NUMERICAL MODELING OF AN EARTH AIR HEAT EXCHANGER UNDER THE LOCAL CONDITIONS OF LAGHOUAT CITY, ALGERIA

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In this work, a numerical simulation of the airflow through an earth-air heat exchanger was carried out using the Computational Fluid Dynamics platform ANSYS FLUENT 2020 R2 to examine the reliability of the 3D numerical model. The results were compared with experimental data from the literature for two flow regimes, steady and transient. The main objective of this numerical study was to evaluate the performance of the earth-air heat exchanger under local seasonal climatic conditions (summer and winter seasons in Laghouat City, Algeria). For this purpose, a parametric analysis was performed to study the effects of inlet air velocity and pipe diameter for both winter and summer seasons on the air temperature at the exchanger outlet. Promising outcomes were demonstrated, with system efficiency reaching 85% in the summer for an inlet air temperature of 43°C and 84% in the winter for an inlet air temperature of -2°C. These results were obtained at an optimal inlet air velocity of 2.5 m/s and a pipe diameter of 0.11 m. It was also found that the earth-air heat exchanger could operate continuously.

Key words*: earth air heat exchanger, computational fluid dynamics, numerical, simulation, summer, winter, temperature*

1. Introduction

Algeria's energy demand increased from 46.5 Mtoe in 2020 to 50.2 Mtoe in 2021, driven by a 12.7% rise in electricity and a 6.5% rise in natural gas consumption. Heating and cooling needs significantly contribute to this demand. With declining oil and gas exploration and depleting reserves, adopting green energy is essential [1].

Cooling and heating through geothermal energy have been traditionally used in the Sahara region, such as in caves. Geothermal energy, which relies on heat stored beneath the Earth's surface, is used to produce electricity and to heat and cool buildings. The stable ground temperature makes it a source of coolness in summer and warmth in winter. One technique to harness this energy is the earth-air heat exchanger (EAHE).

Advancements in computational capabilities have increased the use of Computational Fluid Dynamics (CFD) to simulate complex fluid flows, reducing the need for costly physical experiments. In sustainable building design, CFD helps simulate the performance of EAHE systems by testing various parameters, many researchers have conducted various studies on EAHE systems.

Ahmed et al. [2] conducted a numerical simulation to study the thermal performance of the EAHE. The model was validated using the Nusselt number and friction factor under varying conditions, such as pipe diameters and airflow velocities. The results indicate that increasing the pipe length improves EAHE efficiency by lowering the outlet temperature. Carlos et al. [3] developed an ANSYS/Fluent model to analyze EAHE performance, validating it with experimental data from Grossa, Brazil. The 25-meter EAHE showed excellent thermal performance, maintaining air temperature near comfort levels.

Taşdelen et al. [4] examined EAHE designs for Bitlis, Turkey, comparing horizontal and vertical configurations. Using ANSYS FLUENT 19.2 for CFD simulations, they found vertical EAHEs are recommended for Reynolds numbers of 5 10^3, 10^4, and 2 10^4, while horizontal EAHEs are preferred for Reynolds numbers of 4 10^4, 6 10^4, 8 10^4, and 10^5 for passive heating in winter. Łukasz et al. [5] investigated EAHE flow characteristics using both experimental investigations and CFD modeling. Their CFD model for multi-pipe EAHEs was validated for various geometrical parameters. The results showed that the model's accuracy is sufficient for engineering applications and can be achieved quickly using a standard personal computer. Mushtaq et al. [6] evaluated the impact of design parameters on Earth-to-Air Heat Exchanger (EAHE) performance through numerical simulations validated against experiments. The study highlights soil moisture as a critical factor affecting EAHE performance in both summer and winter in Nasiriyah, Iraq. The results indicate that very moist or saturated soil provides the best EAHE performance, while pipe material and wall thickness have no significant effect. Mohamed et al. [7] conducted numerical CFD and experimental studies to investigate the behavior of an air/ground heat exchanger and its efficiency. The results found that the heat exchanger can lower the air temperature up to 20°C, which is a significant margin. Naoufel et al. [8] used CFD to study the thermal performance of a spiral-shaped EAHE in hot regions. The numerical results, validated against experimental data, showed that increasing the pitch spacing resulted in a 6°C difference in outlet air temperature. Additionally, increasing the air velocity from 2 to 5 m/s reduced the mean efficiency from 60% to 33% and the coefficient of performance (COP) from 2.84 to 0.46 for a pitch spacing of 2.0. Belloufi et al. [9] conducted an analytical and experimental study on an EAHE for air-cooling. They proposed an analytical solution based on energy conservation principles and validated it against experimental data from the University of Biskra, Algeria. The study demonstrated that the EAHE effectively reduced air temperature, achieved thermal comfort for cooling, and could significantly reduce energy consumption. Belloufi et al. [10] investigated the transient behavior of an EAHE in continuous operation mode in Biskra, Algeria, using a 3 m deep polyvinyl chloride pipe (PVC). Through experimental measurements and numerical calculations, their study revealed that continuous operation minimally affects performance, with a maximum air temperature drop of 18.06°C and thermal efficiency of 78.96%. Significant findings include the importance of soil thermal conductivity and the primary cooling contribution of the initial 30m of the pipe. Damodharan et al. [11] analyzed a soil-to-air heat exchanger (SAHE) for domestic buildings, validating the model through temperature predictions and experiments. They found that increasing pipe length and optimizing burial depth improved efficiency by lowering outlet temperatures.

Molina et al. [12] conducted an experimental evaluation of a "U" type EAHE in urban areas. The results showed promising cooling performance, with a maximum COP of 12.8, 88.4% effectiveness, and an air temperature decrease ranging from 5.1°C to 9.4°C.

In addition to all of the above, numerous studies have addressed EAHE, including Zeitoun et al. [13], Gooroochurn, et al. [14], Kaddour et al. [15], Peñaloza Peña et al. [16], Bughioet al. [17] and others.

The main objective of this paper is to develop a numerical model of an EAHE using Ansys Fluent 2020 R2, evaluated for steady state and transient flows. The model's accuracy will be validated by comparing its results with existing literature [9] and [10]. Once validated, local climatic data from Laghouat City, Algeria, will be used to assess the EAHE's performance, considering parameters such as velocity and diameter on a winter day in January and a summer day in August. Additionally, the model will be examined for continuous operation over 24 hours during these periods.

2. Principle of earth/air heat exchanger

An EAHE principle is simple: a pipe such as steel or PVC is buried at a certain depth underground. Air or water are commonly used as the working fluids (in our case air), that pass through the pipe. As the air moves through the pipe, it exchanges heat with the surrounding ground (Fig. 1).

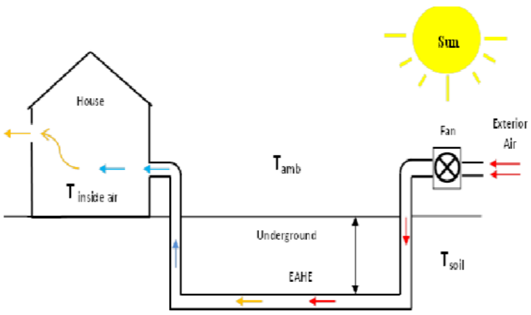


Figure 1. Earth air heat exchanger.

The efficiency ϵ of an EAHE is defined by the equation:

$$\epsilon = \frac{T_{inlet} - T_{outlet}}{T_{inlet} - T_{soil}} \quad (1)$$

Where:

- T_{inlet} : the temperature of the air entering the EAHE(C°).
- T_{outlet} : the temperature of the air exiting the EAHE (C°)
- T_{soil} : the undisturbed soil temperature at the depth of the EAHE (C°).

3. Mathematical modeling

The mathematical model is based on equations describing heat transfer and fluid dynamics through the soil, pipe wall, and airflow inside the pipe. Therefore, the calculations consider:

- The air is considered an incompressible fluid with turbulent flow through the pipe.
- The soil is considered a homogeneous medium with constant thermo-physical properties (ρ, μ, k, C_p) for both the soil and air.

3.1. Soil temperature:

The following equation gives the soil temperature model:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\propto}\frac{\partial T}{\partial t} = 0 \quad (2)$$

T: the soil temperature (C°), $\propto$: the thermal diffusivity of the material (m2 /s), *z*: depth (m), *t*: time (h).

Kusuda et al [18] conducted an experimental study by compiling 63 monthly earth temperature data sets. They proposed an analytical solution for the previous equation, given in Eq. 3:

$$T_{soil}(z,t) = T_{mean} - T_{amp} e^{\left(-z\sqrt{\frac{\pi}{8760*\alpha s}}\right)} x \cos(\frac{2\pi}{8760}(t - t_0 - \frac{z}{2}\sqrt{\frac{8760}{\pi * \alpha s}})) \quad (3)$$

Tsoil(z,t) is the ground temperature at time t (hours) and depth z (meters). T_{mean} is the average soil temperature (°C). T_{amp} is the amplitude of surface temperature (°C), calculated as $(T_{max}-T_{min})/2$. T_{max} and T_{min} are the maximum and minimum ambient temperatures (°C), respectively. t_0 is the time of year when the surface temperature is lowest, and α_s is the soil's thermal diffusivity (m^2/h).

3.2. Governing equations

The flow is considered stationary on average, with constant physical properties of the fluid. It is governed by the three-dimensional Navier-Stokes equations and the energy conservation equation. For turbulent flow, the model used to predict the flow is the $k-\varepsilon$ (k-epsilon) turbulence model [19]:

3.1.1 Continuity equation

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (4)$$

3.1.2 Momentum equation

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} \quad (5)$$

ν = represents the kinematic viscosity (m^2/s).

3.1.3 Energy conservation

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \frac{1}{\rho C_p}\left(\frac{\lambda \partial^2 T}{\partial x_j \partial x_j} + \phi\right) \quad (6)$$

Φ : represents the viscous dissipation (due to friction).

3.1.4 $k-\varepsilon$ Model equations

3.1.4.1 Turbulence kinetic energy equation

$$\frac{\partial}{\partial t}(\rho K) + \frac{\partial}{\partial x_i}(\rho K U_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial K}{\partial x_j}\right] + G_k + \rho\varepsilon \quad (7)$$

3.1.4.2 Specific dissipation rate equation

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon U_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_1\frac{\varepsilon}{K}(G_k) - C_2\rho\,\frac{\varepsilon^2}{K} \quad (8)$$

where the turbulent viscosity μ_t and the production rate G_k are calculated by:

$$\mu_t = C_\mu \rho \frac{K^2}{\varepsilon} \quad (9)$$

$$G_K = \mu_t \frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \quad (10)$$

C_1, C_2, α_k, α_ε , and C_μ are empirical constants specific to the $k-\varepsilon$ model and their values are:
C_1 =1.44, C_2 =1.92, α_k=1.0, α_ε=1.3, C_μ=0.09.

4. Validation and simulation results

In this study, ANSYS Fluent 2020R2 was used as a CFD tool to simulate the airflow through an EAHE. The principle of this CFD tool is to transform the governing equations of the mathematical model into solvable algebraic equations. ANSYS Fluent employs the finite volume method to achieve this transformation. For our simulations, two types of flow will be studied: unsteady and transient. The

steps of the numerical calculation are detailed in the flow chart shown in Fig. 2. To validate our numerical model, its results will be compared for both flow regimes with the experimental data obtained by Belloufi et al. [9] and [10].
Table 1 lists the different parameters used in the experimental measurements [9] and [10].

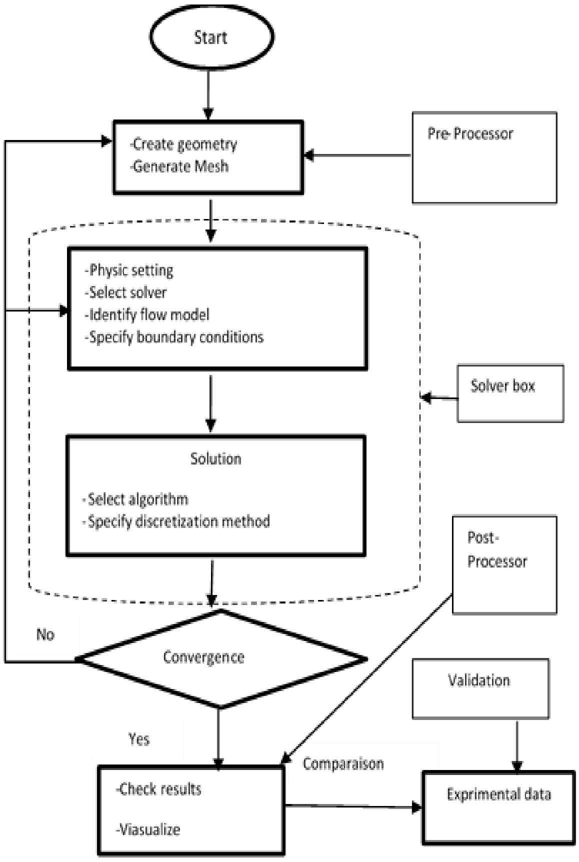


Figure 2. Flow chart of the calculation steps used by ANSYS Fluent.

Table 1. Different experimental system parameters [9] and [10].

Parameters	**Values**
Temperature of the soil T_{soil} at depth of 3m	26 °C
Thermal conductivity of the soil λ	2.5 $Wm^{-1}K^{-1}$
Depth of EAHE z	3 m
Inner diameter of the tube D_{in}	0.11 m
Outer diameter of the tube D_{out}	0.115 m
Thermal conductivity of the tube λ_p (pvc)	0.17 $Wm^{-1}°C^{-1}$
Air inlet velocity u	3.5 m s^{-1}
Air specific heat C_{pair}	1000 $Jkg^{-1}K^{-1}$
Density of the air ρ	1.2 kg m^{-3}
Average convective heat transfer coefficient of the air h	10 Wm-^{2} K^{-1}
Length of EAHE L	53.16 m

4.1. Geometry and mesh

Figures 3 and 4 illustrate, respectively, the air path and the soil domain of the EAHE created by using the Ansys fluent geometrical tool. The EAHE has a depth of 3 m, a total length of 53.16 m, and a distance of 2 m between horizontal pipes. The pipes are made of PVC.

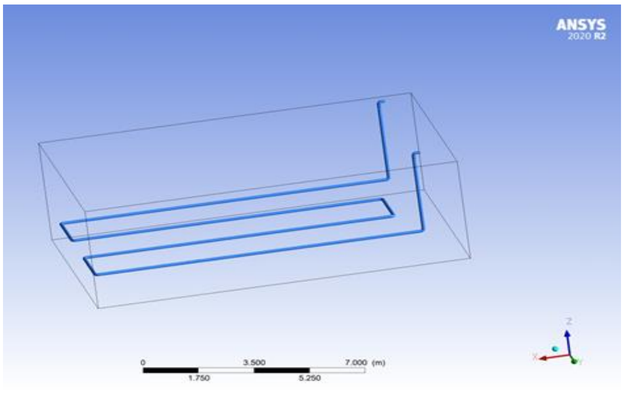


Figure 3. Geometry of the air path.

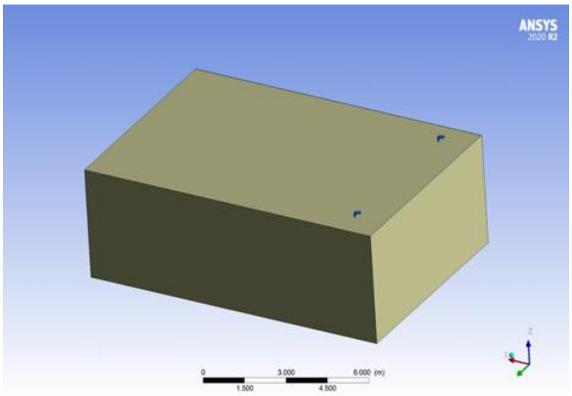
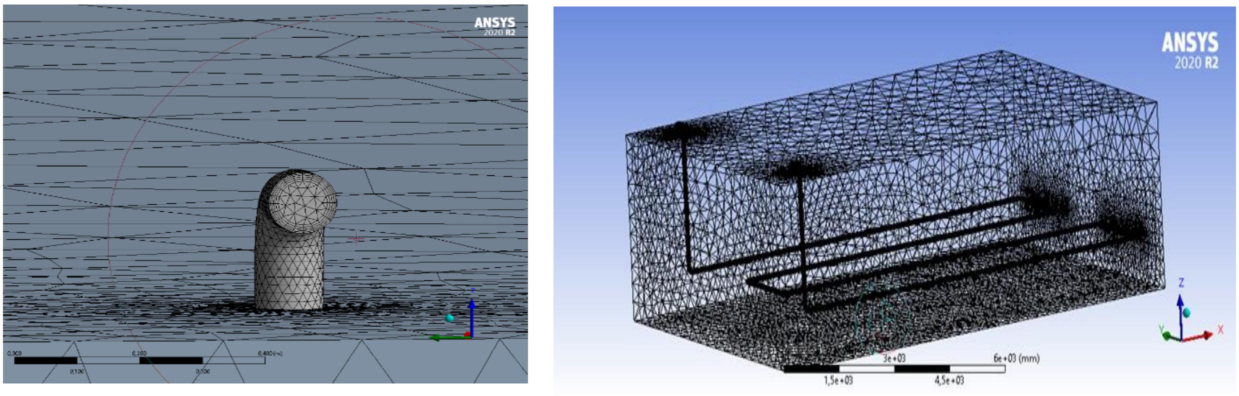


Figure 4. Geometry of the soil domain.

The chosen mesh is tetrahedral with refinement near the walls, as illustrated in Fig. 5. In total, we have 1431586 nodes, and 5250093 elements.



a) Three-dimensional view of air inlet and outlet.

b) Three-dimensional view of earth-air heat exchanger.

Figure 5. Mesh generated on the geometry of the earth-air heat exchanger.

4.2. Steady case

4.2.1 Validating numerical simulation of EAHE

To assess the reliability of the numerical model, it was compared with experimental data from Belloufi et al. [9] at Biskra University, Algeria, under summer conditions with an inlet air temperature of 48.8°C. Figure 6 shows the air temperature distribution along the EAHE, demonstrating strong agreement with experimental findings. With an average relative error of 3% (1°C), the model is highly reliable for evaluating efficiency under the climatic conditions of Laghouat City, Algeria.

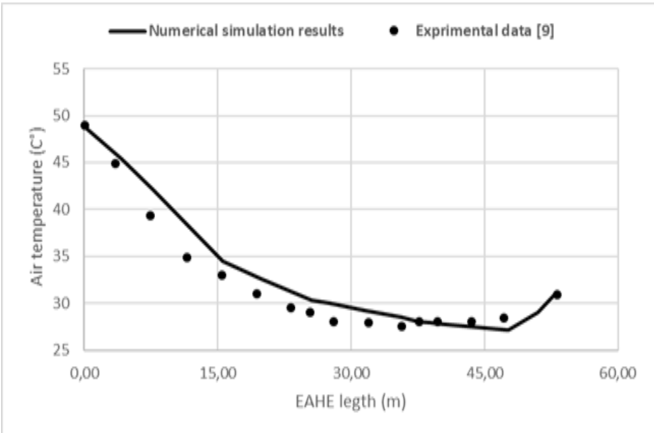


Figure 6. Simulated air temperature distribution along the length of the earth-air heat exchanger vs. experimental data.

4.2.2 Numerical simulation results under Laghouat city weather conditions

After validating the numerical model, our study applies it under the specific climatic conditions of Laghouat City, Algeria. Situated on the northern edge of the Algerian Sahara Desert, Laghouat experiences hot summers with temperatures often exceeding 40°C. In comparison, winters are mild, with average highs around 15°C and occasional nighttime temperatures near 0°C.

Figure 7 illustrates the annulus temperature of the ground at a depth of 3 meters, calculated using Eq. 3 and incorporating weather conditions specific to Laghouat for the year 2020 [20]. This analysis is part of our ongoing investigation into the performance of the numerical model the EAHE in this region under varying weather conditions. It is important to note that the soil, which is argillaceous and sandy, has the same properties as those mentioned in Tab. 1.

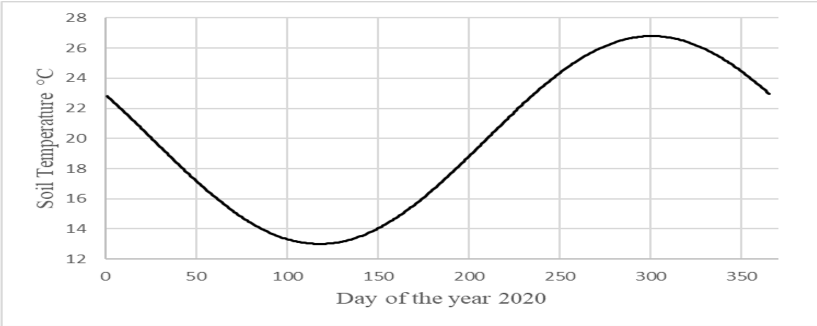


Figure 7. Soil temperatures profile at depth of 3 meters for the year 2020.

As a case study, the numerical model of the EAHE is initially evaluated for August 22, 2020 (summer season). On this day, the ambient temperature reached 43°C [22], the air inlet velocity was 3.5 m/s, and the soil temperature at a depth of 3 meters was approximately 23°C (day of the year 234, as shown in Fig. 7).

Figure 8 represents the distribution of air temperature along the EAHE. The results indicate that the EAHE performed efficiently, achieving a temperature decrease of approximately 17°C, corresponding to an efficiency of 85%.

Figures 9, 10, and 11 show how soil helps cool the air in different parts of the EAHE. Essentially, the soil around the pipes is cooler than the air, so the air gets cooled as it moves through the EAHE. However, the air can warm up at the vertical outlet because the soil temperature increases there. This highlights the crucial role of soil in cooling the air as it passes through the EAHE.

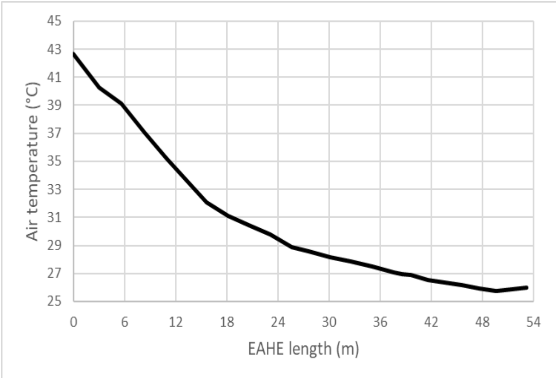


Figure 8. Distribution of air temperature along the length of the earth-air heat exchanger.

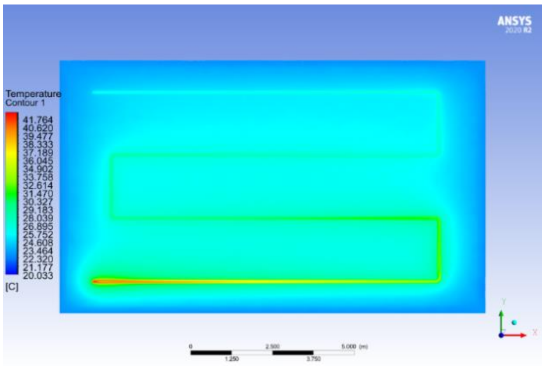


Figure 9. Isothermal contours of soil and the earth-air heat exchanger horizontal Path at 3 m depth.

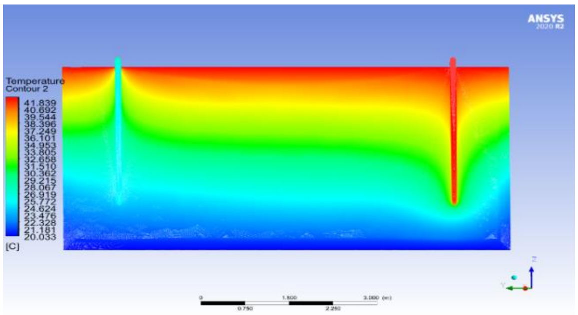


Figure 10. Isotherm contours of soil and vertical path of the earth-air heat exchanger from 0 to 3 m depth.

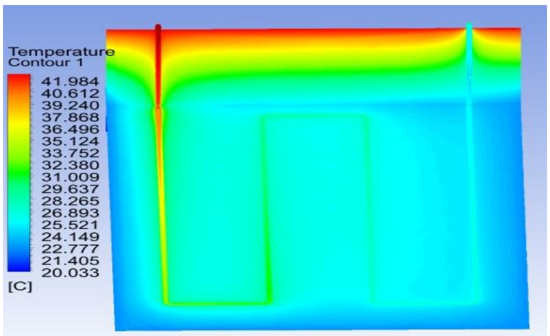


Figure 11. Temperature contours of soil and the earth-air heat exchanger.

To evaluate the effect of pipe diameter, EAHE simulations were conducted with diameters of 0.11 m, 0.16 m, 0.22 m, and 0.3 m. Increasing the diameter led to a decreased the in the EAHE outlet temperature but also reduced efficiency due to less effective heat transfer caused by reduced air residence time. The highest efficiency of 85% was achieved at an outlet temperature of 26 °C for a diameter of 0.11 m (Figs. 12, 13), while the lowest efficiency of 53% was at an outlet temperature of 32.37 °C for a diameter of 0.3 m. Similarly, increasing inlet velocity for a diameter of 0.11 m, resulted in a maximum efficiency of 87% at an outlet temperature of 25 °C for 2.5 m/s and a minimum efficiency of 69% at an outlet temperature of 29 °C for 9.5 m/s (Figs. 14, 15).

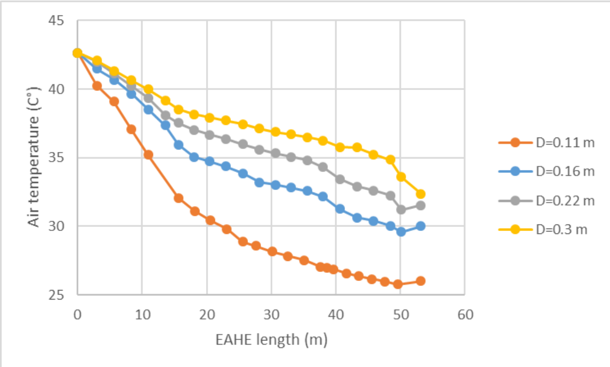


Figure 12. Effect of the pipe's diameter on the earth-air heat exchanger outlet temperature.

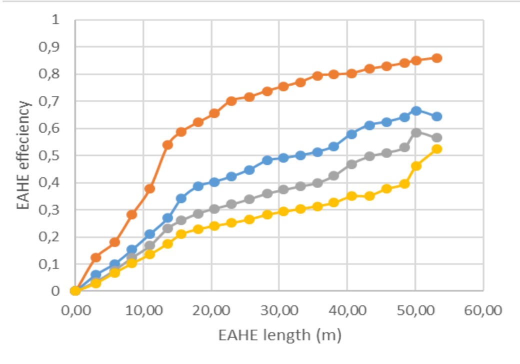


Figure 13. Effect of the pipe's diameter on the earth-air heat exchanger effeciency.

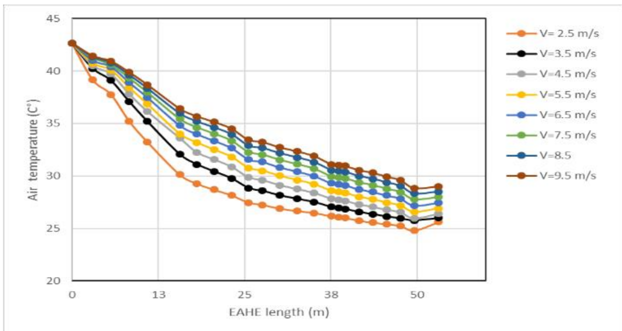


Figure 14. Effect of inlet air velocity on the earth-air heat exchanger outlet temperature.

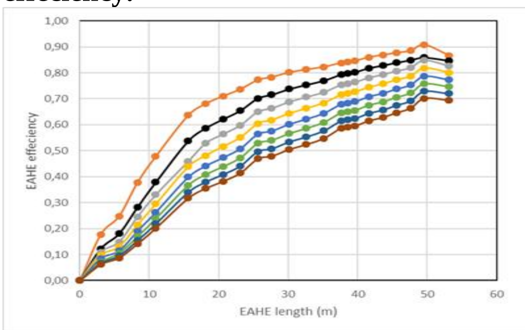


Figure 15. Effect of inlet air velocity on the earth-air heat exchanger effeciency.

In a second scenario, a winter day was studied, January 1, 2020, with an ambient temperature of -2°C at 7:00 am [22] and a soil temperature of 22.5°C (Fig. 7). The air temperature increased by approximately 20°C throughout the EAHE (Fig. 16), resulting in an outlet temperature of 18.55°C and an efficiency of 84%. The soil acted as a heat source, consistently warmer than the air inside the EAHE (Figs. 17, 18, 19). Increasing pipe diameter and inlet air velocity reduced efficiency and outlet temperature due to decreased residence time. The highest efficiency (84%) was with a 0.11 m diameter and an outlet temperature of 18.55°C (Figs. 20, 21), while the optimal inlet velocity was 2.5 m/s, yielding an efficiency of 86% and an outlet temperature of 19°C (Figs. 22, 23).

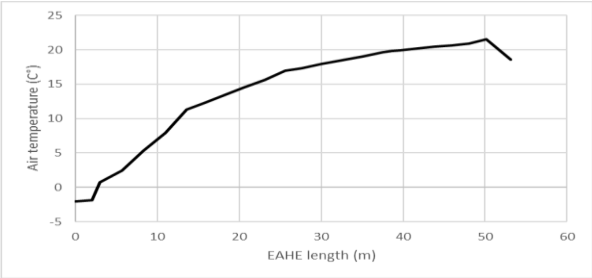


Figure 16. Distribution of air temperature along the length of the earth-air heat exchanger.

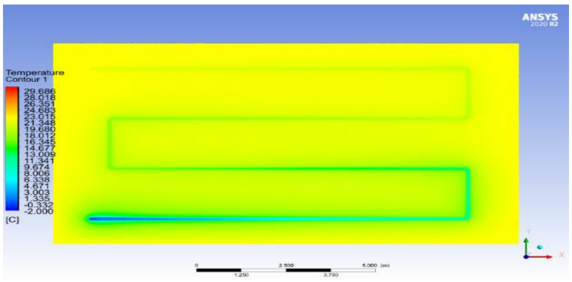


Figure 17. Isothermal contours of soil and the earth-air heat exchanger horizontal Path at 3 m depth.

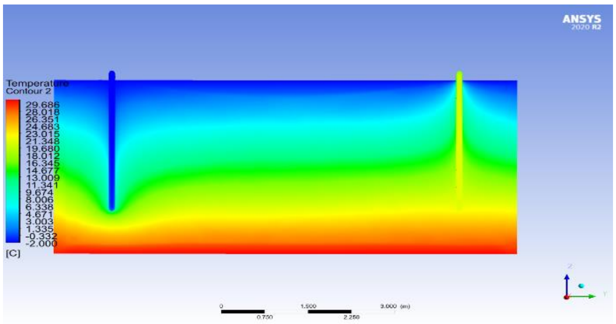


Figure 18. Isotherm contours of soil and vertical path of the earth-air heat exchanger from 0 to 3 m depth.

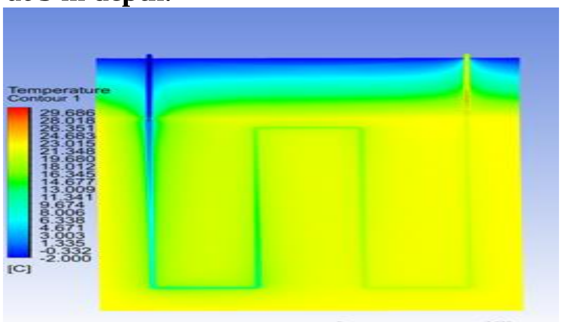


Figure 19. Temperature contours of soil and the earth-air heat exchanger.

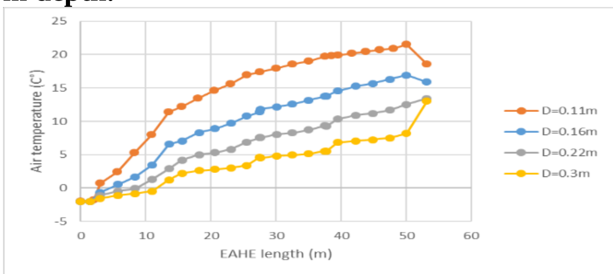


Figure 20. Effect of the pipe's diameter on the earth-air heat exchanger outlet temperature

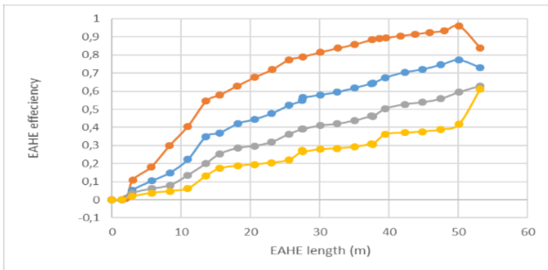


Figure 21. Effect of the pipe's diameter on the earth-air heat exchanger effeciency

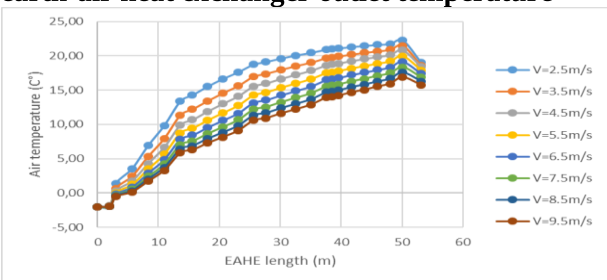


Figure 22. Effect of inlet air velocity on the earth-air heat exchanger outlet temperature.

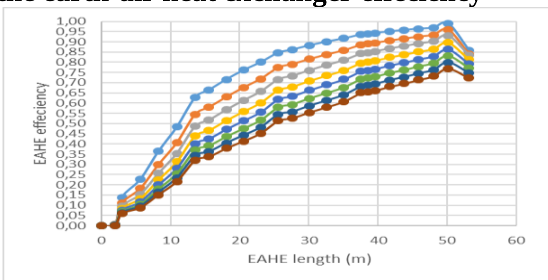
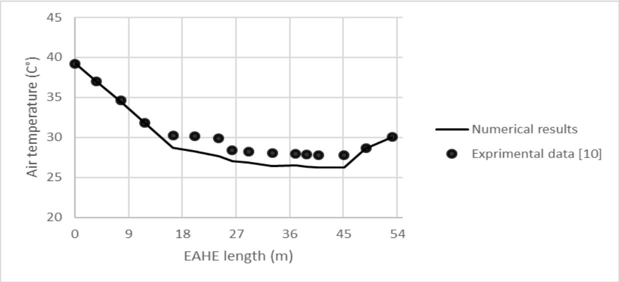


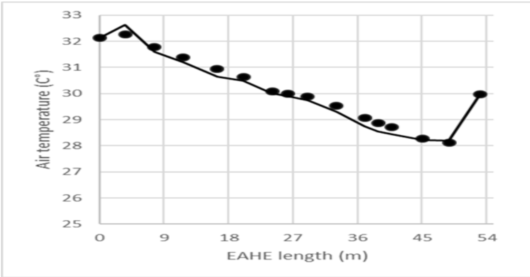
Figure 23. Effect of inlet air velocity on the earth-air heat exchanger efficiency.

4.3. Transient case

To evaluate the EAHE performance over 24 hours, the numerical model was validated against experimental data for various inlet temperatures. It was conducted 20-hour (72,000 seconds) simulations with 1-second time steps and up to 100 iterations per step. The results were compared with experimental data [10]. Figure 24 compares numerical results and experimental data [10] for 3 hours and 20 hours, respectively. The excellent agreement between the results validates our numerical model for continuous operation.



a) 3 hours of calculation



b) 20 hours of calculation

Figure 24. Air temperatures along the the earth-air heat exchanger comparison between numerical results and experimental data

To evaluate the EAHE for continuous operation, data from August 22, 2020, and January 1, 2020, were analyzed each over a 24-hour period. Hourly ambient temperature data was sourced from [20]. Figures 27 and 28 show the ambient air temperatures and the EAHE outlet air temperatures (numerical results) over these periods. The results are summarized as follows:

For both days and at any hour, the EAHE acts as a heating or cooling source depending on the ambient temperature. On the summer day, the ambient temperature peaked at 43°C at 16:00, resulting in an outlet temperature of 26°C, a decrease of 17°C. The lowest ambient temperature was 26.9°C at 07:00, resulting in an outlet temperature of 24°C, a decrease of 2.9°C (Fig. 25). On the winter day, the ambient temperature peaked at 14°C at 14:00, resulting in an outlet temperature of 21°C, an increase of 7°C. The lowest ambient temperature was -2°C at 06:00, resulting in an outlet temperature of 18°C, an increase of 20°C (Fig. 26).

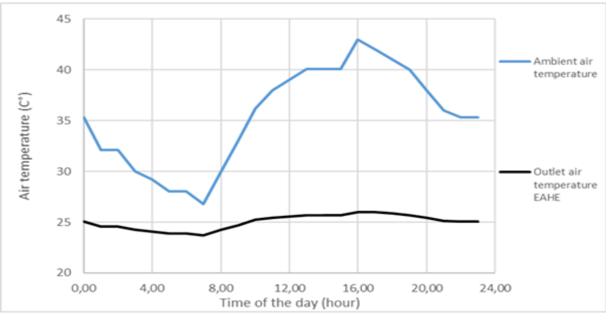


Figure 25. Ambient and the earth-air heat exchanger outlet air temperatures over 24 hours on August 22, 2020

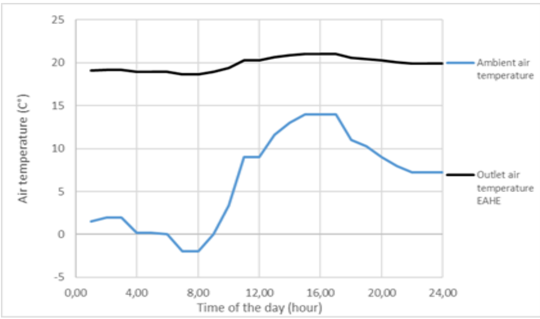


Figure 26. Ambient and the earth-air heat exchanger outlet air temperatures over 24 hours on January 01, 2020

5. Conclusion

Creating and validating a numerical model of an EAHE using ANSYS Fluent 2020R2, with a length of 53.16m at a depth of 3m, and comparing it with experimental data for steady-state and transient conditions, applied to Laghouat city, Algeria, allows us to conclude:

- The comparison between our CFD simulations using ANSYS Fluent and experimental data [9] and [10] for both flow regimes shows a good match. This confirms that our numerical model is reliable under these conditions, providing us with trustworthy results for practical applications using our climatic conditions.
- The ground, with its temperature and thermal inertia, serves as a source for heating and cooling, depending on the season.

- It is noteworthy that increasing the pipe diameter and inlet velocity results in a higher outlet EAHE temperature on summer days. This is primarily due to reduced residence time within the EAHE. The optimal diameter found is 0.11 m, with an inlet velocity of 2.5 m/s, resulting in an outlet temperature of 25°C. This ensures thermal comfort conditions suitable for building applications (taking in consideration ambient temperature of 43°C, and ground temperature of 23°C).
- Similarly, on a winter day with an inlet temperature of -2°C, increasing the pipe diameter and inlet velocity reduces the EAHE outlet temperature. The best results, obtained with an optimal diameter of 0.11 m and inlet velocity of 2.5 m/s, show an outlet temperature of 19°C, which is efficient for heat exchange but may not ensure optimal indoor comfort during winter.
- It is notable that the vertical outlet part of the EAHE decreases and increases the outlet temperature in summer and winter, respectively. It is recommended to insulate it to enhance the efficiency of the EAHE.
- During continuous operation, the EAHE could achieve 85% efficiency for higher temperatures in summer and 84% for lower temperatures in winter, significantly reducing energy consumption. Integration with other heating and cooling sources is strongly recommended for optimal performance.
- One of the recommended applications of EAHE during winter is to use them for heating greenhouses.

Nomenclature

C_p	specific heat [$Jkg^{-1}°C^{-1}$]		*Greek symbols*
D	pipe diameter [m]	λ	thermal conductivity [Wm-1°C^{-1}]
h	convective heat transfer coefficient of the air [Wm^{-2} °C^{-1}]	ρ	Density [kgm^{-3}]
T	Temperature [°C]	μ	viscosity, [$kgm^{-1}s^{-1}$]
u	Air velocity [ms^{-1}]	ϕ	viscous distribution ratio
z	buried pipe depth [m]	ϵ	EAHE efficiency coefficient

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