

CHALLENGES IN HEAT-PUMPING TECHNOLOGIES

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ABSTRACT

There are many types of applications of Heat Pumping Systems and Equipments. Most notably heat pumps for climate control – heating as well as cooling – in buildings. But the concept of heat pumping also includes refrigeration for traditional uses like for the cold chain for food but also for medical applications and low temperature applications in cryogenics.

During the last two decades there has been a technology shift with a transition from using CFC and HCFC to new refrigerants like HFC and “natural” refrigerants. This transition has proceeded in slightly different direction and different emphasis in different parts of the world. It has also provoked a renewed interest in different cycles.

Advanced designs of buildings will reduce the heating demand. Heating of tap water will be a substantial load and also the demand for cooling in summertime. Different climatic conditions give priority to different choices.

A most important challenge is to reduce energy demand as well as demand for peak power. Efficient heat pumping systems require careful choices of cycles and designs of heat sources/sinks as well as heat exchangers with small temperature differences.

Key Words: *direct and indirect emissions, energy systems, energy efficiency. cycle losses.*

1 MANY APPLICATIONS FOR HEAT PUMPING TECHNOLOGIES

The concept of a “Heat Pump” leads our thoughts to units for climate control; *heating and cooling* of buildings and industrial premises. However in the concept of “Heat Pumping Technologies” we must also include refrigeration with a large number of traditional uses; In refrigerated storage of food, in the cold chain for food distribution all the way into the kitchen refrigerator of the user, in medical applications and also in low temperature applications, cryogenics.

Within this frame we find that Heat Pumping Technologies involves a *very* large area of activities worldwide. It is for instance estimated (IIR 2004) that the energy spent to operate refrigerating and AC equipments consumes about 15% of all electric energy word wide – in some parts of the world considerably more. Important to notice is also that this is a rapidly growing industry. Rising living standard means increased demand for the services of heat pumping.

According to DOE (2005) systems for “heating and cooling” use 44% of the total energy in the average US home or small business, another 9% is used for the refrigerator and 14% for water heating. The US DOE also says: “What’s more, heating and cooling systems in the United States add global warming by pumping carbon dioxide into the atmosphere, and they generate sulfur dioxide and nitrogen oxides, the chief ingredients in acid rain.”

Meeting increased demands for comfort and conveniences without increasing emissions harmful to the environment is a *major challenge*. – It is a challenge for us as consumers to install and operate systems in an intelligent way. It is also a most important challenge for our industry in coming years;

Companies that have the ability to meet such demands in a cost effective way are the winners in the coming decades.

A major challenge for industry is thus to furnish their services in a cost effective way with minimum impact on the environment. This includes the choice of:

- Working fluids and designs for minimum emissions.
- Efficient use of energy in systems and equipment

An overall concern for heat pumping technologies is that most system relies on electricity as energy input. Hence it is also important to take into account the

- Power supply for system operation.

2 PHASE OUT OF ODP-FLUIDS AND REDUCTION OF DIRECT EMISSIONS

The Montreal Protocol, which was adopted in 1987, aimed to limit emissions influencing the global ozone layer. Since 1987 the use of CFC-refrigerants (and in many countries also HCFC-fluids) has decreased substantially. In most parts of the world all fluids with any ozone depletion potential have been phased out. This has been a major challenge for the industry over the last decade. Refrigerants of today are different from what was used up to mid-80ties.

The direct *losses* of refrigerants from plants in operation have been reduced in recent years. Especially in older installations in supermarkets (with DX-systems) the annual losses, according to several measurements have been recorded to frightening numbers like 1/3 of the charge lost each year! This is unacceptable. In recent years many efforts have been spent to reduce these losses. From DX-systems annual losses are reported to be in the order of 15% per year (van Baxter, 2004). Still it should be possible to do more. The reductions have been achieved partly by better designs, but it is also a result of focusing on the problem, developing and applying good service practices for handling refrigerants and for service. It is very important to get operational personnel actively involved. A study in Sweden on a group of industrial applications and large supermarkets showed that refrigerant losses could be reduced to the order of 5% per year. This was obtained merely by improving education of personnel, routines for service and only minor design changes.

One way to reduce the rate of leakage of refrigerants from systems – as well as reducing the required refrigerant charge – is to use *indirect systems*. It is possible to design system fully hermetic. Careful hermetic designs may be the path to follow to reach the goal of “zero leakage.”

By applying indirect systems the necessary amount of refrigerant for a given cooling capacity can be reduced substantially. With small charges in the system the number of applications may be increased where flammable refrigerants, like hydrocarbons, can be accepted. *Minimum charge systems* have an advantage not only when using flammable refrigerants but also for HFC-fluids, the price of which has increased. Fernando (2002) describes work aiming for charges less than 150 grams of propane for a 5 kW heat pump. Hrnjak (2002) reports about a chiller of 13 kW cooling capacity with a refrigerant charge of only about 230 grams of ammonia – or 18 grams/kW!

The choice of refrigerants does of course affect the environmental influence of inevitable (small) losses of refrigerants. The use of “natural” refrigerants is of great interest, especially in Europe. In systems with minimum charge even flammable refrigerants like hydrocarbons could find more applications. Such developments are however hampered by the boycott of strong groups of compressor manufacturers.

3 MAJOR CHALLENGE: REDUCE INDIRECT EMISSIONS.

It is estimated that about 20% of the global warming impact of the use of Heat Pumping Systems comes from direct emission of refrigerants on an overall basis (IIR 2004). To a large extent this is due to mobile AC-installations. The remaining 80% comes from *indirect* emissions due to energy demand.

The Kyoto protocol aiming to limit global warming has just passed the political threshold to come in force. A definite problem in this is that countries like the USA and China have not signed. There is an alarming global mal-distribution of the use per capita of primary energy and CO₂ emission.

3.1 Energy Supply for Operation – Efficiency of Systems

Heat pumping technologies give a possibility to reduce primary energy demand for heating by using heat pumps. The backside of the coin is that the increasing use of heat pumping for comfort cooling also causes a rise in global energy use.

Table 1. Comparison of primary energy use for different forms of heating

Heating method	Useful heating energy / heating value of fuel	
Furnace (oil fired or other fuels)		0.80
Electric resistance heating:		
Electricity from condensing plants	$0.9 \cdot 0.5 =$	0.45
Electricity from co-generation plants		
combined with district heating	$0.9 \cdot (0.40+0.50) =$	0.80
Heat pumps operated by electricity:		
Electricity from hydro- or wind power	$0.9 \cdot 2.8 =$	2.52
Electricity from condensing plants	$0.9 \cdot 0.5 \cdot 2.8 =$	1.26
Electricity from co-generation plants		
combined with district heating	$0.9 \cdot (0.40 \cdot 2.8 + 0.50) =$	1.46
Heat Pumps of absorption type	$0.80 \cdot 1.5 =$	1.20
Heat Pumps driven by engine	$0.25 \cdot 2.8 + 0.5 =$	1.20

Assumptions: The thermal efficiency electric generating plants is set to 50%. For co-generation it is assumed that the electric thermal efficiency is 40% and the heat recovery (before distribution losses) are 50%. It is assumed that there are 10% losses in distribution of the electricity as well as in the heat distribution in a district heating system. The seasonal efficiency of local furnaces is set to 80%. The seasonal performance factor of heat pumps is set to 2.8 for mechanically operated and to 1.5 for absorption type. Engine shaft efficiency (for operating heat pump) is set to 25%, and 50 % of the fuel's heating value is assumed to be recovered as heat from the exhaust and the cooling water.

In many countries heat pumps have difficult to defend its place in political quarters due to the fact that electricity is used for operation. Electric energy is often regarded as dirty – if generated in nuclear or fossil fueled plants. “Green energy” is naturally preferred, generated in hydro or wind power stations, solar energy or using bio-fuels. For the recent “COP10” meeting in Buenos Aires on Climate Change an IEA-statement was published indicating: “IEA analysis of an alternative policy scenario shows that emissions can be curbed, mainly through a strong push on energy efficiency policy, support to renewable sources and further use of nuclear, for those countries choosing to do so.”

A short discussion about the primary energy demand is relevant. Table 1 (Granryd 2002) shows schematically how the demand of primary energy (from fuel of some kind to heat) is utilized when different forms of heating are considered. As seen systems involving heat pumps are among the most efficient.

3.2 Waste Heat Energy For Operation

The design of systems using low temperature waste heat for operation is a challenge. There are several solutions. Setterwall et al (2001) describes a one stage absorption unit design which seems to meet theoretical performance quite well in practice claiming a cooling COP of 0.7 to 0.8. It is a 1 MW unit operated by low temperature heat (90 to 70 °C). For applications where heat is available at higher temperatures two or even three stage systems have been developed (De Vault 1990 and later publications) in order to arrive to better COP.

A classical challenge is to design a competitive *solar operated cooling system*. Several attempts have been made. An overview of technical options and cycles for solar driven cooling systems is given by (Pridasawas and Lundqvist 2003).

There are also other schemes to utilize waste heat for the operation to produce cooling – and heating – in an efficient way. One is to use a “double loop system” with a power generating stage to drive the heat pump. Recent developments using CO₂ as a refrigerant may also prove to be interesting for such a double loop scheme. By using supercritical pressures in the power cycle and on the high side of the cooling cycle, it is possible to take advantage of large temperature glides of the heat input for operation as well as the heat output from the cycle. Figure 1 shows a possible scheme.

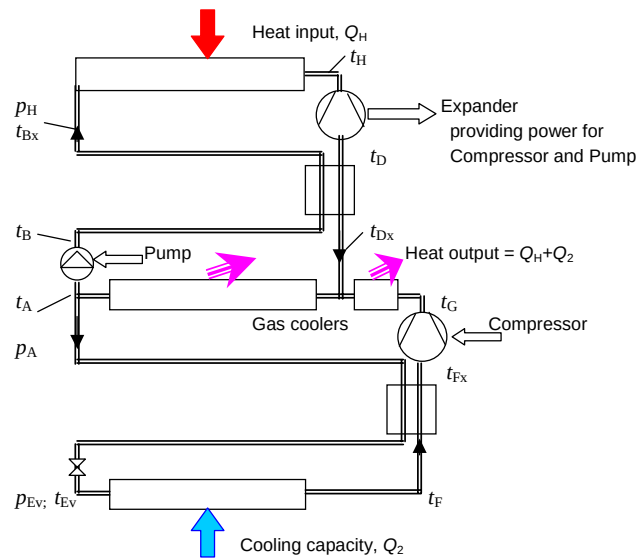


Fig. 1. Transcritical “double loop” cycle with CO₂ as refrigerant.

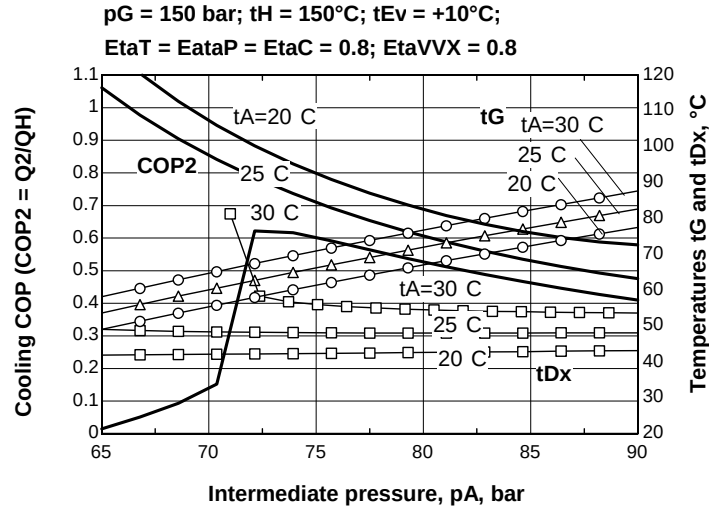


Fig. 2. Example of performance for cycle in Fig. 1 with CO₂ as refrigerant.

High pressures with CO₂ give high power density but require the development of new components. Figure 2 shows an example from a simple theoretical analysis of the performance of a system using this cycle. It shows how the Cooling COP and temperatures available for heat output from the cycle are influenced by the choice of intermediate pressure, p_A , and temperature, t_A , after the gas cooler. As seen these two parameters have a large influence. It is very beneficial to have the temperature t_A below 30°C in the CO₂-systems. Also the “temperature lift” of the cooling cycle has a large influence. Notice that the COP_{heating} is equal to $COP_{\text{cooling}} + 1$. Waste heat can be used to produce cooling without using electricity, as well as providing efficient heating.

4 SMART BUILDINGS AND LOW ENERGY HOUSES

A most important challenge is to design systems as efficient in energy use as possible. This applies to the designs of buildings as well as of installations for climate control.

4.1 Decreasing Load

It is interesting to observe that the heating demand for houses is about the same in several different parts of Europe, in spite of quite different climatic conditions. The reason for this is different building traditions and codes in different areas. The types of designs of houses, insulation and air tightness of the climate shield, the walls and windows, are different. It is of course also a matter of economic insulation: With increasing bills for heating the standards for insulation will be better. However even if this is applied in houses built today, it is a very slow process before it will be noted in statistics involving the whole building stock.

It is obvious that solutions of existing houses are different from systems suitable for new low energy houses. It has been demonstrated that houses can be built with a very small direct energy demand for heating. The energy released by lighting, other appliances and of activities of people in the house, can keep the inside of the house at a comfortable indoor temperature down to exterior temperatures below freezing. An effective heat exchange between exhaust and incoming fresh air is used. Still there is a demand for hot water. A solution for such houses is to use exhaust air heat pump to produce necessary heating of hot water, often combined to produce heating of the premises when needed.

For small new houses in Sweden more or less a standard solution is to use controlled ventilation combined with exhaust air heat pumps. The heat pump can cover all energy supply for hot water demand as well as most of the heating for a well insulated house.

4.2 Low temperature distribution systems

The performance of heat pumps is, as we all know, sensitive to the temperature lift in the cycle. For energy savings it is therefore important to have installations in the building that permits use of low temperature for heating. In northern countries it is customary to have hydronic systems where radiators in each room are used for heat distribution. Many systems in Sweden were originally designed for temperatures of 80/60°C the coldest day -- but were luckily in practice often oversized so that temperatures like 55/45°C the coldest day are sufficient. This makes it possible to use heat pumps also at maximum load conditions.

Of course the temperatures in heating systems when using heat pumps should be as low as possible. At milder ambient conditions lower distribution temperatures are used; on the average the radiator temperatures may be 37/30°C in a system where the design temperature the coldest day is 55/45°C. In order to save energy it is important to adjust the water temperatures in operation according to the demand. Amazingly it was difficult to get acceptance among installers to avoid mixing shunt valves in hydronic systems. Floor heating is favorable for heat pump applications. However there are also disadvantages and, if not carefully designed, the heating load of the building will increase. Advanced designs of convectors may be a future possibility for extreme low temperature heating.

4.3 Heat sources and sinks for heat pumps; use both sides for energy savings

In a building there are different loads with different profiles. In one part of the building there might be a cooling load while there is a heating demand in another part of the building. Such situations can be extremely interesting where a heat pump can be integrated with working conditions giving very small temperature lift. This is an example where both sides of the heat pump can be used and our challenge is to find simple system solutions.

There are other examples where condenser heat recovery from a cooling or refrigerating plant can be used. In most hotels there is a large demand for hot water – this can be effectively heated by using hot gas coolers and condenser heat recovery from refrigerating equipment in the hotel restaurant. A study made about 15 years ago resulted in such an installation at the Grand Hotel, Stockholm, with extremely good result. The pay back period of investments was about 6 months.

Systems with (short term) storage can be very interesting for “*Load Management*.” An example is where heat pumps covering nighttime heating demand (for heating and hot water) use a storage of water as heat source. The cold storage is used in daytime to cover cooling demand. The storage can use water in one phase, by ice on tubes or in the form of an ice-slurry. Such plants were in use in Japan already 1990; one of them was the object of a very interesting technical tour at the IEA Heat Pump Meeting in Tokyo 1990.

Energy storage can be designed in many different forms. Ground Source Heat Pumps utilize one of the most common forms of *seasonal storage*. Combinations for AC-operation are of great interest. In fact this is a way to help nature to recharge the storage. For climates with both heating and cooling demand this is a very interesting possibility. The idea can be described as follows: During the winter season a heat pump use the storage as heat source. The temperature of the storage will decrease during the heating season. During the spring and early part of the cooling season the storage may be used directly for cooling. Later in the cooling season it is instead used as the heat sink for the heat pump in reverse operation, creating very favorable low temperatures for the condenser in AC operation. For the following heating season this heat source will form a (relatively) high temperature of the heat source. Storage with a relatively large temperature swing over the season can thus give very interesting and favorable conditions for the heat pump operation. One example of such a system is described in this conference (Romero et al 2005) using ground for storage. The development of cost effective storage for such systems is a very interesting challenge.

In a northern climate there are possibilities to avoid uncomfortable indoor temperatures summertime just by using outdoor air and increased ventilation; A traditional way of “*Natural*

cooling.” Also for office buildings and industries it is often possible to arrange comfort cooling by using natural sources. For example the district cooling system in Stockholm uses (bottom) water of lake Baltic as a heat sink for a substantial part of the cooling load.

However the situation is quite different in hot climates and the problem is more complex. In many countries the electricity demand has a peak in summertime, caused by the load from all AC-units. There are ways to reduce such load peaks; some were just discussed. There are however numerous possibilities to design buildings in a smart way where internal heat sources (computers, lightings and other appliances) are cooled directly at source (by venting or other means).

5 EFFICIENT EQUIPMENT FOR ENERGY SAVINGS

5.1 Losses in Vapor Compression Systems

Figure 3 gives an illustration of how the *power* demand is influenced by different losses in the system at varying evaporator temperatures. It is obvious that a high evaporating temperature (small temperature lift) reduces the power demand. Different types of losses occur:

- Vapor Compression Cycle Losses. For most refrigerants this is mainly the loss introduced by the throttling of refrigerant from condenser to evaporator pressures. (There is also a certain loss due to isentropic compression, resulting in high gas temperatures. For ammonia as refrigerant the two losses have often about the same influence, but for other refrigerants the throttling loss is the major one.)
- Losses in the compressor (in the electric motor and the compressor itself)
- Power demand for auxiliaries like pumps and fans

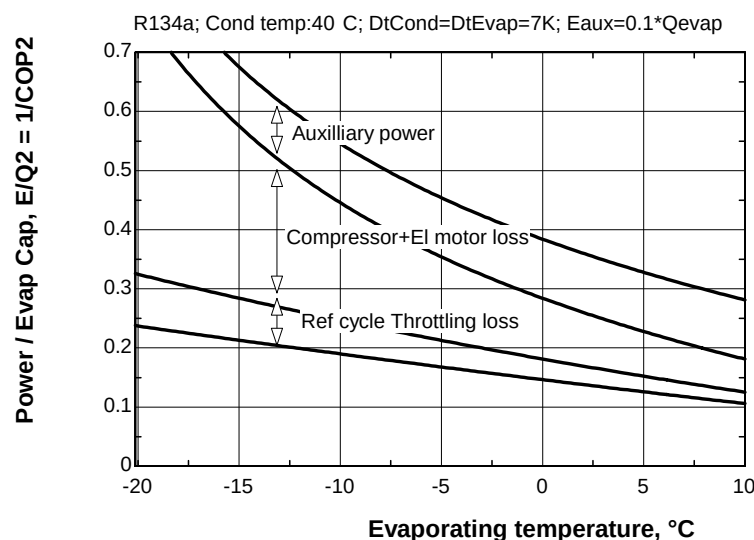


Fig. 3. Power for vapor compression systems. A system with R134a is assumed with no liquid sub-cooling before the throttling device and 5K vapor superheat after evaporator. The condensing temperature is set to +40°C.

Before going into further details let us also study the thermodynamic efficiency of this system.

5.2 Thermodynamic Efficiency

In a thermodynamic perspective the temperature differences in heat exchangers – in the evaporator and the condenser as well as the heat distribution system – have a large influence. An attempt to exemplify the relative influences of the different losses is given in Fig. 4. The diagram shows the thermodynamic efficiency of a system as a function of the evaporator temperature with the same data as in Fig. 3. The thermodynamic efficiency of the system is here defined as

$$\eta = \frac{COP_2}{COP_{Carnot}} \quad \text{where } COP_2 = Q_2/E \text{ and } COP_{Carnot} = \frac{T_{source}}{(T_{source} - T_{sink})}$$

Q_2 = cooling capacity; E = operating energy (for compressor and auxiliaries if applicable)

T_{source} and T_{sink} are the absolute temperatures of the heat source and sink

(Evaporating temperature $T_2 = T_{source} - Dt_{evap}$; Condensing temperature: $T_1 = T_{sink} + Dt_{cond}$).

When we analyze the refrigerant cycle itself the source temperature is identical to the evaporating temperature and the sink temperature is the condensing temperature.

It is disturbing that the thermodynamic efficiency of the system as indicated in Fig. 4 is lower than 20% and that the efficiency at both ends, for smaller and higher temperature lifts, it is even lower. This is a major engineering challenge to improve!

Cycle improvement: Reducing throttling loss

The throttling loss is reduced effectively if the liquid refrigerant can be sub-cooled as effectively as possible before the throttling valve. For some heat pump applications it is possible to utilize the low temperature heat. This is then “free of charge” if possible to incorporate.

There are other ways to reduce the throttling loss: If we could design an effective expander it would be an ideal solution to replace the throttling valve. For large systems there are developments in this direction (Brasz, 2003). Granryd (1975) describes a “regenerative” cycle for loss reduction.

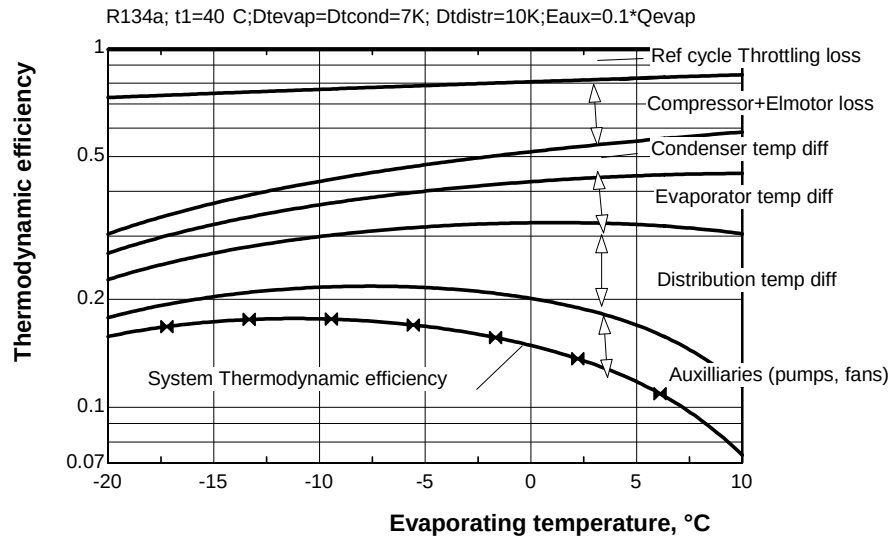


Fig. 4. Thermodynamic efficiency of vapor compression systems. A system with R134a is assumed with same data as the system in Fig. 6. The condensing temperature is +40°C for all applications where however the evaporator temperatures will be different. The temperature differences in the evaporator and condenser are assumed to be 7 K and distribution is assumed to require 10K. Pumps and fans are assumed to be 10% of the cooling capacity.

For systems with compressors in two (or more) stages the classical solution is to use an “economizer” scheme. The principle is then to divide the throttling process in two (or more) stages with “flash gas” removal between each stage. The flash gas is mixed with the gas between the compressor stages.

In some compressor designs, like the screw and scroll types, there is a possibility to arrange an “economizer” port. This makes it possible to introduce “flash gas” during the compression process at an intermediate pressure. Combined with a two stage throttling of the refrigerant liquid it gives a possibility to reduce the throttling loss in a conventional plant. Throttling loss reduction is of special

interest for relatively large temperature lift applications where the throttling loss is substantial, see Fig. 3-4. A good economizer arrangement can cut the throttling loss to half its value for a one stage system.

Compressor Efficiency

One of the losses demonstrated in Fig. 3-4 is the compressor loss. There has been a positive development in compressor performance, both in efficiency and robustness in recent years. Figure 5 is an example of results in terms of isentropic efficiency. The curves have been obtained in different tests over the period 1978 to 2004 with a number of different hermetic compressors in the range 2.5 to 4 kW nominal electric power for conditions typical for heat pump and residential AC applications. The test conditions have been different and far reaching scientific comparisons should therefore be avoided. Still the practical implication is that there have been substantial improvements, especially at moderate pressure ratios (2 to 4) which are important for many heat pump applications.

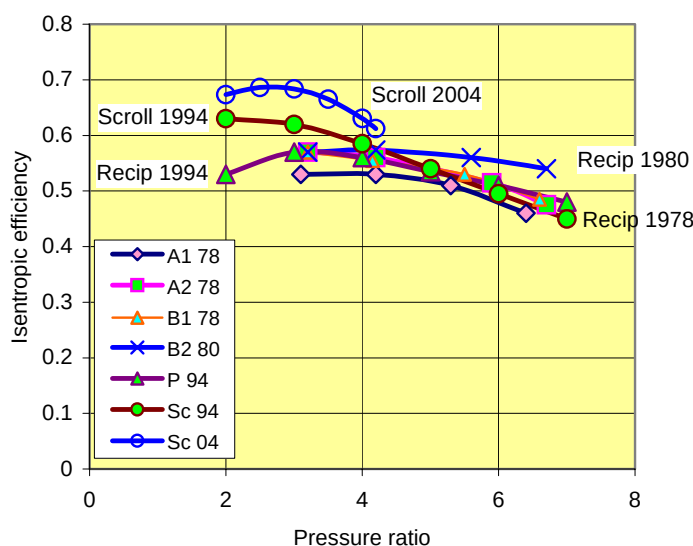


Fig. 5. Examples of results of compressor tests over the years.

Reducing temperature differences.

It is obvious from Fig. 4 that the temperature differences in evaporator, condenser as well as distribution system, should be kept as small as possible. From a thermodynamic perspective these are the largest losses, especially for relatively small temperature lifts. It is a major challenge to design heat exchangers for small temperature differences.

For example: If the temperature difference in the evaporator can be kept small the evaporating temperature will rise. Increasing the evaporating temperature will increase the capacity and the COP of the system. Increasing capacity will (with fixed swept volume of the compressor) also increase the load on the condenser. The condensing temperature will increase slightly as a consequence. The following table indicates the influence of 1 K increasing evaporating temperature from 0 to 1°C for two cases A and B with R134a. In a *Case A* it is assumed that the condensing temperature is constant equal to 40 °C (which could be the situation with capacity control of the compressor). For a *Case B* the influence of the increased condensing temperature (with fixed compressor speed) is included¹.

	<i>Case A</i>	<i>Case B</i>
Increase in evaporator capacity:	3.9%.	3.6%

¹ The influence on the heating capacity is slightly smaller. The relative influence on the heating COP is also somewhat smaller than the numbers for COP₂, since the heating COP (if there are no heat losses from the system) is equal to COP₂+1.

Increase the cooling COP_2 by: 3.4%. 2.4%.

The increase in COP_2 at conditions with smaller temperature lift is even more pronounced. For instance at 0/20°C the increase of COP_2 for the Case A is 6 % per degree.

It is however, difficult to get an evaporator to operate in practice with small temperature differences (smaller than say 5 K). In part this is due to the fact that superheat control represents a limit. By suitable designs evaporators can operate with small superheat, but still conventional evaporators require a certain temperature difference. Evaporators with micro-channels show interesting behavior and this may be a way to obtain designs for smaller temperature differences in the future. Also capacity modulation (variable speed or other means) gives benefits in smaller load on the evaporator and condenser in part load operation. Advanced inverter systems for speed control of electric motors are becoming more and more competitive.

Systems With Gliding Temperatures

If there are large temperature shifts on the circulating media of the heat source and sink side, it is beneficial to match these by gliding temperatures in the heat pump cycle. Potential benefits with gliding temperatures for refrigerant mixtures have not been proven. However with CO_2 there is a great potential for very efficient hot water by using supercritical pressure on the high temperature side of the heat pump as was pointed out by Lorentzen and Peterson (1992), Lorentzen (1994). This can result in a system with small energy losses, thus resulting in a very good COP for e.g. hot water heating. Such units have recently been introduced on the market. An alternative when using conventional cycles is to use multiple stages in series or batch heating. A practical alternative is to have a scheme with several stages in series.

Auxiliaries – Pumps and fans

Energy demand for auxiliaries like fans and pumps are easy to forget. As demonstrated in the previous example (Figs. 3 and 4) they have a substantial influence on the total energy demand of a system; In many practical cases even more than in this example. Figure 6 gives an example where the influence of air velocity in the evaporator is studied. Notice that there is *one velocity for maximum (net) cooling capacity and another (lower) that gives highest net COP of the system*. Often the optimum solution for highest COP of the system corresponds to half the velocity compared to the solution for max capacity. These questions are further discussed by Granryd (1998). Many installations in practice are designed for maximum capacity rather than for minimum total energy demand.

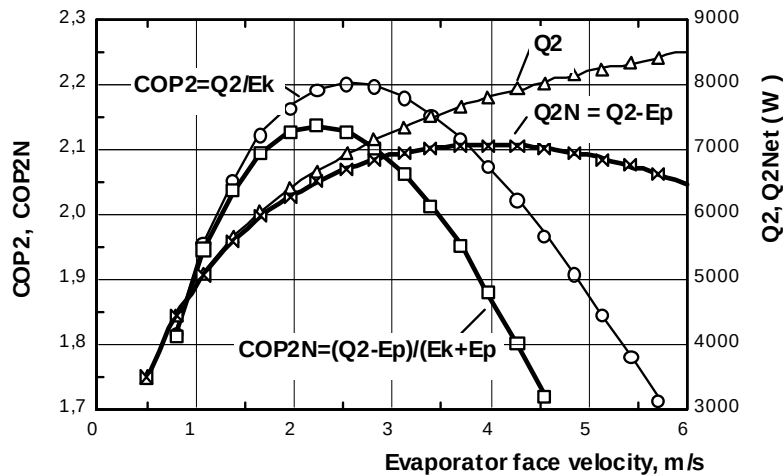


Fig. 6. Influence of evaporator face velocity for an example with a dry microchannel evaporator. A basic refrigerating system with R134a is assumed. (Heat transfer and pressure drop data for the microchannel evaporator is taken from Litch and Hrnjak 1999).

6 SUMMARY

There are many applications of Heat Pumping Systems and Equipments. Most notably heat pumps for climate control – heating as well as cooling – in buildings. The concept of heat pumping also includes refrigeration for traditional very important uses for the food supply, for the cold chain for food, for medical applications and for low temperature applications in cryogenics like LNG, for utilizing superconductivity and for research in ultra low temperature region.

During the last two decades there has been a technology shift when a transition has occurred from the use of CFC and HCFC to new refrigerants like HFC and “natural” refrigerants. This transition has proceeded in slightly different direction and different emphasis in different parts of the world. It has also provoked a renewed interest in different cycles.

Systems research deals among other things with questions about arrangements of heat sink and sources. Different climatic conditions give priority to specific choices. Important challenges are to reduce energy demand as well as demand for peak power.

Advanced designs of buildings will require a relatively small heating demand. However heating of tap water will still be an important load as well as cooling for comfort will be more pronounced even in Nordic climates.

Heat pumping systems in practice have a poor efficiency from a thermodynamic viewpoint. Different losses are discussed. There are many challenges and opportunities for improvements. The session on Advanced Systems and Equipment covers a number of different applications and approaches. Development is going on in many areas around the world.

We can foresee a future with many surprises.

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