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A parametric analysis of the earth air heat exchangers' thermal efficiency and their effect on surrounding soil over time

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ABSTRACT

Earth Air Heat Exchanger (EAHE) system is widely regarded as an efficient and sustainable solution, minimizing the consumption of energy and enhancing indoor thermal comfort. This study seeks to conduct a detailed analysis of the parameters that affect the performance of EAHE systems, including the surrounding soil, climatic conditions, and time variations. A semi analytical numerical model was used and verified with existing literature data. Key parameters such as air velocity, operational periods, and soil thermal conductivity were investigated for their effect on the performance of the EAHE and the surrounding soil. The findings revealed that the model provided predictions that strongly agreed with experimental results, with only a 2.3% error margin. The study found that EAHE performance is predominantly influenced by higher soil conductivity and lower airflow velocity. In contrast, the duration of operation had minimal effect on the outlet air temperature, which increased by just 1 °C over 48 h compared to the 1st h. Lastly, the cooling of the surrounding atmosphere was identified as a key factor in enhancing the exchanger's efficiency, as it helps cool the soil after extended operation, thus restoring its cooling ability.

KEYWORDS

Soil surrounding
EAHE
Cooling
Continuous operation
Thermal performance

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1 Introduction

Algeria is considered the largest African country in terms of area. However, the desert occupies approximately 80% of its area. This fact has made it face significant climate and energy consumption challenges due to the necessity of using the cooling and air conditioning systems, especially during the summer, when 50% of the consumed energy by buildings is used on Heating, Ventilation, and Air Conditioning (HVAC) systems. Furthermore, Algeria faces additional challenges due to increasing temperatures resulting from global warming. According to the World Health Organization, it is expected that the rate of increase in the average annual temperature in Algeria between 1999 and 2100 years will reach about 6.2 °C [1], which increases pressure on energy consumption infrastructure and cooling system demand. The government is working hard to overcome these challenges and increase reliance on renewable and clean energy sources.

Earth Air Heat Exchanger (EAHE) is a popular HVAC technology among researchers. They have been studied numerically and experimentally in diverse climates and countries. According to the literature [2-4], this technology is highly effective in providing a portion of the required thermal needs at lower costs and more straightforward techniques than other available technologies. However, if it is misdesigned, it may be unable to deliver the expected performance. This technology is based on the principle of temperature variation between the earth's surface and its depth, where in summer (or during the day), the earth's temperature is colder than the air, while it becomes warmer in winter (or at night). For this reason, parameters affecting the system's thermal efficiency must be considered during its design in all the operation states (operating continuously over long periods or intermittently over short periods). The factors that have been extensively studied are the influence of pipe diameter, length, material, burial depth, soil types, and airflow rates. Based on the studies presented by Boutera et al. [5, 6] and Belloufi et al. [7], The lower the tube diameter, the greater the heat exchange efficiency in the tube. The research also indicates that heat exchange is maximum in the first part of the tube, and this value in research has ranged from 30 to 80 m depending on the amount of air flowing inside the tube. On the other hand, Laknizi et al. [8] showed that the effect of the type of material used in the tube on thermal performance is negligible. Misra et al. [9] Moreover, Belloufi et al. [10] investigated the effects of continuous operation time, thermal conductivity of soil pipe diameter, and air velocity on the thermal performance of EAHE. According to their findings, the heat exchanger's performance increases with high soil thermal conductivity

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and low air velocities, while the air-cooling rate falls with time in soil with low thermal conductivity.

Based on previous studies, this research aims to profoundly and comprehensively examine various parameters associated with surrounding soil, weather conditions, and temporal factors and how they affect the performance of EAHE systems. This research mainly focuses on improving the comprehension of the EAHE performance systems over time to enhance its efficiency as a sustainable cooling system that responds to environmental challenges and reduces energy consumption and its negative impacts.

2 Methodology

To evaluate the efficiency of the EAHE in cooling operations, analyzing the effect of various factors on its performance during a continuous period of operation, and its interaction with the surrounding weather conditions, data related to air temperatures were collected in the city of Biskra during 48-hours (1 and 2 July 2023) [11].

2.1 Mathematical model

The continuous operation of the EAHE in the cooling case contributes to raising the surrounding soil temperatures over time, while this rise plays a vital role in changing the ability of heat exchange between the soil and the air inside the pipe (Fig. 1). Therefore, this paper relied on a semi-analytical transient GRBM model [12, 13] that considers these factors under the following assumptions:

- The air and soil thermophysical properties are constant.
- The convective heat transfer coefficient is constant along the pipe.
- The soil moisture is neglected.
- Soil surrounding the EAHE is homogenous.

The pipe j[th] layer's air outlet temperature is provided as follows:

$$T_{a(j)}^{out} = (T_{a(j)}^{in} - T_{si}).exp(\frac{-\Delta x}{R_{tot}.\dot{m}_a.cp}) + T_{si} \quad (1)$$

For a given time interval (t_i), Eq. 1 can be expressed as follows, assuming the layer length (Δx) is 1 m, and the air temperature at the inlet of layer (j) is equivalent to the air temperature at the outlet of layer (j-1):

$$T_{a(j+1,i)} = (T_{a(j,i)} - T_{s(j,k,i)})\,exp(\frac{-1}{R_{tot}.\dot{m}_a.cp}) + T_{s(j,k,i)} \quad (2)$$

where $T_{s(j,k,i)}$ is the transient surrounding soil temperature and can be calculated by:

$$T_{s(k,j,i)} = \frac{2.(T_{a(j,i)} - T_{si})}{r_\infty^2.log(\frac{r_{s(j,i-1)}}{r_e})}\sum_{n=1}^{\infty}\frac{1 - e^{-\alpha_s.\beta_n^2.t_i}}{\beta_n^2}\frac{J_0(\beta_n.r_k)J_0(\beta_n.r_e)}{J_1^2(\beta_n.r_\infty)} + T_{si} \quad (3)$$

The overall thermal resistance R_{tot} between the surrounding soil, pipe, and air at the J[th] layer is expressed as follows:

$$R_{tot} = R_a + R_p + R_s \quad (4)$$

Where, Ra, Rp, and Rs represent the thermal resistance associated with convective heat transfer, the thermal resistance of the pipe, and the soil.

$$R_a = \frac{1}{h.2.\pi.r_i} \quad (5)$$

The air convection coefficient h is calculated based on the following Nusselt number correlation:

$$Nu = 0.023.Re^{0.8}.Pr^{0.3} \quad (6)$$

The equation below gives the thermal resistance of the pipe and the soil:

$$R_p = \frac{log(\frac{r_e}{r_i})}{2.\pi.k_p} \quad (7)$$

$$R_s = \frac{log(\frac{r_s}{r_e})}{2.\pi.k_s} \quad (8)$$

The soil radius is calculated by equation (9), where δ is the soil thickness.

$$r_s = r_e + \delta \quad (9)$$

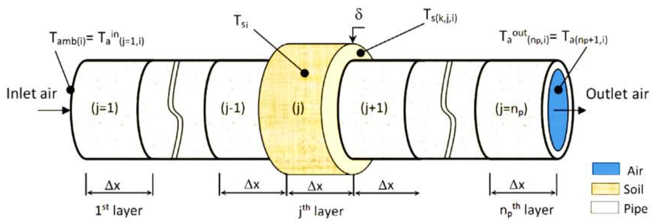

Fig.1. The pipe and soil stratification schematic of the GRBM model (i, j, and k represent time, layer, and radius, respectively).

3 Results and discussion

3.1 Model verification

The mathematical model has been verified with experimental data provided by Mehdid et al. [12] for the EAHE over a continuous 6-hour operation to confirm the accuracy of the results provided in this paper. Table 1 shows all the parameters used in this validation.

Table 1. Air, soil, and pipe thermophysical and geometric properties [12].

	Air	Soil	Pipe
c_p (kg^{-1}.K^{-1})	1005	1800	1380
ρ (kg.m^{-3})	1.225	1340	900
k (W.m^{-1}.K^{-1})	0.0242	1.5	0.16
u (m.s^{-1})	3.5	-	-
T_{si} (°C)	-	22	-
L (m)	-	-	47
Di (m)	-	-	0.11
Pt (m)	-	-	0.005
Pd (m)	-	-	2

Fig. 2 presents the findings of the verification analysis of the numerical model compared to the results of field measurements provided by Mehdid et al. [12], which is the air temperature at the outlet of the EAHE over a continuous operation period of 6 h. This graph shows that the calculation model's numerical findings are compatible with the experimental data, with a 2.3% relative error maximum.

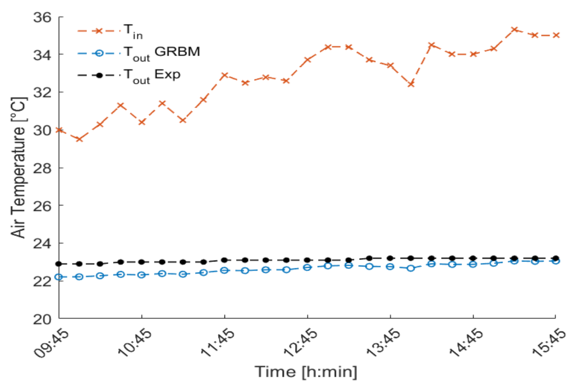

Fig.2. The results of the present paper's numerical model compared to the field measurements obtained by Mehdid et al. [12].

3.2 Operation time effect

The results in Fig. 3, 4, and 5 represent the effect of different operating times (1, 12, 24, 36, and 48 h) on the air temperature along the heat exchanger. The operating time and ambient air temperature appear to affect the air temperature. This effect is observed when comparing the air temperature decrease during the first hour of operation concerning more extended periods (24, 36, and 48 h). However, the ambient air temperatures are similar. The air temperature during the first hour is lower than the last hour of operation (48h) by 1 °C. This can be explained by the high soil temperature surrounding the heat exchanger, shown in Fig. 4. This contributes to reducing heat exchange between them. On the other hand, when the ambient air temperature is very high, it takes longer and longer to achieve equilibrium in the air temperature with approximately the initial soil temperature.

After 48 hours of continuous operation (Fig. 3), the findings show that the EAHE outlet temperatures are somewhat stable despite changes in ambient air temperatures. However, it should be mentioned that the EAHE outlet temperatures increase by 1.14 °C between the maximum (42.4 °C) and minimum (27 °C) ambient air temperatures recorded.

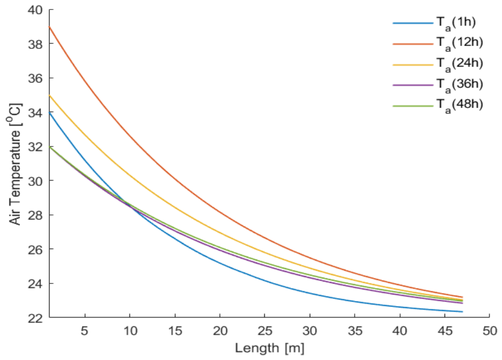

Fig.3. Air temperatures along the EAHE after 1 h, 12 h, 24 h, 36 h and 48 h of continuous operation.

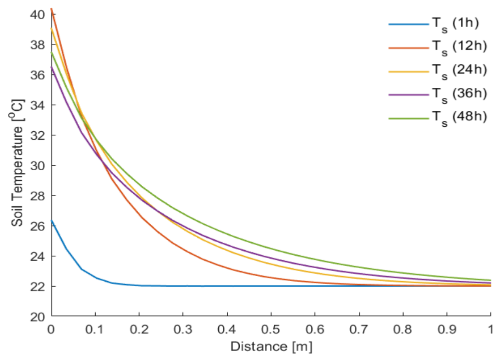

Fig.4. Radial soil temperatures at the EAHE inlet after 1 h, 12 h, 24 h, 36 h and 48 h of continuous operation.

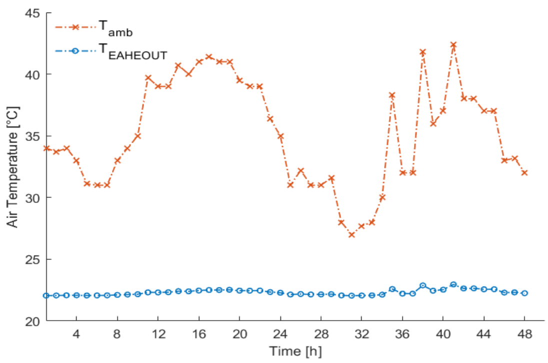

Fig.5. Ambient temperature and Air temperatures at the EAHE outlet after 48 h of continuous operation.

3.3 Air velocity effect

Fig. 6 illustrates the effect of three different speeds (3.5, 5.5, and 7.5 m.s^{-1}) on the air temperature along the EAHE in continuous operation mode for 12 hours.

The findings showed that increasing the velocity led to higher EAHE outlet air temperatures, ranging between 22.1, 23.8, and 25℃ at 3.5, 5.5, and 7.5 m.s^{-1}, respectively. This effect is due to the increased amount of air passing through the pipe, which requires a greater exchange length to transfer sufficient heat to the soil and thus reach temperatures similar to the initial soil.

On the other hand, Fig. 7 and 8 presented the effect of air velocity in EAHE on the radial soil temperature at the middle and outlet of EAHE during continuous operation for 12 hours. The results showed that increasing the flow velocity led to an increase in the temperature of the soil surrounding the pipe due to increasing the heat transfer rate.

The flow rate is less at low air velocities, causing the air to lose heat faster to the soil in the first meters. This phenomenon is also observed in soil temperature, which changes at a lower rate with increasing pipe length due to the soil temperature surrounding the pipe becoming closer to the initial soil temperature. Meanwhile, at higher air velocities, the airflow increases, thus requiring a longer exchange length to achieve total heat exchange. This explains the continued transfer of heat from the air to the soil along the pipe without the air losing its heat completely, and in return, soil temperatures are high.

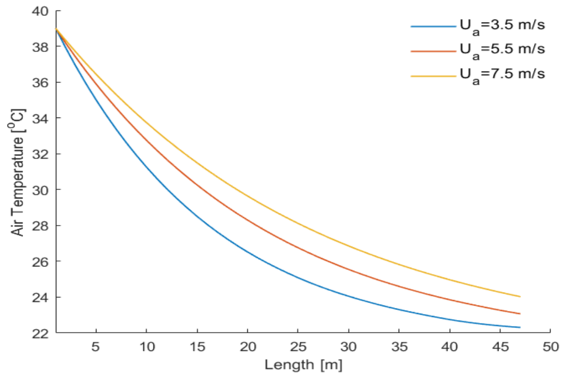

Fig.6. Air temperatures along the EAHE at three velocities after 12 h of continuous operation.

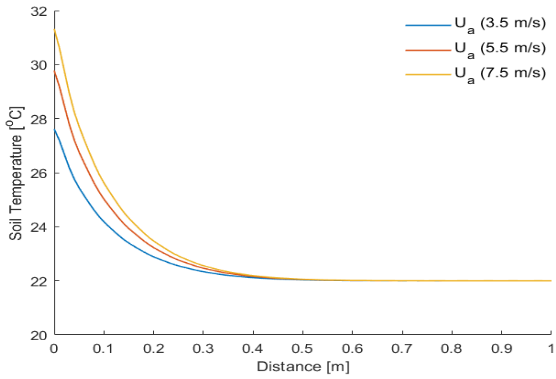

Fig.7. Radial soil temperatures at 23m of EAHE length after 12 h of continuous operation for three air velocities.

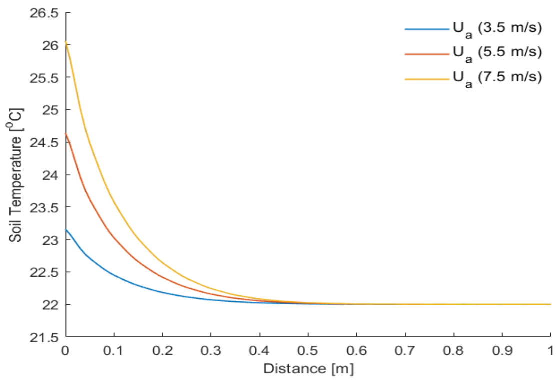

Fig.8. Radial soil temperatures at the outlet of EAHE after 12 h of continuous operation for three air velocities.

3.4 Soil properties effect

The findings presented in Fig. 9 and 10 show a significant effect of three different soil types, which differ in their ability to conduct heat (0.5, 1.5, 4 W.m^{-1}.K^{-1}) on the air temperature along the heat exchanger and the surrounding soil temperature during a continuous operation period lasted 12 hours. It turns out that increasing the soil's ability to conduct heat plays an important role in further reducing air temperature. This is due to improving the soil's ability to transfer heat and facilitating the transfer of accumulated heat toward the ground layers far from the heat exchanger. This effect clearly appears in the temperature of the surrounding soil, as its temperature is higher at higher thermal conductivity.

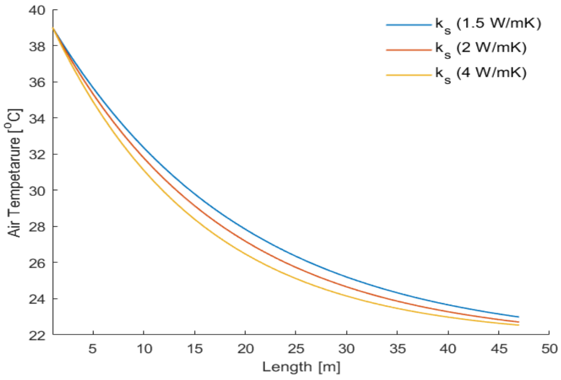

Fig.9. Air temperatures along the EAHE of three soil thermal conductivities after 12 h of continuous operation.

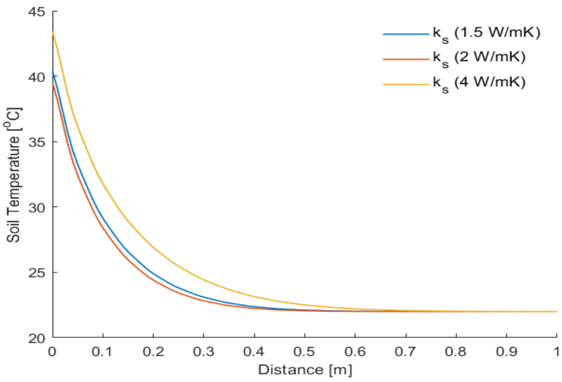

Fig.10. Radial soil temperatures of three soil thermal conductivities at the EAHE inlet after 12 h of continuous operation.

4 Conclusion

This article studied the effect of ambient climatic conditions, surrounding soil type, and time factors on EAHE performance. A semi analytical, numerical model was developed to calculate the soil temperatures and the EAHE's outlet air, and the precision of the numerical results was validated with the experimental data in the literature. The study concluded:

- The numerical model provides accurate results with a maximum error of 2.3% compared to experimental findings.
- Operating time doesn't affect the EAHE's outlet air temperature, with a modest increase of 1 °C within 48 h compared to the 1st h.
- The higher the ambient air temperature, the longer it takes for the cooling process to bring the air temperature into equilibrium with the soil temperature.
- At higher air velocities, the airflow increases and requires a longer exchange length to achieve total heat exchange. This results in continued heat transfer from the air to the soil along the pipe, leading to higher temperatures.
- Soils with higher thermal conductivity are more effective at transferring heat, resulting in lower air and soil temperatures.

In light of these findings, it is clear that a comprehensive understanding of surrounding factors is crucial for the optimal design of EAHE systems. Taking under consideration the effect of ambient temperature, air velocity, and soil properties on heat transfer rates, engineers can create systems that operate at peak performance while minimizing environmental impact and maximizing economic benefits.

Declaration of Competing Interest

The authors declare no competing interests.

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Nomenclature

Cp	Specific heat capacity ($J.kg^{-1}.K^{-1}$).
Di	Inner diameter (mm).
k	Thermal conductivity ($W.m^{-1}.K^{-1}$).
L	Length (mm).
Pd	Pipe distance (mm).
Pt	Pape thickness (mm).
Tsi	Initial soil temperature (°C).
u	Inlet air velocity ($m.s^{-1}$)
ρ	Density ($kg.m^{-3}$)