Potential of geothermal heat exchangers for office building climatisation

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ABSTRACT

Low depth geothermal energy can be efficiently used as a heat sink for building energy produced during summer. In the current work, several geometries of geothermal heat exchangers implemented in office building climatisation projects are evaluated for their energetic performance. For all geometries, simulation models were developed and validated using the experimental data, so that parameter studies could be carried out. A main result of the performance analysis is that the ground coupled heat exchangers have excellent coefficients of performance ranging from 20 – 50 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 is often lower than assumed in the planning phase. In the projects evaluated, the heat dissipation 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 power dissipation varies by plus/minus 30% depending on the soil conductivity. The heat conductivity of vertical tube filling material is very important, as the power dissipation changes by plus/minus 30% for different materials.

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.

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 (2000), 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. Examples are given by Fink et al. (2002).

In Germany, vertical pipes up to a depth of 100 meters are increasingly used for closed - loop direct cooling of buildings, with water as the heat transfer fluid. 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 inside the building using either activated concrete slabs with buried pipes or by a ventilation system, in which the air is cooled by the water using an additional heat exchanger.

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, 2004). 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. This 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. However, the possibility of this approach in India is reported by Kumar et al. (2003).

In this work, summer performance data has been analysed for several large office building projects in Germany. Vertical heat exchangers for ventilation systems and floor cooling systems were implemented in the Solar Info Center in Freiburg, a low depth horizontal heat exchanger was used in a passive standard office building in Tübingen, and foundation piles with water circulation were used in a large office and atrium building in Stuttgart.

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. 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$^3$ up to a maximum volume flow of 5100 m² 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 a 800 m² activated concrete floor cooling system. Due to the very high investment costs of the ground heat exchangers and the low operating times of the ventilation system (214 cooling hours in summer 2005, 327 hours in 2006), 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$^-2$K$^-1$ 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. The volume flow of air during daytime is about 1750 m³ h$^{-1}$. The specific electricity consumption is 0.15 W / (m³ h$^{-1}$) 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 power delivered for the two operation modes ventilation air cooling and concrete floor cooling were measured during two years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cooling / kWh</th>
<th>COP$_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>2759</td>
<td>24,0</td>
</tr>
<tr>
<td>2006</td>
<td>4873</td>
<td>24,7</td>
</tr>
</tbody>
</table>

The thermal power dissipated by the heat exchangers is rather low with a maximum of about 26 W per meter, in case the ventilation system is operating. If the floor cooling system is used, the high pressure drop leads to very low volume flow rates and thus to very low power values.

Figure 1: Power dissipated per meter of ground heat exchangers for the two operation modes floor cooling and ventilation system supply in summer 2006.

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. The coefficients of performance are good due to the low pressure drop across the heat exchanger and the low power consumption of the geothermal heat exchanger pump of 170 W.

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.

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.

The ambient air can be cooled down by as much as 7 K in the heat exchanger. However, supply air to the building is still at 28°C during midday. The soil temperature rises up to nearly 20°C at the end of June. The logarithmic average temperature difference of brine and air across the heat exchanger is about 6.3 K.
4. THEORETICAL MODEL

A 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.

4.1 Parameter study results

By means of the validated simulation model, 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 W m$^{-1}$ K$^{-1}$, representing dry clay, to 2.5 W m$^{-1}$ K$^{-1}$ for water-saturated sand. As can be seen from Figure 2, 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 (1997) and disagreeing with Zhang and Murphy (2003).

![Figure 2 Influence of soil heat conductivity on energy output](image)

Borehole backfill heat conductivities of 0.8 (light concrete), 1.6 (Bentonite) and 3.2 W m$^{-1}$ K$^{-1}$ (high performance backfill) were investigated in the next step. Although light concrete is rarely used as backfill material, it was included in this study for comparison. From Figure 3 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.

![Figure 3 Influence of backfill heat conductivity on energy output](image)

Regarding the mutual distance of vertical ground heat exchangers, Zhang and Murphy (2003) 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 6m. This finding is backed up by the current numerical parameter study. Originating in 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.

![Figure 4 Influence of heat exchanger distance on energy output](image)

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 to a constant of 22°C, representing the output of a thermally activated concrete slab from the building. The table below shows the investigated locations, the average ambient temperature (Tamb), the maximum outlet temperature of the ground heat exchangers (Tmax) and the minimum achievable cooling power (mcp) at a volume flow of 2.4 m³ h⁻¹.

<table>
<thead>
<tr>
<th>Location</th>
<th>Tamb / °C</th>
<th>Tmax / °C</th>
<th>mcp / kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madrid</td>
<td>13.9</td>
<td>18.8</td>
<td>8.6</td>
</tr>
<tr>
<td>Sevilla</td>
<td>18.8</td>
<td>20.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Bangkok</td>
<td>28.1</td>
<td>26.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Crete</td>
<td>19.1</td>
<td>20.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Athens</td>
<td>18.3</td>
<td>20.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 2: Simulation results for different climatic boundary conditions

Obviously, the climate in the area of Bangkok is not suitable for direct geothermal cooling. 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. 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., 2002).

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, both water and air based, reach excellent annual coefficients of performance above 20 using a low pressure drop design. The power dissipation measured per meter of heat exchanger was 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 power was limited mainly by the low cooling energy 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 dissipatio-

REFERENCES