Numerical analysis of the efficiency of earth to air heat exchange systems in cold and hot-arid climates

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Abstract

In order to examine and compare the efficiency of earth to air heat exchanger (EAHE) systems in hot-arid (Yazd) and cold (Hamadan) climates in Iran a steady state model was developed to evaluate the impact of various parameters including inlet air temperatures, pipe lengths and ground temperatures on the cooling and heating potential of EAHEs in both climates. The results demonstrated the ability of the system to not only improve the average temperature and decrease the temperature fluctuation of the outlet air temperature of EAHE, but also to trigger considerable energy saving. It was found that in both climates, the system is highly utilized for pre-heating, and its usage is unfeasible in certain periods throughout the year. In winter, EAHEs have the potential of increasing the air temperature in the range of 0.2-11.2°C and 0.1-17.2°C for Yazd and Hamadan, respectively. However, in summer, the system decreases the air temperature for the aforementioned cities in the range of 1.3-11.4°C and 5.7-11.1°C, respectively. The system ascertains to be more efficient in the hot-arid climate of Yazd, where it can be used on 294 days of the year, leading to 50.1-63.6% energy saving, when compared to the cold climate of Hamadan, where it can be used on 225 days of the year resulting in a reduction of energy consumption by 24.5-47.9%.

Keywords: Earth-air heat exchangers, Buried pipes, Hot-arid climates, Cold climates, Energy efficiency, Cooling/heating potential.

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Nomenclature	Description
$t_{a,out}$	Outlet air temperate or temperature of air coming out of pipe (°C).
t_{ground}	Ground temperature (°C).
$t_{a,in}$	I air temperate or temperature of air entering into the pipe (°C).
t_s	Average temperature of the soil surface(°C).
t_{amp}	Amplitude of the soil temperature(°C).
m_{air}	Rate of air mass flow through the EAHE pipe (kg/s).
C_{air}	Air specific heat capacity at constant pressure (kJ/kg K).
L	Horizontal EAHE pipe length (m).
R_{total}	Total thermal pipe resistance (m ² °C/W).
R_{conv}	Thermal convective resistance between the airflow and the inner pipe surface(m ² °C/W).
R_{cond}	Thermal conductive resistance of the pipe (m ² °C/W).
R_{ground}	Thermal resistance between the outer pipe surface and the ground (m ² °C/W).
$D_{in,pipe}$	Inner diameter of pipe (m).
$D_{out,pipe}$	Outer diameter of pipe (m).
k_{pipe}	Thermal conductivity of pipe (W/m°C).
k_{ground}	Average ground thermal conductivity (W/m°C).
$d_{constant}$	Distance between the pipe surface and the undisturbed ground(m).
h_c	Convection coefficient of the airflow(W/m ² °C).
Nu, Re, Pr	Nusselt, Reynolds and Prandtl numbers.
λ_{air}	Thermal conductivity of air (W/m°C).
r_i	Inner radius of pipe (m).
$V_{a,p}$	Air speed in the pipe (m/s).
v_{air}	Air kinematic viscosity (m ² /s).
μ_{air}	Dynamic viscosity of air (kg/m s).
ρ_{air}	Air density(kg/m ³).
C_{air}	Heat capacity of air(J/Kg·°C)
ρ_{ground}	Soil density(kg/m ³).
C_{ground}	Specific heat capacity of soil (J/Kg·°C)
V	Volume of air (m ³).
Q	Cooling/Heating potential by $t_{a,out}$ (kWh).
z	the depth from the surface in meters
α_s	Soil thermal diffusivity(m ² /day)
n	The number of target day counting from 31 Dec.
n_o	The number of the coldest day of the year counting from 31 Dec.

1.Introduction

In recent years, the building sector has been responsible for about 40% of the world energy consumption [1]. Buildings also contribute to more than 36% of the world total CO₂ emission [2]; a share which is predicted to surge with further population growth, industrial development, and the amelioration of residential thermal comfort [3]. In developed countries, approximately 10-20% of the total energy consumption in buildings is due to the use of HVAC systems, while this ratio reaches to about 50% in developing countries [4]. In Iran, the building industry has been responsible for approximately 34% of the total energy consumption [5]. Additionally, the highest amount of energy demand in buildings is related to the HVAC systems with around 61% [6]. Thus, in order to reduce energy demand in buildings the need for further use of such methods as passive techniques, renewable energies and designing energy efficient buildings is growing [7].

Using ground cooling and heating is a well-known method of reducing building energy consumption and increasing thermal comfort [8] which optimizes the high thermal capacity of the soil and low-temperature fluctuations below the ground surface for cooling in summers and heating in winters [9]. This potential can be exploited through two main strategies: i) Direct Contact, in which all or some part of the building envelope is built into the ground to reduce the heat exchange with the outside [10], and ii) Indirect Contact, in which such fluids as air pass through buried pipes and exchange heat with the ground, and then pass through the building or HVAC systems to cool or heat the space and reduce the energy demand for the building [11]. The two methods are illustrated in Fig. 1.

Fig. 1. Two strategies using earth temperatures, (a): Indirect contact, (b): Direct Contact

The earth to air heat exchange is a method for indirect utilization of ground temperatures for reducing the cooling/heating load [12]. In this method, energy transfer between the air and soil augments the outlet air temperature in winter and decreases it in summer [13]. The amount of heat transfer between the air and ground, and the performance of the EAHE systems depends on several factors such as the thermal properties of the soil and pipes, the air flow rate, the inlet air temperature, the pipe length, diameter and the depth of buried pipes [14].

Research has shown, this system has brought about up to a 20-30% improvement in the comfort conditions and up to a 22°C reduction in the outlet air temperature of office buildings [15]. Studies have shown that the use of this system can result in up to a 74.6 kWh daily cooling capacity [16].

1 A numerical study on an EAHE system with a pipe length of 80m in Mathura in India has shown
2 that this system can create 456 kWh cooling potential in summer and 296 kWh heating potential
3 in winter and maintain the indoor air temperature at about 27.65°C [17]. A study on the
4 performance of EAHEs in the hot-arid climate of Kuwait has shown that the use of EAHE reduced
5 the peak cooling load of the typical buildings by 30% in summer and cause indoor temperature
6 reduction of 2.8 °C during peak hours [18]. Ralegaonkar et al. [19] compared EAHEs with
7 conventional cooling systems were found that EAHEs save 90% electricity and 100% water in
8 comparison with air conditioners and evaporative coolers, respectively. Mathur et al. [20]
9 investigated EAHE performance for three different soil conditions, and concluded that higher
10 thermal conductivity accompanies higher thermal performance. Ahmed et al. [21] examined the
11 impact of different parameters such as pipe lengths, diameters, thicknesses, materials, depths, as
12 well as air velocity on the thermal performance of EAHEs for the humid subtropical climate of
13 Australia. They found that pipes with smaller diameters and thicknesses result in a higher cooling
14 performance. It is also concluded that EAHEs with a 60 m pipe length and 1.5 m/s air velocity
15 have the maximum performance. Gallero et al. [22] developed a new simple model to evaluate
16 thermal behavior of single U-tube ground heat exchangers and validated it against experimental
17 data with 0.3% relative error.

18 The performance of EAHEs have been widely analyzed by numerical methods, experimental
19 studies, and simulations using computational software. Rodrigues et al. [23] used the numerical
20 method to find the impact of different geometrical configurations on EAHE performance. They
21 found that an increase of duct number (complexity of geometry) leads to higher EAHE
22 performance. Khabbaz et al. [24] conducted an experimental and numerical study on the cooling
23 performance of EAHEs with three parallel PVC of 72 m length, as well as a pipe with 0.15 m inner
24 diameter connected to a residential building in a hot-dry climate. Results showed that EAHEs have
25 the potential for reducing cooling loads for one and three pipes 58 W/m² and 55 W/m²,
26 respectively. Misra et al. [25] examined EAHEs performance using Fluent software. In this
27 research, the CFD method was used to simulate the air flow, heat transfer process, and thermal
28 conductivity of the soil in an EAHE system. The modeled EAHE decreased the air temperature
29 under the steady state and transient condition by approximately 18.8°C and 18.7-16.6°C,
30 respectively. Chel and Tiwari [26] studied EAHEs performance integrated with a masonry room.
31 They employed MATLAB software to solve the heat balance equations of buildings, founding that
32 the room air temperature during summer is lower than the ambient air temperature, although it is
33 around 5 °C – 15 °C higher than during winter periods. Mihalakakou et al. [27] developed a
34 numerical model inside TRNSYS, and by virtue of that they calculated the humidity variation of
35 the soil and air.

36 EAHEs can be utilized coupled with other passive techniques to improve their heating or cooling
37 performance, thereby achieving a desirable efficiency. Bansal et al. [28] studied EAHEs assisted
38 with evaporative cooling to improve the cooling potential of EAHEs. Results revealed that the
39 evaporative cooling system enhances EAHE performance; albeit it is uneconomical. Maerefat and
40 Haghighi [29] and Yu et al. [30] studied the integration of solar chimneys with EAHEs which
41 resulted in improving the natural air velocity through the pipe without any need for electricity.
42 Benhammou et al. [31] combined EAHEs with wind catchers. According to this research, the
43 cooling potential of wind catchers coupled with EAHEs is higher than traditional wind catchers

1 with wet surface. Rodrigues and Gillott [32] studied EAHEs to discharge the stored heat of phase
2 change materials (PCMs). Results showed that the combination of PCMs with EAHEs reduces
3 temperature fluctuations in the room by around 47%. Jakhar et al. [33] combined a solar air heating
4 duct and EAHEs in hot-arid climates. This research reported an increase in coefficient of
5 performance (COP) of EAHE systems by 3.73-4.57 in winter, resulting in a 1.1-3.5°C rise in
6 interior temperatures.

7 Due to different performance of EAHEs under various climate conditions, several research has
8 been conducted to evaluate the cooling and heating potential of this system in different climates.
9 Serageldin et al. [34] studied on heating and cooling potential of EAHEs in Egypt. According to
10 the results, the increase of pipe diameter from 2 to 3 in and the air velocity from 1 to 3 m/s
11 decreases performance of EAHEs. Ozenger [35] investigated the heating potential of EAHEs to
12 find an optimal design of a greenhouse heating system for the city of Izmir in Turkey, founding
13 that the exergy of EAHEs is 89.25% and blower and underground tunnel are major exergy
14 destructors. Xamán et al. [36] presented EAHE performances for three cities in Mexico. The
15 modeled EAHE provided 17.4 °C cooling potential in Juárez (extreme weather), 10.2 °C in Mérida
16 (hot weather) and 10 °C in México City (mild weather), as well as 6.3 °C, 12.5 °C and 3.2 °C
17 heating potential, respectively. Do et al. [37] studied the cooling energy saving of a closed-loop
18 EAHE in the hot and humid climate of Texas in the USA, and found that EAHEs could reduce the
19 cooling energy demand for Huston and Dallas around 9.6% and 13.8%, respectively. Bisoniya et
20 al. [38] studied the heating/cooling potential of EAHEs for hot and dry climate of Bhopal in India.
21 According to their research, using EAHEs leads to 9.6-13.8% energy saving over a year.
22 Abbaspour Fard et al. [39] conducted an experimental study to investigate the cooling performance
23 of EAHEs for the semi-arid climates of Iran. The impacts of air velocity, length, diameter, depth
24 and material of duct on the cooling performance of EAHEs were all examined.

25 Although EAHEs have been an extensively studied research subject, literature lacks any major
26 research into comparing their potential for cooling, heating, pre-cooling and pre-heating. The
27 purpose of doing this research is to conduct a numerical study for EAHE performance in two
28 different climates, hot-dry (Yazd) and cold (Hamadan) to have better an understanding the
29 potential of EAHEs for cooling, heating proposes. However, the main contribution of this research
30 is the examination and comparison of EAHEs performance for two different climates in Iran. The
31 rest of this paper is organized as follows: In Section 2, the method and material is presented;
32 Section 3 describes the geographical characteristics of Hamadan and Yazd; in Section 4, materials
33 and methods are discussed in detail. The mathematical model is validated in Section 5, and results
34 are presented in Section 6. Finally, a conclusion is drawn in Section 7.

36 **2. Method and material**

37 In this study, the methodology is designed based on mathematical modeling of the EAHEs in order
38 to understand the system performance under different ambient air temperatures. For two different
39 cities, MATLAB software is employed to develop a numerical model for the desired EAHE
40 system. To develop this model, first the soil temperature at various depths is calculated to find the

optimal depth for the pipes. Then the mathematical model of the EAHE system is designed. It is imperative to note that the proposed EAHE in this paper is modeled as three coupled heat transfer processes, namely, the convection heat transfer between the air flowing in the pipe and the inner surface of the pipe, conduction heat transfer between the inner and outdoor surface of the, and the conduction heat transfer between the outer surface of the pipe and soil.

To achieve the research objective, the hourly weather information for the two cities, gathered from synoptic stations (see Table 1), is applied to obtain the exit air temperature delivered through pipe outlet. Furthermore, the amount of heat transfer along the pipe between air and soil for both hot-dry and cold climates is analyzed. In this paper, performance of modeled EAHE for cooling and heating is compared and calculated. The number of days that EAHE systems can be used for cooling/heating/pre-cooling/pre-heating, and the average monthly energy saving of the system are presented. Fig. 2 illustrates a schematic diagram of the described stages.

Fig. 2. Schematic Steps to the numerical evaluation of the EAHE performance in Yazd and Hamadan

3. Climate description

Yazd; located at (31°54' N, 54°24' E), has a hot-arid climate with low humidity, which results in high diurnal temperature fluctuations; however, Hamadan (34°47' N, 48°30' E) has a cold climate [40, 41]. Climatic characteristics of these cities are presented in Table 1.

Table 1

The main meteorological parameters of Yazd and Hamadan (2002–2012) [42, 43].

City		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
YAZD	Max Temperature (°c)	12.8	17.1	22.8	27.6	33.5	38.4	40.5	38.8	35.0	29.3	20.2	14.2
	Average Temperature (°c)	6.8	11.2	15.7	20.7	26.4	31.1	33.4	31.2	27.1	21.6	13.5	8.0
	Min Temperature (°c)	0.8	4.0	8.6	13.8	19.3	23.8	26.2	23.7	19.2	14.0	6.9	1.7
HAMEDAN	Max Temperature (°c)	1.2	6.3	13.3	16.7	22.5	28.4	30.7	28.8	25.6	20.7	11.8	6
	Average Temperature (°c)	-3.1	1.1	7.1	11.5	16.1	21.8	25.4	24.7	19.8	14.0	5.7	0.7
	Min Temperature (°c)	-11.3	-5.3	-1.45	2.5	6.6	10.6	13.6	12.7	8.7	4.55	-2.2	-6.9

4. Mathematical modeling of EAHE

In this research, the EAHE system has an open loop circulation, and the buried pipe is made of high-density polyethylene with a conductivity of 0.50 W/m°C. The buried pipe also has a circular cross-section with an inner diameter of 20 cm and an outer diameter of 20.5 cm. In addition, the air velocity with constant pressure inside the pipe is maintained at 2.5 m/s by a fan. In this model, $t_{a,in}$ is the inlet air temperature, which is assumed to be equal to hourly ambient air temperatures, and $t_{a,out}$ is the outlet air temperature, i.e. the temperature of the exit air delivered through pipe outlet. For both cities, the average ground thermal conductivity is 2.1 W/m°C. A general schematic diagram of the developed model is shown in Fig. 3.

Fig. 3. Schematic diagram of the modeled EAHE system

4.1. Modeling the ground temperature

The soil temperature at certain depths is one of the most important factors determining the heating and cooling efficiency of EAHE systems. An algorithm for evolution of subsurface soil temperatures is developed by Kusuda-Achenbach [44], and it has been used by Al-Ajmi et al. [18], Peretti et al. [12] and Gan [45]. Through this mathematical formula, soil temperature can be calculated with an error of less than $\pm 1^\circ\text{C}$ [46]. It is significant to note that the soil surrounding the pipe is isotropic, with homogenous thermal conductivity at all depths. The heat conduction by soil is given by the follow equation [47]:

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

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

$$\text{At } z = 0 \rightarrow T(0, t) = t_s + t_{amp} \times \cos(\omega(t - t_0)) \quad \text{and} \quad z = \infty \rightarrow T(\infty, t) = t_s \quad (3)$$

The solution of Eq. (2) gives the following equation to evaluate the ground temperature at a certain time and depth:

$$t_{ground} = t_s - t_{amp} \times \exp\left(-z \sqrt{\frac{\pi}{365\alpha_s}}\right) \sin\left[\frac{2\pi(n - n_o)}{365} - z \sqrt{\frac{\pi}{365\alpha_s}} - \frac{\pi}{2}\right] \quad (4)$$

Where t_{ground} is the ground temperature at a certain depth and time, t_s is the average temperature of the soil surface, t_{amp} is the amplitude of the soil temperature, and α_s is the soil thermal diffusivity is given by:

$$\alpha_s = k_{ground} / (C_{ground} \times \rho_{ground}) \quad (5)$$

Where C_{ground} is specific heat capacity, ρ_{ground} is soil density and k_{ground} is soil thermal conductivity. Both cities are covered with different types of soil, but the major area of land for both cities is covered with sandy-loam soil with 5-15% humidity and 1285-2050 (kg/m³) density. Furthermore, for soil with 1285 (J/Kg.°C) specific heat capacity the thermal conductivity is 2.1 (W/m.°C) [48]. Thus, for both cities, the thermal diffusivity is 0.0045 (m²/hour) or 0.1 (m²/day). The main values required to calculate the daily soil temperature at various depths are listed in Table 2. Where t_s is the annual average of the soil temperature in (°C), n is the number of days from 31 December, n_o is the number of cold days from 31 December. For the city of Yazd n_o is January 18th with 0.8 (°C), and for Hamadan is January 12th with -14.1 (°C). A_o also indicates the amplitude of soil temperature in (°C) and is considered to be 18.0 °C for Yazd and 12.0 °C for Hamadan.

Table 2

Values for the calculation of ground temperature based on 2012 climate data.

City	Climate type	n	n_o	t_{amp} °C	t_s °C	z m	k_{ground} W/m. °C	ρ_{ground} m ³	C_{ground} J/Kg · °C	α_s m ² / day
Yazd	Hot and Dry	1-365	18	14.0	18.0	0.2, 1.0, 3.0 and 5.0	2.1[48]	1285	1285	0.1
Hamadan	Cold		12	12.2	12.0					

4.2. Modeling the outlet air temperature

The air flow into the buried pipes transmitted energy into the soil that has effect on soil temperature over a year. In the present model, the undisturbed soil temperature is at a specified finite radius. And, air pressure and velocity are assumed to be constant over the length of the pipe. An algorithm to evaluate outlet air temperatures has been defined by Elmer and Schiller [49], being used by Derbel and Kanoun [47], Maerefat and Haghighi[50], Belatrache et al. [51]. The energy balance of fluid is given by:

$$dQ = m_{air} \times C_{air} \times \frac{dt_{a,in}}{dx} \times dx \quad (6)$$

or

$$dQ = (t_{ground} - t_{a,in}) \times \left(\frac{1}{R_{total}} \right) dx \quad (7)$$

Where R_{total} is the total thermal resistance of the system. Combining Eqs. (6) and (7), overall energy balance for EAHes can be expressed as follows:

$$m_{air} \times C_{air} \times \frac{dt_{a,in}}{dx} \times dx = (t_{ground} - t_{a,in}) \times \left(\frac{1}{R_{total}} \right) dx \quad (8)$$

$$\frac{dt_{a,in}}{(t_{ground} - t_{a,in})} = \left(\frac{1}{m_{air} \times C_{air} \times R_{total}} \right) dx \quad (9)$$

Eqs. (8) and (9) can be expressed as flow:

$$\begin{cases} \frac{1}{(t_{ground} - t_{a,in})} \times \frac{dt_{a,in}}{dx} - \left(\frac{1}{m_{air} \times C_{air} \times R_{total}} \right) = 0 \\ t_{a,in} = t_{ambient} , \quad x = 0 \end{cases} \quad (10)$$

The solution of Eq. (10) gives the following equation to evaluate outlet air temperatures:

$$t_{a,out} = t_{ground} + (t_{a,in} - t_{ground}) \exp \left(- \frac{L}{m_{air} \times C_{air} \times R_{total}} \right) \quad (11)$$

Where R_{total} is the total thermal resistance of the system, which can be obtained from Eqs. (12) and (13) [52].

$$R_{total} = R_{conv} + R_{cond} + R_{ground} \quad (12)$$

$$R_{total} = \frac{1}{\pi \cdot D_{in,pipe} \times h_c} + \frac{\ln(D_{out,pipe}/D_{in,pipe})}{2\pi k_{pipe}} + \frac{1}{2\pi k_{ground}} \left[\ln \left(\frac{D_{in,pipe} + D_{out,pipe} + d_{constant}}{D_{in,pipe} + D_{out,pipe}} \right) \right] \quad (13)$$

Where $d_{constant}$ is boundary condition that ground temperature remains constant beyond this boundary, which is 5m, h_c is the coefficient of convective heat transfer between air and pipe, which can be calculated using the following equation [31].

$$h_c = (Nu \times \lambda_a) / 2r_i \quad (14)$$

Nusselt number can be obtained from Eq. (15) [13].

$$Nu = 0.214 \times (Re^{0.8} - 100) \times Pr^{0.4} \quad (15)$$

The air mass flow rate, Reynolds and Prandtl numbers can be obtained from Eqs. (16) - (18) [52].

$$Re = (V_{a,p} \times D_{in,pipe}) / \nu_{air} \quad (16)$$

$$Pr = (C_{air} \times \mu_{air}) / \lambda_{air} \quad (17)$$

$$m_{air} = (\rho_{air} \times V_{a,p} (\pi \cdot D_{in,pipe}^2)) / 4 \quad (18)$$

The variables required for numerical calculation of $t_{a,out}$ for both climates are presented in Table 3. Values for kinematic viscosity and dynamic viscosity of air are assumed for 26.7 (°C) temperature.

Table 3
Main parameters to calculate outlet air temperatures.

Parameter	Value	Unit
$t_{a,in}$	Mean daily air temperature	(°C)
t_{ground}	Daily ground temperature at a depth of 5m.	(°C)
L	10-120	(m)
$D_{in,pipe}$	0.2	(m)
$D_{out,pipe}$	0.205	(m)
k_{pipe}	0.5	(W/m°C)
k_{ground}	2.1	(W/m°C)
$d_{constant}$	5.0	(m)
h_c	93.7	(W/m²°C)
Nu	729.2	-
Re	31888	-
Pr	0.71	-
$V_{a,p}$	2.5	(m/s)
ν_{air}	1.568×10^{-5}	(m²/s)
λ_{air}	0.0257	(W/m°C)
C_{air}	1.0	(J/Kg·°C)
μ_{air}	1.846×10^{-5}	(kg/m s)
ρ_{air}	1.225	(kg/m³)
m_{air}	0.096	(kg/s)

4.3. Modeling the cooling and heating potential

The potential of EAHEs for cooling, heating, pre-cooling, and pre-heating can be accurately calculated by a mathematical model. The heat flux entering the building through EAHEs can be calculated using the following equation [53].

$$Q_{EAHE} = m_{air} \times C_{air} \times \rho_{air} (t_{a,out} - t_{a,in}) \quad (19)$$

Where m_{air} is the air volumetric flow, C_{air} is the air specific heat at constant pressure, and ρ_{air} is the air density. $t_{a,in}$ is the inlet air temperature, which is assumed to be equal to ambient air temperature, and $t_{a,out}$ is the outlet air temperature of the EAHE system.

5. Model validation

The model developed in this research to predict outlet air temperatures was validated by virtue of two experimental studies being carried out by Dhaliwal et al. [54] for different pipe lengths and Bansal et al. [55] for different inlet air velocities. The main parameters of the both studies are presented in Table 4 and the results of comparison are tabulated in Table 5 and Table 6.

Table 4

Input parameters for four comparative validations.

System	Experimental data of Bansal et al.[55]	Experimental data of Dhaliwal et al.[54]	Theoretical data of Barakat et al. [52]
Pipe diameter (cm)	0.15	0.3	0.15 and 0.3
Pipe length (m)	23.42	25.00	23.42 and 25.00
Air velocity (m/s)	2, 3, 4 and 5	1.5	2, 3, 4, 5 and 1.5
Soil temperature (°C)	26.7	18.89	26.7 and 18.89
Pipe depth (m)	-	2.13	2.13
Soil thermal conductivity (W/mC)	0.52	1.16	0.52 and 1.16
Soil thermal diffusivity(m ² /h)	-	0.00232	0.00232

As is illustrated, the absolute relative deviation between the reported experimental data and the present model is approximately 7.5%. That is, the maximum difference between the predicted outlet air temperature and the reported data is 1.7 °C for 24.7 m pipe length (Table 5), and also when the air velocity inside the buried pipe is 5 m/s the relative error accounts for merely 0.2% (Table 6). Consequently, the mathematical model can properly predict the thermal performance of EAHEs hereafter.

Table 5

Results of model validation against the experimental of Dhaliwal et al. [54].

Axial distance from the pipe inlet (m)	Outlet air temperature (°C)		
	Experimental data of Dhaliwal et al.[54] T _{out} (°C)	Results of present model	
		T _{out} (°C)	Relative error %
3.35	25.0	24.91	0.36
6.40	24.4	24.37	0.12
9.95	25.0	23.80	4.80
12.50	24.4	23.43	3.97
15.55	23.8	23.03	3.23
24.70	23.8	22.01	7.52

Table 6

Results of model validation against the experimental data of Bansal et al. [55].

Inlet air velocity (m/s)	Inlet air temperature (°C)	Outlet air temperature (°C)		
		Experimental data of Bansal et al. [55]	Results of present model	
			T_{out} (°C)	Relative error %
2	43.4	33.1	31.20	5.74
3	42.5	33.1	32.32	2.36
4	42.3	33.5	33.31	0.57
5	42.2	34.2	34.13	0.20

6. Results and discussion

Eq. (4) and Table 2 are used to calculate soil temperature at depths of 0.2, 1.0, 3.0, 5.0 meters for two cities. As Fig.4 shows, in both climates, greater depths exhibit lower temperature variations, lower maximum soil temperatures, and higher minimum soil temperatures, as these values approach the annual average. As the results show, the amplitude of the soil temperature decreases with depth, so that the soil temperature amplitude at the depths of 1.0, 3.0 and 5.0 m is respectively 10.2, 5.7 and 3.2°C in Yazd and 8.8, 4.9 and 2.7°C in Hamadan. Ultimately, this parameter approaches zero at a depth of 14m in Yazd and 13.2 m in Hamadan. At these depths, the soil temperature reaches the constant values of 18.2 °C for Yazd and 12.1 °C for Hamadan.

In Yazd (Figure 4-a) the maximum and minimum temperatures at a depth of 1 m are, respectively 28.4 °C and 7.6 °C; but at a depth of 4 m, these values are respectively 21.2 °C and 14.8 °C. Fig. 4-b, which shows the variation of soil temperature at different depths for the city of Hamadan, also indicates that a 4m increase in depth raises the minimum temperature and decreases the maximum temperature by 7.4 °C.

Fig. 4. Mean daily ambient temperature and ground temperature at 0.2, 1.0, 3.0 and 5.0 m depth, (a): Yazd, (b): Hamadan

According to Fig. 4, a depth of 5 m is selected as the optimal depth for the placement of EAHE pipes since it has lower fluctuations rather than the other depths. Data from Table 3, Fig. 4 and Eqs. (6) - (18) are used to calculate the outlet air temperature of EAHE systems with pipes of different lengths and different inlet air temperatures for both climates.

Fig. 5 shows the relationship between the inlet air temperature and pipe length at a depth of 5 m. the intersection of horizontal and vertical axes represents the outlet air temperature of the EAHE system. In Fig. 5, green cells indicate that the outlet air temperature is within the range of thermal comfort (18-23°C [56]) and can be directly used for cooling or heating the interior space, blue tones mark the range in which EAHEs operate as a pre-heater, and red tones signify the range in which they act as a pre-cooler. As is shown, in both climates, the pre-heating efficiency of the system is greater than its pre-cooling efficiency. According to the data, in both climates, this system can be generally used throughout the year; however, it is most efficient in terms of compliance of the outlet air temperature, within the comfort zone over 20°C for Yazd and over 25°C for Hamadan.

As Fig. 5 shows, the efficacy of EAHE rises with an increase in pipe length. Additionally, when the air temperature of Yazd and Hamadan is higher than 20°C and 15°C, respectively, an increase in pipe length leads to a lower outlet air temperature (cooling), but for temperatures below 15°C and 10°C for Yazd and Hamadan, the outlet air temperature increases with an augmentation in pipe length (heating).

When inlet air temperature equal to the temperatures of the coldest days in Yazd and Hamadan, i.e. 0.8 and -11°C, the EAHE system with a pipe length of 120 m can increase the temperature by 13°C and 17.9°C respectively; and taking that the inlet air temperature is equal to the temperatures of the warmest days in Yazd and Hamadan, i.e. 38.8 and 30.7°C, the same EAHE can decrease the temperature by 15.7°C and 14.5°C respectively.

Temperature (°C)	-15	-11.2	-7.9	-4.9	-2.3	0.0	2.1	3.9	5.5	6.9	8.2	9.3	10.3
	-10	-6.8	-4.0	-1.5	0.8	2.7	4.5	6.0	7.4	8.6	9.7	10.6	11.5
	-5	-2.4	0.0	2.0	3.8	5.5	6.9	8.2	9.3	10.3	11.2	12.0	12.6
	0	2.1	3.9	5.5	6.9	8.2	9.3	10.3	11.2	12.0	12.7	13.3	13.8
	+5	6.5	7.8	9.0	10.0	10.9	11.7	12.4	13.1	13.6	14.1	14.6	15.0
	+10	10.9	11.7	12.4	13.1	13.6	14.1	14.6	15.0	15.3	15.6	15.9	16.1
	+15	15.3	15.6	15.9	16.2	16.4	16.6	16.7	16.9	17.0	17.1	17.2	17.3
	+20	19.8	19.6	19.4	19.2	19.1	19.0	18.9	18.8	18.7	18.6	18.5	18.5
	+25	24.2	23.5	22.9	22.3	21.8	21.4	21.0	20.6	20.3	20.1	19.8	19.6
	+30	28.6	27.4	26.3	25.4	24.5	23.8	23.1	22.5	22.0	21.6	21.2	20.8
	+35	33.1	31.3	29.8	28.5	27.3	26.2	25.3	24.4	23.7	23.0	22.5	22.0
	+40	37.5	35.3	33.3	31.5	30.0	28.6	27.4	26.3	25.4	24.5	23.8	23.1
(a)		10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m	110 m	120 m
		Pipe length (m)											

Temperature (°C)	-15	-11.9	-9.2	-6.8	-4.6	-2.7	-1.0	0.5	1.8	2.9	4.0	4.9	5.7
	-10	-7.5	-5.3	-3.3	-1.5	0.0	1.4	2.6	3.7	4.6	5.5	6.2	6.9
	-5	-3.1	-1.3	0.2	1.5	2.7	3.8	4.7	5.6	6.3	7.0	7.5	8.0
	0	1.4	2.6	3.7	4.6	5.5	6.2	6.9	7.5	8.0	8.4	8.8	9.2
	+5	5.8	6.5	7.1	7.7	8.2	8.6	9.0	9.4	9.7	9.9	10.2	10.4
	+10	10.2	10.4	10.6	10.8	10.9	11.0	11.1	11.2	11.3	11.4	11.5	11.5
	+15	14.7	14.4	14.1	13.8	13.6	13.4	13.3	13.1	13.0	12.9	12.8	12.7
	+20	19.1	18.3	17.6	16.9	16.4	15.9	15.4	15.0	14.7	14.4	14.1	13.9
	+25	23.5	22.2	21.0	20.0	19.1	18.3	17.6	16.9	16.4	15.9	15.4	15.0
	+30	27.9	26.1	24.5	23.1	21.8	20.7	19.7	18.8	18.0	17.3	16.7	16.2
	+35	32.4	30.0	28.0	26.2	24.5	23.1	21.8	20.7	19.7	18.8	18.0	17.4
	+40	36.8	34.0	31.5	29.2	27.3	25.5	24.0	22.6	21.4	20.3	19.4	18.5
(b)		10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m	110 m	120 m
		Pipe length (m)											

Fig. 5. Impact of pipe length and inlet temperature on EAHE performance (a): Yazd (ground temperature: 18.2°C), (b): Hamadan (ground temperature: 12.1°C)

Table 3, Fig. 4 and Eqs. (6) - (18) are used to calculate the outlet air temperature of the EAHE system with 30, 60 and 90 m pipe lengths buried at a depth of 5 m for both climates. Numerical results obtained for cold and warm months in these cities are illustrated in Fig. 6. The results show that the use of the EAHE with a pipe length of 30, 60 and 90 m in Yazd during the warm season (1 Jun- 31 Sep) decreases the average outlet air temperature by respectively 3.04, 5.16 and 6.06°C, or 11%, 18% and 23%. In addition, the modeled EAHE provides a profitable heating performance in Yazd (the hot- arid climate). During the cold season of Yazd (1 Dec- 31 Jun), this system, with pipe lengths of 30, 60 and 90 m, leads to a 41%, 54% and 60% increase in outlet air temperatures. Results show, this system can work as a cooler, heater, pre-cooler and pre-heater in hot and dry region (Yazd city). The impact of the different pipe length on the EAHE performance during the cold and warm months is shown in Fig. 6-a and 6-b.

According to Fig. 6-c, during the warm season in the city of Hamadan (1 July- 31 Aug), the EAHE with pipe lengths of 30, 60 and 90 m can reduce the average outlet air temperature by 14%, 24%

and 31%, respectively. Moreover, during the cold season of this city (1 Nov- 31 Feb), the use of EAHE systems with pipe lengths of 30, 60 and 90 m leads to the outstanding result of an 82%, 88% and 91% improvement in the average outlet air temperature, see Fig. 6-d. This system, in general, demonstrated an acceptable performance for both heating and cooling purposes in cold climate.

Fig. 6. Mean daily outlet air temperatures EAHE in comparison with inlet air temperature, (a): Warm season of YAZD, (b): Cold season of YAZD, (c): Warm season of HAMADAN, (d): Cold season of HAMADAN

For both climates, the EAHE works as a heater in Jun, Feb, March, Nov and December, and as a cooler in May, Jun, July, Aug and Sep. The best performance of the EAHE to decrease inlet air temperature occurs in July with 9.3°C and 8.6°C reduction for Yazd and Hamadan, respectively. Moreover, the highest performance of the modeled EAHE to work as a heater takes place in Dec with an 8.8°C increase of the inlet air temperature for Yazd, and in January for Hamadan. Results show that this system increases the average inlet air temperature for Hamadan around 10.2°C. Fig. 7a and 7b show the mean monthly inlet air temperature (the ambient air temperature) in comparison with the mean monthly outlet air temperature.

Fig.7. Mean monthly outlet air temperature of EAHE at 5.0 m depth in comparison with inlet air temperature, (a): YAZD, (b): HAMADAN.

According to the results, a pipe length of 90 m seems to provide the highest efficiency during the cold and warm seasons. Table 3, Fig. 4 and Eqs. (6) - (18) are employed to calculate the fluctuations of the outlet air temperature of an EAHE system with a 90 m length of pipe buried at a depth of 5 m. The results show the ability of this system to not only reduce the difference between the maximum and minimum inlet air temperatures, but also to reduce the temperature fluctuations, and to push them closer to the range of thermal comfort.

Throughout the year, as depicted in Fig. 8, using a 90 m pipe length at 5 m depth, daily fluctuation of outlet air temperatures is compared with the fluctuations of the inlet air temperature in the cities of Yazd and Hamadan.

In Yazd, using the EAHE reduces the difference between the maximum and minimum inlet air temperatures by 66%. This means a 9.79 and 3.23 °C decrease in the average maximum and minimum air temperatures during the warm season and a 6.30 and 10.25°C increase in the average maximum and minimum air temperatures during the cold season. For the city of Hamadan, these values are 3.15 and 2.14 °C for the warm season and 4.05 and 10.96°C for the cold season, respectively. In Hamadan, in the case of using the described EAHE system, the difference between the maximum and minimum outlet air temperatures decreases to about one-third of its normal value. Consequently, the annual average of minimum and maximum daily temperatures changes from 18.99 and 5.43°C to 14.38 and 9.84°C.

Fig. 8. Minima and maxima of the outlet air temperature in comparison with minima and maxima of the inlet air temperature, (a): YAZD, (b): HAMADAN

Knowing the outlet air temperature of the EAHE system by using a 90 m pipe, the cooling, heating, pre-cooling and pre-heating potentials of this system can be estimated. When the temperature of outlet air is within the range of thermal comfort, this air can be used directly for heating/cooling; otherwise, it must be used for pre-heating /pre-cooling.

Fig. 9 shows the number of days and months during which the EAHE system can be used for cooling, heating, pre-cooling and pre-heating in these climates. Here, the term “out of work” refers

to the days when the EAHE system cannot change the inlet air temperature or pushes the temperature away from the range of thermal comfort. During Mar-Oct, for instance, this system is not feasible for use in the cold climate, as the outside air temperature is already within the range of thermal comfort.

As Fig. 9 and Table 7 show, for both cold and hot-dry climates, the EAHE system exhibits the highest potential for pre-heating and lowest potential for heating. The only employment of this system for heating is in Yazd in a period of 19 days during Oct-Nov, when it can push the mild temperature of the fall into the range of thermal comfort. Meanwhile, owing to the cold climate of Hamadan, the EAHE system has no pre-cooling and heating potentials, it can be used for the cooling purposes during 56 days of summer; thus, reducing the cooling load by 4869.6×10^3 kWh. In Yazd, the impact of the EAHE system on cooling loads is more significant; i.e. this system can be used for cooling and pre-cooling for a period of 128 days, resulting in a 15888×10^3 kWh reduction in cooling loads.

Fig. 9. Number of days using EAHE for cooling, heating, pre-cooling and pre-heating, (pipe length: 90 m, depth: 5m) (a): Yazd (Hot and Dry), (b): Hamadan (Cold)

Overall, this system exhibits a more superior performance in heating than in other applications. According to Table 7, in both cities, the most frequent use of the system will be for pre-heating. This table shows that EAHEs can be used on 147 days in Yazd and 169 days in Hamadan for pre-heating, which leads to, respectively, a 10202.4×10^3 kWh and 11167.2×10^3 kWh reduction in heating loads. The EAHE system is more efficient in the hot and dry climate than the cold climate; that is, in Yazd it can be used on 294 days of the year and contribute to a 19966.3×10^3 kWh energy saving, which is greater than the 16036.8×10^3 kWh energy which it can save during 225 days when used in Hamadan.

Table 7

Total energy saving (kWh) by EAHE systems during a year (pipe length: 90m, depth: 5m)

City	Total Energy Saving (kWh)			
	Heating	Cooling	Pre-heating	Pre-cooling
Yazd (Hot and Dry)	72.7×10 ³	5685.6×10 ³	10202.4×10 ³	4005.6×10 ³
Day	19	83	147	45
Hamadan (Cold)	-	4869.6×10 ³	11167.2×10 ³	-
Day	0	56	169	0

Eq. (19) is used to calculate the average monthly energy saving of the EAHE system with a 90 m pipe buried at a depth of 5 m, which is shown in Table 8. In this table, positive values represent the ability of the system to reduce cooling/heating loads, and negative values indicate that using the system raises the energy demand of the building. As can be seen, the greatest average energy saving (4165 kWh) pertains to July. Furthermore, this system exhibits a great potential for reducing the heating load during the cold months (Jun and Dec) of the hot and arid climate. The results also show that utilizing this system in Apr and May increases the heating load.

For the city of Hamadan the desirable heating efficiency of EAHEs pertains to the months Jan and Dec, with an energy savings of 4594 and 3741 kWh, respectively. It is important to note that the use of EAHEs during Apr, May, Jun and Sep is counterproductive, as it will increase the energy loss of the building. According to the results, total energy saving of the EAHE system for a year is 50.1-63.6% for Yazd and 24.5-47.9% for Hamadan.

Table 8

Mean monthly inlet and outlet air temperatures (°C) and energy exchange between the air and the ground (kWh).

	City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
YAZD	Inlet temperature	5.4	6.7	11.3	17.2	22.6	27.2	32.2	30.6	24.8	19.4	11.5	6.0
	Outlet temperature	13.6	13.1	13.9	15.6	17.8	20.1	22.9	23.4	22.2	20.6	17.6	14.9
	Energy exchange	+3694	+2830	+1305	-867	-2167	+3177	+4165	+3221	+1265	+813	+2725	+4002
HAMADAN	Inlet temperature	-3.8	0.6	7.4	11.9	16.7	21.6	25.4	24.9	19.2	13.6	5.8	0.8
	Outlet temperature	6.5	6.9	8.5	9.9	11.9	14.4	16.8	17.7	16.5	14.7	11.7	9.1
	Energy exchange	+4594	+2844	+990	-1081	-2170	-3243	+3859	+3229	-1286	+803	+2652	+3741

The EAHE has higher potential to act as cooler in Yazd (the hot-dry climate) than of Hamadan (the cold climate) as heater in. The ground temperature and EAHE potential for both cities are summarized and compared in Table 9.

Table 9

Implementation of EAHEs (pipe length: 90m, depth: 5m) in Yazd (hot-dry climate) and Hamadan (cold climate)

Item	Yazd	Hamadan	Description	Unit
Climate	Hot-dry	Cold	-	-
Min ground temperature	14.8	9.2	at a 5m depth	°c
Max ground temperature	21.2	14.8		
Depth of constant ground temperature	13.2	14.0	-	m
Increase of inlet air temperature (heating)	0.2-11.2	0.1-17.2	min-max	°c
Decrease of inlet air temperature (cooling)	1.3-11.4	5.7-11.1		
Cooling potential	628-4485	2556-4978	min-max	kWh
Heating potential	1031-2691	0		
Pre-cooling potential	2018-5113	0	min-max	
Pre-heating potential	90-5023	45-7714		
Total energy saving	19966.3×10 ³	16036.8×10 ³	during a year	
Number of day	294	225	EAHE can be used as cooler, heater, pre-cooler and pre-heater.	day
Highest heating energy saving	December	January	The maximum heating energy saving during a year, including heating and pre-heating	month
Lowest heating energy saving	May	March	The minimum heating energy saving during a year, including heating and pre-heating.	
Highest cooling energy saving	July	July	The maximum heating energy saving during a year, including cooling and pre-cooling.	
Lowest cooling energy saving	September	September	The minimum heating energy saving during a year, including cooling and pre-cooling.	

7. Conclusion

In this paper, a numerical model developed with MATLAB was used to examine and compare energy saving potential of EAHE in hot-dry and cold climates in Iran. First, the ground temperature at different depths of Yazd(hot-dry) and Hamadan(cold) was examined. Afterwards, the model was developed for high-density polyethylene pipes of different lengths based on a fixed pipe diameter, constant air flow rates, and pipe burial depths.

The results, showed that soil temperature fluctuations decrease with depth until reaching the constant annual averages of 18.2°C at the depth of 13.2 m in Yazd, and 12.1°C at a depth of 14 m in Hamadan. The amplitude of the soil temperature decreases with depth, so that at a depth of 1.0, 3.0 and 5.0 m it accounts for, respectively, 10.2, 5.7 and 3.2°C in Yazd and 8.8, 4.9 and 2.7°C in Hamadan.

Earth to air heat exchanger(EAHE) system can be used in both cities for heating and cooling purposes, but it is most efficient in terms of outlet temperatures meeting the thermal comfort criteria, when the air temperature is over 20°C in Yazd or over 25°C in Hamadan. The effect of this system in reducing the difference between minimum and maximum temperatures varied with climates, i.e. in the hot-arid climate, this system triggered a 66% reduction in the difference between the maximum and minimum daily temperatures throughout the year; whereas, in the cold

climate, it decreased the average maximum and minimum temperatures during the warm season by 3.15 and 2.14°C and increased these values during the cold season by 4.05 and 10.96°C. In both cities, the most frequent use of the system would be for pre-heating and it is more efficient in hot and arid climates than in cold climates. This is since in Yazd, the system can be used on 294 days of the year and save 19966.3×10^3 kWh of energy which is equivalent with 50.1-63.6% energy saving, with the greatest saving being in July (reduction of cooling loads); however, in Hamadan it can be used on 225 days of the year and save 16036.8×10^3 kWh, resulting in a reduction of energy consumption by 24.5-47.9%, with the greatest saving being in January (reduction of heating loads). As results showed, EAHEs have higher potential to act as cooler in hot-dry climates rather than as a heater in cold climates.

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