EXPERIMENTAL AND NUMERICAL STUDY OF AN EARTH-TO-AIR HEAT EXCHANGER FOR BUILDINGS AIR REFRESHMENT IN MARRAKECH

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ABSTRACT

This paper deals with a numerical and experimental study of the thermal performances of an Earth-to-Air Heat Exchanger (EAHX) connected to a country house in Marrakech (31°37' N latitude and 8°2' W longitude). The EAHX consists of three parallel PVC pipes of 72 m length each and 15 cm inside diameter, buried at 2.2-3.2 m depth. Each pipe is equipped with a fan, which push treated air into the house. The experimental study consists of the monitoring of one pipe via measurement of air temperature and humidity along the pipe as well as at its entrance and exit to the house. Dynamic simulations were carried out using TRNSYS software (Type 460). The model was validated through 38 days monitoring of the EAHX. Numerical and experimental results are in good agreement. Air temperatures inside the EAHX reached a quasi-constant value of 22°C at a pipe length of 72 m and a depth of 3.2 m. This corresponds to air temperature reduction of 19.8°C.

INTRODUCTION

The concept of using the soil as a heat sink was used many centuries ago. Iranian people, for example, used wind towers and underground air tunnels for passive cooling (Ozgener 2011). Nowadays underground air tunnels also known as Earth to Air Heat Exchangers (EAHX) or buried pipe system, are in use around the world due to their higher energy efficiency compared to the conventional heating and cooling systems; which lead to a huge increase of electricity consumption and also the Electric Peak load.

In Morocco, buildings represent about 25 % of the total energy consumption in the country with 18% reserved to the residential buildings and 7 % for the tertiary ones (ADEREE). A rational energy strategy has been set since 2009 with a target of 15% of energy consumption reduction by 2030 and promotion of renewable energies.

Important research, both experimental and theoretical, has been carried out around the world on the use of EAHX for air refreshment and preheating in buildings (Santamouris & Kolokotsa 2013; Hollmuller & Lachal 2014; Santamouris et al. 2007; Bansal et al. 2013; Al-Ajmi et al. 2006; Givoni 2007; Kumar et al. 2003; Hollmuller 2002; Bansal et al. 2010; Vaz et al. 2014; Mihalakakou et al. 1994). (Santamouris et al. 2007) reported data and results of 30 buildings experimental projects performed in cold, mild and hot climates around the world. Through the reported results, the benefit of the EAHX system is well established for both heating and cooling in many regions in the world. Nevertheless, it is also established that energy performances of this system greatly depend on climate and soil conditions. The dynamic thermal behavior of an EAHX is therefore not universal and then needs to be studied within the context of climatic, soil and building load conditions. The temperature of soil is known to remain constant throughout the year beyond a depth (typically 1.5 to 3 m) which depends on the local climate and the thermo physical properties of the soil. This constant temperature is called earth's undisturbed temperature which is higher than soil surface temperature in winter and lower in summer.

Regarding mathematical modeling of the EAHX several models consider the single pipe exchanger problem with a cylinder of ground around it (Kumar et al. 2003; Mihalakakou et al. 1994). The model of (Mihalakakou et al. 1994) is based on heat and mass transfer conservation equations with a discretization of the ground in concentric cylinders and axial meshes. The authors use a weighted residuals method with a control volume formulation to get algebraic equations. The latter are solved using the Gauss-Seidel iterative method. (Hollmuller & Lachal 2005) developed a model on this basis. It can consider geometries that are more complex, more ground characteristics and more boundary conditions. It uses the finite differences method. This model may also consider water infiltrations, pressure losses and the control of the direction of air-flow in the pipes and integration into the TRNSYS software environment through Type 460 (Klein 2000).

The objective of this paper is to report and analyze the results of an experimental and numerical study of an EAHX connected to a villa type house located in Marrakech (Morocco) suburb.

DESCRIPTION OF THE EAHX

The EAHX is constituted of 3 parallel and identical PVC pipes of 72 m length each and 15/16 cm inside/outside diameter, buried at 2.2-3.2 m.

The pipes are equidistant with an inter-space of about 14 cm. The vertical ascending parts of the pipe are thermally insulated with 4 cm of polystyrene. Each pipe is equipped by a 44-90 W fan at its entrance located inside a technical shed with openings protected by mosquito netting. The EAHX is installed in a villa type house, called, AMYS located in the suburb of Marrakech (31°37' N latitude and 8°2' W longitude). Two of the pipes are connected to the first floor and the third is connected to the second floor of the house. Figure 1 presents a sketch of the EAHX and its connection to the house. The details of the implementation of the EAHX are presented in Fig. 2.

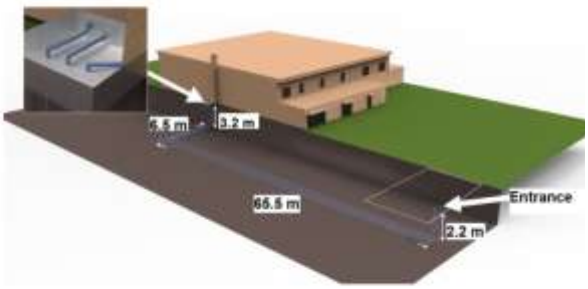

Figure 1: Schematic diagram of the EAHX.

Figure 2: Implementation details of the EAHX.

EXPERIMENTAL PROTOCOL

One pipe of the EAHX was monitored during 38 days of summer 2013, from June 29th to August 5th. During this monitoring, the fans of the two non-monitored pipes were off, except for few hours during some hot days. Two fan powers were tested (44 W and 90 W). The results presented here concern the 44 W fan that procures an air mass flow rate of 244 m^3/h, which corresponds to an air velocity of 4 $m.s^{-1}$ inside the pipe.

The monitoring of the EAHX was conducted through eight dataloggers TESTO174T installed inside the horizontal part of the monitored pipe. These dataloggers, that measure air temperature every 15 min, are fixed to a metallic support well attached to a rope to avoid dataloggers contact with the pipe. The positions of the dataloggers are given in Table 1.

Table 1
Dataloggers axial positions inside the EAHX pipe

DATALOGGER N°	1	2	3	4	5	6	7	8
Position (m)	0	1	3	7	15	31	63	72

It is important to mention that the probe of the dataloggers is protected from radiation. It was carefully checked that the probes measure air temperature.

Two other dataloggers, measuring air temperature and humidity (TESTO174H), were placed in the technical shed and the blowing vent inside the house. The former was suspended at 50 cm from the pipe entrance. It measures ambient air temperature and humidity at the EAHX entrance. The latter measures blown temperature and humidity inside the house.

A weather station was installed on the roof of the technical shed. It measure ambient air temperature and humidity, global solar irradiation, wind velocity and direction. Figure 3, shows the monthly averaged ambient air temperature and global solar radiation during the period from July 1st 2013 to June 30th 2014.

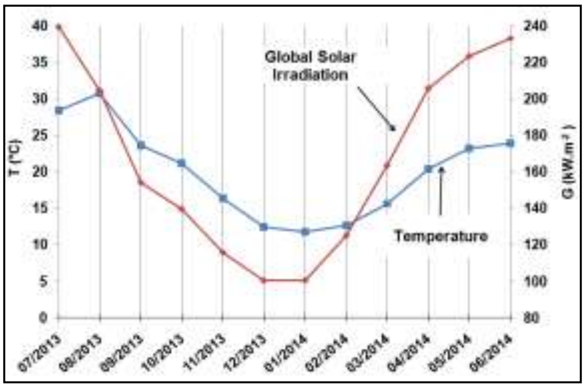

Figure 3: Monthly averaged ambient temperature and solar global irradiation on a horizontal plane (On site measurement, AMYS weather Station).

MATHEMATICAL MODEL AND NUMERICAL METHOD

The numerical study was carried out using thermal modelling of the EAHX by means of the so-called Type 460 developed by (Hollmuller and Lachal 2005) within the TRNSYS software environment (Klein 2000). The vertical parts of the EAHX and the inclination of the pipes are not considered in this study. The pipes are assumed equally spaced with an inter-space of 14 cm and buried at 2.85 m. The soil is assumed homogeneous. Its thermo-physical proprieties are given in Table 2.

In Type 460 model the transient 3D heat diffusion in soil, is considered. Air temperature and velocity are assumed uniform within a pipe section. The frictional losses are taken into account by means of a friction factor obtained from the Moody's diagram. Mass transfer corresponding to phase change (condensation/evaporation) is calculated by the Lewis analogy. Air heat exchange between soil and the pipe is treated by means of an overall convective coefficient, which depends only on air velocity.

Details of Type 460 model are given in (Hollmuller & Lachal 2005). This type has been validated against analytical solution and long term monitoring data from real scale installations.

Table 2
Thermo-physical properties

Material	Density (kg/m³)	Heat capacity kJ/(K.m³)	Thermal conductivity W/(m.K)
Soil	1 415	1 319	1.28
PVC	1 560	476.65	0.2
Air *	1.16	1.17	0.026

(*) Proprieties for T = 27 °C. These proprieties are considered to vary with temperature in the used computer code.

RESULTS AND DISCUSSION

Monitoring Results

Figure 4 shows time variations of the hourly averaged supply air temperature (measured at the pipe outlet at 72 m) during 6 days of summer 2013 (June 30th -5th 2013). Ambient air temperature (measured inside the technical shed at 50 cm above the pipe inlet) is also reported. It can be seen that air is supplied at a quasi-constant temperature of 21.8°C. Indeed outlet air temperature varies between 22.6°C and 20.8°C with day amplitude around 0.15°C. On the other hand, hourly averaged ambient air temperature varies between 37.4 °C and 23.8 °C with day amplitude that may reach 6.3°C.

Figure 5 illustrates air temperature profiles inside the monitored pipe during the day of July 15th 2013. Axial position x = 0 corresponds to the entrance of the horizontal part of the pipe buried at 2.20 m. During the whole day, air temperature tends to a constant value around 22°C at the outlet of the horizontal part of the pipe buried at 3.2m. Air temperature inside the pipe falls below 25°C throughout the day at an axial position around 40m. At the beginning of the day (4:00-8:00 AM), air is slightly heated along the first 15m of the buried pipe and then cooled to the outlet temperature of 22°C. Indeed, ambient air is cooler than soil at these moments and the EAHX is not needed. This point will be addressed in the following sections.

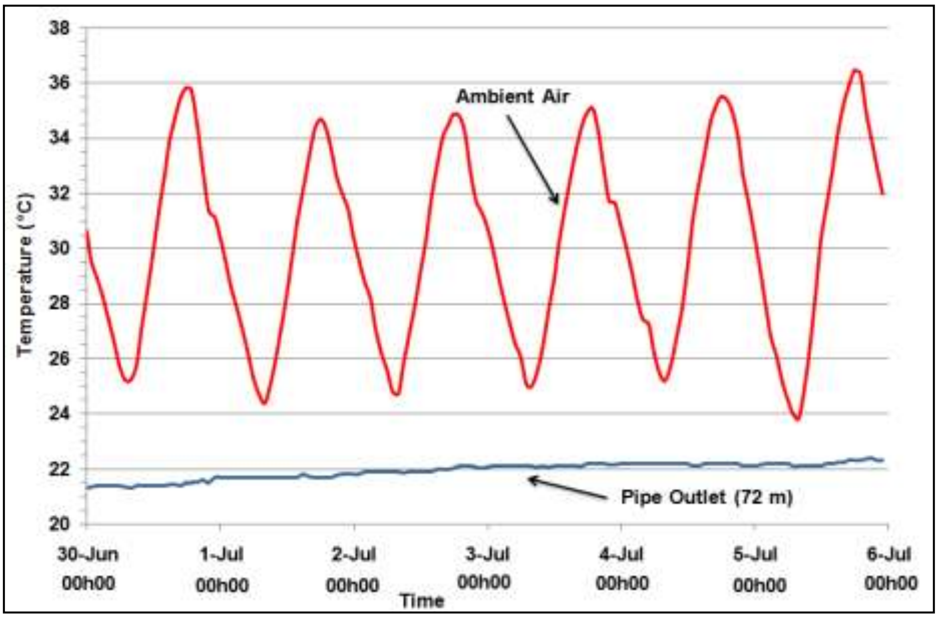

Figure 4: Time variation of the hourly averaged air temperature

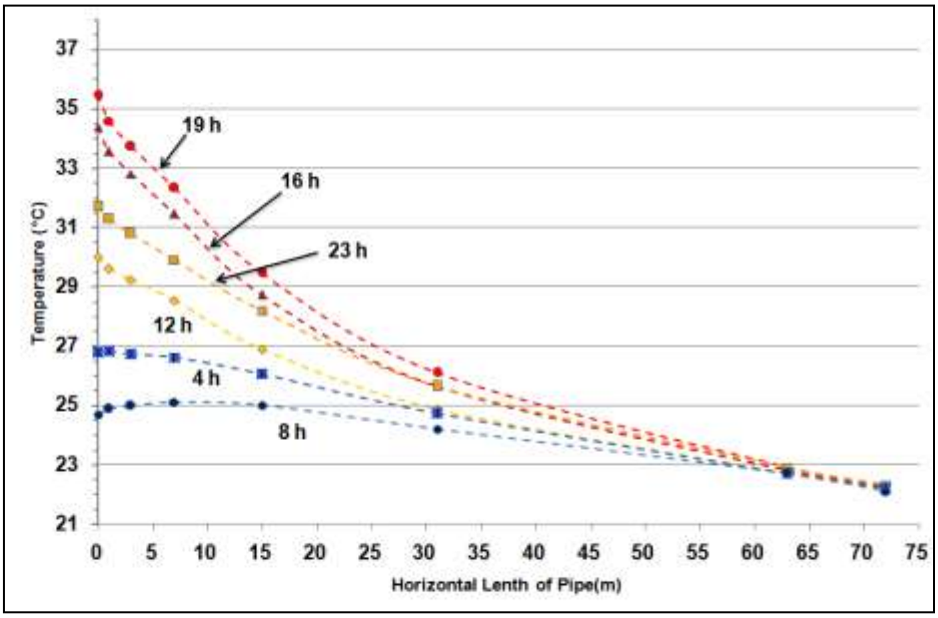

Figure 5: Air temperature profiles along the horizontal part of the monitored pipe during the day of June 5th 2013 (244 m³/h).

Comparison of monitoring and simulation results

A one-year simulation of the EAHX was carried out for Marrakech weather conditions with a time step of 1h. The simulation is repeated two times to ensure that the soil temperature is well estimated. In order to validate the results against the experimental ones, the simulation concerned the monitored pipe with the fan running during the 38 days monitoring period.

Figure 6 shows the time variation of the measured and calculated air temperature at two axial positions. It can be seen that calculated air temperatures at 1 m is in excellent agreement with the measured temperature. Indeed standard deviation is below 0.3 K. Calculated and measured air temperature at 72 m match well, as the corresponding standard deviation is below 0.4 K. It is important to mention that the mathematical model slightly underestimate air temperature at the pipe outlet (72 m). This is attributed to the soil thermo-physical properties, which are roughly estimated and taken constants in the model. The soil thermo-physical properties of the soil are going to be measured in the future.

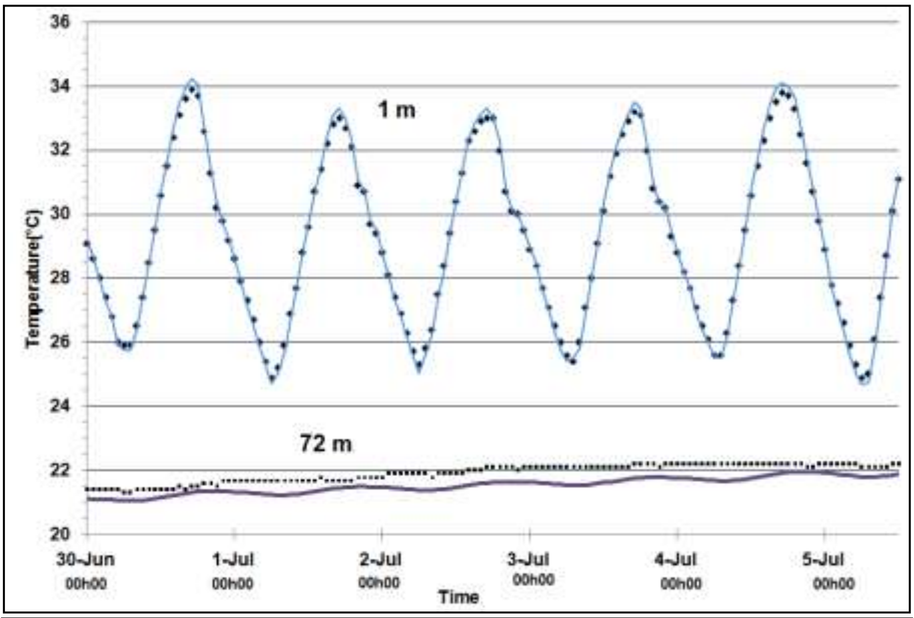

Figure 6: Comparison of the monitoring (Symbols) and simulation (Continuous lines) results at two axial positions for (244 m³/h) airflow rate.

Figure 7 shows a comparison of monitoring and simulation results for air temperature profiles along the pipe during the typical day of July 5th. It is found that the simulation and measurement results are in good agreement especially during hot hours of the day. On the other hand, the mathematical model does not well predict the slight heating of air at the pipe entrance ik the beginning of the day. Although this phenomenon is marginal, it is attributed to the soil physical proprieties.

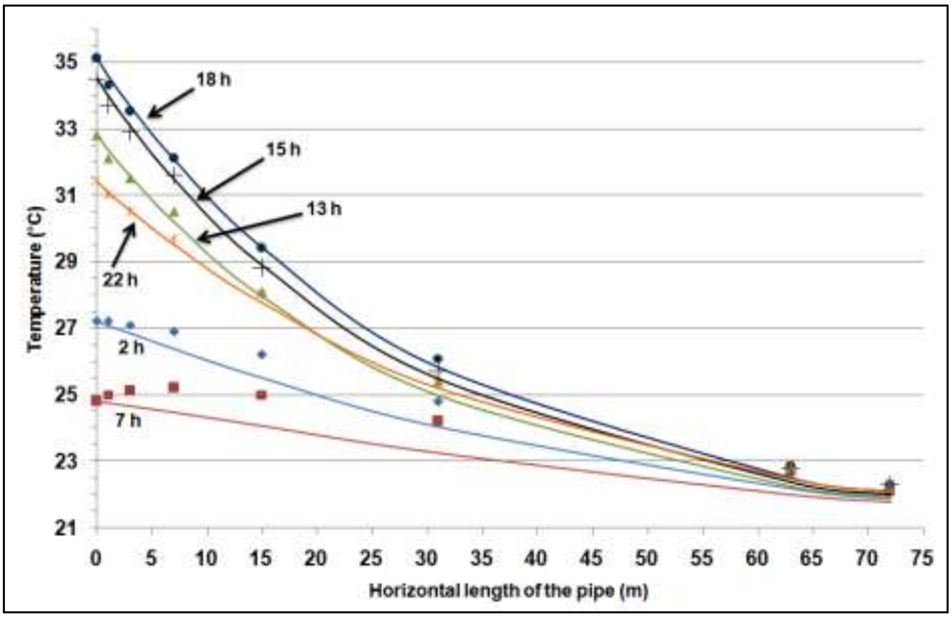

Figure 7: Comparison of monitoring (symbols) and simulation results (lines) for air temperature profiles along the pipe during the day of June 5th 2013 *(244 m³/h).*

Simulation results

The simulation results in this section concern one pipe EAHX continuously running during the whole simulation period (July 1st 2013/June 30th 2014).

Figure 8 shows that the temperature at the exit of the EAHX varies between 16.7°C and 26.5 °C. This annual minimum occurred on December 30th, while the ambient air temperature was 4.2°C. The annual maximum occurred on September 3rd, while the ambient air temperature was 36.7°C. Thus, the annual amplitude of the outlet EAHX air temperature is 4.9°C, while the corresponding amplitude for the ambient air temperature is 22.3°C. Typical air temperatures obtained at the exit of the EAHX varies between 19.6°C and 22.7°C during the hot months (May-September), while the maximum ambient air temperature oscillates between 45°C and 25°C. Thus, the maximum drop in air temperature procured by the EAHX is 19.8°C, which corresponds to an outlet air temperature of 24.8°C and ambient air temperature of 44.6°C. This maximum temperature drop occurs at 4:00 PM of the 31st of July.

These results show that the EAHX is an efficient system for building air refreshment for Marrakech climate. This system procures an acceptable air temperature for human comfort during the hot season (May-September).

During the cold months (Dec-Feb), Fig. 6 reveals that air temperature at the exit of the EAHX varies between 16.7 °C and 21.2 °C, while the corresponding ambient air temperature oscillates between 4.2 °C and 11.9 °C. These results show that the EAHX is not the most efficient system for air heating in Marrakech. Other passive systems installed in the studied house procure more efficient comfort (Benhamou & Bennouna 2013).

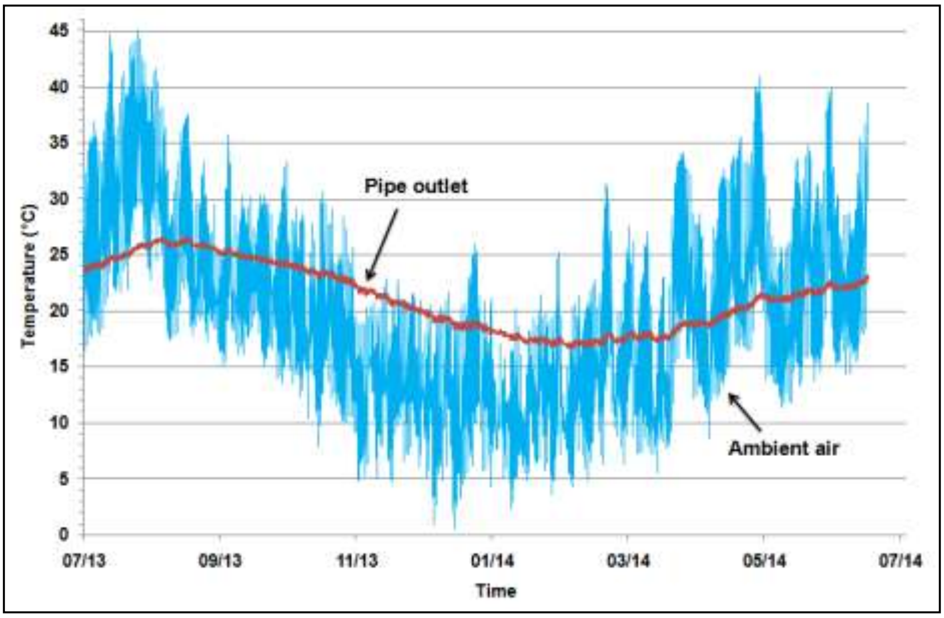

Figure 8: Annual variation of the ambient air and pipe outlet (72 m) air temperature (July 2013/June 2014).

CONCLUSION

In this paper, the results of an experimental and numerical study of an Earth-to-Air Heat Exchanger (EAHX) dedicated to air refreshment of a house in Marrakech are presented and analyzed. Air temperature measurements, conducted during 38 days of summer 2013 inside one of the three EAHX pipes, show that this semi-passive system procures comfortable air to the house. Indeed, while the outside air temperature reaches more than 37°C, the pipe outlet air temperature, burried at 3.2m, was around 22°C and air was supplied to the house at a quasi-constant temperature of 25°C. One-year dynamic simulation, using Type 460 of TRNSYS software, was performed. Simulation results are in good agreement with the experimental ones. Dynamic simulation of The EAHX shows that this systeme provides air temperature reduction up to 19.8°C with mass flow rate of 244 m^3/h, which corresponds to 4 $m.s^{-1}$ air velocity inside the pipe.

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