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Effect of geo-climatic conditions and pipe material on heating performance of earth-air heat exchangers

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Abstract

Climatological and geological site classification intended for Earth-Air Heat Exchanger Technology (EAHE) is an important factor in the design, implementation and optimal operation of such system. In this context, this paper presents an investigation on the heating performance and operating feasibility of two EAHEs in three different geo-climatic regions in Algeria. First, the performances of the EAHEs were experimentally studied in the temperate Oran climate and the corresponding results were used for validation of the numerical part. The experiment allowed to analyze the effect of the pipe material on the performance of the two EAHEs that are made of different materials (PVC and Zinc). After validation of the numerical part, the study was extended to three different climates including a temperate climate for Oran, an arid climate for Bechar and a steppe climate for El-Bayadh cities. For these climates, the heating study is rarely considered in this context. Furthermore, a sensitivity analysis was conducted in order to evaluate the operating feasibility of the EAHEs in the considered regions. The results revealed that the Zinc EAHE is more efficient in a temperate climate with a COP of 9.5 than in an arid or steppe climate with a COP of 8.2 or 8.1, respectively. However, the

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PVC EAHE is much better in an arid climate with a COP of 9.4 than in a temperate or steppe climate with a COP of 7.6 or 8.4, respectively. Otherwise, both EAHEs exhibited similar behavior in a steppe climate. The results show that the thermal performance of EAHE mainly depends on geo-climatic conditions and the type of pipe material.

Keywords: Earth-air heat exchangers (EAHEs); heating performance; pipe material; sensitivity analysis; operating feasibility

1. Introduction

Global energy consumption raises anxieties about supply difficulties due to the exhaustion of conventional energy resources and environmental impacts such as ozone depletion and climate change. In this regard, ensuring energy independence and security, as well as reducing greenhouse gas (GHG) emissions, are real challenges for current and future policies. The building sector is one of the most important sources of energy demand, accounting for 36% of the world's final energy consumption and 40% of total CO_2 emissions [1]. This energy usually comes from non-renewable fossil fuels, mainly used for heating and cooling of buildings. Therefore, the need for sustainable development forces countries to turn towards new renewable and alternative resources to satisfy buildings' energy needs. Among the most frequently used renewable energies over the last decade is shallow geothermal energy, which is easily accessible for space heating and cooling. The technical applications are varied, including the geothermal heat pump, the water-ground heat exchanger and the earth-air heat exchanger (EAHE), etc. Among these systems, the EAHE has the advantages of simple operation and easy installation with moderate investment costs [2]. The latter is known for its potential to increase comfort in a building by using the soil as an energy reservoir instead of the atmosphere [3]. In fact, the EAHE usually uses soil temperatures at depths comprised between 2 and 5 m, which is relatively applicable for damping outdoor air temperatures.

The EAHE is considered as passive system because it requires few electrical input to power a small fan to circulate air [4]. That is why many researchers worldwide have paid attention to the EAHE, not only for its simple structure, but also of its energy efficiency [5 - 8]. Nevertheless, several studies have been conducted to improve the thermal performance of the EAHE, taking into account operating and design parameters such as burial depth, pipe length and diameter, air velocity, climatic site and pipe material [9-13].

A state of the art on the sensitivity of these parameters on EAHE performance has been established, in particular the effect of pipe material and climatic site. Concerning the effect of the pipe material, several works can be found in the literature. Badescu et al. [14] studied the energy potential of an EAHE under real climatic conditions of the Pirmasens PH, Germany. They indicated that the energy provided by the EAHE depends substantially on different design parameters such as depth, diameter and pipe material. A few years later, Bansal et al. [15,16] numerically analyzed the thermal performance and evaluated the heating and cooling potential of two EAHEs of different materials, one in PVC and the other in steel, installed in Ajmar, India. The authors concluded that the performance of the EAHE system was unaffected by the pipe material. In another study presented by Abbaspour-Fard et al. [17], the effect of some operating parameters, including pipe material, on the performance of an EAHE was examined in northeastern Iran. It was shown that the performance of the system was significantly influenced by all parameters except pipe material. Three years later, Patel and Raman [18] compared two EAHEs, one placed vertically and the other horizontally to evaluate their thermal performance. They found that the pipe material had a small effect on the thermal performance of the EAHE. Further, Serageldin et al. [19] analyzed the effect of three different pipe materials, the first of which was PVC, the second steel and the third copper. The results showed a deviation of 0.1 °C between the air temperature at the outlet of the systems. Therefore, it was concluded that pipe material does not affect thermal performance of the EAHEs. In a more recent work, Menhoudj et al. [20] studied the performance of an EAHE for the cooling conditions in Algeria. The effect of the pipe material on the energy performance of the EAHE was also examined. The results revealed that the temperature decrease was 6 °C for the PVC pipe and 6.5 °C for the Zinc pipe, i.e. a difference of 0.5 °C. However, the author concluded that the pipe material does not affect significantly the efficiency of the EAHE. Moreover, Rosa et al. [21] analyzed the variable that most affects the performance of the EAHE. They studied the effect of several design parameters including pipe material. They noted that the pipe had no meaningful effect because the COP of the system simply varied from 2.33 to 2.34 when switching from PVC to steel.

Similarly, the literature provides various works concerning the geo-climatic impact on the EAHE performance, among which are the following works. Ramírez-Dávila et al [22] conducted a numerical study to predict the thermal behaviour of an EAHE for three cities with different climates in Mexico, namely Juárez, México and Merida. It was found that the thermal performance of the EAHE is better in summer than in winter for Juárez and Mexico cities. On the other hand, the EAHE presented better thermal performance in winter for Mérida. It was concluded that the use of the EAHE is appropriate for heating or cooling buildings in extreme and moderate temperature areas where the effect of thermal inertia of the ground is higher. Likewise, Hermes et al [23] numerically analyzed the thermal performance of different EAHEs installations in three sites located in Rio Grande, Brazil. The results revealed that the ideal pipe placement depth is 2 m. At this level, the EAHE's potential is better for heating than for cooling. In addition, significant COP values were estimated in winter and summer using pipes buried at 2 m depth. As for Li et al [24], an exploratory study on the application of the preheating potential of the EAHE, in very cold regions, was conducted. The analyses showed that in heating mode, the EAHE increased the average temperature by 12.4 °C, giving an average COP of 29.7. In the same context, Díaz-Hernández et al. [25] presented an experimental study of an EAHE under a warm humid weather conditions of Mexico. During six months of monitoring, the EAHE only operated effectively as a heater during the first three months of winter, mainly at night. A maximum heating potential of 5.8 °C was observed in January and an average maximum of 3.6 °C in November. Otherwise, Fazlikhani et al. [26] examined and compared the efficiency of EAHE systems in hot-arid (Yazd) and cold (Hamadan) climates in Iran. They found that in both climates, the system is widely used for preheating and that the potential during the winter period increased from 0.2 to 11.2 °C and from 0.1 to 17.2 °C for Yazd and Hamadan, respectively. These results show that the system was more efficient in the hot-arid climate of Yazd compared to the cold climate of Hamadan. Moreover, in recent study, the thermal performance of a building integrating several renewable energy systems, including EAHE, was studied by Lekhal et al. [27]. They indicated that the EAHE can provide gains of up to 7.3 °C. Moreover, using EAHE, the heating needs were reduced by 46%. Li et al. [28]

examined the feasibility of an EAHE for heating in very cold regions. In this regard, extensive measurements of air, soil and energy consumption parameters were carried out. The results showed that the EAHE raised the average temperature by 14 °C without auxiliary heating. Also, the maximum overall COP was 16.3, showing the high efficiency of the system. According to these results, the EAHE can be used in very cold regions with good efficiency.

Algeria is characterized by five climatic regions [29]. Three principal climatic regions were considered in the present study, namely temperate, arid and steppe. For these climates, the literature application of EAHE was only devoted to cooling. According to the current state of the art, no study was conducted on the heating performance of the EAHE for the three Algerian climates mentioned above. Moreover, the parameters selection for operation and EAHE design have been generalized for all regions and climates. In reality, the soil thermal response changes according to the outdoor conditions, depth, soil type and pipe materials. For this purpose, the present paper has the following objectives: (1) to experimentally study the heating performance of two EAHEs in representative real building conditions by evaluating gains provided by the EAHEs and their COP. In fact, few experimental studies have been conducted on a large scale in the concerned region. Then, the obtained experimental data at this scale will be used as reference for the numerical model validation; (2) the pipe material choice is a dichotomy point in the literature, so we proposed to experimentally and numerically highlight pipe material impact on the EAHE performance in the Mediterranean climate; (3) to conduct a sensitivity analysis using TRNSYS software to identify the optimal parameters and evaluate the feasibility of EAHEs according to the pipe materials for three different climatic regions. The study results could be used as support for designers and future EAHE users concerned by these climates. They provide preliminary views to guide application decisions on the parameters related to EAHE performance in order to effectively reduce building energy consumption and improve thermal comfort levels. Moreover, the study is not locally limited to Algeria, but can be extrapolated to other regions of the world characterized by Mediterranean (temperate), arid and steppe climates. In Fig. 1, we present the different areas of the world sharing these studied climates, such as North Africa, Southern Europe, South America and Asia. The research questions corresponding to the objectives are as follows:

- How to experimentally install EAHEs coupled to a full-scale building and implement the operating, measuring and protection equipment?
- How to model a building coupled to an EAHE using the TRNSYS software and what are the appropriate types (soil, pipes, fan) for such system?
- How to conduct a sensitivity analysis of the most influential parameters of the EAHE and identify the optimal parameters according to climate and material type?

In this paper, we propose an experimental and numerical study of the thermal performance of two EAHEs, where the effect of the pipe material was analyzed. These pipes consist of galvanized sheet metal (Zinc) and polyvinyl chloride (PVC). Then, a sensitivity analysis was conducted to identify the operating and design parameters of the EAHEs and to select the appropriate pipe material for each climatic region by evaluating the COP, the provided gains as well as the reduction rate of heating needs.

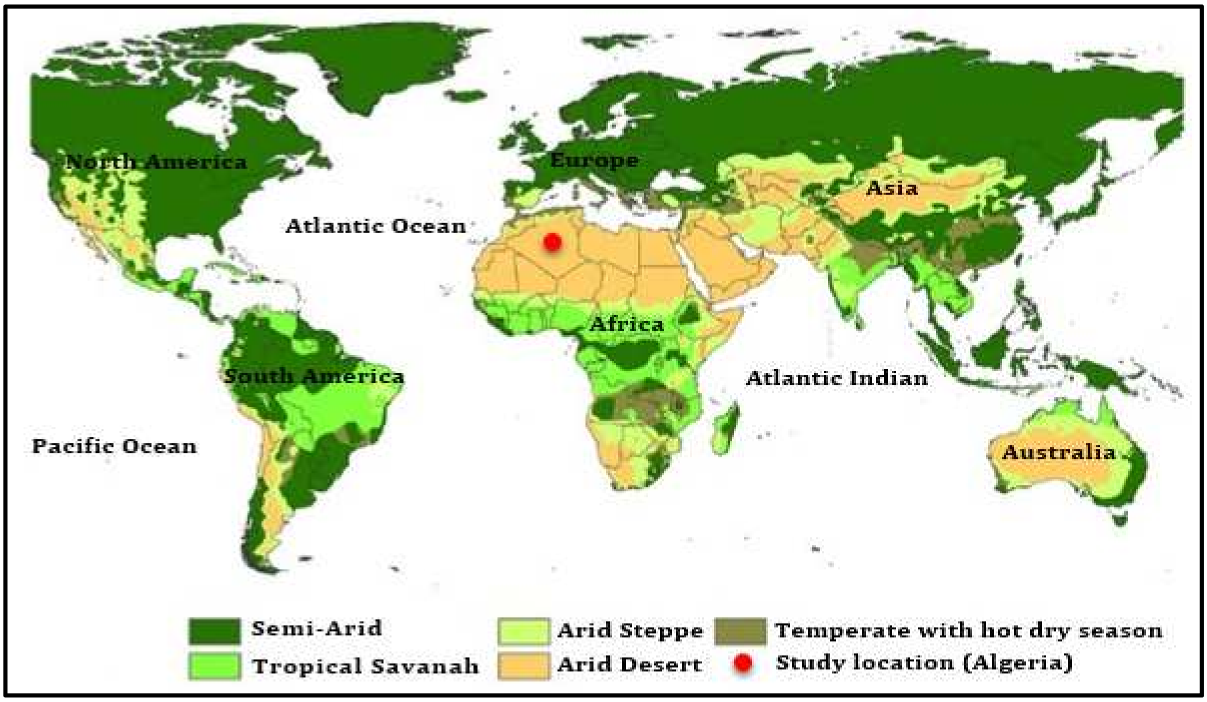


Fig. 1. Geographical position of the study location and areas worldwide with a similar climate (Modified from [30])

2. Methodology

The research methodology of this study is based on the analysis of the thermal performance of two EAHEs of different materials (PVC and Zinc), operating under three different geographical topologies. The first step presents an experimental study of the two EAHE systems in the climatic conditions of Oran. Then, a numerical modelling of the two systems and the soil was developed. The second step discusses the thermal performance results of the two EAHEs, where the effect of pipe material is highlighted. In the third step, a numerical sensitivity analysis was conducted to evaluate the optimal operating and design parameters for the three regions with their different climates. At the end of this study, several recommendations were made, outlining the practical implications as well as the limitations of the study and the future research. The conceptual structure of the study outlining the main sections and steps of the research methodology is presented in Fig. 2. This structure includes four main steps which are detailed in subsequent sections.

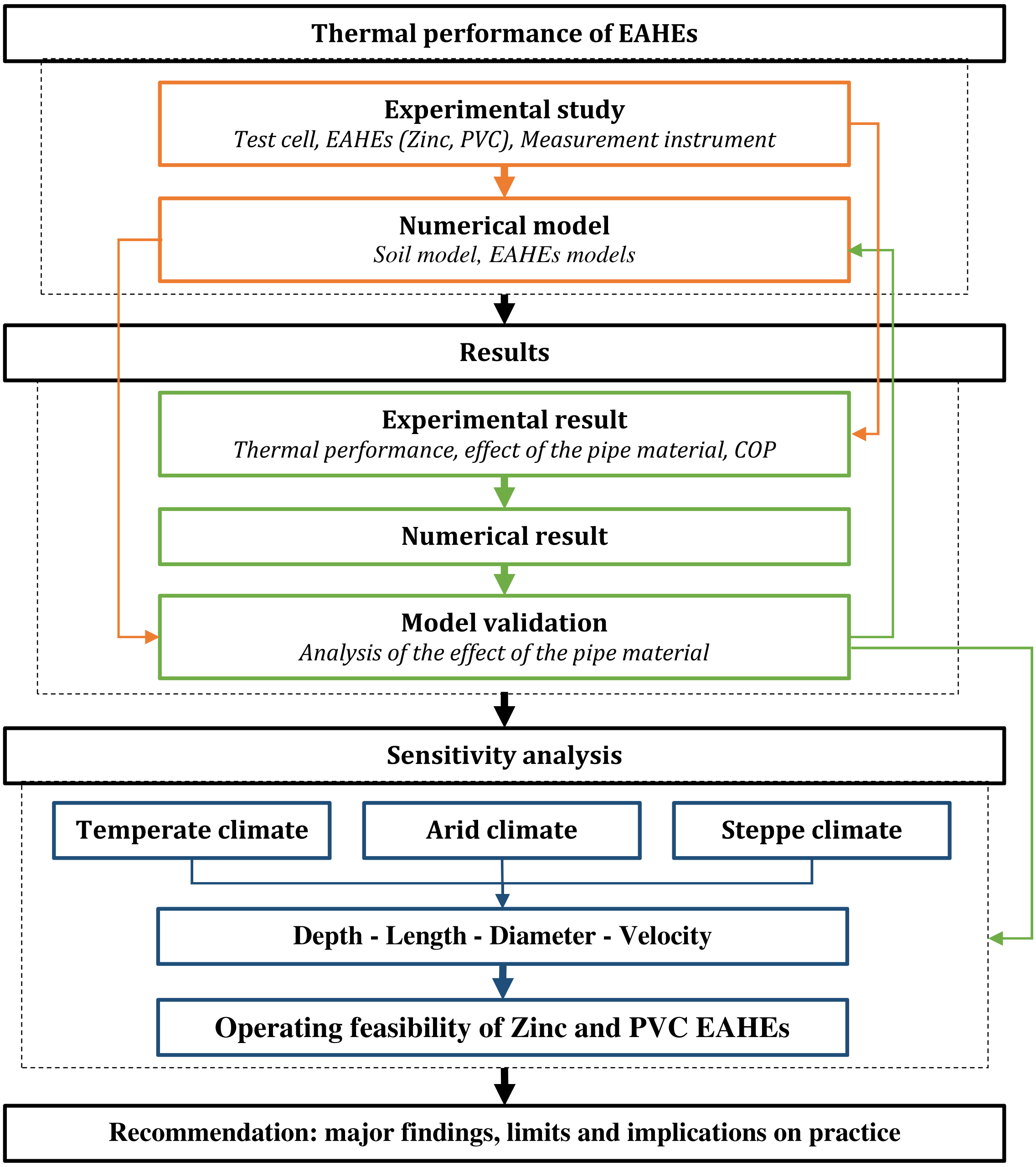


Fig. 2: The conceptual structure of the study.

2.1. Experimental study

2.1.1. Test cell

The experimental study is conducted using a test cell coupled with solar and geothermal systems. The cell is located at the Institute of Civil and Mechanical Engineering of the University of Sciences and Technology of Oran, Algeria, where the coordinates are: 35.65° N, 0.62° W, with north-south orientation. Fig. 3 shows an overall view of the test cell coupled with earth-air heat exchangers (EAHEs) and a solar thermal collector. The test cell consists of two juxtaposed rooms of identical dimensions: 4.7 × 3.7 × 2.8 m^3. The EAHEs are each powered by a fan to drive an air flow of 90 m^3/h from the outside to the inside of the cell. The second room is equipped with a direct solar floor system (DSF) composed of a solar thermal collector of 4.3 m^2 associated with a floor heating [27]. The condition of the test cell construction is considered to be highly isolated and the thermophysical properties of the wall, ceiling and floor are detailed in Table 1.

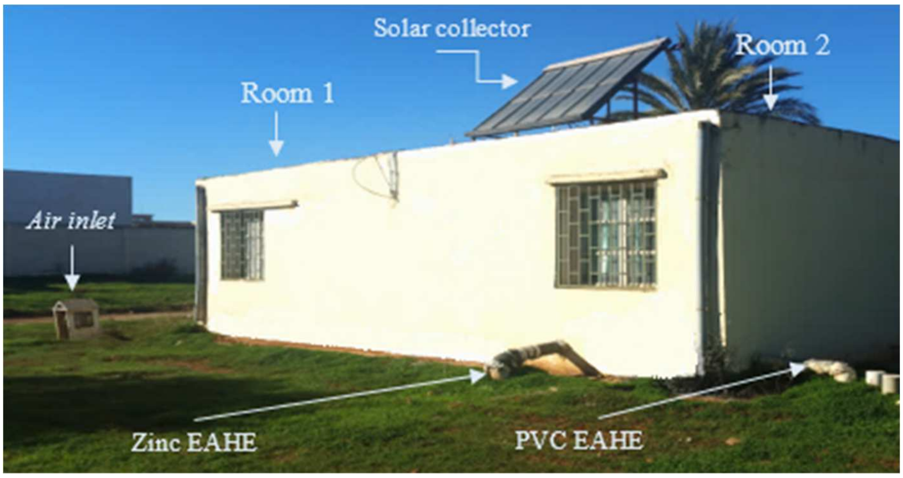


Fig. 3. Test cell coupled to EAHEs in (right) PVC pipe and (left) Zinc pipe.

Table 1: Thermal properties of cell materials.

Wall type and layer name (from inside to outside)	Thickness [m]	Conductivity [W/(m K)]	Specific heat [kJ/(kg K)]	Density [kg/m^3]
External and partition wall				
Cement-coating	0.01	1.15	1.0	1800
Brick	0.1	0.5	0.92	1100
Insulation	0.04	0.03	1.45	20
Brick	0.1	0.5	0.92	1100
Cement-coating	0.01	1.15	1.0	1800
Ceiling				
Cement-coating	0.01	1.15	1.0	1800
Ceiling block	0.16	1.14	0.65	1850
Concrete	0.04	1.75	0.92	2300
Insulation	0.02	0.03	1.45	20
Waterproofing coating	0.03	0.04	0.67	200
Floor				
Gerflex coating	0.003	0.31	1.046	1190
Concrete	0.1	1.75	0.92	2300
Insulation	0.04	0.03	1.45	20
Concrete	0.1	1.75	0.92	2300

Door				
lightwood	0.05	0.2	1600	600
Window				
Single glazed	0.004	1.2	830	2750

2.1.2. Earth-air heat exchangers

As mentioned right below, room 2 is coupled with two EAHEs, one of which is PVC pipe and the other is Zinc pipe. The PVC EAHE is a 20 m long pipe that is buried under 2 m of clay-loam soil. The thermos-physical characteristics of two EAHEs are presented in Table 2. The identification and characterization of the soil and its thermophysical properties were done at the Geotechnical Laboratory of the Institute of Civil and Mechanical Engineering of Oran. The air inlet is an external mouth with a height of 1 m and the air outlet is inside room 2 to ensure the air supply. The Zinc EAHE has the same configuration and dimensions as the PVC EAHE (20 m length and 2 m depth). Fig. 4 shows the design and implementation stages of the EAHEs.

Table 2: Thermo-physical characteristics of two EAHEs.

Type	Characteristics					
	Length [m]	Outside diameter [m]	Inside diameter	Thermal conductivity [W/(m K)]	Thermal capacity [J/(kg K)]	Density [Kg/m^3]
PVC pipe	20	0.12	0.118	0.16	900	1380
Galvanized sheet metal pipe (Zinc)	20	0.12	0.118	110	380	7200

Fig. 4. EAHEs under construction, installation and coupling with the test cell.

2.1.3. Hygiene and protection

2.1.3.1. Condensate drainage system

The drainage of condensate was managed by embedding the pipes in the ground with a slope of 2%. In this way, the pipes are protected from any health problems caused by bacteria such as mold or fungi. Fig. 5 shows the condensate drain for both pipes.

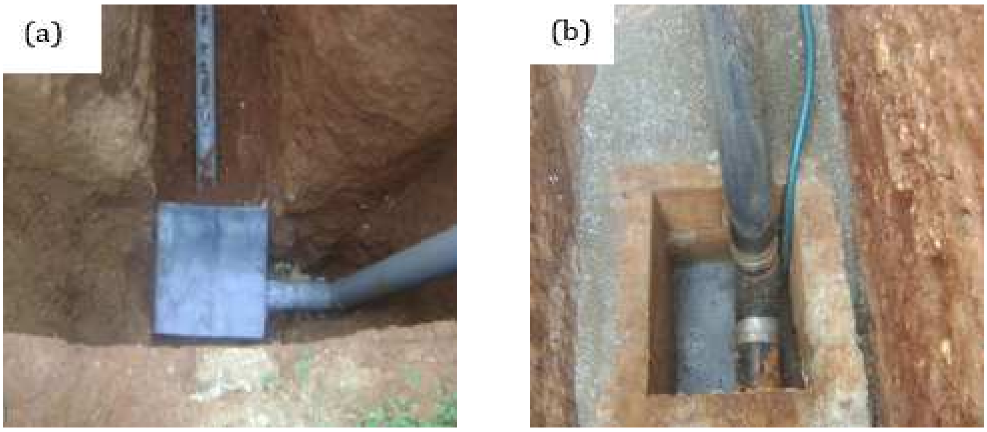


Fig. 5. Condensate evacuation from two pipes, (a) PVC, (b) Zinc.

2.1.3.2. Protection grid

The protection against rainwater infiltration inside the pipe is reinforced by a protection cap. Also, the supply air inlet is screened with a fine-mesh grid to prevent the intrusion of rodents, birds and insects. It is easily accessible for cleaning. The location of the air inlet is installed in a clean and isolated space, away from any source of pollution such as exhaust fumes, compost, etc. Fig. 6 shows the protection cap and screen used for both EAHEs.

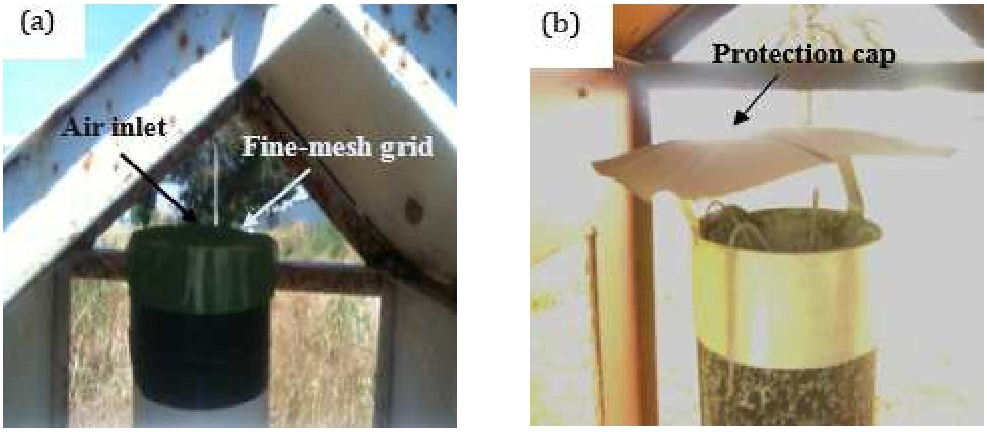


Fig. 6. (a) Fine-mesh grid filter, (b) air inlet with protection cap.

2.1.4. *Fan*

A vacuum / blower type fan is installed at the end section of these EAHEs, blowing continuously (without control system) a flow rate of 90 m^3/h. The fan is powered by an electric motor whose characteristics are shown in Table 3.

Table 3: Fan Characteristics

Electric tension	230 V
Rotational speed	2400 rpm
Electric power	15 W

2.1.5. *Measurement instrument*

The temperatures were measured using K-type thermocouples. These thermocouples are placed at the outlet of EAHEs to measure air temperatures blown by the fans. The outdoor air temperature is monitored using a mini weather station (OREGON type). The latter is equipped with a unit for displaying and recording the measured data with a one-hour step. The collection and storage of measured data is carried out through an acquisition chain (KEITHLEY 7700), which allows the measurements taken at different points to be transmitted to a post-computer. Fig. 7 illustrates both equipment and their measurement instruments.

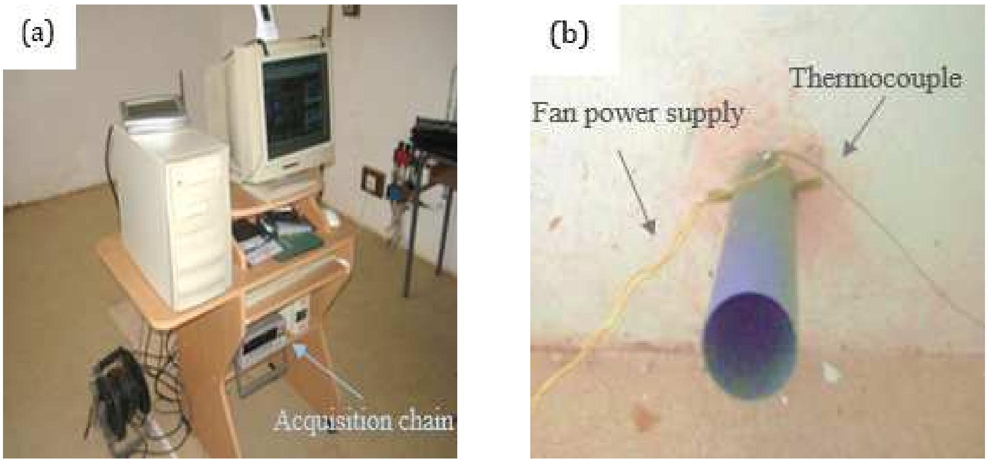


Fig. 7. (a) The acquisition chain and the mini weather station connected to the computer, (b) location of the thermocouple at the outlet of the EAHE.

2.2. *Numerical model*

2.2.1. *Principle of the global system*

The studied EAHE is a pipe buried horizontally in the soil at a defined depth. A fan is placed at the end of the pipe used to draw outdoor air and blow it inside the building after exchanging heat with soil. The system principle is described in Fig. 8. In winter, the air entrained in the pipe exchanges heat with the soil through the pipe wall. The heat absorbed by the air depends on the temperature difference between it and the soil. For this study, no control system is applied to the fan; in other words, the air supply is provided continuously throughout the heating period. An extractor fan is installed to ensure air renewal in the building.

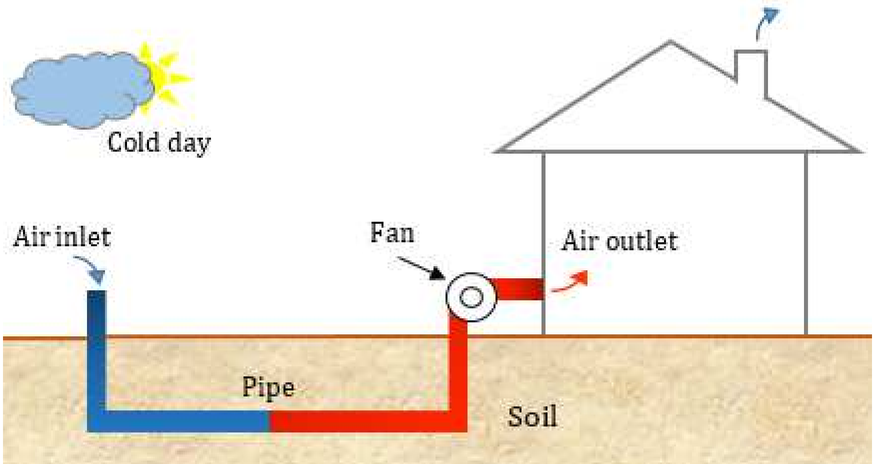


Fig. 8. Diagram of the EAHE principle coupled to a building.

2.2.2. *Thermal soil model*

The soil thermal model developed by Kusuda [31] is used to determine the ground temperature at different depths T (Z, t). This model is available in the TRNSYS software library (Type 77). It is based on the theory of thermal conduction applied to a homogeneous semi-infinite solid. Using this model, the soil temperature evolution (undisturbed) at different depths is obtained.

The following equation provides soil temperatures at different depths:

$$T(Z,t) = T_m - A_s\, exp\left(-Z\left(\frac{\pi}{365\ \delta_{soil}}\right)^{1/2}\right) Cos\left[\frac{2\pi}{365}\left(t - t_o - \frac{Z}{2}\left(\frac{365}{\pi\ \delta_{soil}}\right)^{1/2}\right)\right] \quad (1)$$

For Z = 0, the equation is written as follows:

$$T(Z,t) = T_m - A_s\ Cos\left[\frac{2\pi}{365}(t - t_o)\right] \quad (2)$$

For Z = ∞, the equation became:

$$T(Z,t) = T_m \quad (3)$$

Where Z is the soil depth (m), t is the time (hour), t_0 is the time of year with minimum soil surface temperature (hour), T_m is the mean surface temperature (°C), A_s is the amplitude of soil surface temperature throughout the year (K), and δ_{soil} is the soil thermal diffusivity (m^2/s). This equation is used to evaluate the soil thermal potential according to climatic conditions, burial depth, soil thermal diffusivity and frequency.

2.2.3. *EAHE model*

The EAHE system was modeled using Type 952. This component models a horizontally buried pipe that interacts thermally with the soil. The EAHE model used in the simulation consists of a horizontal pipe for each EAHE, either Zinc or PVC. This model is solved by the finite difference method with a fully implicit scheme. The radial mesh size used in the simulation is 0.02 m. This value was adjusted after performing a precision mesh test on the model. The EAHE model developed under the TRNSYS tool is shown in Fig. 9.

The basic form of the energy balance for an air node is given as follows [31]:

$$m\, Cp_{air} \frac{dT_{air}}{dt} = \dot{Q}_{in} - \dot{Q}_{out} \tag{4}$$

where Cp_{air} is the specific heat of air [J/(m K)], m is the air mass [kg] and T_{air} is the air temperature [K].

For an air node, there are three basic terms in the energy balance. Energy transferred in and out of the node due to air flow, energy transferred due to axial conduction between the air nodes and energy transferred between the air and the pipe wall.

The energy transfer due to flow can be written as follows:

$$\dot{Q}_{in} = \dot{m}_{air}\, Cp_{air} \left(T_{air,n} - T_{air,n-1}\right) \tag{5}$$

$$\dot{Q}_{out} = \dot{m}_{air}\, Cp_{air} \left(T_{air,n+1} - T_{air,n}\right) \tag{6}$$

Energy flow due to axial conduction is calculated as follows:

$$\dot{Q}_{in} = \frac{\lambda_{air} A_{xs}}{L} \left(T_{air,n} - T_{air,n-1}\right) \tag{7}$$

$$\dot{Q}_{out} = \frac{\lambda_{air} A_{xs}}{L} \left(T_{air,n+1} - T_{air,n}\right) \tag{8}$$

where L is the distance between two nodes [m], A_{xs} is the cross sectional area of an air node [m^2] and λ_{air} is the thermal conductivity of the liquid in the pipes [W/m K)].

The inside convection coefficient follows as:

$$h_i = \frac{Nu\, \lambda_{air}}{d_{pipe,i}} \tag{9}$$

The general form of the energy transferred between the air and the pipe wall node can finally be written as:

$$\dot{Q} = \frac{1}{R_{air} + R_{wall}} \left(T_{boundary} - T_{air,n}\right) \tag{10}$$

where

$$R_{air} = \frac{1}{h_i\, S\, A_i} \tag{11}$$

$$R_{wall} = \frac{ln\left(\frac{r_{pipe,i}+\frac{r_{pipe,o}-r_{pipe,i}}{2}}{r_{pipe,i}}\right)}{2\,\pi\, L_{air,n}\lambda_{pipe}} \tag{12}$$

where $d_{pipe,i}$ is the inner pipe diameter [m], $r_{pipe,o}$ is the outer pipe diameter [m], and μ_{air} is the kinematic viscosity of pipe air.

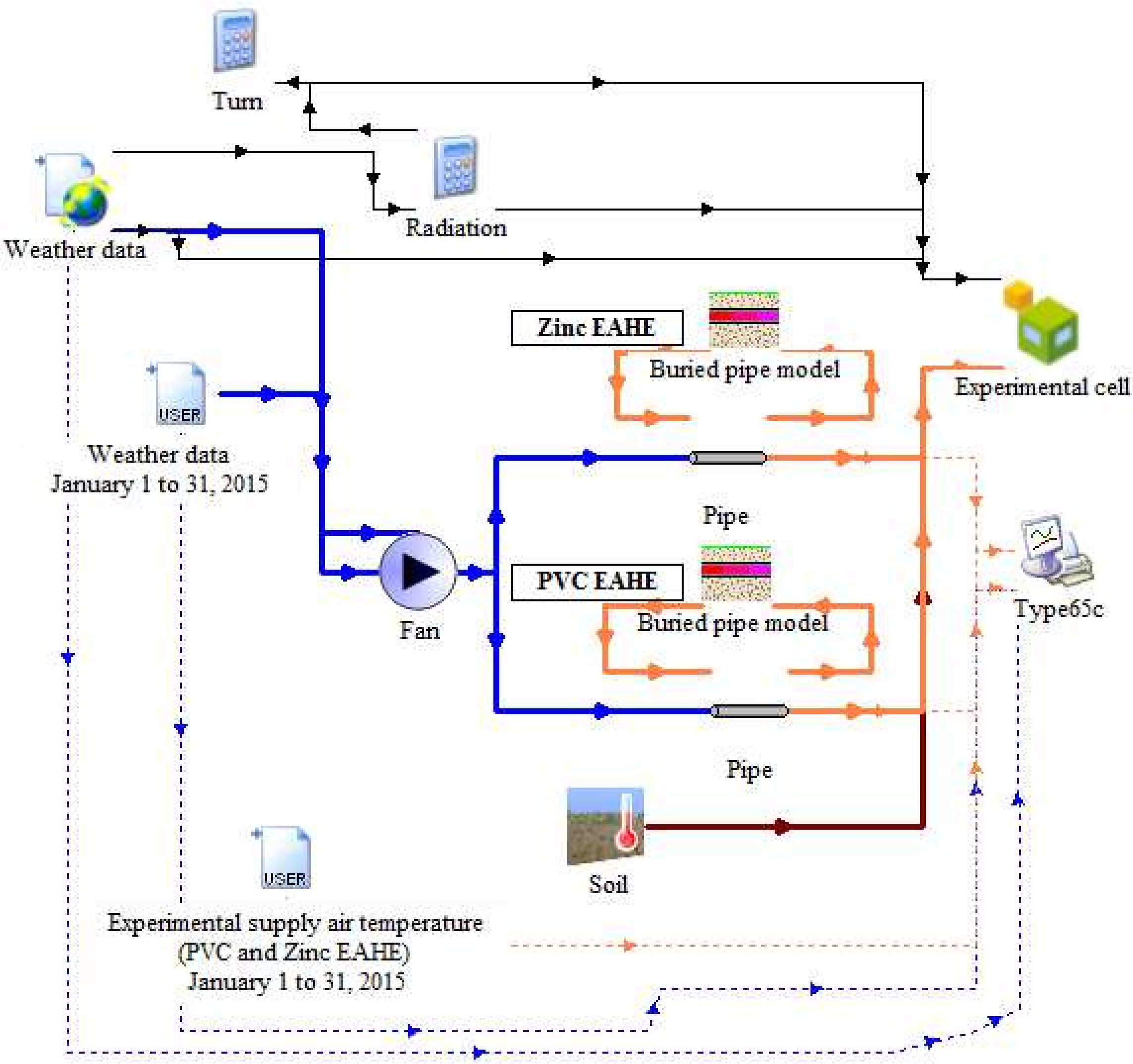


Fig. 9. EAHE models established under TRNSYS.

2.2.4. *Climates description*

Assessment of soil thermal potential is essential for the design of buried systems. The soil temperature depends heavily on meteorological and in situ conditions, i.e. ambient air temperature, solar radiation, wind speed, burial depth, soil nature and thermal properties.

To highlight the geothermal potential of shallow depths suitable for EAHEs for heating and cooling buildings in Algeria, we selected three cities: Oran, Bechar and El-Bayadh. The selection of cities is based on the specificity of climate and soil type. Oran is a city in the northwest. It corresponds to a perfect Mediterranean climate (temperate climate) characterized by hot and dry summers and mild and humid winters with an average annual winter temperature varying around 14.2 °C. It is included in zone Csa in the Köppen-Geiger climate classification. El-Bayadh is a city located in the high plains of Algeria, gives it a steppe climate. This climate is characterized by hot days and cold nights with low precipitation. According to the Köppen-Geiger classification, this climate falls in zone BSk. Its average annual air temperature during the winter is 7.3 °C. Bechar is located on the north-western limit of the Algerian Sahara. It has an arid climate with a winter characterized by much greater precipitation than in summer. Bechar's climate is classified as BWh in the Köppen-Geiger classification. It has an average annual temperature during the winter varies around 9 °C. Fig. 10 shows the geographical position of the three cities (Oran, Bechar and El-Bayadh) under study in Algeria with the existing climatic classifications.

Fig. 10. Geographical positions of the three studied cities (Oran, Bechar and El-Bayadh) and the existing climate classifications in Algeria, ❶, ❷: Mediterranean climate, ❸, ❹: steppe and semi-arid climate, ❺, ❻: desert and arid climate (Modified from [32]).

Climate data for the three cities used for this study are generated by the Meteonorm software in TMY-2 format [33]. TMY-2 is defined as a representative and typical year that brings together all the climatic information that characterizes any given region. Fig. 11 shows the variation of the annual outdoor air temperature in Oran, Bechar and El Bayadh. We note that outdoor air temperatures during the winter months, i.e. January to April and November to December range from 2.3 to 26.2 °C for Oran city, from - 4.2 to 26.3 °C for El-Bayadh city and from 0 to 31 °C for Bechar city. The climate of El-Bayadh region is colder than that of Oran and Bechar, with average temperature differences of up to 6.5 °C and 4.2 °C, respectively. This climate also presents average maximum temperatures that are very close to Oran except the Bechar climate, which has daily temperatures that are slightly higher with variations up to 4.6 °C.

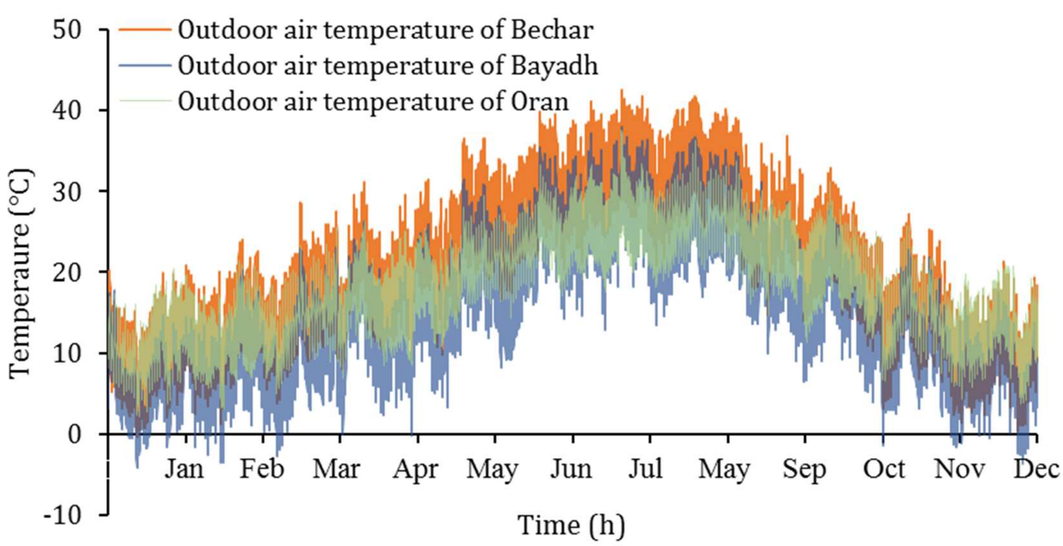


Fig. 11. Annual outdoor air temperature of the cities of Oran, Bechar and El-Bayadh.

2.2.5. Parameter selection for the sensitivity analysis

The sensitivity study of the performance parameters of the EAHE system could be useful in the design, implementation and application of such a system. Using the EAHE model employed in this study, the following parameters were examined: pipe length, pipe diameter, air velocity and burial depth. The optimization study was carried out in the climatic conditions of Oran, Bechar and El-Bayadh, that are respectively characterized by a temperate, arid and steppe climate. In addition, the Zinc EAHE was selected for this study. This choice was adopted based on the promising experimental results presented by the latter. Table 4 shows the simulation conditions for the influence parameters considered. Values are set to cover as far as possible the complete intervals of all influencing parameters. The initial operating conditions of the EAHE were taken as a reference, i.e. 2 m depth, 20 m length, 0.12 m diameter and 0.45 m/s air velocity for an air flow rate of 90 m^3/h. The parameter values vary from 3 to 10 m for depth, 30 to 50 m for length, 0.18 to 0.42 m for diameter and 0.90 to 2.7 m/s for air velocity.

Table 4: Simulation conditions of influence parameters.

Parameters	Default case	Parametric conditions
Depth	2 m	1 m, 3 m, 4 m, 5 m, 6 m and 10 m

Length	20 m	10 m, 30 m, 40 m and 50 m
Diameter	0,118 - 0.12 m	0.058/0.06 m, 0.178/0.18 m, 0.238/0.24 m, 0.298/0.30 m, 0.358/0.36 m and 0.418/0.42 m
Air velocity	0.45 m/s	0.90 m/s, 1.35 m/s, 1.8 m/s, 2.25 m/s and 2.7 m/s

3. Results

3.1. Experimental results

The measurement campaign was started in January, where the heating needs of the cell are important. Fig. 12 shows the experimental variations of the air temperature at the inlet (outdoor air temperature) and outlet of the two EAHEs during January 2015. It is noted that the air temperatures at the outlet of the PVC pipe varied between 11.9 and 17.4 °C against outdoor air temperature variations between 5.2 and 24.1 °C. The PVC EAHE provides a maximum gain of 9 °C recorded at 434 h and an average gain of 3.4 °C by taking only positive values. On the other hand, the air temperatures at the outlet of the Zinc pipe varied between 11.2 °C and 19.5 °C against the same outdoor air temperature variations expressed just above. A maximum gain of 10.5 °C was obtained by the Zinc EAHE recorded at 436 hours, while the average gain is 4.1 °C (positive values).

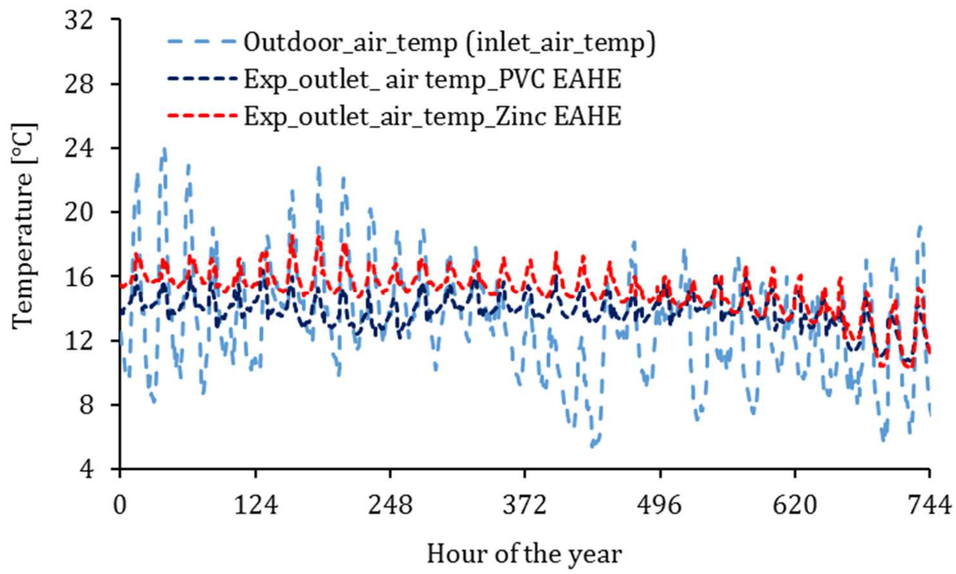


Fig. 12. Experimental measurements of the air temperature at the inlet and outlet of the two PVC and Zinc pipes from 1 to 31 January 2015.

3.1.1. Experimental analysis of the effect of pipe material

The effect of the pipe material on the performance of EAHEs was experimentally analyzed. Fig. 13 shows a comparison of two EAHEs, one in PVC and the other in Zinc, over 72-hour sequences. These sequences were examined by analyzing air temperature variations at the outlet of both EAHEs for 744 hours of January. As shown in Fig. 13 (a), a temperature difference of 4 °C between PVC and zinc was observed. This difference gradually decreased with time until it reached a value of 0.7 °C in the 72 hours, representing a drop of 3.3 °C. However, according to Fig. 13 (b), the air temperature differences between PVC and Zinc pipes are very small. Both EAHEs give almost identical results with minor differences over the 72 hours taken at the end of January. From this analysis, it can be concluded that the performance of EAHEs was affected by the pipe material in early January. On the other hand, the pipe material has practically no effect on the performance of both EAHEs at month's end, i.e. when the winter period begins to run out. Finally, we can say that the effect of the pipe material on the performance of the EAHE depends strongly on the period. This behavior was also observed in other measurement campaigns discussed in previous work by the same author [34].

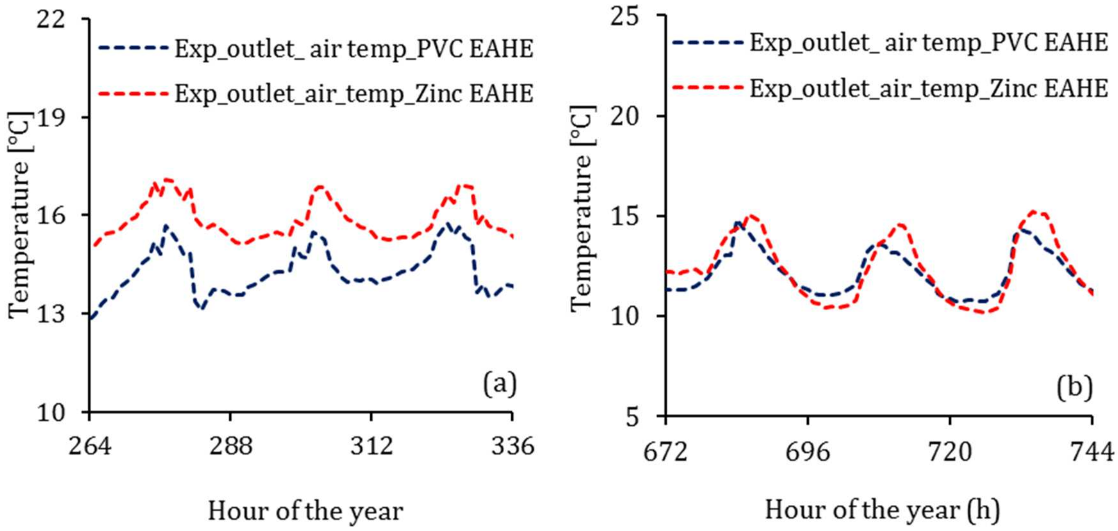


Fig. 13. Comparison of air temperatures at the outlet of the Zinc pipe with that of the PVC pipe for a three-day sequence (72h), (a) January 7-10, 2015, (b) January 28-31, 2015.

The experimental measurements of the temperature differences between the air at the outlet of both pipes and outdoor air are compared in Fig. 14. As this graph shows, the values below the zero scale represent the reverse operation of the system (counter-productive operation), i.e. the system cools air during the heating period rather than warm it. Comparing the two EAHEs, we find that the zinc pipe is more efficient than the PVC one, because the latter works inversely longer, which has an impact on the daily and monthly heating potential of the EAHE. Therefore, a control system is strongly recommended for both EAHEs.

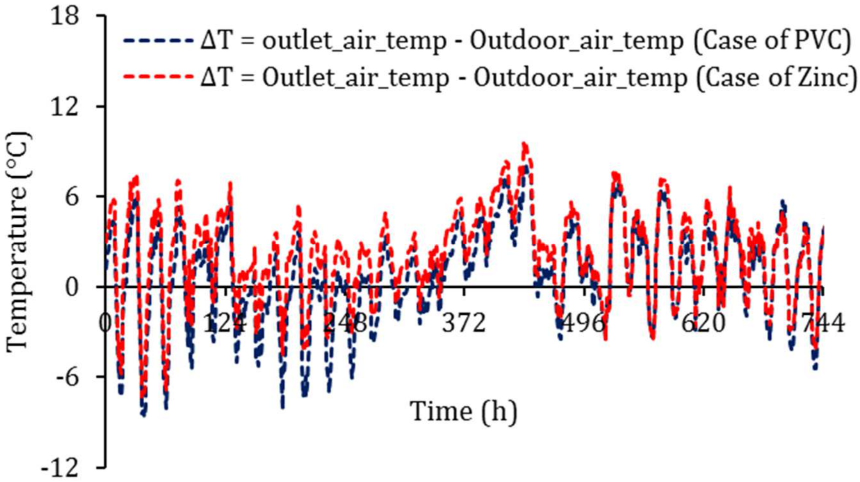


Fig. 14. Experimental comparison of the air temperature difference at the outlet of the two pipes and outdoor air temperature [$\Delta T = T_{a,\,outlet} - T_{a,\,amb}$], January 2015.

3.1.2. Energy gain

The daily heating gains provided by the two EAHEs, PVC and Zinc during January, are presented in Fig. 15. It can be seen from this graph that the heat gain provided by the PVC EAHE is lower than that provided by the zinc EAHE with values ranging from - 49.5 to 163.4 kWh. The PVC EAHE has values below the zero scale, showing that the system has a high cooling capacity during the heating period.

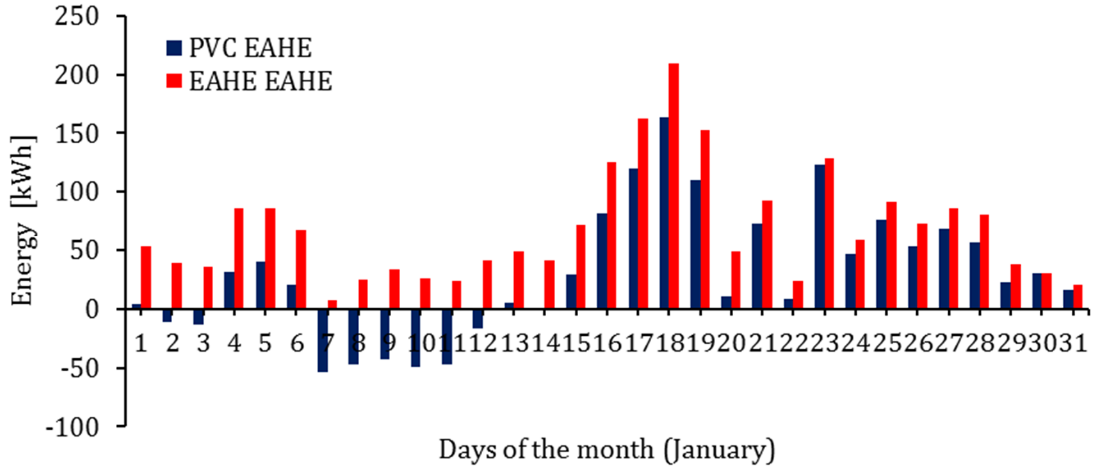


Fig. 15. Daily thermal gain provided by the PVC and Zinc EAHEs.

The monthly heat gain provided by the two EAHEs, PVC and Zinc, is illustrated in Fig. 16. The Zinc pipe-presents a value of 68 kWh, while the PVC pipe provides a monthly gain of 29.4 kWh, more than double with a difference of 38.6 kWh.

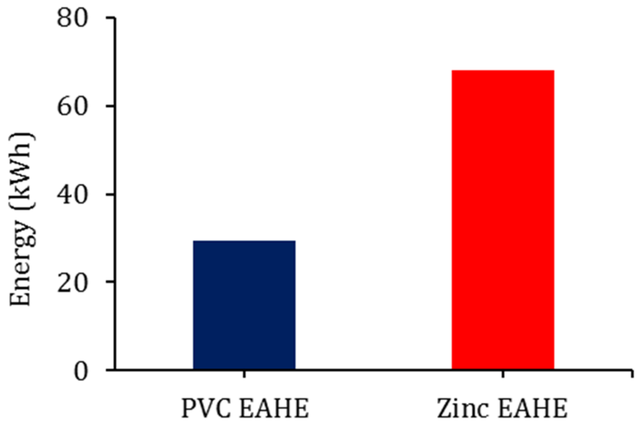


Fig. 16. Monthly heating heat gain provided by the two EAHEs, namely PVC and Zinc.

3.1.3. Coefficient of performance (COP)

The daily evolution of the COP during January for both EAHEs is shown in Fig. 17. The COP of Zinc EAHE varied from 0.5 to 14, while the PVC one varied from -3.4 to 10. During the 31 days of continuous operation of both systems, the Zinc pipe performed significantly better than the PVC pipe, with a maximum difference of 4 and a minimum difference of 3.9. In addition, the PVC pipe indicates

13 days of inefficiency (below reference 1) in January compared to one day of inefficiency for the zinc pipe over the same period.

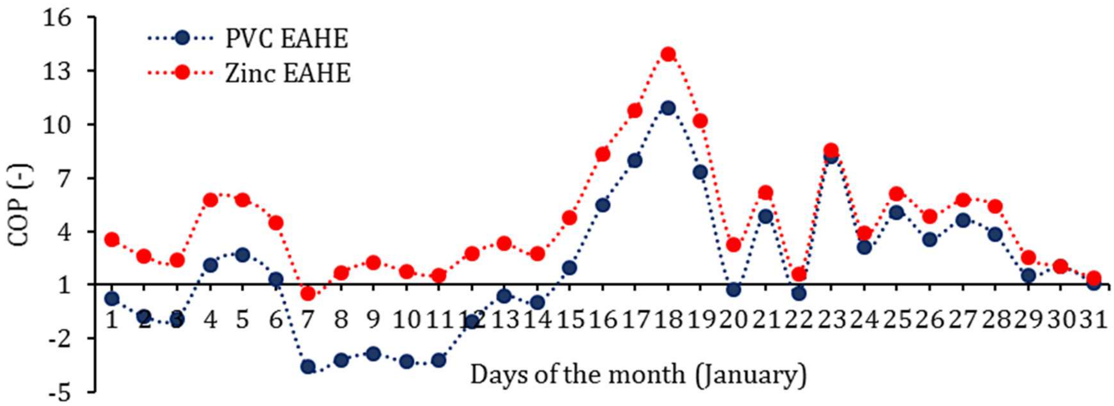


Fig. 17. Daily COP of two EAHEs during January.

The monthly COP of two EAHEs is shown in Fig. 18. The experimental results reveal that the COP of the Zinc pipe is 4.8, while that of the PVC pipe is 2. Therefore, a difference of 2.8 °C between the two EAHEs was found, consequently the Zinc EAHE is more efficient compared to the PVC EAHE. However, the COP given by both systems can be considered very low compared to the standards of heat exchangers including the investment and the supplied electrical energy.

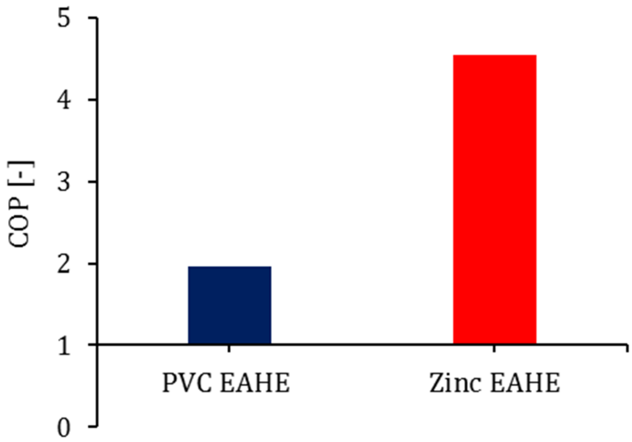


Fig. 18. Monthly COP of two PVC and Zinc EAHEs.

3.2. *Numerical results*

3.2.1. *Soil temperature*

As mentioned above in section 2, we used the soil model integrated into the TRNSYS environment to simulate soil temperatures at different depths of the three sites concerned for this study. The thermo-physical properties of the different soil types studied are presented in Table 5.

Table 5: Thermo-physical properties of the three soil types.

Cities	Soil type	Conductivity $[\mathrm{W/(m\,K)}]$	Density $[\mathbf{kg/m^3}]$	Heat Capacity $[\mathbf{J/(kg\,K)}]$
Oran	Silty Clay	1.5	1530	920
Bechar	Sandy	0.9	1780	1390
El-Bayadh	Silty Sandy	2.6	970	1518

A number of input parameters related to the meteorological state of the site, such as mean annual surface temperature and annual ground temperature amplitude, are required for the soil model. They are identified using a practical approach widely discussed in the literature [35]. This approach uses meteorological data and specifically the outdoor air temperature variation during the year to identify input parameters of the soil model. Based on this, these parameters were obtained for the three regions in question: Oran, Bechar and El-Bayadh, as presented in Table 6. The mean annual temperature of the soil surface is 18.1 °C for the Oran site, 20.9 °C for the Bechar site, and 15.3 °C for the El-Bayadh site.

Table. 6: Coefficients of the underground soil temperature.

Parameters	Cities		
	Oran	Bechar	El-Bayadh
$\boldsymbol{T_m}$ (°C)	18.1	20.9	15.3
$\boldsymbol{A_s}$ (°C)	14.1	15.6	15.5
$\boldsymbol{t_0}$ (h)	419	264	264

The soil model input parameters mentioned in the table above are also used to predict the soil temperature at 2 m depth for the three sites considered in this study, as shown in Fig. 19. We note that the annual soil temperature at 2 m depth ranges from 13 to 26.8 °C for the Oran site, from 15.4 to 26.4

°C for the Bechar site and from 6.2 to 24.3 °C for the El-Bayadh site. The evolution of the soil temperature over the year depends mainly on the evolution of the outdoor air temperature with a damping effect that decreases the outdoor air temperature according to depth. In other words, by increasing the measurement depth, the amplitude of the sinusoidal signal decreases to stabilization at a certain depth.

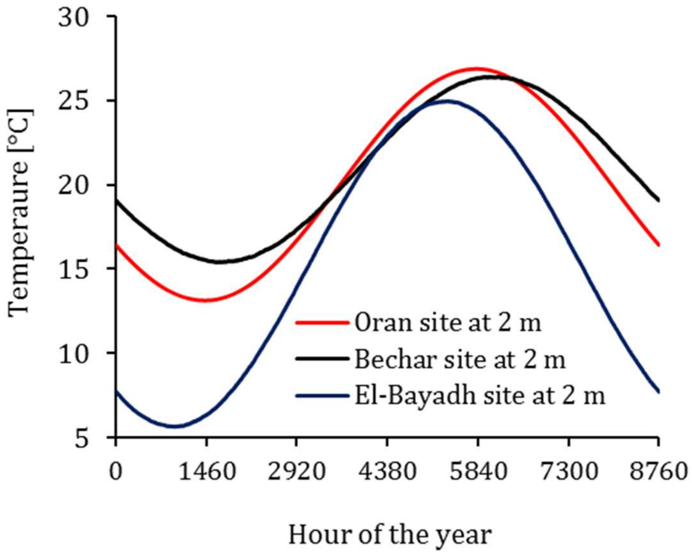


Fig. 19. Soil temperature at 2 m depth for the three regions studied: Oran, Bechar and El-Bayadh.

3.2.2. Model validation

The two EAHE models have been validated separately. They were validated with their own experimentally provided data taking into account their physical, dimensional and dynamic characteristics. The simulation is run with a time interval of 1 hour for both EAHE systems, which is equal to the monitoring time of the real experiment. For the models' error analysis, we introduce the mean square error (MSE), the mean absolute error (MAE) and the relative error (RE) to analyze the accuracy and reliability of the models, as shown in Table 5. They are defined as follows:

Table 5: Model performance.

Parameters	MSE	MAE	RE (%)
Outlet_air_temp_Zinc EAHE	0.87	0.73	4.65
Outlet_air_temp_PVC EAHE	0.51	0.54	3.91

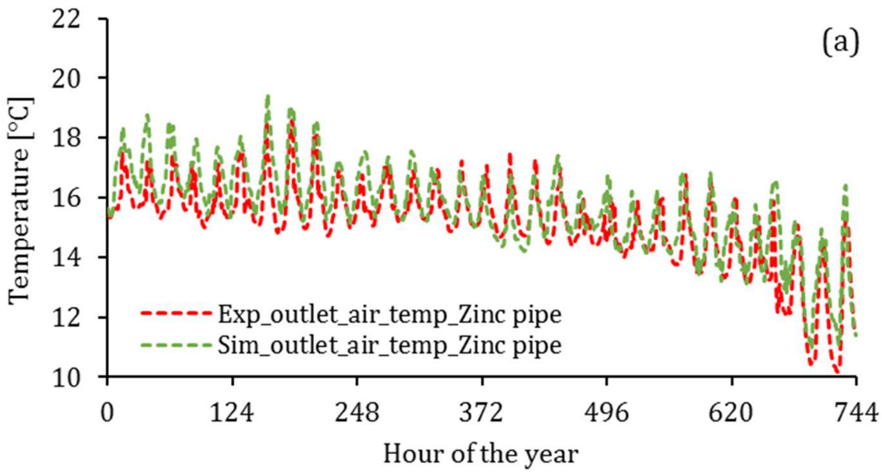
$$MSE = \frac{1}{N}\sum_{K-1}^{N}(y' - y)^2 \quad (13)$$

$$MAE = \frac{1}{N}\sum_{K-1}^{N}|y' - y| \quad (14)$$

$$RE = \left(\frac{\sum_{i=1}^{N}|y' - y|/y'}{N}\right) \times 100 \quad (15)$$

Where y' is the measured variables, y is the predicted variables and N is the number of samples.

The validation of the EAHE models is carried out using experimental data obtained during the winter of 2015. The climatic data corresponding to the outdoor air temperature collected experimentally during the test period are incorporated using Type 9a (input data). The soil model parameters used to turn Type 952 are predefined above: the mean annual temperature of the soil surface is 18.1 °C, the amplitude of surface temperature variation is 14.1 °C and the annual time corresponding to the minimum surface temperature is 419 hours. As described above, these parameters are also used to determine the soil temperature at various depths, which will subsequently be used for the parametric study. Fig. 20 compares the simulated and experimental air temperatures provided by the two pipes during January 2015. As shown in Figs. 20 (a) and 20 (b), the simulation results are in good agreement with those of the experiment, wherein the deviation between them falls within 4.65% for the Zinc pipe and 3.91% for the PVC pipe, respectively.



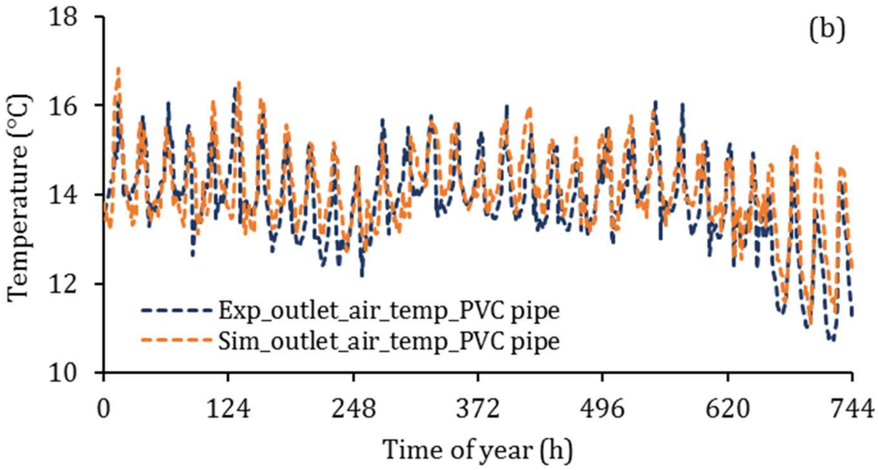


Fig. 20. Comparison between experimental and simulated results of the air temperature at the outlet of the pipe, (a) Zinc pipe; (b) PVC pipe, January.

3.2.3. Numerical analysis of the effect of pipe material

The effect of the pipe material on the performance of the EAHE was numerically analyzed. Simulation sequences of 48 h were performed comparing the two EAHEs, PVC and Zinc, as indicated in Fig. 21. The numerical comparison between the two EAHEs was carried out under the identical operating conditions, i.e. climatic (temperate climate of Oran), geographical (site and nature of the soil), geometrical (pipe length, pipe diameter, pipe thickness, burial depth) and dynamic (air velocity and flow). The design and the operating data of the two EAHEs are presented above (see sections 2 and 3). The results are illustrated as follows: Fig. 21 (a) shows the beginning of the heating period (November 1 and 2), Fig. 21 (b) and (c) show sequences in the middle of the heating period (December 30 and 31 and January 26 and 27) and Fig. 21 (d) shows the periods towards the end of the heating period (February 18 and 19). As seen in Fig. 21 (a), a difference of 0.2 °C between the air temperature at the outlet of the Zinc pipe and that of the PVC pipe was observed. Conversely, in Fig. 21 (d), there is practically no significant difference between the air temperature at the outlet of the two pipes. On Fig. 21 (b) and Fig. 21 (c), differences of up to 2.5 °C and 1.8 °C were estimated, respectively. Based on these results, we can see that when leaving the cooling period and passing through the transition phase until the beginning of the heating period, the pipe material does not affect the performance of the EAHE. In fact, the same analysis was observed when leaving the heating period until the beginning of the cooling period, also passing through the transition phase. When passing from one mode to another (from heating to cooling) that lasts more than a month, the behavior of both EAHEs is the same. On the other hand, we note that during the heating period (period during full heating) the effect of the pipe material is significantly manifested with differences of more than 2 °C.

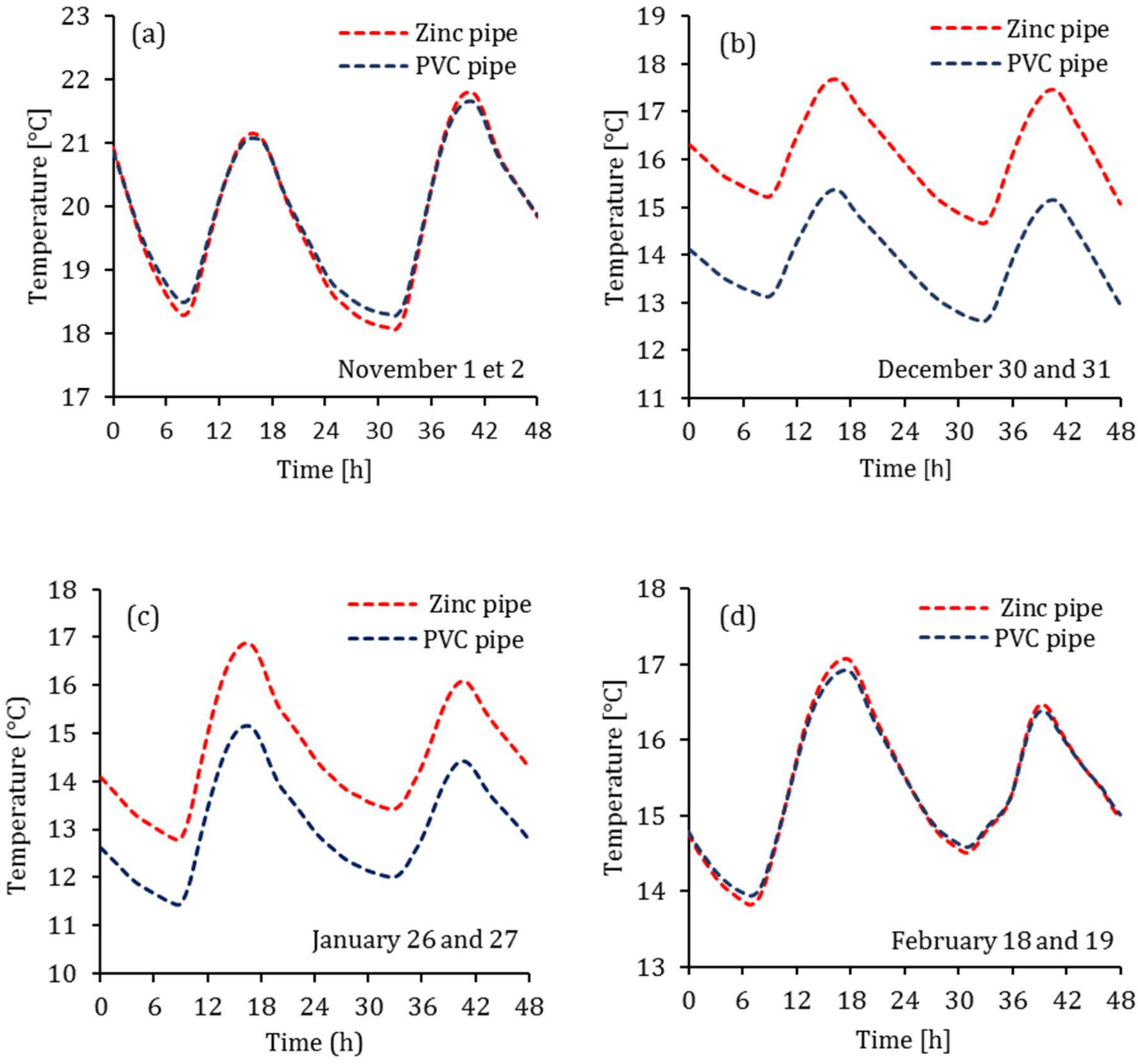


Fig. 21. Viewing the effect of the pipe material on air temperatures at the outlet of two EAHEs, PVC and Zinc.

3.2.4. Effect of the site and climatic conditions

The site and surrounding climatic conditions are important factors to be considered when studying the efficiency of the EAHE. In order to examine the effect of both factors, simulations are carried out under the three climatic sites mentioned above, namely the Mediterranean climate, the arid climate and the Steppe climate. The simulation period is presented over 72 hours, selecting the coldest winter days for each climate type. This choice allows to evaluate the minimal heating potential that the systems can provide under such unfavorable climatic conditions. In addition, the geometric and dynamic characteristics are maintained for the three studied cases. Fig. 22. shows the air temperature variation at the outlet of the pipe for the three sites. From the graphic, we notice that the outdoor air temperature of Oran varies between 2.2 and 14 °C, whereas that at the outlet of the pipe ranges from 11.4 to 14.7 °C. A maximum gain of 9 °C can be provided by the EAHE under this Mediterranean climate. For the arid climate, the outdoor air temperature varies from - 0.5 to 11.5 °C and that provided by the EAHE varies from 12 to 15.3 °C. As we can see, the system can provide a maximum gain of 12.4 °C under these climatic conditions of Bechar. For the steppe climate, the outdoor air temperature varied from -4 to 7.6 °C whereas the air temperature supplied by the EAHE varied from 4 to 7 °C. This generates a maximum gain up to 8 °C under El-Bayadh climate. Also, it can be observed that the air temperature at the outlet of the EAHE is lower than the outdoor air in hours 301 to 305. In fact, the soil temperature is lower (around 6.6 °C) than the outdoor air temperature (around 7.6 °C), so, after heat exchange between them, the air temperature at the outlet of the EAHE is around 6.9 °C. During this period, the EAHE is cooling instead of heating. The results show that the performance of the EAHE can be significantly affected from one region to another due to the surrounding climatic conditions and the geographical location around the system. For the same geometrical (length, diameter and depth) and dynamic conditions, the temperature differences can reach or exceed 4 °C.

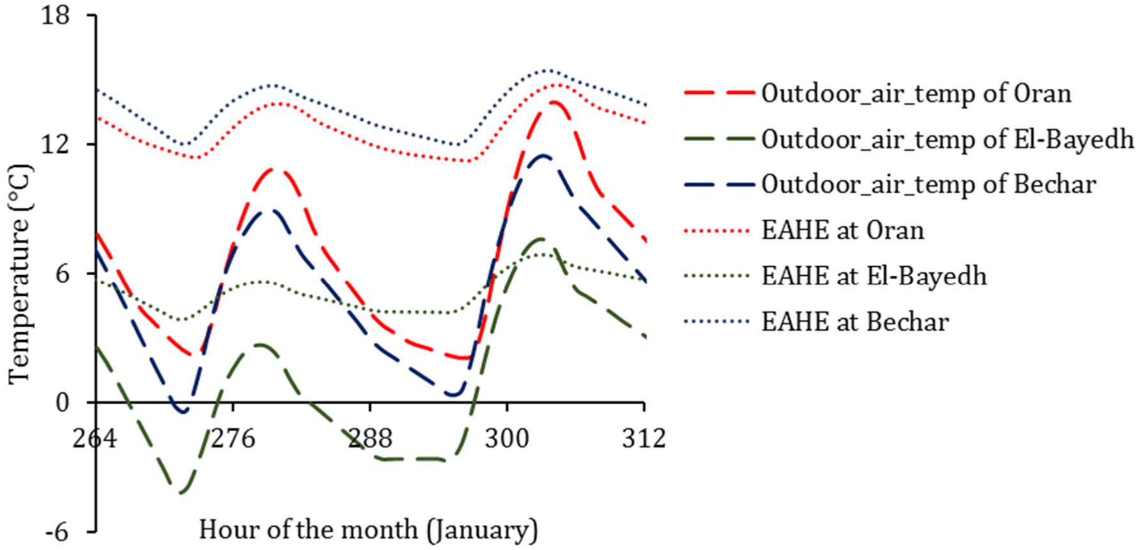


Fig. 22. Air temperature variation at the outlet of the EAHEs for the three sites, viz. Oran, Bechar and El-Bayadh.

3.2.5. Energy gain provided by the EAHE for the three sites

The monthly energy supplied by the Zinc EAHE for the Oran, Bechar and El-Bayadh climates is shown in Fig. 23. The energy supplied was calculated using the initial operating conditions. The results show that the Zinc EAHE achieved significant energy gains at the beginning of the heating period for November, December and January. However, these gains decrease from February to April, when the heating period concludes. This is due to the decrease of the ground temperature at the end of winter and the increase of the outdoor temperature, which reduces the heating capacity and increases the cooling capacity, as clearly seen in March and April. In addition, the system showed better heating performance in the Bechar climate with gains of 178 kWh and 139 kWh compared to 131 kWh and 100 kWh in the Oran climate and 61 kWh and 15 kWh in the El-Bayadh climate for December and January, respectively.

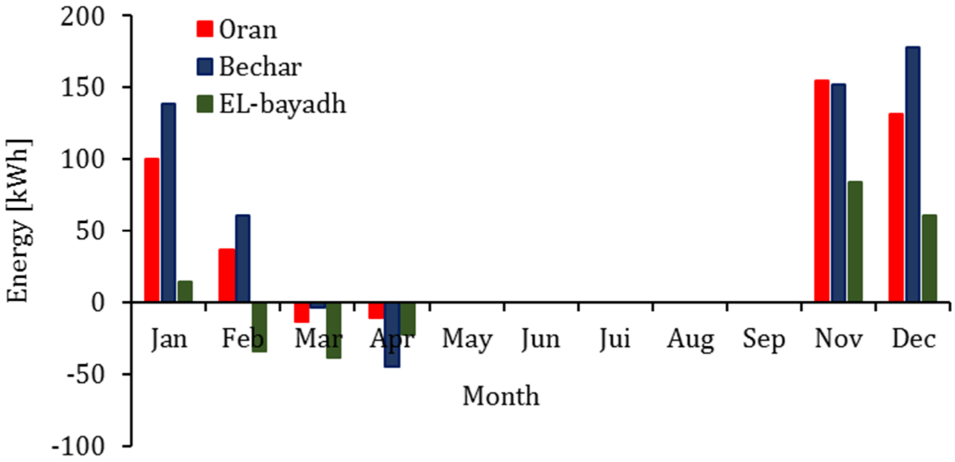


Fig. 23. Monthly energy supplied by EAHE for the three sites, viz. Oran, Bechar and El-Bayadh.

3.2.6. Sensitivity analysis

3.2.6.1. Effect of burial depth

The effect of the depth on the performance of the EAHE was examined. Fig. 24 shows the average evolutions of the air temperature at the outlet of the EAHE and its COP for different depths in three selected regions, Oran, Bechar and El-Bayadh. Further, the evolution of these outlet temperatures was jointly plotted to examine the effect of the site and climate on the performance of the EAHE. Based on the simulation results, the average air temperature at the outlet of the EAHE increases with depth and thus its performance increases. On the other hand, the air temperature at the outlet of the pipe stabilizes when it is in equilibrium with that of the soil. This is due to soil exhaustion and saturation that cannot generate heat gains for the air flowing in the pipe. Meanwhile, the COP evolves with the evolution of the outlet air temperature. For the Oran region, the air temperature at the outlet of the EAHE stabilizes at a depth of 5 m with a temperature of 18.2 °C, as shown in Fig. 24 (a). This value is approximately equal to the soil temperature at this depth. The air temperature at the outlet of the pipe at 3 m depth is 16.6 °C with a difference of 1.3 °C compared to that provided at 2 m depth. As shown in Fig. 24 (b), the average system COP during the heating period is approximately 4.4 to 2 m depth, whereas at 3 m depth, the COP increased to 7, representing an increase of 2.6. In the Bechar region, the air temperature at the outlet of the EAHE stabilizes at a depth of 4 m with a temperature of 18.7 °C, as shown in Fig. 24 (a). The air temperature at the outlet of the pipe is 18.6 °C to 4 m depth and 18 °C to 3 m depth, giving a difference of 0.6 °C. This variation range is considered insufficient in view of soil thermal recovery, which means that the implementation of EAHE at 3 m depth could thermally deplete the soil. During the heating period, the average COP of the EAHE at 2 m depth is about 6, as illustrated in Fig. 24 (b). At El-Bayadh, we can see that the air temperature at the outlet of the EAHE keeps increasing up to 10 m. This means that the soil at this depth is constantly rich in calories and able to provide heat to the air flowing through the pipe. Contrary to the cases of Oran and Bechar, this exchange takes place without affecting or depleting the soil. Based on these results, we find that the optimal depth that meets the investment/efficiency criteria is between 4 and 5 m, which is considered to be somewhat deeper to these systems. As shown in Fig. 24 (b), the average COP of the EAHE during the heating period is 5.4 to 4 m and 7 to 5 m depth.

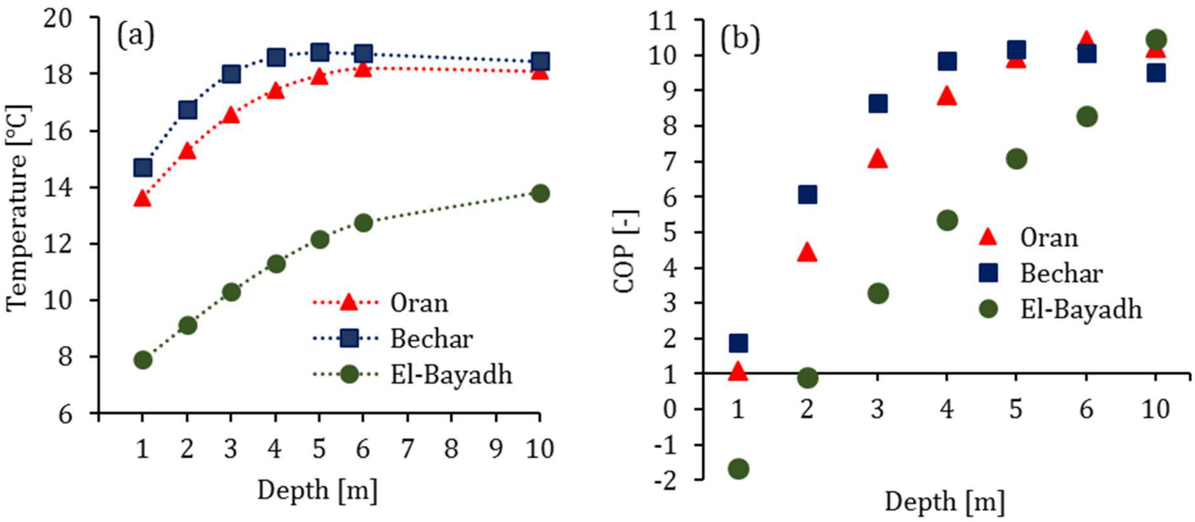


Fig. 24. (a) Average air temperature at the outlet of the pipe and (b) average COP of the EAHE, at different depths for the three studied sites, viz. Oran, Bechar and El-Bayadh.

3.2.6.2. Effect of pipe length

The effect of pipe length on the performance of the EAHE was examined. Fig. 25 shows the average variations of the air temperature at the outlet of the EAHE and COP for different lengths. These variations were plotted for the same experimental conditions, including air velocity, diameter and burial depth. The simulation results are used to identify the ideal length according to the type of the studied climate. For heating, it is well known that more the pipe is longer more the exchange surface with the soil is greater, thus increasing the temperature at the outlet of the pipe. As seen in Fig. 25 (a), the air temperature at the outlet of the pipe increases by 1.6 °C from 10 to 30 m, whereas it only increases by 0.3 °C from 30 to 50 m in the Mediterranean climate. Moreover, in this climate, the average COP of the EAHE increases from 3 to 4 for lengths varying from 20 to 30 m, respectively, as shown in Fig. 25 (a). For the arid climate, indicated in Fig. 25 (a), the outlet air temperature increases by 2.5 °C from 10 to 30 m and by 0.4 °C from 30 to 50 m. Likewise, the mean COP of the EAHE increased from 6 to 8 when the length is extended from 20 to 30 m, as illustrated in Fig 25 (b). Furthermore, in the steppe climate, the air temperature at the outlet of the pipe hardly varies over the length of the pipe, as shown in Fig. 25 (a). This is mainly due to the depth at this level, unable to provide heat to the air because of the very small difference between the air temperature in the pipe and that of the soil taking into account the nature of the soil and the particular meteorological conditions.

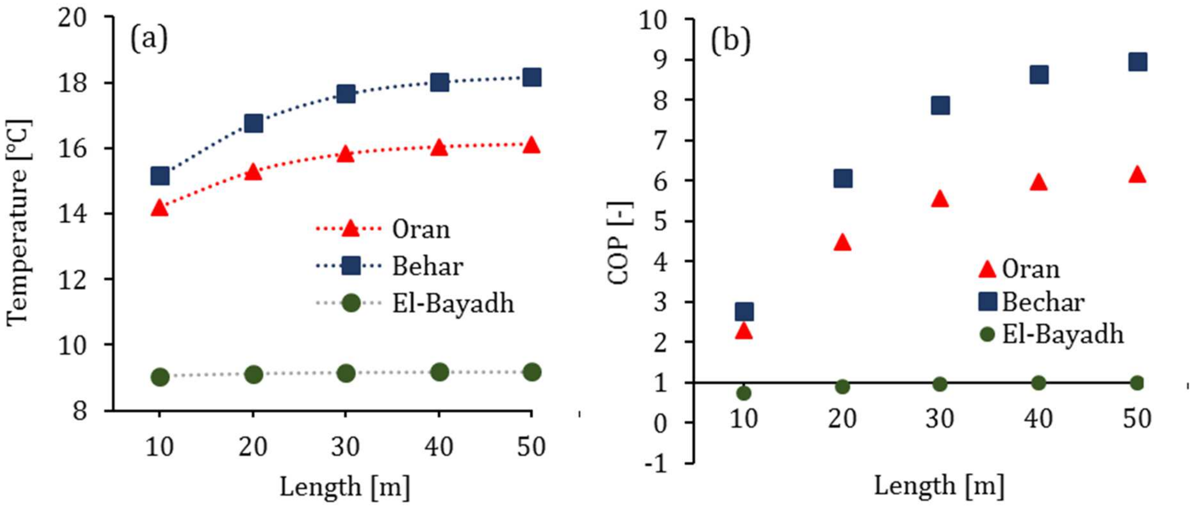


Fig. 25. (a) Air temperature variation at the outlet of the pipe and (b) COP of the EAHE, for different lengths, viz. Oran, Bechar and El-Bayadh.

3.2.6.3. Effect of pipe diameter

The effect of pipe diameter on the performance of the EAHE was examined. Diameter adjustment during the investigation is carried out while maintaining pipe thickness. Fig. 26 shows the average variations of the air temperature at the outlet of the EAHE and COP for different diameters. It can be observed that increasing the pipe diameter increases the air temperature at the outlet of the pipe.

For the Oran region, this increase stabilizes around a diameter of 0.18 m with a difference of 0.3 °C from the operating diameter (0.12 m), as shown in Fig. 26 (a). The mean COP of the EAHE with a diameter of 0.18 m is 5 (Fig. 26 (b)). For the Bechar region, the increase of the air temperature at the outlet of the EAHE stabilizes around 0.3 m in diameter with a difference of 1 °C compared with the operating diameter (0.12 m), see Fig. 26 (a). Thus, the outlet air temperature increases by 0.4 °C when the diameter has increased from 0.18 to 0.3 m. Similarly, as shown in Fig. 26 (b), the average COP of the EAHE with a 0.18 m in diameter is 7.2 and 8.3 for a 0.3 m in diameter. For El-Bayadh, shown in Figs. 26 (a) and (b), the outlet air temperature is practically stagnant.

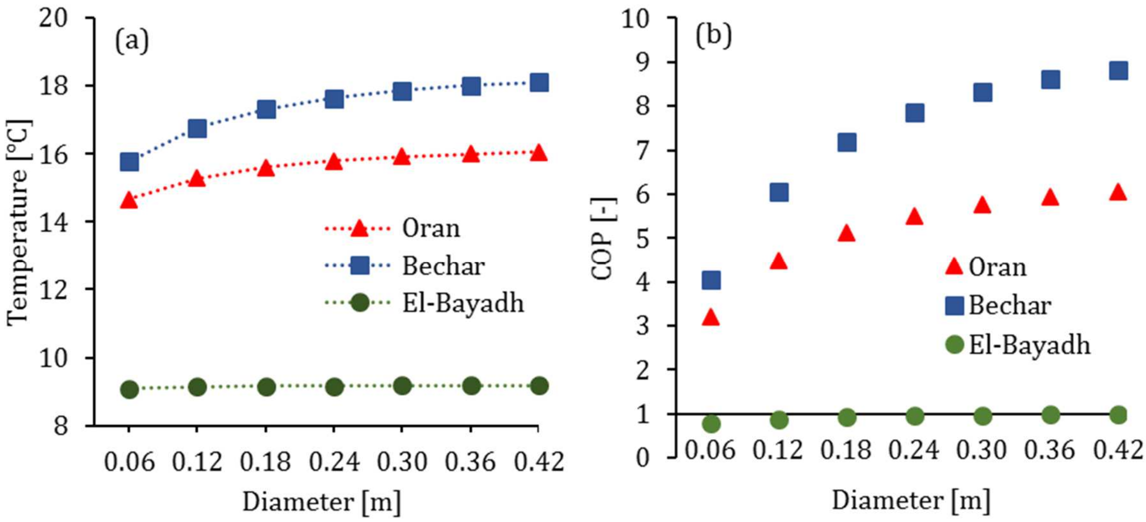


Fig. 26. (a) Air temperature variation at the outlet of the pipe and (b) COP of the EAHE, for different diameters, viz. Oran, Bechar and El-Bayadh.

3.2.6.4. Effect of air velocity

The effect of air velocity on the performance of the EAHE was investigated. Fig. 27 shows the air temperature variations at the outlet of the pipe and the COP of the EAHE for different air velocities. The variations of the average air temperature were plotted using the same experimental conditions, such as a depth of 2 m, a length of 20 m and a diameter of 0.12 m. As the air velocity inside the pipe increases, the air temperature at the outlet of the pipe decreases, which reduces the performance of the EAHE during heating. In fact, the air flow through the pipe exchanges the temperature with the soil, absorbing the stored heat in order to use it for heating. Therefore, increasing the air velocity through the pipe reduces the duration of the heat exchange, which causes a decrease of the air temperature at the outlet of the EAHE. For the Oran climate, the average air temperature at the outlet of the pipe varies around 15.2 °C for an air velocity of 0.45 m/s and 15 °C for a velocity of 0.9 m/s, as shown in Fig. 27 (a). On the other hand, a decrease of air velocity followed by a decrease of air flow rate is thermally efficient for the system, but does not guarantee the building's air renewal. For this reason, it is recommended to calculate the air flow rate supplied in the building at the design phase. For EAHE in the El-Bayadh climate, the outlet air temperature evolved very little. This can be explained by the soil's inability to provide heat at that depth and also by its relatively limited potential due to its thermal characteristics.

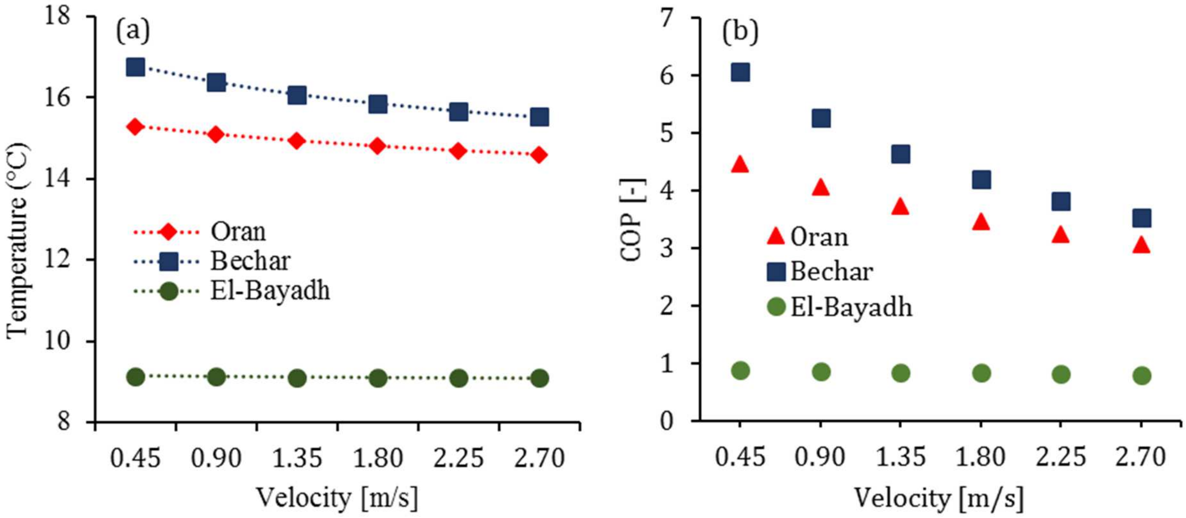


Fig. 27. (a) Air temperature variation at the outlet of the pipe and (b) COP of the EAHE, for different air velocities, viz. Oran, Bechar and El-Bayadh.

3.2.6.5. Optimal parameters

Optimal parameters were identified based on the results of the sensitivity analysis to evaluate the operational feasibility of PVC and Zinc EAHEs in the considered climates, taking into account the nature of the soil, as shown in Tables 8 and 9. The feasibility of the two EAHEs was evaluated for the heating period by calculating the gain, the energy provided, the COP and the reduction rate of the building heating needs. Optimal parameters were identified taking into account investment/efficiency criteria. In addition, they were determined so that thermal saturation of the soil would not be reached and its recovery would not be affected in the long term [36]. For the temperate climate of Oran, the optimal parameters are fixed at 3 m depth, 25 m length, 0.18 m diameter and 0.45 m/s for the air circulation velocity. The Zinc EAHE provided an average gain of 4.7 °C compared to the 3.7 °C obtained by the PVC EAHE, representing a difference of 1 °C. The average COP is 9.5 for the Zinc EAHE and 7.6 for the PVC EAHE (Tables 8 and 9). It represents a difference of 1.9 between both systems. Likewise, the integration of the Zinc EAHE in the building reduced the heating needs by 123 kWh, which represents a reduction of 23.3% of the total needs (Table 8). Furthermore, the heating needs of the building were reduced by 61 kWh with a reduction rate of 11.4% using the PVC EAHE (Table 9). For the arid climate of Bechar, the following values were fixed as optimal parameters: 2 m depth, 30 m length, 0.24 m diameter and 0.45 m/s for air velocity. An average gain of 4.6 °C was provided by the PVC EAHE while the Zinc EAHE supplied an average gain of 4 °C, which represents a difference of 0.6 °C between them. Furthermore, the average heating COP is 9.4 for the PVC EAHE and 8.2 for that of Zinc, representing a difference of 1.2. As for the reduction rate of heating needs, the PVC EAHE reduced about 20.7% of the total needs compared to 15.5% achieved by the Zinc EAHE (Tables 8 and 9). Regarding the steppe climate of El-Bayadh, the optimal parameters were set at 5 m depth, 25 m length, 0.12 m diameter and 0.45 m/s for air circulation velocity. Under these conditions, average gains of 4.1 °C and 4 °C were provided by the PVC and Zinc EAHEs, respectively. In addition, average heating COPs of 8.4 and 8.1 were estimated for the PVC and Zinc EAHEs, respectively. Thus, reductions of 7.6% and 7.3% of heating needs were obtained by the PVC and Zinc EAHEs, respectively (Tables 8 and 9).

Table 8: Summary of optimal parameters simulation results for Zinc EAHE under the different climatic and geographical conditions of Oran, Bechar and El-Bayadh.

Site	**Optimal operating parameters**				**Performance parameters**				
	Depth [m]	Length [m]	Diameter [m]	Velocity [m/s]	ΔT [°C]	Energy gain [kWh]	COP [-]	Energy need of the cell [kWh]	reduction rate (%)
Oran	3	25	0.18	0.45	4.7	143	9.5	412.2	23.3
Bechar	2	30	0.24	0.45	4	123.7	8.2	374.3	15.5
El-Bayadh	5	25	0.12	0.45	4	122	8.1	723	7.3

Table 9: Summary of optimal parameters simulation results for PVC EAHE under the different climatic and geographical conditions of Oran, Bechar and El-Bayadh.

Site	**Optimal operating parameters**				**Performance parameters**				
	Depth [m]	Length [m]	Diameter [m]	Velocity [m/s]	ΔT [°C]	Energy gain [kWh]	COP [-]	Energy need of the cell [kWh]	reduction rate (%)
Oran	3	25	0.18	0.45	3.7	113.5	7.6	474.3	11.4
Bechar	2	30	0.24	0.45	4.6	141	9.4	351	20.4
El-Bayadh	5	25	0.12	0.45	4.1	125.6	8.4	720.4	7.6

4. Discussion

4.1. Summary of major findings

In this paper, we investigated the thermal performance of two EAHEs composed of different pipe materials (PVC and Zinc) for three different climatic regions in Algeria. We also experimentally and numerically analyzed the effect of the pipe material. Also, sensitivity analysis was conducted in order to identify the optimal operating and design parameters of the EAHE in the three climatic regions mentioned above. Using these parameters, the operating feasibility of the EAHEs according to pipe material and climate type was analyzed. The findings of our research are summarized as follows:

- The experimental results show that the gains provided by EAHEs reach 10.5 °C and 9 °C for Zinc and PVC, respectively. Similarly, the energy supplied by these two EAHEs is 209.4 kWh and 163 kWh, respectively. The maximum daily COP that the systems can reach is 14 for Zinc and 10 for PVC. Finally, the monthly COP is estimated at 4.8 for Zinc and 2.8 for PVC.
- Based on the analysis of the experimental results, the effect of the pipe material on the performance of the EAHEs is clearly evident in early January with temperature difference of up to 4 °C. Moreover, it was also observed that this difference decreases until becoming insignificant at the end of the month. This behavior was confirmed by similar results observed in the numerical analysis. In fact, the pipe material does not affect the performance of the EAHE at the end of the heating period and during the transition phase until the beginning of the cooling period and vice versa. Moreover, this effect is significantly manifested with temperature differences of more than 2 °C over the heating period.
- The simulation results show that the performance of the EAHE is significantly affected from one region to another due to climatic and geographical conditions. For the same geometric and dynamic conditions of the experiment, the temperature differences between the three sites reached or exceeded 4 °C. In addition, the EAHE demonstrated better heating performance in the Bechar climate during December and January, with gains of 178 and 139 kWh compared to 131 and 100 kWh in the Oran climate and 61 and 15 kWh in the El-Bayadh climate, respectively.

- The sensitivity study provided optimal operating and design parameters (geometric and dynamic) for the two EAHEs under the three climates considered. The selected parameters are summarized in Tables 8 and 9. Under these conditions, the Zinc EAHE showed better heating performance in the temperate climate with a COP of 9.5, followed by 8.2 for the arid climate and 8.1 for the steppe climate, with heating needs reduction rates of 23.3%, 15.5% and 7.3%, respectively. On the other hand, the PVC EAHE is much better in arid climates with a COP of 9.4, followed by 8.4 for the steppe climate and 7.6 for the temperate climate, with heating needs reduction rates of 20.7%, 7.6% and 11.4%, respectively. In addition, both EAHEs showed almost identical behavior when tested in the steppe climate.

4.2. Study strength and limitations

The strength of the study is the use of an experimental cell coupled to two full-scale EAHEs. The proposed research provides a good understanding of the thermal behaviour of EAHEs and identifies the parameters influencing their performance according to the climatic site. Thereby, this research supports the decision making process on several criteria for good dimensioning of such systems. Another advantage of our study is to help geothermal experts with precise data on EAHE sizing for the three studied climates. In this context, our paper presents one of the few studies where researchers provide the exact choice of materials, depth, length, diameter and air velocity for three different climates without generalizing the sizing decision criteria. A good example is the study of Shojae and Malek [37]. The authors evaluated the thermal performance of an EAHE for different climatic regions of Iran at a static depth of 2.7 m. The calculation of the coverage rate generated by the EAHE at the same depth was generalized for all regions. Therefore, we believe that our research can be applied to other regions. In this sense, we do not give specific local results for only Algeria, but for other regions with the same climatic specificities, such as North Africa, Southern Europe, South America, the Gulf States.

We realize that our study is not flawless, but it should be considered as a new contribution that can be very useful for future work, especially on EAHE operation. In particular, the effect of climatic conditions, soil and pipe material on the performance of EAHES. As, limitations, the model validation period is only for the month of January. The study could have been improved with a longer monitoring period (heating and cooling). Nevertheless, we performed our analysis using the most appropriate data.

4.3. Implications on practice and future research

The study results provide useful elements on the use of EAHEs in different climates of Algeria, where the choice of pipe material was considered. They also provide crucial information on the operating feasibility of EAHEs in the relevant climatic regions. We believe that designers and EAHE users can apply our results to their own concepts for good sizing and better performance in order to significantly reduce energy consumption. There is a large geothermal potential in Algeria, but few studies have been conducted to develop it satisfactorily. Therefore, future work will be oriented towards the development of a new methodology for a better understanding of the long-term ground thermal response to EAHE use for different regions. A fundamental perspective of the present study will be the influence of the optical parameters chosen for each region on the long-term thermal process of the EAHE.

5. Conclusion

The heating performances of two earth-air heat exchangers (EAHEs) of different pipe materials in three climatic regions of Algeria were studied. The effect of the pipe material on the performance of the EAHE was also highlighted. Thereafter, a sensitivity analysis was conducted in order to numerically identify the optimal operating and design parameters for the three climates, Mediterranean, arid and steppe. Finally, the operational feasibility of the two EAHEs was studied in order to establish the most appropriate choice according to the type of pipe material and climate. The results of this study are analyzed and the following conclusions can be drawn:

- The results show that the effect of the pipe material on the performance of the EAHEs is evident during the heating period. However, this effect is clearly not evident during the transition periods from cooling to heating and/or vice versa.
- The performance of the EAHE system can be significantly affected from one region to another due to the surrounding climatic conditions and the geographical location around the system. For

the same geometrical and dynamic operating conditions, differences of air temperature provided by the EAHE between different regions can reach 4 °C or more.

- The sensitivity analysis identified the optimal design and operating parameters for the two EAHEs. The simulation results showed that the Zinc EAHE is more efficient in a temperate climate than in arid or steppe climate, respectively, whereas the PVC EAHE is much more efficient in an arid climate than in a temperate or steppe climate. However, both EAHEs showed similar behavior in a steppe climate.
- The selection of design and operating parameters as well as the choice of pipe material for the EAHE are not standard criteria for all climatic regions.

A number of recommendations are drawn from the findings analysis of this study:

- For the temperate Mediterranean climate, we recommend a burial depth of 3 m, an optimal length of 25 m and a diameter of 0.18 m, while for the arid climate, a burial depth of 2 m, a length of 30 m and a diameter of 0.24 m also advised.
- Air velocity should not exceed 0.45 m/s for all climate regions.
- The use of EAHE in steppe climate (El-Bayadh) is not recommended because the optimal depth can reach or exceed 5 m, and therefore investment and maintenance costs are likely to be higher.
- It is recommended to use EAHEs designed with Zinc in temperate Mediterranean climates and PVC in arid desert climates.

This paper could serve as a guide for designers and users of EAHEs for heating applications in order to reduce heating consumption and improve thermal comfort levels. The study findings will also give users an idea of the operating and design parameters of the most appropriate EAHEs in the Mediterranean (temperate), arid and steppe climate. Moreover, these results are not necessarily restricted to the local scope of Algeria, but can perhaps be extrapolated to other world areas typified by such climates.

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