

## HEAT PUMPS FOR A SUSTAINABLE SOCIETY

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**Abstract:** European governments have committed to significantly reduce the carbon footprint. It is therefore generally accepted that: increasing the uptake of renewable energy systems and improving the thermal performance of both new and existing homes is critical if Europe is to achieve ambitious emission targets. Heat pumps offer the possibility of reducing energy consumption significantly. Taking different applications of heat pumping technologies several items have to be taken into consideration like drive energy, design of the unit, integration into a system and the control strategy. The efficiency of the unit, commonly expressed by the COP, depends on the refrigerant selected and on the components used like the compressor, the size and the design of condenser and evaporator, the flow sheet – single stage, two stage, economiser or cascade – and the internal cycle control. With highly efficient systems the advantages of thermodynamic heating and cooling can be demonstrated. Heat pumps are one of the key technologies for energy conservation, increasing the share of renewable energy used and reducing CO<sub>2</sub> emissions.

**Key Words:** heat pumps, compressors, cycle control, efficiency

### 1 INTRODUCTION

European governments have committed to significantly reduce the carbon footprint of new and existing homes. It is therefore generally accepted that: increasing the uptake of renewable energy systems and improving the thermal performance of both new and existing homes is critical if Europe is to achieve ambitious emission targets. Heat pumps offer the possibility of reducing energy consumption significantly, mainly in the building sector. Taking different applications of heat pumping technologies several items have to be taken into consideration like drive energy, design of the unit, integration into a system and the control strategy.

The efficiency of the unit commonly expressed by the COP, the coefficient of performance. This COP depends on the refrigerant selected and on the components used like the compressor, the size and the design of condenser and evaporator, the flow sheet – single stage, two stage, economiser or cascade – and the internal cycle control. The choice of the refrigerant is most commonly a compromise between efficiency and cost, smaller equipment using a high-pressure working fluid can reduce the cost, a working fluid with low discharge temperatures can avoid a two-stage system. With highly efficient systems the advantages of thermodynamic heating and cooling can be demonstrated and used for reducing the energy demand significantly. Heat pumps are one of the key technologies for energy conservation, increasing the share of renewable energy used and reducing CO<sub>2</sub> emissions.

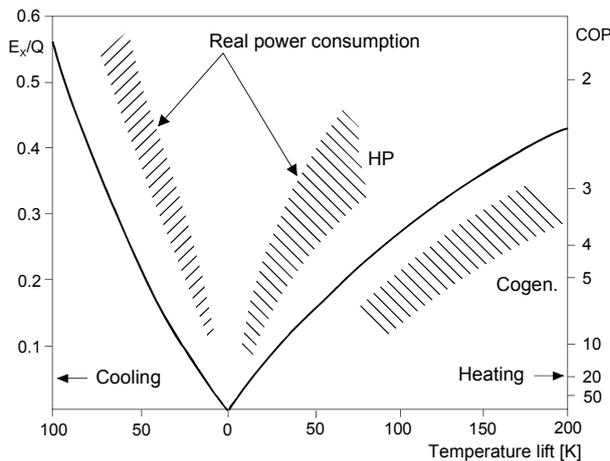
### 2 HEAT PUMPS

The general term heat pumping technologies is used for processes in which the natural heat flow from a higher to a lower temperature level is reversed by adding high value energy, i.e.

exergy. The term heat pump is used for a unit producing useful heat. In Japan and in the USA reversible air conditioning units are called heat pumps. Chillers are more or less always called chillers, even if they are used as heat pump chillers producing also useful heat. In Europe the term heat pump is used for heating-only units with the heat sources outside air or exhaust air from the ventilation system, ground and ground water, combined with hydronic heat distribution systems (Gilli, Halozan 2001).

## 2.1 Efficiencies

Figure 1 demonstrates the efficiencies of thermodynamic heating/cooling.



Over the (positive or negative) effective temperature lift  $\Delta T$  from ambient, the relative exergy  $E_x/Q$  is plotted for the ideal process and for real processes. For the ideal process:

$$E_x/Q = 1 - T_a/T = (T - T_a)/T = \Delta T/T = \eta_c$$

where

$E_x$	Exergy
$Q$	Heat transferred
$T_a$	Ambient temperature, K
$T$	Process temperature, K
$\eta_c$	Ideal (Carnot) efficiency

Figure 1: Ideal and real power consumption  $E_x/Q$  for cooling (freezing, refrigeration, air conditioning) and space heating by heat pumps and by cogeneration district heating

The coefficient of performance (COP) is shown at the right-hand scale:  $COP = Q/E_x$ . The internal efficiency is given by the ratio  $\eta = COP/COP_{ideal}$  at  $\Delta T$ . The left-hand area refers to cooling: freezing, refrigeration and air conditioning including dehumidification, the right-hand area refers to heating: The heat pump area shows a temperature lift of 5 to 70 K,  $E_x/Q$  is between 0.08 and 0.45 and COP therefore between 2.2 and 12.5, the efficiency  $\eta$  is about 0.4...0.7. The important term for the COP is  $\Delta T$ , the temperature lift in the heat pump. This  $\Delta T$  depends on the temperature of the heat source, which can be increased by using the ground as heat source instead of ambient air, and by the temperature required by the heat sink. In highly insulated buildings with floor heating systems this temperature can be reduced to values below 30°C, so  $\Delta T$  can be reduced to 20 K. The coefficient of performance of the area "Cogeneration" is different: Here the real exergy loss is smaller than the theoretical one because of reduced turbine losses and condenser losses.

## 2.2 Performance Factors

The drive energy of heat pumps is most commonly electricity, and for the future improved power generation systems based on renewable and fossil fuels have to be taken into consideration. The power plant efficiency,  $\eta_{PP}$ , is up to 58 % for gas-fired combined-cycle power plants available on the market; with oil as fuel similar values are possible. The power plant efficiency  $\eta_{PP}$  depends, of course, on the kind of fuel (primary energy source).

Table 1 shows the relations for the more important primary energy sources and for heat pump SPF of 4 and 6. PER is highest for direct power generation from renewable sources such as hydro, wind or solar, for which  $\eta_{PP} = 1.0$  by definition. More information than by PER is, however, given by comparing, for a given fuel (primary energy source), the efficiency of the indirect path via power plant and heat pump (PER) to the efficiency of the direct path

of conversion ( $\eta_B$ ) in a boiler. The ratio may be called Useful Energy Ratio  $UER = PER/\eta_B$ . Comparing the same fuel means that all upstream effects cancel each other out.

Table 1: Typical Primary and Useful Energy Ratios

		Coal, Biomass	Gas	Renewables	Nuclear
<u>Efficiencies</u>	Power plant, $\eta_{PP}$	0.4	0.55	1.0	0.33
	Boiler (local conversion), $\eta_B$	0.8	0.98	1.0	1.0
<u>SPF = 4</u>	PER = SPF. $\eta_{PP}$	1.6	2.20	4.0	1.33
	UER = PER/ $\eta_B$	2.0	2.24	4.0	1.33
<u>SPF = 6</u>	PER = SPF. $\eta_{PP}$	2.4	3.30	6.0	1.98
	UER = PER/ $\eta_B$	3.0	3.37	6.0	1.98
<u>SPF = 8</u>	PER = SPF. $\eta_{PP}$	3.2	4.40	8.0	2.64
	UER = PER/ $\eta_B$	4.0	4.49	8.0	2.64

The data of Table 1 show that boiler efficiencies near 1.0 are close to the theoretical limit (i.e. for the gas-fired condensing boiler). A SPF of around 6.0 is far below the theoretical limit of heat pumps; SPFs of 6 or more may be possible and will be economic in the future.

It should be noted that the heat pump, which in most cases grades up free heat from the environment (air, water, ground) and from waste heat, is a major source of renewable energy. The renewable heat  $R$  gained by the heat pump is the difference between the thermal output  $Q$  and the drive energy  $E_x$  (in the case of electricity,  $E = E_x$ ):

$$R = Q - E = Q - Q/SPF = Q(1 - 1/SPF)$$

Obviously, if the drive energy is electricity from renewable sources, all the energy used for the heat pump is renewable energy.

### 3 APPLICATIONS

Taking different applications of heat pumping technologies several items have to be taken into consideration like drive energy, design of the unit, integration into a system and control strategy:

1. The drive energy of heat pumps is most commonly electricity, and for the future improved power generation systems based on renewable and fossil fuels have to be taken into consideration. The power plant efficiency is up to 58 % for gas-fired combined-cycle power plants available on the market; with oil as fuel similar values are possible. The power plant efficiency depends, of course, on the kind of fuel (primary energy source). PER, the primary energy ratio, is highest for direct power generation from renewable sources such as hydro or wind, for which the power plant efficiency  $\eta_{PP} = 1.0$  by definition. PER gives an absolute measure of the units of useful cold/heat obtained from one unit of primary energy at power plant input, neglecting for the moment losses upstream of the power plant such as in production, cleaning, transmission, and distribution losses between power plant and heat pumping equipment. For absorption heat pumping units, PER is the ratio of cold/heat output to primary energy input (not to the power plant but to the heat pumping units).
2. The second item is the efficiency of the unit, which is most commonly expressed by the COP, the coefficient of performance. This COP depends on the refrigerant selected and on the components used like the compressor, the size and the design of condenser and evaporator, the flow sheet – single stage, two stage, economiser or cascade – and the internal cycle control. The choice of the refrigerant is most

commonly a compromise between efficiency and cost, smaller equipment using a high-pressure working fluid can reduce the cost, a working fluid with low discharge temperatures can avoid a two-stage system.

3. The third item is the integration of a unit into a system, and again the choice of the refrigerant may have a large influence on this integration. The most efficient way of heat absorption/heat dissipation is direct evaporation/direct condensation; the alternative are secondary loop systems. Secondary loop systems require an additional temperature lift to transport heat to the evaporator and from the condenser, and most commonly they require circulation pumps with an additional power consumption. Especially in low-temperature applications this may cause problems. This means that secondary loop systems are less efficient than direct evaporation/condensation systems.

However, the unit itself can be designed as a compact unit and the refrigerant content can be minimised. Additionally, if heat absorption/heat dissipation happens in spaces with public access, the working fluid has to be a safety refrigerant, flammable and/or toxic fluids cannot be used. But there are a lot of applications, where the secondary loop system already exists, for example hydronic heating systems or cold water based air conditioning systems. In large cold stores the use of direct systems with flammable and/or toxic working fluids is also possible.

4. The fourth item is now the real operation of the system combined with the control strategy selected, and the operation of the system shows not only full-load, but mainly part-load: many systems lose a lot of efficiency operated in part-load, and taking this part-load operation one will get the SPF, the seasonal performance factor, which includes the cold/heat output, the drive energy at the different operating conditions, and the parasitic energy consumers like fans and circulation pumps. This is the value which has to be taken into account when specifying the TEWI; such a figure is too complicated for a politician and for an environmentalist. But this figure is a basis for the right selection of the whole system (Halozan 2013 b).

#### **4 IMPROVING BUILDINGS**

In general, new buildings get a better thermal insulation and the heat loads are reduced significantly. This means that even in "cold" climates (design temperatures  $-12^{\circ}\text{C}$ , heating degree days 3500, heating period length 200 days) buildings with specific heat loads of  $60\text{ W/m}^2$  and can be heated by ground-coupled heat pump systems achieving SPFs of 4 up to 6.

A further step has been already realised in the so called passive houses: The transmission losses through the building envelope are in the range of  $15\text{ W/m}^2$ . The next step was the introduction of controlled ventilation combined with an exhaust air heat recovery system.

- By means of heat exchangers ventilation losses can be reduced by 50 to 90 %, depending on the type of heat exchanger used. However, heat exchangers can only reduce the ventilation load, they cannot be used for heating purposes.
- With heat pumps the ventilation losses can be reduced also; additionally they can be used for heating purposes, because the fresh air temperature can be increased to a level higher than the indoor temperature. However, in contrast to heat exchangers an energy input is required.

The optimum solution is the combination of both, a heat exchanger and a heat pump. The exhaust air is firstly cooled down in the heat exchanger and then used as heat source for the heat pump; the fresh air is preheated in the heat exchanger and then further heated by the heat pump. Such houses can be heated down to low outside temperatures by the ventilation

system alone, the remaining heating demand can be covered by electric resistance heating, but it can also be covered by further reducing the heat load.

One possibility is preheating the fresh air in the ground. Taking a typical single-family house, a suitable air/ground collector consists of about 60 m pipe with a diameter of 0.25 m buried in the ground in a depth of about 1.5 m around the building. Using such a collector the air temperatures will be always higher than  $-5^{\circ}\text{C}$  even when the outdoor temperature drops below  $-20^{\circ}\text{C}$ . This preheating effect is sufficient to reduce the heat load to a level that the building can be heated with the heat recovery system alone. A further improvement can be achieved by using a ground coil for avoiding frosting/defrosting losses. The SPFs achievable with such systems are about 6 (Fig 2a and 2b).

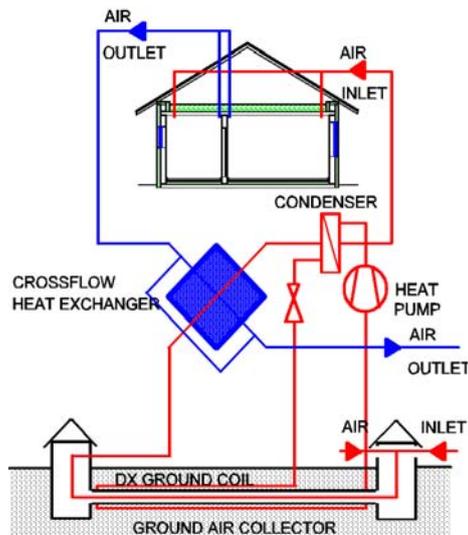


Fig. 2a: System with Air/Ground Collector, Heat Exchanger and DX/Air Heat Pump

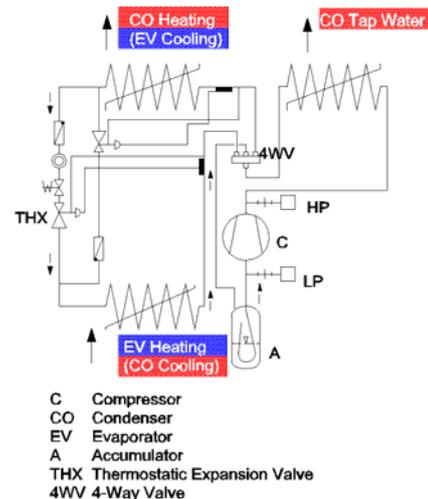


Fig. 2b: Double-Condenser Heat Pump for Heating and Cooling and Hot Water

A step further are “Net Zero Energy Houses” or even “Energy Plus” Houses. They are additionally equipped with a photovoltaic panel producing during the year the electricity needed by the building.

## 5 HEATING AND COOLING SYSTEMS

The need for air conditioning - removing the cooling load and dehumidification of the fresh air - depends not only on the climate, it also depends on the size of the building and the utilisation of a building; an additional point is architecture, glass is modern, and solar gains can become very fast solar loads, which have to be removed by an air conditioning system. There are three types of climates which require air conditioning, climates with daily average temperatures higher than  $24^{\circ}\text{C}$ , climates with a humidity higher than 65 %, and climates, which combine both. If the depth of a building is more than 20 m transverse ventilation becomes difficult due to strong air movement, if the depth is larger besides ventilation internal gains have to be removed, and if a building becomes high in many regions windows cannot be opened due to wind forces. In large commercial buildings high internal loads due to people, lighting, computer equipment etc. occur; these loads have to be removed also. A building envelope of glass is nice for lighting, it causes problems due to solar gains, not only by direct radiation, but also by diffuse radiation. In some of these buildings the best air conditioning system cannot provide comfort through all the year.

There are two possibilities to remove and top collect heat, one is to use the outside air, the second is to use the ground. In the case of outside air a cooling tower and in many climates

an auxiliary heating device is required to cover peak load during the heating season. In the case of using the ground heat removal can and heat extraction can be realised by using the ground. Possible solutions to utilise the ground are ground water or stores like bore holes in the rock, heat exchangers in bore holes in the soil, or pile foundations of buildings (Fig. 3).

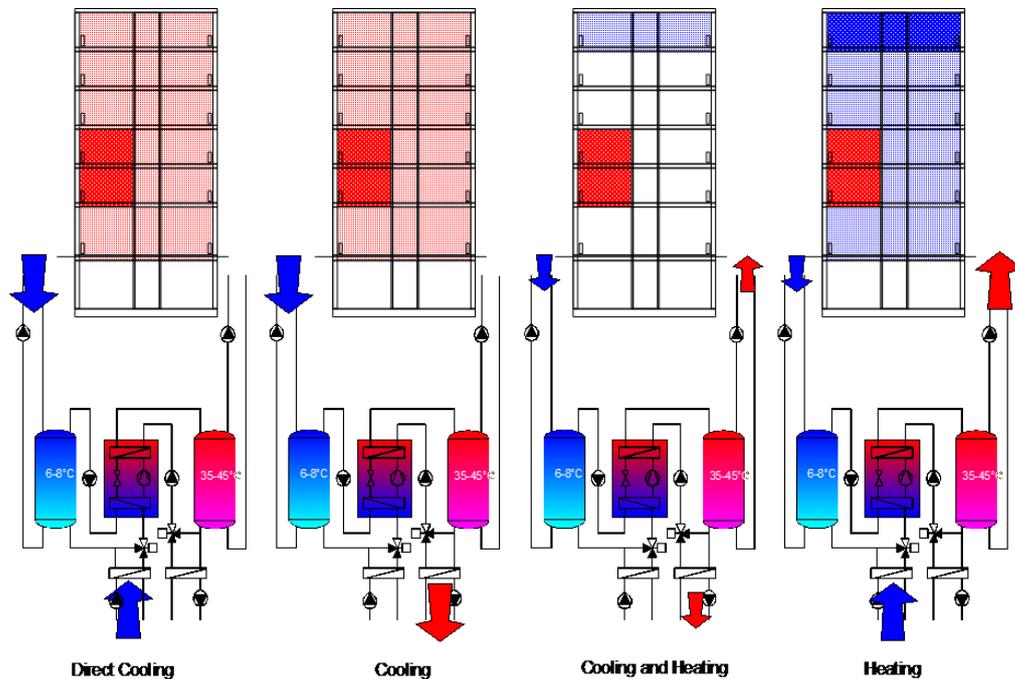


Fig. 3: Ground Source Heating and Cooling System

Taking these preconditions the ground offers heat removal at stable temperatures, which are rising depending on the heat input into the ground, it offers the possibility of heating the building using the ground as heat source, where at the beginning of the heating period the temperature is higher due to the heat removed during the cooling season. At the beginning of the cooling season direct cooling without chiller operation is possible due to the lower ground temperature caused by heat extraction during the heating season.

A further advantage is that no cooling tower is required, and a cooling tower is a device with a significant energy consumption due to fans and pumps, in the case of an open system water treatment is necessary, and also maintenance work is required. Other disadvantages are, that the highest cooling load is combined with the highest outside temperature. In a proper designed ground store all these problems do not occur, additionally compared with outside air peaks do not occur.

Further improvements are possible by so called high-temperature cooling systems and low-temperature heating systems; sometimes they are called low-exergy systems. To get efficient systems the cold water temperature has to be kept as high as possible. For dehumidification 6°C to 8°C are necessary; removing the cooling load is most commonly carried out with the same temperature level, it can be carried out with temperatures of 16°C and higher. To produce cold and to remove hot two solutions are possible, a chiller producing cold water with a temperature of 6°C to 8°C for dehumidification and combined with fan coils and a cooling tower, or one chiller producing cold water with a temperature of 6°C to 8°C for dehumidification and a second producing cold water with a temperature of 16°C to 18°C for removing the cooling load. 1 K increase of the cold water temperature and the evaporation temperature, respectively, means an increase of the COP by about 2 % and an increase of the cooling capacity of about 3 %. In practice the COP is improved by 32 % and the cooling capacity 48 % (Halozan 2010).

Considering that in large buildings more than one chiller is installed the additional cost is the more complicated piping system and not the equipment itself. Such as systems offers a certain amount of additional investment costs, however, concerning operating cost it is unbeatable. It offers direct dehumidification and direct cooling depending on the temperature of the ground store, and it offers monovalent heating operation with the heat pump chiller.

Depending on the climate this store can be used at the beginning of the cooling season for direct cooling without chiller operation. It can also be used for heating the building. The second solution requires a higher first cost; however, LCA will show the advantages of a well designed ground store based system.

However, there is another possibility for dehumidification, it is a DEC (desiccant evaporative cooling) system (see Fig 4), an adsorption system, recharged by the excess heat of the compression system or by solar thermal. With DEC systems the temperature for dehumidification - 6 to 8°C – can be avoided, and for removing the cooling load 17°C are sufficient.

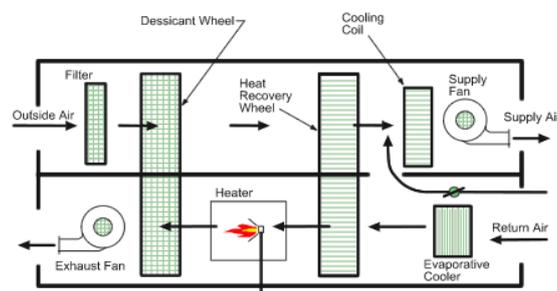


Fig 4: DEC System

## 6 POSSIBLE FUTURE DEVELOPMENT

The main future developments are increasing efficiency and reducing cost.

### 6.1 Electrically driven Units

In the small to medium size capacity range the reciprocating compressor has been practically replaced by the rotary compressor and the scroll compressor. A new development are small centrifugal compressors with high-speed drives and magnetic bearings for oil-free operation.

In this context variable capacity compressors become more and more interesting. In the past two-speed compressors were used, nowadays inverter drives become more and more common. The speed ranges are up to 1-6, and this offers in the case of outside air heat pumps a significant reduction of the excess capacity and the excess temperatures at outside temperature higher than the bivalent temperature. 1 K temperature increase in the condensing or heat pump outlet temperature means a loss in capacity of 1% and a loss in COP of 2%. Additionally mixing losses can be avoided or significantly reduced.

In the past inverters caused relatively high losses, in the meantime with advanced inverters combined with PPM (permanent magnet motors) drives these losses are significantly lower than the gains by avoiding mixing and cycling losses.

Capacity control has not only advantages in the case of outside air heat pumps, in the case of ground coupled heat pumps the temperature drop from the ground to the coil can be reduced significantly, with means, that 1K increase of the evaporation temperature means an increase of the capacity by 3% and an increase of the COP of 2%.

But there are other improvements possible modifying and improving the refrigerant cycle.

- One possibility is an internal heat exchanger. In the case of refrigerants with low discharge gas temperature capacity and COP can be increased.
- For hot water production a de-superheater can be used, offering the possibility of producing hot water with a temperature of 60°C with condensing temperatures below 40°C in combined heating and hot water production mode. If the de-superheater is sized like a condenser, the excess heat from cooling can be directly used for hot water production in summer time.
- In the case of refrigerants with low discharge gas temperatures the economiser flow sheet can be used: In this case two stage compression can be carried out with one scroll or screw compressor equipped with an additional suction port (Fig. 5).
- In the case of refrigerants with high discharge gas temperatures the common two stage compression has to be used.
- In both cases of two-stage compression capacity – important at low heat source temperatures – and COP can be improved.
- Another possibility is a heat pump cascade, where different refrigerants for the low pressure and the high pressure stage can be used. Such a system is interesting for high-temperature applications, i.e. retrofitting existing houses.

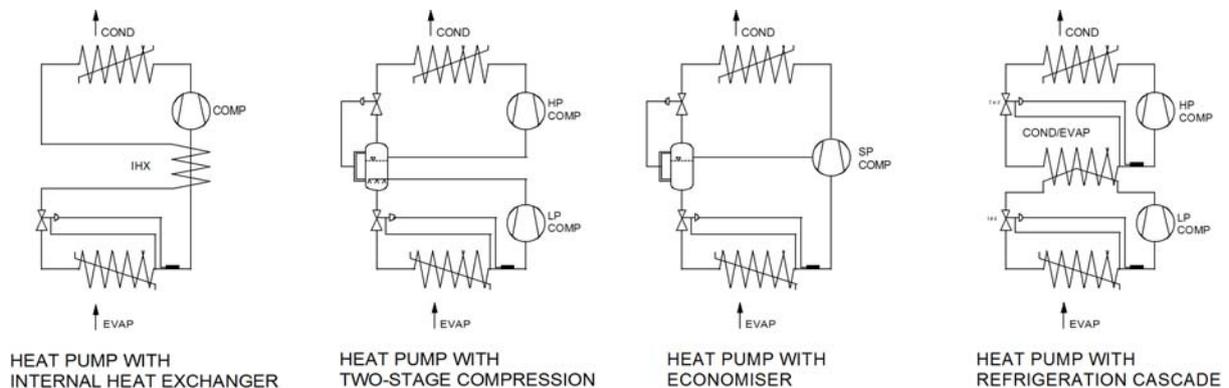


Fig 5: Advanced Cycles

Liquid/refrigerant heat exchangers have changed to welded flat plate heat exchangers, for air/refrigerant heat exchangers multi port micro channel heat exchangers become more and more interesting (Halozan 2013 a).

## 6.2 Thermally Driven Units

There is a potential for sorption systems. Sorption systems have the advantage, that the drive energy is heat, and this offers a variety of different drive energies like gas, which is the drive energy most commonly used, heat of co-generation plants, solar thermal, which is under discussion today under the title solar cooling, but also synthetic gases and biomass.

The two different sorption systems are absorption systems, using a liquid sorbent, and adsorption system, using a solid sorbent. In the case of absorption systems the working pairs most commonly used are ammonia/water and water/lithium bromide. Water/lithium bromide is dominant for air conditioning purposes, ammonia/water for applications, where temperatures below 0°C occur. Large capacities are not the problem, the real problem are small units, and in several countries developments are ongoing to overcome high first cost.

An interesting development is the so called diffusion absorption heat pump, which has been developed by H. Stierlin, Switzerland, based on the Platen-Munters refrigerator. It offers advantages including no moving parts, noise and vibration free operation and operation without electric power. The cycle is similar to a single stage absorption cycle but differs in

that an auxiliary gas is used to equalize the pressures throughout the system and to allow a heat driven bubble pump.

Another development in the direction of small and medium sized units are advanced single-stage units and especially generator absorber heat exchange (GAX) units (Fig. 6). With these GAX units the COP can be increased significantly compared with single stage units, additionally the COP becomes gliding similar to a compression unit. Such units have a chance due to the development of flat plate heat exchanger. Using flat plate heat exchangers absorption units can be assembled by using components produced in large numbers, which reduces the cost significantly.

Adsorption systems, mainly based on water/silica gel and water/zeolite offer the possibility to work with lower drive temperatures, which means an advantage in the case of solar cooling. The operation is intermittent; that means that in principle at least two units are in operation, one for cooling operation and one for charging (Fig. 7).

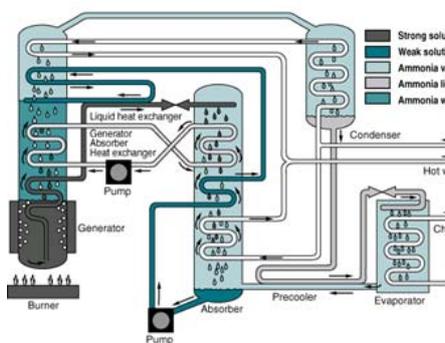


Fig. 6: Absorption GAX Cycle

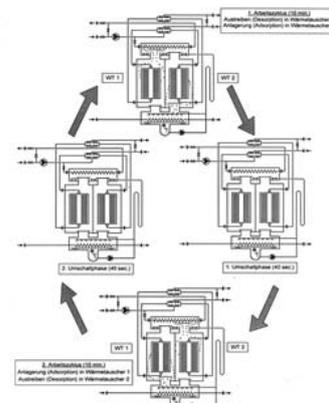
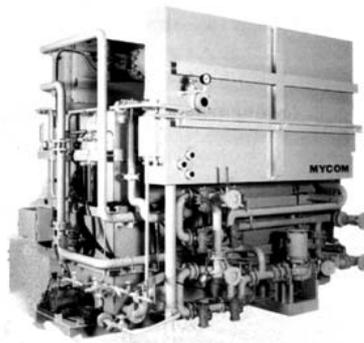


Fig. 7: Adsorption Unit

## 7 CONCLUSION

Heat pumps are an old technology, which has not been extensively used as long as both energy prices and the efficiency of electricity generation have been low. The oil crises have changed this situation, and now Kyoto is a further reason for the increasing market deployment of this technology. Based on recent developments, the following conclusions can be drawn:

- Heat pumps offer the possibility of reducing energy consumption significantly, mainly in the building sector, but also in industry. Basic second law thermodynamics show the advantages: while a condensing boiler can reach a primary energy ratio (PER) of 105 % (the theoretical maximum would be 110 % based on the lower calorific value), heat pumps achieve 200 % and more, with hydro or wind energy even 400 % and more.
- The drive energy is most commonly electricity, and for the future improved power generation systems based on renewables and fossil fuels have to be taken into consideration. The efficiency of gas-fired combined-cycle power plants available on the market is presently about 58 %, with oil as fuel similar values are possible. Ground-source ("geothermal") heat pumps combined with low-temperature heat distribution systems achieve seasonal performance factors (SPFs) of 4 and higher, which means PERs of 220 to 280 %.
- Ground-source heat pumps are presently dominating the heating-only heat pump market in Europe, they have been also identified as energy efficient solution for the heating and cooling market in North America, but also Japan and China.

- New developments like variable-speed heat pump units or heat pumps combined with heat pipe based vertical probes with CO<sub>2</sub> as heat carrier show that there is still room for new ideas for being competitive and successful in the future.
- Direct-exchange ground-source heat pumps already achieve SPFs between 4 and 6 !, if building standards are kept and the overall system design has been made carefully.
- Air conditioning systems have the task to compensate external and internal loads and to provide hygienic conditions and year round comfort for the customers. By means of heat pumps additionally shifting heat from spaces, which have to be cooled to spaces, which have to be heated at the same time is possible.
- Using the ground and/or the foundation as a store heat and cold can be stored and used for direct cooling, and for increasing the heat source temperature for heating; with low-ex systems these effects can be further increased.
- Besides new buildings ground-source heat pumps offer the possibility to retrofit existing buildings from energy wasting to highly efficient systems.
- The choice of refrigerants presently in use - R-407C, R-410A and propane, for large units additionally R-134a and ammonia, is motivated by efficiency, reliability, environmental considerations, safety and regulations.
- The next fight on refrigerants has already started: HFOs versus R32 and the so called naturals like ammonia, the hydrocarbons and CO<sub>2</sub>.
- Sorption systems - absorption, adsorption and DEC systems - also gain importance. The efficiency of sorption units has been improved significantly by introducing welded flat plate heat exchangers for reducing heat transfer losses.
- With highly efficient systems the advantages of thermodynamic heating and cooling can be demonstrated and used for reducing the energy demand, increasing efficiency and increasing the share of renewables (Halozan 2012).

The potential for reducing CO<sub>2</sub> emissions assuming a 30 % share of heat pumps in the building sector using technology presently available is about 6 % of the total world-wide CO<sub>2</sub> emission. With advanced future technologies in power generation, in heat pumps and in integrated control strategies up to 16 % seem to be possible. Therefore, heat pumps are one of the key technologies for energy conservation and reducing CO<sub>2</sub> emissions.

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