Parametric Study of an Earth-Air Heat Exchanger Assisted by a Green Wall for Passive Cooling in Hot Climates

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Abstract: Cooling of buildings during summers in hot climates is an important issue for architects and builders and in terms of energy consumption, residential and tertiary buildings are among the highest consumers. This paper presents a numerical study, focused on a new design for a passive cooling system that uses an earth-air heat exchanger (EAHE), which was assisted by a green wall/air heat exchanger (GAHE) in hot climatic conditions. The tubes buried in the ground and the shadow of a vertical green wall offer considerable advantages for saving energy. The depth of the pipes in the ground was calculated by taking into account the physical properties of the soil. A parametric study was carried out by taking into account the pipe diameter, pipe length, pipe depth in the ground, and the velocity of air in the pipes. The vertical pipe in the green wall allowed a significant additional drop in the air temperature at low air velocities or small pipe depths in the ground. This means that shorter pipe lengths can be used in the earth-air heat exchanger to keep the air outlet temperature of the same order. For an earth air heat exchanger assisted by a green wall operating in hot climates, the design and operation parameters recommended are; pipe diameter 120 mm, length of the buried pipe 4 m, depth in the ground 30 m and air velocity 1 m/s.

Keywords: Thermal comfort, earth-air heat exchanger, green wall, hot climates.

1. INTRODUCTION

Earth-air heat exchangers are characterized by a high potential for saving energy and low maintenance. The use of this type of heat exchangers was first reported by Ahmed *et al*. [1] for heating and cooling buildings and agricultural greenhouses. Tzaferis *et al*. [2] investigated the performance of earth-air heat exchangers while assuming a uniform temperature on the outer surface of the tubes. The soil temperature was either calculated analytically, using the equations of one-dimensional heat transfer in a semi-infinite medium, or taken as a monthly constant value [2]. Mihalakakou *et al*. [3] and Mihalakakou [4] presented a new numerical model to predict the thermal performance of earth-air heat exchangers. This model, validated with experimental data, was recommended for calculating the variation of humidity and the temperature of the air circulating inside the tubes and depending on the temperature and humidity of the soil. The model, developed in the TRNSYS environment, could easily be coupled with building simulation tools to describe the thermal performance of earth-air heat exchangers. Benkert *et al*. [5] developed a calculation tool that is based on a physical model for earth-air heat exchangers. This was validated with experimental data and demonstrated reliable results. Belatrache *et al*. [6] investigated an earth-air heat exchanger, which was used in hot and arid weather conditions in the south of Algeria. The results showed that the EAHE system saved approximately 246.8 kWh of energy per year for a small-scale residential building. The system investigated showed the best performances for cooling and heating during the months of July and December, respectively, under the severe climatic conditions in the province of Adrar in the south of Algeria.

As regards the geometry parameters of earth-air heat exchangers, optimum depth, pipe spacing, optimum length and cross section of the pipes for a given air flow rate should all be calculated using appropriate design criteria. De Paepe and Janssens [7] presented a one-dimensional analysis to investigate how different earth-air heat exchanger design parameters could influence the thermal performance of the system. A relationship between the pressure drop in the air flowing inside the tubes and the thermal efficiency of the system was established. Hollmuller [8] presented an analytical solution for the heat diffusion of a cylindrical heat exchanger with adiabatic and isothermal boundary conditions that were subjected to constant air flow and a harmonic temperature signal at entrance. Wilby [9] investigated the role of green infrastructures for cooling in cities with a view to reducing the energy demand of buildings and improving thermal comfort for humans. This issue has warranted much attention over the last two decades. Different forms of green infrastructures were reported in the literature such as urban forests (McPherson and Nowark [10]) and green walls (Kohler [11]). Kohler [11] presented a review of the research reported in the literature on the green wall and façade technology, especially in Germany. Green façades offer a huge potential for improving urban microclimates and for reducing the ecological footprint brought about by construction. However, this practice is not yet

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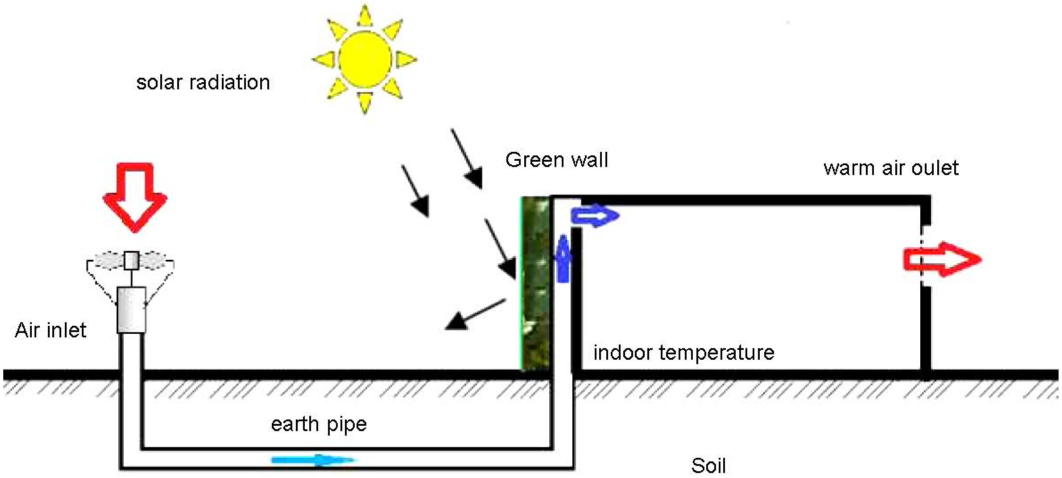

Figure 1: Schematic of an earth-air heat exchanger assisted by a green wall.

widespread outside of Germany because it is not as well-known as the green roof method. There is also a lack of guidelines for implementation or programmes for incentivization in other countries.

The present paper aims to investigate an earth-air heat exchanger (EAHE) assisted by a green wall, used for air conditioning a house in arid climatic conditions. The south wall of the house was covered by a green wall and the tube of the EAHE consisted of two parts. One part was buried in the ground and the other was placed along the green wall before entering the house. This configuration was expected to regulate indoor comfort and save energy. A parametric study was carried out to investigate the effect on thermal performance of the pipe length, pipe diameter, depth in the ground and air flow rate. The study was conducted in the month of July, which registered the highest cooling demand in the year, and the climatic conditions were those of the province of Adrar in the Algerian Sahara.

2. MODELLING OF THE SYSTEM

A schematic of the earth-air heat exchanger (EAHE) assisted by a green wall is presented in Figure **1**. The EAHE consists of two PVC (polyvinyl chloride) pipes. The first is buried in the ground and the second is placed along the green wall before entering the house. The principle of operation is as follows. First, hot outdoor air is pumped by an adequate fan into the buried pipe. The air is cooled by transferring heat to the soil, which is at a lower temperature. Then, the relatively cool air passes along the pipe located on the green wall where it is further cooled before entering the house. Figure **2** shows the typical green wall used in the province of Adrar and the temperature.

The model describing the system operation consists of two sub-models for the buried pipe and the pipe located along the green wall. The equations are presented in the following sections. The initial and boundary conditions applied in the simulation of the earth-air heat exchanger are as follows:

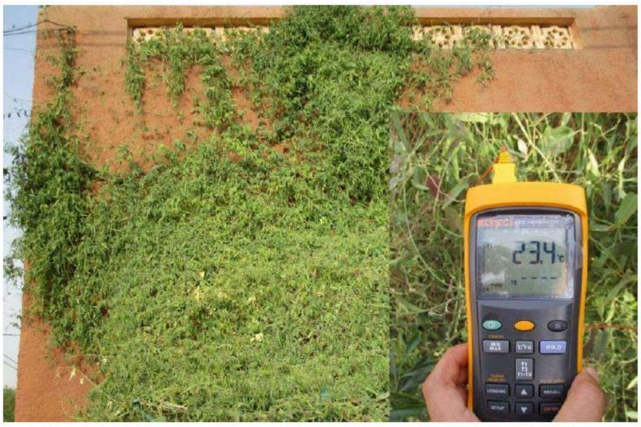

Figure 2: Typical green wall used in the province of Adrar.

One or more pipes are arranged horizontally under the ground at the depth Z = 1 to 5 m.

At ground surface, Z= 0 m

- $T(0, 0, t) = T_{amb}$
- $T(0, x, t) = T_S$

A 5 m vertical spiral pipe, located along the green wall, is connected to the buried horizontal pipe by means of a vertical twisted pipe. The height of the green wall can reach a maximum of 3 m.

At the exit of the spiral vertical pipe, H = 5 m

- $T(5, x, t) = Tsf$.

Based on daily measurements that were carried out by the authors in the province of Adrar, the green wall temperature was set at T_{veg} = 23.5 ºC in the simulations. Table **1** presents the measured values of green wall temperature in a typical summer day. This data shows

Table 1: Green Wall Temperature Profile in a Typical Summer Day (July 17th, 2016)

Time	8h	8h30	9h	9h30	10h	10h30	11h	11h30	12h	12h30	13h
Temperature (ºC)	21.5	21.7	21.9	22.0	21.6	21.4	21.5	21.5	22.3	22.5	23.5
Time	13h30	14h	14h30	15h	15h30	16h					
Temperature (ºC)	23.4	23.5	23.8	24.2	24.9	25.0					

an increase of 1 ºC between 8h and 12h30. An additional increase of 1.5 ºC is observed between 13h and 16h. The green wall temperature at 13h is 23.5 ºC, which is the constant value used for the green wall temperature.

2.1. Modeling of the Soil Temperature

The mathematical model used for the soil temperature was based on the heat conduction theory applied to the earth and considered as a semi-infinite medium. Heat conduction in the soil was given by reference [12]:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{a_{soil}} \times \frac{\partial T}{\partial t} = 0 \qquad (1)$$

$$T(0,t) = T_{mean} + A_s \times \cos\left(\omega\,(t - t_0)\right) \qquad (2)$$

$$T(\infty,t) = T_{mean} \qquad (3)$$

The optimal depth of the underground pipes is a parameter required in the investigation of air-earth exchangers. This parameter depends on the characteristics of the region under study.

The soil temperature was calculated using equation (4), reported in reference [13].

$$T(z,t) = T_{mean} + A_s \times (\mathrm{Exp}^{-(z)\sqrt{\frac{\pi}{365 \times a_{soil}}}} \times \cos\{\omega \times (t - t_0) - (z/\sqrt{365 \times a_{soil}/\pi})\} \qquad (4)$$

Figure **3** shows the hourly variation of the soil temperature at different depths. It is worth noting that the temperature of the top layer of the Earth, at a depth around 1-3 m, is significantly affected by the surface temperature and this effect decreases on increasing the ground depth. Hence, the earth temperature at a depth of 4-5 m is almost constant at 24-27 ºC, and as this is lower than the ambient temperature in summer months, it could be used for cooling purposes in summer.

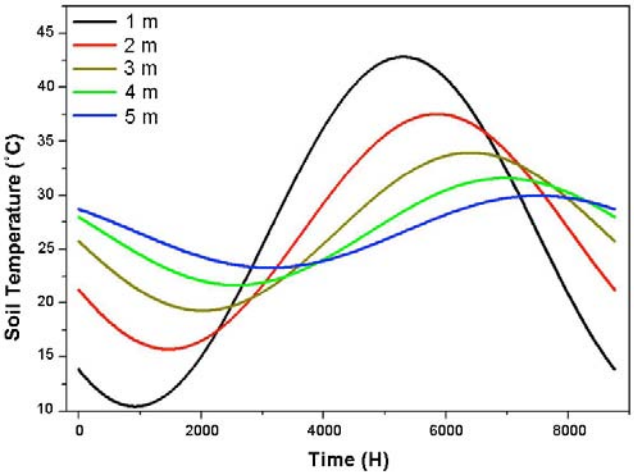

Figure 3: Hourly variation of the soil temperature at different depths in the province of Adrar.

2.2. Modeling of the Earth-Air Heat Exchanger

The mathematical model developed for the system under study is based on the transient energy balance at a constant soil temperature. The model provides the temperature profile versus time through the earth-air heat exchanger, taking into account the following simplifications: (i) outdoor temperature was set from weather data of the region under study, (ii) soil temperature at a given depth was calculated taking into account the thermophysical properties of the soil, (iii) geometric parameters of the buried pipe, air velocity, and length of the spiral pipe along the green wall were all set at constant values.

Figure **4** shows a schematic of the system modelled in the present work. The buried pipe of the earth-air heat exchanger consists of a straight horizontal pipe of a length (L) that is equal to 40 m. It is assumed that the soil temperature is influenced by the air flow and it varies according to equation (4).

The heat transferred along the buried pipe can be expressed as follow:

$$\phi = \dot{m} \times Cp_{air} \times dT(x) = \frac{dx}{R_{conv} + R_{Pipe} + R_{soil}} \times (T(z,t) - T(x)) \qquad (5)$$

The thermal resistance of the convective heat transfer between inlet surface of the pipe and air in the pipe is:

$$R_{conv} = \frac{1}{ri \times h_{conv} \times 2 \times \pi} \qquad (6)$$

The thermal resistance of the pipe can be expressed as:

$$R_{pipe} = \frac{1}{\lambda_{pipe} \times 2 \times \pi} \times \mathrm{Ln}(r_e | r_i) \qquad (7)$$

The thermal resistance of the soil can be expressed as:

$$R_{soil} = \frac{1}{\lambda_{soil\times 2\times \pi}} \times Ln\left(R_{(z,t)}\middle|r_e\right) \quad (8)$$

The total thermal resistance of the buried pipe is then given by:

$$R_A = \left(R_{conv} + R_{pipe} + R_{soil}\right) \quad (9)$$

Combining equations (5) to (9), the energy balance can expressed as follows:

$$\frac{dT(x)}{T(z,t)+T(x)} = \frac{1}{\dot{m}\times Cp_{air}\times R_A}\times dx \quad (10)$$

The integral of equation (8) is then:

$$-\ln\left(T(z,t) + T(x)\right) = \frac{1}{\dot{m}\times Cp_{air}\times R_A}\times x + B \quad (11)$$

The initial condition at the entrance of the buried pipe, x=0, is expressed as follows:

$$T(0) = T_{amb} \rightarrow\ B = \ln(T(z,t) + T_{amb}) \quad (12)$$

Combining equations (11) and (12), we obtain:

$$\ln\left(\frac{T(x)-T(z,t)}{(T_{amb}-T(z,t)}\right) = \frac{-x}{\dot{m}\times Cp_{air}\times R_A} \quad (13)$$

The air temperature at the outlet of the buried pipe is then calculated from equation (13) at x=L.

$$T_s = T_{amb} + (T(z,t) - T_{amb})\times\left(1 - e^{\frac{-Lh}{\dot{m}\times Cp_{air}\times R_A}}\right) \quad (14)$$

The second part of the passive cooling technique, which is called “GAHE”, is represented by a 5 m spiral pipe located along the green wall. The heat balance in this pipe is then:

$$\dot{m}\times Cp_{air}\times dT(y) = \frac{dy}{R_{conv}+R_{Pipe}}\times(T(veg) - T(y)) \quad (15)$$

The thermal resistance of the convective heat transfer between the internal pipe surface and the air flowing in the pipe is:

$$R_{conv} = \frac{1}{ri\times h_{conv}\times 2\times\pi} \quad (16)$$

The thermal resistance of the pipe can be expressed as:

$$R_{pipe} = \frac{1}{\lambda_{pipe\times 2\times\pi}} \times \ln\left(r_e\middle|r_i\right) \quad (17)$$

The overall thermal resistance is then given by:

$$R_B = \left(R_{conv} + R_{pipe}\right) \quad (18)$$

The external temperature of the vertical spiral pipe is assumed to be equal to the green wall temperature, so only two individual thermal resistances are considered, namely the internal convective and pipe resistances.

Introducing the overall thermal resistance, the energy balance of equation (15) can be written as follows:

$$\frac{dT(y)}{T(veg)+T(y)} = \frac{dy}{\dot{m}\times Cp_{air}\times R_B} \quad (19)$$

The integral of equation (17) is then:

$$-\ln(T(veg) + T(y)) = \frac{y}{\dot{m}\times Cp_{air}\times R_B} + C \quad (20)$$

The initial expression at y=0 is as follows:

$$T(0) = T_s \rightarrow\ C = \ln(T(veg) + T_s) \quad (21)$$

Combining equations (20) and (21), we obtain:

$$\ln\left(\frac{T(y)-T(veg)}{(T_s-T(veg)}\right) = \frac{-y}{\dot{m}\times Cp_{air}\times R_B} \quad (22)$$

The air temperature at the outlet of the spiral pipe located on the green wall is calculated from equation (22) at y=L_v.

$$T_{sf} = T_s + (T(veg) - T_s)\times\left(1 - e^{\frac{-Lv}{\dot{m}\times Cp_{air}\times R_B}}\right) \quad (23)$$

Figure 4: Schematic of the modelled system consisting of an earth-air heat exchanger (EAHE) assisted by a green wall (GAHE).

2.3. Model Validation

Before performing the parametric study, the model was validated at different ambient temperatures and air velocities, using the experimental data reported by Bansal *et al*. [14]. The input parameters used for the validation step are presented in Table **2** and the results are tabulated in Table **3**. It can be seen that the absolute relative deviation between our results and the experimental data of Bansal *et al*. [14] is below 9.5%.

When the air flowing inside the pipe is pumped at a velocity of 2 m/s, the absolute relative deviation between our results and the experimental data of reference [14] is even lower than 1%. Therefore, it can be concluded that our model can properly predict the outlet air temperature of the air-earth heat exchanger.

Table 2: **Input Parameters Used for Validation Against the Experimental Data from Bansal *et al.* [14]**

Parameter	Reference value
Pipe length (m)	23.42
Pipe diameter (m)	0.15
Soil density (kg/m^3)	2050
Soil specific heat capacity (J/kg.K)	1840
Soil thermal conductivity (W/m.°C)	0.52
Soil temperature (°C)	26.7

3. RESULTS AND DISCUSSION

A parametric study was carried out in hot climatic conditions to see the effects of the main geometric parameters and air velocity on the performance of the passive cooling system that was proposed. The optimal values which are recommended for these parameters have therefore been identified. Table **4** illustrates the numerical values and intervals of the input parameters used in the simulation.

3.1. Effect of the Pipe Diameter on the Outlet Air Temperature

Figure **5** shows the air temperature versus the pipe length at different values of the inside pipe diameter. The air temperature decrease in the buried pipe is more pronounced at lower values of the inside pipe diameter because the convective heat transfer coefficient of air/pipe is higher. This trend is reversed in the vertical spiral pipe on the green wall. It is worth noting that the air temperature difference is only 0.7 °C at the pipe exit on the green wall, with inside pipe diameters ranging from 80 mm to 120 mm. Therefore, the diameter D = 120 mm is recommended for a pipe used in an earth-air heat exchanger that is assisted by a green wall.

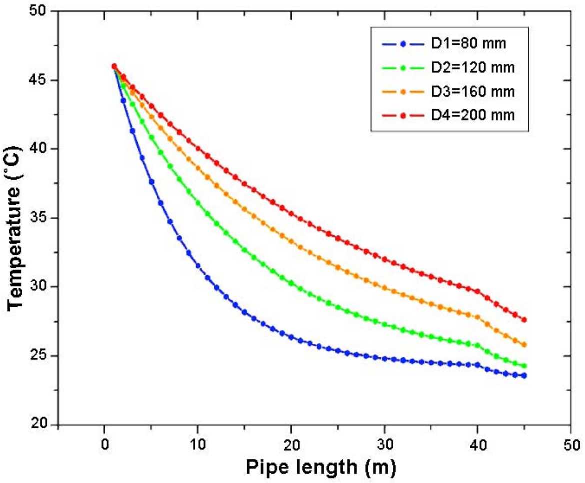

Figure 5: Air temperature versus pipe length at different values of the inside pipe diameter.

3.2. Effect of the Air Velocity on the Outlet Air Temperature

Figure **6** illustrates the variation of the air temperature versus the pipe length at different values

Table 3: **Results of Model Validation against the Experimental Data from Bansal *et al.* [14]**

EAHE parameters	L_h= 23.42 m; Di = 0.15 m, Tsoil = 26.7 °C (pipe in PVC)			
Inlet air velocity (m/s)	Inlet air temperature	Outlet air temperature		
		Experimental data from Bansal *et al.* [14]	Results of present model	
V_{inlet}	T_{inlet} (°C)	T_s (°C)	T_s (°C)	Relative error (%)
2	43.4	33.1	33.4	0.8
3	42.5	33.1	35.3	6.5
4	42.3	33.5	36.6	5.0
5	42.2	34.2	37.4	9.4

Table 4: **Input Parameters Used in the Simulation**

Parameter	Value
Length of the buried pipe (m)	20-40
Length of the spiral pipe in the green wall (m)	5
Inside pipe diameter (mm)	80-200
Air velocity (m/s)	1-4
Depth of the buried pipe in the ground (m)	1-5

of the air velocity and a pipe diameter of 120 mm. As can be observed, the air temperature decrease in the buried pipe is much more significant at lower air velocities. As commented above, this trend is reversed in the vertical spiral pipe on the green wall. At an air velocity of 4 m/s, warm air is cooled from 46 ºC to 32.5 ºC at the pipe exit on the green wall. The outlet temperature of the air drops down to 24.3 ºC when it leaves the green wall pipe at an air velocity of 1 m/s. Heat exchanged is greater at lower air velocities as the residence time of air in the cooling system proposed is increased.

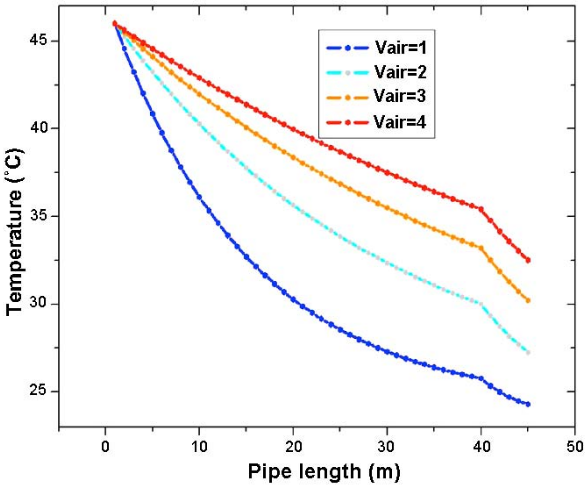

Figure 6: Air temperature versus pipe length at different values of the air velocity.

3.3. Effect of the Pipe Depth in the Ground on the Outlet Air Temperature

Figure **7** shows the air temperature versus the pipe length at different values of the pipe depth in the ground. The air temperature decrease in the buried pipe strongly depends on the pipe depth in the ground, up to a depth of around 4 m. For higher values, this effect is almost insignificant. At 4 m of depth, air is cooled from 46 ºC to 26.1 ºC along 40 m of buried pipe.

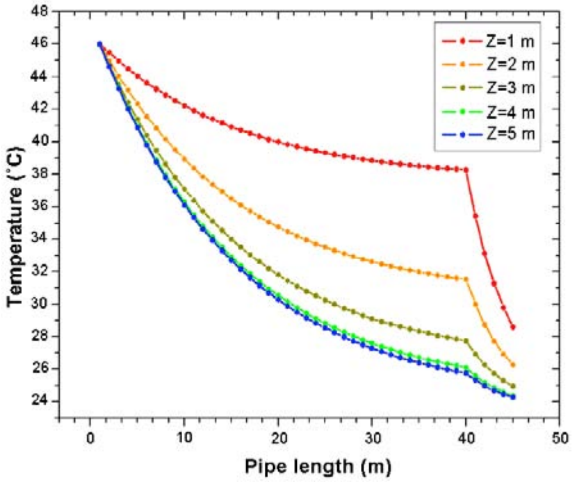

Figure 7: Air temperature versus pipe length at different values of the depth in the ground.

The vertical spiral pipe on the green wall achieves a significant additional air temperature drop when EAHE pipe depth is lower in the ground. These temperature drops are around 9.7 ºC and 5.3 ºC at the pipe depths of 1 m and 2 m, respectively. A pipe depth of 4 m is recommended for the earth-air heat exchanger that is assisted by a green wall.

3.4. Effect of the Pipe Length of the Earth-Air the Exchanger on the Outlet Air Temperature

Figure **8** illustrates the air temperature profile in the earth-air heat exchanger (EAHE), assisted by a green wall, at a buried pipe length ranging from 20 to 40 m, at 5 m intervals. The length of the vertical spiral pipe on the green wall was maintained constant at 5 m. Air velocity, pipe diameter and pipe depth in the ground were set at 1 m/s, 120 mm and 4 m, respectively. As can be observed, the use of the green wall means that it is possible to use shorter pipes in an EAHE and maintain an outlet air temperature of the same order. For instance, for buried pipe lengths of 40 m and 30 m, the outlet air temperature is 24.6 ºC and 25.3 ºC, respectively. This is because heat transfer in the vertical spiral pipe, which is placed on the green wall, is more effective at high temperatures of the air flowing inside the pipe. For best and most economical performance, an optimum length of 30 m is recommended for the buried pipe. Table **5** contains the optimal geometric parameters and air velocity that are recommended for the earth-air heat exchanger, assisted by a green wall, as investigated in the present work.

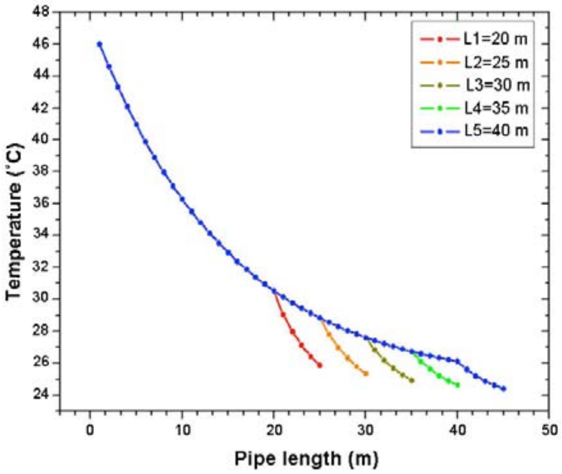

Figure 8: Air temperature versus length of the buried pipe at Z = 4 m, D = 120 mm and V_{air} = 1 m/s.

4. CONCLUSION

The present paper deals with a parametric study of a passive cooling system consisting of an earth-air heat exchanger (EAHE), assisted by a green wall/air heat exchanger (GAHE), operating in hot climatic conditions. A one-dimensional model was developed in a MATLAB environment to investigate the effect of geometric parameters and operating conditions affecting the outlet temperature of the air which was to be circulated in the building. The parameters were those of pipe diameter, pipe length, pipe depth in the ground, and air velocity. The results obtained from this study are summarized as follows:

Table 5: Geometric Parameters and Air Velocity Recommended for an Earth-Air Heat Exchanger Assisted by a Green Wall

Parameter	Reference value
Length of the buried pipe (m)	30
Inside diameter of the pipe (mm)	120
Air velocity (m/s)	1
Depth of the buried pipe in the ground (m)	4

- Hourly variation of the soil temperature improved the accuracy of the results obtained.
- Air temperature decrease in the buried pipe was more pronounced at lower values of the inside pipe diameter. This trend was reversed in the vertical spiral pipe on the green wall. Air temperature difference was around 0.7 ºC at the exit of the green wall pipe with the pipe diameters ranging from 80 to 120 mm.
- Air cooling in the buried pipe was much more significant at lower air velocities. However, temperature drop in the pipe, located on the green wall, was more significant at high air velocities.
- The air temperature decrease in the buried pipe strongly depended on the pipe depth in the ground, up to a depth of around 4 m. The vertical spiral pipe on the green wall achieved a significant additional drop in air temperature at low values of the pipe depth in the ground.
- The use of the green wall made it possible to use shorter pipes in the EAHE and maintained an outlet air temperature of the same order.
- The pipe diameter, length of the buried pipe, pipe depth in the ground, and air velocity recommended, were 120 mm, 4 m, 30 m and 1 m/s, respectively, for an earth-air heat exchanger, assisted by a green wall, operating in hot climates.

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NOMENCLATURE

A_s	Amplitude of the soil surface temperature variation, ºC
a_{soil}	Thermal diffusivity of the ground, m^2/h
B, C	Constants [-]
D_i	Internal pipe diameter, m
V	Velocity, m/s
Cp	Specific heat capacity, J/(kg.K)
r_e	External pipe radius, m
r_i	Internal pipe radius, m
R_A	Total thermal resistance of the buried pipe under the soil, m.K/W
R_B	The total thermal resistance of the pipe into the green wall, m.K/W
$R_{(Z,t)}$	Thermal resistance of the soil, m.K/W
R_{conv}	Thermal resistance of the convective exchange between the air and the pipe, m.K/W
R_{pipe}	Thermal resistance of the buried pipe, m.K/W
R_{soil}	Thermal resistance of the soil, m.K/W
t	Hour of the year, from 1 to 8760
t_0	Hour of maximum surface temperature, equal to 4752
X	Horizontal length of the pipe, m
y	Vertical length of the pipe, m
Z	Depth, m
h	Heat transfer coefficient, W/(m.K)
L_h	Length of the buried pipe (EAHE), m
L_v	Length of the spiral pipe in the green wall, m
$\dot{m}$	Mass flow rate, kg/s
T	Temperature, ºC

Greek Letters

λ_{pipe}	Thermal conductivity of the pipe, W/(m.K)
λ_{soil}	Thermal conductivity of the soil, W/(m.K)

ρ	Density of the soil, kg/m^3
ω	Frequency of the yearly temperature variation (=$\frac{2\pi}{365}$), rad/h

Subscripts

air	Air
mean	Annual mean
veg	Vegetation
amb	Ambient
S	Outlet from EAHE
sf	Outlet from GAHE
inlet	Inlet to EAHE

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