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LARGE DIAMETER EARTH-AIR HEAT EXCHANGER FOR SPACE COOLING AND HEATING: PRELIMINARY POST-OCCUPANCY FINDINGS

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Keywords

Earth-air heat exchanger (EAHE), Ventilation, Geothermal energy, Solar energy, Office building, Hypocriocaust[1]

Abstract

The main goal of the paper is to describe and provide a preliminary discussion of the performance of a large diameter earth-air heat exchanger used in cooling and heating of a small office building located in Alentejo, Portugal. The sole energy consumption associated with this system is that required to operate two fans that move outdoor air into the office spaces. There are no mechanical moving parts inside the office building and the heat exchanger is designed in combination and complementing principles of natural ventilation in the office spaces.

Post-occupancy results show the large diameter design of the earth-air heat exchanger is capable of removing up to 30 kW of heat from the outdoor air using just 2,2 kW of fan power. Despite the significant cooling requirements in Alentejo, Portugal, earth-air heat exchanger outflow air temperatures can be 10 K lower than outdoor temperatures, allowing the removal of office space loads in the morning period and supplying offices in the afternoon with air at temperatures that seldom exceed 27°C, despite outdoor air temperatures of 40°C.

[1] Underground device for cooling and heating.

1 INTRODUCTION

Outdoor air temperatures vary significantly along the day, from day to day and along the year. Earth-air heat exchangers rely on unchanged underground temperatures to remove undesirable loads from outdoor air, stabilizing its temperature. Depending on the soil temperature and on the earth-air heat exchanger design, air leaving the heat exchanger could be used to cool or heat an occupied space, providing all year long comfort conditions. To achieve this purpose, air temperatures entering the space should lay above 18°C and below 27°C.

In the Mediterranean region, soil with temperatures ranging between 18 and 20°C, appropriate for space cooling and contributing, also, for space heating, can be found at depths of 5 to 8 meters [1]. Examples of use of earth-air heat exchangers in Mediterranean traditional architecture are described in [2] and contemporary examples of the use of this technology are provided in [3, 4]. Still, most contemporary reports describe applications in central and northern Europe, often residential applications, providing little detail on the performance of the heat exchange. Examples of large diameter earth-air heat exchangers used in office buildings and located in the Mediterranean region are very seldom found in the scientific literature. Yet, the push towards net zero and net positive energy buildings provides the incentive to research alternatives to conventional mechanical refrigeration systems and, as this paper shows, earth-air heat exchangers combined with sound indoor ventilation strategies is a viable alternative.

This paper describes and presents post-occupancy results for a large diameter earth-air heat exchanger designed and built to heat and cool a NZEB office building in Alentejo, in the south of Portugal. These preliminary results reveal the advantages associated with the selected heat exchanger design, namely the ability to filter out the large outdoor temperature amplitudes, allowing indoor comfort conditions without the need for mechanical refrigeration. Because this paper reports a preliminary study that used only a fraction of the monitoring data available, it is concluded that further effort in processing the available data is justified and important. Indeed, further analysis could contribute to more and improved designs of large diameter earth-air heat exchanger for space cooling and heating and to consequent decarbonisation of buildings.

The next sections describe the earth-air heat exchanger, the connection between this exchanger and the office building, and the ventilation strategy adopted in the office spaces. Afterwards, post-occupancy findings for the 2015 cooling season are presented. For this period, outdoor and heat exchanger outflow air temperatures are compared and, based on values of loads removed from outdoor air, the heat exchanger performance and effectiveness are discussed.

2 THE LARGE DIAMETER EARTH-AIR HEAT EXCHANGER

Figure 1 presents a sketch of the earth-air heat exchanger being analysed.

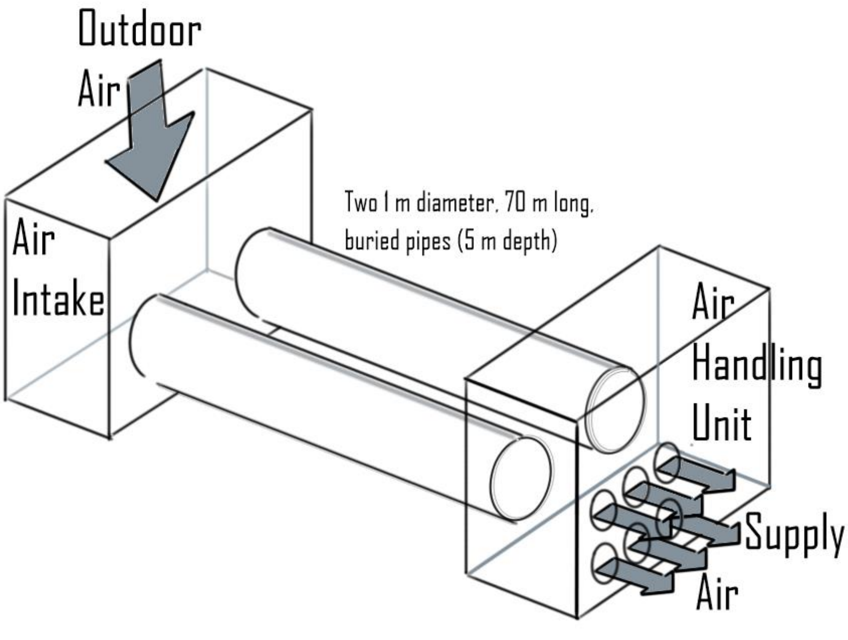

Figure 1. Sketch of the earth-air heat exchanger.

It consists of two 1 m in diameter, 70 m long concrete pipes, buried at the (average) depth of 5 m. An Air Handling Unit (AHU) with two fans capable of moving 14500 m^3/h of air is located downwind forcing the flow of outdoor air through the two pipes.

3 THE CONNECTION BETWEEN THE HEAT EXCHANGER AND THE OFFICE BUILDING

Figure 2 presents a photograph taken during construction representing the technical space that holds the AHU and the supply air piping that leaves this unit heading towards the office spaces.

Figure 2. Photograph taken during construction phase, depicting the supply air pipes leaving the technical space where the AHU lays and heading towards the heated and cooled office spaces.

4 OFFICES VENTILATION STRATEGY

Figure 3 presents a cross-section of an office space depicting the supply air pipe as it connects to the office (lower left corner), delivering air to a plenum at floor level. This air enters the office space and heads to a false ceiling over the corridor (upper left corner). The air is exhausted to the outdoor through an opening at the south facing building façade, behind vertically mounted photovoltaic solar panels.

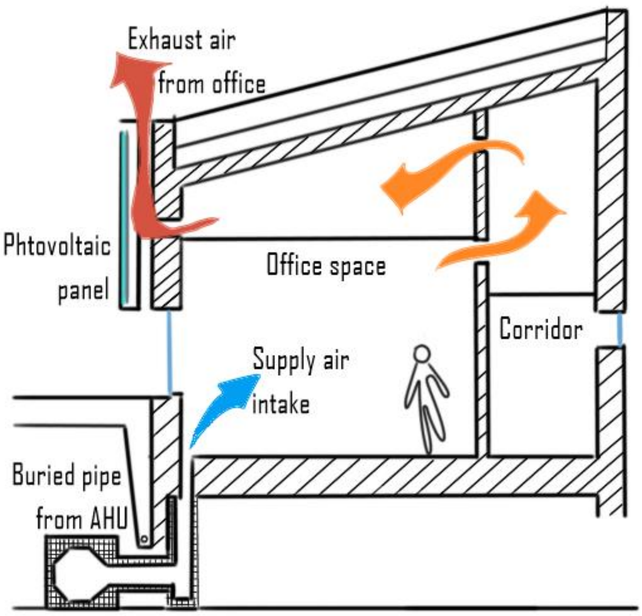

Figure 3. Cross-section of the building depicting the office space and the way supply air enters—at floor level, next to an exterior buried wall—, moves towards a false ceiling over a corridor and how it is exhausted to the outdoor, through an opening at the exterior south facing wall, behind vertically mounted photovoltaic panels.

5 EARTH-AIR HEAT EXCHANGER PERFORMANCE

The performance of the earth-air heat exchanger (EAHE) was assessed during the cooling season of 2015. During this period no control was implemented and the flow of air through the EAHE was kept on day and night at a constant rate of approximately 8000 m^3/h, consuming 2,2 kW.

Figure 4 presents time series plots of outdoor air temperature, T_{outdoor}–temperature of air entering the heat exchanger–, and air temperature as it leaves the heat exchanger, T_{outEAHE}. Additionally, outdoor, $\dot{W}_{\text{outdoor}}$, space[2], $\dot{W}_{\text{space}}$, and total loads removed by the earth-air heat exchanger are also presented (with total loads determined from $\dot{W}_{\text{total}} = \dot{W}_{\text{outdoor}} + \dot{W}_{\text{space}}$).

Prior to the analysis of the results in Figure 4, the use of outdoor, space and total loads to characterise the performance of the EAHE should be explained.

Cooling systems can be pictured as performing two distinct tasks. First, remove the loads[3] from the outdoor air (represented as $\dot{W}_{\text{outdoor}}$), decreasing its temperature to an upper value appropriate for space indoor thermal comfort. Second, remove additional loads from the air supplied to a space, decreasing its temperature below the upper value just described. This allows for the removal of space-specific loads (represented as $\dot{W}_{\text{space}}$), such as internal gains from occupants, lighting, electrical and gas appliances, and heat gains from the space envelope due to solar radiation, conduction and infiltration. For the studied office spaces, given that cooling is achieved without mechanical refrigeration systems, adaptive comfort [5] applies, and an upper indoor air comfort temperature threshold of 27°C is assumed.

The performance of the earth-air heat exchanger can be thus characterised by the equations (assuming cooling mode, $T_{\text{outdoor}} > T_{\text{outEAHE}}$),

$$\dot{W}_{\text{outdoor}} = \rho Q c_p (T_{\text{outEAHE}} - T_{\text{outdoor}}) \Leftarrow T_{\text{outEAHE}} \geq 27ºC \quad , \qquad \text{Eq. (1)}$$

[2] Because heat is exchanged in the path between the EAHE and the office spaces, space cooling loads obtained with Eq. (2) are maxima.

[3] In this preliminary analysis we will focus on sensible loads [kW] only.

$$\dot{W}_{\text{space}} = \rho Q c_p (T_{\text{outEAHE}} - 27) \Leftarrow T_{\text{outEAHE}} < 27ºC \quad , \quad \text{Eq. (2)}$$

with ρ and c_p the density and specific heat of air, respectively, and Q the volume flowrate of air that flows through the heat exchanger. Equation (1) provides the loads removed from outdoor air to bring its temperature down to 27°C, whereas Equation (2) provides the additional loads removed, enabling supply air temperatures to drop below 27°C.

With this information in mind, we head to the analysis of Figure 4.

First, it is worth highlighting the high outdoor air temperatures that reach maxima in excess of 40°C and with average daily values above 25°C. Comparing maxima of outdoor and EAHE outflow air temperatures we conclude that 10 K reductions in temperature are achieved with the EAHE. Indeed, maximum daily outdoor air temperatures of 40°C corresponding outflow EAHE air temperatures of approximately 30°C.

The stabilising effect of the earth-air heat exchanger in the outdoor air temperature—alluded in the Introduction—is highlighted observing in Figure 4 maxima and minima in EAHE outflow air temperature, that lay between 30°C and 16°C, whilst outdoor air temperatures vary between 40°C and (approximately) 10°C. Although the objective of the heat exchanger in the cooling period is to cool, since no control was exerted and flowrates were kept constant day and night, Figure 4 provides additional evidence of the EAHE ability to heat.

A final point related to air temperatures that is worth mentioning is the delay between outdoor and EAHE outflow air temperatures, noticeable, especially, in the phase shift at the end of the sinusoidal curves in the September month.

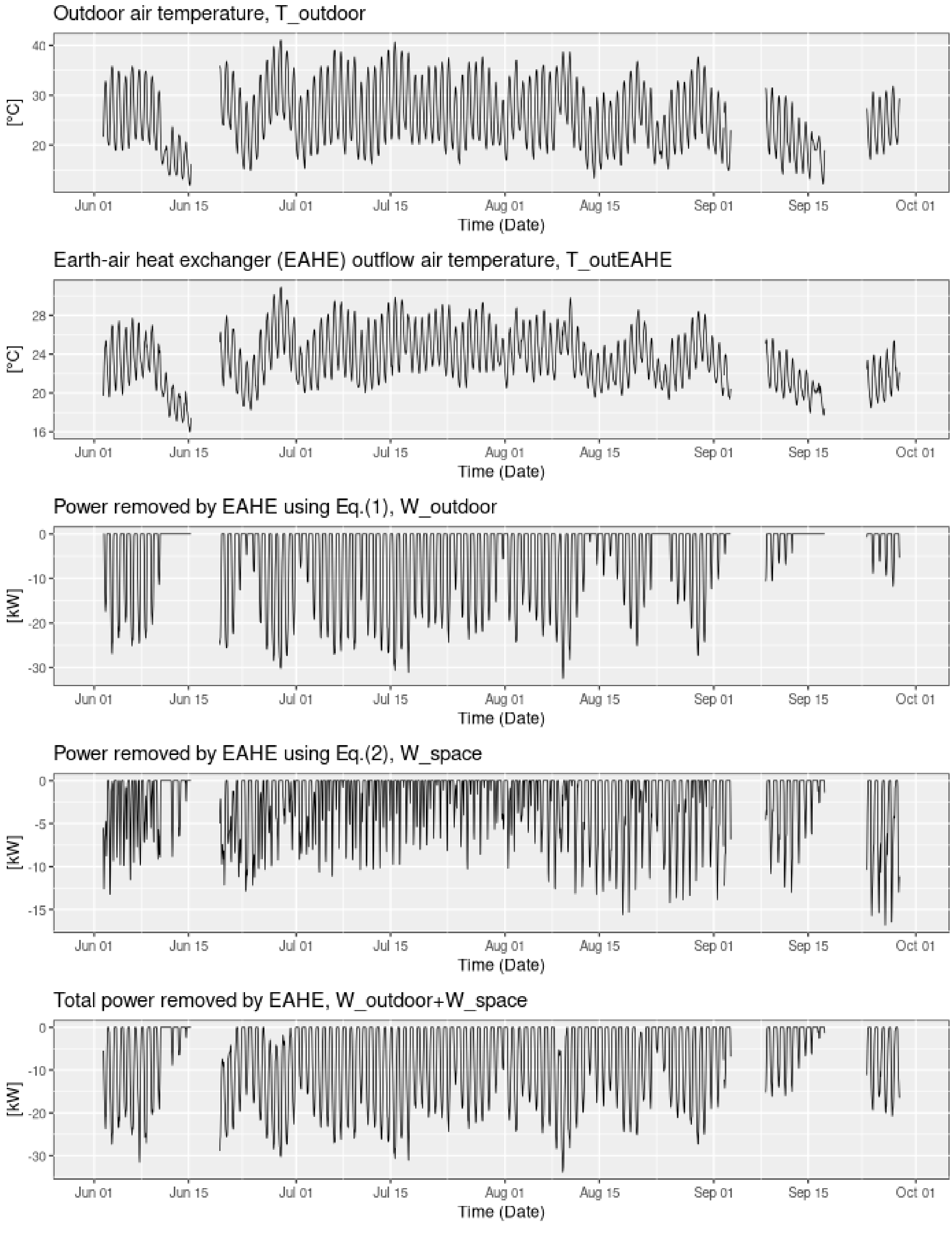

Figure 4. Time series plots of outdoor air temperature, air temperature leaving the heat exchanger, outdoor, space and total loads removed by the earth-air heat exchanger. Values obtained from the 2015 cooling season monitoring period.

As regards the ability to remove loads from the outdoor air and achieve space cooling, Figure 4 shows the EAHE removed[4] up to 30 kW of heat from the outdoor air. These values occur during the day, when outdoor temperatures are higher and temperature differences in Eq. (1) are also higher. As outdoor temperatures decrease, approaching 27°C, $\dot{W}_{\text{outdoor}}$ values (obviously) decrease. Still, Figure 4 shows that for the studied location, with high daytime outdoor air temperatures, most of the time the EAHE is effectively removing loads from the outdoor air.

A consequence of having to remove large outdoor air loads is the EAHE lower capability to reduce supply air temperature below 27°C, compromising the ability to remove space loads. Indeed, space loads removed by the EAHE seldom exceed 5 kW during the warm period between July and the beginning of August, increasing to 10 kW afterwards, when outdoor temperatures decreased.

On this subject of the EAHE reduced ability to remove space loads, it is worth recalling that no control was implemented and prolonged periods with day and night high outdoor air temperatures could have contributed to decrease the efficiency of the heat exchanger. This remark highlights the importance of control in EAHE, linked to outdoor air temperature.

Figure 4 presents bin plots comparing, for the 2015 heating season and for the 24 hours of day, outdoor air temperatures and EAHE outflow air temperatures.

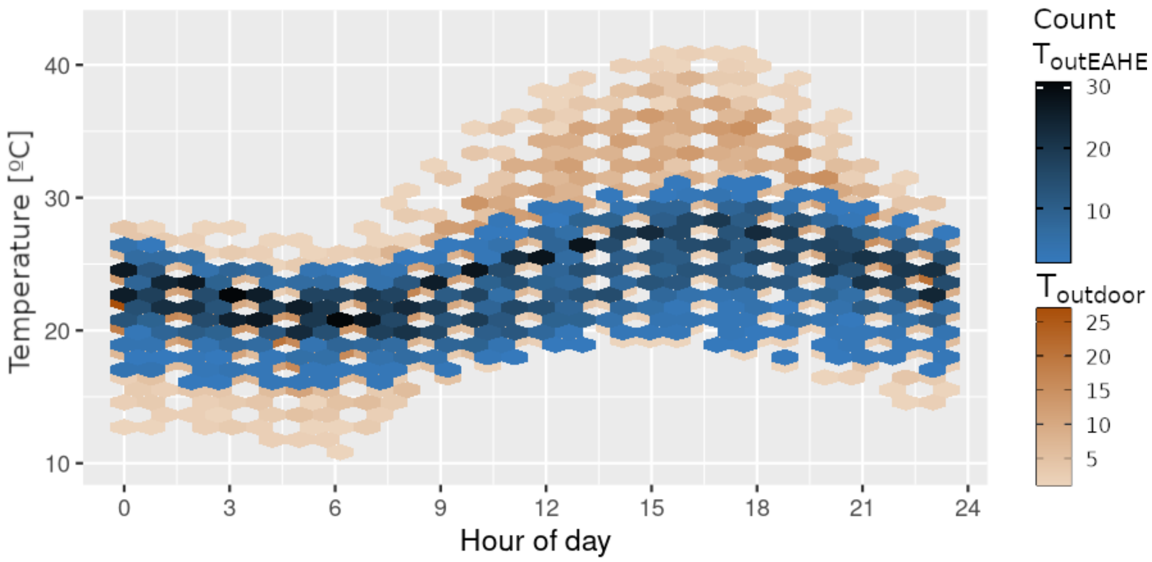

Figure 5. Bin plots comparing, for 2015 heating season and for different hours of the day, outdoor and EAHE outflow air temperatures.

The bin plots in Figure 5 represent larger frequencies in dark brown (outdoor) and dark blue (EAHE outflow). The previously alluded reduction in outdoor air temperature amplitude is made obvious in this plot.

Figure 5 shows that air temperatures are kept (mostly) below 25°C during the morning period, until 12 AM, despite by this time outdoor air temperatures reaching already 35°C. During the afternoon, at 17h the most frequent EAHE outflow temperature is 27°C, preventing removal of space loads. However, by this time, outdoor temperatures are typically 10 K higher. Although it is not shown in this preliminary analysis, the phase shift and amplitude reduction when the supply air enters the office spaces is larger than those represented in Figure 5; a consequence of the thermal inertia introduced by the buried pipes that connect the EAHE and the office spaces.

[4] Therefore, the negative sign.

6 CONCLUSIONS

This paper presented a preliminary analysis of the monitoring data gathered from a large diameter earth-air heat exchanger built for a NZEB office building in Alentejo, Portugal.

For the summer period of 2015 and for a flowrate of approximately 8000 m^3/h (100% fresh air), with a fan power consumption of 2,2 kW, the EAHE consistently removed between 10 and 30 kW of heat from the outdoor and removed between 5 and 15 kW of additional heat, addressing space cooling needs.

Despite the high summer outdoor air temperatures, the large diameter EAHE design allowed a reduction of outdoor air temperature of 10 K during hot periods of day, with most frequent EAHE outflow air temperatures below 25°C until noon and below 27°C in the afternoon, with outdoor air temperatures that reach 40°C. These results confirm personal communications from building occupants who, during the monitoring period, testified for the ability the system had to keep comfort conditions inside the office spaces.

This preliminary analysis provides important insights into the performance of a specific design of an earth-air heat exchanger. These insights are important because reports on earth-air heat exchangers are rare, especially, when large diameter pipes are used. Moreover, it sheds additional light on the dynamics of heat transfer in the large diameter buried pipes.

With the monitoring data that was left out of this study we hope to detail the analysis of comfort in the office spaces, relating it with the behaviour of the EAHE. Considering the results obtained so far, and the EAHE ability to cool air in such extreme (hot) weather conditions, it is believed large diameter EAHE should be seen as another technology contributing to the decarbonisation of the building sector.

Acknowledgements

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