

## PROGRESS AND PERSPECTIVE IN HEAT PUMPING TECHNOLOGIES AND APPLICATIONS

*D. Favrat, Professor; Ecole Polytechnique Fédérale de Lausanne, LENI-IGM-STI, Station 9,  
CH1015 Lausanne, Switzerland;*

**Abstract:** Heat pumps are among the most promising technologies to reduce global warming emissions and to more rationally use energy. The analysis of the transformation chain accounting for various technologies starting from the electricity production shows that systems including heat pumps result in higher efficiencies than presently dominant technologies. However the full exploitation of the potential of heat pumps requires further technological progress and among them, oil-free hermetic compressors have a major role to play both from a global environment standpoint and from a miniaturization consideration. This is valid for decentralized and centralized heat pump systems as well as for the numerous opportunities for heat pump in industrial processes. Novel district heating and cooling systems with heat pumps and an efficient coupling with advanced cogeneration units are also important factors for the more sustainable cities of tomorrow.

**Key Words:** *heat pumps, technology, applications, industrial processes, rational use of energy*

### 1 INTRODUCTION

The capability of pumping heat from a lower to an upper temperature level has been one of the major achievements of our scientific and technological world. Unfortunately the full potential of the technology is far from being completely exploited, in particular for many of the heating services in housing, industrial processes or even transport.

Men discovered direct combustion for heating and cooking some 400 thousand years ago. Today most of the heating is still done by putting an insulated box around the fire, calling it a boiler. Worse the boilers are primarily fed by oil and gas, which are fossil fuels resulting from a slow transformation over millions of years. However global warming, local particulate pollution, the resource scarcity and geographic uneven distribution are all factors, which are gradually gaining in recognition. By allowing a recovery of environmental or waste energy, heat pumps have a crucial role to play in solving the above-mentioned problems that constitute a major challenge for humanity.

In industrialized countries like Switzerland the use of fossil fuels for heating amounts to over 40% of the consumption of distributed energy. Using the same fuels with an adequate combination of power plant or cogeneration and heat pumps can reduce by half or more the consumption of fuels and their related emissions (Figure 1).

### 2 HEAT PUMPS IN BUILDING AND CITIES

Figure 1 reminds the fact that only heat pumps can allow us to achieve higher than 100% First Law efficiency for heating. Being based on electrically driven heat pumps it also illustrates the numerous combinations of technologies, primarily for electricity production, which can achieve significant energy savings. The net result is of course strongly dependent

on the temperature level of heating. Unfortunately this has not yet been fully integrated by architects, operators and planners, a number of them having not yet grasped the change of paradigm required by the fact that the coefficient of performance of heat pumps is inversely proportional to the temperature lift required.

Another information problem is linked to the wide usage of misleading efficiencies only based on the First Law of thermodynamics. A well insulated modern boiler or a Joule electric heater has a nominal First Law efficiency close to 100%. Why do major efforts then, when one is so close to “perfection”? Heat pump manufacturers can of course claim 300% or more but the discredit on the indicator is already done and it is a major drawback.

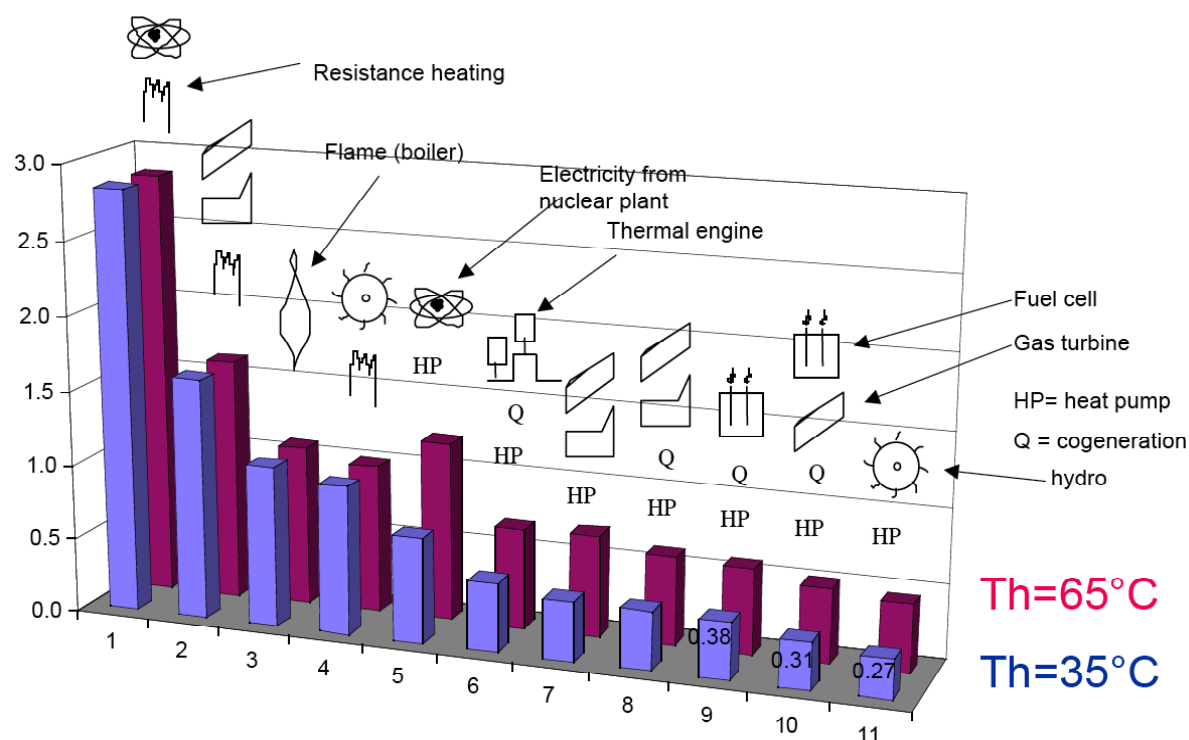


Figure 1: Relative energy consumption of technologies for heating

## 2.1 Exergy efficiencies and heat pumps

Several attempts in the past have been made to introduce a Second Law indicator but with limited success. However one such indicator (exergy efficiency) has been recently introduced in a law on energy (Favrat et al. 2007) in the canton of Geneva in Switzerland. This first approach, requesting the developers of large projects to determine an exergy efficiency of their proposed solution, has been an awakening signal to the importance of heat pumps and of low temperature heating or, for cooling, of relatively high temperature air-conditioning. Heat the coolest as possible and cool the warmest as possible are key messages resulting from the Second Law of thermodynamics.

Table 1 reproduces a simplified synthesis of the heating exergy efficiencies of different common technology combinations, allowing a ranking of solutions but also pointing out the potential for further improvements, considering the relatively low level of efficiency of the present technologies. The basis of the analysis is to consider the full exergy chain from the power plant if required to the convector in the rooms to be heated or cooled. Three types of temperature distribution levels in the building are considered and the problem is formulated so that the overall exergy efficiency results from the product of up to four subsystem efficiencies. For example in the case of an electrically driven district heating heat pump the four subsystems consist of the power plant, the district heating heat pump, the in-house heat exchanger and the room convector which at the end of the chain aims at maintaining a

temperature of 20 °C in the room. To simplify things in Table 1 an average exergy efficiency is considered for the heat pumps, that is independent of the temperature lift. This is justified by the fact that the relative inefficiency of the compressor at high pressure ratios is compensated by the relatively low heat exchanger exergy losses at high temperature lifts (Favrat et al., 2007).

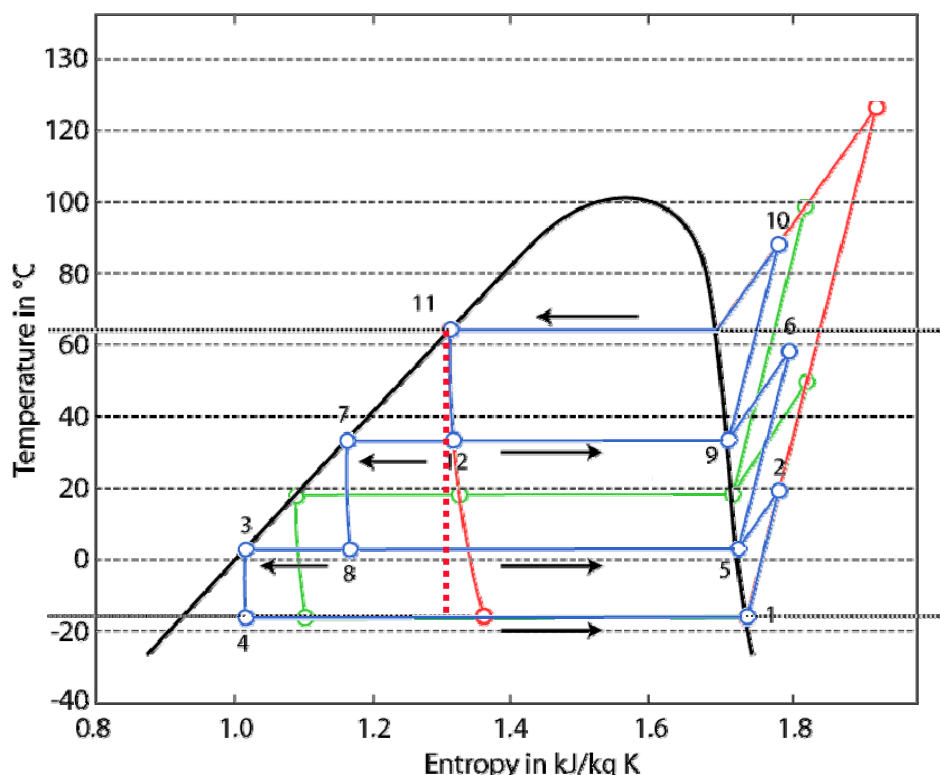
Of course a relative boom in the number of installed heat pumps in new houses of many countries in the last years has given a positive signal. This is a part of the “low hanging fruits” both technologically and economically. However the major market is in the substitution of boilers in houses but also in the buildings of the growing urban areas. Even though progressive house envelop improvements tend to decrease the temperature level required from the heating convectors, relatively high temperature lifts and, when opportune, rejuvenated district energy systems are still essential.

**Table 1 Overall exergy efficiencies of various technology configurations for heating** (Favrat et al. 2007,  $T_a = 273K$ )

Technologies	Power plant	Dist. plant	Building plant			Room convector			Overall exergy efficiency [%]		
			45 / 35	65 / 55	75 / 65	45 / 35	65 / 55	75 / 65	45 / 35	65 / 55	75 / 65
<b>Supply/return temperatures</b>											
Direct electric heating (nuclear power)	0.32					0.07	0.07	0.07	2.2	2.2	2.2
Direct electric heating (combined cycle cogeneration)		0.55				0.07	0.07	0.07	3.7	3.7	3.7
Direct electric heating (hydro power)	0.88					0.07	0.07	0.07	6.0	6.0	6.0
District boiler		0.2	0.54	0.76	0.86	0.53	0.38	0.33	5.8	5.8	5.8
Building non-condensing boiler			0.11	0.16	0.18	0.53	0.38	0.33	6.1	6.1	6.1
Building condensing boiler			0.12			0.53			6.6		
District heat pump (nuclear power)	0.32	0.61	0.54	0.76	0.86	0.53	0.38	0.33	5.6	5.6	5.6
Domestic heat pump (nuclear power)	0.32		0.45	0.45	0.45	0.53	0.38	0.33	7.6	5.4	4.8
Domestic cogeneration engine and heat pump			0.22	0.25	0.26	0.53	0.38	0.33	11.8	9.4	8.7
District heat pump (combined cycle power)	0.54	0.61	0.54	0.76	0.86	0.53	0.38	0.33	9.4	9.4	9.4
Domestic heat pump (combined cycle power)	0.54		0.45	0.45	0.45	0.53	0.38	0.33	12.9	9.2	8.1
Domestic heat pump (cogeneration combined cycle power)		0.55	0.45	0.45	0.45	0.53	0.38	0.33	13.2	9.4	8.3
Cogeneration fuel cell and domestic heat pump			0.25	0.27	0.28	0.53	0.38	0.33	13.4	10.4	9.5
District heat pump (hydropower)	0.88	0.61	0.54	0.76	0.86	0.53	0.38	0.33	15.4	15.4	15.4
Domestic heat pump (hydropower)	0.88		0.45	0.45	0.45	0.53	0.38	0.33	21.2	15.1	13.3

## 2.2 Need for efficient high temperature lift heat pumps

Results from testing centers like Töss, Switzerland (authors 2003) have shown a very slow increase of heat pump efficiencies since about 1996. This tends to show the limits of single stage cycles and the need to go towards more complex cycles to tackle the next efficiency potential. (Zehnder 2004) shows that in single stage heat pumps requiring a high temperature lift (70°C), 50% of the exergy losses are in the compressor, 35% in the expansion valve and 15% in the heat exchangers. Figure 2 shows the evolution towards multi-stage heat pump cycles to improve the efficiency of sub-critical compression heat pumps.



**Figure 2: Towards multi-stage cycles**

Multi-stage cycles are well known for large district heating heat pumps with up to three compressor stages like in the world largest units (Ria 3 and 4 in Goteborg, Sweden). However smaller power technologies still rely heavily on unsealed oil lubricated compressors with an inevitable oil presence in the refrigerant circuit. Among the earlier attempts to improve efficiency, heat rate delivery and high lift capability, let us cite a two-stage air-water prototype with one variable speed compressor (Favrat et al, 1997). Unfortunately the market was not ready for this type of more complex technology and oil prices too low to consider this alternative. A cheaper and less complex technology was to develop what can be called the “two-stage cycle of the poor”. That is to implement with a single scroll compressor an economizer cycle with intermediate vapor injection during compression like has been done for tens of years in large units equipped with screw compressors. Results (Zehnder et al, 2002, 2005) demonstrated the high temperature lift capability (A-13W65), the efficiency increase, and, above all, the significant improvement of the heat rate achievable as a result of the intermediate injection. Other similar attempts have been reported in the literature (Winandy et al, 2002).

The vapor injected scroll compressors and the economizer heat pump cycles are now introduced on the market and allow to partly compensate for the mismatch between the heat pump heat rate and the heat demand at lower atmospheric temperatures.

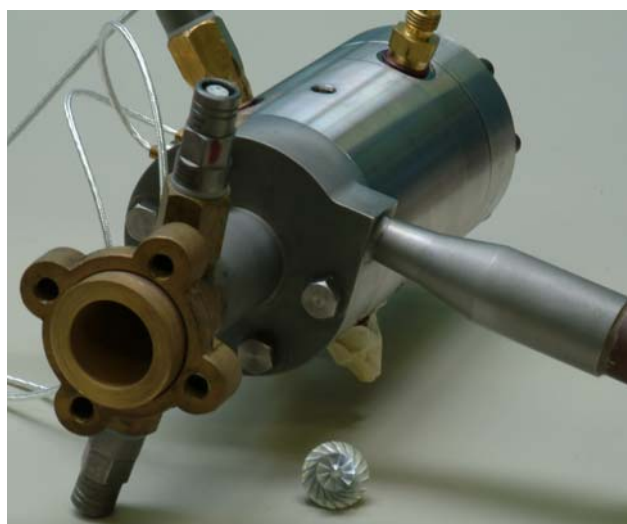
Another attempt towards two-stage cycles in domestic applications is the introduction of a first stage compressor booster as an add-on to conventional scroll compressor based air/water heat pumps. (Zehnder et al, 2002) showed that the heat rate of a standard air-water heat pump could be doubled using a modified low pressure ratio scroll compressor booster. Although such a booster could be less expensive than the main compressor because of the lower operating hours requirement (being used only in extreme conditions to avoid a joule heating backup), it should still have a relatively high inlet volume flow and a cheap hermetic design might not be obvious. This is one more example where new technological progress is required to boost new applications.

The trend towards two stage domestic heat pumps is essential if we want to improve from the present efficiency plateau of the marketed heat pumps. One of the obstacle to the emergence of two-stage domestic heat pumps is the complexity linked to the presence of oil circulating in the more complex circuitry generally ending up in oil unbalance among the compressors which has to be compensated. One approach to limit this drawback is to have two superposed heat pump cycles with an evaporator-condenser linking them. This introduces additional heat transfer exergy losses and regulation complexity. The other hindrance linked to the oil presence is the lower effectiveness of the enhanced heat transfer surfaces in particular in air based heat pump in-tube evaporators (Zurcher et al. 1998). The latter reference shows that the in-tube heat transfer coefficients are generally reduced in presence of oil even though in some narrow vapor quality ranges oil can occasionally slightly improve the heat transfer.

### 2.3 Towards oil-free domestic heat pumps

One interesting effort is to develop oil-free compressors, which would open the application field to more complex and integrated circuitry, being then free from the constraints of oil unbalance and of oil return or potential plugs. Such concepts would also relax the vapor velocity constraints and the associated pressure drops to bring the oil back to the compressor. They could also facilitate the substitution of refrigerant in existing systems and improve the efficiency of heat exchangers.

Open-type quasi-oil-free radial compressors exist in large scale district heat pumps like the ones mentioned above (in fact the bearings and gears are oil-lubricated together with an oil cleaning system). Recently medium scale hermetic units (> 50 kWel), also using radial compressors and based on magnetic bearings, appeared in the refrigeration market. However magnetic bearings are bulky and introduce major constraints on the rotor dynamics at small scale. The other approach is to use the refrigerant itself as a lubricant in either ball bearings with liquid refrigerant or in gas bearings using refrigerant vapor. In both cases the requirements are that the bearing loads stay low. The former has been studied in connection with a corotative scroll compressor (Molyneaux et al. 1996) and the latter is being developed by (Schiffmann et al. 2005). Figure 3 shows a view of the impeller of the first stage of an oil-free compressor of 20 mm diameter together with its prototype casing which includes the bearings and a 6 kW electric motor designed for a two stage unit.



**Figure 3: View of one miniature impeller (20 mm diameter) and its compressor casing for an advanced heat pump compressor concept (Schiffmann et al. 2005)**

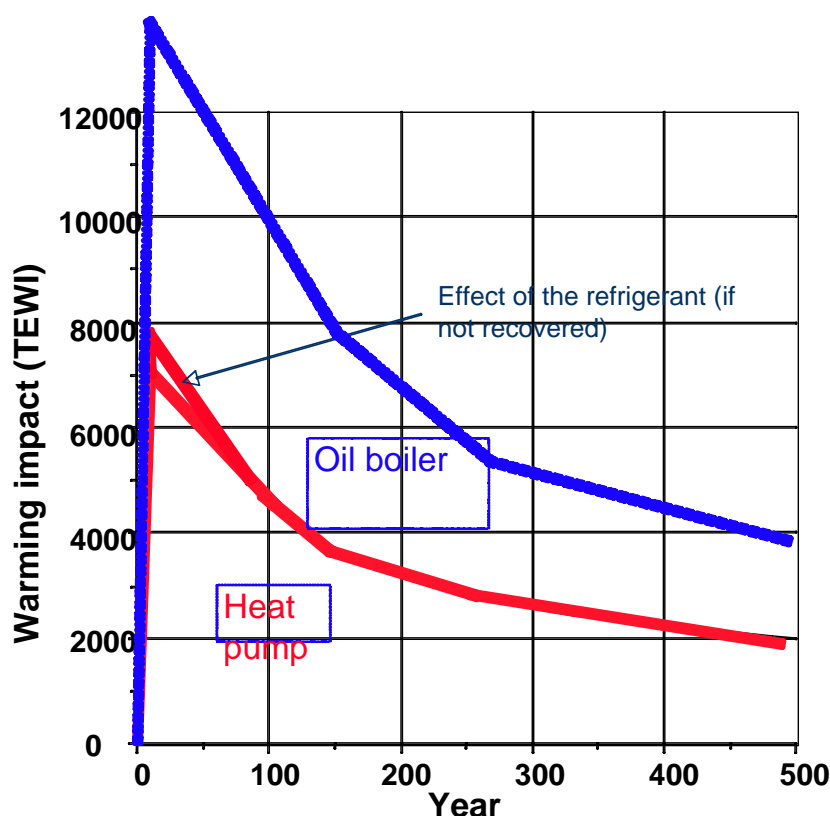
Let us also point to an earlier attempt by (Strong 1980) to develop an ORC-ORC heat pump thermally driven together with a gas bearings supported shaft with an axial turbine driving a radial compressor. It is the view of the author that these attempts failed at the time due to the lack of appropriate dimensionally stable materials and in part to the emerging CFC

substitution problem. The existence of adequate CFC substitutes and the technological progress achieved in the mean time can let us rethink the feasibility of such concepts (Demierre et al, 2008).

The added advantages of oil-free radial compressor concepts are both miniaturization and variable speed, which open the way to wall-hanging heat pumps, reduced cycling losses and reduced electrical disturbances compared to the standard on-off traditional mode of operation. The quality of the frequency inverter is however essential to avoid parasitic harmonics. Miniature radial compressors limit however the choice of working fluid to relatively low density refrigerants like R134a, 245, 600 or the new low GWP HFO-1234yf substitute candidate for 134a.

## 2.4 Global warming impact of heat pumps versus boilers

Since the CFC substitution problem, even zero ozone depletion potential synthetic refrigerants tend to be contested in parts of the world. This relates to a large extent to the car air-conditioning and commercial applications where large leakages are reported. The problem with car air-conditioning is due to the fact that, except for hybrid vehicles, on board electric power is not sufficient to use hermetic electrically driven compressors and shaft seal are still heavily used. This has to be resolved either by CO<sub>2</sub> systems although leakage is likely to be high or by the use of the new low greenhouse potential refrigerants currently under development. In commercial refrigeration CO<sub>2</sub> networks are likely to be more universally used.



**Figure 4: Approximate total equivalent warming impact of a R134a heat pump compared to an oil boiler providing the same service**

To the author's viewpoint the global warming potential of the working fluids should not be a major problem for hermetic domestic heat pumps particularly when considering the dominant alternatives used for heating. Figure 4 is inspired from earlier work from Oak Ridge Nat Lab and approximately shows the global warming impact of a 134a heat pump compared to a boiler. The indicator used is the Total Equivalent Warming Impact (TEWI) and its evolution over centuries, accounting for its natural decay in the environment. The lower solid curve

shows the impact linked to the electricity consumed during the lifetime of the heat pump operation considering a US mix. The intermediate solid curve shows the relative impact of the refrigerant if released when being disposed of (which is against good established practice and should be easy to avoid) and the top curve shows the impact of the emissions of an oil boiler providing the same service. With such an order of magnitude advantage for heat pumps it is awkward to see all the debate around HFCs to be restricted, while boilers are broadly accepted without restrictions.

## **2.5 District heating and cooling with heat pumps**

As pointed out earlier the market for domestic heat pumps is growing in many countries and ground source heat pumps contribute to the growing needs for air-conditioning in the summer without requiring reversible heat pumps.

The implementation of heating and cooling in cities is often hindered by the difficulties linked to the cold source. Geothermal probes are often problematic and lack space, while air solutions tend to be noisy. Even wet cooling towers are more and more questioned in view of side problems like the visual impact and potential diseases like legionella for example.

Therefore we should see a comeback of district heating and cooling networks fed by heat pumps as they flourished during the early eighties in Scandinavia and Japan (Narita 1984, Calm 1988 or Lorentzen 1990). Common solutions include the implementation of separate water and glycol water networks from a centralized plant. In view of the diversity of buildings to be served (new buildings with low temperature heating, renovated buildings with moderate temperature heating or older buildings with high temperature requirements), solutions with relatively high temperature networks tend to generate high exergy losses. Novel approaches with the use of both centralized and decentralized temperature boosting heat pumps have been proposed (Curti et al. 2000) and should be developed in the future. More recently single networks distributing water cold enough to air-condition and serving as a source for decentralized heating heat pumps have been rejuvenated. Those however suffer from the inevitable glide associated with water cooling, within the economic investment constraints which limit the flow rates for any given energy demand. To avoid that, a recent conceptual proposal consisting in a dual pipe of subcritical CO<sub>2</sub> network (one liquid and one vapor) is proposed in this conference (Weber et al., 2008) together with decentralized cogeneration or heat pump units. Such a concept offers the greatest synergy between users of parts or whole cities with a great potential if the use of high pressure CO<sub>2</sub> in cities can gain acceptance. Air conditioning and refrigeration heat from shopping centers, industry or office buildings can then be recovered to be used for other users along the network. In countries with a large number of cities located close to lakes or rivers like Switzerland the potential for resources and emissions savings is substantial. However the final choice of integrated district energy systems including heat pumps is more and more also going to relate to the simultaneous consideration of heating, cooling and electricity cogeneration in whole or parts of cities (Burer et al. 2003).

## **3 HEAT PUMPS IN INDUSTRY**

Waste heat at intermediate temperature levels (50 to 150°C) is very common in industry. Processes like product concentration or drying are very common with high demands in energy. When energy integration theory (pinch technology) is applied results often show pinch temperature levels within the temperature range mentioned above. Because of the short payback times required in industry and the low oil prices of the last two decades, industrial heat pumps had a difficult time during this period. The same applies to the equipment available as some of the developments of the eighties, like the efficient oil-free steam twin screw compressors (Degueurce et al. 1984) are not anymore easily available. The most promising sectors are the wood – pulp & paper, food and chemical industries and the present industrial heat pump park is estimated to be above 4500 units (Flash-Malaspina et al., 2007). Of course a large number of these units rely on inefficient ejectors, which have

no moving parts and are therefore cheap, easy to maintain and to clean. The more efficient units use either:

- roots blowers which are limited to about one bar pressure differential
- volumetric machines like the liquid ring, the scroll and the twin screw compressors
- dynamic machines like the radial compressors, which generally require a large gear box at small scale while we wait for direct high speed electric drives, and the axial compressors in the very large capacity range.

Roots boosters and dynamic compressors require a precise design as they often do not allow a significant overpressure beyond the design value. Volumetric compressors are usually more tolerant to variations of operating conditions, which would result from fouling or an underestimation of the thermal losses in an open cycle mechanical vapor compression heat pump. In volumetric compressors liquid injection using the same working fluid to limit the temperature can be used although it often results in lower volumetric efficiency performance (Afjei et al. 1992). This is caused by the flashing of the saturated liquid, after being heated on the walls, when it expands through the internal leakage passages.

Absorption heat pumps including heat transformers are also used with efficiency limitations unless double effect cycles are used.

Compression heat pumps and in particular the open cycle compression heat pumps (vapor compression or recompression) should be the dominating technology in the future. With the present fossil fuel prices their future is bright but it will strongly depend on technology availability. Significant progress in compressor technology is desired with oil-free technology and the elimination of shaft seals whenever possible. Direct drive variable speed hermetic concepts for an easier management of startup and shut down procedures in processes are probably a key to their future success. This concerns in particular closed cycle heat pumps as well as Organic Rankine cycle turbines used for low grade energy conversion to electricity where similar technology challenges exist (Rickli et al. 2006).

Applications for industrial heat pumps are numerous and a number of examples have been documented in the past but often not realized because of unfavorable economic conditions. Let us cite the following examples.

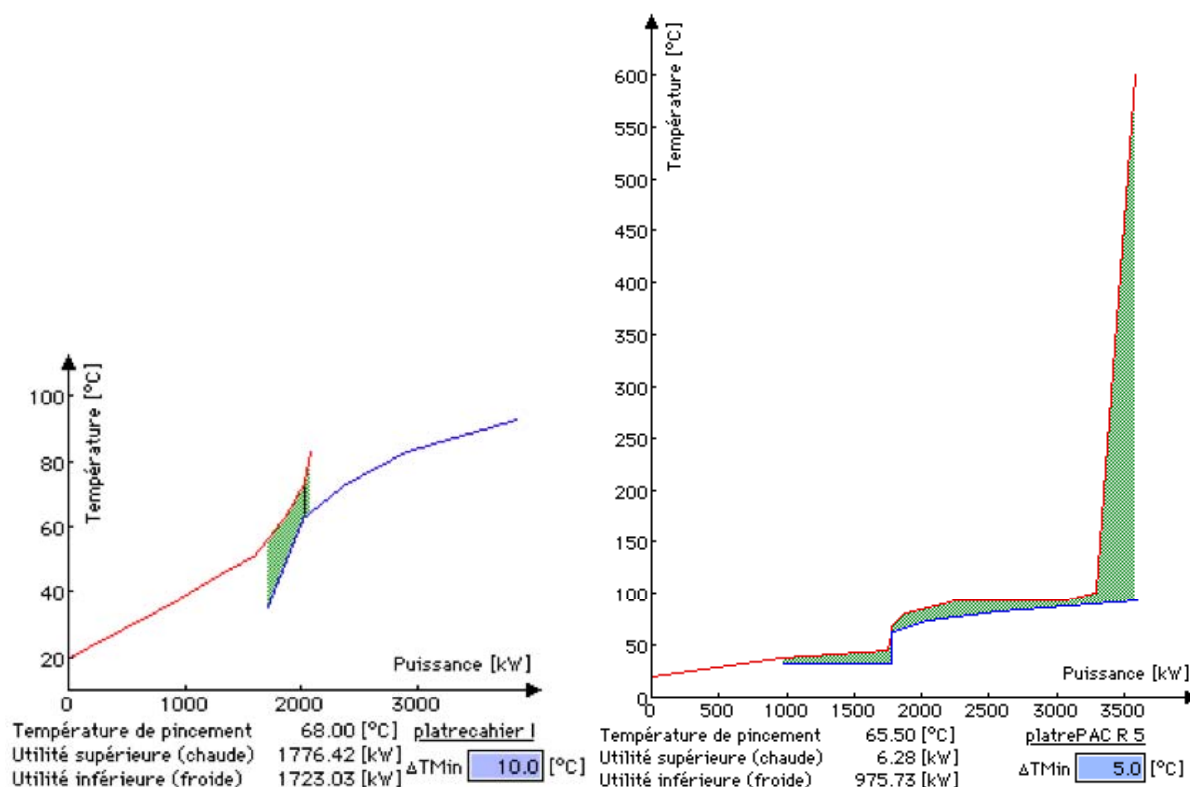
### 3.1 Drying of plaster panels

This case described in (Staine et al. 1991) is illustrative of a significant potential for efficiency improvement using an industrial heat pump. But this potential has been limited by technology component unavailability (cheap two-stage compressor) in a context of regulatory uncertainties linked to the substitution of the CFC refrigerant.

Plaster is first wetted to be later molded into panels with various shapes and design. They are then progressively dried in a drying tunnel. This operation is still largely done by using heaters with pressurized hot water obtained from a fossil fuel boiler. Figure 5a shows the composite curve of the process requesting more than 1.7 MWth from the boiler and Figure 5b shows the expected composite curves after introduction of a gas engine – heat pump combination to satisfy the needs of the process.

The net result of the introduction of the cogeneration and heat pump utility is a reduction of 40% of the fuel consumption. The calculation was based a two-stage R123 heat pump model working between 33 et 93°C with a 265 kW shaft power and a cogeneration engine of 410 kWel supplying also the electric demand of the whole site. A graphical representation of the exergy losses and of the electrical balance of the plant can be found in (Favrat et al. 1999). Reassessing the project at the present time would require a recalculation with R 245fa. This project also highlights the need for efficient two-stage hermetic heat pump compressors as well as a clear regulation, which, for hermetic systems, would eliminate the uncertainties related to the use of HFCs in industry. The latter is an essential part of the future policies to be introduced if we want to exploit the full potential from heat pumps in industry.

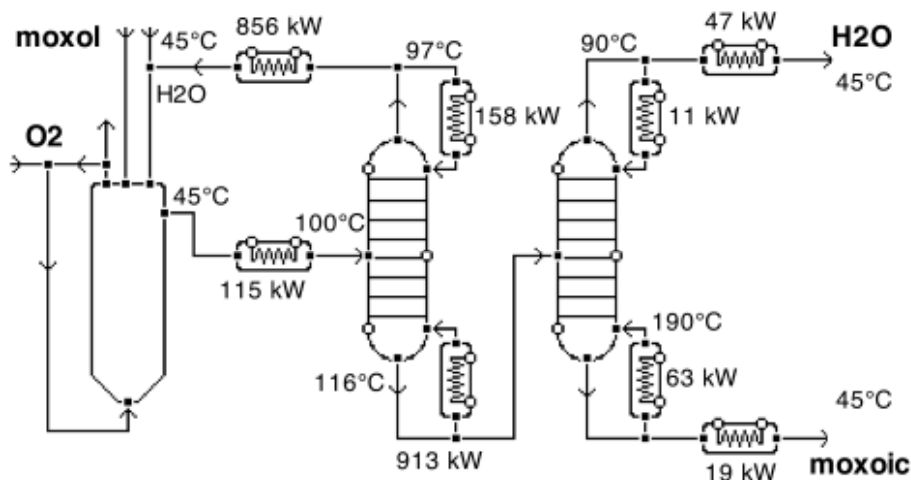




**Figure 5: Composite curves of a plaster panel drying process (left) before retrofit (right) after the introduction of a gas engine combined with a two stage industrial heat pump.**

### 3.2 Mechanical vapor compression in a chemical compound

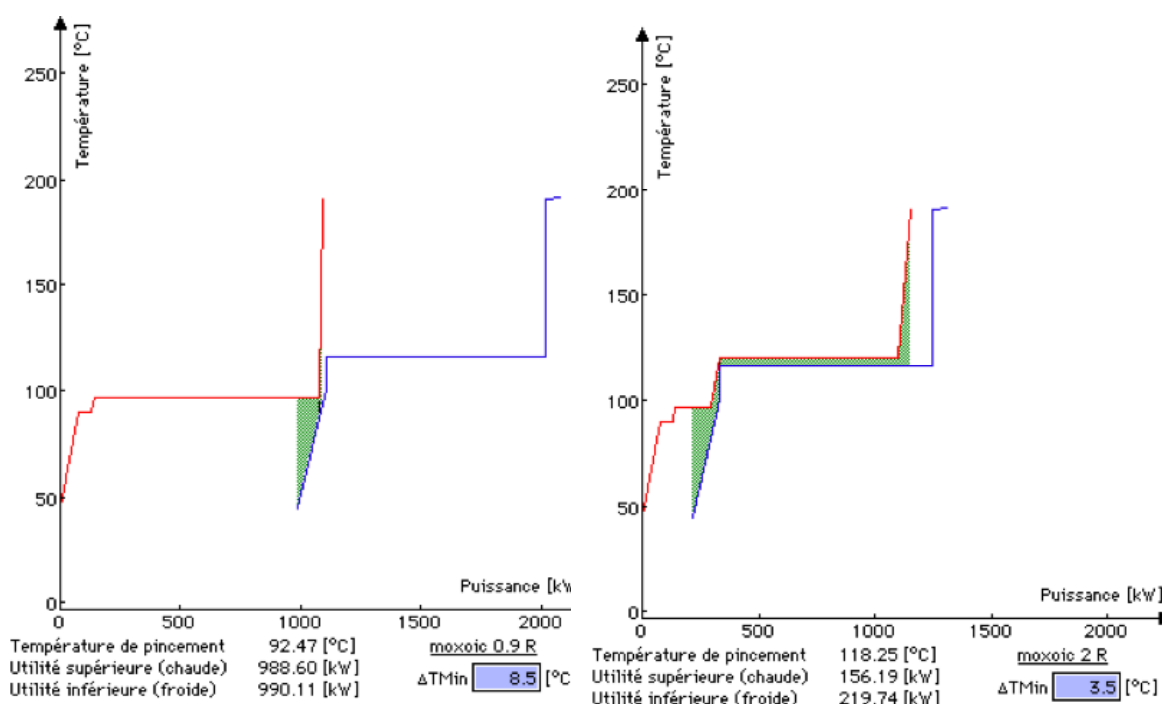
Mechanical vapour (re)compression corresponds to an open cycle heat pump consisting of a vapour compressor and a condenser in which the latent heat of the vapour extracted from the process is recovered to heat the incoming streams. This is a powerful use of heat pumps with often fairly high COPs because the pinch at the evaporator is avoided. Figure 6 shows the flowsheet of the original production process of an acid. Figure 7 shows the composite curves of the process before (left) and after retrofit (right) once a compressor is introduced to elevate the pressure at the head of the first distillation column, so that the vapour can be condensed at a sufficiently high temperature to heat the reboiler at the bottom of the column.



**Figure 6: Flowsheet of an acid production process before retrofit with a heat pump**

The net result of the open cycle heat pump implementation is a reduction of 75% of the exergy losses as a result of a COP higher than 10 for a compressor shaft power of the order

of 62 kW. Once again one of the key element for the success of such a retrofit lies in the availability of a suitable compressor with sufficient guaranties against potential hazard like accidental leakage.



**Figure 7: Composite of the process of the acid production process (a) before retrofit and (b) after the introduction of a mechanical recompression scheme on the first distillation column**

### 3.3 Drying with superheated steam and heat pumps

The first example showed a process of drying with air. The evaporated steam from the product (plaster) is however diluted in air, making the recovery of its latent heat more difficult. An alternative way is to dry the product with superheated steam so that the drying is done essentially in an H<sub>2</sub>O environment. Compressing the steam produced during drying like in mechanical vapor compression processes allows a condensation at a higher temperature than would occur in presence of large amounts of air. One major difficulty with such a scheme is the introduction of the product to be dried without major influx of air, the sealing of the drying unit and occasionally the higher temperatures of the drying process. Similar processes have been explored during the eighties, for paper drying among others, and are today studied for example for laundry drying (Palandre et al. 2007). Once again a key component is the oil-free compressor.

## 4 HEAT PUMPS AND ORC IN TRANSPORT

Some of today's vehicles are becoming so efficient with, in particular, a downsizing of the engine or hybrid systems to the point where an efficient heating can become problematic without the use of an inefficient mode of operation to boost the thermal part of the engine service production. Additional burners are also envisaged to boost heating in some conditions.

Considering that air conditioning is more and more widespread, reversible heat pump might have a major role to play in the future for transport applications. Once again a crucial element will be the compressor, which would have to be hermetic as the hybridization progress and the capacity of batteries improve. Moreover there is a growing interest for ORC

waste heat recovery cycles on board, which might offer synergy possibilities with air-conditioning heat pumps at least from the technology point of view.

## 5 CONCLUSIONS

Heat pumps have a substantial role to play in most of the human activities with significant gains in terms of CO<sub>2</sub> emission reduction thanks to a more rational use of fossil resources. Development opportunities go from comfort conditioning in housing and vehicles to key industrial and commercial processes.

To fully exploit this potential major technological challenges remain in particular to develop oil-free hermetic compressor technologies, which would favor an environmentally friendly use of energy. Multi-stage compression and variable speed permanent magnet motors are among the most promising technologies.

Indicators of sustainability should also be improved, to better account for the Second Law of thermodynamics, in assessing and comparing present and future systems and promote heat pumps.

## 6 REFERENCES

Afjei T., Suter P, Favrat D. 1992. "Experimental Analysis of an Inverter-Driven Scroll Compressor with Liquid Injection". *Purdue Compressor Conference*

Almqvist P. 1988. "Large Heat Pumps in Stockholm", *Newsletter of the IEA Heat Pump Center*, Vol. 6, Number 3.

Authors 1993, WPZ Bulletin 23

Burer M, Favrat D., Tanaka K., Yamada K, 2003. "Multicriteria optimisation of a district heating cogeneration plant integrating a Solid Oxide Fuel Cell-Gas Turbine combined cycle, heat pumps and chillers", *Energy*, 28/6 pp 497 – 518

Calm J.M. 1988. "District heating and cooling with heat pumps outside the United States", *ASHRAE Transactions*, Vol. 94, Number 1.

Lorentzen G. 1990. "Heat Pumps for District Heating Applications", *3rd IEA Heat Pump Conference*.

Curti V., von Spakovsky M., Favrat D. 2000. "An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace, parts I and II", *Int J. of Thermal Sciences*, vol.39, No7.

Degueurce B., Banquet, Denisart J.P., Favrat D. 1984 "Use of a twin-screw compressor for steam recompression". *BHRA Symposium on the Large Scale Application of Heat Pumps*, York (reprinted in : *Hydraulic Pneumatic Mechanical Power and World Pumps Journal*, Dec. 1984, p 335-337).

Demierre J., Favrat D., 2008 "Low power ORC-ORC systems for heat pump applications" *IEA heat pump conference*, Zurich, Switzerland

Favrat D, Nidegger E, Reymond D, 1997. "Comparison between a single stage and a two stage air to water domestic heat pump with one variable speed compressor". *IIR Conference on heat pump systems, energy efficiency and global warming*, Linz.

Favrat D., Marechal F., Epelly O. 2007. "The challenge of introducing an exergy indicator in a local law on energy", *Energy*.

- Favrat D., Staine F., 1999. "Exergy and Environmental Considerations in Process integration". (invited lecture) PI'99 Int Conference on Process Integration, Copenhagen March 7-10.
- Flash-Malaspina N, Favrat D. 2007. "Industrial heat pump market and technology". *Electricité de France workshop printemps de la recherche*. Les Renardières. June.
- Molyneaux A, Zanelli R., 1996 "Externally Pressurised and Hybrid Bearings Lubricated with R134A for Oil-Free Compressors", *Proceedings of the Int. Compressor Engineering Conference at Purdue.*, Vol. II, pp. 419-424.
- Narita K. 1984. "Building the heat pump system in Hikarigaota Park Town: lessons and conclusions", *IEA Heat Pump Conference*
- Palandre L., Clodic D. 2007. "Alternative thermodynamic cycles for a high efficiency heat pump dryer". *IIF-IIR Int refrigeration congress*, Beijing
- Krummenacher P., Staine F., Favrat D., "Process Integration Study at Brasserie du Cardinal: Energy and Cost Savings Opportunities Using Mechanical Vapour Recompression (MVR)". *CADDET Newsletter* 4/92
- Rickli JP., Favrat D., Marechal F., Demierre J, 2006. "Can steam play a role in low to medium power from low temperature heat". *ASME ATI conference on Energy production, distribution and conservation*, Milan, p273-279, May 14-18.
- Schiffmann J., Favrat D., Molyneaux A. 2005, "Theoretical design of a high speed, oil free radial compressor for domestic heat pumps". *Proc. 8th IEA heat pump conference*, Las\_Vegas.
- Staine F., Krummenacher P., Favrat D., 1994. "Heat Recovery in a Pasta Factory. Pinch Analysis Leads to Optimal Heat Pump Usage". *IEA Heat Pump Centre Newsletter*, Vol.12 N°4
- Strong D, 1980 "Development of a directly fired heat pump". *PhD thesis University of Oxford UK*
- Weber C., Favrat D. 2007 "Conventional and advanced district heating systems". *Proc. of ECOS 2007*, ed Mirandola A. et al., Padova, Italy, pp 517-524 (submitted to Energy)
- Winandy E, Lebrun J. 2002. "Scroll compressors using gas and liquid injection: experimental analysis and modeling". *Int J. of Refrigeration*, vol 25, No8, 1143-1156
- Zehnder M., Favrat D.. 2005. "Experiences with hermetic scroll compressors with intermediate vapor injection port in heat pumps for high temperature lift heating applications". *Proc. 8th IEA heat pump conference*, Las Vegas.
- Zurcher O., Thome JR, Favrat D 1998 "In-tube flow boiling of R-407C and R-407C/oil mixtures". *HVAC&R*, vol.4, No 4, p347-399
- Zehnder M., Maréchal F., Guex S., Schiffmann J., Favrat D. 2002. "Pompe à chaleur air-eau à haute température, Phase 2: Cycle à injection optimisé, essais journaliers et compresseur booster; Analyse thermo-économique". *Final report to Swiss Federal Office of Energy* (ENET-Nr. 220219)
- Zehnder M. 2004 "Efficient Air-Water Heat Pumps for High Temperature Lift Residential Heating, including Oil Migration Aspects", PhD thesis No. 2998, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland