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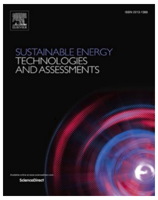

Numerical investigation of serpentine earth-to-air heat exchanger for passive building heating systems by recovery criteria

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ABSTRACT

This paper investigates the performance of the earth-to-air heat exchanger (EAHE) system in the winter for Mashhad. A three-dimensional model of novel serpentine geometry for use in the passive building heating system is proposed. A new and visual method of recovery analysis is performed for regaining the soil energy by considering a period of time to stop the system. The thermal performance of the system is evaluated by analyzing the derating factor, knee point, and heat transfer evaluation criteria for a serpentine model of EAHE. Results demonstrate that the thermal conductivity of the soil and the duration of EAHE's continuous operation has a significant impact on its transient thermal performance. By employing soil thermal conductivities of 1, 2, and 4 W/m.K, the temperature of the outlet reduced 21 %, 12 %, and 6 %, respectively. Finally, the results indicate the highly better performance of the system in soils with higher thermal conductivity during long-term. The temperature of the outlet air in the 24-hours operation mode decreases compared with the 1-hour operation mode. A new method of recovery analysis is performed for regaining soil energy. This paper aims to develop a new model of EAHE system to maximize the energy use of buildings.

Introduction

Based on International Energy Agency, the building sector produced 28 % of global energy-related CO_2 emissions and made up almost one third of total energy consumption worldwide [1]. Employing low-carbon energy sources or clean renewable energies in place of traditional fossil fuels, enhancing human capital, expanding green space, can reduce air pollution [2,3]. The utilization of geothermal energy has become an effective strategy to tackle the current issue. Among different renewable energy sources, Geothermal energy, nonpolluting and accessible, has an important role in thermal applications like space heating [4,5]. Using EAHEs in heating systems has attracted increasing attention in recent decades due to the escalating demand for heating systems in the foreseeable future. EAHE is considered as passive heating. In this system, some pipes are buried underground mostly at the depth of 2–3 m. The pipes absorb heat from the soil (heat source) and transfer it to the outside air (heat exchange) by natural convection to provide the requiems of buildings. Also, this method helps to decrease noise pollution which is social problem these days [6,7].The future cities welcome sustainable solutions despite the fact that there are many ways to reduce greenhouse and air pollution [8,9].

Literature review

Goswami and Dhaliwal [10] used a numerical method for the first time to determine the air temperature of pipe output during the first 24 h of operation. Inalli et al. [11] analyzed ground source heat exchanger systems theoretically. The soil temperature distribution was considered to be bi-dimensional, and the Fourier transformation approach and the finite element method were used to solve the problem. Cooling and preheating by underground buried pipes were carried out with a numerical method. Unlike the previous analyses, which were carried out only considering sensible heat, the sensible and latent energy changes in the pipes were investigated [12]. Chel et al. [5] employed one numerical technique called the "Runge–Kutta" method to solve the energy interaction equation and describe the EAHE system. Another model used by Hollmuller and Lachal [13] to solve the heat transfer equations within

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Nomenclature

C	constant
C_p	specific heat (J/kg K)
d	pipe diameter (m)
DF	derating factor
G	turbulence kinetic energy
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
n	mean velocity (m/s)
p	pressure (Pa)
Q	heat transfer rate (W)
Re	Reynolds number
S	user-defined source term
T	temperature (K)
t	time (s)
u	velocity component in r-direction (m/s)
v	velocity component in θ-direction (m/s)
w	velocity component in z-direction (m/s)
Y	total dissipation

Greeks letters

∂	Prandtl numbers
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)

Subscripts

b	buoyancy
in	inlet
k	mean velocity gradients
L	Length
out	outlet
t	time

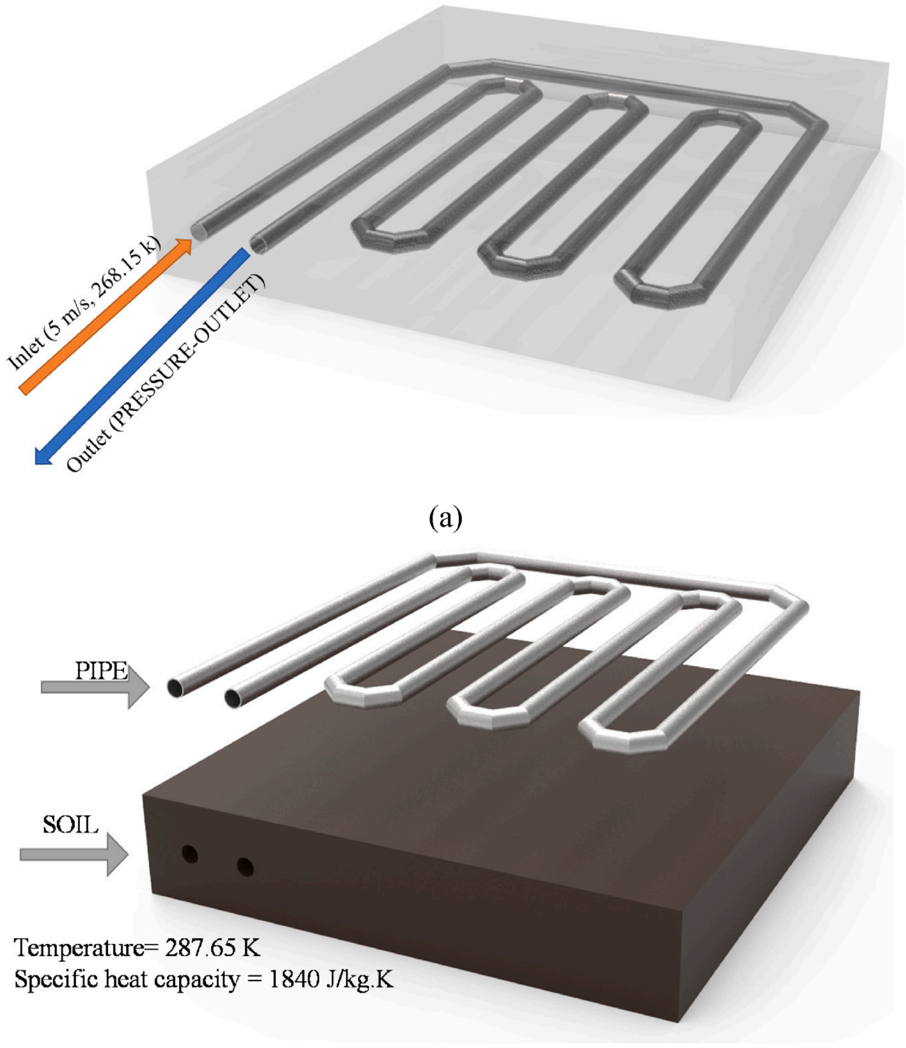
Abbreviations

CFD	computational fluid dynamics
EAHE	earth-to-air heat exchanger
EATHE	earth-to-air thermal heat exchanger
GHE	ground heat exchangers
GSHP	ground source heat pump

the EAHE system was the finite difference method, which is a 3D heat distribution model inflexible boundary conditions. In that model, latent heat and sensible heat exchange are simulated simultaneously. Tittelein et al. [14] introduced a new idea in which the EAHE system is divided into numerous sections. The problem of heat transfer is solved by employing the response factor to decrease the calculation time of each section. Each of the response factors is calculated by the finite element method. Although in that model, a little computational time is required to simulate a pipe in the EAHE system, it is very time-consuming to simulate an EAHE multi-pipe system. Vaz et al. [15] in order to decrease the fossil fuels used for the cooling and heating of the different places proposed a numerical and experimental investigation in southern Brazil for an earth-to-air heat exchanger. The temperature of the earth at various depths and the inlet air, the output, and in the field were calculated by the sensor. Numerical simulation was provided based on computational fluid dynamics by two Gambit and Fluent software package to carry out more extensive analysis on this system. The turbulent flow of air inside the pipe was analyzed by the Reynolds stress model. The temperature of the transient output from the end of the heat exchanger was compared in both experimental and numerical conditions, and it showed a maximum difference of 15 %. The numerical method would give the designer a better perception of thermal behavior in the soil and the fluid flow for a heat exchanger system. This will be very effective in the physical design of these ground source heat exchangers. Hermes et al. [16] numerically investigated the thermal behavior of an EAHE by using the real data of a southern coastal city of Brazil. In this place, by employing the standard penetration tests (SPT), the geotechnical profiles were obtained. The results revealed that the ideal depth for duct placement is 2 m, which has the highest EAHE efficiency in both winter and summer. Bojic et al. [17] were divided the soil into layers whose governing equations are linear for all layers, and then they were solved using the time marching methodology. It deals with the technical performance of the earth-to-air heat exchanger (EAHE) system, which is combined with a building. The results have been shown that the EAHE system is able to supply a part of the daily energy needs of building ventilation. Qi et al. [18] numerically analyzed the effect of humidity caused in greenhouses on the performance of the EAHE system. The impact of inlet air humidity, temperature, and volume flow rate was investigated. Condensation had a negligible effect on airflow distribution but a significant effect on thermal performance, according to the findings. The humid air condensed faster in smaller diameter pipes. As a result, humidity had a significant impact on the performance of the EAHE system and should be taken into account when designing EAHE in greenhouses.

Deglin et al. [19] proposed a 3D non-steady-state heat flow model in order to evaluate the performance of the system in a different type of air velocity and soil. Moreover, the effect of four characteristics of pipes, namely depth, diameter, spacing, and length on the heat transfer rate between ground and airflow were studied. Cui et al. [20] studied the heat exchange in ground heat exchangers (GHEs) using a transient heat conduction model. Furthermore, they extended the finite line source model for considering inclined boreholes. Kabashnikov et al. [21] proposed an analytical model by employing the Fourier integral to predict the heat transfer between the ground and air in the ground heat exchanger systems.

Bansal et al. [22] investigated the thermal performance of an earth-to-air heat exchanger for pipes of different lengths, assuming the impact of soil thermal conductivity and cycles when the EAHE works continuously by using the computational fluid dynamic.it was determined that the characteristics of soil would play an essential role in designing EAHE. Badescu et al. [23] described a two-dimensional numerical transient model which allows us to study the effect of various parameters such as material, depth of the system, and diameter of the pipes. It was illustrated that the efficacy of the system considerably decreased by increasing the external diameter of pipes. Agrawal et al. [24] compared the place of the knee point that occurs in the EAHE system in two dry and wet soil. Givoni et al. [25] considered the EAHEs cooling performances in hot climates. The results demonstrated that the system's potential must be enhanced through the use of various cooling methods such as shading, surface treatment with plants, and surface irrigation. Using computer models, Gan et al. [26] studied the effects of dynamic climate variables and soil conditions such as soil moisture and solar radiation on the EAHE performance. He solved the combined equations of moisture and heat transfer for thermal conductivity, radiation, and evaporation (that influences the soil surface due to climatic changes) in soil boundary conditions. The results showed that the heat transfer rate would change with the system's working period, and the amount would decrease as time passed. Bi et al. [27] investigated the performance and thermodynamic analysis of ground source heat pump (GSHP) for cooling and heating. It was shown that the amount of exergy loss of GSHP for colling is lower than heating mode. Michopoulos et al. [28] analyzed the effects of soil thermophysical characteristics, climatology of the area,



(a)

(b)

Fig. 1. a) EAHE system; b) various layers (pipe, soil, and air).

and building properties such as construction materials, design and the usage of internal parts on the efficiency of GSHP. Yang et al. [29] showed that one of most elements of designing and calculating the ground coupled heat pump is a vertical ground heat exchanger.

Chen et al. [30] numerically simulated the performance of solar assisted ground coupled heat pumps employed for heating the air and water used in a house. TRNSYS was employed by Sagia et al. [31] in order to study the performance of hybrid GSHP. Fayegh et al. [32] illustrated that by using a finite volume numerical model simulated on FLUENT, the Thermal interaction Between multiple vertical ground heat exchangers could be calculated. By comparing the common heating systems, EAHEs show better performance and energy-saving potential [33]. The earth–air–pipe system has attracted attention globally due to using renewable energy [34,35]. Li et al. [36] studied the effect of U-shaped pipes on preparing indoor fresh air. The results illustrated that the heat recovery unit improved the average temperature by more than 85 %. Because of the constant outlet temperature of EAHE, the efficiency of the heat recovery unit was nearly constant. As a result, these types of systems can be widely used in cold areas to cool agricultural greenhouses. Santamouris et al. [37] proposed earth–air–pipe heat exchangers. The possibility of using an earth–air–pipe system as an air condition system with a building with no facility for heating and cooling was calculated by Kumar et al. [38]. They evaluate the ability of the system for cooling a room in India. By employing a single pipe with a length of 80 m, diameter of 0.41 m and airflow velocity inlet of 4.9 m/s, they could keep the temperature of the room at about 27 °C. Amanowicz et al. [39] proposed a multi-pipe heat exchanger to investigate thermal and flow performance in this design. The results indicated that 45° structures might have up to 30 % lower pressure losses than 90° structures.

The possibility of using of earth–air heat exchangers for using in desert climate by was studied Al-Ajmiet al. [40]. Hamidi et al. [41] investigated EAHE in warm places to utilize cooling devices in May and September. The temperature difference between the inlet and outlet was more than 15 °C. The system can be used during the whole summer independently or for pre-cooling. Wei et al. [42]experimentally studied the performance of EAHE in hot and humid conditions. Four different pipes were used to investigate the effect of air temperature, relative humidity, cooling capacity, coefficient of performance, soil thermal response, and recovery rate. In order to measure the potential of earth–air–pipe systems cooling capability Bi et al. [43] used a pipe as a source of a heat pump system.

The potential ability of cooling of earth–air–pipe system was theoretically studied by Sulaiman et al. [44]. Mihalakakou et al. [45] by using TRNSYS, studied the effect ground natural thermal stratification by presenting a numerical model. The concept of “derating factor” was stated by Bansal et al. [22] for the first time in 2013. The results illustrated that the transient thermal performance of the EAHE is

Table 1
Geometrical specifications and material properties [49,50].

Component	Parameter	Unit	Value
Soil	Length	m	5.52
	Width	m	3.9
	Thickness	m	0.4
	Thermal conductivity	W/m.K	1
	Density	kg/m^3	2050
	Specific heat capacity	J/kg.K	1840
Pipe	Outlet diameter	m	0.15
	Space between pipes	m	0.5
	Length	m	45
	Thermal conductivity	W/m.K	16.27
	Density	kg/m^3	8030
	Specific heat capacity	J/kg.K	502.48
Air	Viscosity	kg/(m.s)	0.0000178
	Density	kg/m^3	1.225
	Specific heat capacity	J/kg.K	1006.43
	Thermal conductivity	W/m.K	0.0242
Operating conditions	inlet temperature	K	268.15
	Total mass flow rate	m/s	5
	Soil temperature	K	287.65

considerably influenced by soil conductivity and work-time duration. Shahsavar et al. [46,47] proposed a method for simulation if noise pollution which can be employed to investigate the performance of this system.

This paper aims to develop a new model of EAHE system to maximize the energy use of buildings. To the best of the authors' knowledge, this is the first time that such a model in this working condition is studied. Accordingly, the proposed three-dimension model simulates all layers of the EAHE system with all thermophysical properties as illustrated and explained later in Fig. 1. To improve the previous EAHE system performance, a new model is designed as a novel serpentine form for optimal space use. The performance of the designed EAHE system has been studied in the winter for Mashhad (Iran) in a transient state using the evaluation criteria and in different operating hours considering various soil thermal conductivities. The performance of the designed EAHE system has been validated in different operating hours considering various soil thermal conductivities by an experimental investigation. A new and visual method of recovery analysis which is a crucial part of system operation is studied.

Description of the CFD model

In this section, the heat transfer mechanisms in a earth-to-air thermal heat exchanger (EATHE) module is described and the proposed mathematical modeling along with the thermophysical properties of different parts of the EATHE system is presented. The numerical solution of the governing equations is also discussed.

Physical model

In order to investigate the processes of heat transfer between the airflow and the surrounding soil in an EATHE system, CFD Ansys Fluent software package R17.2 was used in this study. EAHE system is illustrated in Fig. 1. A pipe buries at a depth of 2 m in the soil [48]. It is assumed that the outlet of the buried pipe is integrated into the building while the air enters from the inlet, which is connected to the fresh air.

The geometrical specifications and thermophysical properties and operational conditions of an EATHE system are listed in Table 1.

Materials and methods

In this paper, EAHE systems are designed with steel serpentine pipes. The methods used for analyzing their application are discussed below.

Thermal modeling

In the simulation of an EAHE system, the soil is considered as a solid object through which heat is transmitted by conduction. There is convective heat transfer across the pipe due to the flow of fluid that exchanges heat between the walls of the pipe and the soil. These phenomena are modeled by continuity, energy equations, and momentum. Designed geometry, in other words, the investigated area, includes serpentine air pipes inside the ground and its surrounding soil.

Assumptions

The following assumptions are considered in the present research study:

- physical properties of the soil are considered to be constant, and soil is assumed to be homogeneous [51,52].
- The thickness of the pipe wall and its thermal resistance are not taken into account (due to their ineffectiveness on the performance of the EAHE systems) [53–55].
- The depth for the entire length of the pipe is the effectively horizontal position [56].
- The temperature on the surface of the pipe is the same throughout the experiment because the temperature of the surrounding soil is considered constant at a fixed depth.
- The radiant heat transfer between the inside airflow and the pipe body is ignored [57].
- The inlet air temperature of the EAHE is considered to be the same as ambient temperature [51,55].

Governing equations

The 3-D numerical model used to simulate the heat transfer process for the fluid flow is built on ANSYS Fluent 17.2. The airflow is considered steady, turbulent, and incompressible. The temperature distribution inside the pipe and soil is described by the thermal energy equations, respectively. Continuum, momentum, and energy steady state equations are solved for the fluid inside the pipe.

The equations are given below:

Continuity equation [58]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

x-Momentum equation [59]:

$$\left[u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial x}+\vartheta[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}] \tag{2}$$

y-Momentum equation:

$$\left[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial y}+\vartheta[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}] \tag{3}$$

z-Momentum equation:

$$\left[u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial z}+\vartheta[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}] \tag{4}$$

It is important to.

Reynolds number:

$$Re=\frac{\rho nd}{\mu} \tag{5}$$

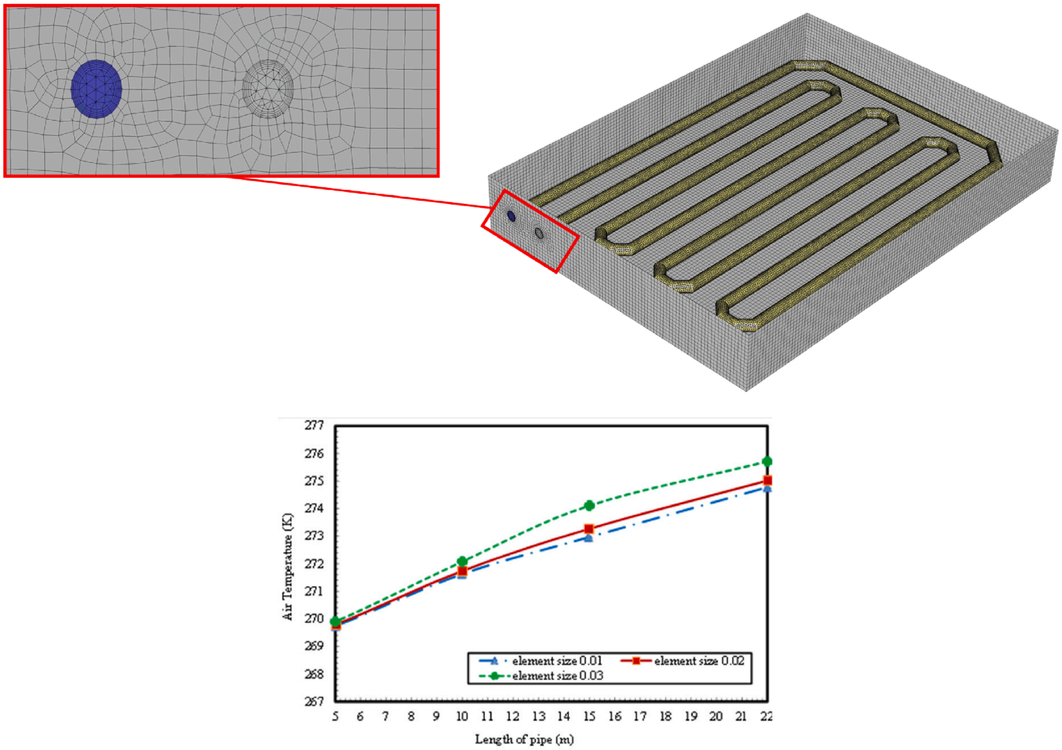
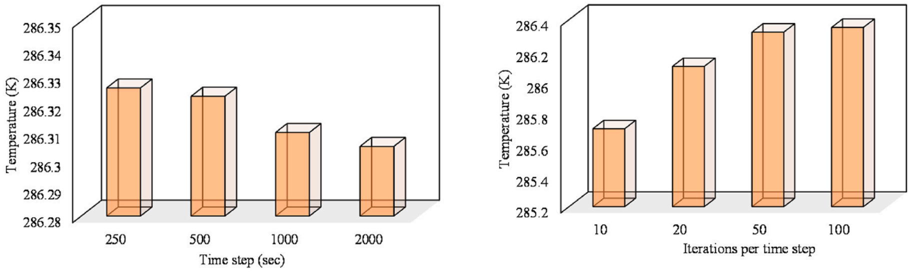


Fig. 2. Grid of EAHE system and its surrounding soil and grid independence test.



(a)

(b)

Fig. 3. (a) Time step independency and *(b)* Iterations independency (per each time step).

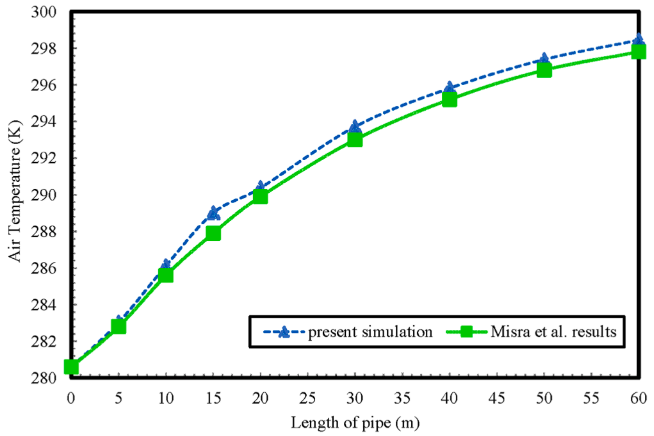


Fig. 4. Comparison between the present study and Misra et al. [60] at 24 h operation of the system.

Where v is the mean velocity of the fluid (m/s), ρ is considered as the density of the fluid (kg/m^3), d is the tube diameter (m), and μ is the dynamic viscosity of the fluid (kg/(m.s)).

Transport equations for the Realizable k- ∊ model [60] can be defined as:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}+G_k+G_b-\rho\epsilon-Y_M+S_K\right. \tag{6}$$

and

$$\frac{\partial}{\partial t}(\rho \epsilon)+\frac{\partial}{\partial x_j}(\rho \epsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \epsilon}{\partial x_j}+\rho C_1 S_\epsilon-\rho C_2\frac{\epsilon^2}{k+\sqrt{v\epsilon}}\right. \\ +C_{1\varepsilon}\frac{\epsilon}{k}C_{3\varepsilon}G_b+S_\epsilon \tag{7}$$

where

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\ \eta=s\frac{k}{\epsilon},\ s=\sqrt{2S_{ij}S_{ij}} \tag{8}$$

In the above equations, G_b shows turbulence kinetic energy

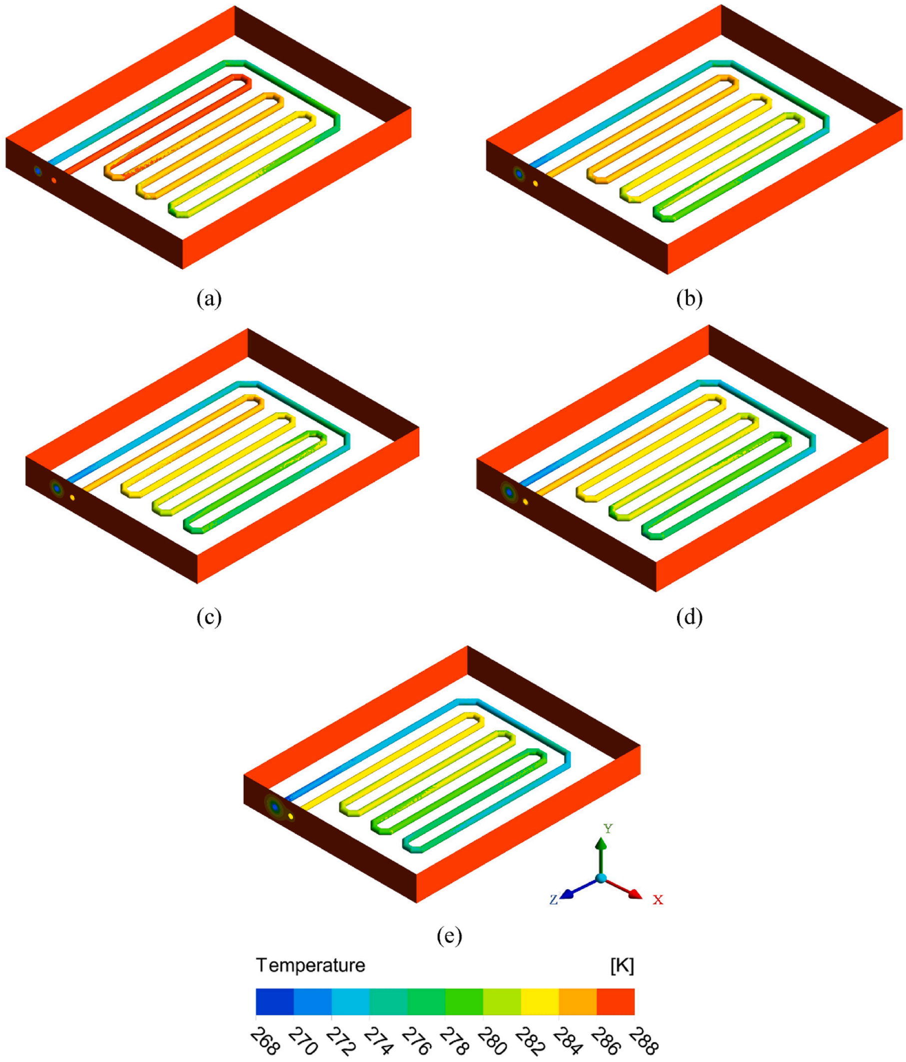

(a) (b) (c) (d) (e)

Fig. 5. Temperature distribution in the EAHE system for various times of operation a) 1 h; b) 4 h; c) 8 h; d) 12 h; e) 24 h.

generation from buoyancy, Y_M represents the fluctuating dilatation contribution to the total dissipation incompressible turbulence, G_k illustrates the turbulence kinetic energy generated from the average velocity gradients, C_1 and C_2 are constants, S_K and S_ϵ are source terms. $\partial\in$ and ∂k are Prandtl numbers for $\in$ and k, respectively. The eddy viscosity is invoked as:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \tag{9}$$

In this equation, constants are $C_{1\in} = 1.44$, $\sigma_\epsilon = 1.2$, $C_2 = 1.9$.

The Derating Factor (DF) is considered as:

$$DF_{L,t} = 1 - \frac{\left(T_{L,t} - T_{in}\right)_{Transient}}{\left(T_{L,t} - T_{in}\right)_{Steady}},\ 0 \le DF \le 1 \tag{10}$$

T is the air temperature, and L, t and in indicate “Length of EAHE”, “time” and “inlet temperature”, respectively.

Energy equation:

$$\left[u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right] = +\alpha\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] \tag{11}$$

According to the above relations, u, v, and w refer to the velocity components in ×, y, and z directions, T and p represent the temperature and pressure of the flowing air.

One of the criteria for assessing the performance of a heat exchanger system for a ground source is the “heat transfer rate” between the air pipes and the surrounding soil. The heat transfer rate relation is given as:

$$Q = \dot{m} C_p \left(T_{out} - T_{in}\right) \tag{12}$$

Q is the rate of heat transfer (W), $\dot{m}$ represents the mass flow rate of air inside the pipe, and C_p is the air specific heat capacity. T_{in}(°C) is the inlet air temperature of EAHE system, T_{out} (°C) is the outlet air temperature of EAHE.

Boundary conditions

For the pipe inlet and outlet flow, boundary conditions of uniform velocity and zero-gauge pressure are considered, respectively. For the soil pipe interface, the boundary condition of a no-slip wall with coupled heat transfer is applied [53,60,61]. The upper and the lowest side of the soil walls are considered to be isothermal with the soil temperature at the buried depth. Furthermore, the sidewalls of soil are supposed to be adiabatic walls (lack of thermal flux) [53,54,60]. This study is conducted to investigate the EAHE performance in winter for the steppe climate and the soil temperature of Mashhad (Iran). The inlet air temperature, which is the same as the ambient air temperature, is considered to be the average of the minimum temperature in January (the coldest month in winter) in Mashhad.

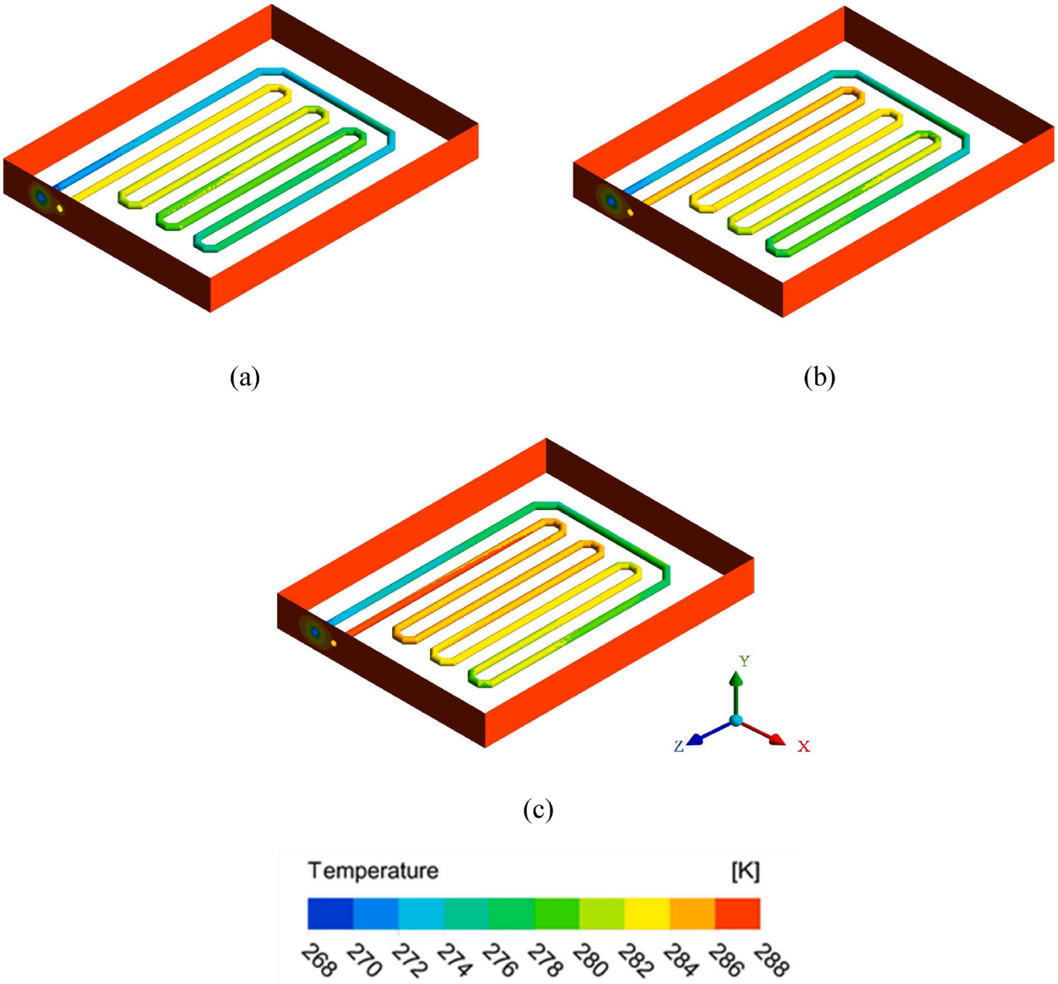


Fig. 6. Temperature distribution in the EAHE system, after 24 hr. of operation for various soil thermal conductivity: a) 1 (W/m.K); b) 2 (W/m.K); c) 4 (W/m.K).

Solution technique

In this paper, the computational fluid dynamics (CFD) software ANSYS-Fluent R17.2, was used to solve the governing equations. The SIMPLE scheme [62] is used for the coupling of pressure-velocity in the segregated solver. Considering the incompressible fluid flow, a pressure-based model was used. In turbulence modeling, the Realizable k-ε model [60] is used in the form of enhanced wall treatment taking thermal effects into account. The transport equations of the realizable k -ε turbulent model [60] is used as reference governing equations. The convergence criteria are set to be 10^{-6} in all variables. The energy equation is activated. A second-order upwind scheme is used to discretize the governing equations.

Grid and time step independency

The independence of the computational grid and time step are examined in Fig. 2. Two regions are modeled, fluid (airflow inside the pipe) and surrounding ground soil as shown in Fig. 2. In this figure, the upper wall is not shown to display the mesh of the pipes. The grid used in the pipe area is smaller than the soil area. Around the pipe's wall, a boundary layer grid was performed because the highest temperature gradient and heat transfer occur at the place of contact between the pipe and the surrounding soil. Finally, the Ansys Fluent software was used to simulate and analysis the designed EAHE system.

In the transient solution, the time step has a considerable effect on the convergence rate. On the other hand, unreasonable minimization of the time step is not only effective in solving the problem but also slows down the solution speed. Accordingly, as reported in Fig. 3.a, the time step of 1000 s is selected for transient simulation due to the lack of change in the pipe output temperature at the specified time steps.

Validation of the CFD model

The validation of the numerical solution is presented. For simulation validation, the results are compared with experimental results and the results of Misra et al. [60] in Fig. 4.

Results & discussion

In this study, the ground source heat exchanger is examined in the transient state. This means that system performance is evaluated over different periods of operation after the start of the system. In this analysis, the performance of the system at 1, 4, 8, 12, and, 24 h after the start of operation is fully investigated using the evaluation criteria.

Performance of EAHE at different operating hours

In Fig. 5, temperature distribution in the EAHE system is shown for various times of operation (1 h, 4 h, 8 h, 12 h, and 24 h operation of the system). As system operation time rises, the soil around the pipes is more affected by buried air pipes, and its temperature is reduced, which decreases system performance, as shown in Fig. 5; This consequently reduces the system's air outlet temperature, which occurs due to loss of

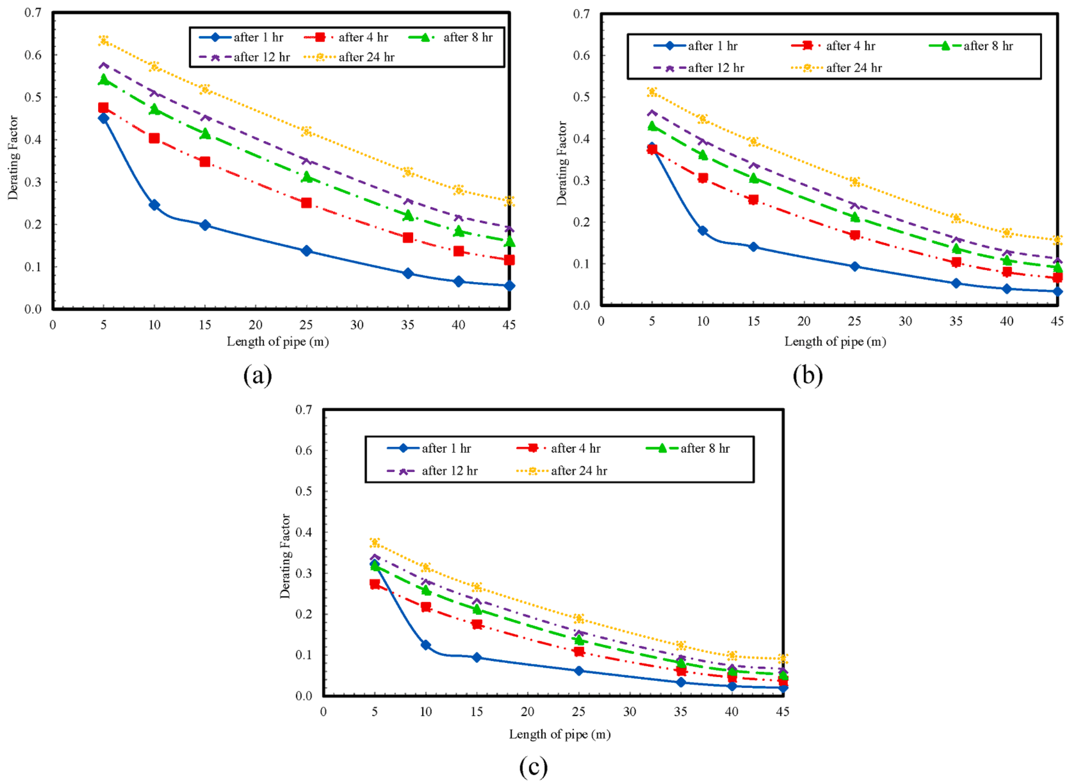


Fig. 7. Derating factor along the EAHE length at different operating times; Soil thermal conductivity: (a) 1 (W/m.K), (b) 2 (W/m.K), and (c) 4 (W/m.K).

energy and temperature of soil over the operating time which is the result of energy transfer from soil to the air inside the pipes.

Effects of soil thermal conductivity on serpentine EAHE

As it is illustrated in Fig. 6, the higher the soil thermal conductivity is, the less the soil near the pipe is affected by the passing air, which causes an increase in the air outlet temperature. Generally, higher soil thermal conductivity results in a higher heat transfer rate to the air inside the pipe, and low effectiveness of buried pipes. All these are due to the much better ability of the soil with higher thermal conductivity to transfer soil thermal energy into the air inside the pipes.

By raising the thermal conductivity coefficient of the soil, the heat transfer rate of the system increases and its performance improves. On the other hand, with the rise in the operating time of the system, the rate of heat transfer decreases because of the decrease in temperature and energy of the surrounding soil. The range of this decrease is different for various soil thermal conductivities. For example, the heat transfer rate difference between the 1 h and 24-hour operation of the system in terms of thermal conductivities of 1, 2, and, 4 for the soil is 401, 249, and, 157 Watts, respectively. The results show that the higher the soil thermal conductivity is, the lower decrease occurs in heat transfer rate in longer operating times, which shows the very positive effect of soil thermal conductivity on system performance in long-term operation due to investigation based on the steppe climate of Mashhad and its soil temperature (using a novel serpentine geometry for EAHE).

Recovery analysis and derating factor analysis

This section examines the effect of recovery and system operating time on the EAHE system operation with a new method, including visuals. The fundamental problem of continuous use of the EAHE system is the reduction of performance due to thermal saturation of soil, and reduction of the surrounding soil temperature due to interaction with cold air pipes.

The Knee Point is a concept for evaluating the effective length of pipe for maximum use of soil energy. The place of knee point demonstrates the length of EAHE at which about 90 % of the increase in air temperature is obtained, which is entirely satisfactory.

The derating factor is an excellent guide for checking the efficiency of the ground source heat exchanger system in a transient state. It converts the temperatures obtained along the length of the pipe into numbers between zero and one, regardless of their range, which enables a comparison of system performance in different states along the pipe length with ease.

The derating factor presents a remarkable comparison between the thermal performance of the ground source heat exchanger operating under a steady state, considering that the pipe surrounded by the soil of EAHE is at constant temperature and transient conditions. In Fig. 7, the derating factor in different sections along the pipe length at different operating hours is presented for soil thermal conductivity coefficients of 1, 2, and 4 W/m.K, respectively. Meanwhile, the derating factor increases by the rise in operating time, which is due to the effect of cold air passing through the buried pipes on soil and the reduction of soil temperature and energy during higher operating hours.

Conclusions

In this study, to improve serpentine earth-to-air heat exchanger (EAHE) system performance, a new geometry for maximizing energy use is introduced as a novel serpentine form. Climate and soil temperature of Mashhad (Iran) is used in this study. A new and visual method of recovery analysis is performed for regaining the soil energy by considering a period of time to stop the system. This research presents a transient analysis of EAHE for the passive house heating system simulated using the Computational Fluid Dynamics (CFD) software package.

System performance has been fully evaluated at various times of 1, 4, 8, 12, and 24-hours operation, using the “derating factor“, ”knee point“ and ”heat transfer rate“ evaluation criteria for a serpentine model of EAHE to analyze the optimized length in each state. The results show that the surrounding soil temperature decreases during operation time, which causes a decrease in the outlet air temperature. The outlet air temperature decreases in the 24 h operation mode compared to the 1-hour operation mode of the system for soils with thermal conductivities of 1, 2, and 4 W/m.K is observed to be 21 %, 12 %, and 6 % (3.84, 2.37, and 1.37 K), respectively, indicating the highly better performance of the system in soils with higher thermal conductivity during long-term operation.

A new and visual method of recovery analysis which is a crucial part of system operation is performed for regaining the soil energy by considering a period of time to stop the system operation. Eventually, 8 h of operation in a day was determined to be the best mode in terms of both operation and soil energy recovery. Generally, by increasing the operation hours, the place of the knee point moves downstream for all types of soils studied. The derating factor also increases, which is due to the reduction of soil temperature and energy in higher operating hours.

As the final analysis, the novel designed serpentine geometry of EAHE led to a good performance of the system and it showed applicability to the steppe climate of Mashhad and similar climates around the world with consideration of the new and visual method of recovery presented in this paper.

This paper aims to develop a new model of EAHE system to maximize the energy use of buildings. Further research can be done in cooling systems, other cities, and new geometries. Moreover, the limitations of this research which is new technology are that it is not used in many countries, and also experimental equipment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

No data was used for the research described in the article.

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