



# A review on modelling, experimental analysis and parametric effects of earth–air heat exchanger

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## Abstract

Earth–air heat exchanger (EAHE) is one of the energy-efficient technology that uses earth-stored heat (earth's subsurface heat) for heating or cooling the buildings and thereby protect the environment. Since this is the ability of the earth that it maintains a constant temperature at a certain depth because of huge heat storage. This constant temperature is higher than the ambient temperature in winter and lower than the ambient temperature in summer. The EAHE system is basically a pipe of different materials buried in the earth at a certain depth through which the fresh air circulates. The EAHE draws heat from the earth's subsurface to heat space in the winter. Similarly, in the summer, EAHE discharges heat to the earth to cool space. The fundamental goal of this paper is to review the previous work related to the EAHE system. Result of more recent related works has been comparing, discussed, and included in this paper. After an intensive review of this article, it has concluded that the proper design of the earth–air heat exchanger gives sufficient cooling and heating for space and offers a reduction in energy consumption, CFC emission. Therefore, this review article provides a piece of useful information to scholars interested in researching passive cooling/heating using the EAHE system.

**Keywords** Earth–air heat exchange · Passive technology · Ground heat exchanger · Renewable energy · Heating/cooling

## Introduction

Since energy is directly linked to individual/society life and is also responsible for the economic growth of any country. So, in this era, the energy conservatives and energy management techniques must be imposed to meet the energy requirement. The challenge of present technocrats and researchers to meet the increased energy may be grant by renewable stored energy. Amongst all renewable energy, one significant energy source is earth subsurface stored energy that comes from solar radiation. Hence the diversification of energy sources and the energy-saving potentials are might be used to meet the energy requirements and reducing harmful emissions. The origin of energy like Solar, wind, biomass, hydropower, geothermal, etc. combined to say the renewable energy that is accountable for reducing the energy produced by non-renewable sources and greenhouse gas emissions.

Presently building sector consumes 32% of global energy demand in which 45% uses in HVAC systems. The conventional HVAC system is generally used for thermal comfort in industries, offices, shopping places, educational institutes, residential buildings, etc. and, is also not environment-friendly. This conventional air conditioning system works on the vapor compression refrigeration cycle that requires a lot of energy for rotating the compressor. Most of the energy has been produced by burning coal or fossil fuels that pay the high cost and negative impact on the environment. The refrigerant used in the vapour compression refrigeration cycle as a working fluid contains chlorofluorocarbons (CFCs) causes' ozone layer depletion and global warming. So, the continuous demand for high-grade energy as well as the negative impact on the environment pushed the world towards renewable energy technology. Hence there are so many renewable techniques now a day used for thermal comfort which bring down the habituation of basic energy expenditure. Earth–air heat exchanger, which employs sun irradiation to store energy in the earth's subsurface, is the most notable and promising approach among them. The earth has a great affinity to absorbs approximately 46% of the total sun's energy, due to

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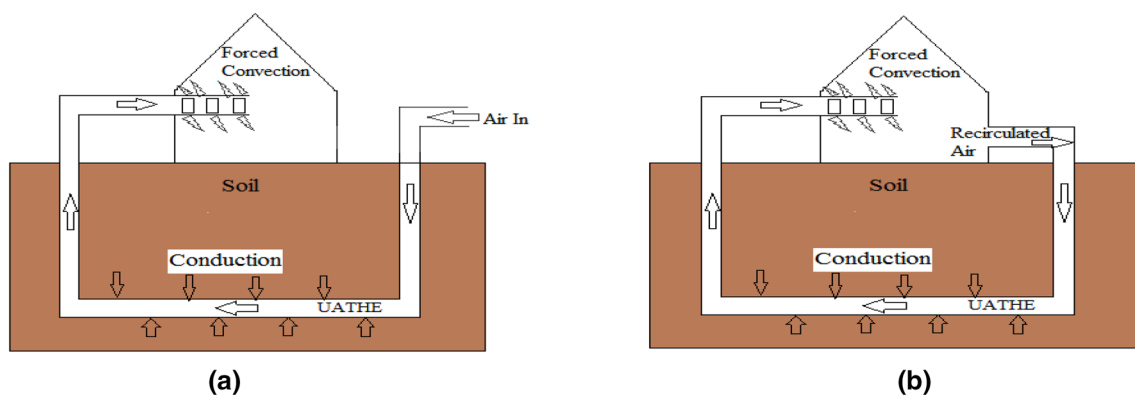
which fluctuation of temperature arises at the earth's surface and underground soil which eventually becomes constant for different locations at a certain depth. The temperature gradient between the earth's surface and underground soil is an important parameter for heating/cooling purposes. Due to the earth subsurface property, the temperature of soil at a depth of 1.5–2 m remains constant throughout the year at a given locations. This underground constant temperature significantly remains more in the winter season than the surrounding temperature and vice-versa in the summer season (Bisoniya et al. 2015a). The earth–air heat exchanger comprises of a pipe of any affordable materials buried in the earth at a given depth. The air that flowing in the pipe with the help of a fan/blower releases heat to soil in summer and absorbs heat from the soil in winter. In this way, the air that comes out from the pipe may be used for thermal comfort purposes. Therefore, the heat transfer between flowing air and pipe surface is taken place by convection mode while heat transfer in pipe material and bounded soil is taken place by conduction mode (Sehli et al. 2012).

The concept of passive cooling comes from a very ancient time since almost 3000 B.C, at that time various architects from Iran bear into wind towers as well as underground air tunnels in summer for cooling purposes and uses the earth as a heat sink (Bahadori 1978; Goswami and Dhaliwal 1985). This system had been also used since the starting of the Persian Empire for a hot and arid climate by coupling it to the solar chimney. In the mid-twentieth century, many researchers have investigated and implemented this system in America, Europe, and cold countries. From the mid of the 1990s, the execution of these systems has become common in Austria, Denmark, Germany, and India (Bisoniya et al. 2013). Before three decades from the present time, the EAHE system was popular but commonly that was not used due to either poor performance or by some disadvantages regarding initial cost, noise transmission to living space produced by fan/blower, etc., loss of air quality due to consistency and longer use, growth of micro-organisms.

In the present scenario due to the threat of the reduction of conventional energy sources, the adoption of renewable and sustainable energy technologies encourages the researchers to use the concept of earth–air heat exchanger. Generally, there are two major types of this system available named open-loop earth–air heat exchanger and closed-loop earth air heat exchanger.

The outdoor fresh air flows directly into the buried pipe in an open-loop system, as shown in Fig. 1a, for either pre-cooling or preheating of air. The air is re-circulated from the building to the buried pipe, which releases or absorbs heat from the soil in a closed-loop system, as shown in Fig. 1b.

Many researchers choose this system in the hybrid configuration by coupling it with different passive techniques for improving the performance of the system in their respective research work using experimental, analytical, Numerical, or some other studies. (Peretti et al. 2013; Tan and Love 2013; Sethi et al. 2013; Bordoloi et al. 2018) reviewed earth–air heat exchanger in terms of design, modelling, recent advancements, environmental aspect in their respective papers. (Ahmad and Prakash 2020a) optimised various parameters of earth–air heat exchanger for cooling application using Taguchi analysis. (Gao et al. 2018) reviewed the latest researches on the ground heat exchanger and demonstrates their potential in achieving zero energy buildings. They also reviewed the integration of various heating or cooling system with ground heat exchangers to improve energy efficiency. (Ahmad and Prakash 2020b) reviewed the various criterion that must be kept in mind before installing the earth–air heat exchanger system. (Rangarajan et al. 2019) developed a three-dimensional transient model of EAHE system and evaluated its performance under a constrained urban environment. Their findings reveal that the cooling system performed just as well at 2 m burial depth near the building's footprint as it did at 4 m deep in open space. Their model predictions were in close accord with the experimentally obtained values. (Gao et al. 2020) carried out the modelling and



**Fig. 1** a Open-loop EAHE, b closed-loop EAHE

thermo hygrometric analysis of underground building with a long vertical earth–air heat exchanger system. The vertical EAHE system, according to their numerical results, may greatly reduce indoor air temperature. (Hamdane et al. 2021) performs the numerical model to predict the outlet air temperature of EAHE system. They consider the axial heat conduction in the soil heat conduction equation for a low air soil temperature difference. (Minaei et al. 2021) developed a hybrid transient heat transfer model of EAHE system based on thermal resistance capacity circuit. They also investigated the effect of buried depth, operation strategies and, fluid velocity on its performance. They compared their results with experimental and numerical results and shows that it was in good agreement.

## Methods

literature was searched by adopting various important terms like earth–air heat exchanger, ground-coupled heat exchanger, buried pipe, underground air tunnel, pre-cooling, or heating of air by ground. Several electronic databases are available that help in searching the literature such as science direct, web of science, research Gate, goggle scholar, PubMed, etc. The selected journal articles, proceedings, and conference papers, relevant reports have been mainly included in the literature. Thus, this review article explores the scientific and systematic ideas that can be used by researchers, designers, policymakers, and consultants for the installation of the EAHE system in the future.

This review paper analyses the following

- Thermal modelling of systems for the calculation of soil temperature and heat transfer in flowing air
- Existing Modelled and experimental studies for getting design, characteristics and performance evaluation ideas of EAHE system. Simulation studies are also discussed.
- Discussion on performance and various parametric effects.

## Thermal modelling of the system

### Models for calculation of soil temperature

To predict the variation of temperature in the soil the thermodynamic numerical model has been developed by researchers in their respective studies. Since the transient heat flux equation for semi-infinite solid having constant thermal properties with no heat generation, flow in one dimension is explained as,

$$\frac{\partial T(z,t)}{\partial t} = \alpha \frac{\partial^2 T(z,t)}{\partial z^2} \tag{1}$$

Here  $z$  is normal coordinate (depth below ground),  $t$  is time and  $\alpha$  is thermal diffusivity. (Hillel 1982) derived a sinusoidal temperature model for variations in heat transfer to the soil at the surface by applying appropriate boundary conditions in the above equation.

$$T(z,t) = T_m + A_z \sin\left(\frac{2\Pi}{P}(t - t_0) - yz - \frac{\Pi}{2}\right) \tag{2}$$

Here  $T(z,t)$  is soil temperature at depth  $z$  and time  $t$ ,  $T_m$  is the mean temperature of the ground surface,  $t_0$  is a time duration to reach soil temperature up to  $T_m$ ,  $A_z$  is temperature fluctuations amplitude at depth  $z$  and time  $t$ .

Ben Jmaa Derbel and Kanoun (2010) introduced a mathematical model for anticipating the temperature of the sub-surface of soil at various depths and validated the model by measuring the temperature of the ground at respective depths. They also tested the thermal conductivity of different soil for investigating the impact of properties of soil on the temperature of the ground.

$$T(z,t) = T_{\text{mean}} + A \cos[\omega(t - t_0) - z/d] \times \exp(-z/d) \tag{3}$$

Here  $T(z,t)$  is soil temperature at depth  $z$  and time  $t$ ,  $\omega$  is the frequency of annual temperature fluctuations,  $A$  is the amplitude of temperature fluctuation at the surface ( $z=0$ ),  $t_0$  is the phase constant,  $d = \sqrt{\frac{2a}{\omega}}$  (Mihalakakou et al. 1994a) modelled the ground temperature at any depth using Carslaw and Jaeger equation as.

$$T(z,t) = T_m - A_s \times \exp(-\lambda z) \times \cos[\omega(t - t_0) - \lambda z] \tag{4}$$

where  $T(z,t)$  is soil temperature at depth  $z$  and time  $t$ ,  $T_m$  is mean annual soil temperature,  $A_s$  ground surface amplitude temperature,  $\omega$  indicates the frequency of annual temperature and  $\lambda$  is defined by the relation as  $\lambda = \left(\frac{\omega}{2a}\right)^{1/2}$  (Al-Hinti et al. 2017) experimented with establishing the year-round temperature profile of different depths of ground in Jordan. Using measured data, they also developed a semi-empirical model of temperature profile by modifying the equation developed by Hillel (1982) as a function of the mean temperature of the ground surface, depth, time, and properties of soil.

$$T(z,t) = T_m + \Delta T_{\text{corr}} + A_0 \exp^{-yz} \sin\left(\frac{2\Pi}{P}(t - D)\right) \tag{5}$$

Here  $T(z,t)$  is soil temperature at depth  $z$  and time  $t$ ,  $P$  is full annual cycle duration,  $A_0$  is the amplitude of annual cycle  $T_m$ ,  $D$  is the phase shift between the ground temperature cycle at given depth, and ground surface temperature cycle.  $\Delta T_{\text{corr}}$  is used for the adjustment of the model.

They found that the average diffusivity of soil increases by increasing the depth. Their experimental and model results have been matched which indicates the degree of accuracy of the model for predicting the temperature profile. Sharan and Ratan (2002) checked soil temperature pattern up to a depth of 3 m at the campus of IIM Ahmadabad, India. They also developed a temperature model by solving the heat conduction equation with appropriate boundary conditions and given as,

$$T(z, t) = T_a + A_0 \exp^{-\alpha z} \cos(\omega t - \alpha z - \epsilon). \quad (6)$$

Here  $T(z, t)$  is soil temperature at depth  $z$  and time  $t$ ,  $T_a$  is the initial constant temperature of the medium,  $A_0$  is the amplitude of temperature,  $\omega$  is the angular frequency of temperature,  $\alpha$  is thermal diffusivity of soil,  $\epsilon$  is a parameter used for time origin.

The empirical model for evaluating the temperature of the soil is given by Santamouris algorithm (Kaushal 2017) as

$$T_s = T_{av..s} - A_s \exp^{-z \left( \frac{\pi}{8760\alpha} \right)^{0.5}} \times \cos \left[ \frac{2\pi}{8760} (t - t_0) - \frac{z}{2} \left( \frac{8769}{\pi\alpha} \right)^{0.5} \right]. \quad (7)$$

Here  $T_s$  is temperature of soil,  $T_{av..s}$  is average surface temperature,  $A_s$  is annual surface temperature amplitude,  $z$  is the depth below the ground,  $\alpha$  is the soil diffusivity,  $t$  is the time,  $t_0$  is phase constant.

Also, this equation has been inserted in the review paper of (Singh et al. 2018b)

$$T(z, t) = T_m + A_s \exp^{-z \left( \frac{\pi}{8760\alpha} \right)^{0.5}} \times \cos \left[ \frac{2\pi}{8760} (t - t_0) - \frac{z}{2} \left( \frac{8769}{\pi\alpha} \right)^{0.5} \right], \quad (8)$$

and that model also is given by Mihalakakou et al. (1994b)

$$T(z, t) = T_m - A_s \exp^{-z \left( \frac{\pi}{365\alpha} \right)^{\frac{1}{2}}} \times \cos \left\{ \frac{2\pi}{365} \left[ t - t_0 - \frac{z}{2} \left( \frac{365}{\pi\alpha} \right)^{\frac{1}{2}} \right] \right\}. \quad (9)$$

Here  $T(z, t)$  is soil temperature at depth  $z$  and time  $t$ ,  $T_m$  is mean annual soil temperature,  $A_s$  ground surface amplitude temperature,  $t_0$  is phase constant,  $\alpha$  is the soil diffusivity.

Some measurement studies have been done by researchers such as (Khedari et al. 2001) perform a field study at Bangkok in Thailand and measured the ground temperature at 1 m depth, where the temperature around the year was almost constant at 27 °C. Pouloupatis et al. (2011) measure soil temperatures for three locations in Cyprus. Their data reveals that below the depth 7 m for a particular location temperature remains constant at 22.6 °C round the year that is 3.1 °C higher than the mean annual ambient air temperature. They compared the data collected from all three places and found there is a negligible difference in temperature distribution regardless of ground compositions.

## Models for calculation of air temperature

### Assumptions

1. The thermophysical properties of air are constant
2. Air flow is uniform along the length of buried pipe (Pfafferott 2003; Badescu 2007a)
3. The soil properties that surrounded the pipe is homogeneous and isotropic and there must be a perfect contact exist between soil and pipe
4. The surface temperature of the ground is assumed to be equals to ambient temperature and is same as to inlet air temperature
5. The soil properties are also not affected by the presence of pipe and also the thermal effect of soil around the pipe is negligible after a distance  $r$  (thermal penetration depth) from the pipe outer surface of pipe where  $r$  is the pipe radius. (Al-Ajmi et al. 2006)
6. The depth of buried pipe is constant throughout the length
7. The cross-section of pipe throughout the length is constant
8. The temperature profile in the pipe vicinity is not affected by the presence of the pipe. Hence the pipe surface temperature is uniform throughout the length
9. The air is well mixed in the tube with no temperature stratification
10. There is no evaporation or freezing in soil; vapor and air in the pore space are assumed to be ideal gases (Tzaferis et al. 1992; Mihalakakou et al. 1994a)
11. The effect of moisture condensation on the cooling capacity of EAHE can be ignored especially when the dew point temperature of the air at inlet of EAHE is higher than the lowest temperature of air along the pipe system (generally the lowest temperature occurs at the pipe outlet) (Bojic et al. 1997)
12. Pressure in the soil is considered to be atmospheric
13. Solar radiation is assumed to be constant
14. Possible latent heat exchanges are not accounted for, which means that no water infiltration is at work and that the air temperature is supposed to remain above its dew point (Gauthier et al. 1997)

The EAHE system is incorporate a buried PVC pipe of length  $L$  and inner and outer diameter as  $D_i$  and  $D_o$  respectively. The concentric cylindrical soil bounded the pipe is called disturbed soil where conduction taken place. the thickness of disturbed soil is given by several researchers as equal to the radius of pipe (Al-Ajmi et al. 2006; Lee and Strand 2008; Ben Jmaa Derbel and Kanoun 2010). Here we indicate  $D_s$  as outside diameter of disturbed soil and  $T_s$  as temperature of outside surface of disturbed soil.

The ambient air that circulates in buried pipe with a mass flow rate  $m$ , transfer heat to and from inner walls of pipe by convection. The heat transfer inside the pipe is done by forced convection.

Let us consider the pipe and disturbed soil are subdivided into several identical infinitesimal elemental sections of length  $\Delta x$  arranged in series in the flow direction as shown in Fig. 2. As per assumption the thermophysical properties of air, the pipe and the disturbed soil are uniform in all the subdivided section.

The heat transfer taken place between flowing air and inner surface of tube wall is due to convection mode, while heat transfer between inner to the outer wall surface of tube is taken place due to conduction mode and also heat transfer between the outer surface of the tube wall and disturbed soil that surrounded the tube is taken place by conduction mode. Hence here we say that process of heat transfer in EAHE system is three while mode of heat transfer is two.

So, there are three thermal resistances that exist for the transfer of heat in the whole system that are formulated below as per unit length.

- i. Thermal resistance due to conduction mode of heat transfer for cylindrical disturbed soil thickness that surrounded the pipe ( $^{\circ}\text{C}/\text{W}$ )

$$R_s = \frac{1}{2\pi k_s} \ln \frac{r_s}{r_o} \tag{10}$$

Here  $k_s$  is thermal conductivity of disturbed soil and  $r_s$  is the radius of outer surface of disturbed soil.

- ii. Thermal resistance due to conduction mode of heat transfer between the inner pipe wall and outer surface of wall surface in ( $^{\circ}\text{C}/\text{W}$ )

$$R_p = \frac{1}{2\pi k_p} \ln \frac{r_o}{r_i} \tag{11}$$

Here  $k_p$  is thermal conductivity of pipe material and  $r_o$  is pipe outer radius

- iii. Thermal resistance due to convection mode of heat transfer between circulating air and inner pipe wall surface in ( $^{\circ}\text{C}/\text{W}$ )

$$R_c = \frac{1}{2\pi r_i h_c} \tag{12}$$

Here  $r_i$  is inner radius of pipe and  $h_c$  is the convective heat transfer coefficient between air and pipe wall.

In Eq. (12) the term  $h_c$  is the function of Nusselt number  $Nu$  and thermal conductivity of air and is given below as,

$$h_c = \frac{Nu K_{\text{air}}}{2r_i} \tag{13}$$

For turbulent flow inside the pipe of smooth inner surface and flow is hydrodynamically and thermally developed. The Nusselt number is evaluated using Dittus-Boelter correction that is the function of Reynolds Number and Prandtl Number

$$Nu = 0.023 Re^{0.8} Pr^n \tag{14}$$

Here exponent  $n$  must be 0.4 for heating and 0.3 for cooling Reynolds number and Prandtl number may be formulated as,

$$Re = \frac{V_{\text{air}} D_i}{\nu_{\text{air}}} \tag{15}$$

$$Pr = \frac{\nu_{\text{air}} \rho_{\text{air}} C_{\text{air}}}{k_{\text{air}}} \tag{16}$$

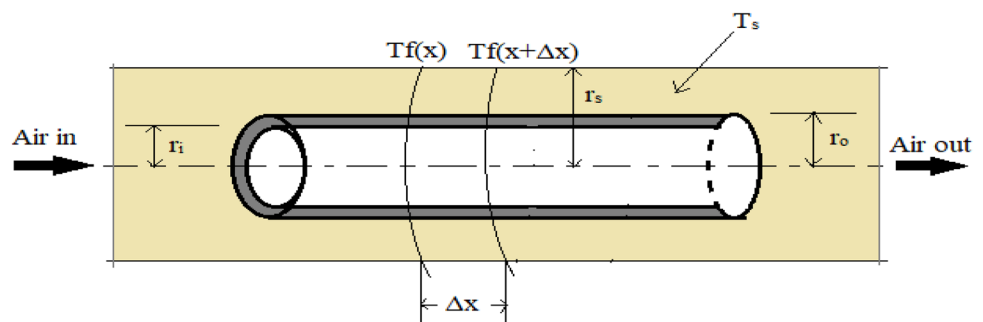
For calculating the heat transfer between air and soil the total thermal conductance should be estimated using all the Eqs. (10)–(12)

Hence the total thermal conductance per unit length may be expressed as,

$$G_t = \frac{1}{R_{\text{Total}}} = \frac{1}{R_c + R_p + R_s} \tag{17}$$

Now the heat ( $dQ$ ) loss or gain by air for the elemental segment when air flows along the pipe is given by

Fig. 2 Cross-sectional view of buried pipe



$$dQ = -m_a c_a dT_f(x). \quad (18)$$

Also, while considering the thermal conductance, the heat transfer between soil and air for the elemental segment is given by,

$$dQ = G_t [T_f(x) - T_{z,t}(x)] dx. \quad (19)$$

Hence, the heat transfer between soil and air inside pipe is equal to the amount of heat loss or gain by air as flows along the pipe, so combining Eqs. (18) and (119)

$$\frac{dT_f(x)}{[T_f(x) - T_{z,t}(x)]} = \frac{-G_t dx}{m_a c_a}. \quad (20)$$

Now by integrating above equation we get,

$$\ln [T_f(x) - T_{z,t}(x)] = \frac{-G_t x}{m_a c_a} + \text{Constant}. \quad (21)$$

There are two boundary conditions such as

When  $x = 0$ , then  $T_f(x) = T_{in} = T_{amb}$

And when  $x = L$ , then  $T_f(x) = T_{out}$

Now applying both the first boundary conditions we get,

$$\ln \left[ \frac{T_f(x) - T_{z,t}(x)}{T_{in} - T_{z,t}} \right] = \frac{-G_t x}{m_a c_a}, \quad (22)$$

$$\ln \left[ \frac{T_o - T_{z,t}}{T_{in} - T_{z,t}} \right] = \frac{-G_t L}{m_a c_a}, \quad (23)$$

also,

$$\left[ \frac{T_o - T_{z,t}}{T_{in} - T_{z,t}} \right] = e^{\frac{-G_t L}{m_a c_a}}, \quad (24)$$

$$T_o = T_{z,t} + (T_{in} - T_{z,t}) e^{\frac{-G_t L}{m_a c_a}}, \quad (25)$$

here  $-G_t L$  is the total thermal conduction of a given length ( $L$ ) of heat exchanger and is equal to  $UA$  where  $U$  is the overall heat transfer coefficient and  $A$  is the surface area.

So,

$$\frac{-G_t L}{m_a c_a} = \frac{-UA}{m_a c_a} = \text{NTU}. \quad (26)$$

Here NTU is the number of transfer unit and is the measure of the size of the heat exchanger for heat transfer point of view.

$m_a$  is the mass flow rate of air and is given as,

$$m_a = \frac{\rho_a V_a \pi D_i}{4}.$$

Now from Eq. (24)

$$\left[ \frac{T_o - T_{z,t}}{T_{in} - T_{z,t}} \right] = e^{-\text{NTU}}. \quad (27)$$

Also,

$$\frac{T_{in} - T_o}{T_{in} - T_{z,t}} = 1 - e^{-\text{NTU}}. \quad (28)$$

Now by the definition of temperature effectiveness

$$\frac{T_o - T_{in}}{T_{z,t} - T_{in}} = \epsilon. \quad (29)$$

Therefore, from Eqs. (28) and (29)

$$\epsilon = 1 - e^{-\text{NTU}}, \quad (30)$$

hence

$$T_o = T_{in} - (T_{in} - T_{z,t}) \epsilon. \quad (31)$$

Therefore, the total heat transfer to or from the air, when it flowing through a buried pipe may be expressed as,

$$Q = m_a c_a (T_{in} - T_o). \quad (32)$$

## Studies based on model development of EAHE

In this section, an overview of EAHE regarding its model development has been given. The various designed data and results that have been proposed by different researchers are presented in Table 1 and the zest of finding are compiled and presented below.

Mihalakakou et al. (1994a) developed the transient, implicit, and accurate numerical model of earth–air tube heat exchanger based on heat and mass transfer for prediction of its thermal performance. The proposed model was developed inside the TRNSYS atmosphere and validated against experimental data. They concluded that the model was suitable for predicting the temperature and humidity variation of the circulating air as well as inside the ground. Singh (1994) developed a mathematical model for the optimization of the earth–air tube heat exchanger system for cooling purposes. Their result shows that the rate of maximum heat removed from the wet surface of the tunnel is 1.7 times faster than the dry surface of the tunnel. Therefore, if plastic pipes (dry) are used instead of concrete pipes (wet), then a larger length of plastic pipes is required. Wagner et al. (2000) carried out simulation and measurement of earth–air tube heat exchangers in Germany. They use a tool named SMILE to simulate it. The differences between simulated and measured thermal output were found 10% only weekly. The simulation

**Table 1** Summary of experimental/analytical data and results

Author	Basis	Place	Purpose	Material of pipe	Length of pipe (m)	Diameter of pipe (m)	Depth (m)	Average velocity (m/s)	Soil Temp. (°C)	Room Temp. (°C)
Choudhury and Misra (2014)	Experimental	India	Cooling	Bamboo + hydra plaster	–	–	–	–	–	25–26
Jakhar et al. (2015)	Experimental	India	Cooling	PVC	60	0.1	3.7	5	27.4	17.5–22.3
Agrawal et al. (2018)	Experimental	India	Cooling	PVC	60	0.1	3.7	5	27.4	17.5–22.3
Misra et al. (2012)	Experimental	India	Cooling	PVC	60	0.1	3.7	5	–	–
Soni et al. (2016)	Experimental	India	Cooling	Steel	11	0.05	3	11	–	25
Tiwari et al. (2006)	Experimental	India	Heating	PVC	39	0.06	1	0.5–1.5	–	–
Abbaspour-Fard et al. (2011)	Experimental	Iran	Heating	PVC and M.S	18	0.1	2.4	7	14–15	–
Serageldin et al. (2016)	Experimental	Egypt	Heating	PVC	5.5	0.0508	2	1–3.9	–	19.7
Li et al. (2014)	Experimental	USA	Cooling	Culvert Steel	57	0.45	3	–	–	–
Vaz et al. (2011)	Experimental	R.G.D Sul	Cooling/Heating	PVC	–	0.11	2	–	–	–
Thanu et al. (2001)	Experimental	India	Heating	PVC	76.5	0.6–0.8	4	6.7	–	–
Ozgener et al. (2013)	Experimental	Turkey	–	G.I	47	0.56	4	3.1	–	–
Ghosal et al. (2004)	Experimental	India	Heating/Cooling	PVC	39	0.06	1	0.5–1.5	–	–
Uddin et al. (2016)	Experimental	Bangladesh	Cooling	PVC	14.32	0.0381	2.438	–	–	–
Li et al. (2009)	Experimental	China	Cooling	HDPE	–	0.0325	47.6	–	–	–
Mehdid et al. (2018)	Experimental	Algeria	Cooling	PVC	47	0.11	3	3.5	–	–
Goswami and Dhaliwal (1985)	Experimental	NorthCarolina	–	Plastic	25	0.3	2.1	–	–	–
Woodson et al. (2012)	Experimental	Africa	–	PVC	25	0.125	1.5	–	–	–
Mogharreb et al. (2014)	Experimental	Thailand	–	–	38.5	0.8	1	–	–	–
Haghighi and Maerefat (2014)	Experimental	Iran	Heating	–	25	0.5	–	–	13	–
Khabbaz et al. (2016)	Experimental	Marrakech	Cooling	PVC	72	0.15	2.2–3.2	–	–	–
Agarwal et al. (2012)	Analytical	India	Cooling	PVC	12	0.0508	3	9.8	30.1	–
Misra et al. (2015)	Analytical	India	Cooling	PVC	25	0.025	3	–	–	20–22
Bansal et al. (2013)	Analytical	India	Cooling	PVC	60	0.1	3.7	0.4–30	–	–
Barakat et al. (2016)	Analytical	Egypt	Cooling	PVC	85	0.35	5	4.5	26.7	29.14
Bisoniya et al. (2015b)	Analytical	India	Cooling/heating	PVC	19.228	0.1016	2	2–5	–	–
Gan (2014)	Analytical	England	Heating	PVC	40	0.1923	1.5	2	14.1	12.7
(Ghosal et al. (2005)	Analytical	India	Heating	PVC	39	0.06	1	0.5–1.5	20	14–22
Kaushal et al. (2015)	Analytical	India	–	–	30	0.1	–	–	–	–

Table 1 (continued)

Author	Basis	Place	Purpose	Material of pipe	Length of pipe (m)	Diameter of pipe (m)	Depth (m)	Average velocity (m/s)	Soil Temp. (°C)	Room Temp. (°C)
Ralegaonkar et al. (2014)	Analytical	Nagpur	Cooling	HDPE	80	0.106	2.5	–	20	–
Schli et al. (2012)	Analytical	South Algeria	Heating	–	60	0.2	4	3.79	24	–
Mihalakakou et al. (1994a)	Analytical	–	Cooling	Plastic	14.8	0.15	1.1	10.5	–	17–33.5
Darkwa et al. (2011)	Analytical	China	Cooling	PVC	50	0.4	1.5–3	–	–	–
Chel and Tiwari (2009)	Analytical	India	–	PVC	78	0.6	1.5	13	–	–
Al-Ajmi et al. (2006)	Analytical	Kuwait	Cooling	–	60	0.25	4	–	–	28
Lee and Strand (2008)	Analytical	USA	Heating	–	24.7	0.3	2.13	1.5	18.89	–
Ascione et al. (2011)	Analytical	Italy	Heating	PVC	50	0.33	3	7.7	–	–
Ben Jmaa Derbel and Kanoun (2010)	Analytical	Tunisia	–	–	60	0.1	3.7	5	–	–
Kabashnikov et al. (2002)	Analytical	Belarus	Ventilations	–	23	0.23	4	–	–	–
Cuny et al. (2018)	Analytical	France	–	–	30	–	0.75	4	–	–
Ahmed et al. (2015)	Analytical	Australia	Cooling	PVC	8	0.02	–	1.1	–	24.9
Xamán et al. (2014)	Analytical	Mexico	Heating	–	5	0.15	10	–	–	–
Niu et al. (2015)	Analytical	USA	Cooling	Steel	57	0.4	3	–	–	–
Serageldin et al. (2016)	Analytical	Egypt	Heating	Copper	5.5	0.0508	2	1–3.9	–	19.8
Thakur and Sharma (2015)	Analytical	India	Cooling	Aluminium	60	0.1	–	3.50	–	–



results for the heating purpose were decreased by 15% after installing it in the undeveloped ground while these results were increased by 22% on installing it below the foundation. Hollmuller and Lachal (2001) examine the basic differences between preheating and cooling with the help of the numerical simulation model. In this regard, they consider the energy balances, diffusion through the soil, latent, and sensible heat exchanges. Kabashnikov et al. (2002) develop a mathematical expression to determine the ground temperature as well as air temperature for ventilation systems for an earth heat exchanger. They evaluated the dependencies of efficiency and thermal power with various parameters. The optimum length of the tube was also calculated using the analytical expression. In the developed expression temperature was shown in Fourier integral. Kumar et al. (2003) developed a numerical model for explaining the thermal performance of the earth–air heat exchanger system. They concluded that the model is best fit in predicting the tube extracted temperature along the length of the pipe. Breesch et al. (2005) evaluated the overall thermal comfort of an office building using a simulation technique. The evaluated results indicate that the passive cooling technique put a great impact on thermal comfort. Ghosal et al. (2005) produces the selection approaches of two types of heat exchangers such as ground collector and earth–air tube heat exchanger using the numerical model at the campus of IIT Delhi in India. They concluded that the ground collector shows better performances than the earth–air tube heat exchanger for heating of a typical greenhouse coupled to that system. Hanby et al. (2005) describe the parametric optimizations of the ground cooling tube in order to minimizing the external consumption of energy and payback time. Kumar et al. (2006) developed the deterministic and intelligent models for passive cooling/heating of buildings. The deterministic model was applied for investigation of heat and mass transfer while later is concerned with the development of artificial neural networks (ANN). Their results show that the accuracy of a deterministic and intelligent model is  $\pm 5.3\%$  and  $\pm 2.6\%$  respectively. Shukla et al. (2006) developed a mathematical model to investigate the thermal performance of the earth–air tube heat exchanger system. The statistical analysis shows that theoretical results agreed with experimental observations round the year. Furthermore, they also worked on thermal performance prediction for Indian climates such as Kolkata, Chennai, Mumbai, and Jodhpur. Sethi and Sharma (2007) developed a mathematical model in order to heating as well as cooling of greenhouse that integrated with an aquifer coupled-cavity flow heat exchanger. They validate this model against experimental results, a fair agreement was found between them. Cucumo et al. (2008) suggest an analytical model so as to appraise the performance and correct installation of EAHE. The proposed model was processed by heat and mass balance criteria of air flowing

inside the pipe. They use two methods for this purpose one is based on Green's functions and others attributed to the principle of superposition. Tittlein et al. (2009) proposed a numerical model for simulating the system, which tends to reduce computational time using the response factors method. Trzaski and Zawada (2011) uses the ground tube heat exchanger model attributed to a three-dimensional finite element method that enables to analyse the energy efficiency and its dependencies on various parameters such as geometry, mode of operation, and environmental factors. Sehli et al. (2012) produced a one-dimensional steady numerical model by considering two parameters namely Reynolds number and form factor to estimate the performance of the EAHE system. It was concluded that only the EAHE system is not enough to maintain indoor thermal comfort, but if it is used in combination with an air conditioning system then energy demand may be reduced in domestic buildings in South Algeria. Kaushal et al. (2015) presented two-dimensional numerical analysis using CFD based software ANSYS Fluent for investigating thermal execution of earth–air heat exchanger combined with a conventional solar-based air heater (hybrid earth–air heat exchanger). They compared the numerical results of the hybrid earth–air tunnel heat exchanger with individual earth–air tunnel heat exchanger and found that the performance of the former system is three times higher than that of a later system.

Rodrigues et al. (2015) perform a numerical investigation related to various geometrical parameters of earth–air tube heat exchanger in order to achieve the maximum thermal potential. As per their results for a given occupied area of ducts and constant flow rate, the number of ducts increases which improve the thermal performance up to 73% for cooling purpose whereas 115% for heating purpose. Benhammou et al. (2017) developed two separate transient numerical models for modelling earth–air tube heat exchanger as well as explaining the behaviour of buildings. They use complex Fourier transformation for solving the differential equation for various components of the system. Cuny et al. (2018) proposed the numerical modelling attributed to the finite element method for earth–air tube heat exchanger for determining the energy impact of various types of coating soil. Mehdi et al. (2018) developed a new transient semi-analytical model named GRBM model in order to predict the temperature of the air inside EAHEs for continuous operation mode. Through the GRBM model, horizontal EAHE can be designed in a simple and precise method with reduced computation time. Rosa et al. (2018) developed an analytical model and verified it with system monitored data. They also performed the parametric study and shows that the various parameters affect the outcome of the system. Hasan et al. (2019) perform a parametric study of earth–air heat exchanger for both heating and cooling applications. Their numerical studies impart the influence of various designed

parameters on overall performance. They also validated the numerical model against the experimental model and found a good agreement between them. D'Agostino et al. (2020) conducted a numerical analysis and compare Earth-to-Air Versus Air-to-Air Heat Exchangers on its Energetic, Economic, and Environmental aspects for office buildings of two places located in Italy. Their results show that the energy performances of air to the air heat exchanger are better in winter while earth to the air heat exchanger is more suitable in summer. So, they coupled both the heat exchanger to buildings and used air to the air heat exchanger in winter while others in summer. Qin et al. (2021) perform numerical model and validated with an onsite experimental test rig of earth–air heat exchanger coupled with phase change material-based solar air heater. Their result reveals that using PCM the outlet temperature can maintain in the range of 33–35.8 °C for 4.5 h and reduce the fluctuation of heating capacity by 38.1%. Gomat et al. (2020) present an analytical model in order to estimate the effect of the vertical part of earth–air heat exchanger. Their modelled results imply that the vertical part of the earth–air heat exchanger on the length of 1.03 m changes the temperature of  $0\text{ °C} \leq \Delta T \leq 0.91\text{ °C}$  before air enters the horizontal part of the EAHE system. Ahmad and Prakash (2021) perform a parametric study on earth–air tube heat exchanger to examine the variation of length with inlet and outlet temperature for the cooling mode of application. Their results reveal that for a comfortable condition of 26 °C the length of tube was 8.42 m with an inner diameter of 0.05 m for an inlet temperature of 36 °C.

### Studies based on experimental analysis of EAHE

In this section, an overview of EAHE regarding its experimental studies has been given. The various designed data and results that have been given by different researchers are compiled in Table 1 and discussed below.

Thanu et al. (2001) conducted an experimental study on the earth-air-pipe system coupled to a building in India. The temperature and relative humidity at every point were measured. They establish a correlation between the inlet and outlet air temperature of the system to get the different parameters at both points. Their study shows the system has high effectiveness during months of summer. Tiwari et al. (2006) present the experimental validation of the thermal performance of greenhouse that integrated into earth–air heat exchanger round the year at the premises of IIT Delhi India. Bansal et al. (2009, 2010) constructed an experimental setup of the EAHE at Ajmer in India that can be applied for reduction of heating load and cooling loads of building in winter and summer respectively. Darkwa et al. (2011) studied the practical implementation of the Earth tube

ventilation system and showed its potential to save energy. For a given period of operation, their result indicates that the system provides 62% and 86% heating and cooling loads respectively, and also attained the corresponding COP of 3.2 and 3.53. Vaz et al. (2011) perform the experimental study at Viamao in southern Brazil to reduce the conventional energy consumption for thermal comfort by using the earth as a reservoir of energy derived from solar radiation. Yildiz et al. (2011) developed an experimental system and investigated the exergetic performance of a solar photovoltaic system (PV) assisted earth-to-air heat exchanger for cooling the greenhouse in Turkey. In their experimental result, 2.84 kWh or 31% energy saving was obtained using 0.9 kW solar PV cell. Woodson et al. (2012) carried out an experimental investigation on earth–air tube heat exchanger (EAHE) in an institute at Burkina Faso and examine its thermal performance. They found that the pipe of the given length able to reduce the air temperature that coming from outside by 7.6 °C. Choudhury and Misra (2014) carried out an experimental investigation on open-loop earth–air tube heat exchanger (EAHE) made by locally available materials like bamboo and soil–cement mixture to minimize the energy consumption and climate change in the northeast part of India. After performing a series of experimental observations, their result reveals that outlet air temperature was reduced by up to 30–35% and the soil–cement mixture plasters have the potential to reduce the humidity by 30–40%. Hepbasli (2013) deals with the exergy modelling as well as analysing the performance of greenhouse heating systems coupled to close loop earth pipe air heat exchangers. Based on the experiment the overall value of exergy efficiency was calculated and found 19.18% with the reference temperature of 0 °C. Their study indicates that due to increment in reference environment temperature the exergy efficiency and sustainability index decreases drastically. Mongkon et al. (2013) perform the experimental investigation of the horizontal earth–air tube heat exchangers system for cooling performance and water condensation in an agricultural greenhouse for different seasons of the tropical climate of Chiang Mai in Thailand. Their study concludes that the use of the studied system is practically suitable in a tropical climate in the month of summer. Mogharreb et al. (2014) perform an experimental investigation and tested the performance of the EAHE system utilizing two self-sustaining variables such as the greenhouse area and level of vegetation inclusion inside the greenhouse for heating and cooling purposes. Their experimental study concludes that the vegetation coverage had a positive effect at the time of heating and a negative impact on cooling. The experimental result also shows that the COP of cooling and heating mode was 4.3 and 1.01 respectively. Jakhar et al. (2015) experimentally investigated earth–air tunnel heat exchanger integrated with solar air heating duct for winter air heating for arid climate

at Ajmer city in India. They coupled solar air heating duct at the exit of the earth–air tunnel heat exchanger. Their results show that the heating limit of the system was increased by 1217.625–1280.753 kWh when it was combined with solar air duct likewise the room temperature increased by 1.1–3.5 °C. The coefficient of performance of the system likewise increased up to 4.57. Uddin et al. (2016) studied the thermal comfort investigation of indoor air using earth–air heat exchanger and life cycle analysis as well as greenhouse gas emission in Bangladesh. Their result revealed that the average increase in temperature and decrease of relative humidity in winter were 9 °C and 28% respectively while an average decrease in temperature and increase in relative humidity in summer was 6 °C and 10% respectively. The analysis of the Life cycle and greenhouse emission had been done for PVC material and MS material and found that the latter material was better for domestic as well as industrial application. Zukowski and Topolanska (2018) conducted research on two types of ground air heat exchangers (GAHE) one is tube type while the others are plate type and both occupied the same area. Their experimental results show that for the heating mode the energy gain for tube and plate GAHE was 13.5 MWh and 16.35 MWh respectively while for cooling mode energy release for tube type and plate type GAHE were 10.3 MWh and 20.41 MWh respectively. On the basis of experimental results, it was concluded from the study that the tube heat exchanger is more efficient in heating mode, whereas the plate heat exchanger is more efficient in cooling mode. Liu et al. (2019a) investigated the vertical earth–air heat exchanger by establishing an experiment. Their experimental results reveal that the outlet air temperature for summer and winter ranges from 22.4 to 24.4 °C and 16 to 18 °C respectively. The energy payback and monetary payback period were determined as 8.2 years and 17.5 years respectively. Also, the economic lifespan of this system was 20 years. By testing its model and checking its viability, Zhao et al. (2019) evaluated the performance and numerous influencing parameters of the earth–air heat exchanger system. Their findings show that the cooling and heating capacities are respectively 21.17 and 21.72 kW, and that temperature extraction efficiencies rise with pipe length and decrease with pipe diameter.

## Discussion on performance and important parameters of EAHE system

The different data regarding various studies have been confined in Table 1. As per this study we have included the following important parameters that affect the performance and outlet temperature of this system that is as follows.

## Climatic and soil components

For winter climates with wet and heavy soil, the system would be saved up to 44% thermal energy for a particular location (Ascione et al. 2011). During summer for achieving better performances, the temperature of soil may be reduced by selecting some processes like spray the water to making it wet, growing grass, shading. The compacted clay or sand should be used around the pipe to increase the heat transfer rate (Kaushal 2017). The experimental studies were performed by Lekhal et al. (2021) to investigate the effect of climatic conditions and pipe materials on the performance of earth–air heat exchangers. Their experimental results reveal that PVC EAHE is more efficient in arid climate than in temperate or steppe climate, whereas Zinc EAHE is much better in temperate climate than in arid or steppe climate. Hence results show that in steppe climate both the EAHE exhibit similar behaviour.

## Inlet air temperature

The performance of this system also depends upon the inlet air temperature, so the effects of inlet air temperature on the EAHE system must be studied before the installation of the system. By establishing a mathematical model, Niu et al. (2015) evaluated the effect of inlet temperature on the performance of earth–air tube heat exchangers. Their findings show that the higher the inlet air temperature, the faster the rate of air temperature decline in the EAHE pipe. Elminshawy et al. (2017) found that for the given three soil compaction level such as loose, medium, and dense the cooling capacity is increased by 116%, 183%, and 227% respectively when air inlet temperature is increased from 40 to 55 °C. Hence the inlet air temperature put a great impact on the performance of the earth–air tube heat exchanger (EAHE) system. As increasing the inlet air temperature, the amount of energy exchanges between air and soil decreases (Jamshidi and Sadafi 2020). The air temperature reduces linearly with inlet air temperature (Wei et al. 2020).

## Inlet air velocity

The performance of this system also greatly affected by a slight variation in air flow velocity (Mihalakakou et al. 1994a, c, 1996; Santamouris et al. 1995). The simulation result of the greenhouse air temperatures varies between 21.1 and 36.4 °C for 4 m/s air velocity and 22.5 and 39.7 °C for 10 m/s in the month of June. So, it is noticeable that the greenhouse indoor air temperature increases with increasing air velocity inside the pipes. This is due to the increase in the mass flow rate. (Wu et al. 2007) predicted the outlet air temperature and cooling capacity of the system using CFD analysis and found that both the results increase by

increasing the air inlet velocity. Lee and Strand (2008) investigate the effect of air velocity inside the pipe on the earth tube heat exchanger at four different locations. Serageldin et al. (2016) observed that mean efficiency, COP and change in air temperature decreases by increasing the air velocity. Zhao et al. (2019) investigated that as the velocity of air increases the temperature extraction efficiency decreases. Rosa et al. (2020) observed that air velocity and pipe diameters are important factors that affect the thermal performance of the earth–air heat exchanger system.

### Pipe's arrangements

For getting the cooling/heating load demands of a building, more than one pipes are buried in the soil to eliminating the many limitations such as space limitations, excavation cost, etc. De Paepe and Janssens (2003) uses two types of arrangement for delimits the allowable length and specific pressure drop such as parallel and serpentine arrangement. To prevent the interference between the neighbouring pipes the distance between the pipes must be at least 1 m. Tiwari et al. (2006) spread the PVC pipe of a total length of 39 m and 0.06 m in diameter in a serpentine manner. The distance between each serpentine pipe is 0.5 m and each serpentine length was 4.8 m. (De Jesus Freire et al. 2013) studied heat exchanger includes a set of pipes that are uniformly distributed in multiple horizontal layers at a certain depth in the soil. This configuration may be better when less area of land is under consideration but due to less heat saturation of the soil, the efficiency may reduce. For a given airflow rate the heat loss increases as reducing the spacing between the pipes. This analysis has been performed by Kabashnikov et al. (2002) through a mathematical model.

### Pipe material

Several researchers investigated the impact of pipe materials on the performance of this system. Bojić et al. (1999) suggest that there is no significant impact of pipe material on the performance of EAHE system. Bansal et al. (2009, 2010) uses two horizontal pipes of different materials like PVC and steel in their experimental study. Their experimental results reveal that the performance of the system was not influenced by pipe material. The selection of material would decide the cost and durability of the system. The steel pipes increase the cost by 25–30% than PVC pipes, but it was suggested that during the backfilling process PVC pipes require more care for preventing the mechanical damage whereas in steel pipes it overcomes the mechanical damages. Abbaspour-Fard et al. (2011) concluded in their study that each of the parameters had some impact on its performance aside from pipe material.

Menhoudj et al. (2018) used two types of materials such as galvanized sheet metal and polyvinyl chloride of the same geometric dimensions for checking the influence of materials on the performance of EAHE. For cooling mode, the decrease in temperature for PVC and Zinc pipe was 6 °C and 6.5 °C respectively. Liu et al. (2019b) compared different materials of the tube and suggest that PVC is more appropriate amongst them. Sakhri et al. (2020) perform a comparison study on the effect of pipe material on the performance of EAHE. Their research indicates that pipe material has a low influence on performance. Hence PVC is more promising to use than steel material because of its low price, low weight, possible shape modifications, and easy to handle.

### Pipe length

Many researchers suggest in their studies that the length of the pipe plays a key role in the performance assessment of EAHE. The effect of optimum length and earth's surface treatments on the thermal performance of pipes used for building heating/cooling has been investigated for hot-dry, composite, and cold climates, respectively, for Jodhpur, Delhi, and Leh (Sodha et al. 1991). Kabashnikov et al. (2002) conducted a numerical and analytical analysis and discovered that as pipe length increases, the rise and fall in air temperature increases. In any case, after a certain length, heat transfer does not increase as the pipe length increases since longer pipes need more air travel time and heat removal rate (Ben Jmaa Derbel and Kanoun 2010). So Lee and Strand (2008) suggest that the optimum length of pipe that equals to the length of 70 m. Wu et al. (2007) perform the computational fluid dynamics study of earth–air pipe heat exchanger for three different pipe length and calculated the outlet air temperature. Their results show that at the length of 20 m the outlet air temperature varies from 26.1 to 33.6 °C and at 40 m the outlet air temperature ranges from 24.7 to 31.2 °C while at 60 m it varies from 23.8 to 29.5 °C (Mihalakakou et al. 1994d; Santamouris et al. 1995; Ghosal and Tiwari 2006). Concluded that by increasing the length of the buried pipe the total rise or drop in air temperature increases up to saturation length of the pipe but after saturation length, its impact on air temperature is less conspicuous. Ben-rachi et al. (2020) perform a numerical parametric study of earth–air heat exchanger and found that the outlet air temperature decreases with increasing the length of the pipe. This effect is also similar to the study performed by Benhammou and Draoui (2015), Belatrache et al. (2017) and Benhammou et al. (2017). In the other study of Wei et al. (2020) it is evident that by increasing pipe length, the air temperature drops exponentially.

## Pipe diameter

The diameter of the buried pipe also plays a key role in the performance of the system presented by numerous researchers in their studies (Mihalakakou et al. 1996; Badescu 2007b; Lee and Strand 2008; Ben Jmaa Derbel and Kanoun 2010). Kabashnikov et al. (2002) ascertained a trivial difference in the performance of system when changing the pipe diameter from 0.1 to 0.4 m. Mihalakakou et al. (1994c) investigate this system and found that for summer season operation as per reducing the pipe diameter the drop-in outlet temperature increases. In another study of Mihalakakou et al. (1994a) for the winter season as per reducing the pipe diameter the rise in outlet temperature taken place. Goswami and Biseli (1993) suggested for a single pipe the optimum diameter is 0.3 m while for the multi-pipe system the optimum diameter should range between 0.2 and 0.25 m. Wu et al. (2007) estimated the outlet air temperature for three different diameters of pipes. Based on their results, they observed that the outlet temperature ranges from 22.3 to 25.6 °C, 22.6 to 28.6 °C and 25.4 to 32.4 °C at diameter of 0.1 m, 0.2 m and 0.3 m respectively. In the later study of (Serageldin et al. 2016) it was observed that the outlet temperature was increases from 0.4C to 18.7 °C, by increasing the tube diameters from 0.0508 to 0.0762 m. The temperature difference between inlet and outlet air decreases by increasing the pipe diameter (Ghosal and Tiwari 2006; Ahmed et al. 2016; Singh et al. 2018a). Liu et al. (2019b) developed a numerical model of vertical earth to air tube heat exchanger and perform its parametric study. Their parametric study indicates that the tube of smaller diameter provides greater thermal capacity at fixed airflow.

## Pipe burial depth

As per various developed temperature distribution models and measuring studies, the temperature gradient increases with increasing buried depth thereby energy exchange rate. Badescu (2007b) investigated that thermal performance of earth–air heat exchanger increases with increasing the depth of pipe but limiting up to the depth of 4 m only. Lee and Strand (2008) investigated that the temperature of air flowing inside the pipe decreases with increasing the depth of buried pipe up to specific limit. Ben Jmaa Derbel and Kanoun (2010) ascertain the efficiency of earth–air pipe system for heating and cooling modes at various depths. Their results reveal that 4 m depth is optimal for heating mode while 2 m depth is optimal for cooling mode. Benhammou and Draoui (2015) suggests that a depth of 2 m is most suitable for cooling applications. Ahmed et al. (2016) investigate the effect of pipe depth on the cooling performance of the EAHE system by keeping the pipe at various depths (0.6 m, 2 m, 4 m, 8 m) and found that the maximum cooling effect achieved at 8 m depth Wu et al. (2007) investigated

the thermal performance of earth–air pipe system at various buried depth. Their results revealed that at a depth of 1.6 m the outlet air temperature varies from 27.2 to 31.7 °C while at a depth of 3.2 m it ranges from 25.7 to 30.7 °C. The impact of burial depth is more noteworthy than pipe length for temperature gain (Mihalakakou et al. 1994b). However, the burial depth might be restricted by certain components, for example, bedrock depth, water level, and cost. Also, by increasing the buried depth the amount of heat picked up or discharges increases (Jamshidi and Sadafi 2020). Wei et al. (2020) perform field experiments on the cooling capability of EAHE in a hot climate. They observed that by increasing buried depth the outlet temperature and moisture content were decreased.

## Conclusions and recommendations

The earth–air heat exchanger is one of the important passive technologies that can be utilized for either preheating or pre-cooling and thereby minimizing the energy consumption in the buildings or agricultural purposes. We may conclude from the numerous literature studies that by increasing the diameter of the pipe total temperature rise in winter and drop in summer decreases but the overall heat transfer rate increases for a given velocity of air. Also, the cost of a large diameter pipe is more than that of a small diameter pipe, so it is prescribed to use multiple small diameter pipes rather than a single large diameter pipe. Pipe materials cannot affect significantly the performance of the system so it is recommended to use cheaper materials instead of costlier. The burial depth of the pipe should be kept at 2–5 m because the trenching/excavating cost dominant over temperature variation when the pipe is buried at more depth. It has been noticed from numerous studies that the ground could not recover its thermal properties for continuous and longer operation of this system, hence it is recommended to use it as an intermittent operation that is it would be used in summer day and winter night. The performance of this system may be increased by coupling it with some renewable energy sources such as solar, wind, etc. Hence it is clear from the review study that the proper design of the earth–air heat exchanger gives sufficient cooling and heating for space and offers a reduction in energy consumption and CFC emission. Since there is limited literature available for the economic analysis of this system so a wide scope in this area is available for researchers. Regardless of these a research study is highly suggested for future work by varying a pipe material for minute temperature drop/rise. Thus, in this way, the review article presented here may be useful for one who interested in researching passive cooling/heating using the EAHE system.

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**Availability of data and material (data transparency)** Data analysed in this study were a re-analysis of existing data, which are openly available at locations cited in the reference section.

**Code availability** Not applicable.

## Declarations

**Conflict of interest** We have no conflicts of interest to disclose.

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