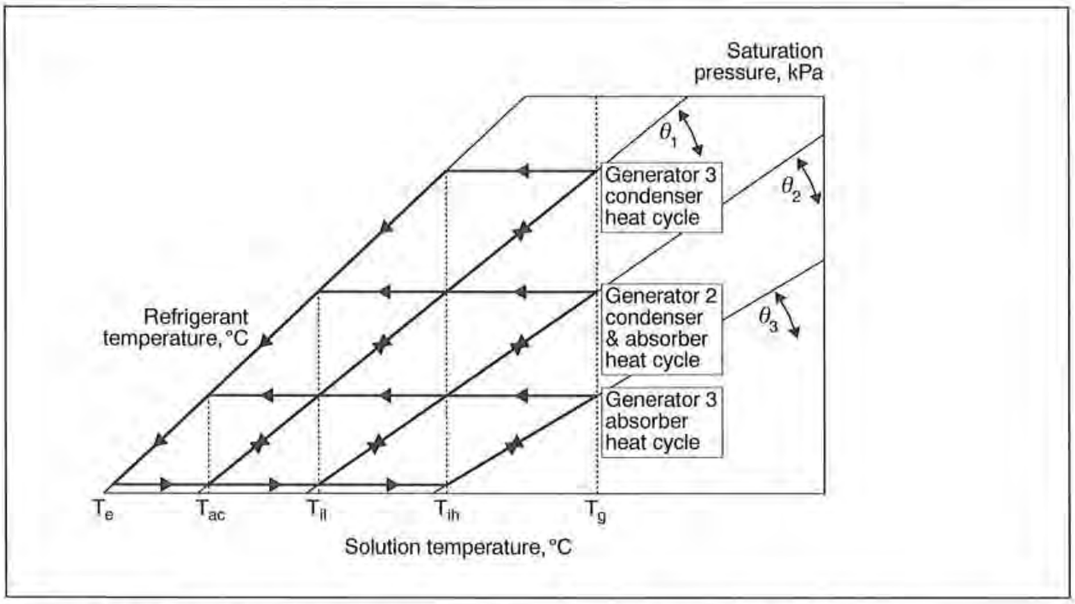

Figure A4.8 *Ideal triple-effect absorption cooling cycles on the PTX diagram.*

On this type of diagram it is easy to see how the three types of multiple-effect cycles have the same temperature relationships. The same concept can be easily seen for double-effect cycles, and can be extended to *E* effects. It can also be noticed that the constant concentration lines are not parallel, and that the gradient of a single-effect cycle solution line is equal to the absorption thermodynamic ratio α, which is equal to the single-effect COP. This is easily understood by considering the origin of the PTX diagram at the absolute zero temperature. The pure refrigerant line has a gradient equal to one. By considering the absorber point of the single-stage cycle together with the origin, the gradient is equal to the evaporator temperature divided by the absorber temperature, and is therefore equal to α. If the second absorber cycle is considered, α^2 is derived, and so on. In general terms the angles of constant concentration lines depend on the absorption thermodynamic ratio α and on the number of effects *N* using absorber heat.

$$\theta_N = \tan^{-1}\left(\alpha^N\right) \tag{28}$$

A4.7 Summary

Alefeld undoubtedly pioneered the analysis and combination of multiple cycles, and developed relationships of COP equations between different cycles, by applying a series of 'rules' [32, 43]. With the thermodynamic fundamentals of ideal sorption cycles now available, it has been possible to extend all these concepts in terms of temperatures, based on valid thermodynamic building blocks, further to multiple cycles [10, 44]. A summary of the main formulae of sorption thermodynamics [6] is detailed in Table A4.1 below:

Table A4.1 *Summary of ideal sorption cycles, COPs and temperature relationships.*

Type of cycle	**No.**	**COP**	**COP**	**Temperature equation**
Cooling, variable No. of effects	Not specified, e.g. GAX	$\frac{Q_e}{Q_g}$	$\frac{T_g - T_a}{T_g} \frac{T_e}{T_c - T_e} \frac{T_c}{T_a}$	Independent driving and cooling sub-cycles
Cooling, fixed No. of effects	Effects (E)	$\frac{Q_e}{Q_g}$	$\alpha + \alpha^2 + \alpha^3 + \ldots + \alpha^E = \frac{\alpha\left(1 - \alpha^E\right)}{1 - \alpha}$	$T_g T_e^E = T_c T_a^E$
Cooling $T_c > T_a$	Stages (S)	$\frac{Q_e}{Q_g}$	$\frac{\alpha\left(1 - \alpha^{1/s}\right)}{1 - \alpha}$	$T_g^S T_e = T_c^S T_a$
Heat pump	Effects (E)	$\frac{Q_a + Q_c}{Q_g}$	$1 + \alpha + \alpha + \ldots + \alpha^E = \frac{1 - \alpha^{E+1}}{1 - \alpha}$	$T_g T_e^E = T_c T_a^E$
Heat transformers	Lifts (L)	$\frac{Q_a}{Q_g + Q_e}$	$\frac{1}{1 + \alpha + \alpha^2 + \alpha^3 + \ldots + \alpha^L} = \frac{1 - \alpha}{1 - \alpha^{L+1}}$	$T_g^L T_e = T_c^L T_a$

Note: α is the ratio of T_e/T_a in all equations above

Appendix 5: Competing Technologies

Closed-cycle vapour compression systems

The basic closed vapour compression heat pump is shown in Figure A5.1. The word 'closed' refers to the fact that the refrigerant is physically separated from the heat source and user streams, and is reused in a cyclical fashion. The most commonly-used heat pumping cycle is the closed vapour compression cycle. The vapour compression system is most widely used for residential and commercial applications such as heating, cooling, refrigeration and automobile air-conditioning.

For most climate-control applications, the two important operating modes are air-cooling and heating. Machines that operate in air-conditioning (or other situations involving cooling processes) are normally referred to as chillers. Machines that operate as heaters are referred to as heat pumps. In fact, many heat pumps will operate in both modes, so that the same machine can be used for both purposes, i.e. reversible heat pumping.

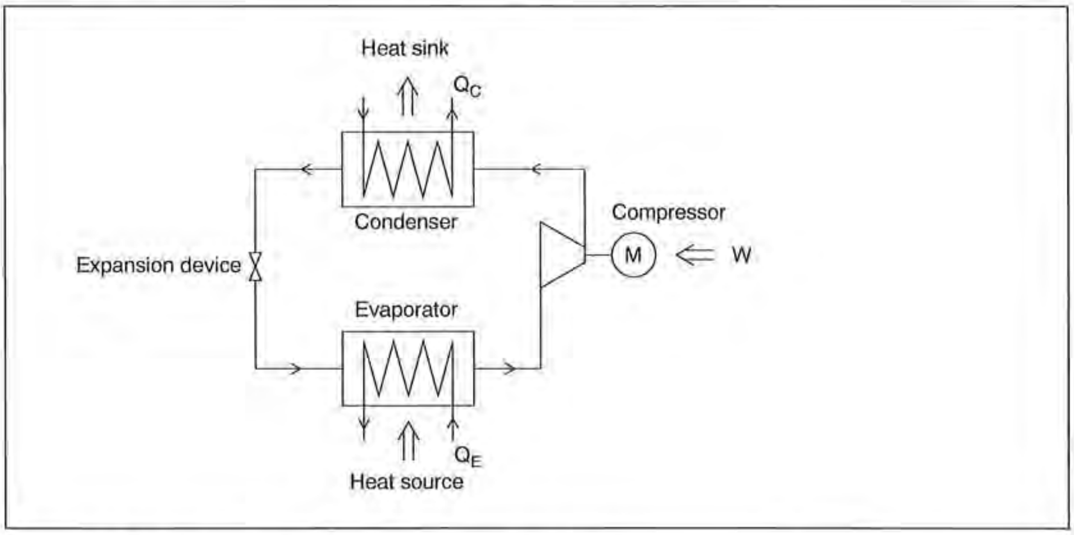

Figure A5.1 Closed vapour compression heat pump.

In the evaporator, the refrigerant is vaporised by extracting heat Q_E from a heat source (which is cooled down). The refrigerant is then compressed, requiring work W, to a higher pressure and temperature in the compressor. In the condenser, the refrigerant condenses, releasing heat Q_C corresponding to the heat taken up in the evaporator and heat equivalent of the compression work. In the throttling valve, the liquefied refrigerant is reduced to the low pressure prevailing in the evaporator.

The coefficient of performance for the heating mode, COP_{heat}, and the cooling mode, COP_{cooling}, can be expressed as:

$$COP_{\text{heat}} = \frac{Q_c}{W} = \frac{Q_e + W}{W} \qquad (1)$$

and

$$COP_{\text{cooling}} = \frac{Q_e}{W} = COP_{\text{heat}} - 1 \qquad (2)$$

The corresponding ideal cycle working between the heat sink temperature T_1 and the heat source temperature T_2 is the Carnot cycle. The *COP* for this ideal cycle is:

$$COP_c = \frac{T_1}{T_1 - T_2} \qquad (3)$$

The *COP* for a real cycle is normally given as:

$$COP = \eta_c \, COP_c \qquad (4)$$

where η_c is called the Carnot efficiency (thermodynamic efficiency). η_c is normally given a value of around 0.7 and is normally regarded as constant with varying values of the heat source and sink temperatures. When compression-type heat pumps are used in industrial applications, the condensate after the condenser is normally sub-cooled by means of an external sub-cooler.

Practically, the cooling COPs in operating systems are always less than the theoretical values. They are normally in the range of 2 – 6 for compression chillers. However, COPs vary with the load on the chiller and they drop if the load is too small.

A specific problem for high-temperature applications in industry is the lack of working fluids in the range of 100 – 140°C. In the temperature range of 100 – 120°C no ideal replacement for the CFC refrigerant R114 is currently available. For the range of 120 – 140°C there is currently no refrigerant or mixture available that fulfils the necessary requirements.

Absorption and compression cycles differ in that the absorption cycle uses a small liquid pump to produce the pressure differential, whereas the compression cycle uses a compressor that consumes relatively large amounts of primary energy. In contrast to the reduction in electricity usage obtained by using absorption chillers, the cooling demand for the absorption process is far greater. Depending on the nature of the primary energy used, the energy consumption has to be evaluated for each heat source and situation. This is also the case for the calculation of environmental impact.

In Table A5.1, a comparison of compression chillers and absorption chillers is given. It should be noted that the table includes both water- and air-cooled chillers, selection of which affect the COP noticeably, as well as the size and weight of the physical hardware. Hence, these figures should be taken only as a guide.

Table A5.1 *Comparison of compression and absorption chillers.*

	CHILLER TECHNOLOGY				
	Compression chillers			**Absorption chillers**	
Parameter	*Reciprocating**	*Screw*	*Centrifugal*	*Single-effect*	*Double-effect*
Driving energy	Electricity (rotational work)	Electricity (rotational work)	Electricity (rotational work)	Hot water (70°C - 150°C) or steam (up to 100 kPa)	Steam (up to 800 kPa) or direct-fired (e.g. natural gas or engine exhaust gases and hot water)
Working fluids	HFC, HCFC, NH_3	HFC, HCFC, NH_3	HFC, HCFC	Water/LiBr or NH_3/water	Water/LiBr or NH_3/water
COP	2 – 5	2.5 – 6	4 - 7	0.6 - 0.8	1.0 - 1.2
Cooling capacity (range) [MW]	0 – 2	0.3 – 7	0.5 - 25	0.1 - 6	0.1 - 6
Surface on ground [m^2/kW]	0.006 - 0.02	0.006 - 0.02	0.006 - 0.02	0.01 - 0.03	0.01 - 0.03
Weight [kg/kW]	5 – 10	5 – 10	5 - 10	8 - 22	8 - 22

* Manufacturers are replacing many reciprocating compressors with scroll compressors of higher efficiencies.

Appendix 6: Case Studies

This appendix provides summaries of and conclusions from selected case studies, reference plants and demonstration projects. The examples cover a wide range of applications in the industrial, commercial, residential and agriculture sectors, where sorption technology can be a viable option in terms of energy efficiency and environmental protection. More details of the studies and installations presented, as well as many more projects and studies, may be found in the workshop proceedings of Annex 24: reports No. HPP-AN24-1 [1], HPP-AN24-2 [2], and HPP-AN24-3 [3] (in preparation) or from national contacts. Other examples are taken from 'Absorption Cooling and Heat Pump Technologies in Europe, Present Status and Future Trends' – Report to European Commission Directorate-General XVII, Energy [27] and from the National Contacts (Appendix 1), e.g. reference [45]. In addition, a few German case studies are included, although Germany did not formally participate in Annex 24.

All the examples included demonstrate some new technologies, or novel application(s) of interest. However, the material is neither fully representative nor developed, which would be a task for a future Annex. With that reservation, the following studies are presented:

1. CHP system in a pharmaceutical plant at Glaxo Wellcome, UK;
2. Tri-generation at the European Central Bank, Germany;
3. District cooling in Gothenburg, Sweden;
4. SE/DL system at Munich Airport, Germany;
5. A closed greenhouse concept using AHPs, The Netherlands;
6. AHPs at the Graab waste incineration plant, Sweden;
7. AHPs for heat recovery, and heating at two temperature levels in Munich, Germany;
8. Preheating water supplied to a boiler in a pulp factory, Japan;
9. Absorption heat pumps for heat recovery at a dye-works, Japan;
10. Heat transformer in the chemical industry, The Netherlands;
11. Heat transformer in the steel industry at Hoogovens, The Netherlands; and
12. Heat transformer at Ishioka alcohol plant, Japan.

1. CHP system in a pharmaceutical plant at Glaxo Wellcome, UK

For buildings and industries requiring cold water for air-conditioning, co-generation heat can be used to drive absorption chillers. Such CCHP systems are an optimal way to compensate for the differences in thermal demand between winter and summer. Absorption chillers are available from 10 to 6,000 kW refrigeration output per unit. Most of the chillers are used for air-conditioning (above 6°C), mostly operating on a water/LiBr mixture. If temperatures below 6°C are required, chillers based on ammonia/water are usual. These chillers allow cooling temperatures of down to –60°C, as is frequently required in the chemical industry. Absorption chillers can be operated without excessive losses at 20% of their nominal output.

The main applications of absorption chillers to CHP are single-effect hot-water-driven chillers applied to gas engines, and double-effect steam-driven chillers applied to gas turbines. There are many examples of these types of installation worldwide, e.g. in Japan, Malaysia, the UK, USA, Spain, the Netherlands, and Germany.

A CHP scheme was installed at Glaxo Wellcome's Dartford site in the UK in 1988, to supply both electricity and steam requirements. The scheme involved two EGT (formerly Ruston) Tornado gas turbines, with separate heat recovery boilers. An important later development was steam injection into the gas turbines to increase electricity generation, and utilisation of rejected heat (Cheng cycle). The CHP project has been very successful. It provides cheap thermal and electric energy to the absorption chillers.

Subsequently a number refinements have been implemented to more fully utilise the surplus heat that is available from the CHP plant during the summer months. These measures include the fitting of turbo-absorption and absorption machines that provide chilled water. The turbo-absorption system is a cascade refrigeration system that has a steam-turbine-driven compression refrigeration cycle and a single-stage absorption chiller operating in tandem. The stand-alone absorption machines are double-effect steam-driven absorption chillers. This case study deals mainly with the latter. Two double-effect steam-driven absorption chillers were installed in 1993 to supply 1 MW each of chilled water to the medium-temperature Dow Therm J reactors via plate heat exchangers. The system is shown in Figure A6.1.

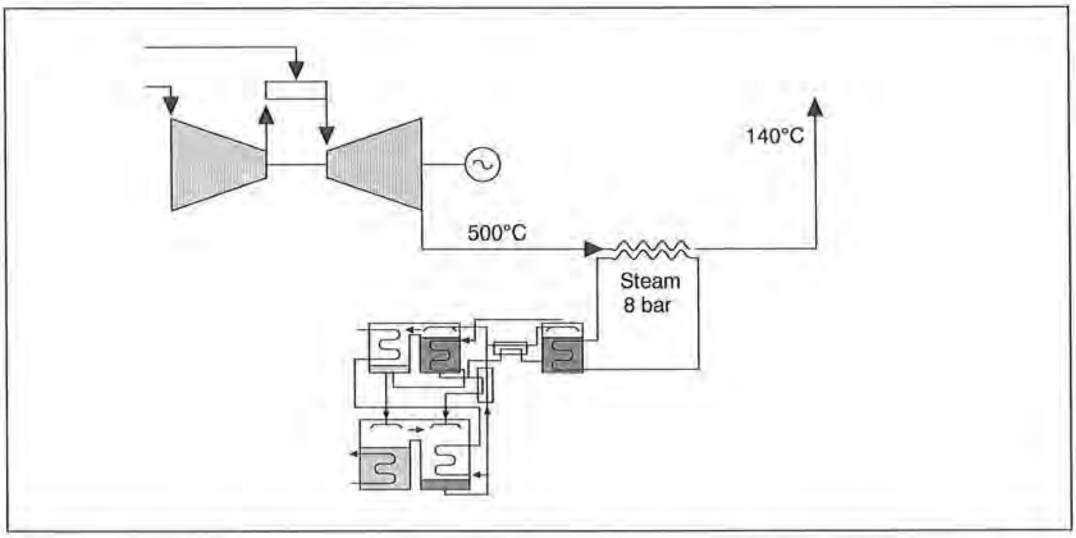

Figure A6.1 *Double-effect steam-driven absorption chiller and a gas-turbine CHP system.*

The design supply chilled water temperature is 11°C and the return temperature is 17°C. The condenser water is cooled by means of cooling towers and the design temperatures are 29–35°C. Steam at 8 bar gauge is supplied to the chillers. Due to the high chilled water temperatures a COP of 1.33 is obtained.

The factors that have made this case study economically successful are:
- Extended chilled water demand (over 6,000 hours)
- Economically sound CHP scheme (payback period under 4 years)
- Medium-to-large-scale cooling demand (1 MW)

The calculations are based on an annual interest rate of 5% over 15 years. The cost ratio of CHP electric to thermal energy is 3.3. Although the environmental impact is presently assessed on TEWI, due consideration regarding the environmental impact should be given to the fact that 28% of the UK's electric energy is of nuclear origin [46].

2. Tri-generation at the European Central Bank, Germany

An example of tri-generation is provided by the Eurotower in Frankfurt, Germany as described in Jenbacher, 2000 [48]. To cover the energy demand of the European Central Bank located in the Eurotower, Jenbacher delivered three co-generation modules. The co-generation plant provides the ECB with electricity, heat and refrigeration. The refrigeration for air-conditioning is produced by absorption chillers driven by part of the heat released by the co-generation plant. Data for the installation are shown in Table A6.2.

Table A6.2 *ECB installation data.*

Country	**Germany**
City:	Frankfurt
Location:	Eurotower – European Central Bank
Start of operation:	1995
Type:	3 x JMS 312 GS-N.LC
Primary fuel:	Natural gas
Use of electricity:	Covering in-house demand
Use of heat:	Air conditioning by absorption chillers and space heating
Electrical output:	1,350 kW
Thermal output:	1,782 kW

3. District cooling in Gothenburg, Sweden

Göteborg Energi AB in Gothenburg, Sweden, began in 1995 to use its district-heating network for district cooling. So far, up to 14 MW of cooling has been contracted to be delivered, by means of centrally-located district-heating-operated water/LiBr chillers. The customers are mainly office buildings, each requiring between 400 kW and 600 kW of cooling capacity, as well as a dental college (1 MW) and a hospital (2 x 3 MW cooling). This implies that the use of freon has decreased by approximately 5.5 tons and the use of electricity by approximately 4,550 MWh annually.

The district heating is primarily based on heat from waste combustion plants, refineries and sewage heat pumps, supplemented with a minimum of oil and bio-fuel. However, during summer, the district heating is normally based on 100% waste heat, which is used to drive the chillers for cold production. The surplus heat amounts to about 100 – 120 MW, which covers a cooling demand of about 70 – 90 MW.

On the basis of the cost calculations and operating experience, the total investment cost for the erection of cooling plant amounted to about 2,500 – 4,500 SEK/kW of cooling installed (280 – 500 USD/kW). Of the total investment cost, the cost of the actual chiller is normally about 25-30%.

4. SE/DL system at Munich Airport, Germany

Another example of district-heating-operated absorption chillers is found at Munich airport. Power, heat and cold are delivered by a CHP plant incorporating centrifugal and absorption chillers. In order to optimise the operation of the CHP plant while minimising power consumption from the grid, a novel two-stage absorption chiller was integrated into the energy system.

The absorption chiller, using the working pair water/LiBr, uses an integrated single-effect/double-lift (SE/DL) cycle, which allows a large temperature glide and low return temperatures of the district heating water. The SE/DL chiller providing 12 – 6°C chilled water with cooling water at 27 – 35°C, and operates with hot water supply/return temperatures at 95 – 62°C. Thus it fits comfortably into the energy system, utilising the hot water leaving the two standard single-effect chillers. The driving hot water is returned to the CHP plants at low temperature, allowing a high electrical load throughout the whole year.

ZAE Bayern developed the SE/DL absorption cycle, which can utilise heat at temperatures as low as 55°C and permits heat source temperature glides of more than 30 K. However, the cost of the SE/DL machine is higher than that of a conventional single-effect chiller.

5. AHPs in a closed greenhouse concept in the Netherlands.

As indicated in Chapter 4 and elsewhere [21], greenhouses are a major economic and energy-intensive sector in the Netherlands. Their use of primary energy is about 140 PJ annually, or 7% of the total energy consumed in the country. Over 80% of this energy is used to keep the temperature in the greenhouse at a desired level by burning gas in co-generation plants and/or gas boilers. By installing heat pumps, it was estimated by Novem that a technical potential for energy conservation of at least 30 – 40 PJ exists. As the need for environmentally-friendly greenhouses is increasing and the greenhouse sector is in a restructuring phase, the time was considered right to investigate further.

A conventional greenhouse system is an open system which loses much heat, water and CO_2. As a result Novem, together with a selected group of commercial partners, took the initiative to investigate absorption heat pumps in combination with a CHP plant, solar energy and seasonal storage for heating greenhouses. In this 'closed greenhouse concept' heat and water are recovered from the greenhouse air, and the ventilation is reduced. Thus less CO_2 is lost, temperature, humidity and CO_2 levels can be better controlled, and it is estimated that the crop yield can be increased.

The pilot project, located in the centre of the country, is in three segments, covering 30 hectares, with a so-called energy conversion station serving each 10 hectares. This station consists of absorption heat pumps, gas-engine-driven CHP plant, high-efficiency gas boilers, cold/hot seasonal storage in a groundwater aquifer, 24-hour heat storage, and solar collectors.

Important for the growth of crops in greenhouses is the production of CO_2 by the burning of natural gas. The waste heat from this process and the solar heat are used by the absorption heat pump and stored for use in winter. The absorption heat pump is a gas-fired two-effect type. Energy conservation for the AHP together with the CHP plant is predicted to be 68%. This is much higher than from these technologies on their own, of which the AHP alone could only save an estimated 45%. Figure A6.5 shows a schematic of the closed greenhouse system.

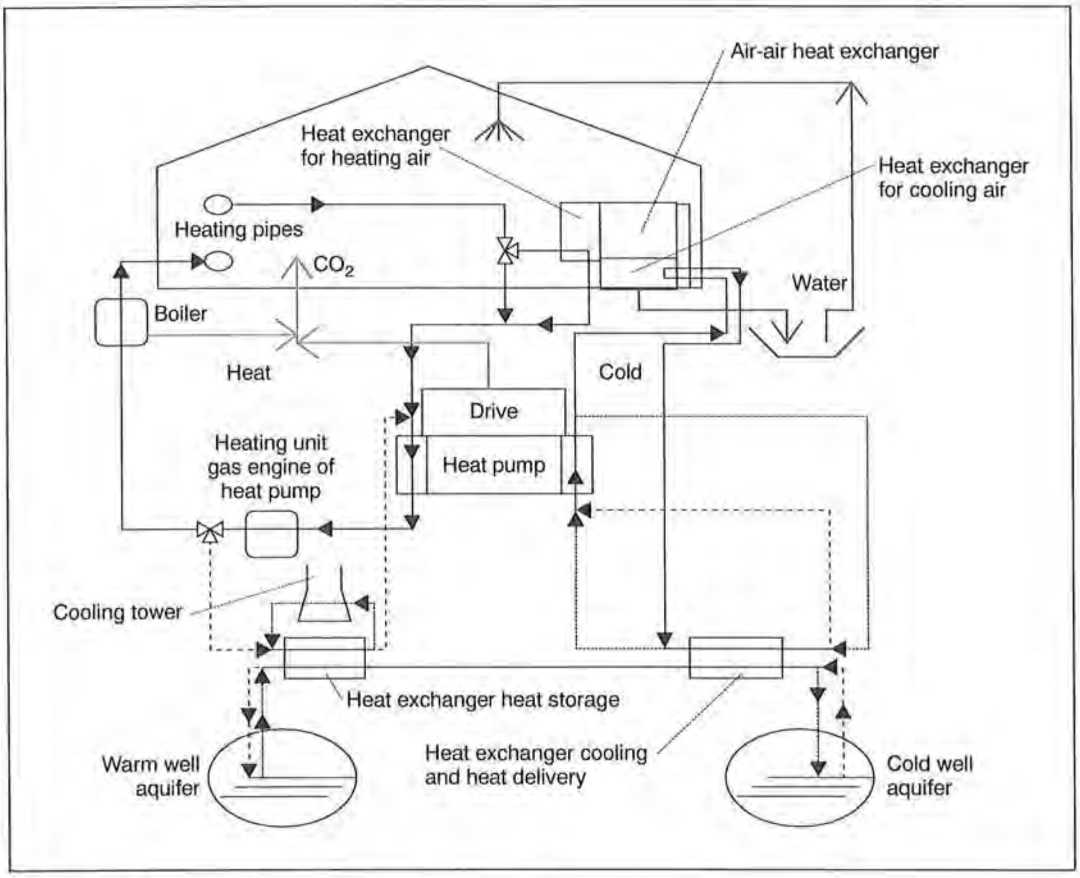

Figure A6.5 *The closed greenhouse system.*

In the closed greenhouse the main elements/functions are :

- Air treatment installation for dehumidifying, cooling and heating the greenhouse air;
- Absorption heat pump (500 –1000 kW/hectare) for the production of cold and heat, and for the production of CO_2;
- Low-temperature (50°C) heat distribution system in the greenhouse;
- Short-term (2 – 4 hours) heat storage system to reduce the starting and stopping of the heat pump;
- Long-term (6 months) storage in an underground water layer (aquifer) to store the heat from the summer cooling, which can be used as a heat source in winter for the heat pump;
- Advanced control system to operate the complex system smoothly.

The heart of the system is the absorption heat pump. This can be a standard gas-driven absorption system which is normally used for generating cold. In this configuration it delivers heat at 55°C for the low-temperature heat distribution system in the greenhouse. York, Sanyo and other manufacturers build suitable units in their standard ranges. As these heat pumps can not give higher temperatures they can only supply part of the base load, which is distributed through the upper heating system. The heat pump is cascaded with a hot-water boiler or a co-generation plant (for roses) in a 70 – 90°C loop.

The closed greenhouse project is at present in the design phase. The partners are already committed and working on the project. A first 500 kW prototype of the concept is under construction.

6. AHPs at the Graab waste incineration plant, Sweden

Applications where absorption heat pumps are utilised for upgrading heat from flue gas condensation can be found e.g. in Sweden and the Netherlands. At the Graab incineration plant in Gothenburg, Sweden refuse is burned, producing electricity and heat for the district heating system (CADDET Project no. SE-97-501 [49]). Up to 1994, the plant used four absorption heat pumps, which cooled the water from the flue gas cleaning system. These heat pumps, each with a cooling capacity of 3.8 MW, had been in operation since 1988. During this period the heat pumps operated without problems at a COP of 1.7, with one exception (see below). The heat pumps, driven by steam (135°C at 3 bar) extracted from the turbine, upgrade the heat in the circulating cooling water from 40 – 45°C to the temperature required by the district heating system, which was increased from the previous 50 – 60°C to 70 – 80°C (a maximum outlet temperature of 82°C is allowed). In 1994, the plant was additionally equipped with two new incinerators and a new absorption heat pump from Ahlstrom Rinheat, with a cooling capacity of 12 MW.

In 1995, the total amount of waste burned was 365,000 tonnes. To reduce the emissions from the plant, it is equipped with a flue gas cleaning system. This system also, with the aid of absorption heat pumps, recovers heat from the flue gases. The refuse is burned in furnaces where steam is produced. This steam is used for electricity production and to drive the absorption heat pumps. Before the gas reaches the condensation system, it is cleaned by removing particles in electrostatic precipitators, and cooled from 220°C to 140°C by the district heating system in an economiser.

In the condensation system, the flue gases are cleaned and cooled below the dew point, causing the water content to condense. This cooling is performed with the aid of a circulating water system. The temperature of the circulating water is raised to 40 – 45°C. It is then cooled down by the absorption heat pumps. Before being sent to stack, the gas is heated with steam in a reheater. The total amount of energy produced from each tonne of waste is 2.9 MWh, of which 0.3 MWh is electricity produced in the turbines. In Figure A6.7 the energy delivered from the different parts of the plant is shown.

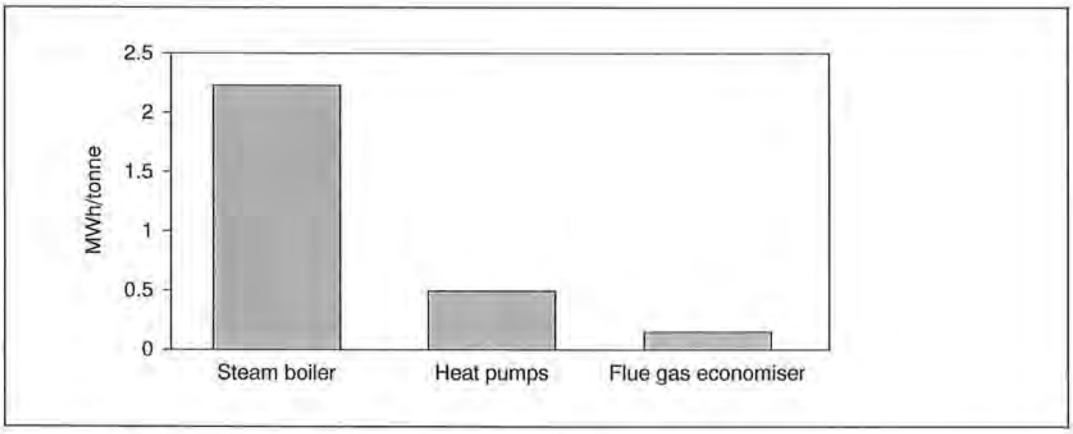

Figure A6.6 *Energy delivered from the Graab plant.*

7. AHPs for heating at two temperature levels in Munich, Germany

At the technical university of Munich a two-effect absorption heat pump with two different temperature lifts has been developed by integrating a double-effect and double-lift absorption cycle. The plant delivers hot water at two different temperature levels, 40°C and 80°C. The ratio of high and low temperature heat is variable. The two-stage absorption heat pump with 600 kW heating capacity was integrated with the heating system of a department of the Deutsches Museum in Munich. The heat pump supplies heat for the floor heating system, and high-temperature heat for the radiator heating. The adaptability of the heat pump results in large seasonally-weighted COP of the heating system. The heat pump is heated by hot water provided by a gas-fired boiler. In future applications the plant could be designed as a direct-fired heat pump as well. The low-temperature heat source is ground water from a well.

8. Preheating water supplied to a boiler in a pulp factory, Japan

At a pulp factory in Japan, an absorption heat pump was installed to recover heat from waste water from the bleaching process (alkaline bleaching solution, at about 50°C) and use it to increase the temperature of pure water supplied to the boiler from 22°C to 80°C. In this installation a COP of 1.70 was achieved by using 0.39 MPa steam as the driving heat source. The operating conditions of the system are shown in Table A6.8 below, and a schematic flow diagram is shown in Figure A6.8.

Table A6.8 *Absorption heat pump operating conditions in the pulp mill.*

	Type	Temperature	Load
Primary heat	Steam	0.39 MPa, 165°C	1.053 MW
Heat source	Water	Inlet: 46.2°C Outlet: 40.8°C	0.739 MW
Heat sink	Water	Inlet: 45°C Outlet: 80°C	1.791 MW

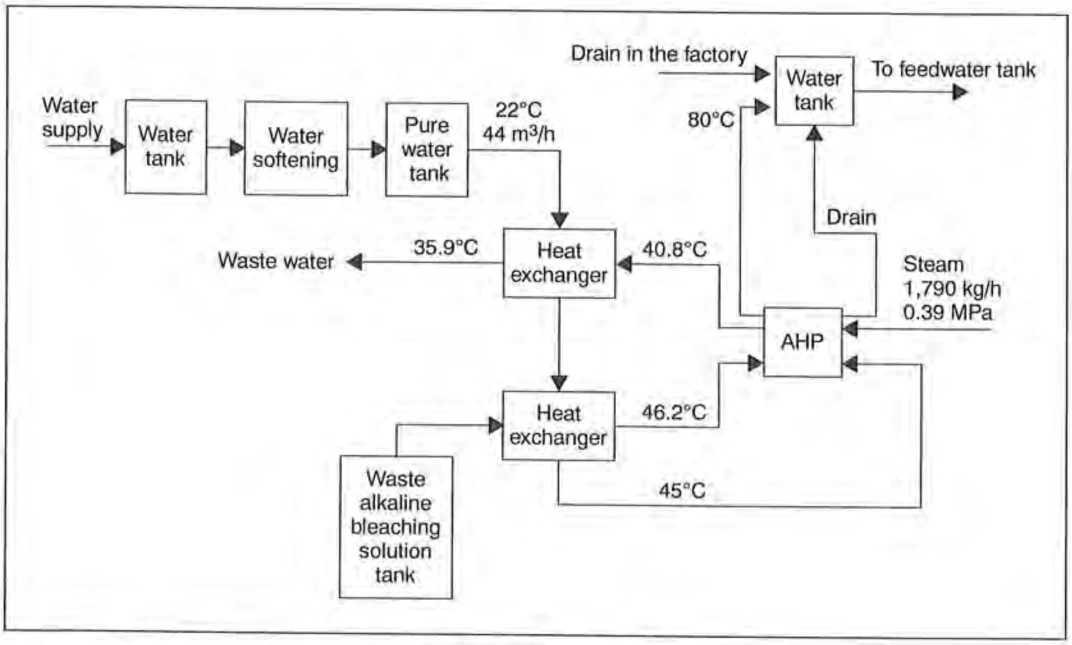

Figure A6.8 *Schematic flow chart of the pulp mill system.*

9. Absorption heat pump at a dye-works, Japan

At a dye-works in Japan, an absorption heat pump was installed to recover heat from the factory waste water (48°C), and use it to produce hot water for dyeing (56°C) and chilled water for factory cooling (12°C). In this installation a COP of 1.67 was achieved by using 0.44 MPa steam as the driving heat source. The operating conditions of the system are shown in Table A6.9 below.

Table A6.9 *Operating conditions in the dye works.*

	Type	Temperature	Load
Primary heat	Steam	0.44 MPa, 147°C	1.051 MW
Heat source	Water	Inlet: 22°C Outlet: 12°C	0.703 MW
Heat sink	Water	Inlet: 30°C Outlet: 65°C	1.754 MW

10. Heat transformer in the chemical industry, The Netherlands

The heat transformer is operated in an ethylene amine plant in the Netherlands, see Figure A6.10 (CADDET Project no. NL-95-524, IEA Heat Pump Centre Newsletter Vol. 8, No. 4, December 1990 [51]). It produces 11 tonnes of saturated steam at 145°C and 4.6 bar at full load, and uses saturated steam at 100°C to drive the system. The measured heating capacity is 6.7 MW at 11 tonnes of steam per hour, whilst 13.7 MW of waste heat is needed to drive the unit.

The measured COP (usable heat output/waste heat input) of the equipment is 0.49. The total power needed for circulating pumps etc. is 53 kW (less than 1% of the output). At the time the system was installed (1985) the payback period was two years.

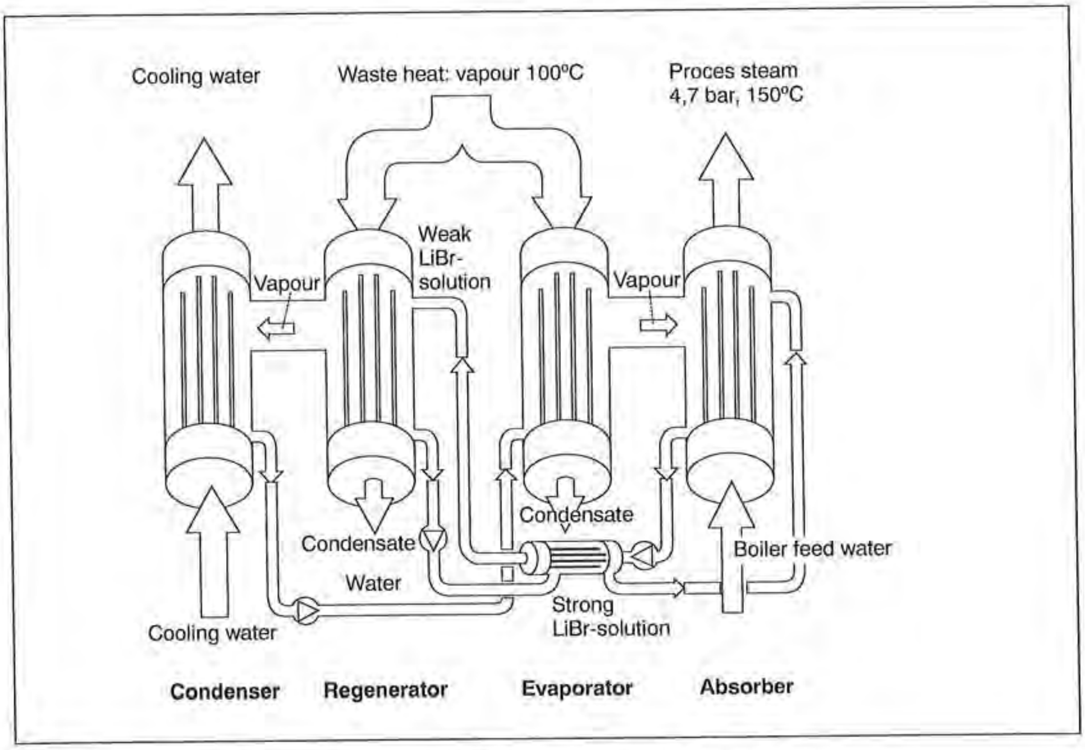

Figure A6.10 *Heat transformer installation at the ethylene plant.*

Experience has resulted in the following recommendations:

- A balanced choice of construction materials is required;
- Operation and inspection of heat transformers requires maximum care;
- Heat transformer components should allow easy access for inspection and maintenance;
- Solution pumps need preventive maintenance at regular intervals;
- Attention should be paid to continuous removal of non-condensable gases;
- Prevention of any leakage of oxygen into the system, and loss of vacuum are needed; and
- Maintenance and monitoring of prescribed inhibitor concentration should be undertaken.

11. Heat transformer in the steel industry at Hoogovens, The Netherlands

Prior to installation of the heat transformer, the steel strip mill at Hoogovens (now Corus) was cooled by water which reached a temperature of 60°C. The heat in the water was released to the environment in a cooling tower (600 TJ annually). At the same time, there was a substantial need for steam at 4.2 bar and 145°C.

To allow installation of the proposed heat transformer, process conditions had to be changed. First, the cooling water temperature was increased from 60°C to 90°C. Second, steam pressure and temperature in the existing network were decreased to 2.7 bar and 136°C.

In operation, 10 MW (268 TJ annually) of heat at a temperature of 90°C is transformed into 4.5 MW of heat at a temperature of 130°C. The heat transformer produces saturated steam. An existing boiler was available to superheat the steam to 136°C, to prevent condensation in the distribution system and to match the supply of steam to the steam demand.

In the design of the heat transformer, several measures were taken to avoid corrosion and improve reliability. Two years after installation, the heat transformer was operating successfully, and it has been shown that the corrosion problems associated with water/LiBr are manageable, but due to the unfavourable plant layout, and the consequently high adaptation costs at Hoogovens, the economics are not so good.

The total investment cost was USD 5.1 million, of which USD 2.1 million was attributable to the heat transformer itself, and to the building. The remainder was due to the cost of a 1.4 km pipeline, and the adaptations to the process cooling water and process steam system. The annual savings of natural gas are 132 TJ. The electricity consumption of the installation is 306 kW, of which only 50 kW is for the heat transformer. The remainder is mainly for the hot and cold water supplies. At a natural gas price of 16 USD/MWh, the payback period is 16 years. In a more typical plant layout, the total cost might have been around 1.5 times the heat transformer cost, i.e. USD 2.78 million. This would have given a more reasonable payback period of 7 years.

New innovations, and further technical development since the start of this project, will enable 20-30% savings on equipment costs in coming projects.

12. Heat transformer at the Ishioka alcohol plant, Japan [52]

At the Ishioka alcohol plant in Japan, operated by the New Energy and Industrial Technology Development Organization (NEDO), a heat transformer using water/LiBr as working fluids is installed in a rectifying column. The column consumes the largest amount of energy in the process. In Figure A6.12, the rectifying column and the heat transformer system flows are shown.

Alcohol vapour (88°C) from the top of the column is used as the heat source for driving the heat pump's evaporator and generator. Heat is recovered in the absorber as hot water, and steam (120°C) is generated as this water is flushed. The steam generated is fed into the bottom of the column as part of the heating steam to the rectifying column. In this way, the column top energy at a low temperature level is made reusable by turning it into column bottom energy at a high temperature. Design specifications of the heat transformer system are found in Table A6.12. A COP of 0.475 was achieved in this plant.

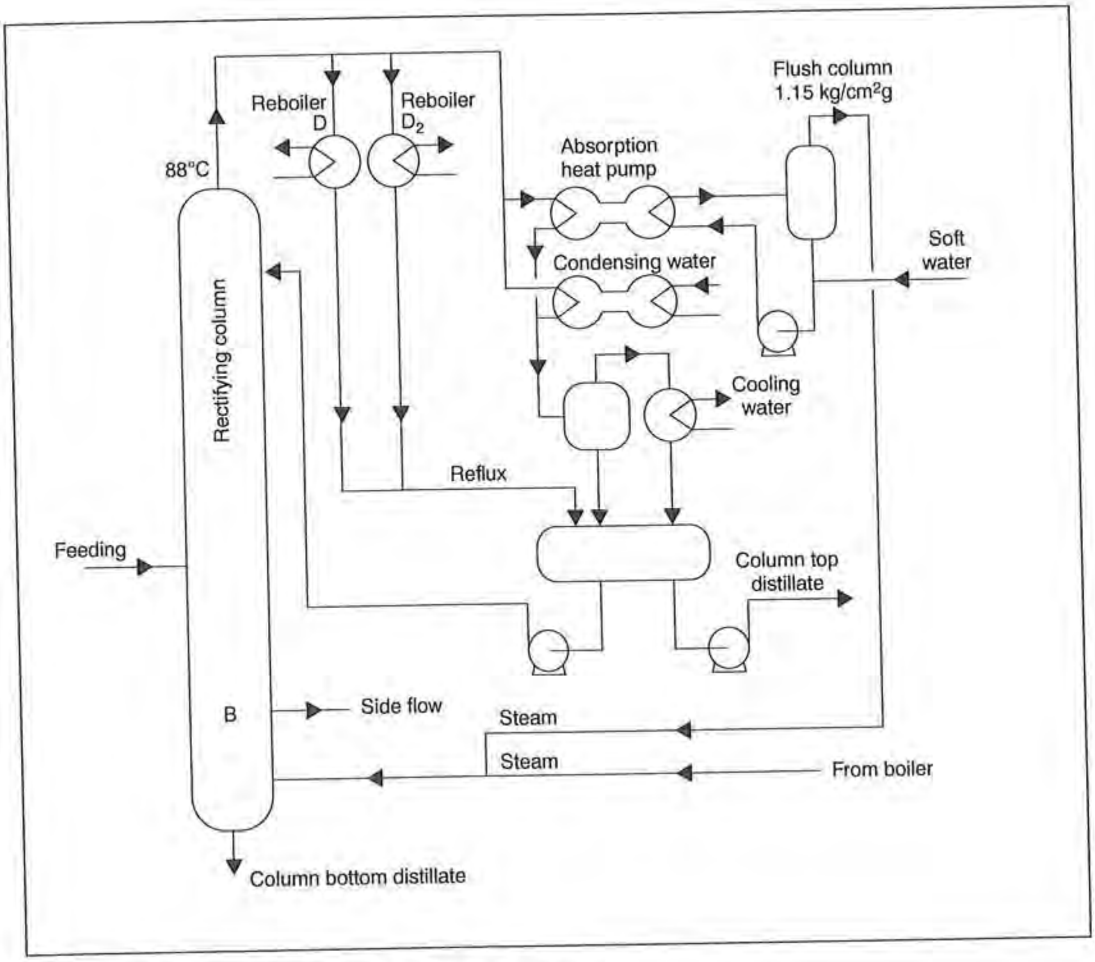

Figure A6.12 *Ishioka alcohol plant in Japan.*

Table A6.12 *Design specifications of the alcohol plant .*

Unit	Mass flow	Temperatures	Load
Water evaporation system	Steam generation rate: 1,650 kg/h	Soft water supply: 74°C	
Heat sink	Hot water flow rate: 105.000 kg/h	Inlet: 122°C Outlet: 131°C	1.10 MW
Heat source	Ethanol vapour flow rate: 11,430 kg/h	Inlet: 89.9°C Outlet: 89.9°C	2.29 MW
Cooling system	Water flow rate: 117,000 kg/h	Inlet: 22.3°C Outlet: 431.0°C	1.19 MW

Appendix 7: Useful Website Addresses

This appendix provides the website addresses of some sources of further information related to sorption technology, e.g. material published by the participating countries, information about pressure systems regulations, relevant documents and literature. If no contact details are given, the material may be supplied by the national contact of the country in question or from the website. National Contacts' and Manufacturers' websites are not included here as they were given in Appendix 1 or 2.

Websites – organisations, associations etc

Annex 24
www.ket.kth.se/Avdelningar/ts/annex24/index.htm

AGCC - American Gas Cooling Centre
www.agcc.org

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
www.ashrae.org

ARI - Air-Conditioning and Refrigeration Institute -Coolnet
www.ari.org

CADDET - IEA Centre for Analysis and Dissemination of Demonstrated Energy Technologies
www.caddet-ee.org

CHP Association
www.chpa.co.uk

Community Heating Internet Solutions
www.communityheating.com.uk

District Energy
www.energy.rochester.edu

European Heat Pump network
www.fiz-karlsruhe.de/hpn

Gas Research Institute (GRI)
www.gri.org

Heat Pump Programme Activities
www.heatpumpcentre.org/network/hpp.htm

HPA - Heat Pump Association
www.feta.co.uk//hpa

IEA Heat Pump Centre (HPC)
www.heatpumpcentre.org

Implementing Agreement on Heat Pumping Technologies (IAHPT)
www.heatpumpcentre.org

Information on heat pumps (European and International)
www.fiz-karlsruhe.de/hpn/hpn.html

International Energy Agency
www.iea.org

International Institute of Refrigeration (IIR)
www.iifiir.org

IZW - Information Centre for Heat Pumps and Refrigeration
www.fiz-karlsruhe.de/peu/peuger.html

Novem - Netherlands agency for energy and the environment
www.novem.org

The Dutch Team Annex 24 homepage
www.gastec.nl

UK Energy Technology Support Unit (ETSU)
www.etsu.com

UK heat pump network
www.ukheatpumpnet.org

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List of Figures

Figure

List of Tables

Table