HEAT PUMPS AND THE ENVIRONMENT

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ABSTRACT

The old aim of governments was to supply their country with sufficient low-cost energy to keep the growth of the economy. In the meantime we have the problem of the climate change, and more or less all industrialised countries, which have signed this agreement, have to reduce their greenhouse gas emissions, mainly CO_2 from burning fossil fuels. Heat pumps offer the possibility of reducing energy consumption and CO_2 emissions significantly, mainly in the building sector, but also in industry. The second law of thermodynamics shows the advantages: While a condensing gas-fired boiler can reach a primary energy ratio (PER) of at best 105 % (i.e. the boiler efficiency η_B; the theoretical maximum would be 110 %, based on the lower calorific value), heat pumps achieve 200 % and more. The potential for reducing CO_2 emissions assuming a 30 % share in the building sector using technology presently available is about 6 % of the total world-wide CO_2 emission. With future technologies in power generation and heat pumps up to 16 % seem possible. Therefore, heat pumps are one of the key technologies for energy conservation and reducing CO_2 emissions.

Key Words: ***heat pump systems, power generation, heating-only operation, heating and cooling operation, ground-coupled systems***

1 INTRODUCTION

Heat pumps offer the possibility of reducing energy consumption significantly, mainly in the building sector, but also in industry. The second law of thermodynamics shows the advantages: While a condensing boiler can reach a primary energy ratio (PER) of at best 105 % (i.e. the boiler efficiency η_B; the theoretical maximum would be 110 %, based on the lower calorific value), heat pumps can achieve 200 % and more (Halozan 2003).

Whereas the thermodynamic principle of the heat pumping process was found at the beginning of the 19th century (by Carnot, Kelvin, and others), it was realized about 1834 for refrigeration. The first example for producing useful heat was not before 1855: In this year, Peter Ritter von Rittinger put into operation the first heat pump, an open-cycle mechanical vapour recompression (MVR) unit, directly driven by hydro energy, in the saltern of Ebensee, Upper Austria (Fig. 1).

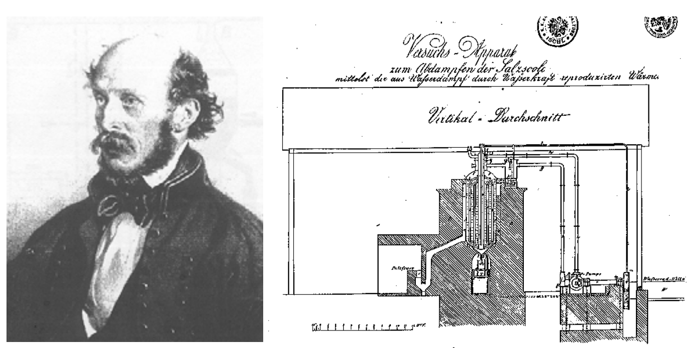

Fig. 1. Peter Ritter von Rittinger – 1st MVR System 1855

This was a special case caused by the lack of biomass and the availability of hydro power, and it was for decades the only example where an open heat pump has been realised. Much later, also the closed vapour process was used for generating useful heat. Essentially after World War II, heat pumping units for air conditioning of homes and individual rooms became common, somewhat later the “reversible” units for both cooling/dehumidifying as well as heating, and after the oil price crisis of 1973 also the heating-only heat pumps for moderate and cold climates. But this happened in a time, when electricity generation has achieved relatively high efficiencies and cost effectiveness could be achieved compared with conventional heating systems.

The refrigerants (working fluids) up to the 1930s were ammonia, carbon dioxide and other fluids, most commonly toxic and/or flammable. Later on the “safety refrigerants” (chlorofluorocarbons, CFCs, and hydrochlorofluorocarbons, HCFCs) were developed and quickly occupied the market. These refrigerants were the basis for the development of hermetic systems, copper as piping material, further on, a 30 bar technology has been established. They were the basis for the development from industrial/commercial applications of refrigeration technologies to household applications. This remained so until at the Vienna Convention of 1986 and the Agreement of Montreal 1997, where the future production of CFCs was limited and in the end essentially banned, for reasons of destroying the stratospheric ozone layer. A few years later (Kopenhagen, 1992) also an agreement for limiting the HCFCs was concluded. The first choice of replacement fluids were after Montreal HCFCs, HFCs (chlorine-free hydrofluorocarbons) and their mixtures, after Kopenhagen HFCs and their mixtures.

In the meantime another problem occurred, global warming, and the discussion on refrigerants started again: the HFCs have no ODP (ozone depletion potential), but they have a GWP (global warming potential). There is, therefore, a tendency in some, mostly European, countries to switch again to old so called “natural” working fluids, containing neither chlorine nor fluorine and with a negligible GWP. Already in use are propane and iso-butane (which are flammable), NH_3 (which is poisonous), which has been used all the time in large cold store installations, CO_2 systems are under development, and water, in former times used in vapour recompression systems, is investigated for the use in chillers.

So the heat pump has undergone and is undergoing several changes in working fluids and design. However, the efficiency today is generally better than before these changes and keeps rising. Thus, not only the environmental effects of the working fluids are being reduced, but also the effects of power plants producing the drive energy for the heat pumps – due to higher SPFs, higher power plant efficiencies (η_{PP}), and an energy sources mix with lower CO_2 emissions. Therefore the TEWI (Total Equivalent Warming Impact) is reduced significantly (Halozan 2002).

2 BASICS

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 in a different way in different regions of the world (Halozan and Gilli 2001).

- In Japan and in the USA reversible air conditioning units, so called heat pump air conditioners, i.e. units which produce both cold (during summer) and hot (during winter), are called heat pumps. Most commonly air to air units are used; however, ground-coupled systems have an increasing share.
- 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 being used originally for heating-only units with the heat sources outside air, ground and ground water, in some applications also exhaust air from the ventilation system, combined with hydronic heat distribution systems. The old hydronic have been high-temperature and medium-temperature systems with design supply temperatures of 90°C and 55°C, in newly constructed buildings low-temperature heat distribution systems with design temperatures of 35°C are very common.

- For commercial/industrial applications the term heat pump is often replaced by other names like mechanical vapour recompression (MVR) system, dryer, dehumidifier etc., and in heat pump based heat recovery systems the term heat pump is very often not even mentioned.

2.1 Efficiencies

Figure 2 demonstrates the efficiencies of thermodynamic heating/cooling. Over the (positive or negative) effective temperature lift ΔT from ambient, the relative exergy E_x/Q is plotted for the ideal process (Carnot process, second law of thermodynamics) and for real processes (Gilli 1995).

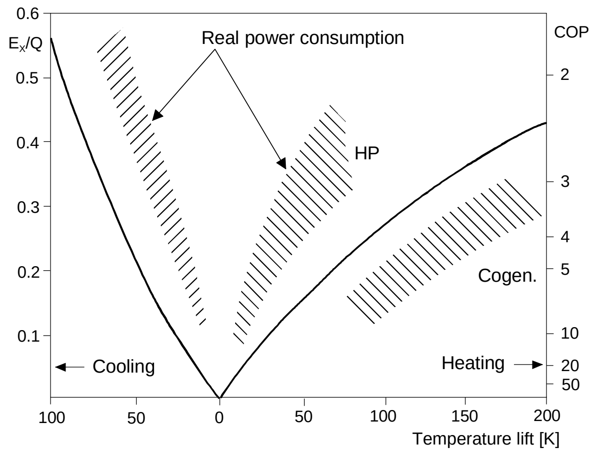

Fig. 2. Ideal and real power consumption E_x/Q for cooling (freezing, refrigeration, air conditioning) and space heating by heat pump and by cogeneration district heating

For the ideal process:

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

where

Ex Exergy
Q Heat transferred
T_a Ambient temperature, K
T Process temperature, K
η_c Ideal (Carnot) efficiency

The coefficient of performance (COP) is shown at the right-hand scale: COP = Q/E_x. The internal - second-law - efficiency is given by the ratio η = COP/COP_{ideal} at ΔT. The left-hand area refers to cooling: freezing, refrigeration and air conditioning including dehumidification. For these applications, E_x/Q ranges from 0.1 to 0.5, the COP therefore from 2 to 10. 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 higher value referring to MVR systems. For heat pumping technologies the efficiency η is about 0.4...0.7.

The area "Cogeneration" is different. Extracting heat from the power generating process means a reduced electricity production, and here the real exergy loss is smaller than the theoretical one because of reduced turbine and condenser losses. Despite this, the COP is, caused by higher operating temperatures, not or not much larger than for the heat pump. In the case of district heating networks the supply temperature has to cover the maximum temperature required by one building; in the case of heat pumps the heat pump outlet temperature can be adapted individually. Additionally thermal losses of the grid can be avoided and the pumping power requirement can be reduced significantly.

2.2 Performance Factors

The drive energy of heat pumps is most commonly electricity, and the electricity generation causes problems in some countries: the common way is to use the overall electricity generation mix for the determination of the PER und the CO_2 emissions of a heat pump system, another way is to valuate the heat pump as an additional electricity consumer, which requires the operation of the oldest power station with the lowest efficiency and the highest CO_2 emissions or even the import of electricity. If the PER of the heat pump is then compared with a condensing gas-fired boiler problems my occur.

The power plant efficiency η_{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 SPFs of 4 and 5. PER is highest for direct power generation from renewable sources such as solar, hydro or wind, for which η_{PP} = 1.0 by definition. PER gives an absolute measure of the units of useful 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 (WEC, 1988), and distribution losses between power plant and heat pumps.

Table 1. Typical Primary and Useful Energy Ratios

Electricity from	Coal, Biomass	Gas	Renewables (hydro, wind)	Nuclear
Efficiencies				
Power plant, η_{PP}	0.4	0.55	1.0	0.33
Boiler (local conversion), η_B	0.8	0.98	1.0	1.0
PER for SPF = 4				
PER = SPF. η_{PP}	1.6	2.20	4.0	1.33
UER = PER/η_B	2.0	2.24	4.0	1.33
PER for SPF = 5				
PER = SPF. η_{PP}	2.0	2.75	5.0	1.67
UER = PER/η_B	2.5	2.81	5.0	1.67

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 (η_B), e.g. in a heating 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. The downstream effects, i.e. the local distribution losses, also cancel each other out in the case of electric heating from hydro, wind, or nuclear plants whereas they may be considered of equal value as a first approximation when comparing electricity for the heat pump, and fuel for the boiler. If, in the latter case, the distribution efficiencies η_d should be markedly different, a more exact formulation would be:

$$UER = (PER/\eta_B)(\eta_{d,,el}/\eta_{d,fuel})$$

where $\eta_{d,,el}$ relates to electricity, and $\eta_{d,fuel}$ to the fuel distribution efficiency.

The data of Table 1 show that

- UER is larger or – for η_B = 1.0, as for electric heating – equal to PER. Only for η_B somewhat higher than 1.0 – as may be the case for very efficient gas-fired condensing boilers – or for $\eta_{d,el} < \eta_{d,fuel}$ could UER become lower than PER.
- For direct electricity from renewables, the efficiencies are 1.0, and UER = PER = SPF.
- For the basic data of Table 1, UER ranges from 1.33 to 5.0.

- Boiler efficiencies near 1.0 are close to the theoretical limit (i.e. for the gas-fired condensing boiler). A SPFs of around 5.0 is far below the theoretical limit of heat pumps; SPFs of 6 or more may be possible and will be economic in the future.

For the future improved power generation systems based on fossil fuels and on renewable sources have to be taken into consideration. Taking the fossil fuels

- the power plant efficiency for gas-fired combined-cycle power plants available on the market is ηPP, is up to 58 % (based on the lower calorific heating value), and 60 % will be exceeded in the near future; with oil as fuel similar values are possible;
- with the combination of high-temperature fuel cells and co-generation systems efficiencies of about 70 % are expected in the future;
- coal-fired power plants with steam conditions of 300 bar/600°C achieve efficiencies of nearly 50 %.

Taking the renewable sources, we have solar energy, wind and hydro. Biomass is valuated as CO_2 neutral, at least by politicians, however, we have to consider the time lag between emission and capturing by the biosphere, which is in the range of 50 to 200 years; scientists do not really agree on this.

But we have other options, i.e. CO_2 capturing and sequestration, Nuclear power is still – or again – an option, and with fast breeders the fuel problem can be solved in a sustainable way, and with superconductive grid systems losses can be minimised.

2.3 Renewable energy gain by heat pumps

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

The sectors where heat pumps are used can be divided in the building sector (residential and commercial), where the majority of heat pumps is in operation, and in the industrial sector. The majority of heat pumps in operation in the residential sector are reversible air-to-air air conditioners for both heating and cooling. The types most commonly used in the small to medium capacity range are

1. Window-type: They are mainly popular in the USA, Brazil, Australia, Saudi Arabia, the Philippines, India, Thailand and Hong Kong.
2. Split-type room air-conditioner (Cooling capacity under 5 kW): They are popular in Japan and China, and also becoming the predominant type in South Korea, Thailand and Malaysia.
3. The unit packaged type air conditioner (unitary air conditioner) which are manufactured and sold mainly in USA. They are also becoming the major types in Australia, the Middle East, Canada and Mexico.
4. The split-type and multi-split-type packaged air conditioner (cooling capacity over 4 kW) are popular mainly in Japan, South Korea and China. Split-type and especially multi-split-type units have been improved significantly as the market expands, including the development of inverter-control methods which regulate air-conditioning performance by varying compressor speed according to thermal load; and simultaneous cooling and heating functions in the multi-split-type air conditioner.

These reversible air-to-air units are very cost-effective due to the fact that the additional feature of dual-mode operation is relatively cheap and due to the long annual operation time.

Europe has been concentrating on heating-only units with ground water, the ground or outside air as heat source, integrated into hydronic heat distribution systems. Ground-coupled systems combined with low-temperature heat distribution systems - hydronic or air-based systems in ultra-low energy houses as shown in Figure 3 - achieve seasonal performance factors of 4 and higher (Halozan 2004, Rieberer 2001). However, also in Europe the market share of air-to-air split air conditioners is rapidly increasing.

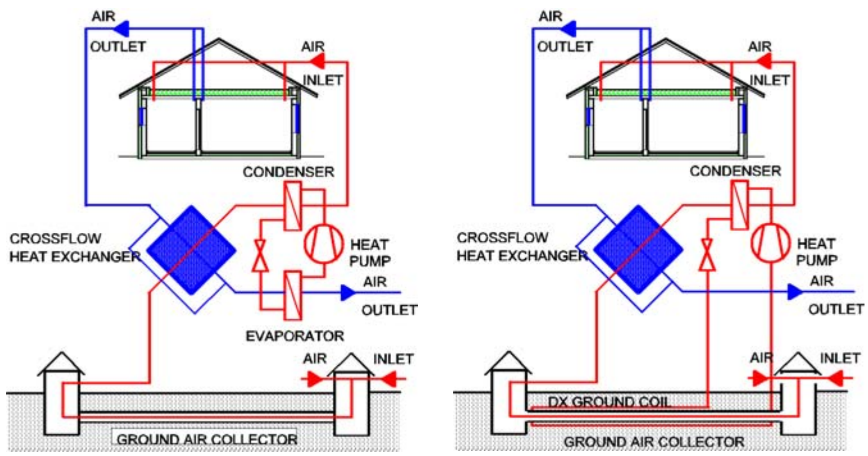

Fig. 3. Ground-coupled systems in ultra low energy houses

In larger systems, especially in commercial buildings, chillers and heat pump chillers are in operation, sometimes ground-coupled systems using the ground as a store (Fig. 4), sometimes water-loop heat pumps are used instead of four-pipe distribution systems with fan-coil units.

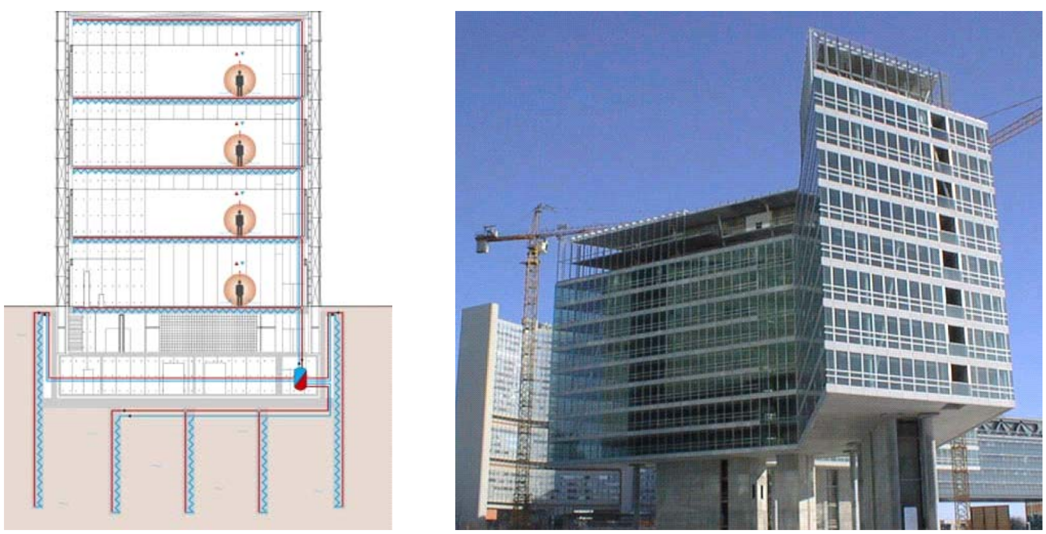

Fig. 4. Building using the pile foundation as a store

In Asia sorption - both absorption and adsorption - systems become popular, the main purpose of these units is load levelling of electric power requirement. Drive energy is most commonly gas, but more and more systems driven by heat from co-generation plants are in operation. The alternative is electrically driven units with ice-storage systems.

Two other types in operation in the residential sector are heat pump water heaters and large units for district heating systems. Large heat pumps with two-stage centrifugal compressors for district heating supply have been built and are operated mainly in Sweden. The heat capacities of these units are usually 10 to 14 MW per unit, but unit capacities go up to 45 MW. The drive energy is electricity, heat sources are treated sewage water, sea water or industrial waste heat.

The industrial heat pump (IHP) in the strict sense is a unit operation, usually heat recovery, within an industrial process, (IEA HPC, 1997) mostly in the chemical, food and lumber industries. The heat pump may be seen as a heat exchanger, working on a negative temperature difference, i.e. the temperature of the heat receiving flow in higher than the one of the heat supply flow. Then, the heat pump yields more freedom in designing a process integration chain. The heat pump may be of the closed-cycle type using a separate working medium as in other energy sectors, or of the open-cycle, where the process medium is also the working medium of the heat pump; one heat transfer loss can be omitted, which increases the efficiency of these systems. Absorption units are used if cheap process heat is available as drive energy. The heat transformer if used if there is excess heat available at a medium temperature level and high temperature heat is required.

4 PRESENT SITUATION

The need for air conditioning 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, 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 do 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 (Fig. 5). In some of these buildings the best air conditioning system cannot provide comfort through all the year.

Fig. 5. Commercial building with glassed facade

The application of heat pumps strongly depends on the climatic conditions and on the building standards.

- The main market is regions with moderate winters - not below –5°C - and summers which require cooling and dehumidification. This is the area prefabricated air/air heat pump air conditioners, which can be easily installed and which, due to a long annual operation time, are highly cost-effective.

- In regions with cold winters, where additionally cooling is required in summer, the heat pump has to compete with conventional heating systems. Air as heat source for heating purposes is due to low SPFs not the best solution in this case.
- Regions with cold winters and no real need for cooling in summer can be a market for heat pumps if heat sources like ground water or the ground can be used. Heat from the ground can be extracted either by horizontally installed collectors (cost-effective in the case of a new building, if enough area is available) or through bore holes .

The world regions were defined as follows: The majority of heat pumps is in operation in Japan, China and in the US, most commonly air-to-air dual-mode (reversible) units for both heating and cooling. In Europe, heating-only heat pumps are used mainly in the Northern and in the Central part, reversible units in the Southern part. Remaining countries are grouped under “Others”.

4.1 Markets in Regions

Japan

The number of heat pumps installed in Japan was 39.3 million in 1992, and 58 million units (68 % of the world total of 85 million units) in January 1997 (Breembroek, 1999). In the year 2000, the number may have reached about 67 million. The number of room air conditioners (RAC) shipped in 1996 has reached a peak of about 8 million in 1996 of which 92 % were equipped for heat pump operation; in 1997 the figures were more than 7 million and 94 %, respectively. The diffusion rate of heat pumps was 62 %, up from 35 % in 1987; it is gradually approaching saturation (Nishimura, 1999). The annual production of packaged air conditioners, mainly for commercial/office buildings, is around 800,000 (Dinghuan, 1999).

An increasing number of larger heat pump systems are equipped with thermal storage systems: water storage up to 1993, mainly ice storage after that date. The shipment of engine-driven heat pumps in Japan has reached more than 40,000 units in 1997, 95 % of them utilising gas engines (GHP), the remainder kerosene (KHP). The number of Sorption systems is increasing, although mainly for cooling. Figure 5 shows the cumulative cooling capacity in 106 RT, being 21 GW.

China

Production of RACs in China was low until 1990, when a rapid upswing started, bringing the production to about 5 million units in 1997, probably around 7 million in 2000, and more in 2001. This means that China has already the largest industry world-wide for producing air conditioners. The heat pump share was 60 % in 1997, and the number of heat pumps installed was 11.4 million in 1997, slightly more than in the US (Breembroek, 1999). Presently, the heat pump stock may be of the order of 25 million.

USA

The number of heat pumps installed in the USA was 9.5 million in 1992 and 11.1 million in 1997 (Breembroek, 1999). Annual sales are about 1.2 million, partly for replacement. The present number may therefore be 13 or 14 million. Numbers include annual sales of 60.000 ground-coupled (geothermal) heat pumps. The problem in the USA are the climatic conditions. Almost in the whole country air conditioning is required, but air-to-air units cannot cover the winter peaks with extremely low temperatures. This results in systems where air conditioners are used for cooling and gas furnaces for heating. The situation in Canada is very similar, considering the populated regions of this country.

Europe

After the oil crisis Europe has been concentrating on heating-only hydronic heat pumps and heat recovery systems, but nowadays sales of dual-mode units are growing. The number of heat pumps in Europe is given as 4.3 million units in 1997 (Breembroek, 1999; Bouma, 1999). The majority of these are reversible air-to-air systems in the residential and commercial sectors in Southern Europe, mainly imported from USA and Japan. The share of these units is increasing. The number of heating-only units and heat recovery units is in the range of 1.5 million units.

A real heat pump market exists in Sweden, other countries have started heat pump programmes - Switzerland, Germany, and the Netherlands – or they are just preparing programmes to increase the market break-through of this technology. The deregulation of the electricity market promises lower tariffs for electricity, which could be an advantage.

Others

In the 1993-1996 market review of the IEA Heat Pump Centre (Breembroek, 1997), there were only 0.6 million units listed for regions other than the four mentioned above (0.5 million for Canada, and less than 0.1 million for South Korea). So the total of 85 million was obtained for 1996/beginning of 1997.

But there are other markets (Dinghuan, 1999) such as Hong Kong, South East Asia (Indonesia, Thailand, Malaysia, Singapore, Philippines), India, Australia/New Zealand, with RAC/PAC annual scales of about 3 million units per year, from which a total number of installed units of about 25 million may be estimated. However, these are mainly cooling-only units and not heat pumps, except the ones in Australia/New Zealand (in total perhaps 3 million units). Adding another estimated 7 million units for South America, Mexico, South Africa, Middle East and the remaining countries, the global number for 1996/97 may be 95 million rather than the above 85 million units for 1997.

The world total number of the RAC and PAC market (cooling only as well as reversible) is estimated to be of the order of 33 million units sold per year (Nishimura, 1999). The split-up of the above 85 million units quoted by the IEA HPC for 1997 is 75 million residential, almost 10 million commercial and about 20,000 industrial units.

4.2 Total

According to the HPC market study (Breembroek, 1999) the world-wide heat pump stock has increased in the four years 1992 to 1996 from 55 to 85 million units, i.e. by 55 %. Assuming for the four years from 1996/97 to 2000/01 a slightly lower increase (due to lower economic growth in Asia during that time), the global number in the year 2001, starting from the 95 million deducted above rather than the 85 million units, may be of the order of 130 to 140 million heat pumps in operation world-wide.

The thermal output of the world`s heat pumps is estimated for 2001 from the data of Table 4 presented in the next chapter as follows:

- Residential: 75 million units, 10.000 kWh/a each:	750 TWh/yr
- Commercial	350 “
- Industrial	200 “
Total	1300 TWh/yr.

According to the relation given in chapter 2.3, the renewable energy R gained by heat pumps becomes 870 TWh/yr.

The diffusion of the heat pump, i.e. the share of useful heat produced by it, is negligible in the transport sector, low in industry, but already substantial in the residential/commercial sector of some countries. In Japan, this share has reached 20 % for the building stock, in Sweden 9.4, in the US 6.9, and in Spain 5 % (Laue, 1999). The share is increasing since for new building it is much higher.

5 POSSIBLE FUTURE DEVELOPMENT

5.1 Technological development

An example for the development is the increase of COPs, e.g. for Room Air Conditioners from a cooling/heating COP of 2.2/3.1 for the 1982 model to 4.1/4.3 for the 1999 model (Itoh, 1998). Similar data (COP = 4.29) are given by Stuij (1995). One of the driving forces for improvements are labelling schemes.

- In the small to medium size capacity range the reciprocating compressor has been practically replaced by the scroll compressor, and liquid/refrigerant heat exchangers have changed to welded flat plate heat exchangers.
- Ground-coupled heating-only heat pumps, especially direct-evaporation systems in Europe, have increased their SPF to 4 and lately to 5 and more. Besides better components, improved building codes with the possibility of reducing supply temperatures required to values below 35°C are responsible for this development.

5.2 Market development

The possible future development can be assessed in two ways: by extrapolating the annual production as per Table 2, part (1), and adding it to the total installation, part (2), accounting for numbers to be taken out of service, and by subsequently assessing the overall thermal output as per parts (3) and (4) of Table 2 (bottom-up method), or by taking the final energy or the three main sectors (industry, residential/commercial, transport) from statistics estimating a maximum share of each sector to be possibly and sensibly covered by heat pumps; also a (lower) share to be covered by some point in time, say the year 2020, which has to be related to the data of Table 2, part 4 for the year 2000 (top-down method).

Table 2. Present and estimated future savings of CO_2 emission by the use of heat pumps

		1997[1]	2001[2]	Savings Potential[1]	
				Present	Future
(a) Residential					
Annual heat demand per residence	kWh	10,000	10,000	9,000	8,000
Specific CO_2 emissions					
from heat pump	kg CO_2/kWh heat	0.215[3]	0.2	0.18	0.12
from oil-fired boiler	"	0.713[4]	0.7	0.67	0.64
Number of residential HP	10^6	65	70	670	1,550
CO_2 emissions					
from oil-fired boilers	$MtCO_2$/yr	204	215	1672	3,500
from heat pumps	"	140	140	1022	1,500
savings by HP		64	75	650	2,000
(b) Savings Commercial	$MtCO_2$/yr	30	35	350	1,100
(c) Savings Residential + Commercial	$MtCO_2$/yr	94	110	1,000	3,100
(d) Savings Industry	$MtCO_2$/yr	20	22	200	600
(a) Total Savings	$MtCO_2$/yr	114	132	1,200	3,700
(f) Percentage CO_2 emission savings by heat pumps[5)]		0.5%	0.6%	6.0%	16.0%

1. from IEA HPC (1997) or deducted from it
2. estimated
3. 0.215 kg CO_2/kWh heat (for 0.55 kg CO_2/kWh electric energy according to the European fuel mix and SPF = 2.5), decreasing to 0.12 for improved power plant efficiency and SPF and reduced fossil fuel in the mix.
4. for 80 % efficiency in 1997, increasing to 90 %.
5. 1997 annual global CO_2 emission: 22 billion tonnes.

6 REDUCTION OF GLOBAL WARMING BY THE HEAT PUMP

According to the Kyoto Agreement, the global emission of greenhouse gases, in particular of industrialised countries, is supposed to be reduced. Of the six greenhouse gases mentioned in the Kyoto Agreement, CO_2 is the most important one (it is responsible for considerably more than 50% of the global warming effect) and at the same time it is the one the emissions of which are most difficult to be reduced world-wide. However, it can be shown that the heat pump is one of the key technologies for energy conservation and reducing CO_2 emission (IEA HPC, 1997).

Table 2 gives present and estimated future savings of CO_2 emissions due to the utilization of heat pumps in the residential and commercial sector as well as in industry. The first column is based on or derived from the data of IEA HPC (1977).

It shows that in 1997 the heat pump saved already 0.6 % of the total global CO_2 emissions. The second column is an extrapolation of the 1977 data to 2001 according to the data of chapter 4. The saving potentials shown in the third and fourth column are again based on data of IEA HPC (1997). The third column refers to the potential savings (6 %) of CO_2 emissions by improved market penetration (30 % in the building sector) using presently available technologies. These 6 % are one of the largest contributions to CO_2 reduction a single technology available on the market can offer. The fourth column is based on greatly advanced future technologies of heat pumps and power plant efficiencies. It yields a 16 % saving of global total CO_2 emissions.

7 CONCLUSIONS

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 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 majority of heat pumps is in operation in Japan, in China and in the US, most commonly air-to-air dual-mode units for both heating and cooling, China has already the largest industry for producing air conditioners, and in South East Asia the trend to this technology is rising rapidly.

- Europe has been concentrating on heating-only hydronic heat pumps and heat recovery systems, but sales of dual-mode units are also growing.

- 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 %. Further improvements are possible in the future.

- 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.

Presently more than 130 million heat pumps with a thermal output of 1300 TWh/a are in operation world-wide, reducing CO_2 emissions by about 0.13 Gt/a. The potential for reducing CO_2 emissions assuming a 30 % share in the building sector using technology presently available is about 6 % of the total world-wide CO_2 emission of 22 Gt/a. With future technologies reductions up to 16 % seem possible. Therefore, heat pumps are one of the key technologies for energy conservation and reducing CO_2 emission.

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