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EXPERIMENTAL AND HYBRID NUMERICAL ANALYTICAL APPROACH OF AN EARTH-TO-AIR HEAT EXCHANGER

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Abstract

The primary goal of this paper is to assess the thermal behaviour of Earth-to-Air Heat Exchanger (EAHE) under continuous operation mode during the cooling period in warm climatic conditions. An experimental setup was conducted in Biskra University (Algeria) to test the ability to use EAHE as an alternative solution to conventional air conditioning systems. Besides, a transient numerical approach for the flowing air within the EAHE was developed using energy balance equations, discretised by the implicit finite differences method and solved by Thomas method. Furthermore, the transient temperature profile of the soil around the EAHE was investigated in order to determine the adiabatic radius of the soil as a function of the duration of operation. In this context, a transient semi-analytical model was integrated to the air model to estimate the transient EAHE's performance deterioration. This deterioration is produced by the thermal saturation of the soil, which is influenced by the heat released from the air inside the pipe. Results showed that continuous operation for a duration of four days has minimal impact on the outlet air temperatures due to the implementation of night purging. Furthermore, the design and thermal efficiency of the EAHE are impacted by factors such as higher air velocity and reduced soil thermal conductivity.

1. Introduction

Shallow geothermal heat exchangers also named Earth-to-Air heat Exchanger (EAHE) are a type of ground-source heat pump system. The technology of EAHE system involves buried pipes that draw in fresh air from outside and use the ground's temperature to either heat or cool it, depending on the season. The heated/cooled air is then circulated inside the building, reducing the reliance on air conditioning systems that consume a lot of energy. EAHE systems can be installed in a variety of buildings, including homes, offices, and schools. It offer numerous benefits such as reducing energy consumption, decreasing greenhouse gas emissions, improving indoor air quality, and lowering operating costs. Additionally, the system is relatively simple and requires minimal maintenance once installed.

Modelling these systems is important for optimizing their performance and predicting their behavior under different operating conditions. There are two main approaches to modelling shallow geothermal heat exchangers: numerical and analytical. Numerical models use computer simulations to represent the processes of heat transfer in the soil to provide detailed and accurate results. Analytical models, on the other hand, use mathematical equations to provide simpler and quicker solutions. Recently, it exists a significant works in the domain of EAHE's modelling, with a focus on numerical, analytical and hybrid numerical-analytical approaches. Albarghooth et al. [1] discusses the investigation of parameters that affect the EAHE's performance in cooling mode with shallow geothermal energy. The study involved both experimental and numerical analysis to determine the impact of pipe length, soil temperature, diameter of the pipe, soil thermal conductivity, inlet air temperature, and airflow velocity on the EAHE's performance. The findings revealed that saturated soil reduces the length of the pipe by 20% compared to dry soil. In addition, the length required to reach 26°C was 62.1 m, which is 55% greater than the case of 29°C with 39.9 m at an air flow speed of 7 m/s. An equation was developed to assess the temperature of the air within the pipe as a function of soil thermal conductivity, temperature of soil, ambient temperature, pipe length and pipe diameter. The obtained results revealed that the length of pipe occurs the nonlinear behaviour in the equation. Mehdid et al. [2-4] published a series of papers on the thermal designing of EAHE. The first paper introduced a transient semi-analytical model that assesses soil thermal resistance as a function of operation duration [4]. Then, to predict the EAHE's thermal performance under transient conditions in cooling operation, a new semi-analytical approach named Generalized RBM model has been developed. The GRBM model [2, 3] was based on subdividing the soil and pipe into several layers and using the previous model named

RBM to estimate the disturbed soil temperature surrounding the EAHE. To validate the GRBM developed model, the calculated results and experimental measurements at different lengths of the EAHE were compared with a relative error of 2.8% on average. The authors highlighted that the simplicity and analytical aspect of the GRBM approach will allow to improve the EAHE's thermal design while reducing calculation time significantly. Minaei et al. [5, 6] presented a transient state equation to assess the EAHE's thermal performance accurately and efficiently. The model uses Laplacian transform to solve the governing equations for soil temperature around the EAHE and air flow velocity. The EAHE's 3D numerical model is also simulated and validated with the obtained experimental data and analytical model for both time varying and constant inlet temperature, and good agreement is observed. The research investigates the thermal satutation in the soil after 6 and 120 hours of functioning continuously and shows that ignoring soil's thermal saturation can lead to an overestimation of the system's performance. To investigate the impact of soil surrounding the EAHE on its length and thermal performance, a numerical study was conducted by Cuny et al. [7] on six EAHE configurations with varying lengths and types of soil adjacent the pipe. It concluded that adding bentonite to the soil ameliorates the thermal performance of the EAHE, and the pipe length can be shortened while maintaining a specific power output. Belloufi et al. [8] evaluate in continuous operation the EAHE's thermal performance utilizing an experimental setup and a transient theoretical approach. Results showed that low air flow velocity and high soil's thermal conductivity are key factors in achieving high thermal performance. The derating factor ranged from 0% to 35% and ignoring it can lead to misinterpretation of EAHE design. The findings showed that the first 33 meters of pipe can reduce air temperature by 91% and the maximum drop in the temperature of the air can reach up to 19°C. In extreme cases and during night functioning, inlet air temperatures decrease to cool the subsoil and allowing it to recover its cooling capacity. Most models used to assess the EAHE's thermal performance assume that heat equation in the soil around the pipe is modelled in radial direction. However, a new simulation model presented by Hamdane et al. [9] solve the entire axisymmetric heat equation in the soil. The developed model were compared to experimental data from the literature and showed better performance than other models that utilized simplified heat equation in one dimension. Rosa et al. [10] predicted the impact of different parameters, namely the flowing air velocity, pipes diameter, and spacing between tubes on the thermal performance of open-loop EAHE in warm-summer Mediterranean climates. ANSYS-CFX® software is utilized to simulate the EAHE under transient conditions during cooling and heating functioning. The study concludes that a

high air flow velocity affects the thermal performance, primarily during cooling, and that reducing the separation between tubes from 1 m to 0.50 m can reduce land area requirements for EAHE pipes by approximately 50%. Nunes et al. [11] presented an EAHE's analytical-numerical model. The study focused on three performance indicators: minimizing airflow pressure drop, soil volume occupation, and thermal potential. The paper have outlined 26 complex geometries, with a straight duct called Reference Installation as the basis. It was discovered that the soil volume occupied by the EAHE can be reduced to 39% using serpentine configuration with small duct spacing. Furthermore, air pressure drops were reduced by 30% in configurations with fewer curves, and complex designs were suggested for increasing the EAHE's thermal performance. Bahmani and Hakkaki-Fard [12] introduced a new hybrid numerical-analytical approach to evaluate the EAHE's thermal performance. The model is based on the theorem of Duhamel, and adapted the infinite line source technique and the principles of superposition to enable quick and uncomplicated simulation. The model also takes into account thermal interference between adjacent pipes. Benchmark cases are used to evaluate the performance and computational time of the proposed model, the outcomes of the proposed approach are evaluated by comparing them to those obtained from the CFD model. It concluded that the new model accurately predicts the linear EAHE's thermal performance with different pipe arrangements. Additionally, the suggested semi-analytical approach can result in processing times up to 50 times quicker compared to the CFD model

From the literature review above, the current analytical approaches to predict the performance of EAHEs are known for their speed, but their accuracy is often compromised due to various simplifications and assumptions made during the calculations. Conversely, numerical methods are renowned for their precision, but their extensive computational requirements make them a costly option. Given the limitations of both methods, there is a pressing need for a new approach that strikes a balance between accuracy and speed in predicting the performance of EAHEs. This approach must provide a high degree of accuracy while also being able to deliver fast results. Such a method would be useful for researchers looking to optimize EAHE designs and maximize their performance. The present study aims to present a new hybrid numerical-analytical method for the thermal design analysis through the EAHE. Considering a transient semi-analytical model (RBM model) for the transient heat conduction in soil surrounding the pipes allows to consider the soil thermal saturation in the proposed hybrid method. Thus, a one dimensional finite difference model was then developed taking into account the temperature of the soil surrounding the pipe found by the RBM model

to predict the air temperature along the EAHE pipes considering the instantaneous variation in soil temperature. This approach allows to achieve great accuracy in the designing of the EAHE

2. Mathematical calculations

To simplify the mathematical equations, the following hypothesis are considered [2, 13]:

- Heat transfer coefficient by convection is constant along the EAHE.
- Soil has isotropic properties.
- Soil's moisture is vanished.
- Soil temperature is constant away the EAHE.

2.1. Air temperature calculation

The air temperature along the EAHE is governed by the thermal balance equation inside the EAHE (Fig. 1):

$$mc_{pair}\frac{DT_a}{Dt} = q_1 - q_2 - q_3 \tag{1}$$

Where m, c_{pair} and T_a are the mass, specific heat and air temperature respectively.
Eq. (1) yields:

$$mc_{pair}\left(\frac{\partial T_a}{\partial t} + u\frac{\partial T_a}{\partial x}\right) = -\lambda_{air}\, s\frac{\partial T_a}{\partial x}\Big|_{l} + \lambda_{air}\, s\frac{\partial T_a}{\partial x}\Big|_{l+\Delta l} + \frac{(T_{soil}-T_a)}{R_{total}} \tag{2}$$

Where u, T_{soil} and R_{total} is the air flow velocity, undisturbed soil temperature and total thermal resistance respectively.

$$R_{total} = R_{soil} + R_{pipe} + R_{cv} \tag{3}$$

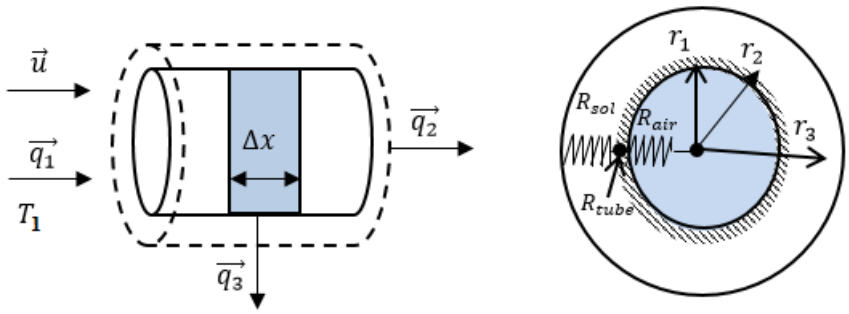


Figure 1. One-dimensional scheme of the EAHE

The pipe's thermal resistance "R_{pipe}" is given as follows:

$$R_{pipe} = \frac{1}{2\pi.\ \lambda_{pipe}.\ \Delta l} ln(r_2/r_1)$$

The air's thermal resistance "R_{air}" is calculated the equation below:

$$R_{cv}=\frac{1}{2\pi\, h\, r_1\, \Delta l}$$

It can calculate the convective heat transfercoefficient h using the following equation:

$$h=(N_u\, k)/(2\, r_1)$$

where $N_u=0.023R_e^{0.8}P_r^{0.3}$ is the Nusselt number [14-16] and $R_e=\rho u/\mu$ is the Reynolds number [16].

The soil's thermal resistance "R_{soil}" is computed as follows:

$$R_{soil}=\frac{1}{2\pi.\ \lambda_{soil}.\ \Delta l}ln(r_s/r_2)$$

where r_s is the soil radius, which is the layer between the undisturbed soil and pipe surface.

Eq. (2) is simplified by incorporating the aforementioned assumptions as follows:

$$\rho s c_{pair}\left(\frac{\partial T_a}{\partial t}+u\frac{\partial T_a}{\partial x}\right)=\frac{(T_{soil}-T_a)}{R_{itotal}} \tag{4}$$

where R_{itotal} is the total thermal resistance of EAHE devided by unit length and s its surface. Thus,

$$\frac{\partial T_a}{\partial t}=-u\frac{\partial T_a}{\partial x}+\frac{(T_{soil}-T_a)}{\gamma} \tag{5}$$

where $\gamma=\rho\,\pi\, r_1^2\, c_{pair}\, R_{itotal}$.

To solve Eq. (5), the following boundary conditions can be used [17-20]:

$$T_a\,(t=0)=T_{soil}$$
$$T_a\,(x=0)=T_1$$

where T_1 is the air temperature at the inlet of the EAHE.

The finite difference method is used to solve Eq. (5), the discretisation of both time and space has been carried out by an implicit scheme (see Fig. 2). For nodes N-1 and up, the centred finite differences method is utilized, however the final node is calculated by using the left differences method. For that, the variables 'x' and 't' are denoted by the indices 'i' and 'k' respectively. The second member of the equation (5) is written the time ($k+1$) where the solution is unknown. Then, this equation in implicit finite differences form can be represented as follows [21]:

$$\frac{1}{\Delta t}\left(T_{i,k+1}-T_{i,k}\right)=-\frac{u}{2\Delta x}\left(T_{i+1,k+1}-T_{i-1,k+1}\right)-\frac{1}{\gamma}T_{i,k+1}+\frac{T_{soil}}{\gamma} \tag{6}$$

After rearranging, it get:

$$T_{i,k}+\frac{\Delta t}{\gamma}T_{soil}=-\frac{u\,\Delta t}{2\Delta x}T_{i-1,k+1}+\left(\frac{\Delta t}{\gamma}+1\right)T_{i,k+1}+\frac{u\,\Delta t}{2\Delta x}T_{i+1,k+1} \tag{7}$$

This equation form was intended for a mesh running from node 2 to node N-1. Furthermore, Eq (5) was subjected to the left finite differences method to calculate the temperature of the air at the outlet of the pipe (final node N) as follows:

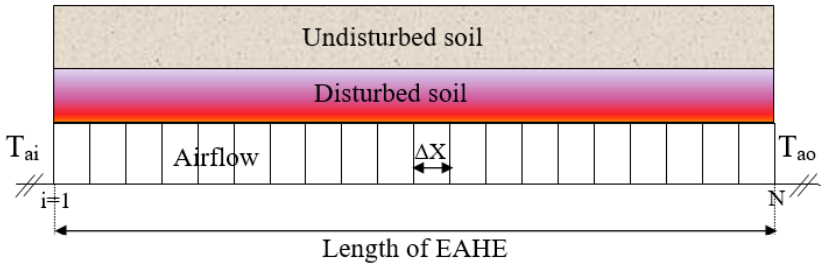


Figure 2. Discretized domain of the EAHE

$$\frac{1}{\Delta t}\left(T_{N,k+1}-T_{N,k}\right)=-\frac{u}{\Delta x}\left(T_{N,k+1}-T_{N-1,k+1}\right)-\frac{1}{\gamma}T_{N,\ k+1}+\frac{T_{soil}}{\gamma} \tag{8}$$

Therefore, the temperature at outlet was expressed as:

$$T_{N,k}+\frac{\Delta t}{\gamma}T_{soil}=-\frac{u\,\Delta t}{\Delta x}T_{N-1,k+1}+\left(\frac{u\,\Delta t}{\Delta x}+\frac{\Delta t}{\gamma}+1\right)T_{N,\ k+1} \tag{9}$$

Thomas method is used to solve Eqs. (7) and (9) in a FORTRAN developed program to predict the transient air temperature.

2.2. Soil radius calculation

Several research studies have investigated the appropriate soil radius (r_s) required for the construction of EAHE, based on the duration of operation [1, 3, 22-24]. These studies have shown that the thermal efficiency of EAHE deteriorates with time because of the heat accumulation in the soil neighbouring the pipelines [3, 22, 23]. Therefore, accurately estimating the thermal resistance of the soil depends on knowing the EAHE's duration of operation.

The study employs equations (10) and (11) from RBM approach, previously presented by Rouag et al. [4], to calculate the soil radius (r_s) required for continuous operation of six hours. The RBM model solves the equation of conduction at the entrance of the EAHE, represented as a hollow cylinder with infinite length, featuring a uniform air heat flux per unit length at $r=r_1$ (Fig. 3). In cylindrical coordinate, the soil temperature is expressed as follow [4]:

$$T_s(r,t) - T_0 = \frac{q}{\pi\lambda_s {r_\infty}^2}\sum_{n=1}^{\infty}\left(\frac{1-e^{-\alpha\beta_n^2 t}}{\beta_n^2}\frac{J_0(\beta_n r)J_0(\beta_n r_1)}{{J_1}^2(\beta_n r_\infty)}\right) \quad (10)$$

Where T_s is the disturbed soil temperature, α is the soil thermal diffusivity, β_n are the positive roots of $J_0(\beta_n r)=0$, J_0, J_1 are the Bessel function of the first kind of the order 0 and the order 1, respectively, and q is the heat flux per unit length which is calculated as:

$$q = \frac{(T_a - T_{soil})}{R_{total}} \quad (11)$$

where R_{total} is the total thermal resistance

On the other hand, when using multiple EAHEs, the computed soil radius r_s is utilized to specify the spacing between EAHEs pipes.

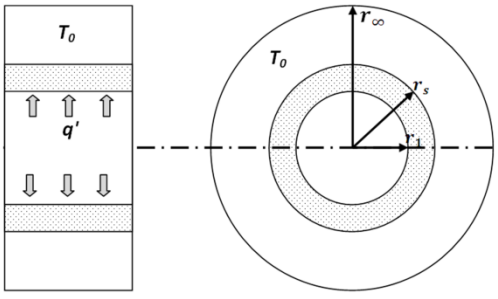


Figure 3. Scheme of the soil neighbouring the pipe [4]

3. Experimental setup

The Earth-to-Air Heat Exchanger is a sustainable cooling system designed to adjust building's air temperature by exploiting the thermal inertia of the soil. Outdoor air is drawn in and directed through an underground pipe system at a well-determined depth along a defined distance (L), where it loses its thermal energy to the surrounding soil. The Mechanical Engineering Laboratory- LGM in the University of Biskra has built an experimental platform of EAHE. Biskra city is located in northeastern Algeria, it has a subtropical desert climate with very hot summer and mild winter. For that, the authors carried out tests on the cooling ability of the air in the summer season. Figure 4 depicts an EAHE made of a PVC tube of a total length of 48 m, buried at 3 m depth in serpentin form, 2% slope and 2 m spacing. The EAHE has been equipped with 15 RTD temperature sensors, which are appropriately positioned (figure 5). Furthermore, these sensors are linked to a data acquisition system provided by National Instrument-NI (figure 6) to assess the air temperature along the EAHE every 15 minutes. A 120W power extractor and a propeller anemometer manage and measure the air flow velocity. Table 1 presents the thermo physical characteristics of the system.



Figure 4. EAHE's experimental platform



Figure 5. Positioning of the air temperature probe within the EAHE



Figure 6. Data acquisitition tool

Table 1. Thermo physical characteristics of the system.

Thermo physical characteristics	Values

Airflow speed (m/s)	3.5
Air's specific heat (J/Kg.°C)	1000
Density of the air (kg/m^3)	1.2
Thermal conductivity of the soil (W/m.°C)	1.25
Thermal conductivity of the tube (W/m.°C)	0.17
Tube's external radius (m)	0.055

4. Results

Figures 7, 8 and 9 show how the air temperature fluctuates on an hourly basis in 08 different EAHE's sections and how the system's continuous functioning affects its thermal performance. It is important to highlight that the air temperatures in sections up to a length of 33 meters, as indicated in these figures, display instability over time because of the influence of varying temperature at the inlet of the EAHE. Furthermore, elevated temperatures cause the build-up of thermal energy in the soil adjacent the EAHE. However, during the night, the temperatures of ambient air decreases as it is mentioned in figure 9, resulting in the cooling of the heated soil in the proximity of the EAHE. This facilitates the restoration of the soil's cooling capacity. At the EAHE's outlet, there is little variation in the temperatures of the air, and the EAHE's thermal efficiency is not significantly affected by heat accumulation. This is because the soil temperature naturally returns to normal during nighttime operation, allowing for self-recovery. According to the statement, the initial 33 meters of the pipe have the capacity to generate an 89% reduction in air temperature. Figure 9 reveal that at the outlet of EAHE, the maximum rise in temperature of the air is 0.85 °C. Furthermore, based on the data, it can be inferred that the continuous mode of operation has no effect on the EAHE's thermal efficiency in the climatic and soil thermophysical conditions of the Biskra region.

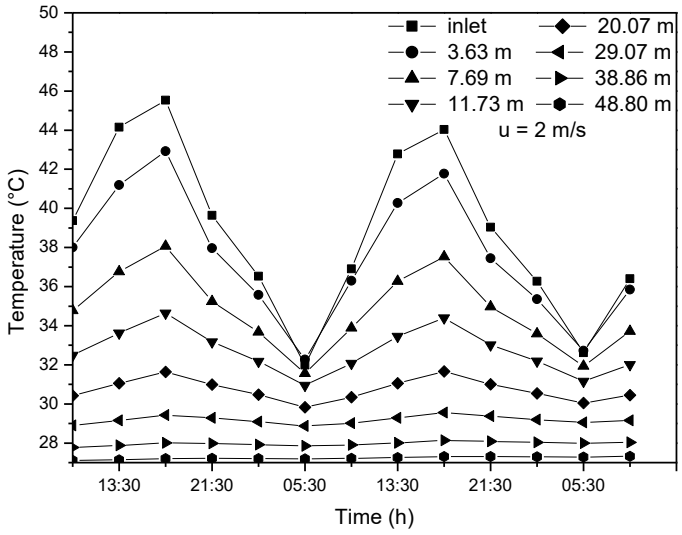


Figure 7. Hourly experimental measurements of air temperature with airflow speed of 2 m/s

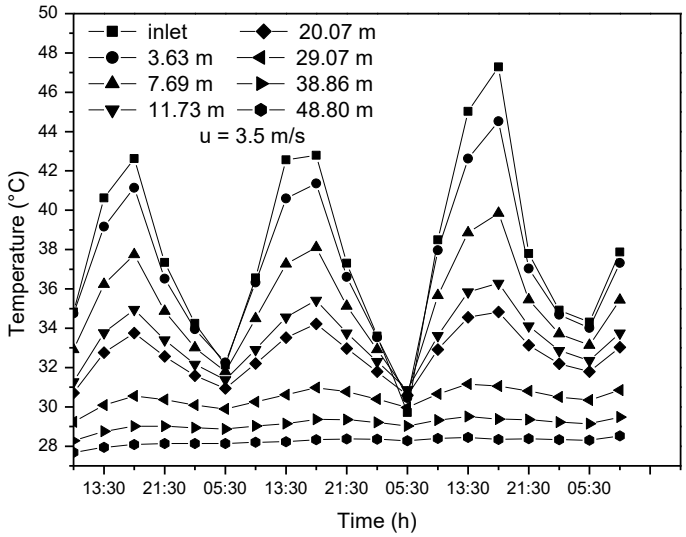


Figure 8. Hourly experimental measurements of air temperature with airflow speed of 3.5 m/s

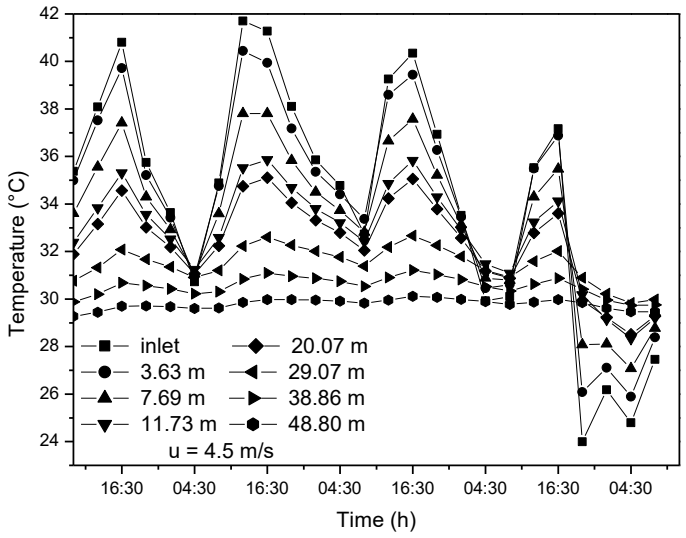


Figure 9. Hourly experimental measurements of air temperature with airflow speed of 4.5 m/s

The validation of the developed transient model was carried out in table 2 using self-experimental data collected at Biskra University. To perform the validation, a 71 hours of continuous operation test of the EAHE and 3.5 m/s of air velocity were selected. The validation results indicate that the mean errors fall within an acceptable range of 0.84, 1,58 and 2.79, which demonstrates a satisfactory agreement between experimental data and developed approach.

Table 2. Validation of the developed approach with experimental measurments.

Length of pipe (m)	After 6 hours			After 54 hours			After 71 hours		
	Num.	Exp.	Error %	Num.	Exp.	Error %	Num.	Exp.	Error %
Inlet	43,56	43,56	0	48,87	48,87	0	37,87	37,87	0
3,63	41,43	41,58	0,35	46,11	44,94	2,60	36,61	37,32	1,90
7,69	38,00	37,71	0,76	41,53	39,34	5,57	34,49	35,43	2,65
11,73	35,43	34,63	2,32	38,09	35,87	6,20	32,90	33,76	2,54
16,04	33,37	33,50	0,37	35,35	34,29	3,10	31,63	33,03	4,23
20,07	31,94	32,33	1,20	33,43	32,95	1,45	30,74	32,30	4,83
24,12	30,85	31,05	0,65	31,97	31,60	1,20	30,07	31,35	4,09
26,37	30,36	30,71	1,13	31,33	31,26	0,20	29,77	31,11	4,32
29,07	29,87	30,33	1,52	30,67	30,82	0,49	29,47	30,85	4,50
33,10	29,29	29,78	1,62	29,90	30,23	1,11	29,11	30,35	4,08
37,01	28,87	29,12	0,87	29,33	29,50	0,58	28,84	29,72	2,93
38,86	28,70	28,87	0,59	29,10	29,25	0,49	28,74	29,48	2,50
40,82	28,55	28,67	0,43	28,90	29,03	0,45	28,65	29,28	2,14
45,10	28,28	28,13	0,52	28,54	28,44	0,34	28,48	28,67	0,66
48,80	28,10	27,99	0,39	28,30	28,29	0,06	28,37	28,52	0,52

Table 3 groups the different data used in the verification. Fig. 10 displays the verification of the developed soil model. This table shows the comparison between the predicted data by the RBM approach and the calculated temperatures of Mathur et al. [22] for different durations of operation and distances from pipe. As shown in fig. 10, the results of the RBM approach verification against the numerical results of Mathur et al. [22] have demonstrated a good agreement between the two with a maximum relative error of 6%. This indicates that the RBM model is reliable and accurately represents the physical phenomenon being modelled. The verification results confirm that the RBM model can be used for further analysis and prediction of the soil temperature of the EAHE system.

Table 3. Thermo physical and geometrical characteristics used in the verification with Mathur et al. [22]

Soil	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m^3)
	0.52	1840	2050
Pipe	Diameter (m)	Surface temperature (°C)	Distance from entrance
	0.1	46.2	10

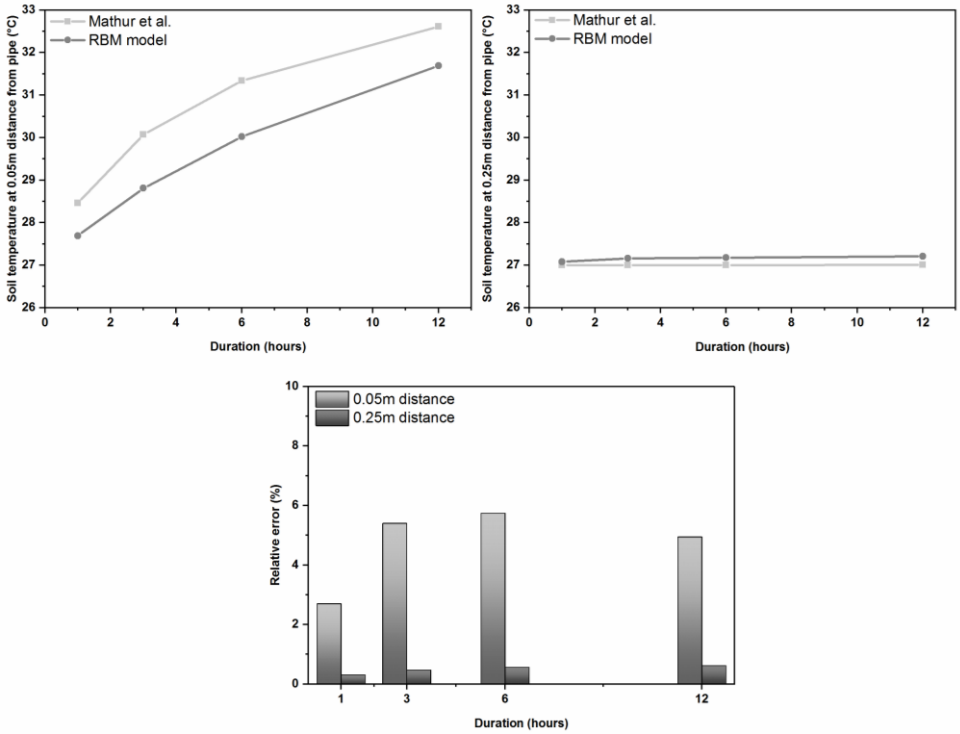


Figure 10. Verification of RBM-estimated soil temperatures with numerical results developed by Mathur et al [22]

The RBM model is applied to assess the radius of the soil in relation to the functioning time of the EAHE in Biskra region of, using Table 11 which provides the soil's thermo physical characteristics and input parameters.

Inlet air temperature T_i affects the EAHE's thermal performance. Thus, extreme operating conditions should be tested to ensure proper system design. In this study, the RBM model predicts the highest degree of decline in thermal performance using the highest temperature ever recorded in the world (T_{air} = 57°C [25]). Figure 11 depicts the heat flux, q, and values of soil radius, rδ, found by the RBM approach as a function of functioning duration. The extent of thermal impact in the soil is linked to the duration of operation, with a direct relationship between the radius and duration. However, an increase in soil radius causes an increase in soil thermal resistance, leading to a decrease in heat dissipated to the adjacent soil and, consequently, a decrease in the performance of the EAHE due to soil accumulation around the tube during continuous functioning. Furthermore, employing transient conditions with uniform heat flux (for every time increment) overestimates the necessary pipe length for maintaining thermal comfort throughout uninterrupted summer operation. In addition, the soil radius presented in Fig. 11 reflect the depth between heat exchangers (case of multiple EAHEs) and, the distance between tubes (case of serpentine-shape heat exchanger), which is not influenced.

Table 4. Different characteristics utilized for the implementation of EAHE in the Biskra area of Algeria.

Soil	Initial temperature (°C)	Diffusivity (m^2/s)	Thermal conductivity (W/m.K)
	20	$2.7x10^{-6}$ [8]	2.5 [8]
Pipe	Inlet temperature (°C)	Diameter (m)	
	57	0.3	

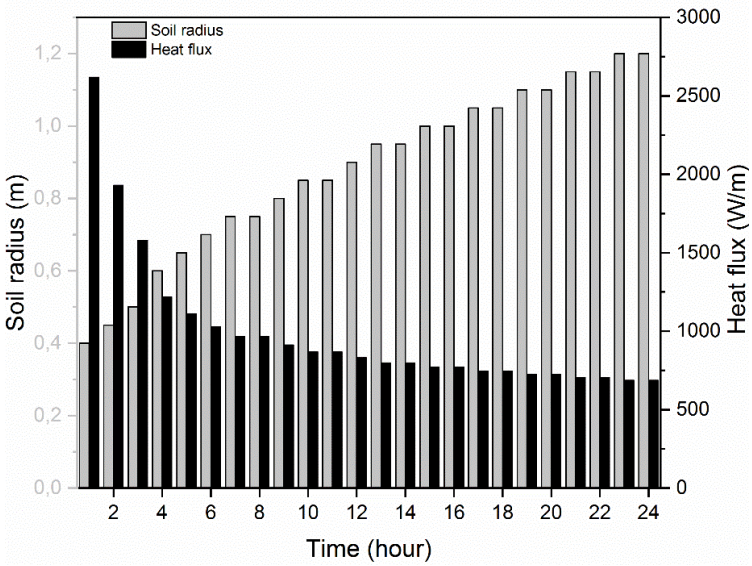


Figure 11. Soil radius rδ used in calculation of the heat flux

Figure 12 presents the distribution of soil temperature surrounding the tube as a function of operating duration at a distance from the tube surface (radius of 0.15 to 0.9). It can be observed that the soil temperature increases for different operating durations. The results from Figure 12 indicate that the increase in soil temperature is faster at the beginning of EAHE operation and gradually decreases along the heat exchanger. The observed temperature increase soil temperature signifies the heat exchange mechanism, which leads to the gradual deterioration in EAHE's thermal performance. Such information is crucial for understanding and optimizing the performance of earth air heat exchange systems.

To investigate EAHE's transient performance, three distinct soil thermal conductivities were employed in table 5 while maintaining a constant pipe diameter of 0.11 m across all thermal conductivities states. From table 5, it noticed that low thermal conductivity hinders the cooling of the air along the pipe. Conversely, the high thermal conductivity makes it possible to evacuate the heat accumulated out of the EAHE and makes it easier for the air to cool down. Hence, to achieve high thermal performance with a reliable cost, it is preferable to install the EAHE in a high soil thermal conductivity. On the other hand, the high constant inlet air

temperature causes the heat buildup within the soil surrounding the EAHE as time elapses, which affecting the thermal efficiency of the EAHE.

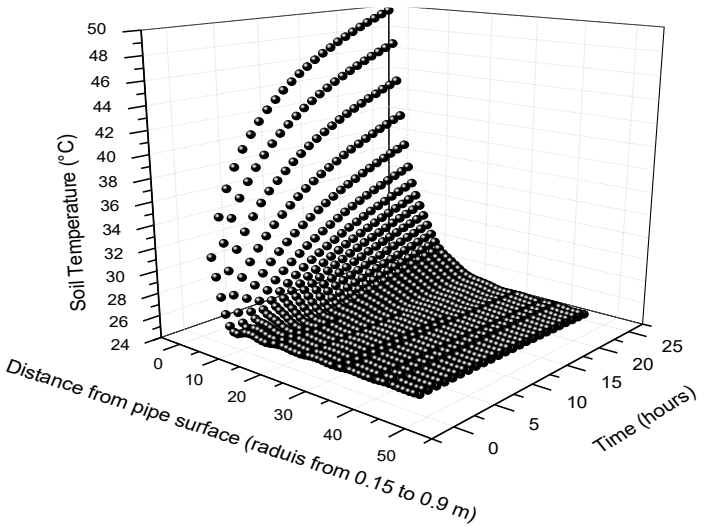


Figure 12. Effect of operating duration on soil temperature

Table 5. Transient air temperature at different sections along the EAHE for different soil thermal conductivities.

Length of pipe (m)	λ_{soil} = 0.5 [W/m.°C]		λ_{soil} = 1.25 [W/m.°C]		λ_{soil} = 4 [W/m.°C]	
	After 6 h	After 24 h	After 6 h	After 24 h	After 6 h	After 24 h
0	48	48	48	48	48	48
3.63	45.46	46.01	44.89	45.35	44.55	44.90
7.69	41.35	42.64	39.96	40.96	38.79	39.39
11.73	38.12	39.85	36.33	37.58	34.84	35.50
16.04	35.41	37.39	33.49	34.81	31.96	32.59
29.07	30.39	32.30	28.84	29.86	27.81	28.18
38.86	28.48	30.04	27.37	28.07	26.74	26.95
48.80	27.38	28.57	26.65	27.10	26.30	26.41

Three distinct air flow velocities after 6 h and 24 h of duration of operation are taken into account in table 6 to elucidate how they impact the EAHE's performance. The diameter's pipe of 0.11 m remained constant across three different flow conditions. In continuous operation mode from 6 h to 24 h, an increase of 0.02, 0.45, and 0.79 m/s are obtained for airflow speed of 1, 3.5, and 5 m/s. Therefore, the increase in air velocity reduces the thermal performance because the air does not have enough time to cool down.

Table 6. Transient air temperature at different sections along the EAHE for different air flow velocities

Length of pipe (m)	u = 1 [m/s]		u = 3.5 [m/s]		u = 5 [m/s]	
	After 6 h	After 24 h	After 6 h	After 24 h	After 6 h	After 24 h
0	48	48	48	48	48	48
3.63	42.74	43.16	44.89	45.35	45.44	45.87
7.69	35.67	36.38	39.96	40.96	41.23	42.21
11.73	31.61	32.30	36.33	37.58	37.94	39.24
16.04	29.13	29.69	33.49	34.81	35.21	36.67
29.07	26.54	26.74	28.84	29.86	30.20	31.55
38.86	26.14	26.22	27.37	28.07	28.33	29.40
48.80	26.04	26.06	26.65	27.10	27.28	28.07

5. Conclusion

In this paper, a Hybrid numerical analytical model was developed for the design of EAHE system. In this model, for the air side, a one dimensional finite differential model is used to investigate the air temperature inside the EAHE's pipes. On the other hand, the soil temperature distribution and soil thermal saturation surrounding the pipe were estimated by using the RBM semi-analytical model developed previously. Therefore, experimental study was performed using the experimental setup installed in the University of Biskra to validate the developed model.

Both numerical and semi-analytical models were validated against temperature measurements of the experimental setup for the air side and numerical results from the literature for the soil side.

Results showed that there is a good agreement between the predicted and compared results for both air and soil models with a maximum relative error of 6%.

The results of the investigation have been examined, leading to the deduction of the subsequent conclusions:

- The developed hybrid model uses variable soil radius over time to give more precision to the thermal design of the EAHE
- The results indicate that the temperature of the soil surrounding the tube increases at varying rates, with a faster rise observed during the initial meters of EAHE, followed by a gradual decrease along the heat exchanger.
- The designing and thermal efficiency of EAHE is affected by increased air velocity.
- According the experimental measurements, the continuous operation mode of 4 days does not affect the outlet air temperatures, thanks to the night purging and significant soil thermal conductivity where the EAHE is installed.

Nomenclature

C_p	Specific heat [J/Kg.°C]
C_p	Specific heat [J/Kg.°C]
h	Convective heat transfer coefficient [W/m^2.°C]
J_0	Bessel function of the first kind of the order 0
J_1	Bessel function of the first kind of the order 1
m	Mass [Kg]
q	Heat flux per unit of length [W/m]
R	Thermal resistance [°C/W]
r_1	Pipe inner radius [m]
r_2	Pipe outer radius [m]
r_3	Undisturbed soil radius [m]
R_i	Thermal resistance per unit length [°C /W.m]
r_s	Soil radius [m]
s	Surface [m]
t	Time [s]
T_1	Air temperature at the inlet of the pipe [°C]
T_a	Air temperature [°C]
T_{soil}	Temperature of the soil [°C]
u	Air velocity [m/s]

Greek symbols

ρ	Density of the air [kg/m^3]
λ_{soil}	Thermal conductivity of the soil [W/m.°C]
α	Thermal diffusivity of the soil [m^2/s]

Abbreviations

EAHE	Earth-to-air heat exchanger

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