GROUND SOURCE HEAT PUMPS – OVERCOMING MARKET AND TECHNICAL BARRIERS (IEA HEAT PUMP PROGRAMME ANNEX 29)

Hermann Halozan, René Rieberer
Institute of Thermal Engineering, Graz University of Technology
Inffeldgasse 25 / B, A-8010 Graz, Austria
Phone: +43 316 873-7303 (Fax: -7305)
E-mail: halozan@iwt.tu-graz.ac.at

ABSTRACT

Within the framework of the IEA, the Heat Pump Programme has carried out three Annexes on ground source heat pumps (GSHP), the IEA Energy Conservation through Energy Storage Implementing Agreement one, and both Programmes came to the result that utilising the ground highly efficient solutions for the building sector can be achieved. The work in Annex 29 will include a matrix of GSHP applications depending on climate, ground conditions and applications, a study on how to improve technical performance and cost of GSHP, the identification of market barriers and innovative approaches to increase GSHP.

Ground-coupled heat pumps gain importance world-wide with respect to energy efficiency in heating and cooling operation. The ground acting as a store offers the possibility of damping the effects of the outside air temperature fluctuations, in colder climates it enables monovalent heating operation of the heat pump, and for utilities it is – compared with outside air operated heat pumps **-** a tool for demand side management measures.

Key Words: ground-coupled heat pumps, direct expansion systems, heating-only operation, heating and cooling operation, underground thermal storage

1 INTRODUCTION

First considerations to use the ground as a heat source were made in 1912 by Zölly from Switzerland. In the forties, investigations on ground-source heat pumps started again in the US; the systems, partly direct-expansion systems, worked very reliably. Similar work has been carried out in Germany. However, 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-expansion (evaporation) systems, especially in combination with horizontally installed ground coils, have been introduced (Sanner, 1992).

In the last decades, heat pumps have acquired fundamental shares in markets such as Japan and the United States. Other markets including Europe - with the exception of Sweden and Switzerland - and other continental zones are struggling to develop the implementation of heat pump technologies as basic heating and comfort cooling devices (Halozan, 1996).

Since the Eighties heat pump units and the components used like compressors and flat plate heat exchangers, respectively, have been improved significantly. The development of heat source systems and heat sink systems on the one side and the system approach on the other side took much more time, and the development in the direction of highly efficient systems is still going on.

Nowadays an increasing share of ground-coupled heat pump systems is in operation world-wide, the heating-only systems in Europe achieve Seasonal Performance Factors (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.

Within the framework of the IEA, the Heat Pump Programme has carried out three Annexes on ground source heat pumps (GSHP), the IEA Energy Conservation through Energy Storage Implementing Agreement one, and both Programmes came to the result that utilising the ground highly efficient solutions for the building sector can be achieved. The work in Annex 29 will include a matrix of GSHP applications depending on climate, ground conditions and applications, a study on how to improve technical performance and cost of GSHP, the identification of market barriers and innovative approaches to increase GSHP.

2 GROUND-COUPLED HEAT PUMP SYSTEMS

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. Eliminating peaks of the outside air temperature, the ground is an efficient heat source for heat pumps. Ground source heat pumps can be applied for different climates, different ground properties, for small and large systems, and for heating-only as well as heating and cooling applications.

Climate: The climate has a strong influence on the ground temperature available and on the operating conditions of heat pump systems (cold, moderate and hot climate, hot and humid climate, oceanic climate with small temperature fluctuations or continental climate with large temperature fluctuations).

Ground Properties: Ground properties are responsible for the type of ground utilisation and the heat disposal/heat extraction method, i.e. open or closed loop system. In the case of a closed loop system they are also responsible for the ground heat exchanger type used.

Small systems: The common characteristic of small systems is natural ground recovery, mainly by solar radiation collected by the ground surface. Small systems are in use for heating as well as heating and cooling, they can be used, depending on the climate and the distribution system, for direct cooling (without heat pump operation), at least at the beginning of the cooling season.

Large systems: For large system recovery of the ground has to happen by heat removal and heat extraction. Sometimes additional systems for recharging the store have to be provided. Heat removal can happen by direct cooling (without heat pump operation) and indirect cooling (with heat pump operation).

3 HEATING-ONLY OPERATION

For the utilisation of the ground as a heat source for heating-only operation various system designs have been developed (Fig. 1); the differences are mainly caused by the capacity of the system and the area available (VDI, 1998):

Horizontally installed ground coils are most commonly installed at a depth of about 0.3 m below frosting depth, i.e. in the populated regions of Austria at a depth of about 0.8 - 1.2 m. At such a depth, the ground temperature changes during the year: At the beginning of the heating season it is higher than the undisturbed ground temperature (15 to 17°C instead of 10 to 12°C); during the heating season it drops below 0°C caused by heat extraction, but moisture migration to and frost formation around the coil increase heat conductivity and help to stabilise the temperature where heat extraction takes place.

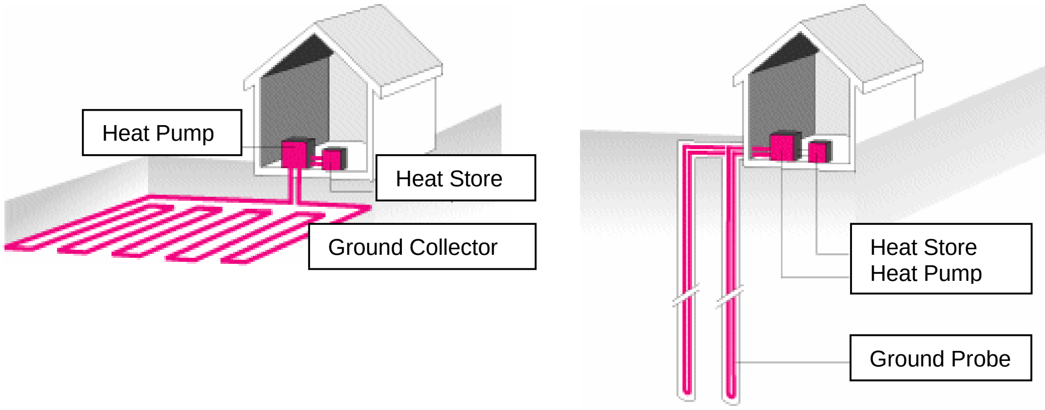

Fig. 1. Horizontally and Vertically Installed Ground Coils

At the end of the heating season natural recharging starts and heat is delivered from the surface to the coil; if the system design is correct vegetation above the coil is hardly influenced at all.

Vertical wells are required if the surface area available is insufficient for horizontal systems. In the case of vertical wells, two designs are possible, either shallow wells down to a depth of 20 m or deep wells down to 100 m or even more (250 m). The depth depends on the ground conditions and on the drilling equipment available. The heat exchangers are either of the U-tube and double U-tube type, which are commonly used, or of the coaxial type. Other versions of ground heat exchangers are the ditch collector, which is a compromise between a horizontal and a vertical system, and spiral heat exchangers for bore holes with larger diameters as developed by O. Svec, Canada (Halozan and Svec, 1993).

The systems installed worldwide are most commonly secondary loop systems. Besides these secondary loop systems, which dominate globally the application of ground-source heat pumps, direct expansion systems have been developed, and especially in Austria more than 60 % of the installed heating-only ground-coupled heat pumps use this technology.

3.1 Secondary Loop Systems

In the case of secondary loop systems the heat pump unit and the heat extraction system are separated.

- The heat pump unit is being designed as a compact brine/water unit, where the refrigerant content can be minimised and which can be manufactured and tested in the factory to fulfil the requirements of leak tightness. Leak tightness means that – taking the present technology – no greenhouse gases are emitted directly to the environment.

- The problem of this concept is the secondary loop system: The heat carrier, most commonly a glycol/water mixture, has to be circulated through the ground coil by means of a circulation pump. Compared with water the properties of these mixtures are worse, the density is slightly higher, but the specific heat capacity is lower, and the viscosity is higher with a tendency to increase significantly at decreasing temperatures. This results in a circulation pump which has to be sized for the lowest temperature which may occur, because in the case of a transition to laminar flow the heat transfer coefficients drop and at the same time also the brine temperature.

Each temperature drop has a negative influence on the COP, i.e. the power requirement rises and increases the indirect greenhouse gas emissions due to increased drive energy generation. Under-sizing the ground coil or the circulation pump can result in a male function of the system.

3.2 Direct Expansion Systems

Direct expansion systems have some advantages compared with secondary loop systems (Halozan, Rieberer, 2002):

- The evaporator of the heat pump unit is directly installed in the ground, which means that the heat transfer from the ground to the refrigerant takes place directly, i.e. one heat transfer loss can be avoided.

- The drive energy for the circulation of the refrigerant in the evaporator comes from the compressor and from the throttling loss, respectively; this means that no additional power for a circulation pump is needed.

- Additionally, heat transfer conditions of copper tubes (with a diameter of 12 to 14 mm coated with a thin plastic film to avoid corrosion) used in direct-expansion coils are better than those of plastic tubes used for secondary loop systems. The heat conductivity of the plastic material used for the tubes of secondary loop coil is relatively low.

- This means that in the case of an appropriate design direct evaporation systems are more efficient than secondary loop systems. The SPFs of direct evaporation systems in new well insulated buildings with specific heat loads below 60 W/m^2 equipped with low-temperature floor heating systems are in the range of 4 to 5 and higher!

To achieve such high SPFs the design of the heat pump unit and the construction of the whole system have to be carried out very carefully (Fig. 2):

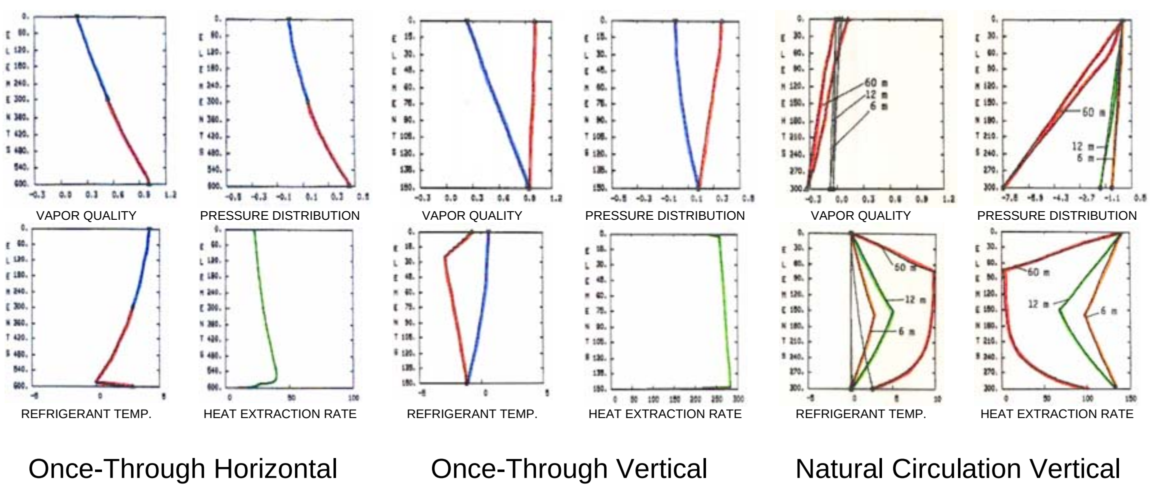

Fig. 2. Refrigerant Flow through Possible Direct-Evaporation Concepts

- The refrigerant velocity in the evaporator has to be kept as small as possible to minimize the pressure drop, which means also a drop in the evaporation temperature: but it has to be high enough to ensure oil return. In horizontally installed collectors the required velocity at the evaporator outlet has to be about 5 m/s, in vertical systems it has to be about 7 m/s. To achieve this velocity and to make a sufficient mass of ground accessible, the diameter of the evaporator tubes has to be smaller than that of secondary loop systems; this means that the temperature drop from the ground to the tube surface becomes larger or the heat transfer area has to be increased.

- The refrigerant cycle control cannot be carried out using a conventional thermostatic expansion valve due to the fact that the length of the tubes used is 60 m and 75 m, respectively, and the run-through time is in the range of more than 30 seconds. Possible solutions are capillary tubes or thermostatic expansion valves based on liquid sub-cooling, which is the best solution (see Fig. 3).

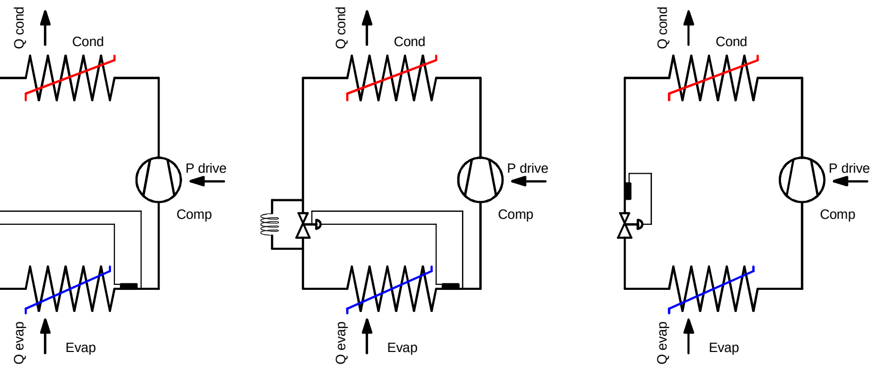

Fig. 3. Refrigerant Flow Control with Suction Gas Superheating Control and Liquid Subcooling Control

- The design of the coils of vertical systems has to be carried out very carefully (Fig. 3). In horizontally installed systems the pressure decreases from the inlet to the outlet, and with the pressure the evaporation temperature decreases as well. In the case of vertical systems one has to consider the pressure gains in the down comer. Without evaporation in this section systems with a depth of 50 m to 60 m cannot be realised, because the evaporation temperature will rise significantly, and it may become higher than the ground temperature. Evaporation in the down comer has to be used to compensate pressure wins caused by gravity. The riser has to be sized to guarantee oil return to the compressor. Using pressure gains in the down comer and pressure losses in the riser, it is possible to size a vertical coil in a way that externally, between inlet and outlet, no pressure loss exists.

- However, these pressure gains in the down comer avoid the design of natural circulation systems, which would result in a perfect cycle control. But due to the variation of pressure and evaporation temperature only shallow systems can be realised.

- In the case of part-load operation by means of two-speed (variable-speed) compressors or two compressors arranged in parallel, which is an efficient measure to increase the SPF, the speed drops. Thus for the oil return, maximum capacity operation at the beginning of a cycle or after a defined time interval has to be implemented.

If these preconditions are fulfilled, there will be no serious problems for an efficient and reliable operation. However, there are also some disadvantages of direct-evaporation systems:

- Soldering at the site is (was!) necessary to connect the ground collector and the heat pump unit, refrigerant losses and pollution of the ground water can occur.

- The ground coil evaporator becomes much larger than the evaporator of a compact heat pump unit, thus the refrigerant charge increases.

These disadvantages have been solved by manufacturers and installers of direct-expansion systems (Halozan, 1997). These manufacturers are small companies with employees highly skilled in both refrigeration systems and heating systems, they are designers and constructors and not only heat pump manufacturers or heating system installers, and that is the reason why direct expansion systems are so successful in Austria and why the SPFs are significantly higher than those of secondary loop systems.

In principle, these small system designers and constructors save first cost by investing their knowledge and experience into these systems. It is possible to achieve such high SPFs also with secondary loop systems, and some companies are successful in almost achieving these values. However, the systems become more expensive due to a larger ground coil, which results in an increase of the secondary fluid temperature and the evaporation temperature, respectively, and this increase has to be utilised for reducing and compensating the electric power consumption of the circulation pump.

3.3 Further Developments

But the development of heat pumping technologies goes on, and heat pumps are strongly influenced by advancements in refrigeration technology - positively - and by regulations, which are sometimes an obstacle.

3.2.1 Packaged Direct Evaporation Heat Pump with Propane as Working Fluid

Propane is an excellent substitute for R-22, practically a drop-in, and using an internal heat exchanger it becomes even more efficient than R-22 with about the same cooling capacity; additionally, the refrigerant charge can be reduced by about 50 % compared with R-22. One problem of propane are restrictions due to existing regulations and restrictions introduced by compressor manufacturers, and it seems that at least one large compressor manufacturer in the USA wants to prevent the use of the hydrocarbons in Europe. Nevertheless, some manufacturers still use hydrocarbons like propane as refrigerants (Halozan, 1995).

One of the small heat pump manufacturers in Austria has developed a packaged direct-expansion heat pump using propane as refrigerant. The heat pump unit – designed for outdoor installation due to Austrian regulations – connected with the ground evaporator is prefabricated, filled with the refrigerant charge required, and proven in the factory. The complete unit is transported to the site on a pallet, the heat pump part is mounted on a small foundation, the evaporator coil, folded on the pallet, is being laid out into the excavated ground, covered with sand and than filled up with the excavated ground material.

The connection to the heating system in the building consists of the supply and the return pipe and cables for power supply and control. The control itself and the heating water circulation pump are mounted in the building.

3.2.2 CO_2 Heat Pipe Based Ground Probe

A very interesting refrigerant is CO_2: The "natural" working fluid CO_2 (R-744), in Europe introduced by Linde already in the year 1881, became an important refrigerant: It has been used until the end of the Thirties as refrigerant for marine cooling and for air conditioning systems in buildings, both applications where a "safety" refrigerant was required. Difficulties have been caused by the thermodynamic properties, the critical data are about 31°C and 74 bar. This resulted at high ambient temperatures in a trans-critical operation where both capacity and efficiency dropped significantly. G. Lorentzen initiated the revival of this interesting high-pressure refrigerant again (Lorentzen, 1993).

An interesting development has been carried out by K. Mittermayr of the M-tec company, who developed a heat-pipe based ground probe with CO_2 as working fluid for vertical wells down to a depth of about 70 m (Rieberer and Mittermayr, 2001) (see Fig. 4).

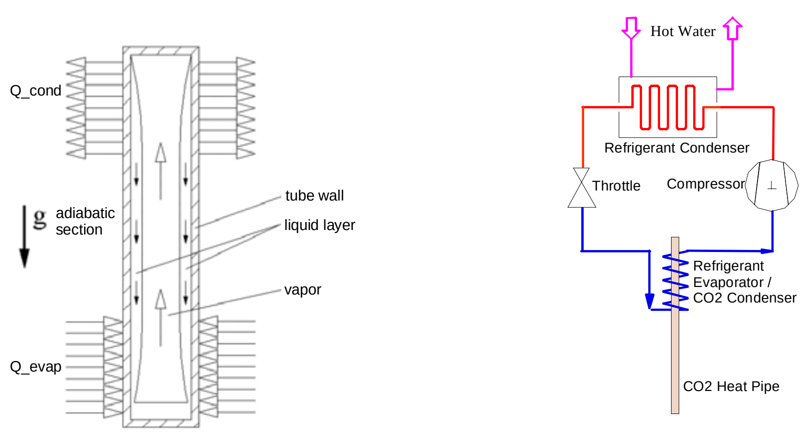

Fig. 4. Working principle of a heat pipe (two-phase thermosyphon) and heat pump system layout

This self-circulating system is environmentally fully acceptable – the probe works oil-free – and it has the advantage that no circulation pump is required. The working principle of a heat pipe can be described as follows (compare left chart of Fig. 4): due to gravity the liquid working fluid (CO_2) flows along the tube wall to the 'heated' section of the probe where it becomes evaporated, thus the liquid film becomes thinner and thinner while the vapour rises to the top due to the buoyancy. In the “cooled” section – at the top of the heat pipe – the vapour becomes condensed and the cycle starts again.

The system design leads to a heat pump cycle that is physically de-coupled from the heat source cycle, the CO_2 cycle (compare right chart of Fig. 4). The refrigeration cascade consists of the earth probe in which CO_2 is evaporated, and the “probe-head” which is both the CO_2-condenser and the refrigerant-evaporator of the conventional heat pump using R-410A as refrigerant. The experimental analysis confirms that the proposed CO_2 heat pipe is a reliable and a highly efficient as well as environmentally friendly alternative to common ground-coupled systems. With a prototype heat pump a system SPF of higher than 5 has been measured.

3.2.3 Highly Insulated New 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°C, heating degree days 3500, heating period length 200 days) buildings with specific heat loads of 60 W/m^2 and can be heated by ground-coupled heat pump systems achieving SPFs of 4 to 5.

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 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 (Fig. 5). 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 when the outdoor temperature drops below -20°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 (Fig 6). The SPFs achievable with such systems using a heat pump with CO_2 as working fluid are about 6.

This seems to be one future solution for low heating-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 (Rieberer and Halozan, 1997).

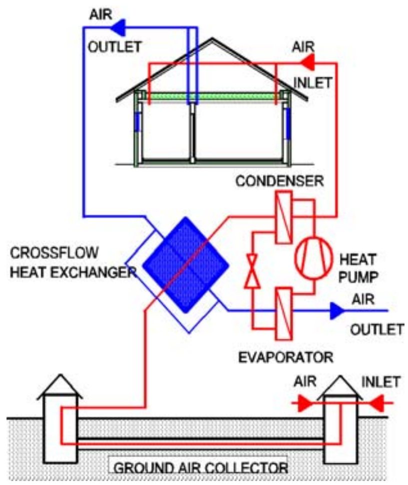

Fig 5. System with Air/Ground Collector, Heat Exchanger and Air/Air Heat Pump

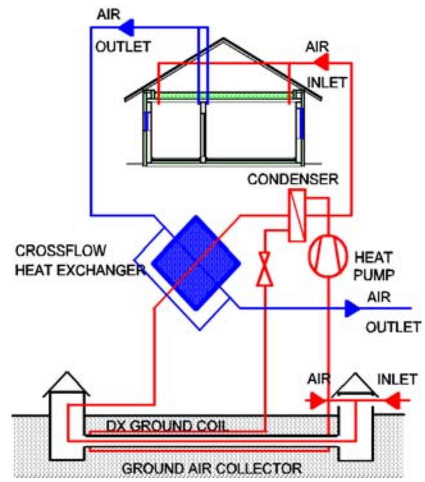

Fig. 6. System with Air/Ground Collector, Heat Exchanger and DX/Air Heat Pump

4 HEATING AND COOLING SYSTEMS

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 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 be 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 (see Fig. 7).

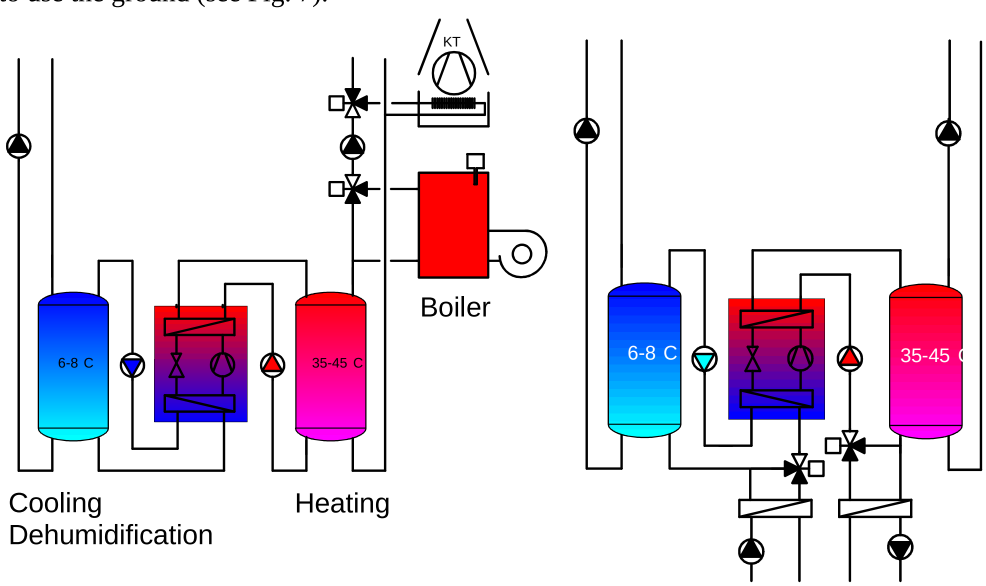

Fig. 7: Change of the heat sink/heat source from the air to the ground

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 aquifers (Fig. 8). Another possibility is to use the foundation of the building, if a pile foundation is available or necessary (Fig. 9 and Fig. 10).

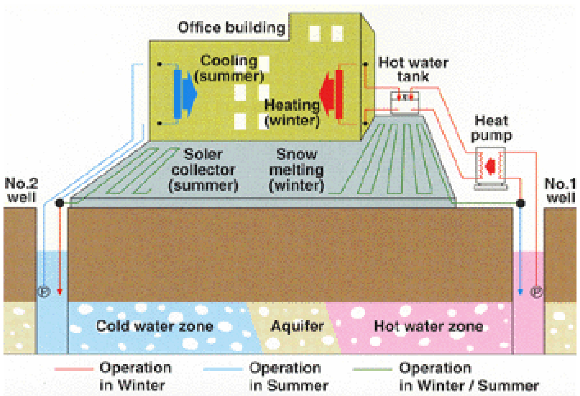

Fig. 8. Aquifer System

Fig. 9. Pile System

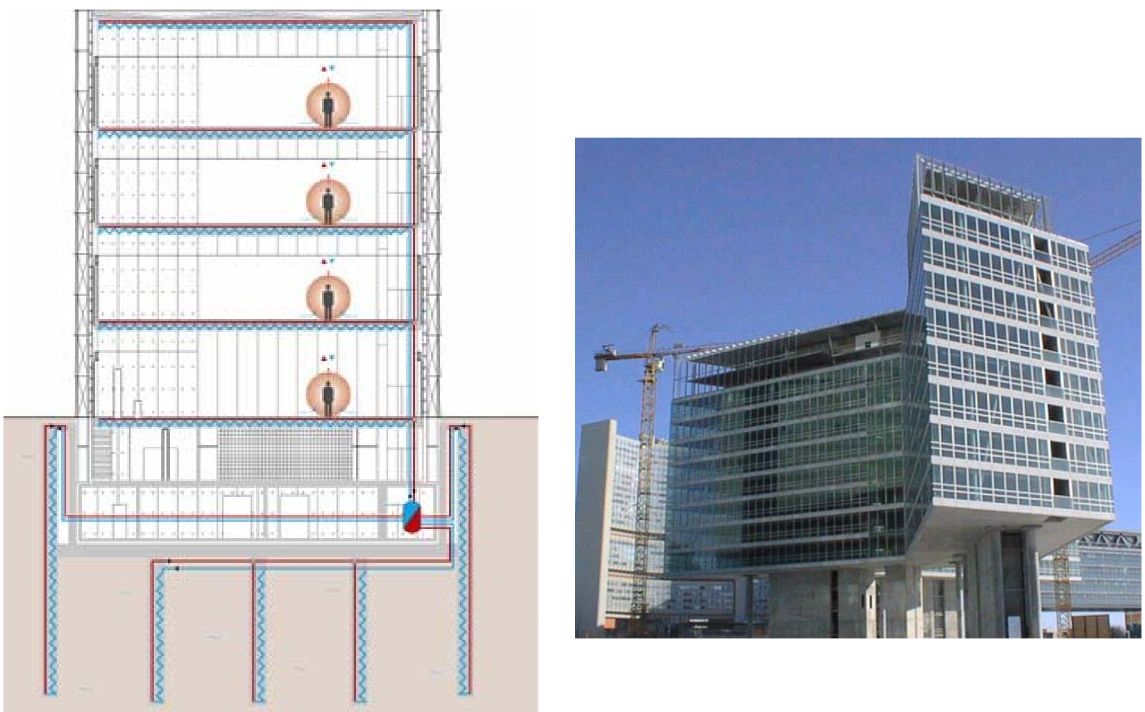

Fig. 10. Pile System – Scheme and Building

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. 11).

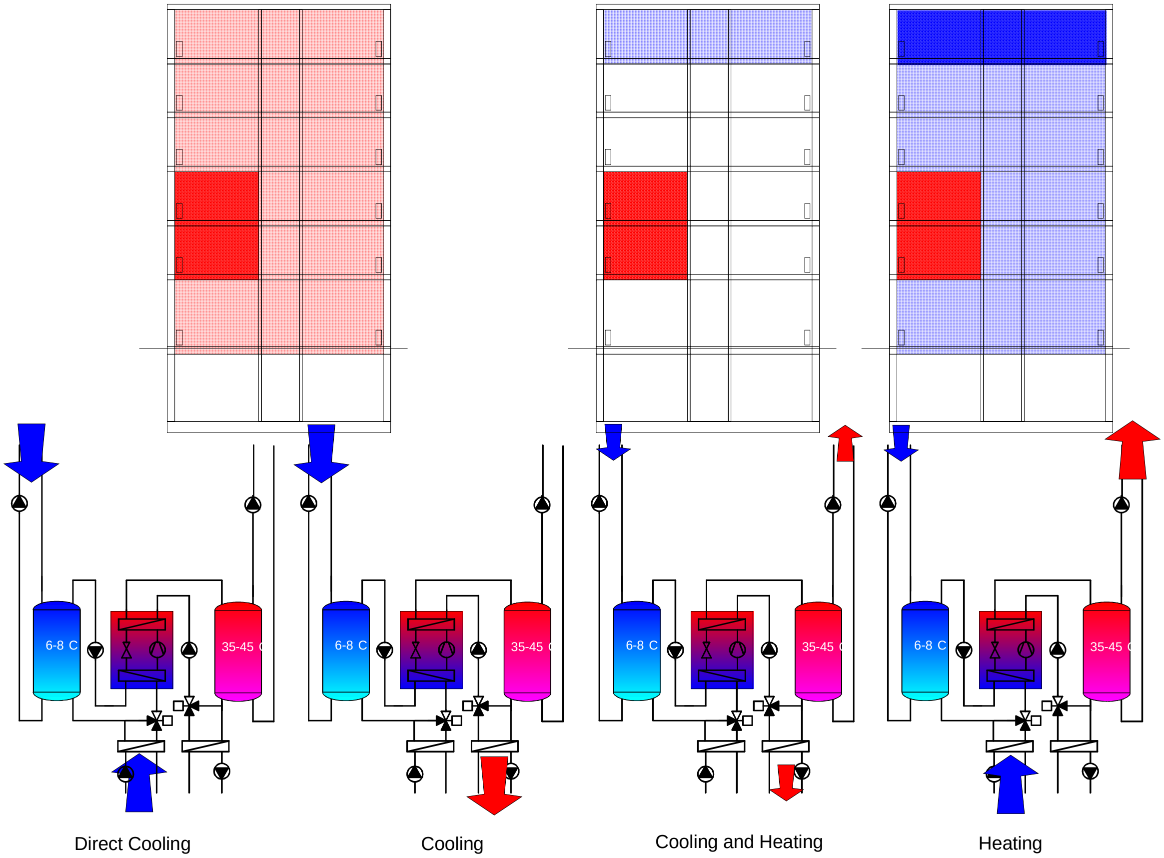

Fig. 11. Operation modes of an advanced AC system

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.

5 LOW-EX SYSTEMS

Further improvements are possible by so called high-temperature cooling systems and low-temperature heating systems; sometimes they are called low-energy 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, both combined with a ground store (Fig. 12).

For dehumidification and removing the cooling load two solutions are possible,

- one chiller producing cold water with a temperature of 6°C to 8°C for both dehumidification and removing the cooling load working with a cooling tower, or

- two chillers, one 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 connected to a ground store.

A 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 %.

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 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.

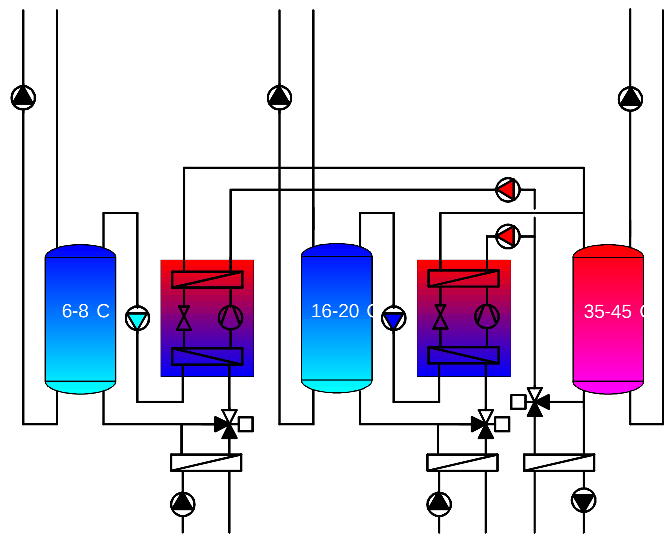

Fig. 12. AC system with separated dehumidification and cooling cycles

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.

6 SUMMARY

Ground-coupled heat pumps gain importance world-wide with respect to energy efficiency in heating and cooling operation. The ground acting as a storage offers the possibility of damping the effects of the outside air temperature fluctuations, in colder climates it enables monovalent heating operation of the heat pump, and for utilities it is a tool for demand side management measures. New developments like improved heat pump units, advanced direct-expansion heat pumps or heat pumps combined with heat pipe based vertical probes show that there is still room for new ideas, which may be necessary for being competitive and successful in the future.

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 these effects can be further increased.

REFERENCES

Halozan, H., 1996, Effective Use of Ground-Source Heat Pumps, Workshop Proc. Systems and Controls for Energy Efficiency, Tokyo, May 7-8, 1996, p. 149-160.

Halozan, H., Svec, O., 1993, Heat Pump Systems with Direct Expansion Ground Coils, Final Report of Annex 15, IEA, Paris.

Halozan, H., 1995, Propane for Heat Pumps, Proc. 19th Congress IIR/IIF, 20.-26. August 1995, The Hague, The Netherlands.

Halozan, H., 1997, Direct-Evaporation Ground-Coupled Heat Pumps in Austria, IEA HPC Newsletter 3/97, Sittard, The Netherlands, p. 22-23.

Halozan, H., Rieberer, R., 2002, Ground Coupled Heat Pumps - Direct Evaporation Systems versus Secondary Loop Systems, Proc. of the IIR/IIF Conference Minimum Charge – Zero Leakage, Stockholm, 26-28 August 2002.

Halozan, H., Rieberer, R. (2005) AC Systems in Large Commercial Buildings, Proceedings IIR Congress Compressors ‘2004, Casta Papiernicka, September 9 – October 1, 2004

Lorentzen, G., 1993, Revival of Carbon Dioxide as a Refrigerant, Proc. U.K. Institute of Refrigeration Conference, London, 1993.

Rieberer, R., Halozan, H., 1997, CO2 Air Heating System for Low-Heating-Energy Buildings, Workshop Proc. IIR Linz '97 "Heat Pump Systems, Energy Efficiency, and Global Warming", September 28 to October 1, 1997, Linz, Austria.

Rieberer, R., Mittermayr, K., 2001, CO2 – Heat Pipe, Final Report of the ETP-Project supported by the Upper-Austrian government, Austria.

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

VDI, 1998, Thermische Nutzung des Untergrundes – Erdgekoppelte Wärmepumpenanlagen, VDI-Guidline 4640 Blatt 2, Draft February 1998, Düsseldorf, Germany.