

Potential of geothermal heat exchangers for office building climatisation

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ABSTRACT

Low depth geothermal heat exchangers can be efficiently used as a heat sink for building energy produced during summer. If annual average temperatures are low enough, direct cooling of a building is possible. Alternatively the heat exchangers can replace cooling towers in combination with active cooling systems. In the current work, the performance of vertical and horizontal geothermal heat exchangers implemented in two office building climatisation projects is evaluated.

A main result of the performance analysis is that the ground coupled heat exchangers have good coefficients of performance ranging from 13 – 20 as average annual ratios of cold produced to electricity used. Best performance is reached, if the ground cooling system is used to cool down high temperature ambient air. The maximum heat dissipation per meter of ground heat exchanger measured was lower than planned and varied between 8 W per meter for the low depth horizontal heat exchangers up to 25 W per meter for the vertical heat exchangers.

The experimental results were used to validate a numerical simulation model, which was then used to study the influence of soil parameters and inlet temperatures to the ground heat exchangers. The power dissipation varies by plus/minus 30% depending on the soil conductivity. The heat conductivity of vertical tube filling material influences performance by another plus/minus 30% for different materials. Depending on the inlet temperature level to the ground heat exchanger, the dissipated power increases from 2 W m⁻¹ for direct cooling applications at 20°C up to 52 W m⁻¹ for cooling tower substitutions at 40°C. This directly influences the cooling costs, which vary between 0.12 €kWh⁻¹ and 2.8 €kWh⁻¹.

As a result of the work, planning and operation recommendations for the optimal choice of ground coupled heat exchangers for office building cooling can be given.

KEYWORDS: Geothermal cooling, geothermal heat exchangers, building climatisation, low energy cooling

1. INTRODUCTION

Research into ground coupled cooling systems, that are more energy efficient than conventional compression cooling, has been carried out for many years. The initial interest was in direct coupling of buildings with the earth as described by Dahlem [3], with the principal disadvantage of a missing thermal separation and thus additional heating demand in winter. Also multi-storey office building cannot be effectively coupled to the ground. However, the ground may still be used as a heat sink by means of either earth - air or earth - water heat exchangers (Kumar et al. [5])

Direct cooling of a building is only possible if the temperature of the soil adjacent to the intake pipe is lower than the desired temperature of the indoor air. With alternated signs, this is equally true for direct heating (Rafferty [10]). The main restriction of the system is the available ground temperature level, which at 15 meter depth corresponds approximately to the annual average air temperature above ground and then increases again by about 3 K per 100 meters. Thus the before mentioned condition cannot be met in practice in many locations, especially in the warmer regions most in need of cooling, such as North Africa, the Middle East, parts of China, India and most tropical countries.

In moderate climates, earth heat exchangers are increasingly used for closed - loop direct cooling of buildings, with water or brine as the heat transfer fluid. They are either designed in a horizontal configuration with a shallow depth of about 2 m or installed as vertical loops up to about 100 m depth. Vertical ground heat exchangers are constructed by inserting one or two high density polyethylene U-tubes in vertical boreholes of 75 to 220 mm diameter. They are usually connected in parallel to reduce pressure drop. In Europe, double U-tubes are common, whereas in the United States single tubes prevail. Zeng et al. [14] show that double U-tubes reduce the borehole resistance by 30 - 90% and thus improve heat transfer.

The high heat capacity of water is advantageous, as the electrical energy needed for circulating the fluid through the earth heat exchanger is considerably lower than if air is used. The water cooled through contact with the earth is then distributed in the building using either activated concrete slabs with buried pipes or an air - based ventilation system, in which the air is cooled by the water in an additional heat exchanger.

If the ground temperature level is too close to the desired room temperature, the cooling power of such a system is too low to be cost effective. This problem may be overcome by one of two methods:

- By employing indirect cooling systems, such as reversible heat pumps (chillers), which use the ground as a heat sink and are therefore more efficient compared to similar systems exposed to cooling tower temperatures or hot ambient air (Karagiorgas et al [4]).
- By cooling the soil below its undisturbed temperature prior to circulating fluid through the heat exchanger. When horizontal heat exchangers at shallow depths are used, soil temperature may be influenced by surface treatment. At greater depths, the ground may be cooled in the winter season, as heat pumps in the heating mode extract energy from the soil. Li et al. [7] show that unbalanced heat extraction from the ground reduces temperature levels by 6°C within 5 years for heat pump operation only. If only heat is rejected to the ground from a cooling machine, after 13 years the soil temperature was over 35°C and no longer suitable for air conditioning. Only balanced heat fluxes kept ground temperatures constant over a 30 year period.

The main task of the design process is to determine the required length of tubing for the required thermal energy to be extracted or rejected. Modelling the thermal response of the surrounding soil requires information about the ground temperature distribution, the moisture content, groundwater movement, freezing or thawing of the soil and the geometry of the heat exchanger. Furthermore, experimental results showed that the temperature distribution around soil tubes is often not symmetric (Bi et al. [1]). The soil

surrounding the borehole is usually considered as homogeneous with a mean thermal conductivity and mean diffusivity.

Simulation models are often separated in "inner" solutions for the heat transfer between the fluid and the perimeter of the borehole including the mutual influence of the U-tubes and the outer region between the edge of the borehole and the ground. The simplest model for the inner borehole is to calculate the heat flux per unit length of the borehole from the resistance, the mean fluid temperature and a mean borehole temperature. The thermal resistance contains the convective resistance between fluid and pipe wall and the conductive resistances of the wall and borehole filling material. As the steepest temperature gradients occur at the pipe - soil or backfill material interface, several authors developed detailed models for the near temperature field. Zeng et al. [14] develop analytical models for a range of tube configurations within the borehole; Piechowski [9] solves heat and moisture transport equations for horizontal pipes embedded in soil. The author states that the soil temperature around a pipe drops by 30 - 40% within a few centimetres, indicating the influence of precise near field models.

To obtain the mean temperature of the borehole and to calculate the complete soil temperature field, the heat conduction equation has to be solved as a function of time, depth and distance from the borehole. The height dependence of the temperature is often ignored and the simplest solution is obtained, if a step function heat input is applied at the centre of the borehole. The solution is known as Kelvin's infinite line source theory and is used to analyse thermal response test data.

An extension of the line source approach has been proposed by Eskilson and Claesson [2]. This includes the height dependence of the temperature field. The

integrals in the solution of the temperature field are called g-functions, which are computed numerically and then mostly used in tabulated form. Recently analytical solutions have been developed for the g-functions by Lamarche and Beauchamp [6]. If the g-function is known, the temperature at the perimeter of the borehole can be easily calculated. Using the g-function approach, Lamarche and Beauchamp calculate the time, when the height dependence (so-called axial effect) becomes important for a 100 m borehole length. For a wet sandy soil, this takes 3.7 years. Thermal interference between 2 boreholes separated by 5 m becomes relevant after half a year.

Numerical models offer more flexibility in the temperature field calculation for arbitrary geometries and time varying heat fluxes and inlet temperature levels (Signorelli et al. [12]). Therefore, a three dimensional numerical model was used in this work to analyse the influence of soil properties and operation strategies. This approach allowed us to extrapolate the results from the monitoring projects to other climates and soil conditions.

2. BUILDING DESCRIPTION AND GEOTHERMAL COOLING CONCEPTS

2.1 *Low energy office building in Freiburg*

The Solar Info Centre (SIC) in Freiburg/ Germany is an energy efficient office building for renewable energy companies. The net floor area of about 14000 m² is distributed over 6 floors in the northern and western wing and 3 floors in the eastern wing. Located on the first floor, there is a seminar room with a floor area of 178 m² and a volume of 695 m³. Air-conditioning of this room is achieved by geothermal energy. Five vertical borehole heat exchangers of 80 m depth each supply cooling and heating energy. This system is designed for a cooling load of 16 kW. The fan has two setpoints with volume flows of 3000 m³ h⁻¹ up to a maximum volume flow of 5100 m³ h⁻¹. As the ventilation

system of the seminar room is only manually switched on, if the room is in use, the geothermal heat sink can also be connected to 157 m² activated concrete floor cooling system in the foyer of the building (see Figure 1). Due to the high investment costs of the ground heat exchangers and the low operating times of the ventilation system, this double use improves the economics of the system.

2.2 *Rehabilitated office building in Tübingen*

The passive energy office building in Tübingen/Germany is part of a former military ground called the Thiepval barracks and has been rehabilitated. Roof and wall insulation with 30 cm and 24 cm thickness and triple glazed windows with a U-value of 0.8 W m⁻²K⁻¹ correspond to passive house standards. The floor insulation in the existing building could only be 7.5 cm due to low ceiling heights so that low cost perimeter insulation was chosen to prevent excessive ground losses. The building has a useful floor area of 838 m². It is mechanically ventilated with winter heat recovery and summer precooling of the ambient air through a brine-based ground coupled heat exchanger installed around the building perimeter. The geothermal system consists of five horizontal earth-brine heat exchangers with a length of 100 m each, which are installed shallow under the soil surface (about 1.5 m depth). During summer they are used for cooling of supply air (see Figure 2). The volume flow of air during daytime is 1750 m³ h⁻¹. The specific electricity consumption is 0.15 W m⁻³h⁻¹ for standard ventilation during summer at an air change of 1 h⁻¹.

3. EXPERIMENTAL RESULTS

3.1 *Vertical ground heat exchangers (SIC building)*

The measured average soil temperature is close to 16°C during the summer. The brine temperature rises steadily as soon as the pump is turned on, increasing by nearly 3 K during the day. However, the soil recovers quickly during the nights when the pump is shut off. Still a rising trend of the soil temperature is clearly visible from below 15°C to almost 17°C within a week. The temperature spread in the geothermal circuit is about 3K. Supply air temperatures during operation were between 18 and 22°C (see Figure 3). The measured average coefficients of performance for summer cooling are between 13 and 20. The COP was calculated from the cooling energy delivered by the ground heat exchanger divided by the total electricity demand. The electricity demand contains the power of the geothermal heat exchanger pump (here 170 W electrical power) and the ventilation system electricity. Here only the additional electricity demand to overcome the pressure drop across the air to water heat exchanger was considered. In case that the geothermal heat exchanger was used for floor cooling, only the pumping electrical energy was considered.

Using the geothermal heat exchanger as the only cooling source for the seminar room in summer, it could be shown that during occupation, the air temperature can be kept at comfortable levels below 26°C (see Figure 4).

The thermal power dissipated by the heat exchangers is rather low with a maximum of about 26 W per meter borehole depth, in case the ventilation system is operating. If the floor cooling system is used, the high pressure drop reduces the volume flow rates by a factor of five approximately and the thermal power dissipated by the earth heat exchangers drops to 5 – 10 W m⁻¹ (see Figure 5). The first idea to increase the floor cooling power was therefore to increase the volume flow of the pump. However, the

analysis of temperature levels showed, that the temperature level delivered to the floor cooling system was 18°C minimum in order to prevent condensation (see Figure 6, Brine to floor temperature level). The heat uptake from the room increased this temperature level to an average of 20°C, which is the return temperature to the earth heat exchanger (EHX inlet in Figure 6). As the temperature difference is only 2 K, an increase of volume flow would not improve the situation.

The limiting factor for the EHX cooling power is the restricted surface area of the floor cooling system. The mean temperature difference between the circulated fluid in the floor and the air is about 6 K, so that the estimated cooling power is about 20 Wm². For 157 m² active floor cooling area, this results in a maximum cooling power of only 3 kW. Also the installed pump has quite a low efficiency at the high pressure drop operation (below 40%) compared to 68% at nominal conditions. The choice of a different pump would benefit the COP for floor cooling operation.

The energy delivered by the ground heat exchangers was measured during two years for the two operation modes ventilation air cooling and concrete floor cooling (see Table 1). The number of cooling hours was between 2500 and 3200 hours per year, which is quite high. The low COP for heating in 2006 is due to the fact that the geothermal system was operated at very low temperature differences between ambient air and ground heat exchanger output for long times.

The analysis of the system operation also revealed problems with the operation of the ventilation system, which caused a high total electricity consumption. The manual switching of the ventilation system by the users was not effective, as the system was often left on during the night (see Figure 7 with 2005 data).

In the present system the ventilation system can operate in two levels with a power consumption of 1.36 kW for the first level and 2.7 kW for the second level. In the first three months 2005, a total electricity consumption of 1985 kWh was measured. If the ventilation system would have been switched off during the night, savings up to 42% could have been achieved (see Table 2).

In 2006, the ventilation system was still on several times during the night, which was necessary to maintain the room setpoint temperature at 17°C (see Figure 8). The main problem is an undersized heat exchanger in the ventilation system, which did not allow raising the supply air temperature to sufficiently high levels.

3.2 Horizontal ground heat exchangers

For air preheating and cooling of the Eboek building in Tübingen / Germany five horizontal earth-brine heat exchangers with a length of 100 m each are installed shallow under the soil surface (about 1.5 m depth). During a hot fourteen days measurement period in June 2005 an average cooling power of 1.5 kW with a maximum of 4 kW was measured. Due to the close proximity and low depth of the tubes, the maximum heat dissipation per meter of tube is only 8 W. Due to the low depth of the heat exchangers the brine temperature levels are about 3 K higher than for the vertical heat exchangers. After five days of daytime operation, the temperature level increases by about 2 K and reaches temperature levels of 20°C.

The pressure drop due to the brine-air heat exchanger amounts to only 12 Pa. The installed fan needs an electrical power of 30 W to overcome this drop, whereas the brine pump consumes about 60 W. This results in maximum coefficients of performance of 40 and an average COP of 18.4 (see Figure 9).

The ambient air can be cooled down by as much as 7 K in the heat exchanger. However, for ambient air temperatures between 30 and 35°C, this results in rather high supply air temperatures to the building between 26 and 28°C during midday (see Figure 10). The logarithmic average temperature difference of brine and air across the heat exchanger is about 6.3 K. A larger heat exchanger would be useful to lower the supply air temperatures.

4. PARAMETER STUDIES AND POTENTIAL ANALYSIS

To study the influence of the system operation and of soil parameters, a three dimensional numerical heat transfer model for vertical geothermal heat exchangers was developed and implemented in the simulation environment INSEL (www.insel.eu). It is based on the heat conduction equation and uses a rectangular discretisation geometry for a single ground heat exchanger and a parallelogram geometry to simulate a field of heat exchangers. The model has been validated using the experimental data from the Solar Info Centre project and reproduces the measured temperature and power levels well during winter operation (see Figure 11). During summer operation the experimental results for air cooling at high volume flows is also simulated with less than 1 K error. For floor cooling operation, the errors are slightly higher (1-2 K). This is mainly due to the uncertainty of the low volume flow regime, which is estimated from the pump data sheet using the measured pressure drop and pump electrical power (see Figure 12).

4.1 Parameter study results

The model was used to study the influence of the soil heat conductivity, the borehole backfill heat conductivity as well as the mutual distance of boreholes on the energy output is investigated. The boundary conditions are those of the SIC building in Freiburg. The soil heat conductivities range from $0.5 \text{ W m}^{-1} \text{ K}^{-1}$, representing dry clay, to

2.5 W m⁻¹ K⁻¹ for water-saturated sand. As can be seen from Figure 13, the soil heat conductivity has a major influence on the cooling performance. Compared to the standard moraine soil, the energy output is lessened by 39% if the underground consists of dry clay, verifying the statements of Sanner and Rybach [11], who show that the specific energy extraction rate increases with increasing soil heat conductivity. Zhang and Murphy [15] support this finding but stress that the effectivity of thermal storage may decrease.

Borehole backfill heat conductivities of 0.8 (light concrete), 1.6 (Bentonite) and 3.2 W m⁻¹ K⁻¹ (high performance backfill) are investigated in the next step. Although light concrete is rarely used as backfill material, it was included in this study for comparison. From Figure 14 it can be seen, that the effect on the energy output is relevant. However it can be expected that the influence decreases if the heat conductivity of the surrounding soil is low.

Thermal response tests have been conducted at the Stuttgart University of Applied Sciences to determine the effective heat conductivity for different backfill materials. Two borehole heat exchangers with lengths of 80 m were built, one with standard backfill with a heat conductivity of 1.6 W m⁻¹ K⁻¹ and the other with Stuewathern backfill with a heat conductivity of 2.0 W m⁻¹ K⁻¹. The borehole heat exchangers are tested with a thermal power of 3 kW. The heat conductivities of the complete system (tube, backfill and surrounding soil), as derived from the thermal response tests, are 1.94 W m⁻¹ K⁻¹ and 2.17 W m⁻¹ K⁻¹ respectively. The use of high performance backfill leads to a 12% higher total heat conductivity.

Regarding the mutual distance of vertical ground heat exchangers, Zhang and Murphy [15] state that the spacing of the boreholes is of major significance regarding the thermal effectiveness and that the single heat exchangers can be regarded as isolated from each other if the distance is greater than 6 m. This finding is backed up by the current numerical parameter study. Starting with the standard distance of 6 m, the distances are subsequently decreased to 3 m and 1.5 m, keeping the total soil volume of the geothermal system constant. This results in a 2 times, respectively 4 times, greater number of heat exchangers with decreasing distance. Although the overall energy output rises, that of each heat exchanger is reduced due to the mutual influence (see Figure 15).

4.2 Influence of climatic boundary conditions on cooling performance

A field of five vertical ground heat exchangers with a length of 80 m each is simulated in different climatic boundary conditions in order to investigate the climate influence on cooling performance. The average ambient temperatures of several cities in warm climates represent the undisturbed soil temperatures around the heat exchangers. Each system is operated for four months, 12 hours every day. An average sand type soil was assumed as surrounding soil. The inlet temperature into the ground heat exchangers is set constant to 22°C, representing the output of a thermally activated concrete slab from the building. Table 3 shows the investigated locations, the average ambient temperature (T_{amb}), the maximum outlet temperature of the ground heat exchangers (T_{max}), the mean cooling power (P_{mean}), the minimum achievable cooling power (P_{min}), the maximum specific thermal power for the ground heat exchanger (P_{max}), the total thermal energy (E_{tot}) and the specific energy cost at a volume flow of $2.4 \text{ m}^3 \text{ h}^{-1}$. The cost is derived from an annuity of 3570 €, which corresponds to the typical cost of the vertical ground heat exchangers in Germany. Assumptions for this calculation are investment costs of 18000 €, a lifetime of 20 years, maintenance expenses of 2.0% of

the investment cost, electricity costs of 0.18 €kWh^{-1} , a discount rate of 4.0% and an inflation rate of 1.9%.

Obviously, the climate of Bangkok is not suitable for direct geothermal cooling, as the inlet temperature from the building is lower than the ground temperature. Active chillers are needed here in order to reach the desired temperatures. However, even in the warm climate of Crete, the outlet temperature of the ground heat exchangers does not exceed 21°C at the end of the summer period (see Table 3). The direct use of geothermal energy via thermally activated concrete slabs is thus possible, although the achievable cooling power is relatively low bearing in mind the high investment cost. In all locations, the ground temperature regenerates to between 0.5°C and 1.5°C above the undisturbed temperature at the end of each 12 hours operation cycle, rising only slightly during the 4 months period. This aspect is important regarding the long term performance of any geothermal system (Pahud et al. [9]).

4.3 Influence of inlet temperature on cooling performance

In order to determine the influence of the temperature level of the direct cooling system on the performance of the geothermal system, the same geothermal simulation as above was executed with several different inlet temperatures. The Greek island of Crete was chosen as location with a mean ambient air temperature of 19.1°C . Inlet temperatures between 20°C and 24°C were used to represent the combined operation with a floor cooling system, whereas the inlet temperatures of 35°C and 40°C represent the replacement of a standard cooling tower by the borehole heat exchangers.

From Table 4 it can be seen, that the maximum outlet temperature T_{max} , the mean thermal power P_{mean} , the minimum thermal power P_{min} as well as maximum specific thermal power P_{max} rise approximately proportional to the inlet temperature. This leads to the conclusion that the ground temperature around the heat exchanger regenerates

almost completely during the downtime of the circulation pump. Regarding the operation of the borehole heat exchangers as a 'cooling tower' it can be stated that geothermal heat exchangers are an interesting alternative concerning effectiveness and cost.

5. CONCLUSIONS

In summary, the work presents new experimental results for geothermal heat exchanger performance in some of the best German office buildings today. The earth heat exchangers reach excellent annual coefficients of performance above 20 using a low pressure drop design. The power dissipation measured per meter of heat exchanger is rather low at 8 W per meter for low depth horizontal heat exchangers and 26 W per meter for 80 m deep vertical heat exchangers. In case of the vertical heat exchangers the cooling power is limited mainly by the low heat uptake within the building.

Simulation studies showed that the earth heat exchangers can be directly used for building cooling also in warmer Mediterranean climates, although the power dissipation level drops at higher soil temperatures. In the Crete climate, even after a four months summer period, the maximum outlet temperature of the heat exchanger was not higher than 21°C, so that activated concrete ceilings can still be operated efficiently. The cost per kWh of cold produced directly depends on the mean power delivered by the heat exchanger, which in turn increases with temperature difference between ground and inlet water. Using the geothermal heat exchangers for recooling of chillers in summer and with heat pumps in winter results in lower cost than direct heating and cooling of building materials or ventilation air, which on the other hand is energetically preferable.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

- Figure 1: System drawing of geothermal heat exchanger coupled to the ventilation system of the seminar room or to the activated floor of the foyer.
- Figure 2: System drawing of horizontal absorbers in the rehabilitated office.
- Figure 3: Temperature levels of ventilation air before and after the geothermal heat exchanger during a hot fortnight in summer 2005. The operation time of the ventilation system is also shown (status=1 means that the system is ON).
- Figure 4: Measured ambient, supply air and room temperatures during a hot fortnight in summer 2005 with geothermal cooling only. The volume flow of the ventilation system is shown.
- Figure 5: Power dissipated per meter of ground heat exchangers for the two operation modes floor cooling and ventilation system supply in summer 2006.
- Figure 6: Temperature levels and volume flows of earth heat exchangers and foyer room cooled by ground concrete floor cooling system.
- Figure 7: Operating hours of ventilation system in 2005.
- Figure 8: Operating hours of ventilation system in 2006.
- Figure 9: Cooling power and COP of horizontal earth heat exchanger for a hot fortnight in 2005.
- Figure 10: Temperature levels of earth heat exchanger and supply air in the horizontal geothermal system in 2006.
- Figure 11: Measured and simulated temperature levels and temperature difference for winter operation of the heat exchanger with ventilation air preheating.
- Figure 12: Measurement and simulation results of Solar Info Centre vertical heat exchanger in cooling mode. The high volume flows represent ventilation system operation, the low volume flows correspond to floor cooling operation.
- Figure 13: Relative change of energy output for different soil conductivities. The operating conditions were identical to the Solar Info Centre, which has a moraine soil type.
- Figure 14: Relative change of energy output for different backfill heat conductivities. The reference condition of the Solar Info Centre heat exchanger is a bentonite.
- Figure 15: Relative change of energy output for different earth heat exchanger distances. The standard distance is 6 m.

TABLE CAPTIONS

Table 1: Summary of performance results for the vertical heat exchangers in the Solar Info Centre Freiburg.

Table 2: Electricity savings for time controlled ventilation system.

Table 3: Cooling power and cooling costs for different climatic boundary conditions.

Table 4: Cooling power and costs of vertical geothermal heat exchangers for different inlet temperatures.

FIGURES

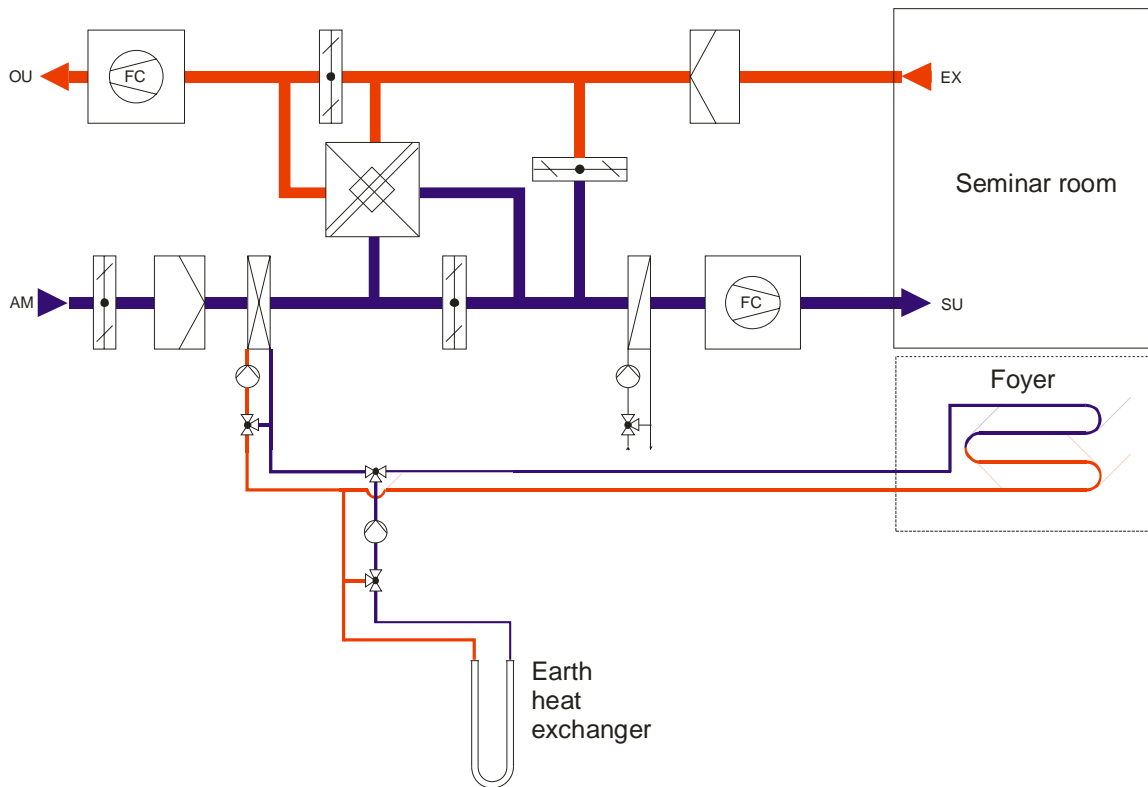


Figure 1: System drawing of geothermal heat exchanger coupled to the ventilation system of the seminar room or to the activated floor of the foyer

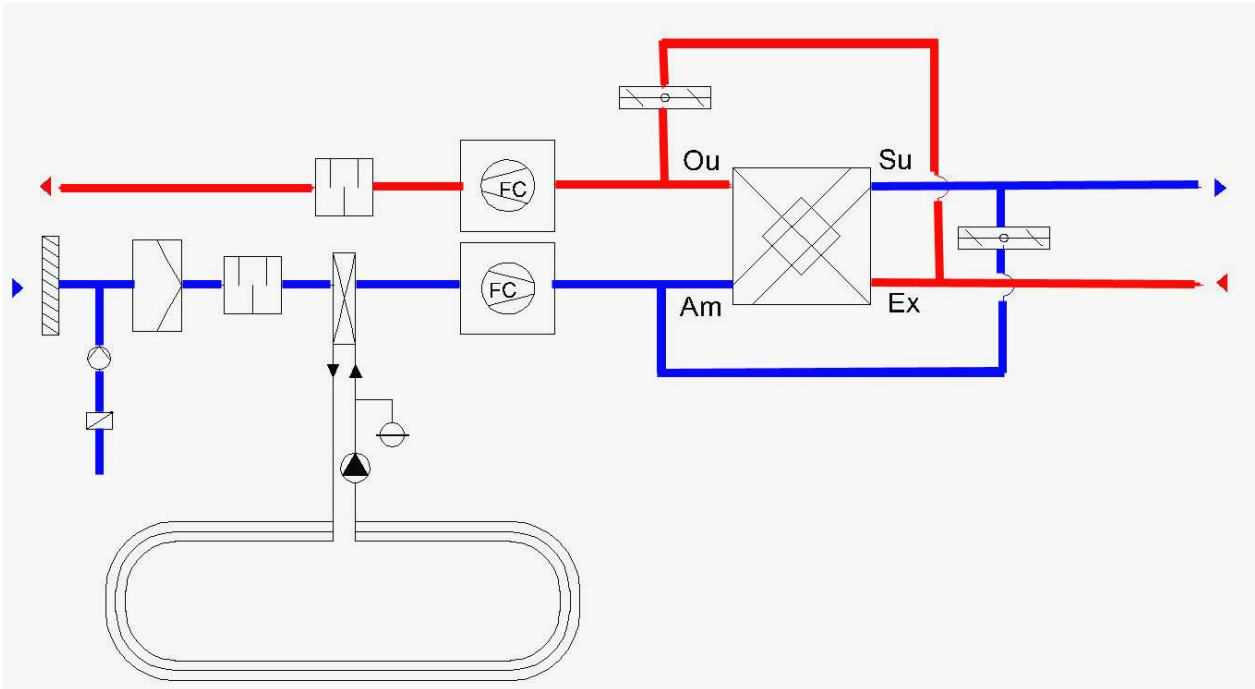


Figure 2: System drawing of horizontal absorbers in the rehabilitated office.

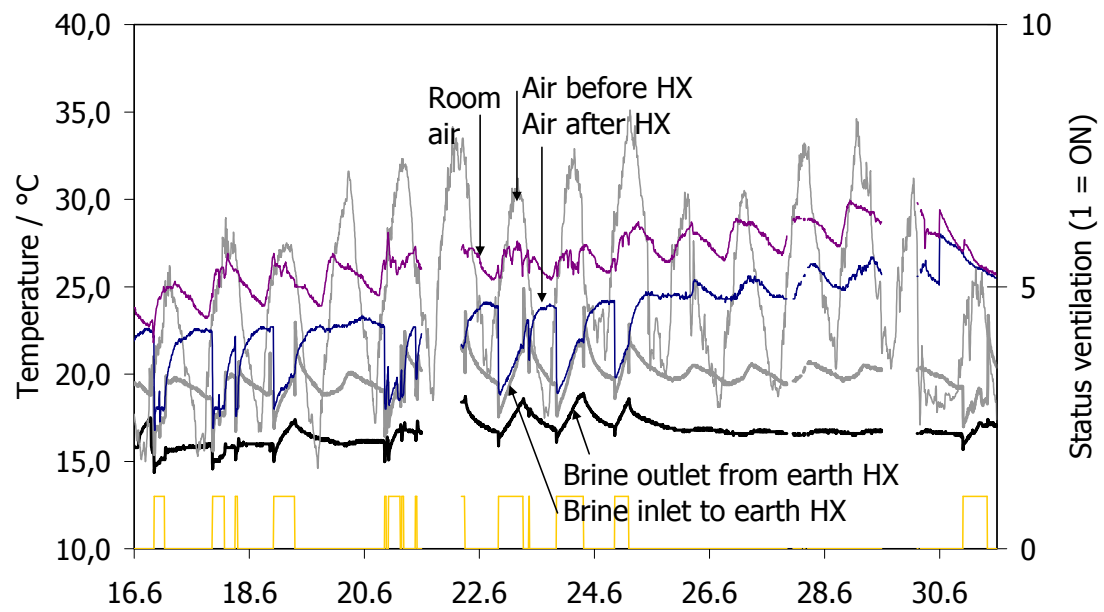


Figure 3: Temperature levels of ventilation air before and after the geothermal heat exchanger during a hot fortnight in summer 2005. The operation time of the ventilation system is also shown (status=1 means that the system is ON).

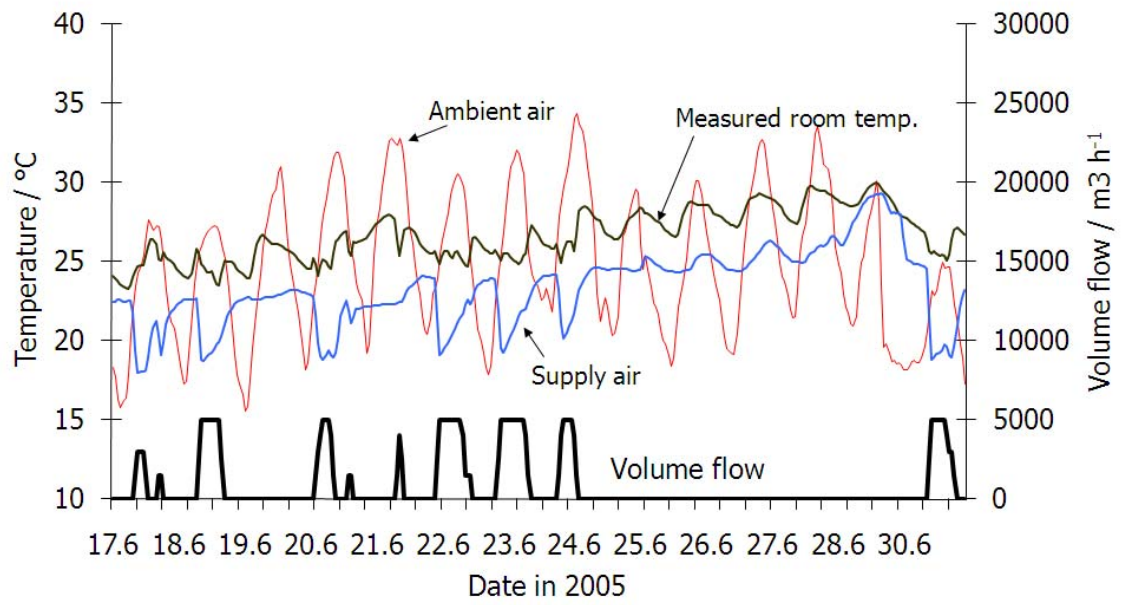


Figure 4: Measured ambient, supply air and room temperatures during a hot fortnight in summer 2005 with geothermal cooling only. The volume flow of the ventilation system is shown.

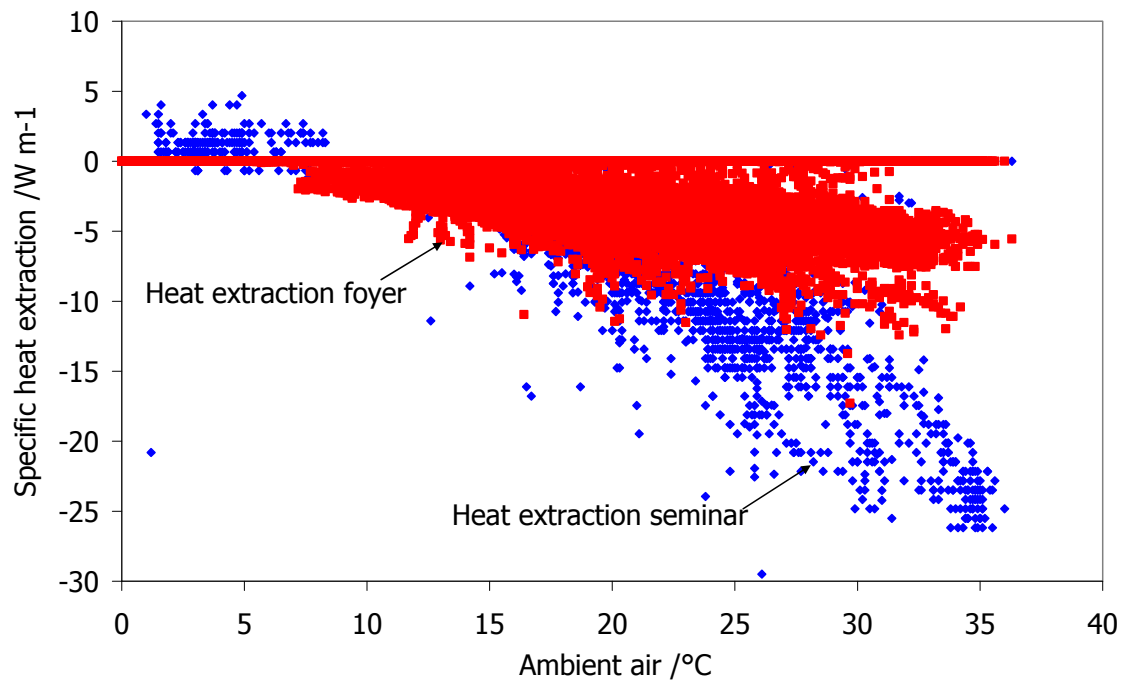


Figure 5: Power dissipated per meter of ground heat exchangers for the two operation modes floor cooling and ventilation system supply in summer 2006

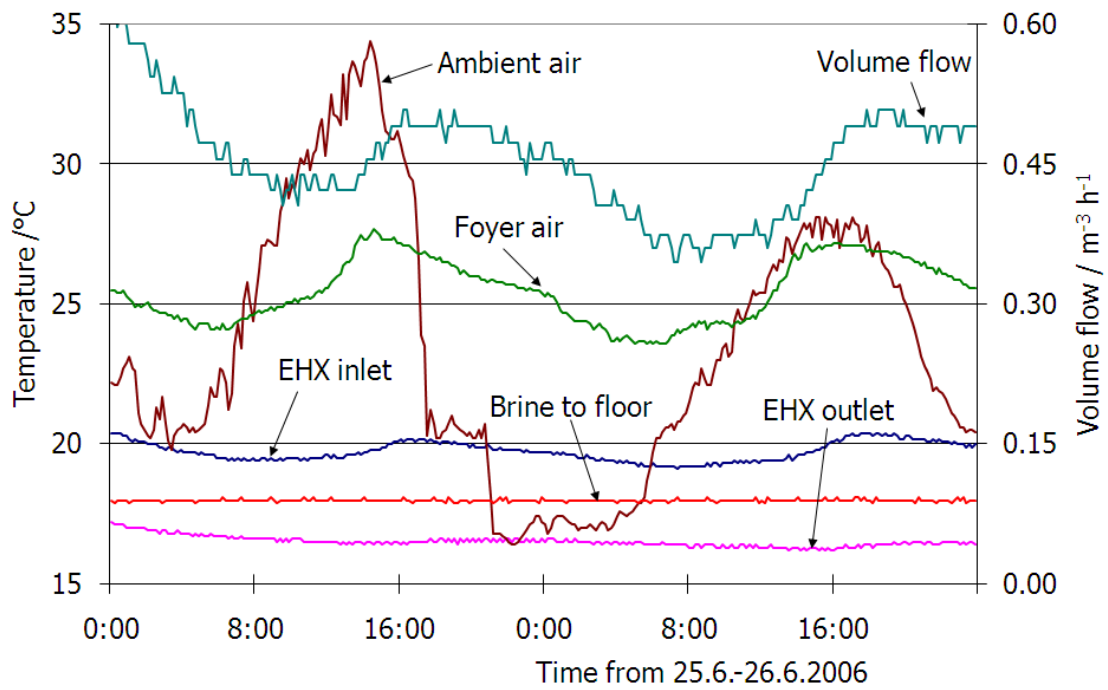


Figure 6: Temperature levels and volume flows of earth heat exchangers and foyer room cooled by ground concrete floor cooling system

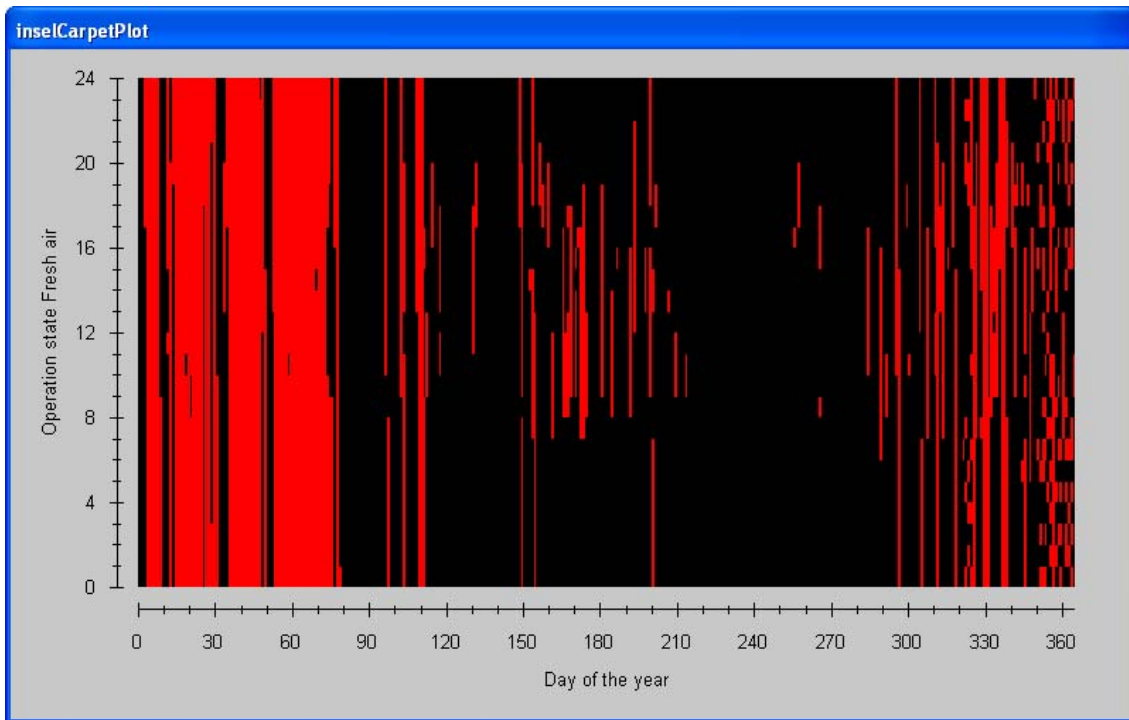


Figure 7: Operating hours of ventilation system in 2005

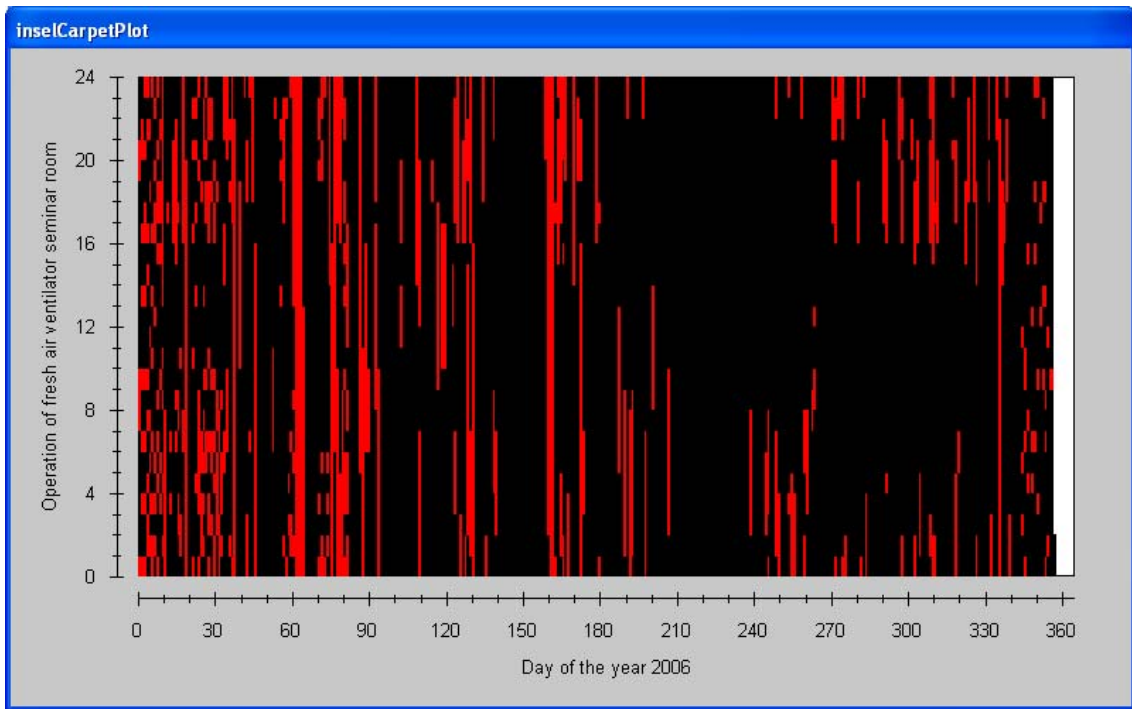


Figure 8: Operating hours of ventilation system in 2006

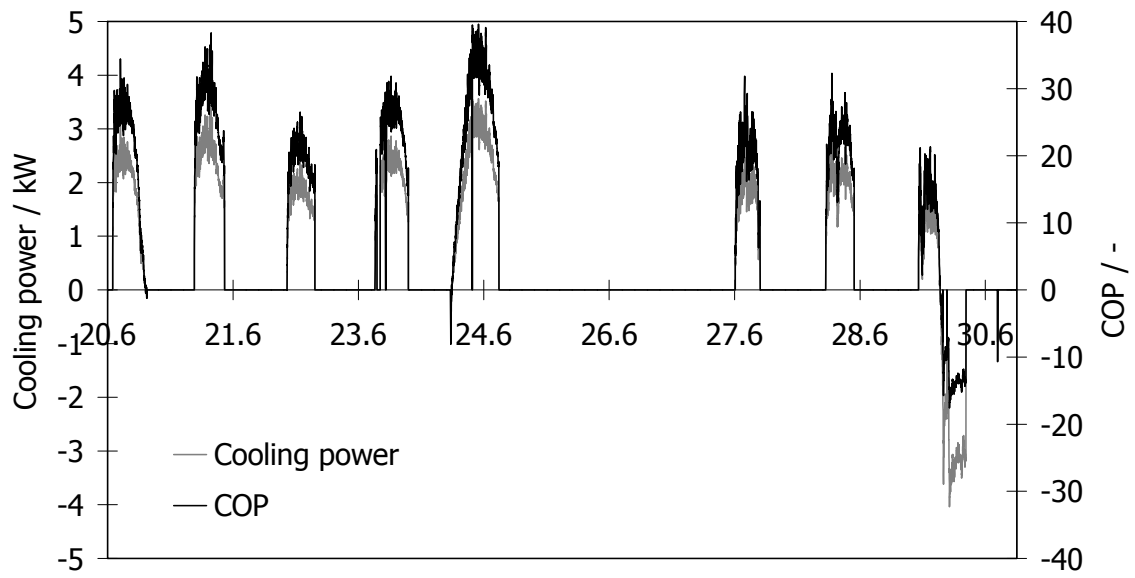


Figure 9: Cooling power and COP of horizontal earth heat exchanger for a hot fortnight in 2005

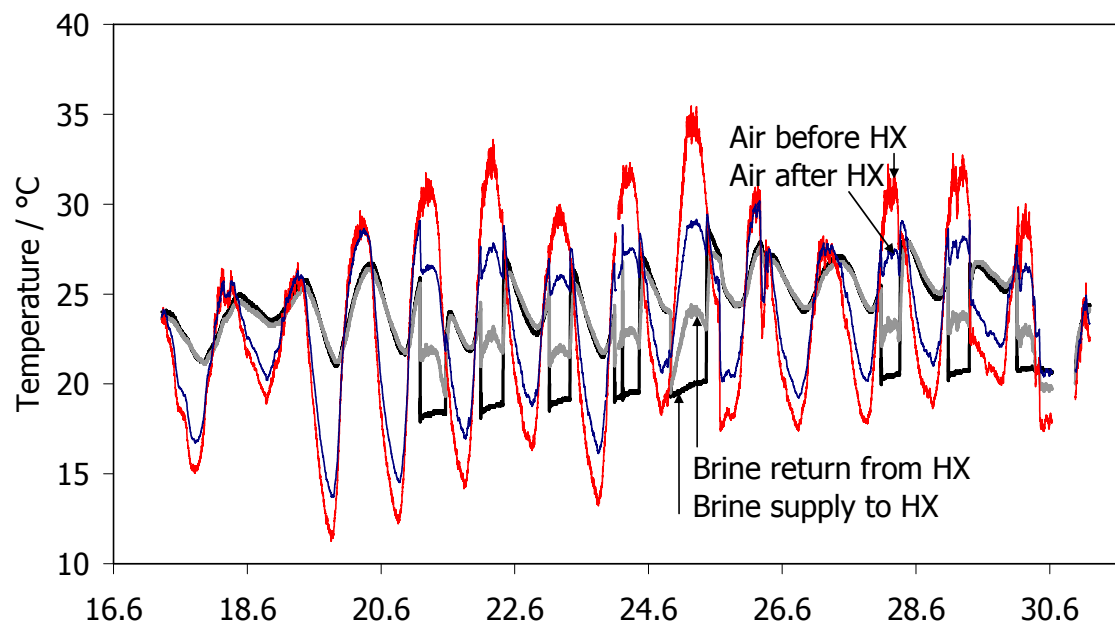


Figure 10: Temperature levels of earth heat exchanger and supply air in the horizontal geothermal system in 2006

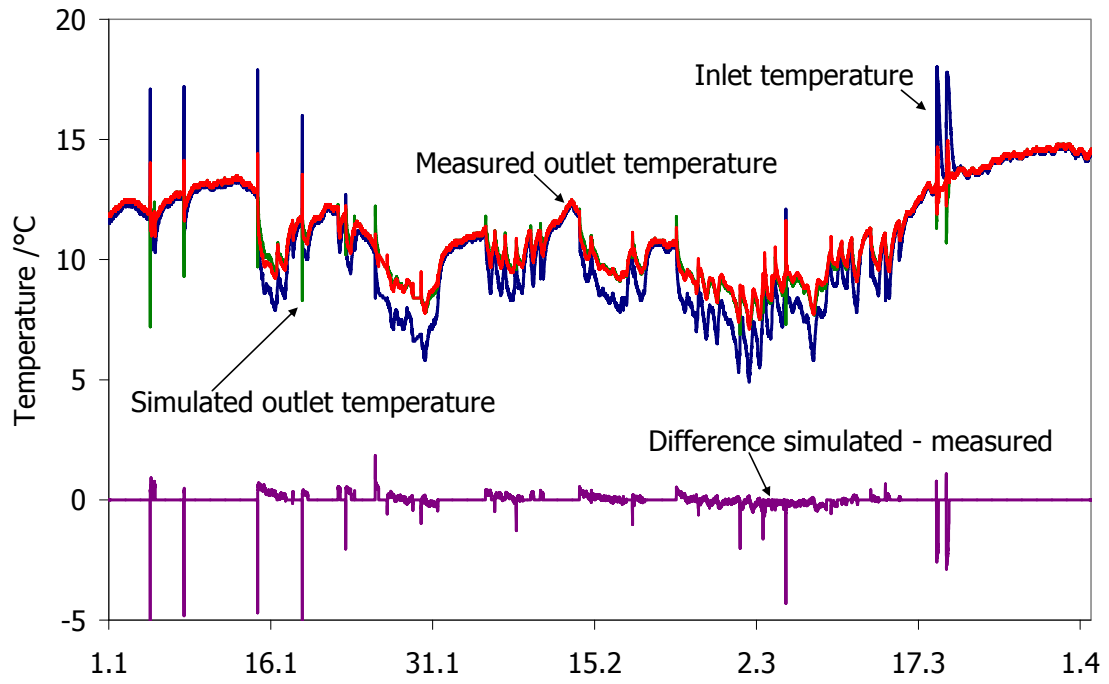


Figure 11: Measured and simulated temperature levels and temperature difference for winter operation of the heat exchanger with ventilation air preheating.

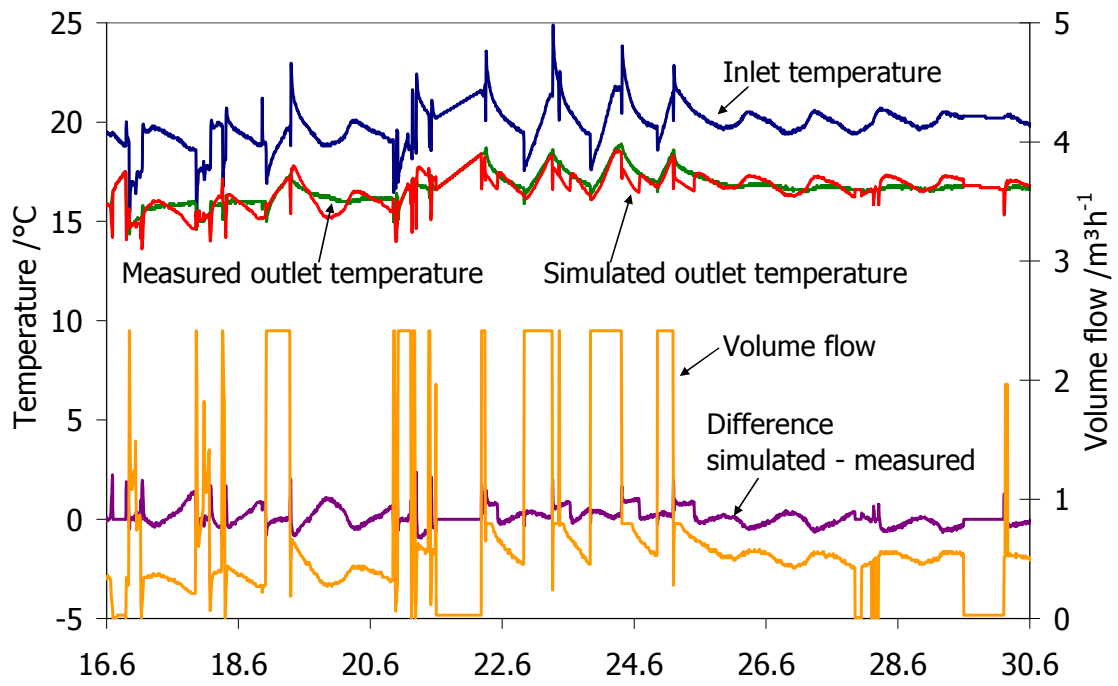


Figure 12: Measurement and simulation results of Solar Info Centre vertical heat exchanger in cooling mode

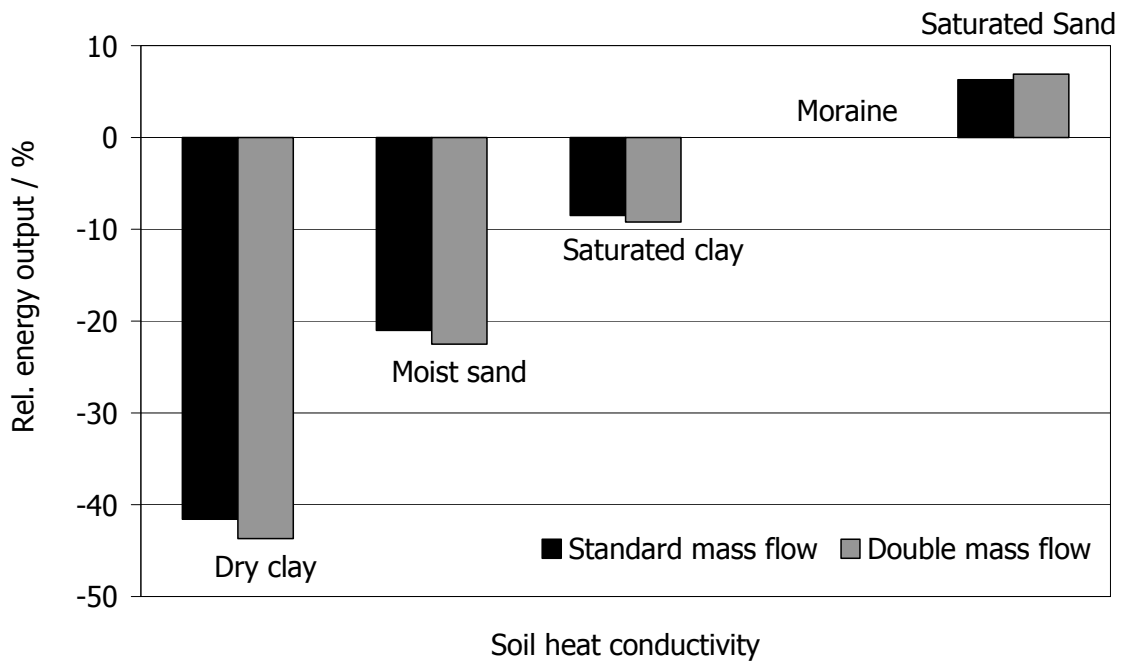


Figure 13: Relative change of energy output for different soil conductivities. The operating conditions were identical to the Solar Info Centre, which has a moraine soil type.

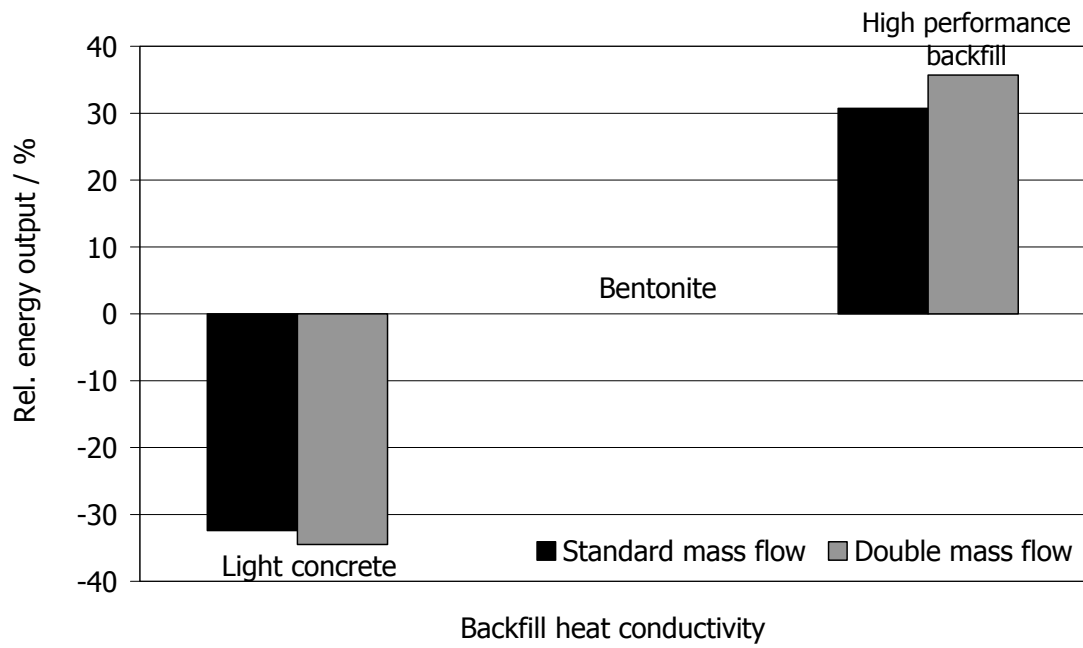


Figure 14: Relative change of energy output for different backfill heat conductivities. The reference condition of the Solar Info Centre heat exchanger is a bentonite.

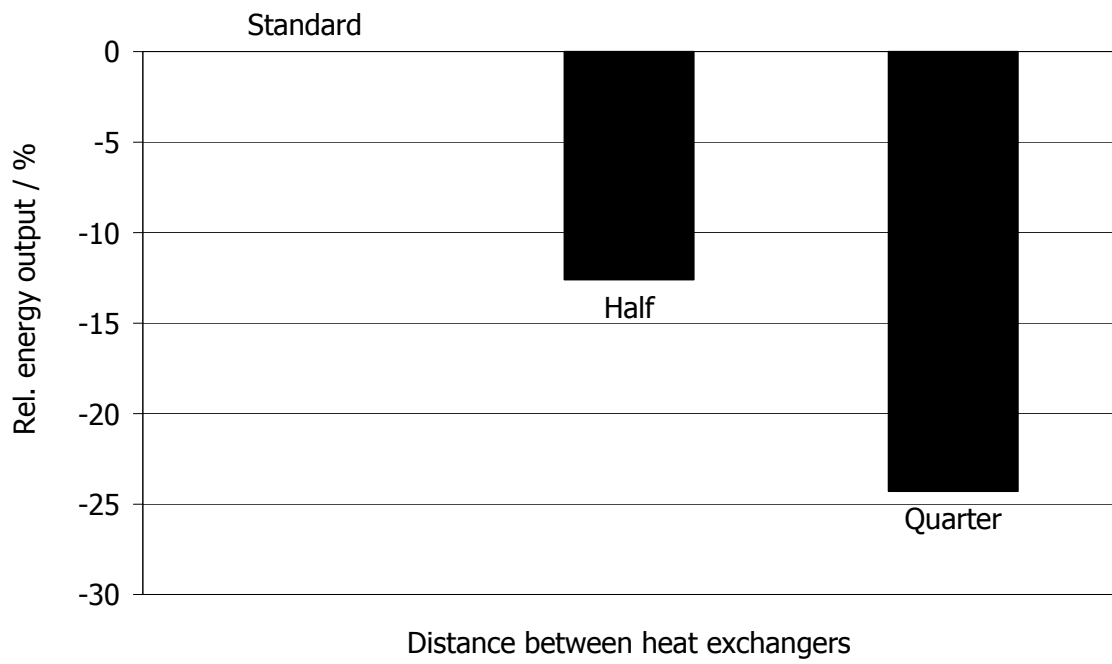


Figure 15: Relative change of energy output for different earth heat exchanger distances. The standard distance is 6 m.

Tables

Year	Cooling / kWh	Heating / kWh	COP _c	COP _h	Hours Cooling seminar	Hours Cooling floor	Hours heating
2005	2759	2846	20,1	12,8	233	2289	856
2006	4873	246	13,5	5,2	327	2911	289

Table 1: Summary of performance results for the vertical heat exchangers in the Solar Info Centre Freiburg.

Night switch off	Savings / kWh	Savings / %
21.00h - 7.00h	840	42
22.00h - 6.00h	672	34
23.00h - 5.00h	503	25

Table 2: Electricity savings for time controlled ventilation system.

Location	Tamb / °C	Tmax / °C	Pmean / W m ⁻¹	Pmin / W m ⁻¹	Pmax / W m ⁻¹	Etot / MWh	Cost / €kWh ⁻¹
Madrid	13.9	19.4	20.0	17.5	54.0	11.6	0.31
Sevilla	18.8	21.0	8.0	7.0	21.3	4.6	0.78
Bangkok	28.1	-	-	-	-	-	-
Crete	19.1	21.1	7.3	6.3	19.3	4.1	0.86
Athens	18.3	20.8	9.0	8.0	24.7	5.3	0.68

Table 3: Cooling power and cooling costs for different climatic boundary conditions.

Location	T _{inl} / °C	T _{max} / °C	P _{mean} / W m ⁻¹	P _{min} / W m ⁻¹	P _{max} / W m ⁻¹	E _{tot} / MWh	Cost / €kWh ⁻¹
Crete	20.0	19.7	2.3	2.0	6.0	1.3	2.78
Crete	21.0	20.4	4.8	4.0	12.7	2.7	1.32
Crete	22.0	21.1	7.3	6.3	19.3	4.1	0.86
Crete	23.0	21.7	9.8	8.5	26.0	5.6	0.64
Crete	24.0	22.4	12.3	10.5	32.7	7.0	0.51
Crete	35.0	29.8	39.7	34.5	106.0	22.8	0.16
Crete	40.0	33.2	52.2	45.4	139.4	30.0	0.12

Table 4: Cooling power and costs of vertical geothermal heat exchangers for different inlet temperatures.