Limits and potentials of office building climatisation with ambient air

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ABSTRACT

One of the first passive energy standard office buildings in Europe was extensively monitored to analyse the summer performance of highly insulated, well sun-shaded and mechanically ventilated buildings. During typical German summer conditions with less than 160 hours outside air temperatures above 25°C these buildings perform excellently during summer, even if the internal loads are rather high. If ambient air temperatures are significantly higher like in summer 2003 with more than 3K higher average temperatures, nearly 10% of all office hours are above 26°C. Detailed measurements showed that the night discharging of heavy thermal masses such as concrete ceilings was not very effective under free convection conditions, although night air changes were always above 5 h^{-1}. Air temperature decreases due to night ventilation are limited to 2-3K.

Three year measurements and simulation of the earth heat exchanger showed, that excellent performance is achieved with COP´s between 35 and 50. Due to the limited fresh air volume flow in such buildings, the earth heat exchanger only removes a fraction of the total loads, here about 18% of the total internal loads.

1. INTRODUCTION

Ambient air can be directly used to cool office buildings through night ventilation or daytime ventilation using earth heat exchangers. Night ventilation can solely rely on buoyancy or cross ventilation driven natural forces, whereas fans are required to drive the volume flow through the earth heat exchanger or to support the night ventilation volume flow control.

For natural ventilation to be efficient, daily cooling loads should not exceed 150 Wh/m² and the 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, 2003). If summer nights are very cool with ambient temperatures below 16°C, internal loads up to 250 Wh/m²d can be removed.

In this work, a highly optimised office building with passive energy building standard in Weilheim/Germany constructed in 1999 has been monitored for three years to experimentally evaluate the performance of both the natural night ventilation concept and the performance of the earth heat exchanger and to compare its performance to literature (photo see Fig. 1). Extensive data sets were recorded including 170 hours of tracer gas measurements for the air exchange rates in the hot summer 2003.

2. BUILDING DESCRIPTION AND COOLING CONCEPT

The building has a net surface area of 1488 m² with a brut room volume of 5540 m³, of which 1000 m² are heated and mechanically ventilated. The average U-value of the building is 0,3 W/m²K, using triple glazed windows with wooden frames combined with highly insulated roof, wall and floor constructions with U-values between 0.1 – 0.16 W/m²K.

The building’s heating energy is distributed via the mechanical ventilation system with heat recovery, covering an extremely low measured heating energy demand between 15 and 19 kWh/m²a.

Summer cooling is done with a passive night ventilation concept, whereby the user has to

Figure 1: Passive standard office building.

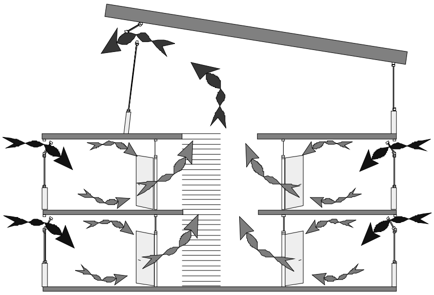


Figure 2: Night ventilation concept for ground and first floor of offices with opening flap at the roof.

manually open the upper section of the windows (4000 cm² open cross section for two windows) and air flow takes places via opened corridor doors to the roof, where flaps automatically open, if the internal air temperature is 2 K above ambient temperature (Fig. 2).

In addition, an earth heat exchanger cools the fresh air supply of the building. It is positioned around the building and consists of two PE pipes with diameters of 350 mm and a length of 90 m respectively. The pipes are laid in a mean depth of 2,80 m (Fig. 3). The operation of this device is based on the finding that the temperature of the subsoil is almost constant below a depth of 2 m, closely matching the annual mean temperature of the ambient air (Henne, 1999). Thus by ventilating ambient air through the system, it is cooled in summer and heated in winter.

The earth-air heat exchanger of the Lamparter office building is mainly built for preheating of ambient air. This treatment serves two goals. One is the reduction of heat losses due to fresh air ventilation; the other is the prevention of freezing of the cross flow heat exchanger of the ventilation system. During summer the earth-air heat exchanger helps meeting the cooling loads of the building. A main design goal was to achieve a small pressure loss (Pfafferott, 2003).

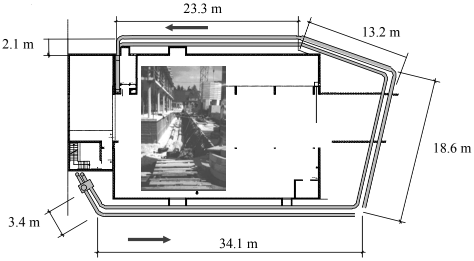


Figure 3: Outline of the Lamparter office building with earth-air heat exchanger.

The target air temperature inside the rooms is 22 °C. The optimum control strategy for the earth-air heat exchanger is as follows. It is used only when a need for heating or cooling exists and the volume flow can be controlled continuously in a way that no useless gains occur.

In the Lamparter project, the operation control of the earth-air heat exchanger differs between heating (ambient air below 15 °C) and cooling period (ambient air above 15 °C). During the heating period it is bypassed if the soil is colder than the ambient air and the room temperature is below 22 °C. During the cooling period the earth-air heat exchanger is bypassed if the room temperature is below 22 °C, regardless of the soil temperature. As there is no comparison of the heat exchanger exit temperature and ambient air, unwanted gains occur. Therefore the Lamparter control does not resemble the mentioned optimum strategy.

3. EXPERIMENTAL RESULTS

3.1 Night ventilation

Two office rooms were analysed in detail: on the south/western side of the building a 20 m² office is occupied by two persons with one computer workplace and on the north/east side a similar office has two persons with two CAD workplaces. The daily internal loads on the south facing office are around 200-250 Wh/m²d during summer and about 400 Wh/m²d for the heavier equipped north office.

Under typical German climatic conditions such as the summers of 2001 and 2002, the night ventilation concept is highly efficient with only 1,9 to 2.4 % of all office hour room temperatures above 26 °C. This corresponds to only 50-60 hours above 26 °C or 10-30 hours above 27 °C.

In 2003 with a mean summer temperature 3.2 K higher than usual, however, 9.4 % of the office hours have room temperatures above 26 °C, which is more than 230 h or about 5 weeks. Although this value is just below the maximum allowed value of 10 % according to German standard DIN 4108, the comfort level is not satisfactory (Fig. 4).

The air exchange rates measured during 170 night hours in summer 2003 gave an average of 9.3 h^{-1} at an average wind speed of 1.1 m/s. The wind direction was between east and south for 90 % of all measurements with decreasing speed over the course of the night. The analysis of air flow within the building using artificial fog showed that the high air exchange was largely due to cross ventilation and that the thermal buoyancy effect was especially small in the first floor offices. Due to insufficient sizes of the roof flap openings, the neutral zone is within the first floor and the driving pressure for buoyancy is too small.

Although the air exchange rates were sufficiently high during summer, the ceilings were not effectively discharged, as cool air entering the windows drops to the floor and leaves the room via the opened doors. The ceiling directly at the window openings cools down by about 1.5 K during a warm summer night and the ceiling at the room centre by only 1 K (Table 1).

The air changes measured during the night varied between 6 and 14 h^{-1} and followed the external wind velocity. See Figure 5.

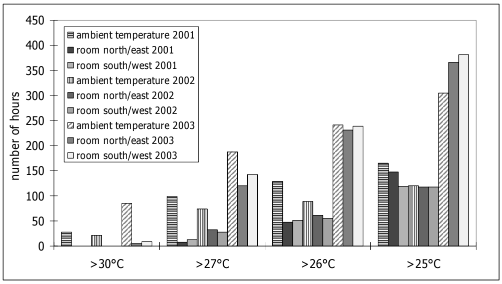


Figure 4: Number of hours, where given temperature levels are exceeded.

Table 1: Temperature profile during a warm summer night (8.8.-9.8.2003).

Time	Ambient air /°C	Room air /°C	Floor to corridor /°C	Ceiling centre /°C	Ceiling between /°C	Ceiling at window /°C
$20.^{00}$	29,3	28,8	26,7	29,1	28,4	28,0
$22.^{00}$	25,3	28,7	26,7	29,0	28,3	27,8
$00.^{10}$	23,5	28,5	26,6	28,9	28,1	27,2
$00.^{50}$	23,1	27,5	26,5	28,8	28,0	26,7
$3.^{00}$	21,2	26,2	26,1	28,4	27,8	26,2
$5.^{00}$	19,8	26,3	25,6	28,0	27,5	25,8
$7.^{10}$	19,7	26,1	25,2	27,7	27,2	25,4
$9.^{30}$	22,6	26,7	25,3	27,9	27,3	26,5

Only if night air temperatures are significantly lower, temperature decreases of the surfaces of 3-4 K can be achieved. Again the heat transfer is significantly better on the ceiling part near the windows (Table 2). Infrared measurements of the ceiling also showed the ineffective discharge during the night.

In parallel heat flux measurements were carried out on several points of the ceiling and the time integrated values gave low values of 15 – 20 Wh per square meter and night. During the day, about 45 – 50 Wh/m²d were taken up by the ceiling, which leads to ever increasing temperature levels during the hot season (Fig. 6).

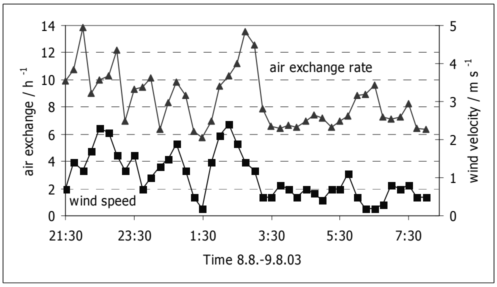


Figure 5: Air exchange rates and wind speed.

Table 2: Temperature profile during a cool summer night (22.8.-23.8.2003).

Time	Ambient air /°C	Room air /°C	Floor to corridor /°C	Ceiling centre /°C	Ceiling between /°C	Ceiling at window /°C
$20.^{00}$	26,0	25,5	24,2	25,0	25,0	25,0
$23.^{30}$	18,0	25,1	24,1	25,1	24,2	23,1
$00.^{10}$	16,8	25,2	24,1	25,1	24,2	23,2
$00.^{50}$	16,2	23,7	24,0	25,0	23,5	22,9
$3.^{00}$	15,6	22,2	22,5	24,3	22,7	20,8
$5.^{00}$	14,2	20,5	22,0	24,1	22,1	20,8
$7.^{10}$	13,2	22,3	21,6	24,0	22,6	21,6
$8.^{50}$	17,6	22,7	21,8	23,8	22,4	21,4

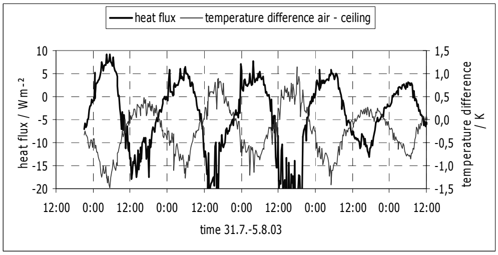


Figure 6: Measured heat fluxes and temperature differences between the room air measured 40 cm below the ceiling and the ceiling surface temperature.

The air temperature at 40 cm below the ceiling was very close to the surface temperature, indicating little air exchange at that layer.

In conclusion, the user-driven night ventilation concept works very satisfactorily during moderate central European summers with no more than 100-150 h above 25 °C.

During hotter summers with 300 h above 25 °C, nearly 10 % of all office hours were above 26 °C in both south and north facing offices, which shows the limits of passive cooling concepts in warmer climatic regions.

3.2 Earth-air heat exchanger performance

The contribution of the earth heat exchanger during day time operation was also investigated both experimentally and theoretically. Inside the earth-air heat exchanger temperature sensors are placed with a mutual distance of 9 m. Additionally the humidity of the air is measured at the inlet and the outlet of the tubes. The soil temperature is measured at the frontside and at the backside of the building at various depths and at a range of distances from the tubes of the heat exchanger.

At inlet ambient air temperatures for the earth-air heat exchanger between 9 °C and 16 °C, overlaps occur between heating and cooling operation. This means that sometimes the air is heated during the cooling period (summer) and vice versa. This indicates a suboptimal control of the device.

The annual coefficients of performance ((heating + cooling energy)/(electrical energy consumed) are 50, 35 and 38 in the years 2001 to 2003 (Fig. 7). However, the earth heat exchanger can not fully remove the daily cooling load: the hygienically required fresh air volume flow limits the cooling power, which can be supplied by such systems. From the average internal loads of 131 Wh/m²d the earth heat exchanger efficiently provided 24 Wh/m²d in the summer period 2003, i.e. 18 %.

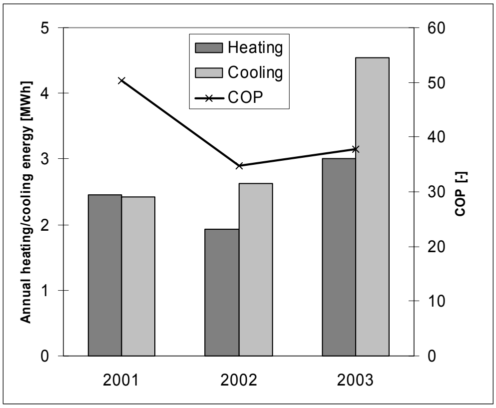
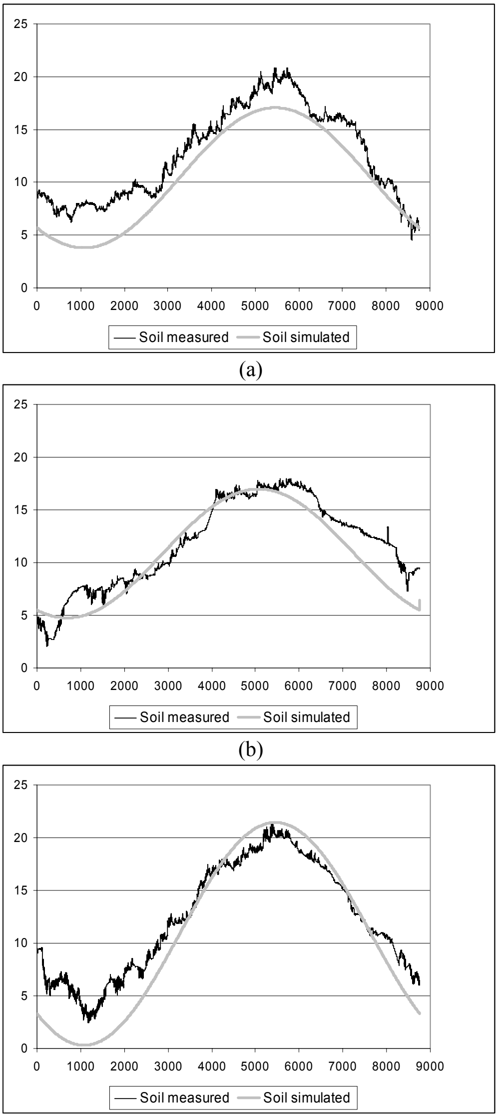


Figure 7: Annual heating and cooling energy as well as respective COPs for the years 2001 to 2003.

4. THEORETICAL MODEL

The extensive set of experimental data was then used to validate theoretical models. A numerical simulation model of the earth-air heat exchanger was implemented, which enables the user to check the performance of the system under extreme conditions as well as to test different control strategies. The model is mainly based on the theoretical work of Albers (1991). It is build as a block for the INSEL® simulation environment and features a graphical user interface (Schumacher, 2004).

Among others, one required input for the model is the undisturbed ground temperature. This parameter is difficult to quantify and even more difficult to simulate (Dibowski and Rittenhofer, 2000). It depends on the history of the ambient temperature and also on the thermal properties of the subsoil. The latter are not exactly known since they strongly depend on the moisture content, which may vary considerably. Pfafferott (2003) therefore considers the undisturbed ground temperature a hypothetical value. However, Tzaferis et al., (1992) state that it must be regarded as one of the key parameters for determining the outlet air temperature. In this work the ground temperature is calculated according to the German guideline VDI 4640, which uses a sinusoidal wave function (Fig. 8). All other inputs to the model are measured within the framework of the Lamparter project and are read directly from a data file. A time step of one hour was chosen, which can be regarded as the minimum step for this kind of model. Outputs of the calculation are the exit air temperature and the thermal power.



(a)

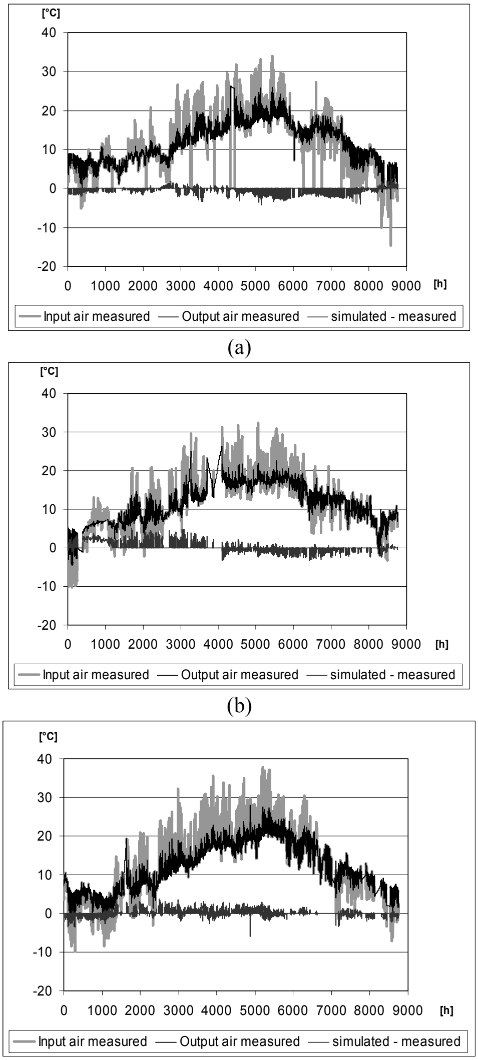
(b)

(c)

Figure 8: Measured and simulated soil temperature for the years 2001 (a), 2002 (b) and 2003 (c).

Model performance

For validation purposes the calculated exit air temperatures are carefully compared to the measured values of the Lamparter building for the three years from 2001 to 2003. In spite of the simple calculation of the undisturbed ground temperature and the constant thermal underground parameters, the agreement is found to be very satisfactory (Fig. 9). In spite of the limited



(a)

(b)

(c)

Figure 9: Inlet temperatures, outlet temperatures and simulation error of the Lamparter earth-air heat exchanger for the years 2001 (a), 2002 (b) and 2003 (c).

input effort and the fast calculation process, even dynamic situations can be modelled with acceptable results down to a resolution of one hour. The mean differences between measured and simulated outlet temperature for the years 2001 to 2003 are 0.4 K, 0.7 K and 0.4 K respectively.

5. CONCLUSIONS

In summary, the work presents new experimental results for night ventilation and earth heat exchanger performance in one of the best European office buildings today. The earth heat exchanger reaches excellent performance using a low pressure drop design and covers about 20 % of the internal load. The night ventilation passive cooling concept is sufficient during standard German summer conditions, but reaches its limits for thermal comfort, if ambient temperatures are 3 K higher than usual.

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