# ENERGY PERFORMANCE OF EARTH-AIR HEAT EXCHANGER IN A BELGIAN OFFICE BUILDING

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**ABSTRACT**
An earth-air heat exchanger (EAHX) has been implemented in a low-energy office building in Kortrijk, Belgium. An extensive monitoring campaign was conducted to define the energy consumption in the building and the contribution of the EAHX to energy savings. This paper presents the results of the measurements and compares the measured performance of the EAHX to the building energy use and to results of a simulation model for 3D transient heat transfer.

## KEYWORDS

Earth-air heat exchanger, energy use, monitoring, simulation

## INTRODUCTION

Earth-air heat exchangers (EAHX), also called ground tube heat exchangers, are a possible technique to reduce energy consumption for heating and cooling in buildings. Tubes are put into the ground, through which ventilation air is drawn. Thus EAHX can cool or heat the ventilation air, using the soil as a heat source or sink. Their performance depends on the air flow rate, convective heat transfer at the tube surface, depth, dimensions and number of pipes and soil properties (De Paepe and Janssens, 2003). Only a moderate climate having a large temperature difference between summer and winter is suited for EAHX. As the heat exchanger has a good peak performance but a limited seasonal capacity, it is an interesting technique in combination with other energy saving measures. For instance, the EAHX may prevent frosting of a conventional air-air heat exchanger during cold weather, thus increasing the number of operation hours of the heat exchanger combination. Furthermore, in combination with other low-energy cooling techniques (eg night cooling) and good thermal building design, the EAHX may eliminate the need for an air conditioning system (IEA-Annex 28, 1999).
In several European countries this technique is gradually introduced, both in housing as in office buildings (Pfafferot 2003). Also in some new office buildings in Belgium, EAHXs have been implemented (Breesch et al. 2005). The Belgian moderate climate is suitable for an adequate operation of earth to air heat exchangers, with a yearly mean temperature of 9.8 °C and normal extremes of –8.6°C and 29.9°C (RMI, 2004). Architects and building service designers are often interested in installing EAHX, but still lack confidence to apply these techniques in the absence of information on design methods and on the performance of existing applications in Belgium. Therefore, this paper discusses the energy performance of an EAHX applied in a low-energy office building in Kortrijk, Belgium. The EAHX was designed according to a design method published by De Paepe and Janssens (2003). In a first part of the paper this design method is briefly explained, and the expected design performance of the EAHX is presented. Further, the energy performance of the EAHX is evaluated based

on an extensive monitoring campaign conducted by VITO in 2003 (Desmedt et al. 2004). The performance is related to the building gas and electricity use. In a last part the EAHX is evaluated using a simulation model for 3D transient heat transfer. Differences between simulation and measuring results are discussed.

## OFFICE BUILDING DESCRIPTION

The office building 'SD Worx' is located in Kortrijk, Belgium and consists of two office floors on top of a limited ground floor with building services (design: Stramien arch., study: Cenergie cvba). On the south side, the floors are connected with an open stairwell and circulation zone. The building is in operation since spring 2002. Figure 1 shows a vertical section. It was the ambition of the project to create an office building (total floor area: 1350 m²) with good thermal comfort and with half the energy consumption of a standard office building. This was achieved by several means: very good thermal insulation, energy efficient ventilation, solar shading, passive cooling techniques, enhanced control automation,… In winter, two condensing boilers of 46 kW each supply hot water to a hydronic radiator system. Fresh air is provided by means of a demand controlled, balanced ventilation system. The ventilation flow rate is controlled from a minimum of 2000 $m^3/h$ up to 8000 $m^3/h$ in response to measurements of IAQ and temperature in the offices. The supply air passes through an EAHX and is further pre-heated by a regenerative heat exchanger (RHX, nominal thermal effectiveness 90%). The EAHX includes two concrete pipes with an internal diameter of 80 cm and a length of 40 m each, buried in clay ground under groundwater level at depths of 3 and 5 m and connected to the ventilation system by PE-pipes with an internal diameter of 40 cm. In summer, the building is cooled by passive means. By night a natural night ventilation system is active: outside air enters the office floors through bottom hung windows, located near the ceiling in the offices on the north side. The air cools down the exposed ceiling and leaves the building in the circulation zone through outlet windows. By day, the ground tubes precool the supply air. The supply flow rate increases proportionally from 5400 m³/h at 23 °C indoor temperature to 8000 m³/h at 26 °C and above. In cooling mode, the exhaust air leaves the building through the outlet windows on top of the circulation zone. In addition to the passive cooling techniques a packaged water chiller (21 kW) is installed to remove excess heat from a server and computer room located on the ground floor.
Previously, Breesch et al. (2005) reported on the thermal comfort during summer in this office building and on the contribution of the EAHX to achieve good comfort, relative to the contribution of night cooling. Breesch et al. used a coupled thermal and building simulation model to demonstrate that the night cooling system was more efficient than EAHX to improve thermal comfort. However only the combination of both techniques appeared capable to achieve an acceptable comfort without additional active cooling in the offices.

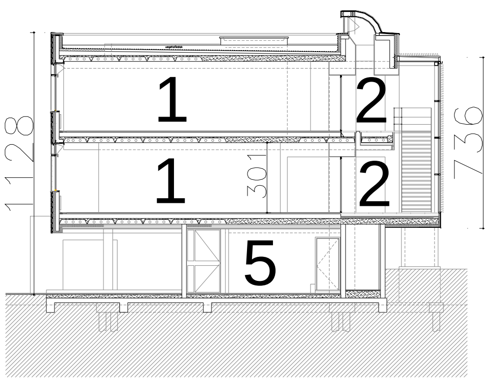


Figure 1: vertical section

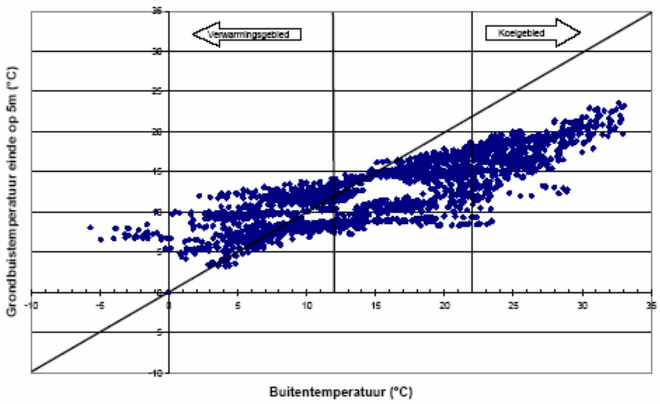


Figure 2: Measured outlet vs inlet EAHX temperature

## DESIGN PERFORMANCE

The EAHX was designed according to a sizing method based on thermal and pressure drop optimization (De Paepe and Janssens 2003). In this method the thermal performance of the heat exchanger is characterized by means of the steady state effectiveness ε:

$$\varepsilon = \frac{T_a - T_e}{T_s - T_e} = 1 - \exp\left(-\frac{\pi hLD}{\dot{m}_a c}\right) \quad (1)$$

with $T_a$ the air temperature after passing the EAHX, $T_e$ the exterior air temperature at the inlet, $T_s$ the constant tube wall temperature, h the convection coefficient inside the tube (W/m²K), L and D the tube length and diameter (m), $m_a$ the air flow rate per tube (kg/s) and c the thermal capacity of air (J/kgK). The convection coefficient is also function of the air flow rate and the diameter of the ground tubes.

The desired effectiveness follows from the design requirements and climate conditions, but often an effectiveness of 80% is considered to be an optimum for an EAHX (IEA Annex 28 1999). In the original design of the EAHX for the building an effectiveness of 80% was proposed. However, due to difficulties during construction, the original design was abandoned and the configuration with two 80 cm diameter tubes was built. Since the ventilation rate in the office building is demand controlled, the effectiveness of the EAHX changes as a function of the actual ventilation rate. Table 1 lists the EAHX performance indicators for the minimum, mean and maximum ventilation rate. As the table shows the design effectiveness of the built configuration is rather low, in between 38 and 48%. On the other hand, the pressure drop across the tubes is very small, so the presence of the EAHX has a negligible effect on the electricity consumption of the fans. The table further shows that the ventilation rate may be varied over a wide range with minor change in effectiveness.

TABLE 1: Design performance as a function of ventilation rate

| Ventilation rate ($m^3$/h) | 2000 | 5400 | 8000 |
|---|---|---|---|
| Effectiveness (%) | 48 | 40 | 38 |
| h (W/m²K) | 2.2 | 4.7 | 6.3 |
| Pressure across tube (Pa) | 0.2 | 1.3 | 2.5 |

## MEASURED PERFORMANCE IN RELATION TO BUILDING ENERGY USE

This section presents the measured energy consumption of the building in the year 2003 and discusses the energy performance of the earth-air heat exchanger (Desmedt et al. 2004). It is good to bear in mind that the year 2003 was exceptionally warm: the yearly mean temperature was 11.1°C where 9.8°C is a normal value in Belgium (RMI 2004). This high yearly mean was primarily caused by high temperatures in spring and summer (with a 13 day long heat wave in august). Therefore the heating degree days were only 7% lower than the normal value: $G_{eq}$(16.5/16.5) = 2296°d in stead of 2458°d.

Table 2 lists the measured gas and electricity consumption in the building. The results show that the designers met the ambition to decrease the energy consumption by two compared to typical values for office buildings in Belgium.

Table 2: Measured gas and electricity consumption in 2003 (Desmedt et al. 2004)

| | Energy consumption | Normalized consumption per heated floor area | Typical values for offices in Belgium (VITO 2002) |
|---|---|---|---|
| Gas (space heating) | 7317 $m^3$ | 61 kWh/m²* | 147-214 kWh/m² |
| Electricity | | 65 kWh/m² | 75-133 kWh/m² |
| - Fans | 10130 kWh | | |
| - Chiller | 5244 kWh | | |
| - Other | 72376 kWh | | |

* calorific value: 10.5 kWh/$m^3$ and corrected to normal heating degree days

The EAHX and the RHX that pre-heat the ventilation air reduce the space heating demand. The energy delivered by the heat exchangers was measured by monitoring the ventilation flow rates of the fans and the temperature differences across the heat exchangers. Figure 2 shows the measured air temperature at the exit of the deepest ground tube (5m) as a function of the external air temperature. The graph confirms that the EAHX has a good peak performance. A temperature difference of 9 to 14°C is achieved across the EAHX during weather extremes, resulting in a maximum heat gain of 10 kW and a maximum heat removal of 25 kW measured across the EAHX. However in milder weather the EAHX may have an adverse effect: it still cools the air during part of the time when the building has a space heating need (at outside temperatures below 12°C).
The energy supplied by the heat exchangers is shown in Figure 3 relative to the net total heat delivered by the hydronic system (assuming a system efficiency of 85%). The yearly sums are listed in Table 3. Here it is assumed that the energy delivered by the EAHX is always in line with the heating or cooling needs of the building. This way the energy performance of the EAHX is overestimated. Still the results show that the amount of energy saved by the EAHX is relatively small but not unimportant, considering its limited steady state effectiveness. Without the EAHX the gas and electricity consumption in 2003 would have increased by a maximum of 5 and 7%, respectively. The cooling performance of the EAHX outweighed its heating performance. This is related to the increased number of operation hours, to the increased airflow rate and to the extremely warm weather during summer 2003. The avoided equivalent electricity use for cooling is in the same order as the electricity consumed by the 21kW chiller.

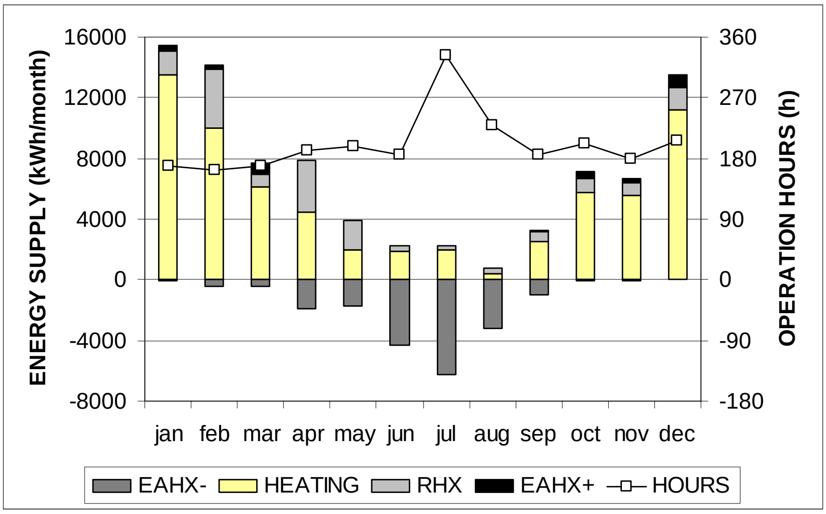


Figure 4: Measured energy supply (Desmedt et al. 2004)

Table 3: Yearly sums of sensible heat supplied by heat exchangers

| | Heating | | | Cooling | |
|---|---|---|---|---|---|
| | EAHX | RHX | Heating system | EAHX | Eq. Electricity |
| Energy supply (kWh/a) | 3044 | 16513 | 65300 | 19367 | 6455 (COP = 3) |
| Relative to measured needs | 5% | 25% | | | 7% |

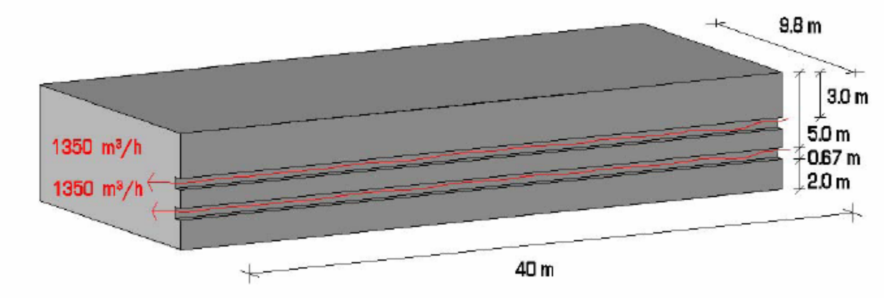


Figure 4: Model geometry and calculation domain (Steeman 2005)

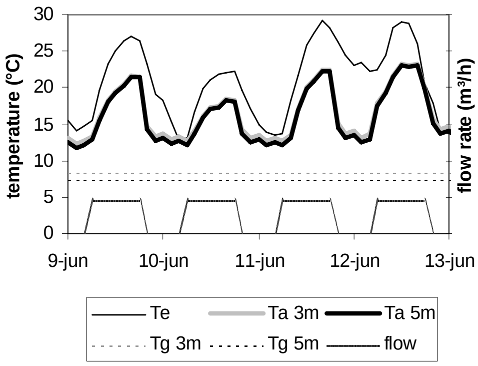


Figure 5: Simulation output

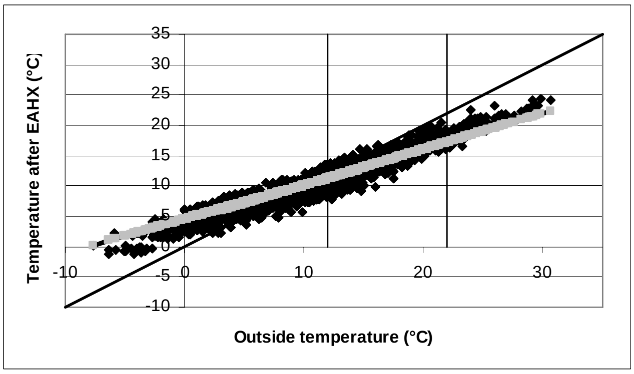


Figure 6: Predicted outlet vs inlet EAHX temperature

## SIMULATED PERFORMANCE OF EAHX

This section presents results of dynamic thermal simulations of the case study EAHX (Steeman 2005). The predicted performances are compared to the measured performance and to performance indicators reported in literature. For this purpose the software VOLTRA was used (Physibel 2003). This is a numerical calculation tool for 3D transient heat transfer (control volume based). Apart from heat conduction and storage in solids, the model also takes convective heat transfer into account. The user may introduce mass flow rates and convective surface coefficients in a predefined flow path as a specific boundary condition. Figure 4 shows the calculation domain for the symmetric problem of the EAHX. Only the horizontal part of the EAHX is considered. The ground is assumed to be homogeneous clay: $\lambda = 1.5$ W/m²K, $\rho c = 3$ MJ/m$^3$K. A climatic data file with hourly mean values for temperature and solar radiation defines the boundary conditions at the ground surface and at the inlets of the EAHX. In order to evaluate the performance under normal climatic conditions the Test Reference Year (TRY) for Ukkel, Belgium is used. It is assumed that ventilation is active during 12 hours a day (6-18h) at a rate of 3000 m$^3$/h from November to March and of 5400 m$^3$/h from April to October. The convection coefficient in the ground tubes is adjusted accordingly (Table 1).

Figure 5 shows a typical output of the calculations during a warm week in June: when ventilation ceases over night, the temperature in the EAHX falls back to a constant ground temperature. However, operation of the EAHX tends to heat the ground in summer: this is clear by comparison with the undisturbed ground temperatures in absence of EAHX, also indicated on the graph. Figure 6 shows the predicted air temperature at the exit of the deepest ground tube (5m) as a function of the external air temperature. The results of the dynamic simulations are compared to calculations with the steady state method (Equation 1), assuming a constant tube wall temperature equal to the outside yearly mean (10°C). As the graph shows there is a good correlation between both results, but the simple steady state method overestimates the peak performance relative to the transient simulations.

## DISCUSSION

The results of measurements and simulations are compared by means of two performance indicators. The characteristic thermal response presented in Figures 2 and 6 is the first. The yearly sensible heat supply is the second. In order to derive representative values, the monthly heat supply following from the simulations is corrected in order to match the measured number of operation hours of the EAHX. Further it is common to express the heat supply as a specific value, relative to the wall surface area of the ground tubes. This number is often used in literature to compare energy performance of EAHX. Table 4 lists the resulting numbers. The measured and simulated energy gains are in the same order as the values reported in literature, except for the very large measured cooling energy supply. The comparison further shows that the simulations underestimate the performance of the EAHX compared to the measured performance. The differences in energy performance may partly be attributed to climatic differences: in 2003 the number of days with temperature extremes above 25°C was the double of a normal year (RMI 2004), resulting in a larger cooling supply. The warm summer may also have caused higher ground temperatures during autumn, resulting in a larger heating supply. During a normal year the heating and cooling energy gain from the EAHX would therefore have been smaller. Still, when comparing the predicted with the measured temperatures (Figures 2 and 6), it is clear that the differences between simulated and measured performance is not the result of climatic differences alone. The heat exchange in the EAHX is underestimated in the simulations, as appears from smaller temperature differences between inlet and outlet air compared to measurements. The reason for these deviations is unclear. Perhaps the thermal properties of the soil entered for the simulations are incorrect. The calculations may also be sensitive to the correct schedule and flow rate of the ventilation system. In this respect it is known that short operation hours result in better peak performance (IEA Annex 28 1999).

Still, considering that at ambient temperatures of 30°C the maximum measured air temperature at the outlet of the EAHX was 22°C, it is clear that the EAHX alone is not suited to effectively cool a building during warm weather. It merely eliminates ventilation heat gains and should be combined with other measures that reduce room cooling loads, in order to help avoid the need for active cooling.

Table 4: Energy gains for heating and cooling across the EAHX, relative to ground coupling area

| | Measurement | Simulation | Literature (Pfafferot 2003) |
|---|---|---|---|
| Specific heating | 15 kWh/(m²a) | 11 kWh/(m²a) | 16-51 kWh/(m²a) |
| Specific cooling | 96 kWh/(m²a) | 31 kWh/(m²a) | 12-24 kWh/(m²a) |
| Operation hours | 2412 h | 2412 h | 3701-4096 |
| Specific surface area | 0.05 m²/(m$^3$/h) | 0.05 m²/(m$^3$/h) | 0.08-0.18 m²/(m$^3$/h) |
| Heating degree days | 2296 °d | 2458 °d | ±2600 |

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