

NUMERICAL STUDY ON COOLING PERFORMANCE OF HORIZONTAL EARTH HEAT EXCHANGER IN HOT SEMI-ARID CLIMAT

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ABSTRACT: In this paper we numerically study the performance of an earth-to-air heat exchanger (EAHE) using the finite volume method. The impact of some parameters, like air temperature, humidity, soil temperature, diameter and length of the pipe, and the air flow at the inlet of the EAHE, on the performance of the EAHE, under the climatic conditions of Constantine city in eastern Algeria, have been examined. The main findings of the study indicate that there is a direct correlation between the length of the pipe and the outlet air temperature from the EAHE. The air relative humidity increased faster under high inlet temperatures. Increasing the diameter of the pipe led to an increase in the outlet air temperature of the EAHE. The humidity ratio under a small diameter pipe declined at a faster rate compared to a large diameter pipe. The outlet air temperature of EAHE increases with the tube's surface temperature. The main conclusions of this work are useful for designing and optimizing the geothermal system (EAHE).

KEY WORDS: geothermal energy, cooling, air heat exchanger, humidity, control volume.

NOTATIONS

A : Amplitude of the soil surface temperature variation (°C)	P : Perimeter of tube (m)
C_{pair} : Specific heat at constant pressure of air (J/kg K)	Pr : Prandtl number
D : Pipe diameter (m)	Re : Reynolds number
f : Enhancement coefficient	S : Exchange area (m ²)
H : Humidity ratio	Sh : Sherwood number
h : Mass enthalpy (J/kg)	t : Time of the year (hours)
h_c : Heat transfer coefficient (W/m ² K)	t_0 : Phase constant of the soil surface (hours)
k_{air} : Thermal conductivity of air (W/m °C)	T_a : Air temperature (°C)
L : Pipe length (m)	T_{moy} : Average soil temperature (°C)
$\dot{m}$: Mass flow rate of air (kg/h)	T_n : Air temperature at different points along the meshed pipe (°C)
Nu : Nusselt number	$T_s(z, t)$: Soil temperature (°C)
	v_{air} : Velocity of air (m/s)

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w :	Diffusion coefficient (m^2/s)	β :	Convective mass transfer coefficient (m/s)
z :	Depths (m)	μ_{air} :	Dynamic viscosity of air (kg/m s)
θ :	Difference of temperatures ($^{\circ}\text{C}$)	ν_{air} :	Kinematic viscosity of air (m^2/s)
α :	Thermal diffusivity of the soil (m^2/h)		

1 INTRODUCTION

The use of geothermal energy to meet the heating and cooling needs of buildings has received increasing attention in recent decades. This is due to its high natural availability and lower environmental impact than, exhaustible conventional energy sources. It is an alternative for generating power and storing energy. It can also reduce electricity costs and provide thermal comfort [1].

The Earth-To-Air Heat Exchanger (EAHE) uses geothermal energy. This underground cooling system consists of pipes buried at a certain depth below the ground [2].

Over the last few decades, scientists have tested EAHE systems, providing valuable insights into their efficiency and effectiveness under different conditions [3–5]. Amanowicz et al. [6] described recent advances in ventilation systems to reduce energy consumption in buildings. Furthermore, Liu et al. [7] reviewed the use of shallow geothermal ventilation systems to improve the thermal performance of buildings, showing they are a cost-effective alternative to conventional air conditioning. In addition, the EAHE with different design configurations has also been reported in the literature.

Bansal et al. [3] examined the performance of an earth heat exchanger during summer cooling. They achieved that was a notable reduction in inlet and outlet temperatures. Vaz et al. [8] as well as Abadie et al. [9] and Vivas and Guerra [10] analysed the EAHE in Brazil. Abadie et al. [9] concluded that climatic conditions and solar radiation must be taken into account in the calculations. However, Vaz et al. [8] in their study, demonstrated that the heat exchanger utilized for heating purposes, exhibited a maximum temperature increase of 3°C , with the potential for reaching 8°C . For cooling applications, the analysis indicated a potential temperature increase of 4°C . In addition, Vivas and Guerra [10] developed models of the EAHE to evaluate the influence of some parameters on the thermal performances of the system used in Belém city, Brazil. The results showed a maximum relative difference of 4.14% between the experimental and calculated data. It was also concluded that the use of lower air velocities reduces the length required to obtain a specific temperature reduction.

Mongkon et al. [11] and Greco and Masselli [12] tested some geometric parameters on the efficiency of the EAHE. Mongkon et al. [11] found that increasing pipe diameter and air velocity maximises coefficient of performance. Greco and

Masselli [12] investigated optimising thermal performance of horizontal single-duct EAHE in Naples. The EAHE's thermal performance increased with length until saturation, with smaller diameters and slower air flows. Additionally, they recommended the use of a pipe with a smaller diameter and low air velocity to achieve a closer air outlet temperature to the soil temperature. Mathur et al. [13] presented the findings from a series of experiments, using a spiral heat exchanger design, buried at a depth of 3 m. They examined the coefficient of performance (COP) for a spiral. Liu et al. [5] studied the thermal performance of EAHE in hot summer and cold winter. They showed that at a distance of 20 m, the inlet air temperature approaches the soil temperature and the COP which represents the energy utilization efficiency of systems and the heating capacity Q decreased with increasing inlet air temperature but increased with increasing pipe length. Qi et al. [14] found that condensation had little effect on the uniformity of the EAHE airflow distribution, and that humid air condensed more easily in small pipes. The influence of the configurations on the performance of the air condensation was also examined.

In addition to the analytical solution on an EAHE, many researchers carried out the numerical model of an EAHE. Most of the simulation studies were aiming at evaluating the performance and studying its dependency on other system parameters [15, 16].

Nejad et al. [17] investigated an underground air conditioning tunnel for Tehran's climate using ANSYS/Fluent. The heat exchanger provided comfortable conditions except for a short period of the day. The system was not suitable for continuous operation due to thermal saturation of the soil, and a depth of 3 m was appropriate for burying the pipe.

To analyse the effect of tube dimensions and material on thermal performance, Serageldin et al. [18] developed a parametric study of an EAHE through simulations in ANSYS/Fluent. The authors found that increasing the pipe diameter and air velocity reduces EAHE heat transfer. Furthermore, (Taşdelen and Dağtekin [19], investigated the performance of an EAHE using the computational fluid dynamics ANSYS FLUENT program to examine the thermal comfort condition of a typical building. In this study, the thermal performance of the EAHE was analysed at different ground depths. It was found that the best thermal performance was obtained at the smallest air inlet velocity, reducing the cooling energy consumption required to provide the thermal comfort condition for a typical building. Mironov et al. [20] developed a horizontal ground heat exchanger model to describe heat transfer between the exchanger and the ground. The model demonstrates that the heat transfer rate declines with a distance between tubes of less than 2 m.

Many results of studies carried out in Algeria have been reported [21–23].

An air-to-earth heat exchanger under transient conditions in cooling mode was

described and tested at Biskra, Algeria by Belloufi et al. [24], The performance of the system was analysed for 71 h of continuous operation based on a PVC pipe buried at a depth of 3 m. The experimental results showed that no significant effect on the outlet air temperature, and thus on the EAHE performances, during all the continuous operations. In addition to this finding, a good agreement was achieved between their developed model and the measured temperature.

Menhoudj et al. [23] used an EAHE experimental model in Algeria, validating a numerical model using TRNSYS software to assess thermal performance by optimising some design parameters: length, installation depth and pipe diameter. Benrachi et al. [22] studied the use of EAHE in some arid Algerian areas. They reported that the soil temperature ranged from 26°C at a depth of 6 m to 22.2°C at a depth of 5 m for the cities of Adrar and El-Oued, respectively.

Benrachi et al. [25] studied a spiral configuration of an EAHE for summer cooling in the hot and arid regions of Algeria. The effect of pitch, depth, pipe length and flow velocity on the outlet air temperature and the mean efficiency of the EAHE as well as its coefficient of performance were investigated. The authors found that when the pitch varied between 0.2 and 2 m, the outlet air temperature difference increased by 6°C. When the air velocity increased from 2 to 5 m/s, the average efficiency and COP of the EAHE decreased. Hacini et al. [21] compared the performance of an EAHE in three Algerian regions: Jijel (humid climate), Djelfa (semi-arid climate) and Timimoun (hot and arid climate). The study concluded that 5 m depth should be used in the hot and arid region and 2 m for the other sites, with pipe lengths of 45, 30 and 30 m. A typical hot day's cooling potential was estimated at 26.21 kWh in Timimoun, 13.83 kWh in Djelfa and 7.66 kWh in Jijel.

Based on the previous studies, the effect of the air humidity has received little or no attention. In this context, the present work presents the influence of some parameters including the air humidity on the performance of the EAHE, using the finite volume method.

2 MATHEMATIC MODELING OF AN EAHE

When the heat conduction principle (Ozgener et al. [26]) applied to a semi-infinite solid, it predicts the soil temperature $T_s(z, t)$ at various times of year (t) and at different depths (z). The standard for ground temperature is assumed to be equal to the surface temperature in most cases.

$$(1) \quad T_s(z, t) = T_{\text{moy}} - A \exp\left(-z\sqrt{\frac{\pi}{365\alpha}}\right) \cos\left(\frac{2\pi}{365}\left(t - t_0 - \frac{z}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right).$$

To model the earth-to-air heat exchanger, some assumptions were considered:

- 1) One dimensional heat transfer.
- 2) Pipe cross section is uniform
- 3) Thermal properties of the ground in the vicinity of the pipe are homogeneous.
- 4) Air is considered incompressible with constant thermal properties.
- 5) Air is well mixed in the pipe.

The pipe is made of PVC material with a length (L) and a diameter (D), buried at a known depth (z). The soil temperature is known and the radius of the soil layer is twice the radius of the pipe. The thermal resistance due to the thickness of the PVC pipe is not considered, as the wall thickness of EAHE pipe is considered very small.

Figure 1 shows the EAHE pipe mesh along its length and the energy balance within a small individual control volume. The mass transfer was also considered. The finite volume method is used to solve the governing equations.

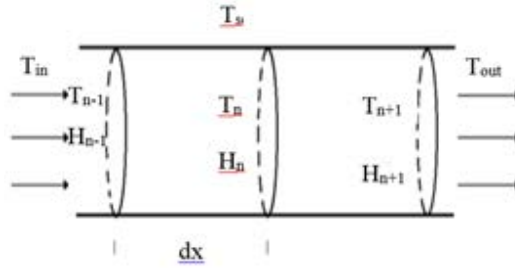


Fig. 1. Control volume method.

2.1 HEAT TRANSFER

Heat balance for a control volume gives

$$(2) \quad \dot{m}C_{\text{pair}} \frac{dT}{dx} = h_c P (T_s - T_a) .$$

After reorganizing the terms, the air temperature in each small control volume becomes

$$(3) \quad a \frac{\partial \theta}{\partial x} + \theta = 0 ,$$

$$(4) \quad \theta = (T_a - T_s) \quad \text{and} \quad a = \frac{\dot{m}C_{\text{pair}}}{ph_c} ,$$

$$(5) \quad h_c = \frac{Nu k_{\text{air}}}{D} ,$$

k_{air} is calculated, according to Hanby [28] as:

$$(6) \quad k_{\text{air}} = 0.02442 + (10^{-4}(0.6992T_a)) .$$

The Nusselt number (Nu), the Reynolds number (Re) and the Prandtl number (Pr) are given by the equations (7), (8) and (9) respectively:

$$(7) \quad Nu = 0.0223Re^{0.8}Pr^{0.33} ,$$

$$(8) \quad Re = \frac{v_{\text{air}}D}{\vartheta_{\text{air}}} ,$$

$$(9) \quad Pr = \frac{\mu_{\text{air}}C_{\text{pair}}}{k_{\text{air}}} ,$$

$$(10) \quad \vartheta_{\text{air}} = 10^{-4}(0.13350 + 0.000925T_a) .$$

With the air temperature within each control volume, Eq. (2) can be differentiated as

$$(11) \quad \dot{m}C_{\text{pair}}(T_{n-1} - T_n) = Sfh_c(T_a - T_s) ,$$

where f and S are, respectively, the enhancement coefficient and the exchange area.

The air temperature along the exchanger is expressed for each control volume as

$$(12) \quad T_a(x) = T_s + (T_a - T_s) \exp\left(\frac{-ph_c}{\dot{m}C_{\text{pair}}}x\right) .$$

The representative air temperature in each element can be obtained by averaging the air temperatures in the included i sub-elements

$$(13) \quad T_a = \sum_i \left[\frac{T_s - (T_s - T_{n-1}) \exp\left(\frac{-ph_c}{\dot{m}C_{\text{pair}}}x_i\right)}{i} \right] .$$

The air temperature at different points along the meshed pipe, from inlet to outlet, is given by

$$(14) \quad T_n = T_{n-1} - \frac{Ah_c}{\dot{m}C_{\text{pair}}} \left[\sum_i \left(\frac{T_s - (T_s - T_{n-1}) \exp\left(\frac{-ph_c}{\dot{m}C_{\text{pair}}}x_i\right)}{i} \right) - T_s \right] .$$

Coupling the heat and mass transfer balance for each control volume, the total governing equation becomes [29]

$$(15) \quad \dot{m}C_{\text{pair}}(T_{n-1} - T_n) + \dot{m}(H_{n-1} - H_n)h = Sfh_c(T_a - T_s) .$$

Knowing that when the air temperature in a control volume drops to the corresponding dew point then the condensation happens. The mass transfer governing equation will be

$$(16) \quad \dot{m}(H_{n-1} - H_n) = S\beta\rho_{\text{air}}(H_{\text{air}} - H_{\text{sat},s}) \quad \text{with} \quad \beta = \frac{Shw}{D}.$$

where the driving force for mass transfer between the air and the EAHE surface is the air humidity ratio and the saturated humidity ratio corresponding to the EAHE surface temperature.

3 NUMERICAL SOLUTION AND VALIDATION

A code based on the finite volume method was developed using matlab software program to calculate the temperature and humidity of the air. The surface temperature of the EAHE pipe was assumed constant for a short period of time. This is achieved by using the undisturbed soil temperature at the depth of the buried pipe.

By comparing the air temperature and the corresponding air dew point in each control volume, the program determines whether condensation should be included or not.

The soil model was used to determine the temperature at different installation depths.

The required heat transfer between air and pipe surface was calculated for the inlet

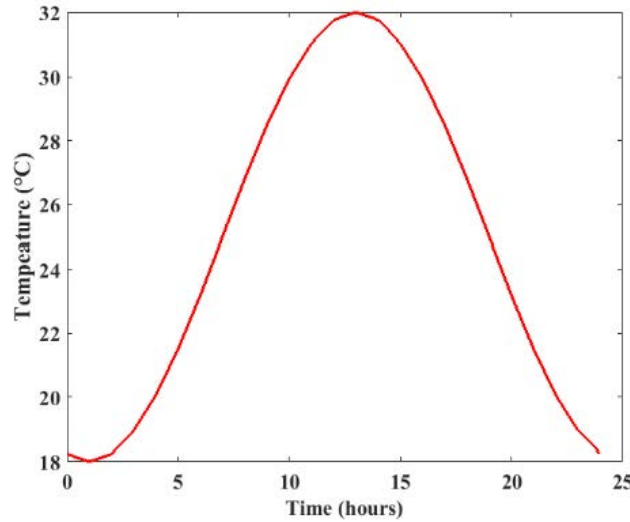


Fig. 2. Variation of the ambient temperature.

and outlet temperature. It was assumed that the pipe surface and soil temperature were the same. The input parameters are calculated from meteorological data. The mean annual soil surface temperature (A) was 15°C and the amplitude of surface temperature variation (T_{moy}) was 12°C. Soil temperatures at two depths of 1 m and 7 m were measured and simulated.

The temperature variation over a summer day is shown in Fig. 2. The ambient temperature reaches its maximum value (32 degrees) at 13:30 on a summer's day (July).

The variation of soil temperature in the Constantine region throughout the year, described by equation (1), for different depths is shown in Fig. 3.

From this figure it can be seen that there is little variation in temperature at greater depths. There are comfortable temperatures between 15 and 20°C at a depth of 3 m. Therefore, a depth of 3 m was chosen for the EAHE system to achieve a maximum temperature of 20°C and a minimum of 15°C. The month of July (5112 hours) was specifically chosen for this study as it is the warmest month with an average temperature of 32°C. The humidity ratio was assumed to be 40%.

The grid sensitivity analysis was carried out using two cases of meshes along the pipe and the soil. A coarse and fine grids (Gr1 and Gr2 respectively) with tetrahedral elements were tested. The fine grids were obtained by refining the coarse grid twice by a factor of about 2. A total of 750,890 elements and 168,608 elements were adopted for Gr1 and Gr2 respectively. The results are presented in Fig. 4, where the

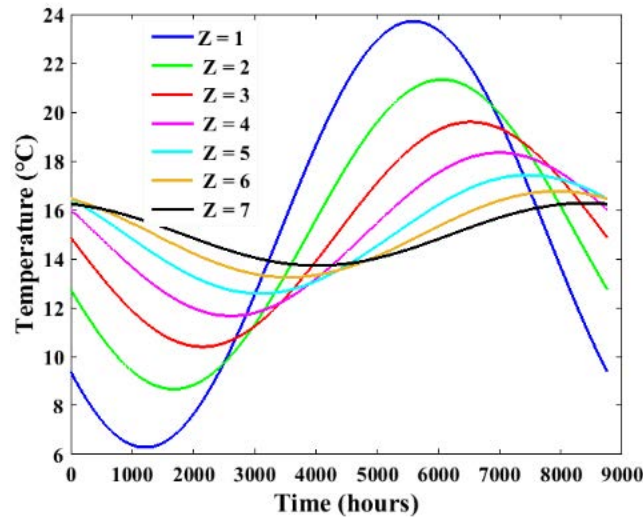


Fig. 3. Variation of soil temperature.

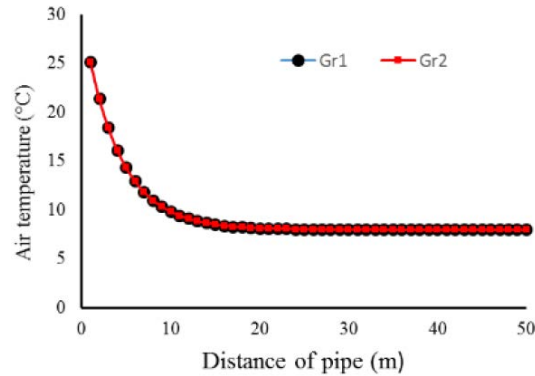


Fig. 4. Outlet air temperature for different grid meshes.

air temperature along the length of the pipe was not affected by the grid refinement. Therefore, the fine grid was considered and used to perform the simulations.

The results of the developed model were compared with those of Misra et al. [30]. The parameters used are: pipe diameter of 10 cm, a length of 60 m, and a depth of burial of 3.7 m. The temperature distribution along the EAHE pipe was measured with a constant air velocity of 5 m/s, and a pipe surface temperature of 300.2 K.

Figure 5 shows the compared temperature distribution along the length of the EAHE pipe for the soil with thermal conductivity of $0.52 \text{ (W m}^{-1}\text{K}^{-1}\text{)}$. An average error of 4% is observed between the present model and the numerical results of Misra et al. [30], whereas the error becomes about 1% when comparing the present results

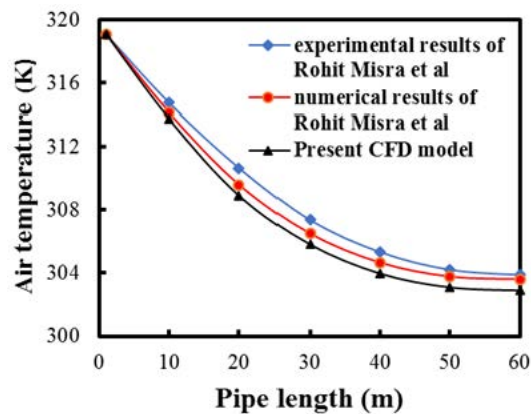


Fig. 5. Comparison between present results with those of Misra et al. [30].

with those of simulated ones of Misra et al. [30]. So, the results are acceptable and the model can be considered good enough for simulating the thermal performance of EAHE.

4 RESULTS AND DISCUSSION

4.1 EFFECT OF INLET AIR TEMPERATURE

Figure 6 displays the variation of inlet air temperature and humidity as a function of pipe length for different inlet air temperature conditions. It is clear that the air temperature decreased more rapidly in the first 10 meters and then remained constant. On the inlet side, there was a great difference between the air temperature and the surface temperature of the pipe. When the inlet air temperature was 40°C, the air temperature drop rate was the highest. If the pipe had been longer, the outlet temper-

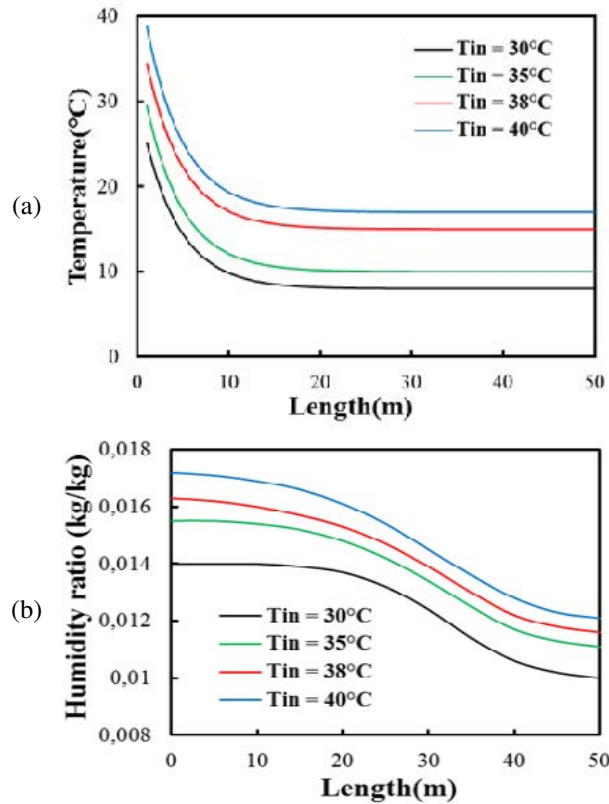


Fig. 6. Performance of EAHE under different inlet air temperature $T_s = 12^\circ\text{C}$, $D = 160$ mm, $V = 1.5$ m/s, $Re = 1.7 \times 10^3$, $Nu = 9.46$, $Pr = 0.71$.

ature would have been close to the pipe surface temperature. Figure 6(b) shows that the air humidity ratio kept a constant value initially and then began dropping. When the air humidity ratio began to drop, it meant that the air achieved the saturated state at that point, and that water vapor began to condense. Consequently, the humidity decreased rapidly for a high air temperature.

4.2 EFFECT OF TUBE SURFACE TEMPERATURE

The air temperature and humidity ratio along the length of the EAHE under the different pipe surface temperature conditions are displayed in Fig. 7. It can be clearly observed that the air temperature decreased more rapidly at lower soil temperatures. When the pipe surface temperature was 8°C, the outlet air temperature was 8°C. From Fig. 7(b) it can be seen that the humidity ratio under the low pipe surface temperature

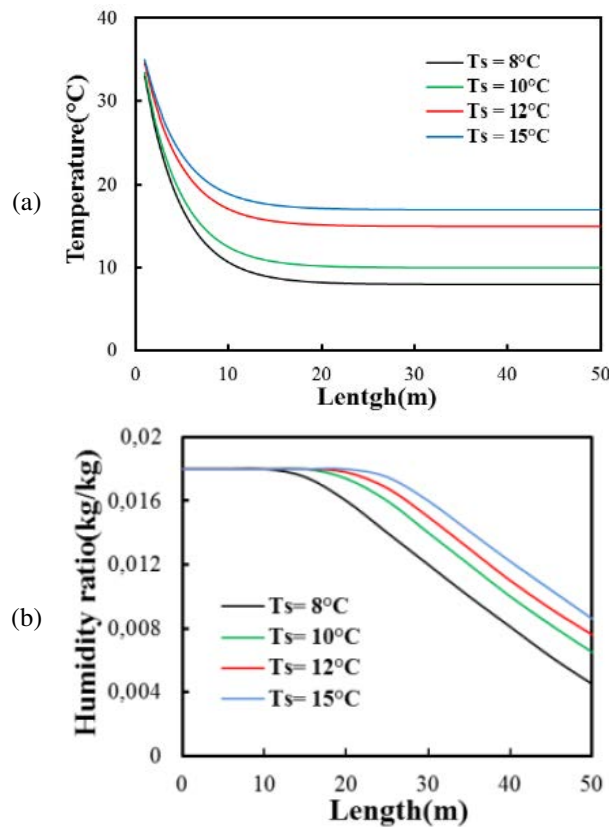


Fig. 7. Performance of EAHE under the different tube surface temperature $T_{in} = 38^\circ\text{C}$, $D = 160\text{ mm}$, $V = 1.5\text{ m/s}$, $Re = 1.7 \times 10^3$, $Nu = 9.46$, $Pr = 0.71$.

reached the saturation state faster than that under the high surface temperature. In addition, the humidity ratio under the low pipe surface temperature decreased faster than that under the high surface temperature.

4.3 EFFECT OF EXCHANGER PIPE DIAMETER

Figure 8 shows the variation of the air temperature and humidity ratio along the length of the EAHE for different tube diameters in order to evaluate the effect of the exchanger diameter on the performance of the EAHE. It can be noted that air temperature decreases exponentially for the different diameters, Fig. 8(a). The cooling of air is proportional to the increase in pipe diameter; this is attributed to the increase in the total exchange surface, which results in a better heat transfer between

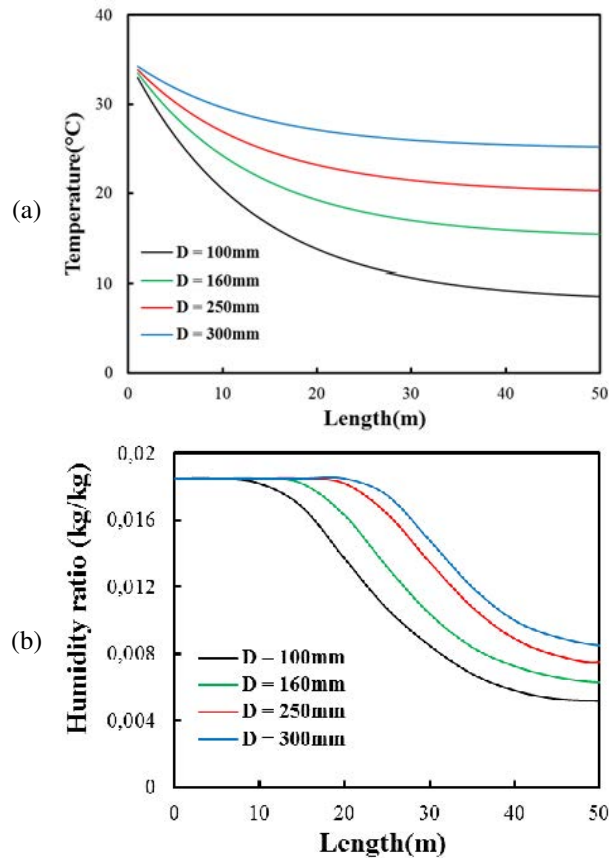


Fig. 8. Performance of EAHE under the different tube diameters. $T_{in} = 38^{\circ}\text{C}$, $T_s = 12^{\circ}\text{C}$, $V = 1.5 \text{ m/s}$, $Pr = 0.71$.

the outer wall of the pipe and the surrounding soil. In other words, the air temperature under the large pipe diameter decreased more slowly than that of the small pipe diameter up to a constant value beyond a length of $L = 50$ m. As can be seen from Fig. 8(b), the humidity ratio of the small pipe diameter reached the saturation first. It also decreased faster than the large pipe's.

4.4 EFFECT OF AIR VELOCITY

The effect of air velocity on the EAHE was analysed. Figure 9 shows the temperature and the humidity ratio along with EAHE length at different air velocities. The rate of decrease in air temperature was fastest at velocity of 1 m/s. The decrease in air velocity corresponded to a faster decrease in air temperature and a lower outlet air temperature. At low velocity, air stayed in the pipe longer. If we increase the air

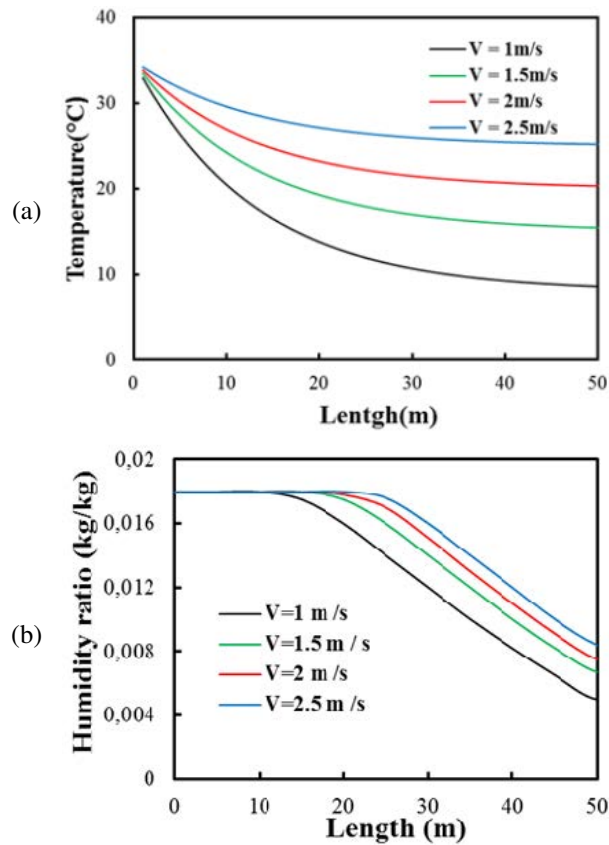


Fig. 9. Performance of EAHE under the different air velocity. $T_{in} = 38^\circ\text{C}$, $T_s = 12^\circ\text{C}$, $D = 160$ mm, $Pr = 0.71$.

velocity, there will be insufficient time for the fluid to transfer heat with the soil. It is not advisable to increase it much. Figure 9(b) shows the humidity ratio initially remaining constant and then decreasing. The condensation point under low air velocity came out earlier than under high velocity.

5 CONCLUSIONS

Due to the relative stability of the soil temperature at a certain depth of underground surface, the EAHE can be used for the cooling of buildings. This paper presented a numerical study to show the effect of design parameters (such as the tube surface temperature, the tube length and diameter, the air temperature and relative humidity, the air velocity at the inlet of EAHE) of the EAHE pipe on its overall performance under the climatic conditions of Constantine city in eastern Algeria. From the simulation results obtained in the present work, the following remarks can be made:

- With increase in the length of the pipe, the outlet air temperature from the EAHE decreases. The decrease in air temperature was sharp for the first 10 m of the pipe's length and became constant afterwards.
- The air relative humidity under the high inlet air temperature condition increased faster than that of the low air temperature condition.
- The increase in pipe diameter induces an increase in the outlet air temperature of EAHE. This is due to the decrease of convective heat transfer coefficient at inner surface of pipe at higher pipe diameters.
- The humidity ratio under the small tube diameter declined faster than that of a large diameter.
- The outlet air temperature of EAHE system increases with increase in tube surface temperature.
- The humidity ratio under the low surface temperature of tube declined faster than that of high surface temperature.
- The decrease in air velocity corresponded to a faster decrease in air temperature and a lower outlet air temperature.
- In addition, the condensation point under low air velocity came out earlier than under high velocity.

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