Experimental and numerical study of an earth-to-air heat exchanger for air cooling in a residential building in hot semi-arid climate

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Abstract

This work deals with an experimental and numerical study of an Earth-to-Air Heat Exchanger (EAHX) for air cooling, connected to a residential building located in Marrakech (Morocco) which climate is a hot semi-arid one. 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 blows treated air into the building. The experimental study consists of summer monitoring of the EAHX via measurements of air temperature and humidity throughout the exchanger, as well as at its inlet and outlet to the building for two fixed values of the airflow rate. The experimental results show that the EAHX is a good semi-passive system for air refreshment, as the recorded blown air temperature into the building is quasi-constant at 25 °C with air humidity around 40%, even though the outside temperature reaches more than 40 °C. Furthermore, the reduction of daily and annual air temperature amplitudes is characterized by an exponential drop as a function of pipe length. The characteristic length is found to be around 20 m and 70 m [...]
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EXPERIMENTAL AND NUMERICAL STUDY OF AN EARTH-TO-AIR HEAT EXCHANGER FOR AIR COOLING IN A RESIDENTIAL BUILDING IN HOT SEMI-ARID CLIMATE

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Highlights

Experimental and dynamic simulation studies of a three parallel pipes Earth-to-Air Heat Exchanger (EAHX) for air cooling connected to a residential building in Marrakech (Morocco) were performed. Air temperature and humidity throughout one pipe of the EAHX, as well as at its entrance and exit to the building for two fixed values of the airflow rate were measured during 24 days of summer. Blown air temperature to the building from the EAHX is quasi-constant and does not exceed 25 °C with air humidity around 40%, even though the outside temperature reaches more than 40°C. The characteristic length for the reduction of daily and annual air temperature amplitudes is found to be around 20m and 70m respectively. Good agreement was found between the simulation and experimental results. Dynamic simulations of continuously running EAHX show that its maximum specific cooling capacity is 58.2 W/m² (for one pipe) and 54.6 W/m² (for three pipes) obtained for air temperatures of 25 °C and 26 °C respectively, at the EAHX outlet and 44.6 °C at its inlet.
ABSTRACT

This work deals with an experimental and numerical study of an Earth-to-Air Heat Exchanger (EAHX) for air cooling, connected to a residential building located in Marrakech (Morocco) which climate is a hot semi-arid one. 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 blows treated air into the building. The experimental study consists of summer monitoring of the EAHX via measurements of air temperature and humidity throughout the exchanger, as well as at its inlet and outlet to the building for two fixed values of the airflow rate. The experimental results show that the EAHX is a good semi-passive system for air refreshment, as the recorded blown air temperature in to the building is quasi-constant at 25 °C with air humidity around 40%, even though the outside temperature reaches more than 40 °C. Furthermore, the reduction of daily and annual air temperature amplitudes is characterized by an exponential drop as a function of pipe length. The characteristic length is found to be around 20m and 70m respectively for the daily and annual air temperature amplitudes reduction. Moreover, it is shown that the design guidelines from literature cannot straightforwardly be applied to an EAHX which is subject to meteorological disturbance from the upper surface and/or which is not operated all year round, for which numerical simulation with a validated models remains necessary.

On the other hand, dynamic simulations of the EAHX using TRNSYS software (TYPE 460) were performed with one pipe or three pipes continuously running. Good agreement was found between the simulation and experimental results. Simulation results show that the EAHX can perform a maximum drop of air temperature as high as 19.5 °C and 18.3 °C respectively for an EAHX with one and three pipes. The achieving specific cooling capacity is 58 W/m² (one pipe) and 55 W/m² (three pipes) obtained for air temperatures of 25 °C and 26 °C respectively, at the EAHX outlet and 44.6 °C at its inlet.

Keywords: TRNSYS, air cooling, monitoring, EAHX, residential building

NOMENCLATURE

\( c \) Specific heat (J.kg\(^{-1}\).K\(^{-1}\))
\( d \) Tube diameter (m)
\( f \) Friction factor
\( G \) Global solar radiation on a horizontal surface (kWh.m\(^{-2}\))
\( Gm \) Daily mean global solar radiation on a horizontal surface (kW.m\(^{-2}\))
\( h \) Heat transfer coefficient (W.K\(^{-1}\).m\(^{-2}\))
\( h_{fg} \) Latent heat of vaporization (J.kg\(^{-1}\))
\( k \) Thermal conductivity (W.K\(^{-1}\).m\(^{-1}\))
\( L \) Length of the horizontal part of the pipe (m)
\( M \) Molar mass (kg.mol\(^{-1}\))
\( m \) Mass (kg)
\( m_{\text{conv}} \) Air/tube convective mass exchange (kg.s\(^{-1}\))
\( N \) Number of the EAHX running pipes (= 1 or 3)
\( Nu \) Nusselt number (= h.d.k\(^{-1}\))
\( Q_{\text{cooling}} \) Specific cooling capacity (W.m\(^{-2}\))
\( Q_{\text{fric}} \) Friction losses (W)
\( Q_{\text{lt}} \) Latent heat transfer rate (W)
\( Q_{s} \) Sensible heat transfer rate (W)
\( Q_{\text{diff}} \) Heat diffusion rate (W)
\( Q_{\text{int}} \) Heat gain of the pipe (W)
\( P \) Pressure (Pa)
\( Pr \) Prandtl number (= ν/α)
\( Re \) Reynolds number (= 4.\( m_{\text{conv}} \)/(π.d.ρ.v) )
$S$  Lateral node surface (m²)
$S_l$  Total lateral inner area of the running pipes ($S_l = N \cdot \pi \cdot d \cdot l$) (m²)
$S_{pipe}$  Lateral surface of the pipe at a given pipe node (m²)
$T$  Temperature (K)
$T_{day}$  Daily air temperature at a given axial position of the pipe (K)
$T_{year,avg}$  Average annual air temperature (K)
$t$  Time (s)
$v$  Velocity (m/s)
$V$  Node volume, m³
$x$  Position along the pipe axis (m)

Greek symbols
$\alpha$  Thermal diffusivity (m²/s)
$\Delta t$  Time step (s)
$\Delta T$  Air temperature amplitude (K)
$\phi$  Relative humidity (%)  
$\nu$  Kinematic diffusivity (m²/s)
$\theta$  Relative air temperature amplitude
$\rho$  Density (kg/m³)
$\omega$  Humidity ratio of air (kg of water vapor/kg of air)

Subscripts
$\text{air}$  air
$\text{amb}$  ambient air
$\text{avg}$  average
$\text{lat}$  latent (condensation/evaporation)
$\text{max}$  maximum
$\text{min}$  minimum
$\text{pipe}$  pipe
$\text{sat}$  saturation
$\text{soil}$  soil
$\text{surf}$  soil surface
$\text{vap}$  vapor
$\text{wat}$  water
$\text{in}$  at the inlet of the horizontal part of the pipe ($x = 0$)
$\text{out}$  at the outlet of the horizontal part of the pipe ($x = 72$ m)
1. INTRODUCTION

The use of conventional electric air conditioning systems became very popular worldwide. This leads to a huge increase of electricity consumption and the Electric Peak load. Cooling demand is one of the significant responsible of such situation in many countries with hot climates such as in Morocco. Indeed, buildings represent about 51% of electricity consumption in Morocco with 33% for residential buildings [1]. The national agency for renewable energies and energy efficiency [2] has developed a strategy for energy efficiency in the most energy consumer sectors, including residential buildings. One of the main objectives of this strategy is to integrate passive systems, such as thermal insulation and solar protection, to the new buildings starting from November 2015. It is believed that, in some climate zones of the country, such as Z5 (Marrakech) [3], passive or hybrid heat dissipation techniques have to be considered.

One of these interesting techniques consists in forcing air from outdoor through buried pipes for dampening its temperature oscillations, the soil serving as an energy buffer [4,5]. As a matter of fact, beyond a certain depth (typically 2 to 3 m, depending on the thermos-physical properties of the soil) the temperature of the soil is known to remain fairly constant throughout the year, at a value close to the local annual meteorological average [6]. This constant temperature, called earth’s undisturbed temperature, is higher than the soil surface temperature in winter and lower in summer. Mostly known in the literature as Earth-to-Air Heat Exchanger (EAHX), this system is also called, air-soil heat exchanger, earth–air tunnel, buried pipe system or underground air tunnel.

Experimental projects and guidelines

The concept of using the soil as a heat sink was used many centuries ago. For example, in ancient time, Iranian architects used wind towers and underground air tunnels as passive climate control technique [7]. Nowadays, the EAHX is in use around the world as one of the current settlements to the problem of rational use of energy and comfort control in buildings, due to their higher energy efficiency compared to the conventional heating and cooling systems. Significant research, both experimental and theoretical, has been carried out on the use of EAHX for air refreshment in buildings. Santamouris and Kolokotsa [6] reported data and results of 30 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 cooling and heating in many regions. However, these energy performances depend highly on climate and soil conditions. Recently, Soni et al. [8] performed a literature review of performances evaluation of ground coupled heat exchangers including the EAHX. The authors reported experimental as well as numerical investigations on EAHX alone or coupled with other active/passive systems such as electrical air conditioner, wind catcher, solar chimney and solar duct heater. One of the main conclusions of the authors is that the EAHX performances are significantly affected by the soil conditions rather than by the material of the buried pipes.

Vaz and co-workers [9,10] investigated, experimentally and numerically, the thermal behavior of an EAHX coupled to a built environment, located in the city of Viamão (southern Brazil, with humid subtropical climate). Based on the experimental work of Vaz et al. [9], Brum et al. [11] developed a so-called “reduced model” to predict the thermal performance of the EAHX. This model was used to study the potential of heating/cooling of soil in the city of Viamão. Hollmuller and Lachal [12] analyzed the constraints and potential of buried pipe systems for the case of a typical Central European climate (Geneva, Switzerland), with cold winters and warm summers, pointing out the distinct issues linked to preheating (winter) and cooling (summer). Finally, some authors examine the combination of EAHX with evaporative cooling [13].

Several experimental and/or numerical studies on the EAHX cooling performances in hot climate, such as one of Marrakech (Morocco), have been performed through the world [9–11,14–21]. All of these studies concluded on the very interesting performances of the EAHX
for air cooling, although these performances depend on many parameters, in particular the soil properties and the local climate.

Hollmuller and Lachal [5] analyze various aspects of EAHX for heating and cooling of buildings. Based on an analytical model with explicit treatment of heat diffusion in the soil, the authors derive climate independent design guidelines, for dampening of the daily and/or the yearly temperature oscillation carried by the air flow inside the buried pipes. However, these guidelines do not take into account the effect of the meteorological temperature and solar radiation on the upper surface, nor of discontinuous airflow. A specific study on the thermal saturation and recovery of the soil under intermittent and continuous EAHX operation is performed by Mathur et al.[22].

Models

In the 80s and early 90s of the last century, most authors were dimensioning air/soil heat exchangers by way of simple static exchange models [23–26]. Although such models are easy to handle, the overall air/soil heat transfer coefficient is evaluated by way of diverse suppositions which do not explicitly take into account the complex phenomenon of heat diffusion in the soil, resulting in inaccurate calculation of transient regimes. As a notable step forward, Hollmuller [27] resolved the case of a constant airflow submitted to sinusoidal temperature oscillation at entrance of a cylindrical pipe, with explicit treatment of heat diffusion in a finite cylindrical soil layer, with adiabatic or isothermal boundary condition. The authors integrated this analytical solution in a pre-design tool for easy and fast calculation of the hourly temperature output over an entire year [5], taking into account all the frequencies embedded in the meteorological dynamic. As pointed out above, this model does however not take into account the effect of the meteorological temperature and solar irradiation on the upper surface.

As a complementary approach, many authors report on the development of numerical models. Most of these models are based on finite differences. Some of them are limited to the description of only one “typical” pipe [14, 18, 28–31]. Others deal with several parallel running pipes, with or without possibility to treat more complicated cases than steady state flow rate, homogenous and laterally adiabatic soils, or sole sensible heat exchange [32–35]. As far as validation is concerned, it usually remains limited to a few hours or days and does generally only concern lab-operated installations. In this context, Hollmuller and Lachal [36] developed a revised version of the numerical model of Boulard et al. [33, 37]. In addition to the simultaneous sensible-latent heat transfer and fully 3D heat diffusion in soil, the new model account for various geometries, soil properties and border conditions, as well as frictional losses, possible water infiltration and control of airflow direction. The TYPE 460 model was adapted to TRNSYS software, a modular environment for transient simulation of energy systems, allowing for links to the pre-existing modules like buildings [38]. TYPE 460 has been thoroughly validated against: i) an analytical solution concerning heat diffusion of a single buried pipe subject to sinusoidal temperature variation at pipe inlet; ii) long term monitoring data (one year or more) of two EAHX systems operated in real conditions [39]. However, both these systems were situated underneath a building, so that the model was up to now not confronted to monitoring data of an EAHX buried underneath a free upper surface, under the influence of ambient temperature and solar radiation, as will be the case in this study.

Objectives

As stated above, it is well established that energy performances of the EAHX depend highly 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. In this context, the first 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) with 3 buried pipes running 2-3 m below the outdoor area. As a specific innovative contribution, we will characterize the reduction of daily and annual meteorological amplitudes as a function of pipe length, and compare the results with previously established theoretical guidelines. As a second objective, confrontation of monitoring data with the above referenced TYPE 460 numerical model will allow to extend latter’s validation to a situation where the upper surface is under the influence of ambient temperature and solar radiation. Finally, we will use the TYPE 460 model for carrying out a sensitivity analysis concerning: i) continuous operation (365/365 days) versus operation during the summer period only; ii) the use of 1 versus 3 parallel running pipes, with the induced interaction between the pipes.

2. DESCRIPTION OF THE EAHX

The EAHX considered in this study is installed in a villa type house, called AMYS, located in the suburbs of Marrakech (31°37’ N latitude and 8°2’ W longitude). The EAHX is constituted of three parallel U-form PVC pipes of 77.7 m length each (vertical parts included) and 15 cm inside diameter with 0.5 cm thickness. The pipes are buried at 2.2 to 3.5 m. They are equidistant with an inter-space of about 14 cm. The vertical ascending parts of the pipe are thermally insulated with 4 cm of expanded polystyrene. Each pipe is equipped with a fan at its inlet, located inside a technical shed with openings protected by mosquito netting. Two of the pipes are connected to the first floor of the building 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.

For the numerical study, the vertical parts and the inclination of the pipes are not considered. Thus the EAHX is assumed to be constituted by 3 parallel pipes of 72 m length each. The pipes are assumed horizontal, equally spaced with an inter-space of 14 cm and buried at the mean depth of 2.85 m (Fig. 3). The thermo-physical characteristics of the soil and the pipe are assumed constants; they are reported in Table 1.

3. NUMERICAL MODEL

The numerical study is carried out with TYPE 460, a finite element model adapted to the TRNSYS software environment, developed by Hollmuller [36, 39]. Sensible and latent heat transfers between the airflow and the pipe are the heart of TYPE 460 (Fig. 4). They are combined with transient 3D thermal diffusion in the soil, by way of a finite element numerical method with orthogonal meshing. Simulation covers two consecutive years, of which the first one serves only for thermal conditioning of the soil, in relation with the outdoor air variation at the upper surface. The overall computing scheme of the model is presented in Fig. 5.

So as to be flexible, the orthogonal meshing allows for variable node widths in all three dimensions. Circular tubes are represented by way of equivalent square sections, lateral exchange surface being computed by way of an adequate corrective factor. Air temperature and velocity are assumed to be uniform within a pipe section. Heat exchange between the airflow and the pipe is treated by means of an overall convective coefficient, which depends on the velocity. The related mass transfer, which corresponds to phase change (condensation/evaporation), is calculated by the Lewis analogy. The thermal effect of the frictional losses is taken into account by means of a friction factor obtained from the Moody’s diagram.

The main equations of the mathematical model concern the airflow-pipe transfer, which is computed consecutively for each tube node, from inlet towards outlet. For each tube node, the sensible heat lost by the airflow is [37],

\[ Q_s = S_{pipe} h (T_{air} - T_{pipe}) \]  

The convective heat transfer coefficient is calculated according to the Gnielinski correlation [40].
\[ h = \frac{k_{\text{air}}}{d} Nu \]  

\[ Nu = 0.0214 \left( \text{Re}^{0.8} - 100 \right) \text{Pr}^{0.4} \left( 1 + \left( \frac{d}{L} \right)^{2/3} \right) \left( \frac{T_{\text{air}}}{T_{\text{pipe}}} \right)^{0.45} \]  

The latent heat transfers are calculated using the Lewis heat-mass transfer analogy. The former sensible heat (Eq. 1) is considered to result from convective transfer between the flow and a superficial air layer on the tube surface, at latter's temperature and saturated in humidity (Fig. 4). Thus, Lewis analogy gives the exchanged air mass rate [41],

\[ \dot{m}_{\text{conv}} = \frac{Q_s}{c_{\text{air}}(T_{\text{air}} - T_{\text{pipe}})} \]  

This air exchange induces water vapor transfer, which is determined by the difference in humidity ratios of the main air flow and the superficial saturated air layer,

\[ \dot{m}_{\text{lat}} = (\omega_{\text{air}} - \omega_{\text{pipe}}) \dot{m}_{\text{conv}} \]  

where \( \omega_{\text{pipe}} \) is the humidity ratio of the saturated air layer above the condensed water vapor (Fig. 4), which is assumed to be at the pipe’s temperature.

According to the perfect gases law [42],

\[ \omega_{\text{air}} = \frac{\phi P_{\text{sat}}(T_{\text{air}}) M_{\text{wat}}}{P_{\text{air}} M_{\text{air}}} \]  

\[ \omega_{\text{pipe}} = \frac{100\% P_{\text{sat}}(T_{\text{pipe}}) M_{\text{wat}}}{P_{\text{air}} M_{\text{air}}} \]  

Positive values of the mass transfer flow rate \( \dot{m}_{\text{lat}} \) correspond to vapor condensation, while negative values correspond to evaporation of the free water. The associated latent heat transfer is,

\[ Q_{\text{L}} = h_{fg} \dot{m}_{\text{lat}} \]  

The heat diffusion flux from the 4 lateral soil nodes and the preceding and following pipe nodes (Fig. 4) is given by,

\[ Q_{\text{diff}} = \sum_{i \in \text{soil}} S_i h_i(T_{\text{soil},i,T-\Delta t} - T_{\text{pipe}}) + \sum_{i \in \text{pipe}} S_i h_i(T_{\text{pipe},i,T-\Delta t} - T_{\text{pipe}}) \]  

The energy balance at the considered section (Fig. 4) is then,

\[ Q_{\text{in}} - (Q_{s} + Q_{\text{L}} + Q_{\text{diff}}) = 0 \]  

Where the heat gain \( Q_{\text{int}} \) at the level of the pipe (including possible free water from condensation) is given by,

\[ Q_{\text{int}} = \frac{(c_{\text{pipe}} m_{\text{pipe}} + c_{\text{wat}} m_{\text{wat},j-\Delta t})(T_{\text{pipe}} - T_{\text{pipe},j-\Delta t})}{\Delta t} \]  

The free water balance is,

\[ m_{\text{wat}} = m_{\text{wat},j-\Delta t} + \dot{m}_{\text{lat}} \Delta t \]  

Head losses are taken into account by means of a friction coefficient \( f \), for which typical values are to be found on the Moody diagram [43],

\[ Q_{\text{fric}} = \dot{m}_{\text{air}} f \frac{L}{d} \frac{v_{\text{air}}^2}{2} \]  

The preceding energy and mass balances yield the air input conditions of the next pipe node,
Computations are repeated with the same equations (Eqs. 1-15), until each pipe exit (Fig. 5). After completing this calculation for all the tubes, the finite element numerical method allows to compute the 3D thermal diffusion in the soil. Therefore, for each soil node, the heat diffusion flux from the 6 neighbor soil nodes is computed as [44],

$$Q_{diff} = \sum_i S_i h_i (T_{soil,i,t-\Delta t} - T_{soil,j,t-\Delta t})$$

From where the new node temperature can be derived,

$$T_{soil} = T_{soil,t-\Delta t} + \frac{Q_{diff} \Delta t}{c_{soil} \rho_{soil} \gamma_{soil}}$$

The model takes into account user-specified border conditions at the free upper surface (typically transient air temperature and solar absorption or adiabatic conditions), whereas lateral border conditions are adiabatic, typically 20 m away from the pipes, where the latter have no more influence on the undisturbed soil (Fig. 3). The initial temperature of soil is set to the yearly average temperature of the location.

4. DESCRIPTION OF THE MONITORING PROCEDURE

One pipe of the EAHX was monitored during 24 days of summer 2013, from June 30th to July 24th. During this monitoring, the fans of the two non-monitored pipes were off, except during a few hours of some hot days. The fan of the monitored pipe was continuously running all around the day. Two fan powers were tested, that procure airflow rates of 244 m³/h and 312 m³/h which correspond respectively to air velocities of 3.8 and 5 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 that the dataloggers enter in contact with the pipe. The dataloggers are distributed within the pipe according to a logarithmic scale. Thus, the greater number of the dataloggers was placed in the first 40 meters where the heat exchange between the soil and the air flowing in the tube is maximum. The positions of the dataloggers are given in Table 2.

Two other dataloggers, measuring air temperature and humidity (TESTO174H), were placed in the technical shed (where the EAHX entrance is located) and in the blowing vent inside the house. The first one was suspended at 50 cm from the pipe entrance. It measures ambient air temperature and humidity at the EAHX inlet. The other datalogger measures air temperature and humidity blown into the house (Fig. 6). It is important to mention that the probes of the dataloggers are protected from radiation. It was carefully checked that these probes measure actual air temperature.

Measurement uncertainties of the dataloggers for temperature and relative humidity are 0.5°C and 3%. Air flow rate values are obtained from measurement of air velocity inside the pipe using an anemometer whose measurement uncertainty is 0.2 m/s. The resulting mass flow rate error is 1%.

A weather station was installed on the roof of the technical shed. It measures ambient air temperature, humidity and pressure as well as global solar radiation, wind velocity and direction. Figure 7 shows hourly average measured ambient temperature and solar global radiation during the one year period considered in this study (July 1st 2013 to June 30th 2014). Table 3 presents some of the measured meteorological data. Notice that the minimum ambient air temperature occurs during December (0.1°C) even though this month is slightly warmer compared to January. The coldest months are December, January and February. On the other hand, the maximum of ambient air temperature occurs during August, which is the hottest
month, although the sunniest month is July. Table 3 shows that the daily mean solar radiation varies from 3.23 kWh.m$^{-2}$/days to 7.78 kWh.m$^{-2}$/days. It is important to notice, from Fig. 7, the high daily, as well as yearly, oscillations of ambient air temperature.

5. RESULTS AND DISCUSSION

5.1 MONITORING RESULTS

Overall assessment

Figure 8 shows the monitored air flow and outdoor temperature, as well as various temperatures recorded along the horizontal pipe (0 and 72 m corresponding to pipe inlet and outlet, respectively), over the 24 full days of operation of the EAHX (30 June – 23 July of 2013). On notes two distinct phases, with the airflow rate set to 244 and 312 m$^3$/h, as well as short operation discontinuities on 6, 9 and 10 July. During this hot summer monitoring period, the average outdoor temperature is 30.7 $^\circ$C. It reaches between 34 and 40 $^\circ$C during the day, and rarely drops below 26 $^\circ$C during the night. The effect of blowing the air through the EAHX is twofold: i/ as the air moves along the pipe and benefits from the thermal inertia of the soil, the daily oscillations (peak-to-peak difference) are drastically reduced, from an average of 9.8 $^\circ$C at pipe inlet to 0.3 $^\circ$C at pipe outlet; ii/ at the same time the average daily temperature is also decreasing, from an average of 30.7 $^\circ$C at pipe inlet to an average of 23.2 $^\circ$C at pipe outlet. At pipe outlet, the temperature hence remains fairly constant and comfortable, along the entire period (between 21.3 and 24.1 $^\circ$C). Despite a drop of the average inlet temperature towards the end of the monitoring period, we observe a 3 $^\circ$C average rise at pipe outlet. In principle this results from a combination of following three factors: i/ thermal inertia of the EAHX, which induces a delayed thermal response to the operation start (29 June) and to the outdoor heat wave (7 – 11 July); ii/ absorption of solar radiation on the upper surface, which accumulates in the soil over the summer; (iii) enhanced airflow rate (starting on 7 July), resulting in a smaller specific exchange surface (pipe) and storage volume (soil).

Figure 9 shows the evolution of the relative humidity (top part of the figure) as well as the associated water vapor pressure (bottom part of the figure), at pipe inlet and outlet. Note that the humidity sensor at pipe outlet was only in operation from 14 July onwards. The relative inlet humidity is low: approximately 40 – 50% during the day, respectively 10 – 20% during the night, which is typical of the semi-arid climate of Marrakech. At pipe outlet, the relative humidity has a smaller amplitude and is somewhat higher than at pipe inlet, but remains way below saturation. This indicates that no condensation/evaporation is at work inside the EAHX. Such is confirmed: (i) by comparing the inlet and outlet water vapor pressures, which are very similar to each other (same water vapor content), the apparent discrepancy (maximum of 0.3 hPa) remaining within the 3% monitoring precision of the humidity sensors; (ii) by numeric simulation (see section 5.2). Finally, the low humidity at pipe outlet indicates a potential for combination of EAHX with evaporative cooling.

Figure 10 shows the air temperature profile along the horizontal part of the EAHX, for various hours of 15 July 2013. During the whole day, recorded air temperature profiles tend to a constant value around 24 $^\circ$C at the outlet of the horizontal part of the pipe (x = 72 m). On the other hand, for the early times of the day (2:30-8:30 AM), air is slightly heated along the first 10 m of the buried pipe and then cooled to the outlet temperature of 24 $^\circ$C. Indeed, at these moments, ambient air is cooler than soil and the EAHX is not needed for air cooling. This is confirmed by temperatures of ambient and blown air into the house measured at the pipe exit into the house, inside the blowing vent recorded for the same day and shown in Fig. 11. This figure points out that the EAHX procures air at higher temperature than the outdoor ambient air starting from 1:00 AM to 9:30 AM. It is clear that there is no need for the EAHX air cooling during these night hours. However, as suggested by Mathur et al. [22], running the EAHX during night time, when ambient air temperature is lower than the soil temperature, may be used for soil temperature recovering. Furthermore, Fig. 10 shows that the EAHX
blows air to the house at a quasi-constant temperature around 25 °C, during all the day. This temperature is 1 °C higher than the one measured at the outlet of the horizontal part of the monitored pipe (Fig. 8, position x = 72 m). This slight temperature elevation is attributed to the EAHX manhole where the pipes are not insulated and exposed to solar radiation, essentially by the end of the day (Fig. 2). The recorded temperature of air blown into the house, during the whole monitoring period, showed that the EAHX is able to provide comfortable cool air to the house, all day, at around 25 °C even when the outdoor air temperature reached 40 °C.

Characterization of daily and annual amplitude reduction

Figure 10 allows to visualize the superposed reduction of the daily and annual thermal amplitudes carried by the airflow. As the air moves along the pipe: i/ the difference between the daily extremes tends to vanish; ii/ the daily average values tend to reduce, and eventually to approach the undisturbed soil temperature (i.e. the meteorological annual average), which however cannot be achieved with the available pipe length.

We now define the daily and annual air temperature amplitudes of a particular day (as well as their relative or reduced forms) as follows:

- Daily amplitude:
  \[ \Delta T_{\text{day}}(x) = \frac{1}{2} \left[ T_{\text{day,max}}(x) - T_{\text{day,min}}(x) \right] \]  
  \[ (18) \]

- Annual amplitude:
  \[ \Delta T_{\text{an}}(x) = T_{\text{day,avg}}(x) - T_{\text{year,avg}} \]  
  \[ (19) \]

- Relative daily amplitude:
  \[ \theta_{\text{day}}(x) = \frac{\Delta T_{\text{day}}(x)}{\Delta T_{\text{day}}(x = 0)} \]  
  \[ (20) \]

- Relative annual amplitude:
  \[ \theta_{\text{an}}(x) = \frac{\Delta T_{\text{an}}(x)}{\Delta T_{\text{an}}(x = 0)} \]  
  \[ (21) \]

Preceding values are calculated for all of the 24 days of the monitoring period, with the average annual temperature \( T_{\text{year,avg}} \) set to 19.1 °C, as given by the onsite meteorological data shown in Fig. 7.

Figure 12 shows separately the relative daily amplitude (left) and relative annual amplitude (right) as a function of horizontal distance. The daily values are given for each day of the monitoring period (white dots), with a focus on 15 July 2013 (black dots) which was visualized previously in Fig. 10. The exponential regressions concern the entire monitoring period. We see that both the daily and annual reductions can be characterized by an exponential drop as a function of pipe length. On the one hand, the reduction of the daily amplitude is very well characterized by the exponential regression, with a characteristic length of 20 m (pipe length for achieving a residual amplitude of \( e^{-1} = 37\% \)). On the other hand, the reduction of the annual amplitude has a rather large scattering, with an average characteristic length of about 67 m. However, what seemingly appears as scattering actually corresponds to an evolution over the monitoring period: as a matter of fact, the characteristic length varies from 45 m during the first few days (lower points of the plot) to 100 m during the last few days (upper points of the plot). Note that this behavior corresponds to the discussion of Fig. 8, where the average outlet temperature was seen to slightly increase towards the end of the monitoring period, despite a drop of the average inlet temperature, due to three factors (thermal inertia of EAHX, absorption of solar radiation, increased airflow rate).

Above results can be discussed in relation to previously developed guidelines by Hollmuller and Lachal [5]. These guidelines were developed on the basis of an analytical solution, for a constant airflow (24/24 h and 365/365 days) and in absence of disturbance from the upper surface (EAHX underneath an insulated building). For the case of a unique pipe at 3m depth and for an airflow in the range of 240 – 320 m³/h, the established guidelines
are as follows. For reduction of the daily amplitude, the characteristic length is expected to be in the range of 19 – 23 m, which is in complete agreement with the 20 m observed for our EAHX. For reduction of the annual amplitude, the characteristic length is expected to be in the range of 35 – 45 m. The upper bound remains in agreement with the 45 m observed during the first days of operation of our EAHX; it does however not correspond to the average value of 67 m observed over the entire period, and even less to the 100 m observed over the last days of operation. Let us however remind that preceding guidelines were established for an EAHX: i/ in absence of disturbance from the upper surface; ii/ with constant airflow all over the year, allowing for recharge of the soil during the winter months, which is not the case in our case study. It can be deduced that existing guidelines [5], which are handy for dimensioning of EAHX and estimation of temperature outlet, can hence not straightforwardly be applied to an EAHX which is subject to meteorological disturbance from the upper surface and/or which is not operated all year round. In such a case it is actually not even clear whether the monitored exponential drop can be extrapolated to a longer pipe, i.e. whether the pipe outlet would eventually reach the meteorological annual average. For such cases, assessment of the performance of the EAHX necessarily requires the use of numeric simulation, by way of a well validated model.

5.2 COMPARISON OF MONITORING AND SIMULATION RESULTS

The simulation described in this section concerns comparison of the numerical and experimental results (model validation). For the sake of thermal conditioning of the soil in relation with the outdoor air variation at the upper surface, the simulation covers two consecutive years, with the fan running only during the 24 days of the operating/monitoring period described above.

Figure 13 shows the monitored temperatures (full line) and simulated temperatures (dashed lines) along the pipe, over the 24 full days of operation of the second year. The airflow rate is also reported along with the short periods where the fan was off due to power outages. These short operation discontinuities were taken into account in the simulation. From Fig. 13, it can be seen that at all distances along the pipe, the monitored temperatures are very well reproduced, in terms of average temperatures, oscillation amplitudes, as well as hourly and seasonal dynamic (in particular phase-shifting of the heat wave of 7 – 10 July). Furthermore, the simulated latent heat exchange (not presented in the figure) remains null over the entire period, corroborating the fact that no condensation is at work.

The discrepancies between simulation and monitoring are further analyzed in Fig. 14, which shows the simulated versus monitored temperatures at diverse horizontal distances, in hourly values, over the entire monitoring period (top). Hourly simulation errors as a function of horizontal distance are also shown in Fig. 14 (bottom). On the basis of this figure, the main results of the validation process can be summarized as follows: i/ in average, the numerical model has a slight tendency to underestimate the monitored values; this happens in particular during the first 10 days of operation (see Fig. 13); however, the average error (average difference between simulated and monitored values) always remains below 0.5 °C (which occurs at around 30 m horizontal distance) and vanishes towards pipe outlet; (ii) the average absolute error (average absolute difference between simulated and monitored values) also remains below 0.5 °C, and decreases to 0.2 °C at pipe outlet; (iii) exceptionally, the absolute error reaches a maximum 1.3 °C at 7 m distance, but doesn’t exceed 0.6 °C at pipe outlet.

These excellent results confirm the robustness of the numerical mode, in particular for simulation of an EAHX which is subject to meteorological disturbance from the upper surface and which is not operated all year round.

5.3 SIMULATION WITH CONTINUOUS OPERATION

As an alternative to operating the EAHX with one pipe and over a restricted period only (as was the case in the experimental study), the simulation results in this section concern one or three pipes of the EAHX continuously in operation over the entire year (1st July 2013 –
30th June 2014). As mentioned above, simulations are repeated twice consecutively. The results are presented for the second run.

Figure 15 shows the hourly ambient air temperature and pipe outlet temperature, for a continuous airflow rate of 312 m$^3$/h. The outlet air temperature for three pipes is the average of all the pipes exit. While the ambient air temperature varies between 46.1 °C on the hottest summer day and 0.1°C on the coldest winter day (see Table 3), the air temperature at the EAHX outlet remains all year round between 16.7 °C and 26.5 °C (1 pipe), respectively between 14.8 °C and 29.0 °C (3 pipes). The annual minimums of the calculated air temperature at the pipe outlet occur on February 20th and January 31st respectively for one and three pipes, while the annual maximums occur on August 23rd and August 14th respectively. Thus, the annual amplitude (half of the peak-to-peak difference) of the EAHX outlet air temperature is 5.3 °C and 7.1 °C respectively for one or three pipes. These results show that the annual air temperature dampening procured by the 3 pipes is slightly less than with one pipe, as there is mutual interaction between the pipes (less storage volume per pipe). However, the daily air temperature dampening is not affected by the number of pipes. In parallel to annual and daily amplitude-dampening, one can also notice a phase shift of the extremes, which is slightly lower for the EAHX with three pipes.

**Cooling**

Figure 15 reveals that during the hot months (May-September), while the maximum ambient air temperature oscillates between 46.1 °C and 25 °C, air temperatures obtained at the EAHX outlet typically remains in the range of 19.6 – 26.8 °C (1 pipe), respectively 20.0 – 28.6 °C (3 pipes). During the hottest day (31 July 2013), when the air temperature reaches 44.6 °C, the EAHX outlet is 25.1 °C (1 pipe) and 26.3 °C (3 pipes), corresponding to respective temperature drops of 19.5 °C and 18.3 °C.

The results can also be analyzed in terms of specific cooling capacity of the studied system, defined by [45],

$$Q_{cooling} = \frac{m_{air} c_{air} (T_{in} - T_{out})}{S_i}$$  \hspace{1cm} (16)

Where $S_i$ is the total inner area of the pipes which contributes for heat transfer with the airflow. The considered mass airflow is the total flow rate over all pipes in operation.

The maximum specific cooling capacity, obtained on 31 July, is 58.2 W/m$^2$ (1 pipe) and 54.6 W/m$^2$ (3 pipes). This value is in agreement with the literature results [6]. The mean value of the specific cooling capacity during the hot months (May-September) is 19.9 W/m$^2$ (1 pipe) and 18.5 W/m$^2$ (3 pipes).

As a complement, Figure 16 presents the time variation of the calculated specific cooling capacity during a typical day of summer (July 15th, 2013), for an EAHX with 1 or 3 pipes and for two different airflow rates (244 or 312 m$^3$/h per pipe). The hourly average ambient air temperature is also reported. We see that: i/ when going from 244 to 312 m$^3$/h, the specific cooling capacity has an increase which is proportional to the flow rate; ii/ when going from 1 to 3 pipes it has a slight drop, due to the interaction between the pipes. Thus the thermal performance of the EAHX decrease as the number of pipes increases.

As a conclusion, the preceding results show that the EAHX is an efficient system for buildings air refreshment in semi-arid climates like the one of Marrakech, as it procures an acceptable air temperature for human comfort during the hot season (May-September).

**Heating**

Regarding, the heating performance of the EAHX, Figure 15 reveals during the cold months (Dec-Feb), when the minimum ambient air temperature oscillates between 0.1 °C and 11.8 °C, the EAHX outlet remains in the range of 16.3 °C - 25.0 °C (1 pipe), respectively 14.5 – 24.6 °C (3 pipes). In principle, the EAHX can hence also be considered as a suitable system for air heating in hot semi-arid climates like the one of Marrakech. In the particular case of
the AMYS house, considered in the present study, Benhamou and Bennouna [46] however showed that, thanks to direct solar gains and thermal insulation of the walls and the roof, the air temperature during the cold months never drops below 19°C, without need to operate the EAHX.

6. CONCLUSION

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 24 days in summer of 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 40 °C, the temperature of the air cooled by the EAHX and blown into the house is quasi-constant and equal to 25 °C with air humidity around 40%.

Exponential reduction of daily and annual air temperature amplitudes were characterized in terms of characteristic pipe length for reduction of the respective amplitudes by a factor e\(^{-1}\). It was shown that the design guidelines from literature cannot straightforwardly be applied to an EAHX which is subject to meteorological disturbance from the upper surface and/or which is not operated all year round, for which numerical simulation with a validated models remains necessary.

Thirdly, dynamic simulation using the TYPE 460 of TRNSYS software was performed, and the results are in good agreement with the experimental data. This results in an additional validation of TYPE 460 in a situation where the upper surface of the EAHX is under the influence of ambient temperature and solar irradiation.

Finally, dynamic simulation of the EAHX, with continuous operation of one or three pipes, shows that this system provides air temperature reductions up to 19.5 °C and 18.3 °C respectively for an EAHX with one and three pipes, with an outlet air temperature of 25.1 °C and 26.3 °C respectively, for an inlet air temperature of 44.6 °C. The present study shows that the EAHX is an efficient system for building air refreshment in semi-arid climate like in Marrakech region, as it procures an acceptable air temperature for human comfort during the hot season (May-September). Moreover, the EAHX may also be considered for air heating in such climate.

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http://www.iea.org/techno/essentials2.pdf


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Tables

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg.m(^{-3}))</th>
<th>Heat capacity (kJ.K(^{-1}).m(^{-3}))</th>
<th>Thermal conductivity (W.m(^{-1}).K(^{-1}))</th>
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<td>Air *</td>
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<td>1.17</td>
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Table 1: Physical and thermal parameters of the soil, PVC tube and air
(* Proprieties for T = 27 °C. These proprieties are considered to vary with temperature in the computer code.)
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<th>data logger</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
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<td>1</td>
<td>3</td>
<td>7</td>
<td>15</td>
<td>31</td>
<td>63</td>
<td>72 (-3,2)</td>
<td>72 (-0,2)</td>
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Table 2: Dataloggers’ axial (and vertical) positions inside the EAHX pipe.
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<thead>
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<th>Month</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>$T_{\text{mean}}$ (°C)</th>
<th>$G$ (kWh.m$^{-2}$)</th>
<th>$G_{\text{mean}}$ (kWh.m$^{-2}$.day$^{-1}$)</th>
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<tbody>
<tr>
<td>July 2013</td>
<td>45.5</td>
<td>16.2</td>
<td>28.5</td>
<td>239.42</td>
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<td>204.47</td>
<td>6.60</td>
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<tr>
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<td>15.0</td>
<td>23.6</td>
<td>154.06</td>
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<td>33.7</td>
<td>7.6</td>
<td>21.1</td>
<td>139.74</td>
<td>4.51</td>
</tr>
<tr>
<td>November 2013</td>
<td>31.1</td>
<td>3.8</td>
<td>16.3</td>
<td>115.84</td>
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<td>23.9</td>
<td>233.37</td>
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Table 3: Measured meteorological data (Marrakech, in-situ weather station)