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Numerical Assessment of EAHE Systems for Refreshment in Desert Algerian Regions

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ABSTRACT

As an example of green energy (geothermal energy), which has been the subject of advanced research in recent decades, the earth-to-air heat exchanger (EAHE) is the application of an air heat exchanger to soil temperatures, in which air circulates in tubes in thermal contact with the ground. The performance of the EAHE cooling system is evaluated at two separate sites (arid and semi-arid) in Algeria throughout this investigation. The impact of the EAHE system's entombed depth is then considered in this paper. According to our earlier research, the proper depth of the inhumed pipes is set at 3 m. The thermo-physical properties of the soil at several sites located in southern Algeria (Ghardaia: 32° 22′ 54″ North, 3° 47′ 58″ East) and Ouargla: 31° 55′ 53″ North, 5° 24′ 24″ East) are implemented by writing a program with the Scilab 6.0.2 software. Based on the results obtained, it can be concluded that the thermal range parameter is a more relevant and efficient parameter for evaluating the thermal performance of the EAHE (Earth-to-Air Heat Exchanger) system. Furthermore, the Ouargla region is a suitable location for the experimental realization of the EAHE system. The thermal amplitude interval (T_{range}) in Ouargla during the annual period is larger compared to Ghardaïa, with maximum values of 22.5°C and 20°C respectively. It is worth noting that the thermal comfort level (20–27°C) is more suitable for the Ouargla region rather than Ghardaïa. Additionally, there is an average difference of around 2.5°C in the thermal amplitude between the two zones during the hot season, further highlighting the superiority of the Ouargla region.

1. INTRODUCTION

Utilizing geothermal energy as a renewable source in the bioclimatic sector of housing is crucial for achieving optimal thermal comfort and energy efficiency. Numerous studies in the literature have highlighted the use of renewable energy management techniques such as mechanical ventilation [1-3], control of PV energy [4], etc. To enhance the comfort of occupants, it is important to reduce energy losses in buildings. While traditional methods of heating and cooling require a significant amount of energy, researchers are currently exploring more feasible and economical alternatives such as EAHE. An example of such research can be found in the following studies (Xamán et al. [5]; Sakhri et al. [6, 7]; Hamdi et al. [8]; Ahmad and Prakash [9]; Sehli et al. [10]; Kaddour et al. [11]; Ismael et al. [12]; Belloufi et al. [13]; Rodrigues et al. [14]).

Researchers have conducted numerous studies to assess the effectiveness of Earth-to-Air Heat Exchanger (EAHE) systems by considering various geometric and environmental factors. For instance, Bansal et al. [15] conducted a case study in the Indian city of Ajmer, where they tested a mathematical model and evaluated the performance of two soil air exchangers made of different materials. Similarly, Hadjadj et al. [16] performed an experimental evaluation of the energy and exertion levels of the Horizontal Wind-Driven EAHE (HWAHE) system in El Oued, Algeria.

By reducing space heating and cooling from 14.82-1.67 GJ to 12.74-0.93 GJ, or 14-44%, respectively, Michalak [17] were able to minimize annual energy consumption. During both the summer and winter periods, Ascion et al. [18] carried out an evaluation of an EAHE system for an air-conditioned building. The energy requirements of the systems in various Italian climates were also calculated. Annual experimental researches on the EAHE was conducted by Rose et al. [19] in a typical Portuguese home. D'Agostino et al. [20] demonstrated that using EAHX reduces the thermal power of the air handling unit's coils by more than 40% in most circumstances. Belatrache et al. [21] carried out a parametric analysis on the EAHE in arid environments, aided by a green wall. Hassan et al. [22] completed a numerical assessment of the EAHE overall performance in the climatic circumstances of Nasiriyah, Iraq.

Li et al. [23] established the heating capacity and the coefficient of performance (COP) by taking measurements of the humidity and temperature of the air along the length of the pipe to determine variations within the EAHE. According to Bhusare et al. [24] found that the optimal combination of an EAHE to achieve the desired cooling load is 0.2 m and 3 m/s, the pipe diameter and the velocity of air, respectively. Ahmad and Prakash [25] studied the thermal efficiency of the EAHE by utilizing Gangetic soil from the Patna region, examining it at a specified depth in a controlled environment using a laboratory-scale experimental setup.

According to findings of Pakari and Ghani [26], at an air flow rate of 607 m^3/h, the EAHE was able to cool the surrounding air by as much as 8.5°C, resulting in a cooling capacity of 1700 W and a COP of 17. Rodríguez-Vázquez et al. [27] determined that the EAHE is highly suitable for dry climates, such as those present in northern Mexico, but not recommended for humid climates found in the southern and southeastern regions of the country. Previous investigations on EAHEs have examined various scenarios and diverse locations throughout Algeria, see Ahmad et al. [28]; and Sakhri et al. [29-35].

The building industry can significantly reduce energy consumption by effectively utilizing eco-friendly and long-lasting renewable energy sources. The EAHE, which uses soil temperatures to circulate air through tubes in thermal contact with the ground, is one such green energy. This study examines the performance of the EAHE in two different locations in southern Algeria during the cooling season. Previous studies have mostly focused on measuring the outlet temperature or thermal efficiency of the EAHE system. However, the present study introduces a new parameter, 'thermal range', to assess the thermal performance of the EAHE system. On one hand, this system maintains a comfortable temperature for habitation in arid regions, while on the other hand, it provides cooling for agricultural greenhouses and regulates the interior temperature throughout the year.

2. REPRESENTATION OF THE SYSTEM

The current EAHE system operates based on the following principles: external air is continuously introduced into the buried tube, resulting in a temperature that closely resembles the ground temperature, as depicted in Figure 1.

The pipe is comprised of two vertical sections, each with a length of 3 meters; one section extends downwards, while the other extends upwards. Heat exchange with the surrounding soil takes place along the length of these sections, and the temperature gradient varies with depth, which is denoted by variable Z. The remaining section of the pipe is horizontal and has a fixed depth of 3 meters, with a length of 60 meters. It is worth noting that this horizontal section is primarily responsible for the overall thermal transformation of the air flowing inside the pipe.

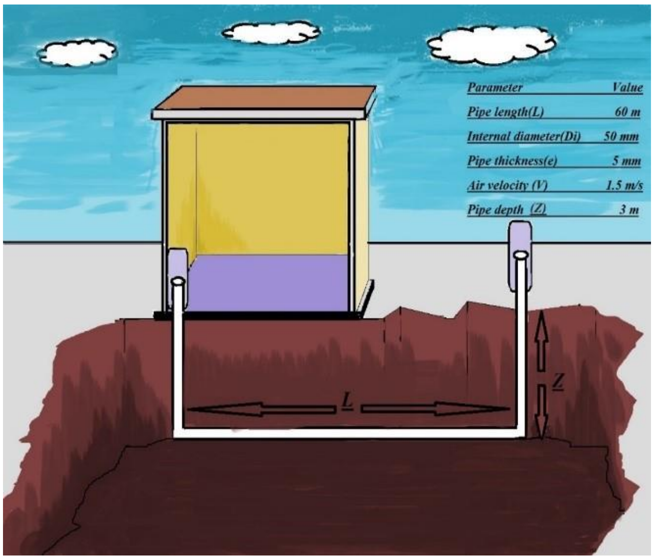


Figure 1. Diagram of EAHE system

3. GROUND TEMPERATURE MODELING

The mathematical representation of soil temperature is achieved through the application of the following 1D transient heat conduction theory to a semi-infinite medium [11, 21]:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \tag{1}$$

$$T(0,t) = T_{mean} + A_a \cos\big(\omega(t - t_0)\big) \tag{2}$$

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

The thermal diffusivity of the soil is provided by [11, 21]:

$$\alpha = \frac{\lambda}{\rho\, C_p} \tag{4}$$

$$T(z,t) = T_{mean} + A_s \left(Exp - (z)\sqrt{\frac{\pi}{365\,\alpha}} \cos\left\{\frac{2\pi}{365}(t - t_0) - (z/2)\sqrt{\frac{\pi}{365\,\alpha}}\right\}\right) \tag{5}$$

The estimated air temperature at the EAHE output is as follows [11, 21]:

$$T_s = T_{amb} + (T(z,t) - T_{amb}) \times \left(1 - e^{-\frac{G_{Tot}}{\dot{m}\, C_{Pf}} x}\right) \tag{6}$$

The EAHE's average seasonal thermal efficiency is described as:

$$\eta_{mean} = \frac{\sum_{i=1}^{24}(T_{amb}(i) - T_{out}(i))}{\sum_{i=1}^{24}(T_{amb}(i) - T_{soil})} \tag{7}$$

4. EAHE SYSTEM MODELING

The 60-meter-long EAHE is broken into 100 0.6-meter-long elements. The air movement is thought to have a greater impact on soil temperature. The following correlation was used to express the number of Nusselt [11, 21]:

$$Nu = 0.0214\ (Re^{0.8} - 100)\ \ Pr^{0.4} \tag{8}$$

Inside the tube, the Reynolds and Prandtl numbers are determined as follows:

$$Re = \frac{V_{air}\ D_i}{\upsilon} \tag{9}$$

$$Pr = \frac{\upsilon\ \rho\ cp}{\lambda} \tag{10}$$

The EAHE's total heat transfer coefficient is thus stated as:

$$G_{Tot} = \frac{1}{(R_{conv} + R_{pipe} + R_{soil})} \tag{11}$$

The ground surface boundary equation is:

$$T(0) = T_{amb} \tag{12}$$

Additionally, the air temperature at the output can be estimated in the following manner:

$$T_s = T_0 + (T(z,t) - T_0)\left(1 - e^{-\frac{G_{Tot}}{\dot{m}\ C_{Pf}}x}\right) \tag{13}$$

Thermal range:
T_{avrg}: the average thermal range for two studied regions.

$$\langle T_{avrg} \rangle = \frac{\sum_{365} \frac{\left|T_i^{rang-Ourgl} + T_i^{rang-Ghar}\right|}{2}}{365} \approx 10 \tag{14}$$

$$\begin{cases} T_i^{rang-Ourgl} = \left|(T_{\max} - T_{\min})_i^{Ourgl}\right| \\ T_i^{rang-Ghar} = \left|(T_{\max} - T_{\min})_i^{Ghar}\right| \end{cases} \quad i = 1 \rightarrow 365 \tag{15}$$

input: file 1 Tamb (Ghardaia; Ouargla) /hr
↓
file 2 Tsoil at 3 m (Ghardaia; Ouargla) /hr
↓
input: file 3 properties (air; soil 1; soil 2; pipe)
↓
file 4 Tout (Ghardaia; Ouargla) /hr
↓
file 5 Tout (Ghardaia; Ouargla) /day efficiency of EAHE system in (2sites)/ cooling mode /day
↓
file 6 Tm (Ghardaia; Ouargla) thermal range of EAHE system in (2 sites)/ cooling mode /day

Figure 2. Plan of our study's flowchart

The equations mentioned above are solved in a step-by-step manner for every segment of the Earth-to-Air Heat Exchanger (EAHE) system, starting from the entrance and progressing towards the outlet. This process is carried out with the aid of a Fortran software program [11], as illustrated in Figure 2.

Meteorological data, including temperature, humidity, and wind speed, are obtained through the use of an ONM station located in Ouargla. The data is then analyzed using specific parameters to draw conclusions in this study.

The choice was made to track the hourly changes of all the variables, including temperature, humidity, and wind speed, in the program. This decision was based on two reasons. Firstly, it enables us to derive the daily and monthly changes required for the analysis of the results. Secondly, hourly tracking of the weather variables provides more precise and useful information in the meteorological station data.

Figure 3 schematizes the variation in annual ambient air temperature for the two different regions (Ghardaïa: 32° 22′ 54″ North, 3° 47′ 58″ East) and (Ouargla: 31° 55′ 53″ North, 5° 24′ 24″ East).

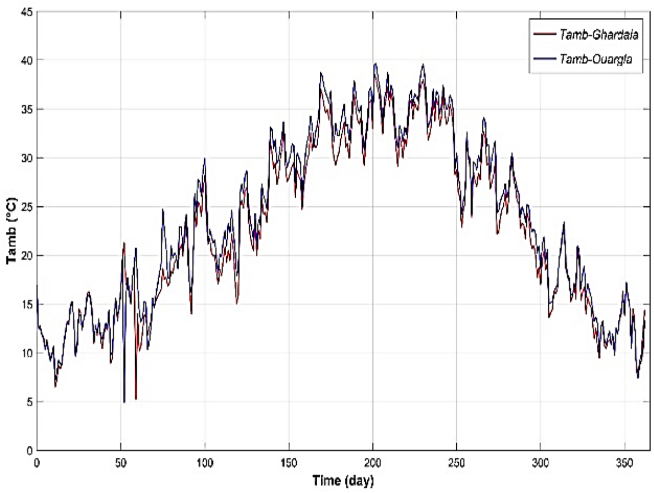


Figure 3. Annual ambient temperature for two selected regions

Note that the curves have the same shape with a slight difference of around 1.1°C on average. The minimum temperature indicated in the winter season (December, January, and February) is between 4.89 °C and 5.26°C. On the other hand, the maximum temperature indicated in the summer season (June, July, and August) is between 38.57°C and 39.62°C.

5. VALIDATION OF THE MODEL

To validate the proposed model, the experimental results reported by Bansal et al. [15] were utilized prior to conducting the parametric analysis (see Table 1). The experiment involved circulating air through a PVC pipe that was 23.42 m in length and had an inner diameter of 0.15 m. The soil temperature was maintained at 26.7°C, and the air inlet velocity was set at 3 m/s under these specified conditions.

It can be concluded that the established model can accurately predict the thermal performance of EAHE systems, as demonstrated by the comparison to the experimental results of Bansal et al. [15]. With an absolute relative difference of less than 2.01% (see Eqns. (16)-(18)), the present model provides reliable and precise estimates of the EAHE's thermal efficiency. This makes it an effective tool for further research and practical applications in this field.

$$\Delta T = (\sum_{i=1}^{24} Error_i)/24 = 0.69°C \tag{16}$$

$$T_{in} = (\sum_{i=1}^{24} Tinlet_i)/24 = 34.48°C \tag{17}$$

$$Error\% = \frac{\Delta T}{Tin} \times 100 = 2.01\% \tag{18}$$

Table 1. Comparison of the present study with Bansal's experimental data

$T_{inlet} = T_{amb}$ (°C)	T_{outlet} (°C)	T_{outlet} (°C) Bansal [15]	$Error_i$ (°C)
31,400	27,390	28,300	00,910
32,300	27,822	28,700	00,878
34,000	28,639	29,400	00,761
35,600	29,408	30,100	00,692
37,000	30,082	30,600	00,518
38,200	30,660	31,200	00,540
38,900	30,998	31,300	00,302
39,300	31,191	31,600	00,409
39,300	31,191	31,600	00,409
38,800	30,949	31,300	00,351
37,900	30,516	31,100	00,584
36,700	29,938	30,500	00,562
35,500	29,360	30,000	00,640
34,100	28,687	29,400	00,713
32,600	27,966	28,900	00,934
31,200	27,294	28,200	00,906
31,300	27,342	28,200	00,858
32,100	27,726	28,600	00,874
32,600	27,966	28,900	00,934
32,800	28,062	29,000	00,938
32,700	28,014	28,900	00,886
32,200	27,774	28,600	00,826
31,200	27,294	28,200	00,906
30,000	26,718	27,000	00,282

6. FINDINGS AND ANALYSIS

Table 2 take into account the thermal and physical properties of air, pipe, and soil materials to evaluate the effect of different design and operational parameters on the efficiency of EAHE.

Table 3 lists the input EAHE parameters that were employed.

Figure 4 shows the simulation of the annual ground temperature for the two cities (Ghardaïa and Ouargla). In consideration of the difference in the homogeneity of the soils, the nature of the soil is compact and rocky in the region of Ghardaïa. On the other hand, the region of Ouargla belongs to the family of sandy soils. According to Figure 4, we obtained the sinusoidal form of the ground temperature at a certain optimum depth of 3 m. We note that the amplitude of the soil temperature curves is significant, with an average difference of 2.52°C.

Figure 5 represents the annual evolution of temperatures at the entrance and exit of the EAHE exchanger for the two regions. It can be seen that there is a temperature gain in the winter period between the end of October and mid-March. Conversely, a loss in heat quantity was noticed between the beginning of May and the end of September. There is a random variation during the off-season.

Table 2. Material thermophysical properties, such as those of air, PVC and soil

Thermophysical characteristics of materials including:			
Air [1]			
ρ_{air} in Kg. m^{-3}	1.1774		
K_{air} in W. m^{-1}. K^{-1}	0.02624		
Cp_{air} in J. kg^{-1}. K^{-1}	1005.7		
PVC [1]			
ρ_{PVC} in Kg. m^{-3}	1380		
K_{PVC} in W. m^{-1}. K^{-1}	0.16		
Cp_{PVC} in J. kg^{-1}. K^{-1}	900		
Soil			
Region of Ouargla		Region of Ghardaia [11]	
ρ_{soil} in Kg. m^{-3}	1780	P_{soil} in Kg. m^{-3}	2044
K_{soil} in W. m^{-1}. K^{-1}	0.93	K_{soil} in W. m^{-1}. K^{-1}	2.3
Cp_{soil} in J. kg^{-1}. K^{-1}	1390	Cp_{soil} in J. kg^{-1}. K^{-1}	1000
α_{soil} in m^2. s^{-1}	3.76×10^{-7}	α_{soil} in m^2. s^{-1}	8.39×10^{-7}
$T_{average\ annual}$ in °C	22	$T_{average\ annual}$ in °C	21.7

Table 3. The simulation's input EAHE parameters

Physical magnitude	Value	Unit
D	3	m
D_i	50×10^{-3}	m
L	60	m
W_p	5×10^{-3}	m
V_{air}	1.5	m. s^{-1}

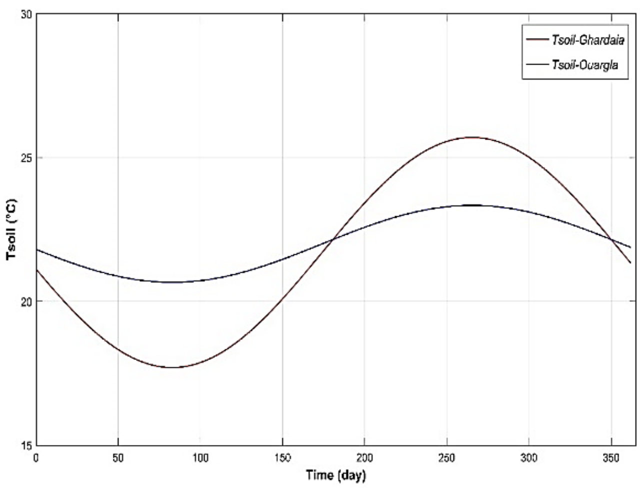
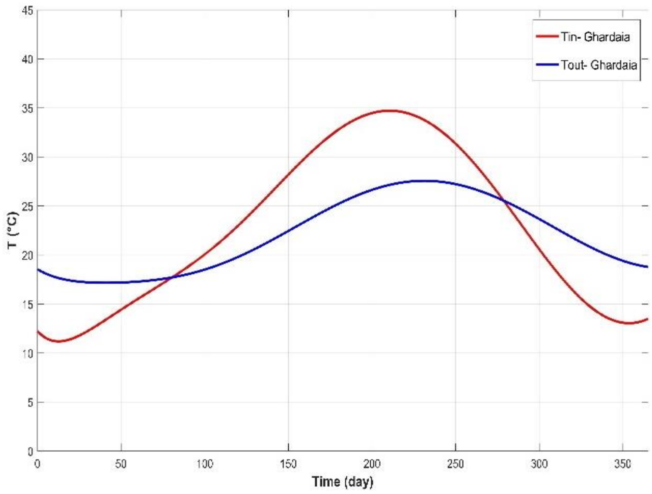


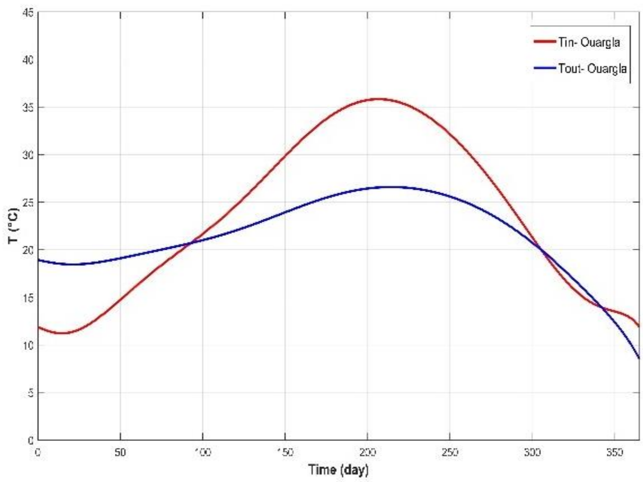
Figure 4. Simulated data of annual ground temperature for two selected regions

The daily temperature variations All within the Ouargla site are between 15.519°C (this corresponds to the 52nd day) and 29.962°C (this corresponds to the 201.75th day). This interval, however, varies between 13.859°C (the 59.33rd day) and 30.409°C (the 242.66th day) at the Ghardaia site.

For a better determination of the optimal site for controlling the operation of the EAHE exchanger, we compared the simulated EAHE outlet temperatures for the two regions studied (see Figure 6). Everything is practically identical between the days of 180 and 200, which correspond to the June and July months, and correspond to temperatures of 25°C and 26°C, respectively. During days 320 and 365 (beginning of November until the end of December), the evolution of the temperature is almost identical, with a difference of 1°C. The performance of the EAHE exchanger is better adapted to the region of Ouargla than that of Ghardaia. We note that the thermal comfort (20–27°C) is quite adequate, which corresponds to the region of Ouargla rather than that of Ghardaïa (see Figure 6).



(a)



(b)

Figure 5. Evolution of inlet and outlet EAHE temperatures: (a) Ghardaia region, (b) Ouargla region

According to Figure 7, the thermal range T_{range} parameter was determined to determine the influence of the EAHE system on thermal comfort. The figure illustrates the variation of the thermal range T_{range} factor between the two regions.

The results of the study demonstrate that the thermal range interval T_{range} in Ouargla is wider compared to Ghardaïa throughout the year (365 days), with maximum values of 22.5°C and 20°C, respectively, as presented in Figure 7(a). The analysis of the cooling period in arid and semi-arid regions (Figure 7(b)) provided further insights into the importance of our EAHE system. It was observed that the zone located above the T_{range}=10°C produced the most favorable outcomes in terms of thermal comfort during the months studied, which spanned from early April until early October. Notably, the Ouargla region proved to be more optimal than Ghardaïa, with an average difference of approximately 2.5°C during the hot season. These findings highlight the significance of our EAHE system in enhancing thermal comfort in areas experiencing extreme heat.

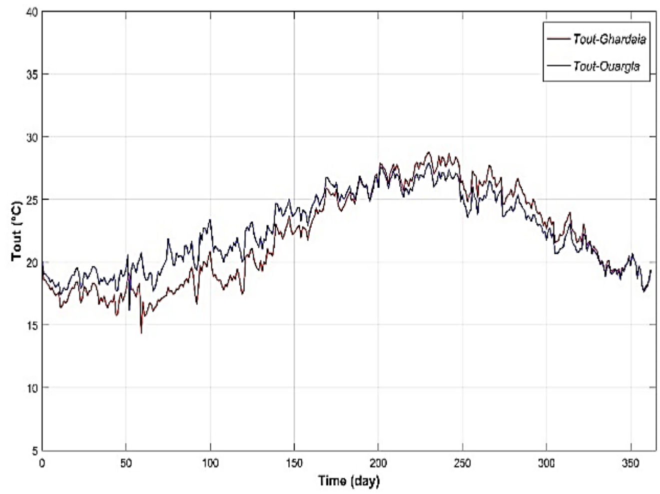
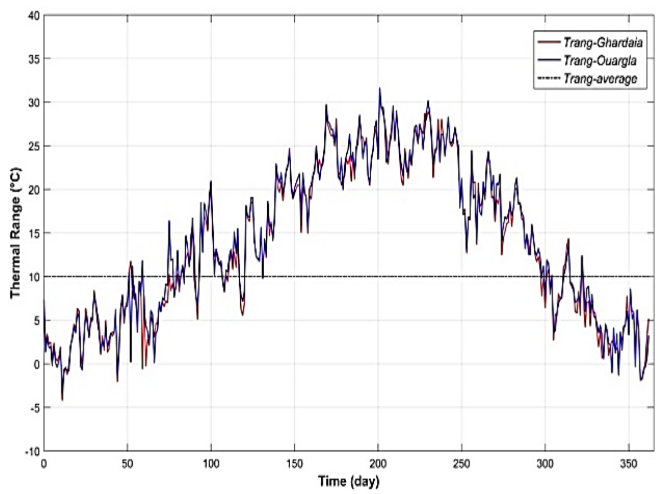
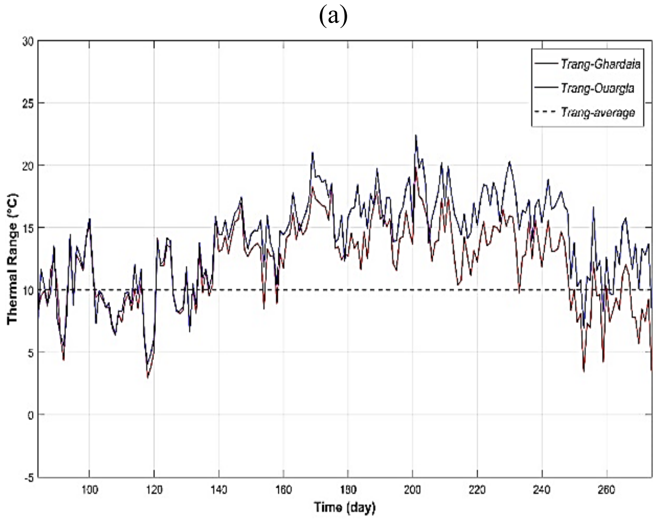


Figure 6. Annual outlet EAHE temperature for two selected sites

Therefore, the EAHE system studied is relevant and effective according to the evaluation of thermal comfort via the thermal range parameter. According to our study, we consider that the region of Ouargla is perfectly compatible for the experimental realization of the exchanger.



(a)



(b)

Figure 7. Annual thermal range for two regions: (a) Global period 365 days, (b) cooling period

Table 4. Evaluation of EAHE's efficiency in comparison to other systems

Type of study	Energy efficiency in %	Station	Geometry considerations	Author (s)
Numerical	71	Ghardaia, Algeria	EAHE	Present study
	72	Ouargla, Algeria	(horizontal; L = 60 m)	
Numerical	51	Jaipur, India	EAHE (horizontal; L = 23.42 m)	Bansal et al. [15]
Experimental	62	Borj Cedria, Tunisia	CBGHE (L = 100 m)	Boughanmi et al. [36]
Numerical	33	Adrar, Algeria	EAHE Horizontal design Length 23,42m	Belatrache et al. [37]

A comparison of the EAHE system's efficiency with other studied systems is presented in Table 4, clearly demonstrating its performance.

Numerous researchers have undertaken scientific studies to assess the influence of various factors on the performance of GHE systems. These factors include the system's geometry, soil properties, and local climate conditions. One notable study by Bansal et al. [15] investigated the effectiveness of incorporating an EAHE alongside a vapor compression machine. Their findings indicated that the combination of the two led to a substantial decrease in electrical energy consumption, specifically by 18.1%. This highlights the potential of integrating EAHEs into GHE systems as a means of enhancing their overall performance and reducing energy consumption.

The thermal efficiency of a novel geothermal heat exchanger designed in the shape of a conical basket was analyzed by Boughanmi et al. [36]. This type of heat exchanger is intended for use in greenhouse applications for both heating and cooling purposes. According to their findings, they determined that the specific heat exchange values for the conical basket geothermal heat exchanger (CBGHE) ranged from 20 W. m^{-1} to 50 W. m^{-1}. They also identified that the highest energetic and exergetic efficiencies of the CBGHE were achieved at a mass flow rate of 0.1 kg. s^{-1}, with values of 62% and 37%, respectively. Belatrache et al. [37] conducted a parametric study in which they varied the length and radius of the pipe, as well as the air velocity within the pipe. They found that the maximum daily cooling capacity of the EAHE under investigation was 1.755 kWh.

7. CONCLUSIONS

In this article, an EAHE has been experimentally studied for building cooling in the climatic conditions of two distinct locations in the Algerian desert, namely, Ghardaia and Ouargla. This exchanger is three meters underground and made of PVC.

As a study period, an entire year has been tested. The system was simulated using Scilab 6.0.2 Software, and the results are as follows:

- The EAHE's main application in the arid regions is the cooling season, which begins 80 to 300 days into the year;

- A comfort standard for the thermal range is 10 degrees Celsius:

Comfort zone: $T_{range}\geq 10$; Discomfort zone: $T_{range}<10$;

- For the installation of EAHE, the Ouargla region is more suitable than the Ghardaia region.

- Sandy soil sites are more practical and applicable to the EAHE exchanger industry.

The study found that Ouargla has a greater thermal range T_{range}, with a maximum value of 22.5°C compared to 20°C in Ghardaïa, throughout the year (365 days). Based on the thermal comfort zone, which is between 20°C and 27°C, Ouargla is considered to be a better location than Ghardaïa. Additionally, during the cooling period (from the 84th to the 274th day), the average thermal range in Ouargla is 2.5°C greater than that of Ghardaïa.

The study also showed that using an EAHE system consumes less energy compared to conventional air conditioning. In future studies, the focus will be on improving the thermal performance of the system by exploring different designs of the EAHE exchanger.

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NOMENCLATURE

Cp	Specific heat, J.kg^{-1}.K^{-1}
D	Pipe diameter, m
GTot	Total thermal conductance of the EAHE, W/m.K
k	Thermal conductivity, W.m^{-1}.K^{-1}
L	Pipe length, m
Nu	Nusselt Number
Pr	Prandtl Number
Rconv	Convective thermal resistance, m.K/W
Re	Reynolds Number
Rpipe	Thermal resistance of the pipe, m.K/W
Rsoil	Thermal resistance of the soil, $m.K/W$
t	Time, hour
T	Temperature, °C
Ts	Air outlet temperature of EAHE, °C
V	Air velocity, m/s
x	Elementary part of pipe length, m
z	Depth from the earth surface, m