# DYNAMIC SIMULATION OF AN EARTH-TO-AIR HEAT EXCHANGER CONNECTED TO A VILLA TYPE HOUSE IN MARRAKECH

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## ABSTRACT

This paper deals with a numerical study of the thermal performance of an Earth-to-Air Heat Exchanger (EAHX) connected to a villa type house located in Marrakech suburb. The EAHX consists of 3 parallel and identical PVC pipes of 77.7 m length each and 15 cm inside diameter. The pipes are buried at 2.2-3.5 m depth. Dynamic simulations were carried out for the year 2009 using TRNSYS software (Type 460). Typical air temperatures at the EAHX outlet are in the interval 20-28.8 °C for the hot period of the year (April-August), while for the same period, the maximum ambient air temperature often reaches 44 °C. For the hot period of the year, the EAHX procures a temperature reduction up to 17.6 °C. This study shows that the EAHX is an efficient system for building air refreshment for Marrakech climate.

## INTRODUCTION

There is significant rise in the use of air-conditioning systems in Marrakech during the last decades. This leads to a huge increase of electricity consumption and also the electric peak load. Comfort cooling consumes substantial amounts of energy in hot climates. It is established that a conditioned building consumes almost 2-3 times more energy compared to its consumption without air conditioning (Santamouris 1992). Thus, there is a necessity to reduce the thermal load of the buildings using passive or semi-passive systems. One of these systems is the Earth-to-Air Heat Exchanger (EAHX). Earth-air heat exchanger can be considered as one of the current responses to the problem of rational use of energy and comfort control in buildings. The concept of cooling using EAHX is well established, but the behavior of such system depends on climatic and soil conditions. The dynamic thermal behavior of an EAHX is therefore not universal and 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 soil. This constant temperature is called earth's undisturbed temperature which is higher than surface temperature of earth in winter season and lower in summer season.

(Givoni 2007) has shown that the potential of the EAHX system in hot climates may however be improved using various soil cooling strategies to lower the natural subsurface soil temperature such as shading, surface irrigation, surface treatment using plants and pebbles. Cooling capacity of earth air heat exchangers for domestic buildings in a desert climate was analyzed by (Ajmi et al., 2006).

(Bansal et al., 2012) developed a new concept of 'Derating factor' for assessment of thermal performance of EAHX under transient operating conditions. The authors concluded that under transient conditions, thermal performance of EAHX declines due to continuous use of EAHX for long durations.

Several models consider the single pipe exchanger problem by considering that only a cylinder of ground around the pipe is disturbed by the exchanger (Mihalakakou et al., 1994; Kumar et al., 2003). The model of (Mihalakakou et al., 1994) is based on a discretization of the ground in concentric cylinders and axial meshes. The numerical method used is described by the author as a mix of the finite differences method and the finite elements method. A model was developed on this basis by (Hollmuller and Lachal 2005); it can consider more complex geometries, more ground characteristics and more boundary conditions. It uses the finite differences method for the resolution. It can also consider water infiltrations, pressure losses and the control of the direction of air-flow in the pipes and integration into the simulation environment TRNSYS through Type460.

The aim of this paper is to study the dynamic behavior of an EAHX under Marrakech climatic and soil conditions.

After review of existing models/tools, the air-soil heat exchanger model (Type 460) developed by (Hollmuller and Lachal 2005) has been selected and adopted for this study.

## DESCRIPTION OF THE EAHX

The EAHX is constituted with 3 parallel and identical PVC pipes of 77.7 m length each, 15 cm inside diameter and 16 cm outside diameter buried at 2.2-3.5 m. Each pipe is equipped by a 70 W fan. The EAHX is installed in a villa type house located in the suburb of Marrakech (31°37' N latitude and 8°2' W longitude). Fig. 1 presents a scheme of the EAHX and its connection to the house. The details of the implementation of the EAHX are presented in Fig. 2.

Hourly measured meteorological data of Marrakech for the year 2009 (temperature, humidity and global solar radiation) have been used (Fig. 3, Table 1).

It is noticed that the minimal temperature occurs during January (-1.8 °C) even that this month is sunny compared to December. During February and December, the minimum air temperature approaches 0 °C. The coldest months are January, February and December. On the other hand, the maximal air temperature occurs during July, which is the sunniest month in 2009. Marrakech weather in 2009, began to be hot starting in March. Indeed the mean air temperature increases suddenly by 3.5 °C in this month compared to February. The hottest period in 2009 is April-August. During these five months the mean air temperature increases by about 4 °C each month, while it decreases suddenly by 4.9 °C in September. It is important to notice the great oscillation of the temperature, which is a characteristic of Marrakech climate. The peak-to-peak amplitude of these oscillations may reach 29.5 °C (in July). The minimum of this amplitude is 23.2 °C, which occurs in three months (January, February and October ). Table 1 show that the daily mean solar radiation varies from 2.76 to 6.92 kW.m$^{-2}$.

Figure 3 presents the mean monthly ambient air temperature and humidity. The mean temperature of the soil surface is also reported in this figure. This temperature is calculated by the relation given by:

$$T_{surf} = T_{amb} + R_{surf}\alpha\ G \qquad (1)$$

The soil solar absorbtivity is taken equal to 0.8. Figure 4 reveals that the soil surface mean temperature is slightly higher than the ambient air temperature, which is a result of high solar radiation (Table 1). The difference between these two temperatures oscillates between 1.13 °C and 2.75 °C.

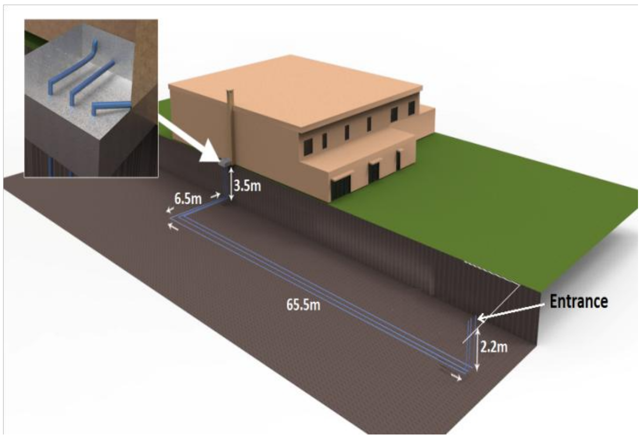

*Figure 1: Schematic of the EAHX.*

*Figure 2: Implementation details of the EAHX.*

*Table 1: Meteorological data for Marrakech in 2009 [Agdal Station]*

| Month | Tmax °C | Tmin °C | Tmean. °C | G kWh.m⁻² | Gm kWh.m⁻² |
|---|---|---|---|---|---|
| January | 21.4 | -1.8 | 8.6 | 92.86 | 3.00 |
| February | 25.0 | 1.8 | 11.8 | 104.53 | 3.73 |
| March | 30.9 | 4.4 | 15.3 | 138.28 | 4.61 |
| April | 33.9 | 4.8 | 16.4 | 188.94 | 6.09 |
| May | 34.7 | 8.2 | 20.7 | 205.25 | 6.62 |
| June | 40.9 | 12.0 | 24.5 | 198.17 | 6.61 |
| July | 44.0 | 14.5 | 28.7 | 214.42 | 6.92 |
| August | 42.5 | 15.8 | 27.0 | 204.77 | 6.61 |
| September | 36.0 | 11.4 | 21.9 | 158.08 | 5.27 |
| October | 34.6 | 11.4 | 21.3 | 138.41 | 4.46 |
| November | 30.4 | 4.6 | 15.8 | 102.54 | 3.42 |
| December | 24.3 | 0.8 | 12.7 | 85.68 | 2.76 |

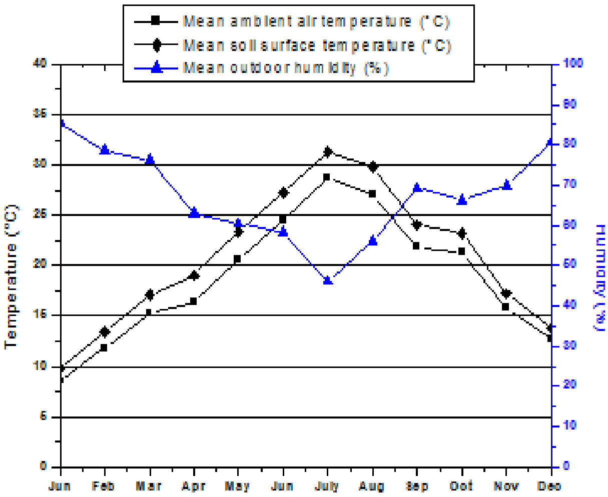

*Figure 3: Meteorological data for 2009 in Marrakech [Agdal-Marrakech Meteorological Station]*

## PHYSICAL MODEL OF THE EAHX

The vertical parts and the inclination of the pipes (Fig. 1) are not considered in this study. Thus the EAHX is assumed to be constituted by 3 parallel pipes of 72 m length each with 15 cm inside diameter and 0.5 cm thickness. The pipes are assumed horizontal, equally spaced with an inter-space of 14 cm and buried at 3 m depth (Fig. 4). The soil is considered homogenous. The thermo-physical characteristics of the soil and the pipe are given in Table 2. The airflow inside each pipe is 197 $m^3/h$. This corresponds to an average velocity of 3.1 m/s (Re = 30 667). The considered airflow procures the minimum air change required in the studied building.

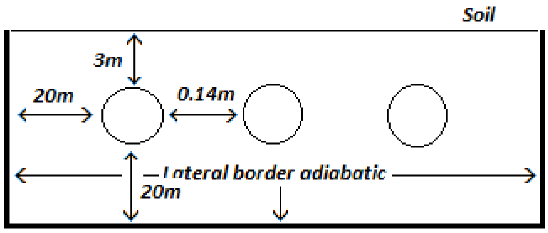

*Figure 4: Schematic diagram of the physical model of the EAHX.*

*Table 2: Physical and thermal parameters of the soil, PVC tube and Air (Incropera and De Witt 1990).*

| Material | Density $(Kg/m^3)$ | heat capacity $kJ/(k.m^3)$ | Thermal conductivity W/(m.K) |
|---|---|---|---|
| Soil | 1415 | 408 | 0.6 |
| PVC | 1560 | 476.65 | 0.197 |
| Air * | 1.1614 | 1.17 | 0.0263 |

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

## MATHEMATICAL MODEL AND NUMERICAL METHOD

This study was carried out using thermal modeling of the EAHX evaluated within the TRNSYS software (TRNSYS17 2010).

The EAHX is modeled using the finite difference numerical model developed by (Hollmuller and Lachal 2005) adapted to TRNSYS (type 460). In this model the transient 3D heat diffusion in soil, is considered. The air temperature and velocity are assumed to be 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 velocity.

The Type 460 model has been validated against analytical solution and long term monitoring data from real scale installations (Hollmuller and Lachal 2005).

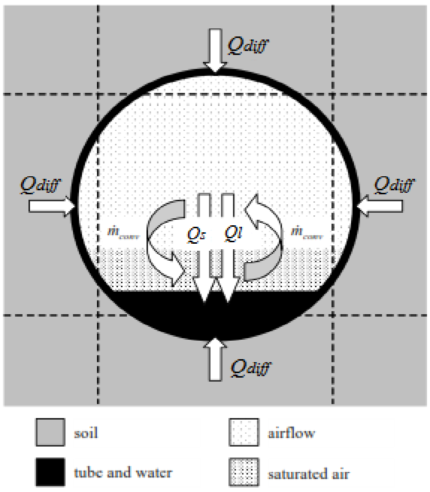

*Figure 5: Energy and mass transfer in a tube node (Hollmuller 2002).*

**Algorithm**

The heart of the Type460 model is the pipe mass and energy exchanges between airflow and pipe (Fig. 5). They are computed consecutively for each tube node, from inlet towards outlet (Hollmuller and Lachal 2005).

The sensible heat lost by the airflow is determined using Eq.2.

$$Q_s = S_{pipe} h (T_{air} - T_{pipe}) \tag{2}$$

Where:

*h* is assumed to be an affine function of air velocity. Its value is 11.76 W/ (K.m²).

The latent heat, determined by the Lewis analogy, which actually considers former sensible heat to result from a convective air exchange between the flow and a superficial air layer on the tube surface, at latter's temperature and saturated in humidity, the analogy imply following convective air exchange rate:

$$\dot{m}_{\text{cov}} = \frac{Q_s}{c_{air}(T_{air} - T_{pipe})} \tag{3}$$

The air layer is saturated in humidity, with induces a water vapor exchange.

$$\dot{m}_{lat} = (\omega_{air} - \omega_{pipe})\,\dot{\text{m}}_{\text{cov}} \tag{4}$$

Where, according to the perfect gases law:

$$\omega_{air} = \frac{\phi \text{P}_{sat}(T_{air}) M_{wat}}{\text{P}_{air} M_{air}} \tag{5}$$

$$\omega_{pipe} = \frac{100\% \, \text{P}_{sat}(T_{pipe}) M_{wat}}{\text{P}_{air} M_{air}} \tag{6}$$

When positive, this vapor transfer corresponds to condensation, when negative to evaporation.

Latent heat exchange expresses as:

$$Q_l = h_{fg}\,\dot{\text{m}}_{lat} \tag{7}$$

The heat diffusion from the 4 lateral soil nodes and the 2 preceding and following pipe nodes is given by:

$$Q_{diff} = \sum_{i \in soil} S_i k_i (T_{soil,i,t-1} - T_{pipe}) + \sum_{i \in pipe} S_i k_i (T_{\text{pipe},i,t-1} - T_{pipe}) \tag{8}$$

The saturation pressure being non-linear in terms of temperature, the value of $T_{pipe}$ as well as preceding heat rates are being determined by iterative resolution of the energy balance:

$$Q_{\text{int}} - (\text{Q}_s + Q_l + Q_{diff}) = 0 \tag{9}$$

Where the capacitive gains of the pipe and the free water are given by:

$$Q_{\text{int}} = \frac{(c_{pipe} m_{pipe} + c_{wat} m_{wat,t-1})(T_{pipe} - T_{\text{pipe},t-1})}{\Delta t} \tag{10}$$

The associated hydric balance on its turn allows determining the new water content of the node:

$$m_{wat} = m_{wat,t-1} + (\dot{\text{m}}_{\text{inf}} - \dot{m}_{lat})\Delta t \tag{11}$$

Charge losses are taken in account by way of a friction coefficient *f*, for which typical values are to be found on a Moody diagram (ASHRAE, Ch.2, 1989):

$$Q_{fric} = \dot{m}_{air}\, f \, \frac{l}{d} \, \frac{v_{air}^2}{2} \tag{12}$$

Finally, from the energy and mass balances yield the air input conditions of the pipe node:

$$T_{air,i} = T_{air} + \frac{Q_{fric} - Q_s}{(c_{air} + c_{vap}\omega_{air})\,\dot{\text{m}}_{air}} \tag{13}$$

$$\omega_{air,i} = \omega_{air} - \frac{\dot{m}_{lat}}{\dot{m}_{air}} \tag{14}$$

After completing this calculation for all tube nodes, computation treats diffusion of heat into soil nodes, taking into account user-specified boundary conditions (adiabatic, in/out flowing energy rate, temperature).

## RESULTS & DISCUSSION

A one year simulation of the EAHX is carried out for Marrakech weather conditions with a time step of 1h. The simulations are repeated 2 times to ensure that the soil temperature is well estimated. The EAHX is supposed to be run continuously in the whole simulation period (2009 year).

Figure 6 presents the annual calculated EAHX outlet air temperature for 2009. This figure shows that the temperature at the exit of the EAHX varies between 10 °C (22nd January, $T_{\text{amb}}$ = 2.57 °C) and 28.8 °C (30th July, $T_{\text{amb}}$ = 35.79 °C). Thus, the annual amplitude of the outlet EAHX air temperature is 18.8 °C; while the corresponding amplitude for the ambient air temperature is 45.8 °C (Fig.7). Typical air temperatures obtained at the exit of the EAHX varies between 20 °C and 28.8 °C during the hot months (April-August), while the maximum ambient air temperature oscillates between 30 °C and 44 °C. Thus, the maximum drop in air temperature procured by the EAHX is 17.6 °C, which corresponds to $T_{\text{out}}$ = 23.4 °C and $T_{\text{amb}}$ = 40.9 °C and occurs at 11:00 AM on the 13rd of June. 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 at least 4 months (April-August 2009).

During the cold months (Dec-Feb), Figure 6 reveals that the air temperature at the exit of the EAHX varies between 10 °C and 17 °C, while the corresponding ambient air temperature oscillates between -1.8 °C and 25 °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 (Laaouina et al., 2012).

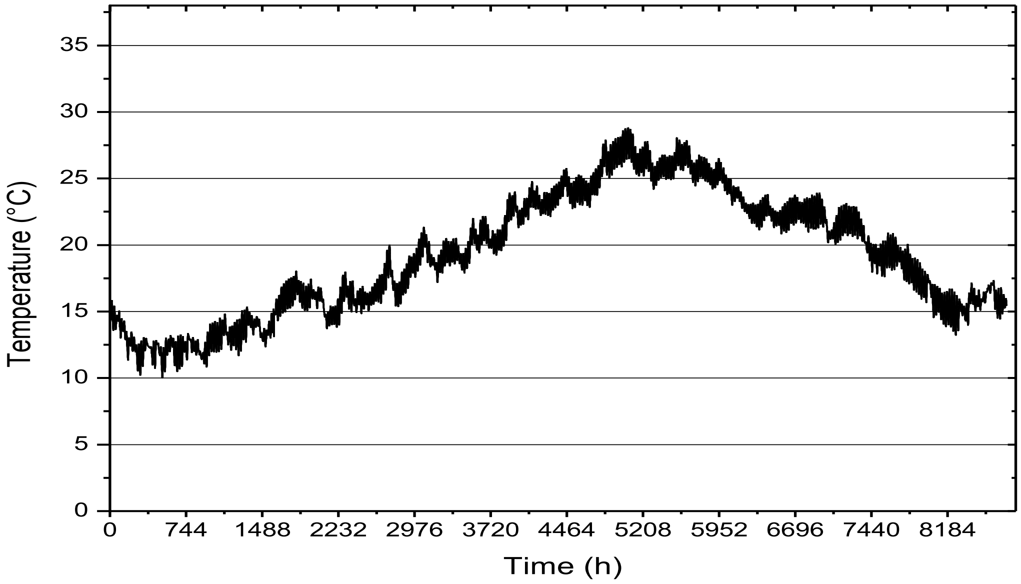

*Figure 6: Annual variation of the outlet pipe temperature.*

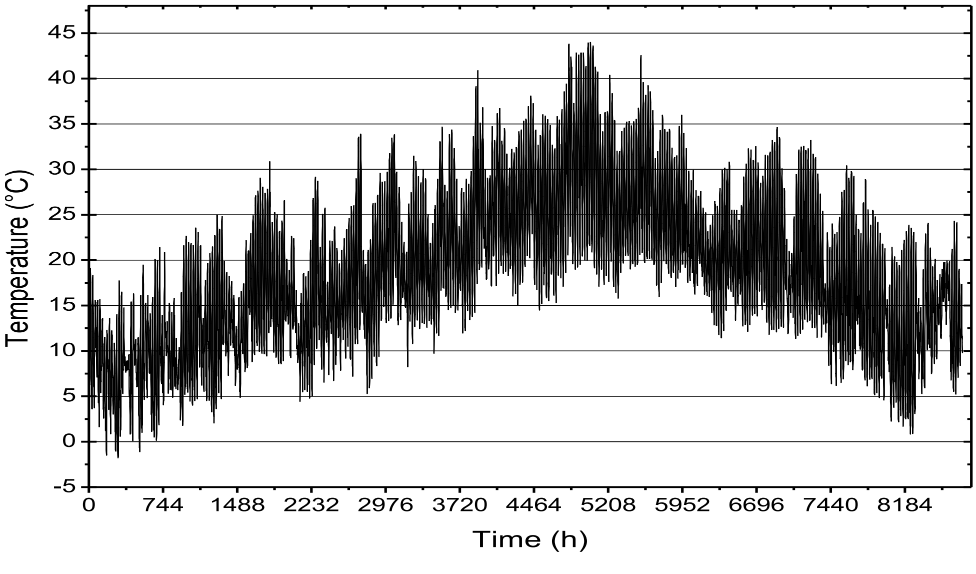

*Figure 7: Annual variations of the ambient air temperature for 2009 in Marrakech [Agdal Station]*

Figure 8 presents the ambient and exit air temperature for the hottest day in 2009 ($29^{th}$ July). This figure shows that the air temperature at the exit of the EAHX varies between 26.3 °C (7:00 AM) and 28.17 °C (5:00 PM), while the ambient air temperature oscillates between 21.5 °C and 44 °C. Thus, the amplitude of the outlet EAHX air temperature during this day is 2.6 °C; while the corresponding amplitude for the ambient air temperature is 22.4 °C. It is clear that the reduction in air temperature during this day is excellent. One interesting result is that the EAHX provides a higher temperature than the ambient air during the night and the beginning of the day (0:00-8:30 AM). Obviously, the EAHX does not procure any air refreshment during these hours. Therefore, it may be advised that the EAHX has to be run starting from 8:30 AM.

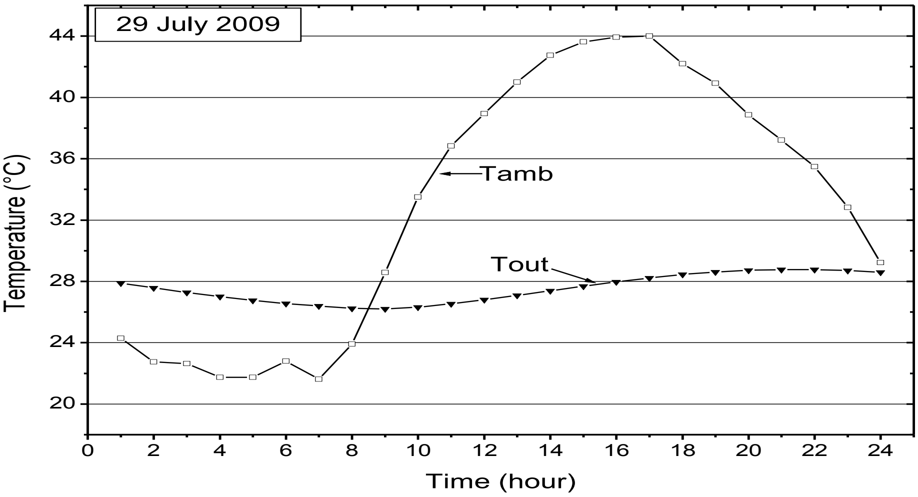

*Figure 8: 24-hour variation of ambient and outlet pipe air temperature for typical day in summer (29 July 2009).*

Figure 9 shows the evolution of the heat rate $Q_l$ along the year. The latent heat exchange between the air and the tube, which is due to phase change, occurs during the period 14-31 December and 1st January to March 7th. Except for these periods and for few special days (March 23th, Sept 10th and Oct 19th), there is no heat exchange between air and tube due to phase change (condensation - evaporation of water). An important latent heat exchange is observed in winter when the air flow is humid.

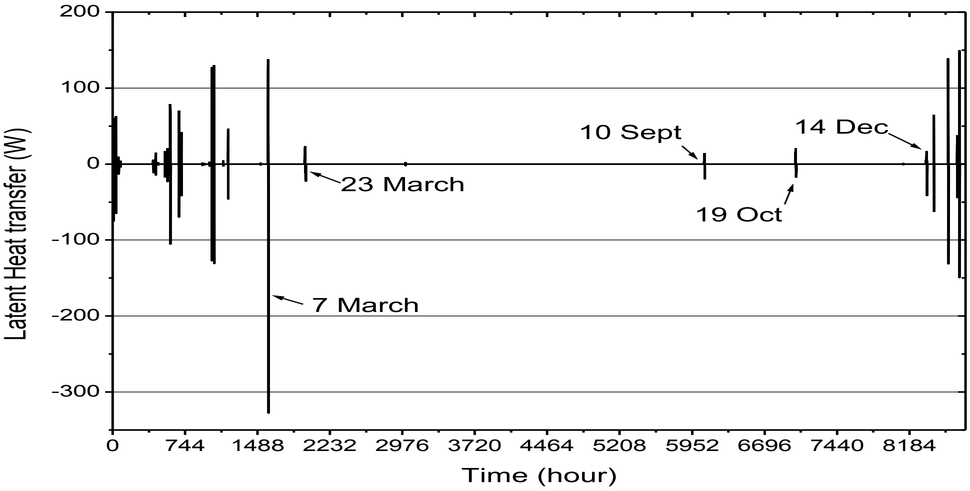

*Figure 9 : Latent heat exchanges variation.*

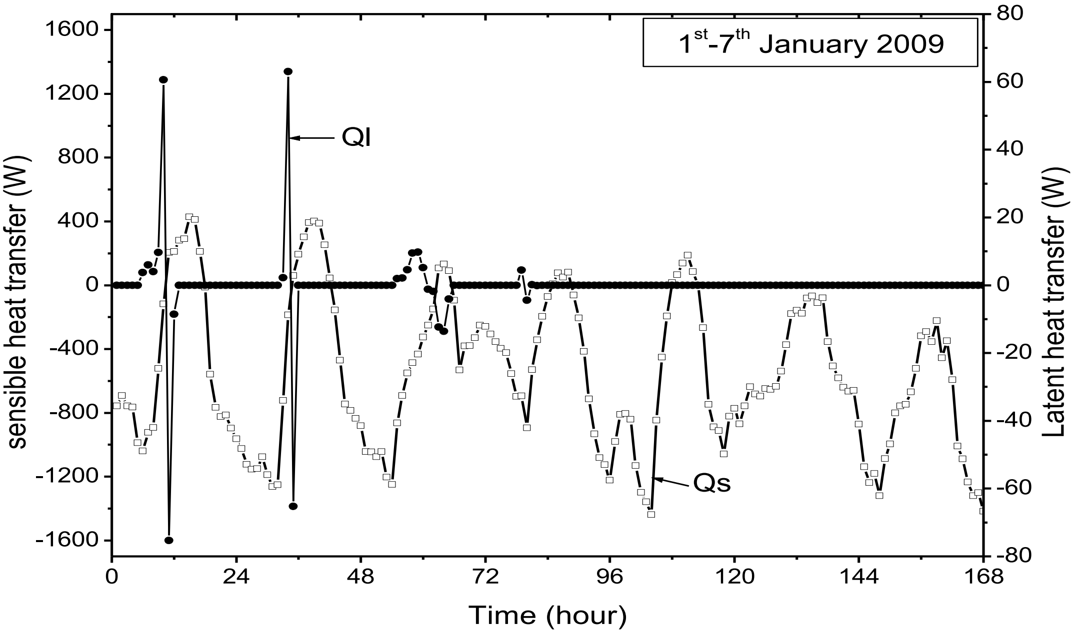

*Figure 10: Sensible and latent heat exchanges variation.*

Figure 10 shows the overall thermal power exchanged between the air and the tube during the first week of January. This heat is exchanged as sensible heat (cooling or heating of the air) and / or latent heat (water condensation or evaporation). The sensitive heat rate exchanged $Q_s$ is positive for air cooling (storage period) and negative for air heating (period of discharge). Moreover, the latent heat rate exchanged $Q_l$ is positive when the water vapor in the air condenses on the walls of the tube. This heat rate $Q_l$ is negative when liquid water accumulated on the surface of the tube evaporates.

## CONCLUSION

Thermal performance of an EAHX installed in a villa type house in the Marrakech suburb is studied by means of dynamic simulation using the TRNSYS Type 460 model. The simulations were carried out for the year 2009 and repeated two times to ensure the exact estimation of the soil temperature. The results show that the EAHX is able to maintain the outlet temperature below 23.4 C° when the outdoor air temperature reaches 40.9 °C and thus achieving a temperature reduction up to 17.6 °C. Typical EAHX outlet air temperature are in the interval 20-28.8 °C during the hot period of the year (April-August), while the maximum ambient air temperature is in the range 30-44 °C for the same period. During the cold period of the year (Jan., Feb. and Dec.), the EAHX maintains the air temperature in the range 10-17 °C, while the ambient air temperature oscillates between -1.8 °C and 25 °C in the same period.

It can be concluded through this study, 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 at least the hot period of the year (April-August 2009). On the other hand, for the cold period of the year (Jan., Feb. and Dec. 2009), the EAHX seems not to be the most efficient system for air heating in Marrakech.

These simulation results are undergoing a validation process by comparison to the experimental ones. Indeed, the installed EAHX is under monitoring and the experimental results are expected to be available for next summer. These experimental results will be presented during the congress.

## NOMENCLATURE

$\alpha$ = Soil solar absorptivity
$c_{air}$ = Specific heat of air J/(kg.K)
$c_{soil}$ = Specific heat of soil J/(kg.K)
$c_{pipe}$ = Specific heat of pipe J/(Kg.K)
$c_{vap}$ = Specific heat of vapor J/(kg.K)
$c_{wat}$ = Specific heat of water J/(Kg.K)
$d$ = 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 ($kWh.m^{-2}$)
$h_{fg}$ = Latent heat of water (J/kg)
$h$ = Heat transfer coefficient W/($K.m^2$)
k = Conductive heat coefficient W/($K.m^2$)
$l$ = Tube length (m)
$M_{air}$ = Molar mass of air (kg/mol)
$M_{wat}$ = Molar mass of water (kg/mol)
$\dot{m}_{air}$ = Airflow (kg/s)
$\dot{m}_{\mathrm{cov}}$ = Air/tube convective exchange (kg/s)
$\dot{m}_{lat}$ = Condensation / evaporation flowrate (kg/s)
$\dot{m}_{\mathrm{inf}}$ = Water infiltration (Kg/s)
$m_{pipe}$ = Mass of tube (Kg)
$\mathrm{m}_{\mathrm{wat}}$ = Mass of free water (Kg)
$Q_{fric}$ = Frictional losses (W)
$Q_L$ = Latent heat transfer rate (W)
$Q_s$ = Sensible heat transfer rate (W)
$Q_{diff}$ = Heat diffusion (W)
$Q_{int}$ = Internal heat gain (W)
$P_{air}$ = Partial pressure of air (Pa)
$P_{sat}$ = Water vapor saturation pressure (Pa)
$\phi$ = Relative humidity (%)
$R_{surf}$ = convective earth-to-air resistance ($K.m^2$)/W
$S$ = Lateral node surface ($m^2$)
$S_{pipe}$ = Pipe surface area ($m^2$)
$T_{amb}$ = Ambient air temperature (°C)
$T_{air}$ = Air temperature (°C)
$T_{pipe}$ = Pipe surface temperature (°C)
$T_{surf}$ = Soil surface temperature (°C)
$T_{soil}$ = Temperature of soil (°C)
$v_{air}$ = Velocity of air (m/s)
$\omega_{air}$ = Humidity ratio of air (Kg.water/Kg.air)
$\omega_{pipe}$ = Humidity ratio at tube surface (Kg.water/Kg.air)
$\Delta T$ = Time step (s)

## ACKNOWLEDGMENT

This study is a part of the RafriBAT project which is financially supported by a grant from the Academy Hassan II of Sciences and Techniques, Morocco.

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