Cooling strategies, summer comfort and energy performance of a rehabilitated passive standard office building

Ursula Eicker
Research Centre zafl.net, University of Applied Sciences Stuttgart,
Schellingstrasse 24, D-70174 Stuttgart,
Tel +49 711 8926 2831, Fax +49 711 8926 2698, Email: ursula.eicker@hft-stuttgart.de

Abstract

One of the first rehabilitated passive energy standard office buildings in Europe was extensively monitored over two years to analyse the cooling performance of a ground heat exchanger and mechanical night ventilation together with the summer comfort in the building. To increase the storage mass in the lightweight top floor, phase change materials (PCM) were used in the ceiling and wall construction. The earth heat exchanger installed at a low depth of 1.2m has an excellent electrical cooling coefficient of performance of 18, but with an average cooling power of about 1.5 kW does not contribute significantly to cooling load removal. Mechanical night ventilation with two air changes also delivered cold at a good coefficient of performance of 6 with 14 kW maximum power. However, the night air exchange was too low to completely discharge the ceilings, so that the PCM material was not effective in a warm period of several days. In the ground floor offices the heat removal through the floor to ground of 2 – 3 W m⁻² K⁻¹ was in the same order of magnitude than the charging heat flux of the ceilings. Despite the limited heat removal the summer comfort level was acceptable with about 10% of all office hours above 26°C. The energy performance of the building is excellent with a total primary energy consumption for heating and electricity of 107 – 115 kWh m⁻² a⁻¹, without computing equipment only 40 – 45 kWh m⁻² a⁻¹.

Keywords: passive cooling, earth heat exchanger, summer building performance, PCM

Introduction

Existing office buildings today often have a primary energy consumption of several hundred kilowatthours per square meter and year. In moderate European climates, a large fraction of the consumption is due to heating energy, although in modern office buildings electricity consumption starts to dominate the total consumption. Many demonstration projects have shown that existing buildings can be refurbished to reach passive building standards, i.e. very low heating energy demand. The energy concept always involves an extremely well insulated building skin and a mechanical ventilation system with heat recovery. The fresh air is often preheated or precooled with ground heat exchangers. For summer climatisation passive buildings rely on the ground heat exchanger as a daytime
heat sink and on night ventilation for cooling.

The main question for summer comfort is whether these concepts are sufficient to maintain summer comfort. In the UK, the Chartered Institution of Building Services Engineers CIBSE suggested that for acceptable thermal comfort the internal temperature should not exceed 25°C for more than 5% of occupied hours. In a more recent technical memorandum (CIBSE, 2005) [3] and Design Guide A (CIBSE, 2006) [4] a limit of no more than 1% of occupied hours over a 28°C dry resultant temperature is given. This means that in central London locations with annual average temperatures 2 K higher than at the city edges, auxiliary cooling has to be used to support natural ventilation strategies (Short et al, 2009) [15]. In Germany, the allowed exceedance of room temperature levels above 25 –27°C (depending on the climatic zone) is 10% of all working hours (DIN 4108-2). In the US, the ASHRAE Standard 55-2004 places an upper limit on the allowable operative temperature of 28°C, or 27°C when the moisture content increases to the limiting value of 12 g kg⁻¹ of dry air (ASHRAE, 2004) [1]. For naturally ventilated buildings an adaptive comfort model can be used, which is also defined in the European standard EN 15251. Here 80% and 90% acceptability limits of indoor operative temperature are proposed as a function of mean monthly outdoor air temperature. Generally speaking, the temperature requirements are relaxed. Investigations are carried out, whether these higher admissible temperature levels decrease office working performance and whether the adaptive comfort model is also useful for mechanically ventilated and cooled buildings. Results by Toftum et al (2009) [16] in Singapore climate showed that performance decrease was negligible in buildings without mechanical cooling.

Summer comfort measurements in passive standard residential buildings in the European CEPHEUS project showed that room temperatures were between 22 and 25°C on average and 95% of all hours were below 27°C maximum for locations in Germany and Austria (Feist et al, 2005) [8]. The room comfort conditions were generally described as agreeable. Air conditioned buildings on the other hand often face subjective thermal comfort problems in summer, although measured temperature, humidity or air movement levels are within the acceptable comfort range (Hens, 2009) [9].

Room temperature levels are a function of internal and external loads and obviously of meteorological conditions. Zimmermann states that daily cooling loads should not exceed 150 Wh m⁻² for night ventilation to be efficient, and that night time ambient temperature should be at least 5 K below room temperature for more than 6 h at air exchange rates of 5 h⁻¹ (Zimmermann et al, 2003) [20]. If summer nights are very cool with ambient temperatures below 16°C, loads up to 250 Wh m⁻² day⁻¹ can be removed. Shaviv claims that 20 air changes per hour are needed for locations in Israel and recommends forced night ventilation strategies, if natural ventilation does not reach this air exchange rate (Shaviv et al, 2001) [14]. Measured night air changes at low energy office buildings such as the Fraunhofer Institute of Solar Energy in Freiburg and the railway building DB Netz AG Hamm on the other hand are only 2 – 5 h⁻¹ (Pfaafferott, 2003 and 2004) [12], [13]. This led to only 1.2 K room temperature decrease
during the working hours, if passive cooling alone was used. Investigations on one of the first passive office buildings in Germany showed that despite high measured nightly air changes above 5 h\(^{-1}\) the room air temperature decrease was only between 2 and 3 K although the ambient air temperature swing was 8 – 10 K (Eicker et al, 2006) [6].

In addition to night ventilation, ground heat exchangers contribute to the removal of cooling loads and are often used as air to earth heat exchanger for the required ventilation air. Three year measurements and simulation of an air to ground earth heat exchanger in a passive standard office building in southern Germany showed an excellent performance with COP’s between 35 and 50. Due to the limited fresh air volume flow in such buildings, the earth heat exchanger only removed about 18% of the total internal loads (Eicker et al, 2009) [7].

A further issue for passive buildings concerns the role of transmission losses for summer comfort. In refurbished buildings, some parts of the building skin cannot be insulated as well as new buildings. In case of the floor plate towards ground this can be an advantage, as this can remove cooling loads in summer. Obviously, in winter the limited insulation increases heating energy demand. There is also still a discussion ongoing whether higher insulation standards lead to increased summer cooling loads (for example Yilmaz, 2007) [18]. This can only be true if the average ambient temperature is lower than the indoor temperature in summer, which is not the case in many southern European or even hotter climates. Quite on the contrary, high insulation standards reduce heat gains from transmission caused by short wave irradiance absorption as well as convective and radiative gain during the day. During the night, ventilation then removes the heat gains much more efficiently than by transmission losses. A high thermal mass of the walls helps to maintain more stable indoor temperatures, but this should not be confused with total heat transmission reduction, which can only be achieved by insulation materials (Zhu et al., 2009) [19].

Light weight constructions have to cope with very dynamic temperature changes if external or internal loads increase. If all storage masses have been charged, room temperatures then increase strongly. Phase change materials (PCM) have the potential to increase the heat capacity, but need to be efficiently discharged to use the full latent heat capacity. For a given temperature difference the heat stored or released consists of the sensible heat up to the melting or crystallisation temperature and the latent heat for the phase change. In order to be useful to stabilise the room temperature within the thermal comfort range below 26°– 27°C, the melting temperature of the PCM needs to be some degrees lower. However, if the melting temperature is too low, night ambient air temperatures might not be low enough to allow discharging. Different materials were analysed by Butala and Stritih (2009) [2] with melting points between 19 and 24°C. 3.6 kg of paraffin with a melting point of 22°C and a latent heat of 172 kJ/kg was solidified using night ventilation, here with very low ambient temperatures below 15°C and could take up daily heat for about 4 hours, when charged with 26°C room air at a high air speed of 1.5 m s\(^{-1}\). The heat transfer was supported by a fin structure, into which the paraffin was placed. The testing conditions are not very relevant for typical building operation, where
Figure 1: Rehabilitated passive standard office building in Tübingen.

Night cooling should work at higher ambient temperatures and where the daytime charging of the material takes place at very low air speeds. More realistic conditions were used by Kuznik and Virgone (2009) [11], who tested wallboards with 60% microencapsulated paraffin in a climatic chamber with step change or sinusoidal temperature variations and a mean internal air speeds of $0.5 \text{ m s}^{-1}$. They showed a hysteresis effect, which aggravates the use of the material in naturally ventilated buildings: the melting process had a peak temperature of $22^\circ\text{C}$ and the solidification of $19^\circ\text{C}$. This means that night discharging requires significantly lower air temperatures than daytime charging temperatures.

The purpose of this work is to analyse the summer performance of a highly insulated passive standard office building with mechanical night ventilation, ground heat exchange and PCM storage.

Building description and cooling concepts

The passive energy office building in Tübingen/Germany has been rehabilitated and is now occupied by the engineering company ebök GmbH and is part of a former military ground called the Thiepval barracks (see figure 1).

The building was rehabilitated to reach passive building standard: roof insulation with 30 cm cellulose material at a heat conductivity $\lambda=0.04 \text{ W m}^{-1}\text{K}^{-1}$, wall insulation 24 cm with $\lambda=0.035 \text{ W m}^{-2}\text{K}^{-1}$, triple glazed windows with polycarbonate spacers and a mixed wood - polyurethane frame with a $U$ - value of $0.8 \text{ W m}^{-2}\text{K}^{-1}$ and a $g$ - value of 0.52. The floor insulation in the existing building could only be 7.5 cm (3 cm perlites with $0.05 \text{ W m}^{-1}\text{K}^{-1}$ and 4.5 cm polyurethane with $0.025 \text{ W m}^{-1}\text{K}^{-1}$), as the room height in the ground floor is low. In addition a low cost perimeter insulation with 1.5 m height and 20 cm thickness was chosen to prevent excessive ground losses. The components are
<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Thickness (cm)</th>
<th>Conductivity (W m$^{-1}$ K$^{-1}$)</th>
<th>U-value (W m$^{-2}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>Cellulose</td>
<td>30</td>
<td>0.04</td>
<td>0.138</td>
</tr>
<tr>
<td>Wall</td>
<td>Polystyrene</td>
<td>24</td>
<td>0.035</td>
<td>0.136</td>
</tr>
<tr>
<td>Floor</td>
<td>Perlite</td>
<td>3</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4.5</td>
<td>0.025</td>
<td>0.39</td>
</tr>
<tr>
<td>Perimeter</td>
<td>Expanded polystyrene</td>
<td>20</td>
<td>0.04</td>
<td>0.20</td>
</tr>
<tr>
<td>Window</td>
<td>Triple glazed, polycarbonate spacer, wood - polyurethane frame</td>
<td>20</td>
<td>0.04</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 1: Materials and U values used for the refurbishment.

The building has a useful heated floor area of 833 m$^2$ and a gross room volume of 3724 m$^3$. The window surface area related to the total floor space is moderate at 23%. All workspaces are well daylit and glare is prevented by interior venetian blinds. The installation of an external sun shading system was not possible due to building conservation issues. The artificial lighting via fluorescent tubes with electronic balasts is daylight controlled and in addition switched by presence detectors.

The building 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. A natural ventilation concept was difficult to implement due to the low height of the building, resulting security problems with window openings and restrictions due to the protection of listed buildings (window partitions not possible). Therefore the mechanical ventilation system has been sized to provide up to 4000 m$^3$ h$^{-1}$ (about two air changes) for night ventilation at a low pressure drop. The specific electricity consumption for night ventilation is a total of 0.48 W / (m$^3$h$^{-1}$) for both supply and exhaust fan (measured results were 1072 W for the supply fan at 4021 m$^3$ h$^{-1}$ and 850 W for the exhaust fan with a slightly lower volume flow of 3600 m$^3$ h$^{-1}$). This compares to daytime ventilation with a reduced volume flow of 2000 m$^3$ h$^{-1}$ and a total electricity demand for the two fans of 0.17 W / (m$^3$h$^{-1}$). The building is very airtight with a measured air change n$_{50}$ of only 0.2 h$^{-1}$ at 50 Pa pressure difference between inside and outside. The average winter heat recovery efficiency measured was 0.72 when calculated from the difference of room exhaust air temperature $T_{ex}$ and outlet temperature $T_{out}$ and 0.86 when obtained from the difference between supply air temperature $T_{su}$ and ambient air temperature $T_{amb}$.

$$\Phi_{ex} = \frac{T_{ex} - T_{out}}{T_{ex} - T_{amb}}$$

$$\Phi_{su} = \frac{T_{su} - T_{amb}}{T_{ex} - T_{amb}}$$
The effective efficiency $\eta_{\text{eff}}$ includes the heat produced by the electrical driving power of the fans and is 0.76.

The net construction sum for the refurbishment was 810.000 Euro, of which 60.000 Euro (or 75 Euro per square meter) were additional costs to reach the passive building standard. An evaluation of economic efficiency was done by (Werner, 2005) [17]. After 30 years the additional investment costs result in a net present value of 120.000 Euros at an interest rate on capital costs of 5%. The saved energy costs due to the extra measures reach the break even point after 16 years at an annual energy price increase of 11%.

**Overall performance and meteorological boundary conditions**

The building was monitored for two years and showed excellent performance results, which correspond well to the planned values. The heating demand calculated from monthly energy balances was 22.4 kWh m$^{-2}$ a$^{-1}$, the measured consumption was 22.9 kWh m$^{-2}$ a$^{-1}$ in 2005 and 24.8 kWh m$^{-2}$ a$^{-1}$ in 2006 (without warm water). The predicted electricity consumption was 27.7 kWh m$^{-2}$ a$^{-1}$ including computing equipment and measured values were between 27.7 and 29.6 kWh m$^{-2}$ a$^{-1}$ (see figure 2). Converted to primary energy with a factor 2.7 for electricity and 1.1 for gas this results in a total consumption between 107 and 115 kWh m$^{-2}$ a$^{-1}$ primary energy. The current legislation in Germany only regulates consumption of heat, cold, technical supply electricity and lighting. Within these categories the building only consumes 40 kWh m$^{-2}$ a$^{-1}$, whereas more than 300 kWh m$^{-2}$ a$^{-1}$ would be allowed for such a refurbishment project! The primary energy calculation method proposed by the new standard DIN 18599 exceeds the real consumption by 240%, whereas the often used method of the passive building planning software deviates only 10% from the measured consumption (Kirtschig et al., 2008 [10]).

46% of the total end energy is used for heating and warm water and 54% for electricity. The electricity consumption is dominated by computing equipment (73% of total electricity consumption). About half of the computing equipment consumption is due to personal computers and monitors, the other half is split rather equally between server consumption and other equipment such as copying and fax machines. The technical supply electricity is dominated by the consumption of the ventilation system (76%), the other 24% are caused by the heating pump (17%) and the circulation pump of the geothermal heat exchanger (7%).

The monthly mean temperatures and irradiance values measured during the two monitoring years correspond well to the long term mean values during the winter months. The minimum mean daily temperature measured in January
Figure 2: Measured final energy consumption and resulting primary energy consumption for the years 2005 and 2006.

2005 was - 14.4°C However, during summer, the mean monthly temperature levels were 3 – 5 K higher than average (see table 2). The highest mean daily temperature was 38.6°C in July 2006. If mean monthly temperatures during summer are above 18°C, it is acceptable within German regulations to exceed 27°C room temperature during 10% of all office hours. The discrepancy between longterm average temperature levels and measured values during the last years is an often observed problem for building cooling load simulations and should be carefully considered when designing passive or active cooling systems.

Summer performance results

Mechanical ventilation concept

The ebök building in Tübingen uses active ventilation for supply and exhaust air. During the night a volume flow up to 4000 m³ h⁻¹ of ambient air is injected into the building for cooling purposes, which corresponds to two air exchanges per hour. As can be seen from figure 3, the cooling loads of the day cannot be fully removed during night times, resulting in room temperatures above 26 °C in the morning hours of the second week of a rather moderate warm period. This means a drop of only 2 – 3 K compared to the preceeding evening.

A maximum of 147 Wh m⁻² night⁻¹ of internal loads are removed during the evaluated time (last two weeks of June 2005) while the average is about 85 Wh m⁻² night⁻¹. The peak cooling power is nearly 14 kW with an average of 7.4 kW. Mechanical night ventilation obviously requires electrical power for the fans, which is significant even if highly efficient fans are used. In the ebök building, the mean COP for night ventilation during the two week measurement
Table 2: Monthly mean temperatures according to DIN 4108 - Part 6 for the Southern German Region 11 and measured temperature levels.

<table>
<thead>
<tr>
<th>Month</th>
<th>Long term average / °C</th>
<th>Measured 2005</th>
<th>Measured 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>-0.4</td>
<td>1.8</td>
<td>-1.9</td>
</tr>
<tr>
<td>Feb</td>
<td>0.8</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Mar</td>
<td>4.2</td>
<td>5.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Apr</td>
<td>8.0</td>
<td>12.1</td>
<td>9.1</td>
</tr>
<tr>
<td>May</td>
<td>12.5</td>
<td>14.9</td>
<td>15.2</td>
</tr>
<tr>
<td>Jun</td>
<td>15.7</td>
<td>19.8</td>
<td>18.8</td>
</tr>
<tr>
<td>Jul</td>
<td>17.7</td>
<td>19.5</td>
<td>23.5</td>
</tr>
<tr>
<td>Aug</td>
<td>17.0</td>
<td>17.5</td>
<td>16.1</td>
</tr>
<tr>
<td>Sep</td>
<td>13.7</td>
<td>16.1</td>
<td>18.1</td>
</tr>
<tr>
<td>Oct</td>
<td>9.0</td>
<td>11.8</td>
<td>13.0</td>
</tr>
<tr>
<td>Nov</td>
<td>3.9</td>
<td>4.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Dec</td>
<td>0.6</td>
<td>1.2</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Figure 3: Ambient air and room temperatures in the eboek building during summer 2005.
Figure 4: Cooling power and coefficient of performance of mechanical night ventilation system.

campaign 2005 was 4.0, with a maximum value of 7.8 (see figure 4). The design power of the fans for summer ventilation was 300 W for a total daily volume flow of 2000 m$^3$ h$^{-1}$ and 1100 W for night ventilation with 4000 m$^3$ h$^{-1}$ total flow rate. Measurements of the installed system showed that at 2066 m$^3$ h$^{-1}$ supply air flow and pressure drops of 123 Pa in the supply and 84 Pa in the exhaust channel, the power consumption was 200 W for the supply fan and 155 W for the exhaust fan, i.e. matching closely the design value. The specific total consumption of 0.17 W / (m$^3$ h$^{-1}$) is excellent. During night ventilation with a measured supply air volume flow of 4021 m$^3$ h$^{-1}$ at a pressure drop of 395 Pa, the supply air fan consumed 1072 W, the exhaust air fan at a slightly lower flow and pressure drop (3600 m$^3$ h$^{-1}$ and 356 Pa) required 850 W. The specific total consumption related to the supply air flow is 0.48 W / (m$^3$ h$^{-1}$), still a good value for ventilation systems, but 75% higher than the design value.

Further measurements in several rooms were done in 2006 with a very hot period in July. Internal loads average over 24 hours were only 4 W m$^{-2}$ in the top floor and 5 W m$^{-2}$ in the bottom floor offices. External loads including sun shading systems were 7.5 W m$^{-2}$ on average on the ground floor and 4.6 W m$^{-2}$ on the top floor. The ground floor has a significant heat transfer to the ground due to rather low insulation thickness of the floor (U – value of 0.35 W m$^{-2}$ K$^{-1}$). The measured heat flux via the floor to the earth was between 2 and 3 W m$^{-2}$ on average. This is the same amount than the measured heat flux removed from the ceiling during night ventilation (2.7 W m$^{-2}$ on average). The measured effective discharging time of the ceiling during mechanical night ventilation was about 13 hours with a ceiling temperature decrease of 1.5 K. The main limitation to a more effective night discharging of storage masses is the total air exchange rate, which is limited here to 2 air exchanges per hour. The air outlet injection to the ceiling worked effectively, as can be seen from the
infrared measurements during the day and after a period of night ventilation (see figure 5). Ambient air temperatures during night ventilation were 4.2 K lower than room temperatures and a mean cooling power of 7.6 W m\(^{-2}\) could be achieved (Doose, 2005 [5]).

Strong drops in room temperature were observed, when the user fully opened the windows in the morning (for example on 19.7. in the ground floor west office in figure 6). However, the rapid rise of temperature after closing the windows showed that only the air was cooled, but the storage masses could not be discharged during the time. There is a clear temperature stratification in the building of about 1K for rooms of the same orientation. This can be attributed to a heat flux of 2 – 3 W m\(^{-2}\) via the ground floor and higher storage masses of the ground floor ceiling.

Generally the temperature level at the ceiling near the window is about 1K higher than close to the inner door, but also nearly 1K cooler after night ventilation, as the mechanical ventilation directs the cool air towards the window at the ceiling (see figure 5). The ceiling temperature difference is 3K between day and night. The temperature at the ceiling near the window has a daily maximum at 11:00h, after which external irradiance on the east facade lessens (see figure 7). The operative temperature had a maximum of 27°C for external temperatures up to 35°C. During the heating up phase of the room the average heat flux of the ceiling is –2 W m\(^{-2}\), i.e. there is a net heat flux into the ceiling. During a cooling down period of the room (for example 15.7. – 21.7.2005) the average heat flux is positive at 4 W m\(^{-2}\), i.e. there is a net discharge of the ceiling at night.

The use of phase change materials (PCM) in the gypsum boards of the top floor ceiling and wall (16.2 and 19 m\(^2\)) did not significantly improve the
Figure 6: Ambient and room temperatures in the eboek office building during a hot period in July 2006.

Figure 7: Temperature levels of room surfaces and globe thermometer and heat fluxes to and from the surfaces (positive = heat flux from surface) from 1.7.2006 – 6.7.2006 in a ground floor office.
situation. The melting point is rather high (26°C – 28°C) and the latent heat capacity limited to about 80 Wh m\(^{-2}\). The main problem, however, is again the low heat flux for discharging the PCM boards during the night with a maximum night air exchange of 2.6 h\(^{-1}\). The average nightly heat flux from the ceiling is less than 2 W m\(^{-2}\), corresponding to a total energy removed of 30 Wh m\(^{-2}\). The reference gypsum board without PCM showed a slightly higher temperature swing (0.5 K) and a slightly lower heat removal of 25 Wh m\(^{-2}\) and night. Detailed measurements during a hot week in July 2006 showed that the charging of the PCM material works well with heat fluxes up to 6 W m\(^{-2}\), especially during the morning hours, and that the PCM plates can be charged for a longer time period during the day than the conventional gypsum board. At midday a reduction in heat flux can be observed due to lower internal loads during lunchtime break. After three warm days, the additional charging capacity is exhausted and the PCM ceiling boards behave exactly the same as the gypsum board (see figure 8). This has to be attributed to the insufficient night discharging of the room surfaces. The night supply air temperature levels never drop below 20°C, although ambient air night temperatures are often below 16°C. From ambient air up to the air distribution box after the air handling unit, there is already a temperature increase of 2K. A further 2K temperature increase then occurs until the air outlets are reached. This high night supply air temperature level combined with rather low air exchange rates leads to night heat fluxes of only 1 – 2 W m\(^{-2}\).

Despite the limitations in heat removal through mechanical night ventilation, summer comfort in the eboek building is generally acceptable. In summer 2005 with 220 hours ambient temperatures above 25°C, all rooms had very satisfactory room air conditions, with an average of 4.2% of all office hours above
26°C and in the worst case 7.7% (see figure 9). The total number of working hours was 2871 h.

In summer 2006 with mean ambient temperature in July 4K higher than average, 10.6% of all office hours had more than 26°C room air temperatures with maximum values of 16.6%. With monthly average temperatures of 23.5°C in July, a room air temperature level of 27°C is considered acceptable and here only 6% of all office hours are above 27°C (see figure 10). The temperature distribution of one of the problematic rooms in the top floor during all working hours shows that even if ambient air temperatures are already low, the room temperature is often still above 26°C (see figure 11).

**Performance of horizontal earth-brine-air heat exchanger**

An alternative to the direct air based ground heat exchange is the indirect cooling of air by circulating a brine solution through the ground and then using an air – brine heat exchanger. This system has the advantage of avoiding any hygienic problems, which might occur in air based systems, if condensation water is not reliably removed. Furthermore, pressure drops are usually lower in such liquid based systems. A simple horizontal absorber placed round the perimeter of the building was experimentally analysed in 2005. Five horizontal earth-brine heat exchangers with a length of 100 m each are installed shallow under the soil surface (about 1.2 m depth). During summer they are used for cooling of supply air (see figure 12).

The earth temperature levels were measured for two years directly in between the tubes at 1.2 m depth and a distance of 0.5 m from the building and compared to the undisturbed soil temperatures in 1.2 m and 2.0 m depth. The sensors for the undisturbed temperature measurements were 3.5 m away from the northern

![](image.png)

Figure 9: Hours in the year 2005, where the room air temperature exceeds a given value (only working days from 8 – 18h are considered).
Figure 10: Hours in the year 2006, where the room air temperature exceeds a given value (only working days from 8 – 18h are considered).

Figure 11: Temperature levels in the East facing top floor office rooms in 2006 during the working hours.
Figure 12: System drawing of horizontal heat exchanger coupled to the mechanical ventilation system.

part of the building and 12 m from the neighbouring next building. With increasing depth, the phase shift between ambient air temperature and soil temperature increases up to about 1.5 month at 2 m depth. When the earth heat exchanger is operating, for example for two months during summer 2006, the daily mean earth temperature increases by about 2 – 3 K compared to the undisturbed soil at the same depth (see figure 13). The regeneration of the soil temperature is very fast both in summer and winter.

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 (see figure 14). It can be seen that a phase of heating occurred during the last two days due to the relatively warm soil temperature. This high soil temperature is mainly due to the shallow depth of the pipes.

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 (see figure 15). The logarithmic average temperature difference of brine and air across the heat exchanger is about 6.3 K.

In conclusion, the earth heat exchanger has high coefficients of performance, but contributes only a low cooling power. Detailed measurements in one ground
Figure 13: Measured daily mean temperatures of the soil at 3.5 m distance from the building ("undisturbed") and directly measured between the earth heat exchanger tubes in 1.2 m depth.

Figure 14: Cooling power and coefficient of performance of horizontal brine heat exchanger in the eboek building during summer 2005.
Figure 15: Horizontal heat exchanger performance with temperature levels of the brine supply to the heat exchanger and its return as well as the ambient air before and after the heat exchanger in summer 2005.

Floor room during July 2005 showed that during daytime the cooling power provided by the earth heat exchanger was only 1 W m\(^{-2}\) or 0.6 W m\(^{-2}\) as a 24 hour average.

**Conclusions**

Performance results of one of the best rehabilitated office buildings were presented with a special focus on summer comfort issues. The cooling concept of the building consists of daytime mechanical ventilation with air precooling through a shallow horizontal brine soil heat exchanger. Night ventilation is also mechanical with a rather low air exchange rate of about 2 h\(^{-1}\). In addition the building’s storage mass was increased in the top floor area using PCM plates.

The earth heat exchanger has a very high coefficient of performance of about 18 on average, but contributes only a low cooling power of about 1 – 2 kW. Due to the close proximity and low depth of the tubes, the maximum heat dissipation per meter of tube is only 8 W and the soil temperature levels are rather high. Although the ambient air can be cooled down by as much as 7 K in the heat exchanger, the supply air to the building during hot summer days stays high at 28°C during midday.

The mechanical night ventilation concept also works well with night volume flows up to 4000 m\(^3\) h\(^{-1}\). However, the cooling loads of the day cannot be fully removed with this air exchange. During a two weeks measurement campaign, a maximum of 147 Wh m\(^{-2}\) night\(^{-1}\) of internal load removal was observed while the average is about 85 Wh m\(^{-2}\) night\(^{-1}\). The peak cooling power is nearly 14 kW with an average of 7.4 kW. The mean COP for night ventilation was 4.0,
with a maximum value of 7.8.

The use of phase change materials (PCM) in the gypsum boards of the top floor ceiling and wall did not effectively control the room temperature level. The melting point is rather high (26°C – 28°C) and the latent heat capacity limited to about 80 Wh m⁻². The main problem, however, was the low heat flux for discharging the PCM boards during the night with the limited air exchange rates. The average nightly heat flux from the ceiling is less than 2 W m⁻², corresponding to a total energy removed of 30 Wh m⁻².

It was interesting to notice that the ground floor contributes significantly to the heat removal due to rather low insulation thickness of the floor (U-value of 0.35 W m⁻² K⁻¹). The measured heat flux via the floor to the earth was between 2 and 3 W m⁻² on average. This is the same amount as the measured heat flux removed from the ceiling during night ventilation (2.7 W m⁻² on average).

Despite the limitations in heat removal through mechanical night ventilation, summer comfort in the ebök building is generally acceptable. In summer 2005 with 220 hours ambient temperatures above 25°C, all rooms had very satisfactory room air conditions, with 4.2% of all office hours above 26°C. In summer 2006 with mean ambient temperature in July 4K higher than average, 10.6% of all office hours had more than 26°C room air temperatures.

In conclusion, the building functions well both in summer and winter and has an extremely low total primary energy consumption of 40 – 45 kWh m⁻² a⁻¹ for heating, lighting, ventilation and auxiliary electricity consumption.

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References


