HEAT PUMPS AND THE BUILT ENVIRONMENT

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Abstract: The need for air conditioning depends not only on the climatic conditions, it also depends on the size of the building, and the utilisation; an additional problem is architecture, presently glass is a favorite construction element, and this means that solar gains become very fast solar loads, which have to be removed by a powerful air conditioning system. We cannot change architecture, but we can improve the efficiency of air conditioning systems. To get efficient systems it is necessary to keep temperature lifts required as small as possible, the heat sink/heat source temperature should be low in the cooling season and high in the heating season. Using the ground as store as heat sink/heat source, these requirements for low heat sink temperatures/high heat source temperatures can be achieved. Such a solution requires higher first cost; however, running cost can be reduced significantly.

Key Words: heat pumps, buildings, efficiency

1 INTRODUCTION

The need for air conditioning depends not only on the climatic conditions, it also depends on the size of the building, i.e. the ration of volume to surface, and on the utilisation of the building; i.e. the internal loads caused by persons and equipment. An additional problem is architecture, presently glass is a favorite construction element, double skin facades are modern, and this means that solar gains become very fast tremendous solar loads, which have to be removed by a powerful air conditioning system.

There are three types of climate which require air conditioning:

- climates with daily average temperatures higher than 24,
- climates with a humidity higher than 65 %, and
- climates which combine both; in this case the latent load can become higher than the sensible load.

Besides hygienic and comfort conditions in residential applications air conditioning systems can create an indoor climate, where customers are working efficiently (a 1 K higher temperature means a reduction of the performance by 7 %), and this influence of comfort conditions is being considered relatively seldom.

Another problem are the improvements of our buildings, especially the building shell. Improving the building shell means increasing the influence of internal gains, and this means – on the northern hemisphere – moving buildings in direction south with a lower heating demand, but also with an additionally cooling demand. This effect can be recognised in all large commercial buildings, but also in many of the “passive houses” designed with relatively large windows to use solar gains in winter time and as light construction buildings, which cannot utilize solar gains in winter time efficiently without sufficient storage mass. Additionally, besides the climate change we are producing heat islands in our cities with temperatures significantly higher, up to 8 K, than in the natural surrounding areas, (Fig. 1).

Both effects result in reduced heating loads and significantly increased cooling loads; 20 years ago nobody expected cooling in Central and Northern Europe.

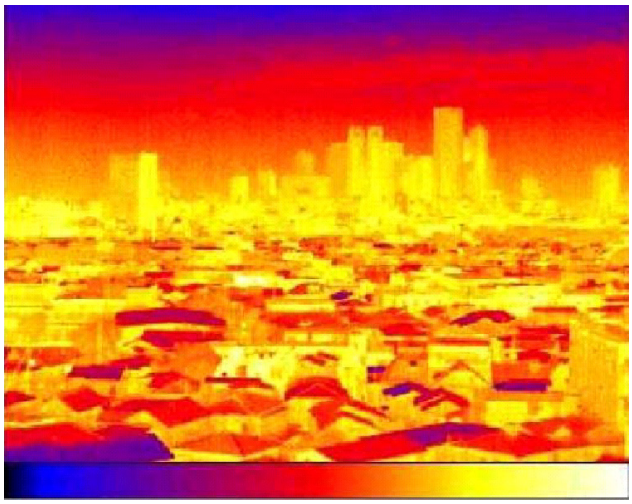


Fig 1: Heat Islands in the Cities

2 HEAT PUMPS AND BUILDINGS

Presently the situation in the building sector in Central Europe is characterized by two different types of buildings: Old existing buildings with poor thermal insulation of the building envelope, equipped with high-temperature heat distribution systems with radiators sized for supply/return temperatures of 90/70°C, with an annual heat consumption in the range of 300 kWh/m2 heated area, newer buildings developed during the last decade with good thermal insulation, with heat distribution systems with low-temperature radiators or medium-temperature floor heating systems sized for supply/return temperatures of 55/45°C or 45/38°C and an annual heat consumptions of about 120 kWh/m2 heated area, and new buildings with excellent thermal insulation, with low-temperature floor heating systems sized for supply/return temperatures of 35/30°C, with an annual heat consumption below 50 kWh/m2 heated area, i.e. low-heating-energy buildings. Taking these different heat distribution systems and annual heat consumption rates one has to analyze the reasons for these developments to achieve even more energy efficient systems.

2.1 Improving the Building Envelope

One of the most important developments was the improvement of the buildings envelope: new bricks and other wall designs reduced the U-values of the walls significantly, new glasses for windows with infra red coatings and argon fillings improved windows by a factor of 3 and more. The annual heat consumption has been reduced from 250 kWh/m2 for the building stock to about 50 kWh/m2 a for a low energy heating building. However, these technologies were mainly used for new buildings, not for retrofitting existing buildings.

Using these technologies the transmission losses through the building envelope, originally 70 to 80 % of the total losses, can be reduced to less then 40 % of the total losses, which means that the ventilation loss dominates the thermal losses of a building. And ventilation was and still is a problem: the new windows became tight, and sufficient ventilation rates were no longer guaranteed.

2.2 Controlled Ventilation Systems with Heat Recovery

Therefore, a logical step should be the introduction of a controlled ventilation system with exhaust air heat recovery with recovery rates between 60 and 85 %. Possibilities for such heat recovery systems are:

- 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, 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 is the combination of both, a heat exchanger and a heat pump. The exhaust air is firstly cooled down in the heat exchanger and than 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, it can also be covered by further reducing the heat load (Fig. 2).
- A simple, but also excellent method is the exhaust air heat pump, where the heat collected from the exhaust air is used to heat water either for heating purposes or for hot water production (Fig. 3).

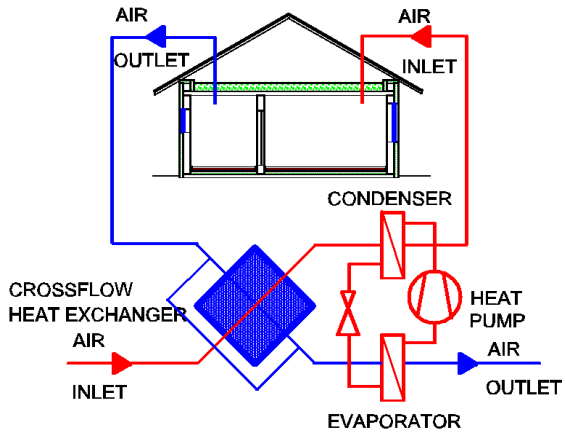


Fig. 2: Exhaust Air Heat Recovery Consisting of a Heat Exchanger and an Air/Air Heat Pump

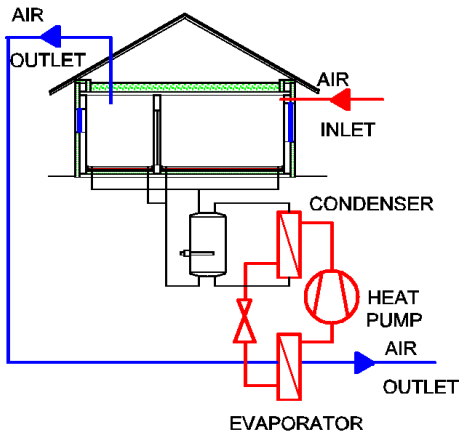


Fig. 3: Exhaust Air Utilisation by means of an Air/Water Heat Pump

- One additional possibility is preheating the fresh air in the ground (Fig. 4a). 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 · C even the outdoor temperature drops below -20 · C. This preheating effect is sufficient to heat the building with the heat recovery system alone.
- A further improvement can be achieved by using a ground coil for avoiding frosting/defrosting losses (Fig 4b). The SPFs achievable with such systems using a heat pump with CO2 as working fluid are 6 for the system (COPover) and 4 for the heat pump (COP), in the case of the DX-heat pump it is about 10 % higher.

Using such systems the annual heat consumption can be further reduced, from 50 kWh/m2 a for low heating energy houses to 15 kWh/m2 a in the case of passive houses. The heat pump units used for such applications are suitable for heating, for cooling and dehumidification, respectively, and for hot water production. (Fig. 6).

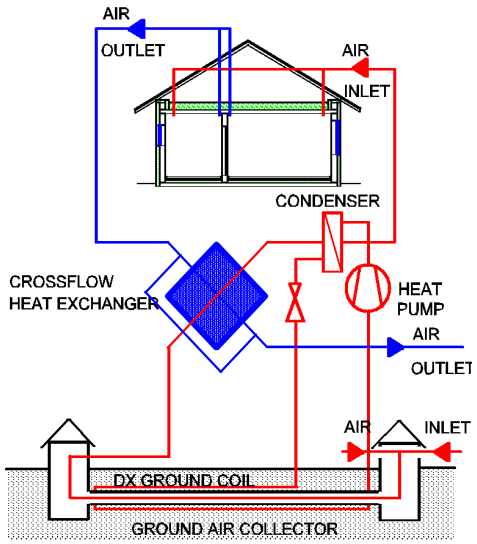


Fig. 4a: System with Air/Ground Collector, Heat Exchanger and DX/Air Heat Pump

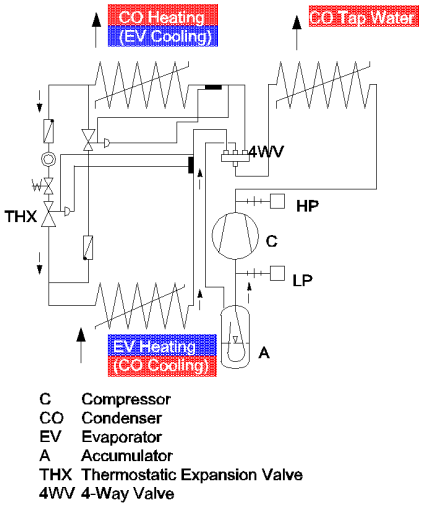


Fig. 4b: Double-Condenser Heat Pump for Heating and Cooling and Hot Water Production

2.3 Improving the Heating System

In the same time frame heating systems have been improved, and especially floor heating systems have achieved a wider market. Boilers have been also improved, but the most important development happened on heat pump systems, especially ground-coupled systems. The commercial utilisation of the ground as a heat source for heat pumps began in the Seventies after the first oil price shock.

The systems installed at this time were mainly secondary loop systems. Later on, direct evaporation (expansion) systems, especially in combination with horizontally installed ground coils, have been introduced (Sanner 1992). Nowadays an increasing share of ground-coupled heat pump systems is in operation world-wide, the heating-only systems in Europe achieve SPFs of 4 and higher. These SPFs sound great and everybody expects a highly sophisticated design of the heat pump units used in these installations. But the philosophy behind these systems is not the heat pump alone, it is the approach to consider the overall system consisting of the building, the heat distribution system, the heat pump and the ground coil, linked by the system control in a way that optimum comfort and minimum power consumption can be achieved for the customer of such a system.

2.4 Commercial Buildings

The design of large commercial buildings has changed significantly during the last decades. Besides their original task of providing space for offices, stores or shopping centres they got as an additional task representation, representation of the city, representation of the company, and very often the owners of large commercial buildings are banks, assurance companies or head quarters of large international institutions. To show the potential of the entity the building has to be higher than the building of the competitor, which can be another country, another city or another company. The task of the building to represent the entity becomes sometimes more important than the original one, creating space for working or living, and very often functionality of the building and energy efficiency considerations are lost.

This development in the building sector is not very new: the church has used this principle, emperors have used this principle for their palaces and castles, governments have used it for their administrative buildings; nowadays banks, assurance companies and multinational companies have overtaken this role, they are obviously the emperors of the world.

Another development happened in architecture. Before the 20th century no artificial air conditioning system was available and the old large buildings like castles and palaces had courtyards, the depth of the buildings was therefore not larger than 12 to 15 m. This design offered the possibility of efficient natural ventilation, it offered also the possibility of day-lighting. The height of the rooms was larger than now, the windows had the size which was necessary for lighting, shading equipment was part of the building, some times it was integrated in the building structure. The mass of the building structure has been used as a store to stabilise the indoor temperature and to damp the influence of outside air temperature fluctuation as well as solar radiation.

Nowadays things have changed significantly: buildings become higher and higher, presently we have reached more than 500 m, and the limitation for the height is no longer the building material available as it was in the past, it seems to be the capacity of the elevators. After facades of bricks, concrete, natural stones and later steel or aluminium, glass became the main material for the envelope of large commercial buildings.

Glass has excellent properties concerning corrosion and cleaning. The problem of the present architecture is that it is not only used as cover, very often the whole building becomes transparent. Additionally some architects have introduced double skin glass facades to offer the possibility of opening the windows for natural ventilation and for increasing the comfort even in high-rise buildings in regions with strong winds. The natural circulation within the shell and the building envelope is used for cooling and as an additional thermal insulation; as an additional advantage noise protection is mentioned.

The result of such designs are large cold surfaces in winter time and problems with overheating in summer time, especially on western oriented facades; surfaces below the height of a table cannot be used for lighting. Such buildings require cooling on the side with solar radiation and heating on the opposite side – without solar radiation – even at temperatures significantly below 0°C, at the same time. Additionally mass for damping outdoor effects no longer exists in modern buildings (Fig 5).

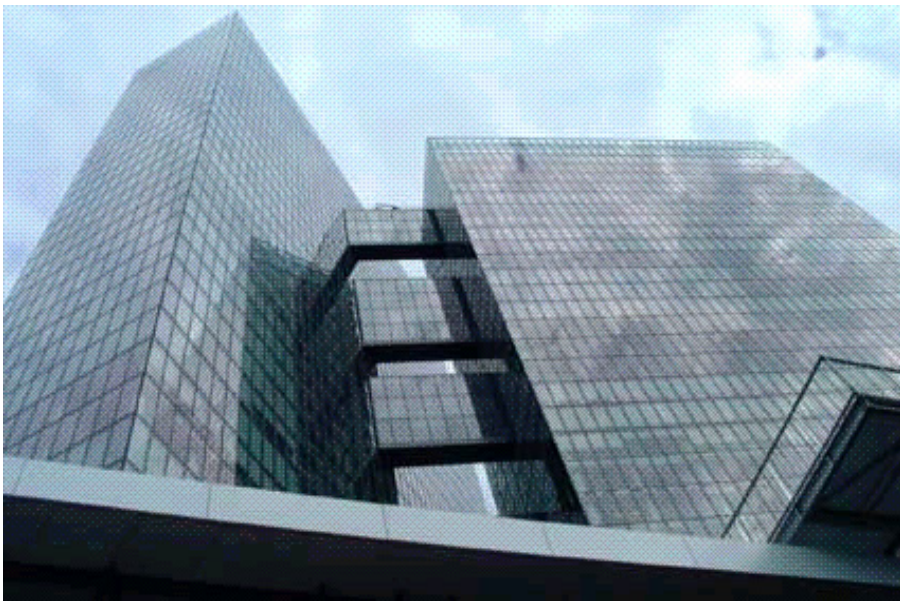


Fig 5: Transparent Building with Glass Facade

An additional influence is the solar radiation through the windows: it means an increase of the room temperature, which cannot be compensated by a lower room air temperature and surface temperature; the only solution is shading the glass facade.

3 AIR CONDITIONING SYSTEMS

A real air conditioning system consists of a controlled ventilation system including filtering of the air and equipment for humidification in winter time and for dehumidification in summer time, all together called the air handling unit, additionally the heat load in wintertime has to be provided and the cooling load in summer time has to be removed, i.e. heating and cooling devices are required.

There are different systems available to provide these features:

- if the air is used for providing the fresh air rate required und for providing the heat load and for removing the cooling load, the system is called an air-only system;
- if the air is only used for providing the fresh air rate required and for providing the heat load and removing the cooling load a hydronic system is used, the system is called an air-water system. This means that the air handling unit, the system providing the heat load and the system removing the cooling load can be completely separated systems.

In the past providing cold and hot was strictly separated: cold was produced by a refrigeration machine, most commonly a chiller, which produced cold water for cooling and dehumidification purposes, and the heat resulting of this process was removed to the ambient by means of a cooling tower; hot was produced by a boiler, and this boiler was even used in summer time for end-heating air after dehumidification. Later on people started using the waste heat of the chiller for reheating the air, they also used the heat pump chiller for shifting heat from spaces, which have to be cooled, to spaces, which have to be heated at the same time. Covering the total heat demand by this heat pump chiller was usually not possible, because the cooling tower was optimised for heat rejection, however, it was not a good heat source system for heating operation (Gilli 2001, Halozan 2003).

4 USING THE GROUND AS A STORE

A next step was the change from air to the ground: the ground acts as a seasonal storage. At a depth of about 10 m the undisturbed ground temperature remains constant over the year; the value of this temperature corresponds to the annual average outside air temperature. Between the table where the constant temperature occurs and the surface, the ground temperature changes due to the outside conditions; depending on the depth, these changes are damped and delayed; peaks of the outside air temperature are being eliminated (Sanner 1992, VDI 1998). 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 aquifers (Fig 6).

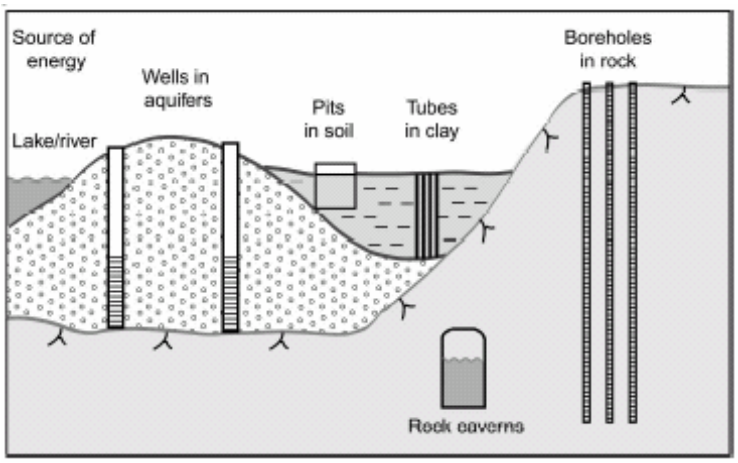


Fig. 6: Using the Ground as a Store

Another possibility is to use the foundation of the building, especially in the case where a pile foundation is necessary (Fig. 7).



Fig. 7: Pile Foundation of a Building Used as Ground Heat Exchanger

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 (Fig. 8).

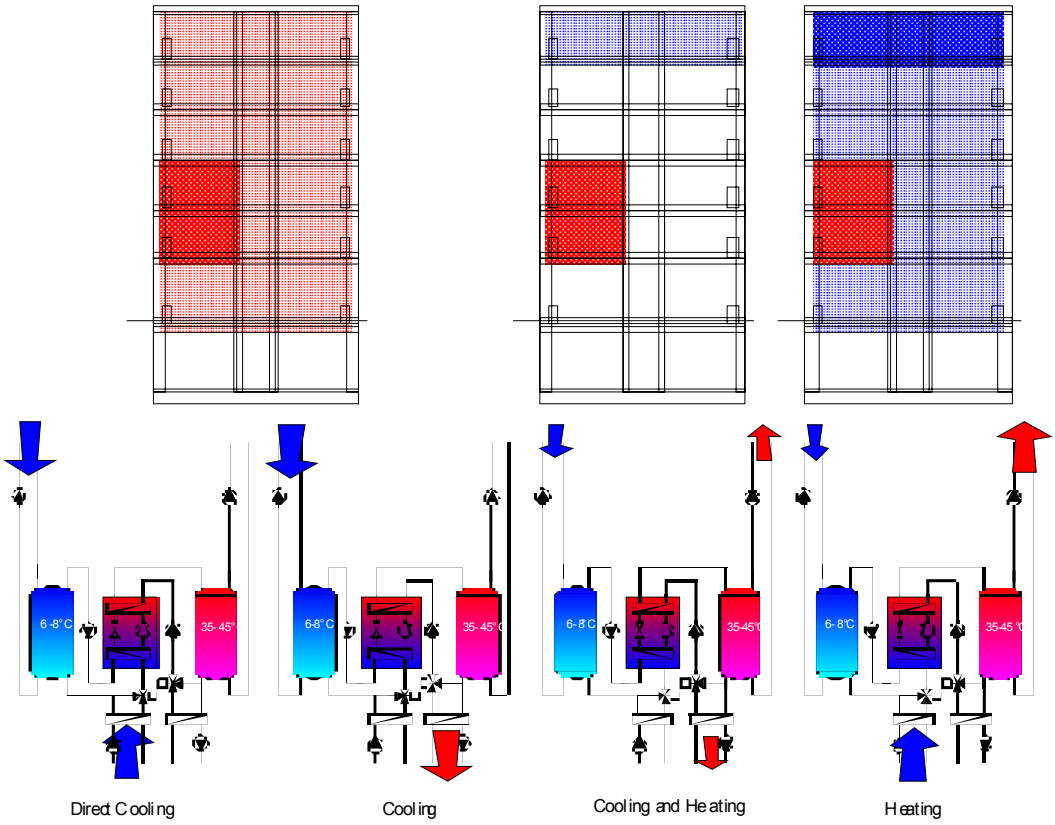


Fig. 8: Ground Coupled Air Conditioning System – Operation Modes

In a proper designed ground store all these problems do not occur, additionally compared with outside air peaks do not occur (Halozan 2004, Halozan 2008, Halozan et.al. 2010[2]).

However, one has to remember, that in the case of a store heat extraction and heat removal have to be in a balance, otherwise the average temperature of the store will increase or decrease, respectively. In such a case hybrid systems have to be used, and the additional heat sink is most commonly outside air (Fig. 9).

Further improvements are possible by so called high-temperature cooling systems and low-temperature heating systems; sometimes they are called low-exergy systems (Fig. 10).

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 20°C for removing the cooling load, both combined with a ground store.

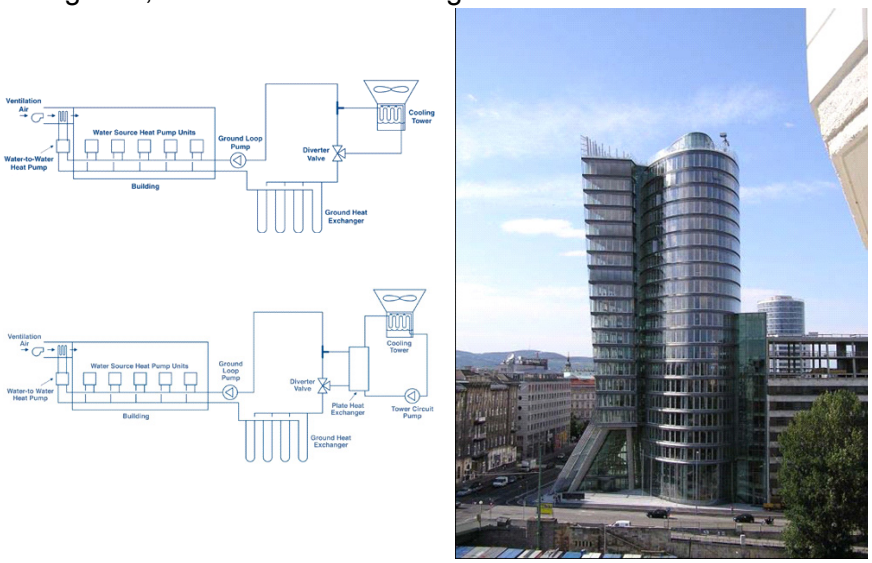


Fig. 9: Hybrid System –Ground Store and Ambient Air

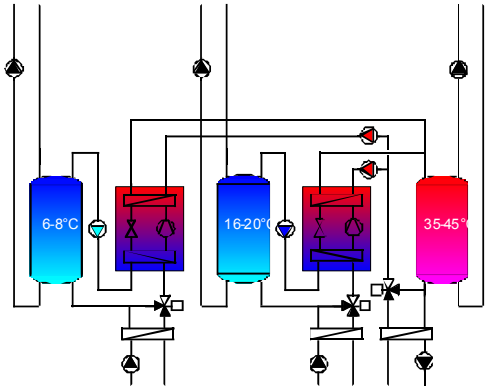


Fig. 10: Low-Ex System with 2 Chillers, one for De-Humidification and one for Cooling

1 K increase of the chilled 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 2008).

Using low-ex systems with “high-temperature cooling” and “low-temperature heating” by means of cooling ceilings or an activated building structure all these effects can be further increased and we can achieve highly efficient air conditioning systems.

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.

However, there is another possibility: dehumidification can also be carried out using a DEC (Desiccant Evaporative Cooling) system. If such a system is again designed as a hybrid system - the DEC system is used mainly for dehumidification and the conventional system for removing the cooling load – the condenser heat can be used for recovering the DEC wheel.

5 DEVELOPMENTS REQUIRED

These developments seem to be one future solution for low-energy buildings. Due to the high thermal insulation standard and the controlled ventilation system, they provide excellent hygienic conditions as well as high comfort for the consumer combined with a low energy bill. However, these developments show what has happened in and with new houses, respectively, but what can we do with the existing houses ? Different solutions are possible and necessary depending on the status of the buildings, and this status can be very different.

- Improving the building envelope is necessary:

  In such a case the heating system has to be redesigned and one has to consider a controlled ventilation system. The remaining heat demand can be covered by a water-based system or an air-based system, where the comfort of static heat transfer surfaces is higher than in the case of dynamic air systems. As heat generation system heat pumps are possible, in the case of a cooling demand in summer time heat pumps are necessary. By using a flat plate heat exchanger for once-through hot water production, the temperature of the stored water can be kept at a temperature level of about 45°C instead of 60°C, which means a further increase of the efficiency of the heat pump.

- Improving the building envelope further is not economic:

  In such a case a controlled ventilation system has to be considered. Medium-temperature heat pumps are possible, they can become efficient by utilizing two-stage compression or the economiser flow sheet.

An additional feature is how to design the ventilation and the heat pump system: Both solutions are possible, centralised systems and decentralised systems.

- In the case of centralised systems the components most commonly achieve a higher efficiency. Such systems are available on the market.

- In the case of decentralised systems the overall efficiency can become higher caused by the effect of a single-room control. Presently the development of decentralised air conditioning systems becomes very popular. In this context new developments are necessary. Single-room ventilation systems with heat recovery are already available on the market. The same concept can be realised with heat pump based systems. A small Austrian company has already developed systems for commercial application, which are in principle window units, however they have the features ventilation with heat recovery, as well as heating and cooling/dehumidification. For the residential sector the capacity of these units has to be reduced.

6 CONCLUSIONS

The choice of an air conditioning systems for a commercial building depends on the climatic conditions, on the building and on the utilisation of the building. In the meantime the design of the building became the main factor concerning energy consumption.

The air conditioning system has the task to compensate external and internal loads and to provide hygienic conditions and year round comfort for the customers. Additionally the air conditioning system offers possibilities to carry out this task with a minimum amount on energy by shifting heat from spaces, which have to be cooled to spaces, which have to be heated at the same time.

Using the ground as a store additionally heat and cold can be stored to a certain extent and used for providing cold without additional energy input, i.e. for direct cooling, and for increasing the heat source temperature for heating. Using low-ex systems with “high-temperature cooling” and “low-temperature heating” by means of cooling ceilings or an activated building structure all these effects can be further increased and we can achieve highly efficient air conditioning systems.

7 REFERENCES

Gilli, P.V., Halozan, H. (2001), Heat Pumps for Different World Regions – Now and in the Future, Proc. 18th WEC Congress, Buenos Aires, Argentina.

Halozan, H. (2003), Energy efficient heating and cooling systems for buildings, Proceedings International Congress of Refrigeration 2003, Washington D.C.

Halozan, H., Rieberer, R. (2004), AC Systems in Large Commercial Buildings, Proceedings IIR Congress Compressors ‘2004, Casta Papiernicka, September 9 – October 1, 2004

Halozan, H., (2008) Highly Efficient HVAC Systems, IIR Congress HVAC Energy Efficiency Best Practice conference, September 18–19, 2008, Melbourne, Australia

Halozan, H., Schranzhofer, H., Rieberer, R. (2010), Ground Source Heat Pumps - Overcoming Market and Technical Barriers, HPP Annex 29 Final Report, November 10, 2010, SP Boras, Sweden

Sanner, B. (1992) Erdgekoppelte Wärmepumpen, Geschichte, Systeme, Auslegung, Installation, IZW-Bericht 2/92, Karlsruhe, Germany.

VDI (1998), Thermische Nutzung des Untergrundes – Erdgekoppelte Wärmepumpen-anlagen, VDI-Guidline 4640 Blatt 2, February 1998, Düsseldorf, Germany.