Exploring Earth Air Heat Exchanger as an Innovative and Sustainable Application for Cooling and Heating: Excerpts from Literature

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Abstract

Energy needs and alarming CO_2 emissions across the globe have brought considerable attention to the development and implementation of renewable energy and energy-saving systems. An important aspect of the earth's thermodynamics is that its temperature remains low and constant throughout the year. This is in comparison to outdoor air temperatures.The ground temperature is used in Earth Air Heat Exchanger (EAHE) systems to pre-condition air before it enters a building. It effectively reduces the energy consumption of traditional Heating, Ventilation, and Air Conditioning (HVAC) systems. This paper provides a concise review of EAHE technology application in space heating and cooling. The write-up also emphasized on the iinfluence of air velocity, diameter,depth, material type and length of a buried pipe on the thermal behavior of the EAHE system. EAHE performance is not greatly affected by the material of the pipe, in contrast to the length and diameter of the pipe. The findings suggest that the most efficient cooling and heating effect is provided by pipes with smaller diameters. Additionally, it is indicative that longer pipes improve the cooling/heating output in the EAHE system. Overall, fund available for the construction determines the type of pipe material and length to use for an efficient EAHE system. Lower air velocities provide higher thermal performance than higher flow rates. Furthermore, the integration of the EAHE with other HVAC systems may increase the energy saving. Typically, these systems may contribute to reduction of energy consumption for heating by approximately 25 – 40%. This percentage range could yield to an EAHE efficiency almost 0.9.

Keywords: *Soil temperature; Earth Air Heat Exchanger system; sustainable energy; thermal comfort; heating and cooling systems; Renewable or green energy.*

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Introduction

Globally, energy consumption in buildings has become a significant issue due to the increasing demand for energy and the consequent increase in greenhouse gas emissions. Heating and cooling systems are responsible for a large proportion of energy consumption in buildings. Air conditioning systems (ACs) are used to maintain interior thermal comfort, using around 15% of all energy consumed. By 2050, ACs number is predicted to rise from 1.6 billion to 5.6 billion, increasing the power consumption for ACs by thrice[1].The COVID-19 pandemic condition posed serious issues about regulating the interior environment to reduce virus transmission[2–4].

Therefore, new guidelines have been released to control the spread of COVID-19 in Heating, Ventilation, Air Conditioning (HVAC) systems. These guidelines recommend that fresh air should be increased up to 100% in enclosed spaces. Also, recirculated air should be avoided. These results in increased cooling/heating loads and hence increased energy consumption[2]. If the world's economy is to satisfy these expanding energy demands, the use of renewable energy sources such as biofuel, wind, solar and geothermal will be critical[5].

Buildings are responsible for one-third of total energy greenhouse gases emissions[6]. Buildings' thermal performance has been immensely improved over the past few years due to highly intensive energy savings measures and technologies. While this is mostly true in developed countries, the energy needs for cooling have significantly increased in the warmer developing world due to rising living standards, urban temperature increases, as well as global climate change[7]. For instance, the energy used by the construction industry for cooling has been significantly impacted by global climate change. As temperatures rise in Greece, researchers predict a 248% rise in energy consumption for building cooling by 2100, but a 50% decrease in energy demand for buildings[8]. In Europe, air conditioning raises the typical commercial building's overall energy usage to roughly 40 $kWh/m^2/y$[9,10].

Thermal comfort is directly linked to human productivity. So, office buildings must ensure that their thermal environment is of high quality. Heating systems are critical in cold climates for various reasons. They provide necessary comfort and sustain a living atmosphere by keeping interior temperatures comfortable throughout the winter seasons. Humans would be exposed to extremely low temperatures in the absence of heating equipment, causing discomfort, unproductivity, health problems, and even hypothermia.. Extreme cold can cause water to freeze and expand, resulting in broken pipes and structural issues. Heating systems assist in averting these problems by keeping indoors temperatures above freezing, thus safeguarding buildings and their occupants[11].

The minimisation of energy consumption and greenhouse gases emissions can be done by applying modern heating techniques like high-efficiency boilers, photovoltaic/thermal collectors, and geothermal systems (such as heat pumps and earth air heat exchangers). However, the type of energy source used by these systems gives the difference of their climate impact. In fact, to distinguish between the combustion of fossil fuels and biomass is essential. The combustion of fossil fuels causes additional CO_2 into the atmosphere. This is due to the release of underground storage of the aged carbon. Biomass burning emit CO_2 that was absorbed from the atmosphere during the growth of plant. The last type of combustion can be considered as a more sustainable and carbon-neutral option[12]. Moreover, as a contribution of the circular economy objectives and waste management, in addition to reduction of fossil fuels dependence, it is advisable to use alternative and waste biomass utilisation e.g. organic municipal or agricultural wastes and residues, animal manure or forest residues[13,14]. Potentially, this will support environmental preservation.

A passive climate control technology applicable to farm and residential buildings is an Earth Air Heat Exchanger (EAHE). This is a method based mainly on temperature distribution at the surface of the ground[15]. It relies on underground soil temperatures which remain fairly constant at a depth of about 2.5 to 3 m from the surface (Figure 2), throughout the year. It is usually greater or less than the ambient temperature of winter or summer, respectively. That reflects the average yearly air temperature of the region[16].This is commonly referred to as the 'critical depth'.[17–19]. This study gives an overview of EAHE technology, with an emphasis on the way they could enhance building energy use and sustainability. By summarizing sevral recent research findings on the use of EAHE systems in buildings air conditioning purposes, the valuable potential of such suistanable, novel and energy-efficient solution for building are depicted. This review presents the state-of-the-art of EAHE technique, its functional fundamentals and the impact of soil properties on the performance of this system. Another interesting highlight in the installation of the EAHE is the design parameters of such system (pipe material, pipe diameter, length of the pipe and the buried depth of the EAHE pipe, in addition to speed of the air passing through the pipe). Therefore, this investigation aimed to concluded the recommended parameters based on various research. The main novel sections covered in this study:

- The operation concept of an EAHE and basic heat transfer modes that happen whitin the system;
- The major classifications of the EAHE systems (including closed- and open-loop system);
- The impact of various design parameters on the EAHE performance;
- Possibility of integrating EAHE with other HVAC system to enhance the energy saving.

1. State-of-the-art of EAHE technology

The use of Earth Air Heat Exchangers (EAHEs), which may offer natural ventilation and use the consistent ground temperature to provide cooling and heating, is one substitute for traditional heating and cooling systems. Research has anchored on enhancing several features of EAHE systems, including design, operation, and performance evaluation. A number of factors are investigated in studies [20–22], together with ground heat transfer, airflow patterns, heat recovery efficiency, and control strategies. These sustainable systems have many benefits over conventional heating and cooling systems[23–26]. Al-Ajmi et al.[27] developed an analytical model for the prediction of air outlet temperatures and cooling potential of EAHEs in hot and arid climates. Their model is based on the ratio of the thickness of the disturbed soil to the radius of the buried pipe, without considering the thermal resistance of the pipe material. This model was implemented into the TRNSYS environment after being validated with previous published experimental research. It examined the thermal performance of a typical house combined with an EAHE under Kuwaiti climate conditions. It was discovered that the EAHE can provide 30% of the summertime demand for cooling energy. There was an analysis for the thermal efficiency of vault roof buildings integrated with earth-to-air heat exchangers. The results revealed that during the winter months, the temperature in the room increased by about 5.1–15.7°C, whereas in the summer, it decreased within the same interval[28]. With the aid of the FLUENT software, a numerical simulation was conducted based on Computational Fluid Dynamic (CFD) to estimate the heating and cooling capacity of earth-air-pipe heat exchanger systems[29,30]. An additional study of a model used a one-dimensional transient analytical approach to detect the influence of burial depth on the thermal performance of EAHE systems[31].

According to Nayak et al.[32] another study evaluated EAHE system for greenhouse heating. The system in that study combines a photovoltaic/thermal collector (PV/T) and an EAHE in different configurations. During the winter months, it was seen that the greenhouse's interior temperatures rose by around 7.1-8.2 °C at night. It is worthy to note that different European countries have licensed REHAU Ecoair[TM] for the implementation of the EAHE system when constructing large-scale buildings. Beneath a TESCO supermarket building in Zdzieszowice, Poland, there were 0.2 m heat transfer pipes with 0.5 m header pipes. Regarding that project, REHAU used an EAHE system to address heating and cooling needs of 3,250 m^2 of this building space. Heat transfer and header pipes combined to have total lengths of 700 m and 50 m, with 2700 m^3/hour air flow, respectively. A temperature of 15 °C increment in air temperature (from -2 to 13 °C) in the winter season was achieved with this system. This provided nearly half of the annual heating demand and was estimated to save 2,000 € per year. Additionally, the system generated an annual cooling output of 10,700 kW h, which increased the savings by € 1,000 from the conventional air conditioner[33]. In the Italian climate, an EAHE system was also used for both cooling and heating of an office building. The study concluded that it is an economical and feasible system[34]. An experimental study of an EAHE was conducted in France for heating and cooling purposes of the dining room of floor area 380 m2. This system was combined with 11 pipes which were buried under the ground. The diameter of the pipes and their depth were 0.2 m and 2 m respectively. The result was 14 kW of cooling power at a flow rate of 7200 m^3/hour throughout the months of July and August[35]. Rodrigues et al.[36] created a transient, numerical model that simulates the thermal performance of an

EAHE system for several soil types at three distinct locations in a Brazilian coastal area. For the modeling of the air flow inside the tube, as well as the calculation of the air temperature inside the tube, a set of differential equations defining continuity, momentum, and energy was used. For the soil temperature distribution, heat conduction equations were utilized.

Siepsiak[37] evaluated an EAHE technique in Poland for about three years, with energy efficiency as an indicator in several freshening scenarios. The system provided approximately 124 W of cooling per hour and 257 W of heating. This highlighted the system's capability in improving indoor thermal comfort. The outcomes were useful to identify the ideal HVAC system scenarios for engineering designs. Brata et al.[38] evaluated the performance of a EAHE in Timisoara, Romania. The system featured a 35 m long exchanger pipe with a 0.2 m diameter, buried at a depth of approximately 2 m. During winter, it supplied around 31% of the energy required by the ventilation system. A research conducted by Amanowicz and Wojtkowiak for multi-and single pipe EAHE systems in Central Europe, concentrated on energy gains and power usage. The findings indicated that a multipipe EAHE can effectively alternate with a single-pipe system while maintaining similar thermal efficiency and pressure losses, provided that a tube with the appropriate diameter is selected. Thus, more appropriate for temperate climates[39]. Another investigation[40] examined the efficiency of an EAHE system in Bechar, Algeria. The setup had a PVC pipe with a diameter of 11 cm and 66-meter-long, buried at 1.5 m under the ground. During the humidification, this system achieved an increment of 19% in relative humidity and a drop of 27% during dehumidification. These findings highlight the EAHE's capability to improve hygrometry of buildings in arid regions. A study of EAHE systems with pipe lengths between 67 and 107 m, buried at approximately 2 m, and functioning under different air velocities (500 m^3/h, 2500 m^3/h and 3000 m^3/h) was conducted in Germany. A variation of 16 to 51 kWh/m^2 was realized for the yearly heating energy outcome of the system, while between 12 and 23.8 kWh/m^2 was reported for the annual cooling energy gain[41].

Kaushal[42] conducted an experiment in the Lower Himalayan region, where an EAHE system with 0.5 m/s airflow rate and pipe length of 60 m demonstrated a peak heating potential of around 28 kWh and cooling potential close to 15 kWh. The EAHE system also contributed to reducing energy consumption for heating by approximately 25–30%[43]. Xiao et al.[44] investigated the thermal behavior of an EAHE system integrated into a greenhouse in Northern China. The research merged CFD simulations with experiments to assess the system's effectiveness across different seasons. The outcomes of the investigations indicate that the EAHE system raised the greenhouse's night-time air temperature by 1.4 °C in winter, while in summer it decreased the daytime air temperature by 2 °C. Furthermore, the variations between the EAHE's inlet and exit air temperatures were 9.3 °C in winter and 10.6 °C in summer with an efficiency of 22.49% and 23.52%, respectively. Another study by Jilani[45] utilized CFD simulations to evaluate a Quonset-type greenhouse integrated with thin-film photovoltaics (GiTPV) and an EAHE system. The results demonstrated that the EAHE could enhance the greenhouse air temperature by 8.2 °C and the plant temperature by 9.1 °C at a mass flow rate of 0.5 kg/s. The GiTPV system enables self-sustainability in cold climates by delivering daily electrical energy production of 15 kWh. Khorchef et al.[46] employed a full factorial design to identify optimal configurations of EAHEs for winter and summer. The focus was on three variables, airflow, pipe length and thermal conductivity. The research highlights that air velocity has a considerable influence, thermal conductivity had a lesser, but still significant impact while pipe length had the most significant influence on the temperature regulation. The pipe length accounted for more than 59.3% of variability in winter and 49.5% in summer.

Goyal et al.[47] designed and analyzed a unique bank-type EAHE in an experimental setting. The research aimed to assess its effectiveness in the hot, dry, and humid climate of Ferozepur, India. With a decrease in ambient temperature to 29 °C, this study demonstrated an improved accuracy compared to previous investigations. Zhang et al.[48] investigated the operation and energy efficiency of EAHEs in Lanzhou, China. Applying orthogonal simulation, the research identified that the optimal system parameters are 7 m/s as airflow velocity, 20 m pipe length, 4 m burial depth and diameter of 0.1 m. These selection enhanced heat transfer efficiency by 38% and reduce unit heat transfer cost by 8,000 CNY/kW compared to the original design.

Table 1: Summary of new case studies on the EAHE behaviour in different sites.

Authors	Location	Performance achieved / design parameters	References
Siepsiak	Poland	The system supplied around 124 W of cooling per hour and 257 W of heating.	[37]
Brata et al.	Timisoara, Romania	The system has a pipe length of 35 m with a 0.2 m diameter, buried at a depth of approximately 2 m. During winter, it provided around 31% of the energy required by the ventilation system.	[38]
Sakhri et al.	Bechar, Algeria	The system had a length of 66 m, PVC pipe with a diameter of 11 cm and, buried at 1.5 m under the ground. During dehumidification this system achieved a drop of 27% and during the humidification, an increment of 19% in relative humidity.	[40]
Pfafferott	Germany	Pipe lengths between 67 and 107 m, buried at approximately 2 m, and functioning under different air velocities (500 m³/h, 2500 m³/h and 3000 m³/h). Outcome of the system was between 12 and 23.8 kWh/m² as the annual cooling energy while,16 to 51 kWh/m² is as a yearly heating energy.	[41]
Kaushal	the Lower Himalayan Region	The setup has 0.5 m/s airflow rate and pipe length of 60 m. It demonstrated a peak heating potential of 28 kWh and cooling potential close to 15 kWh. The system contributed to reducing energy consumption for heating by almost 25–30%	[42], [43]
Xiao et al.	Northern China	The differential between the input and outlet air temperatures of the EAHE was 9.3 °C in winter and 10.6 °C in summer, with an efficiency of 22.49% and 23.52%, respectively.	[44]
Goyal et al.	Ferozepur, India	Assess EAHE effectiveness in the hot, dry, and humid climate. It show a decrease in ambient temperature to 29 °C	[47]
Zhang et al.	Lanzhou, China	The optimal system parameters are 20 m pipe length, 7 m/s as airflow velocity, diameter of 0.1 m and 4 m burial depth. This design reduce unit heat transfer cost by 8,000 CNY/kW and improved heat transfer efficiency by 38%.	[48]

2. EAHE system: Operating principle and Ground Temperature Profile

The fundamental concept of EAHE is based on multi- or single pipes that are buried under the ground. One terminal of the pipe system (the inlet) serves as an ambient outdoor air entry point, while the opposite terminal (the outlet) evacuates air into the inside of a building. Fresh air enters through the pipe inlet, moving within the pipe and exchanging heat with walls of the pipe which are in contact with the underground soil. In this manner, the air in the tube is conditioned as it travels down the pipe. Heat is transferred then by convection to or from the soil around it and by conduction in the pipe wall [49,50].

Profile of ground temperature indicates how soil temperature changes at different depths under the surface (Figure 1). It generally displays the fluctuations of temperatures near the surface which is in response to daily and seasonal variations. Meanwhile, deeper levels tend to sustain more consistent temperatures over the year. This profile plays an important role in the design of EAHE systems.

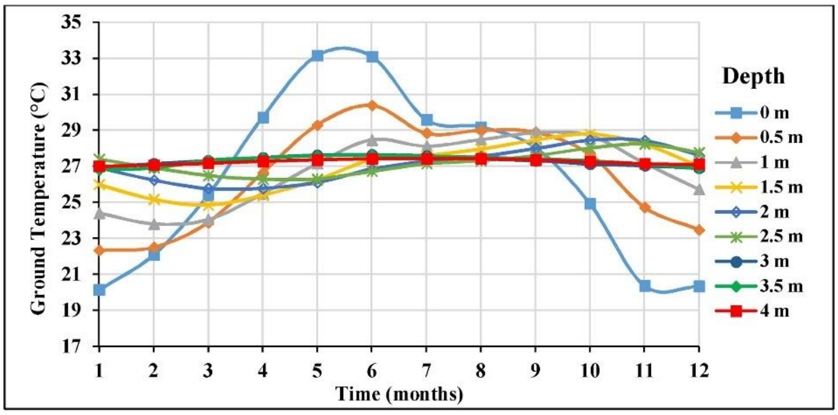

Figure 7: Annual variation in temperature distribution at different depths in Ajmer, India[51]

3. Classification of the EAHE

The significant advancements of EAHE leads to diverse system types recognized by changes in configurations, materials and control strategies. The classification of this technology can be based on pipe orientation, pipe material, pipe configuration and airflow configuration. In addition to the factor of development in control strategies: combination and integration with renewable energy sources and automated control systems.

EAHE as sustainable solution can be effectively used alone, but recently, hybrid configurations is often selected. Several researchers are working on combining EAHE with various passive techniques to enhance system performance. Figure 2 presents the classification of this technology that aids in comprehending the development and optimization of EAHE systems.

The EAHE technique can be classified based on two macro categories:

a. Source of air entering the system:

- ***Open- loop system:*** the outdoor ambient air (fresh air) is passing through the EAHE pipes. While, the air is drawn into the buried pipes, it transfers thermal energy with the adjacent soil before it enters the room (Figure 3.(a)).
- ***Closed- loop system:*** recirculating indoor air is used rather than fresh air. The air is extracted from the inside of the building, transported through the subterranean pipes to facilitate heat exchange with the surrounding soil, and then returned to the building (Figure 3.(b)).

Based on the literature, the open-loop system is often chosen over the closed-loop system since it provides fresh air[52].

b. Pipe layout:

- **Horizontal EAHE system (HEAHE):** defined by the installation of pipes in parallel to the ground surface (horizontal lines). It presents specific benefits. Among them, its simplicity in the implementation in regions where groundwater levels are shallow. Though, it requires large ground space, this system still easier and cheaper to install. Particularly, in open spaces. However, its thermal efficiency may be affected by changes in soil temperature and moisture levels, which typically vary more strongly near the surface[53].
- **Vertical EAHE system (VEAHE):** the pipes are positioned in a vertical orientation within boreholes that extend deep into the ground. VEAHE are frequently favored in urban or highly populated areas where land is limited, as well as in situations that demand enhanced heat transfer rates[54]. This system offers multiple benefits more than the horizontal counterparts by tapping into deeper ground temperatures[55]. As the depth increases, ground temperature becomes less affected by external environmental conditions. This reduces the influence of seasonal surface temperature changes, leading to more consistent and reliable yearly heat transfer. That increase the system's overall performance[56,57]. However, it usually requires drilling equipment and is more expensive to install.

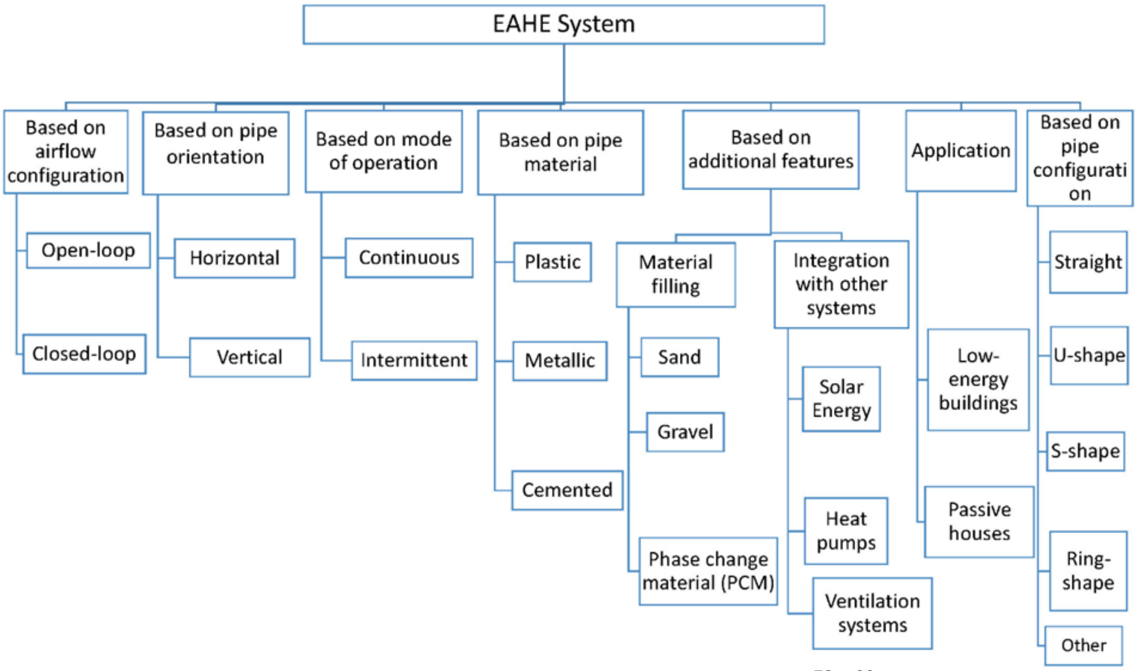

***Figure 2: EAHE system classification*[58 – 60]**

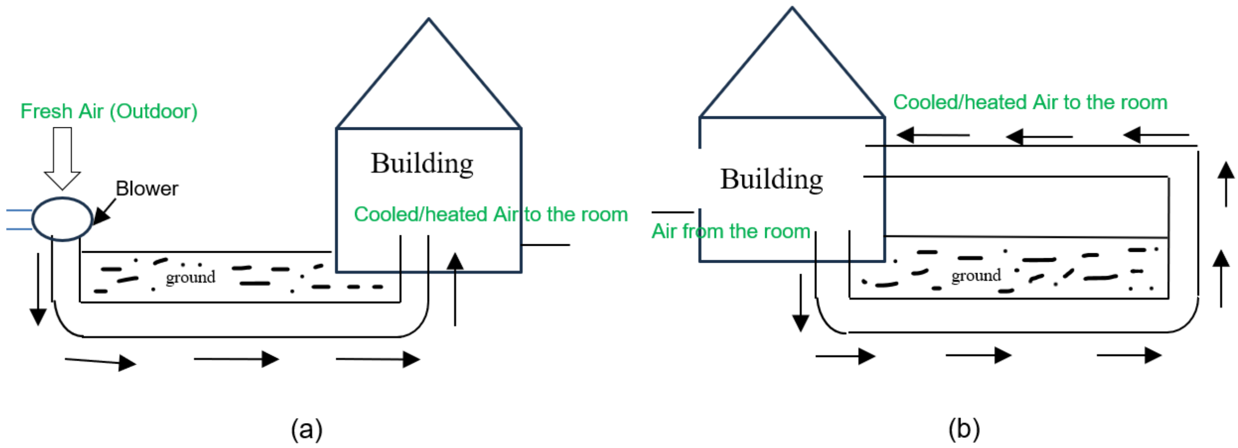

Figure 3: EAHE with (a) open loop and (b) closed loop

4. Heat Exchange Mechanisms within EAHE

a. Conduction and convection concept:

Heat exchange mechanisms enable the transmission of heat between the ambient air and the ground in EAHE systems. The fundamental principle of the operation of EAHE is based on two primary heat exchange mechanisms:

Conduction: using it as a means of transferring heat, the soil moves heat from warmer (higher temperature regions) parts to cooler parts (lower temperature regions). By passing through buried ducts or tubes in contact with the ground, the incoming ventilation air can gain or lose heat.

Convection: since the air and ground are at different temperatures, convection occurs when air flows through underground ducts. The heat exchange process is enhanced when cooler air absorbs heat from warmer ground and vice versa. Convection plays pivotal role in the heat transfer mechanisms for EAHE. This mechanism can be considered as natural convection. However, according to the literature, it is usually predominantly forced, driven by a mechanical blower responsible for moving the air within the pipes. Therefore, improving the heat exchange process. For example, Bansal et al.[61] analysed the performance of EAHE for cooling purposes by varying several factors (pipe material and air velocity). Their results presented that the air speed highly influenced the thermal behaviour of the system. In general, the effect of natural convection is negligible (minor) when comparing it to the forced convection impact.

Through a combination of these mechanisms, the ground temperature moderates the incoming ventilation air's temperature, bringing the indoor temperature closer to equilibrium and achieving a more comfortable indoor environment.

b. Fundamental equations in the EAHE physical model:

Heat transport and fluid dynamics define the performance of an Earth–Air Heat Exchanger (EAHE) system. Mass, momentum, and energy conservation are the basic equations applied in EAHE system modeling of physical phenomena. The following are the key equations typically applied:

- ***Energy Balance of the Air Stream***

Under the assumption of steady-state, one-dimensional flow with minimal axial conduction, the energy balance can be expressed as:

$$\frac{\partial Ta}{\partial t} + v\frac{\partial Ta}{\partial x} = \frac{hP}{\rho_a c_{p,a} A}(Ts - Ta)$$

where: *Ta*: temperature of air inside the pipe (K), *Ts*: temperature of the pipe wall or surrounding soil (K), *x:* distance along the pipe (m), *v*: velocity of air (m/s), *h*: convective heat transfer coefficient (W/m²·K), *P*: inner perimeter of the pipe (m), *A*: cross-sectional area of the pipe (m²) and ρ is the air density (kg/m³).

- ***Forced Convection and Thermal Conductivity:***

The process of heat transfer from the air to the inner wall of the pipe is dictated by forced convection. The convective heat transfer coefficient *h* is frequently determined through the Dittus–Boelter equation:

$$h = \frac{Nu.ka}{D} \quad \text{where } N_u = 0.023.Re^{0.8}.Pr^{0.3}$$

with: *Nu*: Nusselt number, *Re*=$\frac{\rho v D}{\mu}$: Reynolds number, $r = \frac{C_p \mu}{ka}$: Prandtl number, *h*: convective heat transfer coefficient (W/m²·K), *ka*: thermal conductivity of air (W/m·K), *D*: pipe diameter (m), *ρ*: air density (kg/m³), *v*: air velocity (m/s), μ: dynamic viscosity of air (Pa·s) and *cp*: specific heat of air (J/kg·K).

The adjacent soil is considered a semi-infinite medium, facilitating radial heat conduction from the buried pipe. The transient heat conduction in cylindrical coordinates is described as follows:

$$\frac{\partial Ts}{\partial t} = \alpha s \left(\frac{\partial^2 Ts}{\partial r^2} + \frac{1}{r}\frac{\partial Ts}{\partial r}\right)$$

where: *Ts*: temperature of the soil (K), *r*: radial distance from the pipe center (m), αs: thermal diffusivity of soil (m²/s), *ks*: thermal conductivity of soil (W/m·K) and *ρs*: soil density (kg/m³).

- ***Heat Transfer Equation in a Buried Pipe:***

The total heat transferred to the air while passing through a buried pipe is expressed as follows:

$$Q_h = \dot{m}C_p(T_{out} - T_{in})$$

where: $\dot{m}$ is air mass flow rate (kg/s), C_p is air specific heat (J/kg.K), T_{out} is EAHE pipe outlet air temperature (°C), and T_{in} is EAHE pipe inlet air temperature (°C).

- ***Pressure Drop in the Earth-to-Air Heat Exchanger (EAHE)***

The pressure drop in the pipe due to friction is a key factor in EAHE performance, as it affects fan power consumption. It is typically calculated using the Darcy-Weisbach equation:

$$\Delta P = f\frac{L}{D}\cdot\frac{\rho v^2}{2}$$

with: ΔP: pressure drop (Pa), *L*: length of the pipe (m), *D*: internal diameter of the pipe (m) and $f = \frac{64}{Re}$ if Re < 2300 while $f = 0.3164\,.Re^{-0.25}$ if Re > 4000[62,63]

The effectiveness ε of an EAHE system quantifies how efficiently the system transfers heat between the air and the ground, relative to the maximum possible heat transfer and it can be calculated as:

$$\varepsilon = \frac{Tout - Tin}{Tsoil - Tin}$$

where: *Tout*: temperature at the outlet of the pipe (°C), *Tin*: temperature at the inlet of the pipe (°C) and *Tsoil*: is soil temperature (°C).

5. Advantage of the EAHE system

EAHE systems provide an eco-friendly method for energy conservation by using the soil's consistent temperature for heating and cooling purposes. They serve multiple benefits:

- By harnessing the stable subterranean temperature to pre-treat incoming air, when it is functioning as a primary element unit to another HVAC system. It plays an important role in reducing the load of such HVAC system, contributing to significant energy savings in both heating and cooling seasons.
- Supporting sustainability and environmental protection aspect by cutting down energy consumption from conventional systems and reduces greenhouse gas emissions.
- It enhances building thermal comfort and indoor air quality.
- Featured by improving building energy saving when it is combined with other renewable energy technologies (e.g., solar chimneys, heat pumps).

6. Impact of design parameters on the EAHE performance

a. Soil's undisturbed temperature

The soil's stable temperature is a crucial factor in the construction of an EAHE system. Given homogeneous soil with constant thermal diffusivity, the temperature at each depth z and time t may be approximated by the following formula [64,65]:

$$T_{z,t} = T_m - A_s \exp[-z\left(\frac{\pi}{365\alpha_s}\right)^{\frac{1}{2}}]\cos\{\frac{2\pi}{365}[t - t_0 - \frac{z}{2}\left(\frac{365}{\pi\alpha_s}\right)^{\frac{1}{2}}]\}$$

where temperature of the ground at depth *z* (m) and time *t* (s) is denoted at $T_{z,t}$, whereas T_m represents the average soil surface temperature (°C). The amplitude of soil surface fluctuation (°C) is denoted as A_s, and α_s representing soil thermal diffusivity (m²/s; m²/day), *t* signifies the time passed from the commencement of the calendar year (day), and t_o indicates the phase constant of the soil surface (s; days).

Accurately calculating the value of soil's undisturbed temperature is challenging due to the frequent lack of knowledge regarding soil properties. Furthermore, it is specified for average soil characteristics.

Thus, the undisturbed temperature of the soil is a theoretical value that may be regarded as equivalent to the yearly average soil surface temperature of a certain area. Additionally, usually the soil surface temperature is presumed to be equivalent to the ambient air temperature.

b. Impact of Burial Depth

The ground's temperature shows substantial depth-dependent fluctuation[66]. To maximize system performance while reducing installation costs, it is necessary to determine the ideal burial depth for EAHE systems. A clear temperature gradient where temperatures decrease as the depth increases have been noted in many investigations[67–69]. Nonetheless, it was noted that the enhancement in performance was minimal beyond depths of 4 m[70–72]. Variations in depth are impacted by variables including local ground temperature profiles, soil characteristics, and climatic conditions. Sanusi et al.[73] determined that 1 m is the ideal depth in Malaysia, while Khan et al.[74] advised 4.5 m for Lahore, Pakistan and Babar et al.[75] suggested 3.96 m as suitable for Sahiwal, Pakistan. In another investigation, Badescu[76] concluded that the depth of the buried pipe enhances the thermal potential of the system, however limited to a maximum of 4 meters. Mihalakakou et al.[77] examined the impact of pipe depth on performance in cooling mode, implementing depths of 1 m, 2.1 m, and 3.2 m. The analyses revealed that a pipe positioned at a depth of 3 m gave the most effective cooling results. Wu et al.[78] conducted an examination on the effectiveness of the EAHE system at different depths of buried pipe. The temperature variations of the air were observed to range from 7.2 ˚C to 31.7 ˚C, and from 5.6 ˚C to 30.6 ˚C at depths of 1.6 m and 3.2 m of the pipe, respectively.

c. Impact of pipe diameter and length

Ghosal and Tiwari[79] examined the influence of buried pipe diameter and length, its depth and mass flow rate of air temperatures inside a greenhouse in addition to soil types. Based on the result an increment of pipe length between 30-50 m affected the EAHE performance directly. Consequently, a rise in air temperature during the winter and a drop during the summer were observed. The primary reason for this is that an extended pipe length provides a greater duration for thermal heat exchange to occur between the air within the pipe and the ground[80.] Simultaneously, regarding the impact of the underground pipe diameter of the EAHE, an increase in diameter leads to reduced greenhouse air temperatures in winter and higher temperatures in summer. This phenomenon is attributed to the reduction in heat transmission from the soil or a decreased convective heat transfer coefficient resulting from an increase in pipe surface area and a decrease in air flow velocity. Another investigation[81] confirms that the diameter of the pipe plays a crucial role in determining the thermal efficiency of environmentally sustainable technology. At specific depths, the temperature of the basement stays stable, exhibiting higher values during the winter months and lower values in the summer. Ahmed et al.[82]examined the influence of pipe diameter on the thermal performance of a horizontal earth pipe system, utilizing pipes with diameters of 0.400m, 0.200 m, 0.125 m and 0.062 m. They found that the smaller diameter pipe yields the most effective cooling effect.

Regarding the length of pipe effect, Agrawal et al.[83] observed that the EAHE air temperature decreases in the summer and rises in the winter season as the length of the pipeline increases. Yet, the performance rate fluctuates based on climatic conditions and geographical location. In this experiment, it was observed that for the 50 m pipeline length, the outlet temperature of the EAHE system consistently matched the basement temperature. Bansal et al.[84] performed an analysis of thermal performance for different lengths of EAHE pipes in India. The study also examined the impact of soil thermal conductivity and the duration of continuous EAHE operation. The findings from an investigation by Zhang et al.[67] indicate that an optimal pipe length of 80 m is recommended to ensure effective pre-heating and pre-cooling performance for the EAHE-assisted building air conditioning system year-round. Given the balance between thermal efficiency and construction expenses of the EAHE system, an additional increase in pipe length might not result in beneficial results. In this investigation the influence of pipe diameter was also conducted. It ranges from 100 mm to 200 mm, affecting the airflow rate within the buried pipe. Increasing the pipe diameter has a minor effect on outlet air temperature, resulting in a small rise during summer and a decrease in winter. The typical precooling performance and daily cooling capacity range from 9.5 °C to 9.2 °C and from 20.1 kWh to 19.5 kWh, respectively. Comparable outcomes can be noted during the heating season. In an EAHE system, the difference in air temperature between the inlet and outlet of the pipe is enhanced by extending the length of the pipe[85], while it diminishes with a rise in pipe diameter[8682]

d. Impact of material of the pipe

The conclusion drawn from various studies indicates that pipe materials selection primarily centers on the material's availability and associated costs. The outlet temperature of the buried pipe can be more effectively reduced by using materials with a higher thermal conductivity. Parametric research was conducted in EnergyPlus software to compare several pipe materials, specifically PVC, polyethylene (PE), clay, Polyvinyl Chloride (PVC) and brick[73]. This research expands the classification of subterranean pipelines. The results indicated that clay pipes produce the lowest output air temperature between the four types of pipes. In another side, Bansal et al.[87] examined the thermal capacity and evaluated the air conditioning potential of two EAHE systems constructed mostly from steel and PVC materials. The authors determined that the pipe material had no strong effect on the effectiveness of the EAHE system. Serageldin et al.[88] tested the efficiency of an EAHE in Egypt's hot and cold climate. A mathematical model for energy conservation based on one-dimensional, unsteady and quasi-state equation were used or produced?. In addition, a three-dimensional steady-state CFD ANSYS Fluent simulation model for predicting air and soil temperatures have been developed. Three various pipe materials were utilized: PVC, steel, and copper. Output air temperatures were 19.8 °C for copper and steel and 19.7 °C for PVC pipe. This led to the conclusion that there is no noticeable difference in the output air temperature for the different pipe materials. Menhoudj et al.[89] conducted a comparison of the performance of the EAHE system using two pipe materials, Zinc and PVC. The findings indicated that the air temperature drop was 6.5°C for the Zinc pipe and 6°C for the PVC pipe. Consequently, the cost of the pipe material and its lifespan come out as the most important factors in the selection process, rather than the heat transfer properties. All the above-stated research results presented that the material of the pipe has a minimal (negligible) effect on the thermal performance of the EAHE system.

e. Impact of air flow

The airflow rate predominantly dictates the system's capability for cooling or heating and its overall performance[90,91]. Benrachi et al.[92] demonstrated that an increase in velocity of the wind from 2 m/s to 2.5 m/s led to a significant reduction in cooling effectiveness, dropping from 60% to 33%. Furthermore, Bhandari et al.[93] investigated how airflow velocity affects heat transfer rates, showing that a reduction in velocity and an increase in diameter lead to a lower pressure drop across the pipe length throughout airflow. Bansal et al. examined the influence of flow velocity (2.0, 3.2, 4.0, and 5.0 m/s) and contrasted the simulation results with the experimental data obtained. The outcomes showed a reliable agreement between experimental data and simulated results. Using a pipe length of 24 m gives cooling performance vary from 8 to 13 °C for the above speeds air[61,87]. Dubey et al.[94] observed a decrease in air temperature from 9 to 4.2 °C, alongside a reduction in the coefficient of performance (COP) from 6 to 3.7 as the air velocity varied from 4 to 12 m/s. A mathematical parametric study was carried out by Ahmed et al.[82] employing four separate airflow rates to assess the impact of air velocity on the thermal performance of the pipe–Earth technique during the cooling process. The report indicated that an air flow of approximately 1.4 m/s was the optimal choice for summer efficiency. Other studies by Mihalakakou et al.[95–97] documented how air velocity affects the EAHE system's ability to maintain thermal comfort. The researchers looked at the EAHE system's evaporative temperature and how it changed in response to a modest change in air velocity. It has also been noted that the system's heating capacity decreases as the air velocity increases. The effectiveness of an EAHE system may be measured by the number of Reynolds, according to Abdelkrim et al.[98]. They found that when the Reynolds number increases, the out-flow air temperature rises because the air residence time within the pipe reduces.

7. Effect of soil properties on the EAHE's system performance

The thermo-physical qualities of the soil have a significant impact on the thermal performance of an EAHE system. Soil thermal conductivity and diffusivity are two important parameters of the EAHE system. Due to the high temperature difference and rapid heat transfer rate, the system performs better as the thermal conductivity increases. High thermal diffusivity, on the other hand, increases the quantity of heat transmission from soil to pipes via conduction and from pipes to air via convection[17,51]. Thermal conductivity, specific heat, and density of soils are the most important thermo- physical properties that determine the performance of the EAHE system. Therefore, as the most important soil property for the EAHE system, thermal diffusivity plays a significant role. Because heat accumulates in the soil layers near the pipe and does not transfer to the next layers quickly, the soil gradually becomes thermally saturated, reducing the performance of the EAHE system[99]. There is a direct correlation between thermal conductivity and thermal diffusivity of soil. The investigation of Mathur et al.[100] present that soil with a higher thermal diffusivity transfer heat more rapidly from nearby soil to outer subsoil, which increases heat transfer rates. In this study the thermal performance of EAHE systems was evaluated using three different soil thermal diffusivities: $1.37\times10^{(-7)}$ m^2/s,$4.37\times10^{(-7)}$ m^2/s and $9.69\times10^{(-7)}$ m^2/s. It is important to note that soil thermal conductivity is significantly affected by temperature. In the study by Bansal et al.[84] the impact of duration of operation and the thermal conductivity of the soil on the EAHE performance was analysed by choosing 3 different soils. They highlighted the significance of involving soil thermal characteristics in the design and functioning of EAHE. They observed that even during extended continuous operation, EAHE system installed on soil with enhanced thermal conductivity has higher thermal performance. The phenomenon of improved thermal behaviour of soil characterised by high thermal conductivity is attributed to the fast dissipation of heat from the soil layers Moreover, Donde and Maurya[101] experimentally characterised the thermal property of soil for EAHE applications. They investigated the influence of different soil types on the system performance, particularly, assessing the soil's potential to store or dissipate heat. Their results stated that for prolonged continuous operation of EAHE, the soil with lower thermal storage capacity but higher thermal conductivity and diffusivity, is preferable. This soil may rapidly transfer heat from the pipe, ensuring a greater difference in temperature between the air within the pipe and the adjacent soil. Therefore, enhancing heat exchange efficiency.

8. Opportunities of integrating EAHE with other system (Future work):

In recent years, research and development towards energy saving has grown as a significant focus for researchers worldwide. For efficient energy saving, the use of EAHE as primary pre-conditioning unit to another system should be more analyzed.

Besides conditioning air for indoor comfort, the EAHE system may be modified for preheating the combustion air supplied to boilers, furnaces, or industrial burners in winter. This is particularly advantageous in settings where external temperatures fall significantly beyond the soil temperature; where the cold ambient air is drawn through the pipes of the EAHE and absorbs heat from the warmer ground. The preheated air is then fed into the combustion chamber. This reduces the energy needed to reach optimal combustion temperatures and provides complete combustion and lower emissions; helps in fuel saving while improving combustion quality.

In another applications, when combining passive geothermal energy with active air distribution, EAHE may be linked with an Air Handling Unit (AHU) to raise the energy efficiency of heating, ventilation, and air conditioning systems in buildings[102]. In this configuration, outdoor air is sent through underground pipes, typically located 1.5 to 4 m deep, where it participates in heat exchange with the surrounding soil. The air is cooled or heated depending on the season. Later, the temperature-moderated air exits the pipes and is delivered to AHU. It additionally filters, humidifies or dehumidifies, heats, or cools the air as necessary to achieve the preferred indoor comfort conditions. The AHU afterwards distributes the treated air within the building using several terminals. This will result in various benefits. For instance, in energy savings where it decreases the thermal load on the AHU by pre-conditioning the air; reduces the HVAC size and enhances comfort due to the better stable and comfortable indoor air conditions.

Conclusion

With the growing demand for sustainable building solutions and energy saving, EAHE systems are likely to become more widely adopted in the future. An overview of the EAHE system has been provided in this study, along with some important parameters to consider. These are the key conclusions.

- The EAHE system can provide adequate cooling and heating for small and large buildings with substantial energy savings.
- The performance of EAHEs is affected by various factors, such as the type of soil, the depth and length of the system, the airflow rate, and the thermal properties of the heat exchanger. This technology should also be designed to minimize heat losses during the heating and cooling cycles, to maximize the system's efficiency.
- The cooling and heating capacity of the EAHE system increases with installation depth. However, beyond a certain depth (more than 4 m), no substantial enhancement in performance is expected. Rather, the excavation cost of the trench escalates with the depth of the pipe.
- Research findings indicate that the pipe material has a minimal (negligible) effect on the thermal performance of the EAHE system. Consequently, the expense of the pipe, its longevity, and its corrosion resistance are essential criteria for choosing the pipe material.
- PVC pipe is favored for the EAHE system due to its low cost, flexibility, superior corrosion resistance and ease of installation.
- The length of the buried pipe plays a critical role, as it directly affects the heat transfer surface area and the residence time of the air-fluid. Therefore, the extended pipe offers an extensive route for heat transfer and 80-120m is the recommended pipe length.
- EAHE pipe with a smaller diameter offers the most effective cooling and heating impact.
- A higher moisture content and good thermal conductivity of the soil surrounding the EAHE pipe can improve the performance of the system. Thus watering the ground is a suitable solution to raise the thermal conductivity of the soil.
- Better thermal performance is achieved at lower air velocities compared to higher flow rates. This phenomenon occurs because the air remains in contact with the surrounding soil for a longer duration, allowing more effective heat exchange. In contrast, at higher velocities, the reduced residence time limits the air's ability to reach thermal equilibrium with the soil.
- A system such as this should be used in extreme atmospheric conditions since the temperature difference between the ambient air and undisturbed ground will be greater.

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Skúmanie vzduchového výmenníka tepla ako inovatívnej a udržateľnej aplikácie na chladenie a vykurovanie: výbery z literatúry

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Súhrn

Energetické potreby a alarmujúce emisie CO2 na celom svete pritiahli značnú pozornosť k vývoju a implementácii obnoviteľných zdrojov energie a systémov na úsporu energie. Dôležitým aspektom termodynamiky Zeme je, že jej teplota zostáva nízka a konštantná počas celého roka. V porovnaní s vonkajšími teplotami vzduchu. Teplota zeme sa používa v systémoch výmenníkov tepla zem-vzduch (EAHE) na predúpravu vzduchu pred jeho vstupom do budovy. Účinne znižuje spotrebu energie tradičných systémov vykurovania, vetrania a klimatizácie (HVAC). Tento článok poskytuje stručný prehľad aplikácie technológie EAHE pri vykurovaní a chladení priestorov. Článok tiež zdôraznil vplyv rýchlosti vzduchu, priemeru, hĺbky, typu materiálu a dĺžky zakopaného potrubia na tepelné správanie systému EAHE. Výkon EAHE nie je výrazne ovplyvnený materiálom potrubia, na rozdiel od dĺžky a priemeru potrubia. Zistenia naznačujú, že najúčinnejší chladiaci a vykurovací účinok zabezpečujú potrubia s menšími priemermi. Okrem toho je svedčiace o tom, že dlhšie potrubia zlepšujú chladiaci/vykurovací výkon v systéme EAHE. Celkovo dostupné finančné prostriedky na výstavbu určujú typ materiálu a dĺžku potrubia, ktoré sa majú použiť pre efektívny systém EAHE. Nižšie rýchlosti vzduchu poskytujú vyšší tepelný výkon ako vyššie prietoky. Okrem toho integrácia EAHE s inými systémami HVAC môže zvýšiť úsporu energie. Tieto systémy môžu typicky prispieť k zníženiu spotreby energie na vykurovanie približne o 25 – 40 %. Toto percentuálne rozpätie by mohlo viesť k účinnosti EAHE takmer 0,9.

Klíčová slova: *Teplota pôdy; systém výmenníka tepla zem-vzduch; udržateľná energia; tepelná pohoda; vykurovacie a chladiace systémy; obnoviteľná alebo zelená energia.*