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Review Article

Parametric Study of Earth-Air Heat Exchanger based on Physical Experimentation

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The depletion of non-renewable energy resources at an alarming rate has instigated a heightened interest in renewable energy systems or those that use minimal non-renewable energy sources. Although the earth's temperature varies based on depth and ambient temperature, it reaches a constant temperature known as Earth's Undisturbed Temperature (EUT) at a certain depth. The EUT has been utilized to preheat or pre-cool the ambient air via an Earth Air Heat Exchanger (EAHE), as it is lower than the ambient temperature in summer and higher than the ambient temperature in winter. Researchers across the world have conducted physical and numerical experiments to assess the EAHE's performance under various inlet parameters and materials. This paper presents a review of the findings by various researchers, along with their novel and innovative ideas.

Keywords: Cooling or heating potentials, Earth air heat exchanger, Earth's Undisturbed Temperature, Energy Saving, Temperature difference

1 Introduction

Air conditioning is essential for ensuring the comfort and productivity of individuals in both work and home environments, particularly in areas with extreme weather conditions. However, the consumption of non-renewable energy sources required for air conditioning is significant. To address this challenge, researchers worldwide have been studying various techniques and technologies that employ renewable energy sources to minimize dependency on non-renewable resources.

One such technology is Earth-to-Air Heat Exchangers (EAHEs), which have been utilized as either a heat source or sink since ancient times, as evidenced by the use of wind towers and underground air tubes for cooling in Iran. EAHEs are essential in pre-cooling or preheating incoming air to the conditioned space or conventional air conditioning ventilation system, thus reducing the consumption of energy. This approach is particularly relevant given that air conditioning accounts for almost 20% of global electrical energy consumption and contributes significantly to harmful emissions, which has become a prevalent threat to humanity.

EAHE is a passive technology that has involved burying multiple pipes underground at a particular depth where the temperature of earth reaches a consistent level. Secondary fluid like air is then passed through these pipes. During this process, heat transfer occurs between the underground soil, pipe surface, and the flowing air, resulting in air that is either colder or warmer depending on whether its temperature is higher or lower than the EUT. EAHEs are classified based on various parameters, including the types of pipes (metallic, plastic, concrete), configurations (straight, U shape, serpentine/series, helical, coil, spiral, grid/parallel), the flow of air (open-loop, closed-loop, combination of both), orientation (vertical, horizontal), and the duration of operation (continuous, intermittent).

Several materials such as mild steel, polyvinylchloride, brass, and zinc aluminium, and various configurations like L, U, and Z have been experimented with by researchers to study their impact on the performance of EAHE. This paper will summarize all the findings in a concise and meaningful way that will be useful while designing the system for various applications.

2 Materials and Methods

The literature was extensively reviewed, revealing that only 25-30% of the work done on the use of EAHEs was experimental, while the rest comprised numerical or analytical simulations validated with

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other researchers' experimental results. This paper graphically depicts the parameters used by different researchers and discusses the findings under various headings. The most commonly varied parameters were the length, diameter, depth, and material of pipes. Some scholars examined the effect of soil conductivity or type on EAHE performance. Globally, experimentation was carried out in various countries.

As discussed below, the performance parameters taken for the same are temperature difference, cooling potential, effectiveness, and the effect of influencing parameters on the performance parameters.

2.1 Effect of velocity

Several studies have examined the impact of changes in velocity on air flow through pipes, and they have all reached the same conclusion: when air flow velocity increases, the temperature differential between inlet and outlet decreases[1–5]. This finding has been supported by multiple researchers, with the exception of one researcher in Indonesia who found that increasing velocity from 2 m/s to 3 m/s improved system effectiveness from 0.84 to 0.9. This result was subsequently confirmed with simulation. Figure 1 displays a line graph that illustrates how changes in velocity have affected the effectiveness reported in literature by different researchers.

2.2 Effect of pipe materials used

The experimental results were compared with numerical simulation results carried out using TRANSYS 16, and a good agreement was achieved. The performance of EAHE for two different materials, Zinc and PVC, was observed[6], and it was concluded that under the same geometric conditions, the cooling potential of PVC is better than that of Zinc. The cooling potential for Zinc was found to be 35.41%, and for PVC, it was calculated as 58.42%.

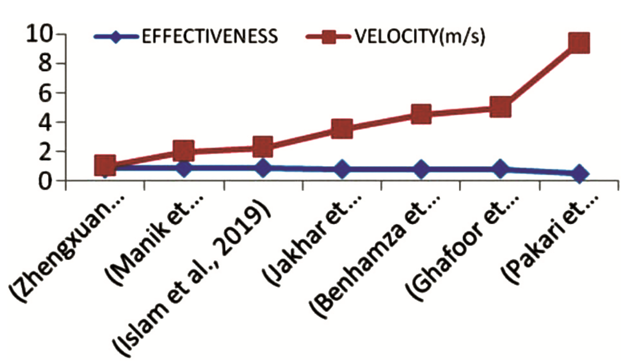

Fig. 1 — Impact of velocity of air on effectiveness achieved.

Two pipe materials, i.e., PVC and Zinc, were considered for study[7] under three different geo-climatic conditions of Algeria. It was concluded that Zinc is more efficient in temperate regions with a COP of 9.5, PVC better in an arid climate with a cop of 9.4, and both similar in steppe regions.

A pair of two materials were taken for study, i.e., PVC and steel[8] and similar EAHEs were built. It was concluded that the material of the pipe does not have much effect. The temperature difference obtained with PVC pipe was 8.4°C, and with steel was 9.8°C, which is not very significant considering the difference in cost of the two materials. Steel pipes are almost five times costlier than PVC. The difference is attributed to the fact that steel has higher thermal conductivity than PVC.

Two pipe materials, PVC and Zinc, have been studied under identical conditions in winter season[9], and it has been noticed that there is a temperature difference of 7.5°C with Zinc and 5.5 °C with PVC at the start of the winter season, then the difference reduced and when the season changed from winter to summer, this temperature difference approached zero. The performance of Zinc is found to be better than PVC due to its high thermal conductivity, but no material is effective during change of season.

Humidification of soil on the performance of EAHE has been studied on two different material pipes[10], i.e., steel and PVC, and it has been concluded that the difference in air temperature for both the materials for moist or dry soil is observed to be 10%. A Pie chart represents the proportion of different materials used in experimental research.

2.3 Effect of depth of EAHE

The field experiments were conducted on the cooling capability of EAHE in hot and humid climates[3] ,and it was observed that an increase in depth where the pipes are buried increases the temperature difference, and the maximum amount of cooling was obtained at 3 m depth. Although the inlet temperature varies considerably, the outlet temperature and humidity levels remain stable at higher depths.

EAHE sub-surface soil temperature model has been developed, and its performance has been evaluated under a constrained urban environment[11]. It was concluded that if the EAHE is installed below a building, the performance for 2 m depth is the same as that at 4 m. Thus it has been suggested that an EAHE may be installed at a shallower depth, thus reducing the excavation charges.

Variation of soil temperature with depth has been studied[12], and it was concluded that the temperature of the soil does change with depth and that the effect of ambient temperature on the temperature of soil decreases as the depth is increased, thus stable outlet temperature is achieved.

The effect of the depth of EAHE pipes on the effectiveness achieved is shown in Fig. 2.

2.4 Effect of diameter of pipes

A pilot EAHE was modeled and analyzed for its performance for year[1]. It was concluded that the temperature difference between inlet and outlet air is inversely proportional to pipe diameter because, with the increase in diameter, the air at the center of the pipe does not come in contact with the pipe material and goes as bypass air. The field experiments were conducted on the cooling capability of EAHE in hot and humid climates[3], and it was observed that a decrease in diameter increases the temperature difference, and the maximum amount of cooling was obtained with 0.16 m diameter and 3 m depth. Sensible cooling capacity achieved was 60-80%, and latent cooling capacity achieved was 17- 40%. The effect of the diameter of pipes used by various researchers for experimentation on achieved effectiveness is shown in Fig. 3.

2.5 Effect of length of pipe

A pilot EAHE was modeled and analyzed for its performance for year[1]. It was concluded that the temperature difference between inlet and outlet air is directly proportional to the length of the pipe, whereas the EAHE is more efficient in the cooling season. A pair of two materials were taken for study, i.e., PVC and steel, and similar EAHEs were built[8]. It was concluded that pipe length is directly proportional to the performance of EAHE. The more the pipe length, the more stable is the outlet temperature for the vertical heat exchanger as well[13]. The effect of length of pipes buried taken for experimentation by different researchers on effectiveness is shown in Fig. 4.

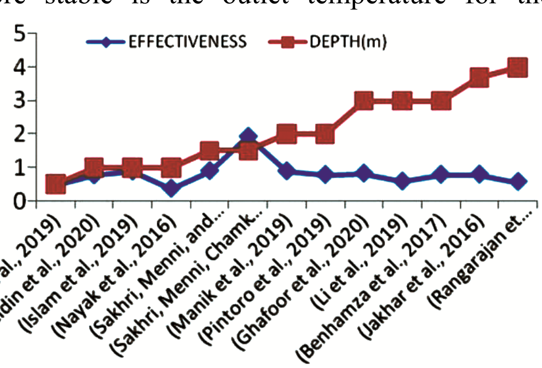

Fig. 2 — Effect of depth on the effectiveness.

2.6 Effect of vertical configuration

A vertical U tube Heat exchanger was studied experimentally and numerically, and it was concluded that the vertical design has better efficiency with the benefit of condensate water discharge[2] and high geothermal energy utilization efficiency[13]. Output temperature is almost constant, and the increase in velocity decreases the temperature difference achieved. The outlet temperature almost remained constant from 22°C-24°C at a velocity of 1m/s, though the inlet temperature ranged from 40 °C to 28 °C during the day.

2.7 Effect of continuous and intermittent operation

The field experiments were conducted on the cooling capability of EAHE in hot and humid climate[3] Moreover, it was observed that intermittent operation is always better than continuous operation as it helps the system recover.

Buildings with environmental quality management were studied[14], and it was concluded that the periodic use of EAHE gives time for the regeneration of soil

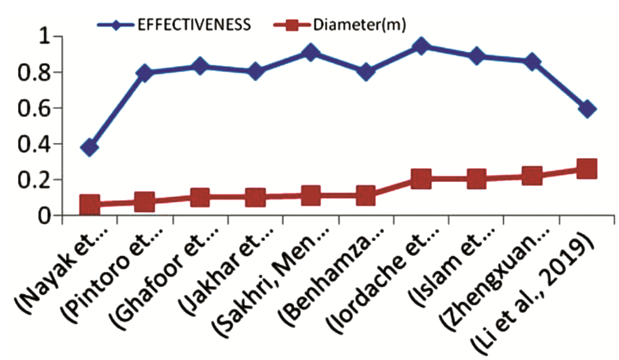

Fig. 3 — Effect of diameter on effectiveness achieved.

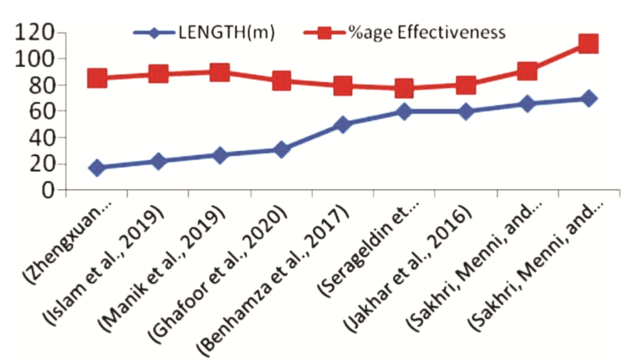

Fig. 4 — Effect of length on effectiveness achieved.

adjoining the EAHE pipes. It is also recommended that the buildings not be too tight to meet ventilation requirements as mechanical ventilation comes with a cost.

It was analyzed that continuous operation of EAHE reduces its optimum performance due to sudden increase or decrease of temperature of outside air[15]. So, in that case, some other source of inlet air like a ventilation unit should be considered. There should be some control system that controls the source of ventilation air.

2.8 Effect of airflow and pressure losses

1:4 scale experimental setup was set up to study the airflow in each branch pipe of multi-pipe set up[7], and it was concluded that due to non-uniform airflow in branched pipes, the performance might go down by 20% as compared to if the airflow is uniform in branched pipes. Also, the joint angle of 45 °C in place of 90 °C leads to a decrease in pressure losses by 30%, and the U type configuration is better than the Z type.

It was demonstrated that the efficiency of EAHEs also depends on the total pressure losses that arise due to uneven airflow through multi-pipe heat exchangers[16] Various parameters have been changed, like the number of parallel pipes, pipe length, and main pipe diameter. It was concluded that Z type structure has higher pressure losses than U type structure by 6-36%, and U type structure also improves airflow characteristics. Also, pressure losses are reduced if the main pipe diameter is 1.4 times that of parallel pipes. Longer pipes have higher pressure losses than shorter pipes.

2.9 Effect of soil composition

A pilot EAHE was modeled and analyzed for its performance for a full year[1], and it was concluded that the temperature difference between inlet and outlet air is directly proportional to ground thermal conductivity.

Various backfilling materials regarding their thermal conductivity were studied[17], and it was concluded that the mixture of sand and clay gave the biggest temperature decline, followed by the mixture of sand and bentonite as the thermal conductivity of sand and clay mixture higher. Also, the sand-clay mixture is quite affordable and can be easily employed to improve the performance of EAHE.

A 2-dimensional soil resolution was modeled[18] using a finite element model for the backfilling material around the heat exchanger pipe, and the output air temperature for different types of backfilling materials was calculated. The numerical model was validated with experimental results, and it was concluded that the soil, which can store water for a longer period, has a positive effect on the thermal performance of EAHE like a mixture of sand and bentonite.

Thermal and mechanical tests were conducted on five different compositions of soil clay mixture[19] ranging from 0-100% clay by weight, and it was concluded that thermal conductivity increases with an increase in sand content in the soil-clay mixture, and the performance of EAHE is directly proportional to the thermal conductivity of the soil.

The effect of salinity of the soil on the thermal conductivity of soil was investigated[20]. It was concluded that thermal conductivity decreases with increased soil salinity, resulting from groundwater entering the soil due to capillary action.

2.10 Effect of rain or moisture in soil

Humidification of soil on the performance of EAHE has been studied on two different material pipes[10], i.e., steel and PVC, and it has been found that the difference in air temperature for both the materials for moist or dry soil is 10%. Therefore any location having moist soil is a better place for EAHE.

Rain intermittently does not affect the performance much at a depth where EAHE is installed. If the soil remains moistened to its maximum capacity all the time, it has a positive effect[21] as the performance is improved by 16%. It has been observed for EAHE buried at a depth less than 2m that even with a single rainfall event of 3 hrs, the variation in soil moisture can reach up to 65%.

Experiments have been conducted to assess the performance of EAHE with wet soil[22]. Wet soil helps decrease the depth and length of pipe and increases the cooling potential and COP of the system. The irrigation system was adopted, and the soil moisture was changed from 0.37 to 0.42 cm^3/cm^3. The output temperature was reduced by 1.6°C. As the moisture reached 3m depth, the second pipe for comparison was installed at 2.5 m.

2.11 Effect of solar chimney

The researchers correlated the ventilation rate, solar chimney design parameters, EAHE geometrical specifications, pressure drop, and climatic conditions[23], which are used to optimize passive cooling/heating and ventilation systems. They studied 02 cases, one with a blower and the other without a blower, and found that the system with a blower is more efficient and reduces temperature by 9°C in the summer season. The system without a blower decreases the temperature by 5°C in summer and increases temperature by 10°C compared to ambient air temperature in winter.

The chimney effect replaced the fan and blower at exit[24] to increase the speed of the air passing through the system. The same system cooled the air from 11°C to 3°C and then heated the air using a solar chimney. Air temperature could be increased by 14°C on the third day and decreased by 11.6°C on the fifth day, leading to heating and cooling with the same system. The PVC tube at the outlet was used as a solar chimney by insulating the inlet tube and keeping the outlet exposed to the sunlight. The relative humidity of air also increased or decreased by 45-46%.

2.12 Effect of using ventilation system

A controlled ventilation system using an earth tube heat exchanger has been investigated experimentally[25], and a COP of 1.5 in summer and 5.13 for winters has been achieved. So, in that case, some other source of inlet air like a ventilation unit should be considered, and a control system should control the air source. A combination of EAHE and ventilation unit has been explored[26] and it has been sensed that if a proper computerized control system is employed to decide when to take inlet air from the environment or EAHE, it will improve the performance of the system.

2.13 Effect of using ceiling material

A phase change material has been used as a ceiling material[27] for storing heat energy in the winter season, and the supply of air is given through EAHE. It has been observed that the temperature difference increased by almost 2.7°C in 12 hours.

2.14 Effect of grass cover

An EAHE has been studied with grass cover near the surface[28]. The benefit achieved was that the EAHE at a lower depth could be installed as the grass cover reduces the surface temperature.

Various input parameters at which experimentation has been done are tabulated in Table 1.

The following gaps are identified from the previous literature studies:

Table 1 — Parameters used by various researchers for experimentation

YEAR	PLACE	LENGTH (m)	DEPTH (m)	DIAMETER (m)	MATERIAL	VELOCITY (m/s)	SHAPE	AIR FLOW RATE (m^3/h)	TYPE OF SOIL	Citation
2018	—	5-100	—	0.110 , 0.160, 0.400	PVC, HDPE, Steel	1 to 3	—	—	—	Rosa[1]
2018	Changsha, China	—	16.5	0.219	SS with insulation of polyurethrene	1	—	—	—	Liu[2]
2020	South West China	40-45	1, 2,3	0.11, 0.16, 0.11, 0.075	—	—	—	—	—	Wei[3]
2018	Algeria	20	2	0.120	Zinc, PVC	2	—	450	Silty Clay	Menhoudj[6]
2021	Algeria	20	2	0.118	PVC, Zinc	0.45	—	90	Clay Loam Soil	Lekhal[7]
2020	Algeria	60	1, 1.5	—	PVC, steel	—	—	—	—	Serageldin[8]
2020	Algeria	20	2	0.118	PVC, Zinc	—	—	—	Clay Loam	Lekhal [9]
2018	—	60	1.5	0.200	PVC	—	—	—	—	Romanska[14]
2018	—	76d to 300d	—	—	—	—	Z and U	—	—	Amanowicz[16]
2020	France	30	65	0.10 c	—	4	—	—	Sand, Sand And Bentonite, Natural Soil	Cuny[21]
2020	Algeria	60	1.5	0.110	PVC	—	open loop	—	Sandy Loam Soil	Sakhri[24]
2020	Erbil, Iraq	31	3	0.10 c	Polyethylene	5	closed loop	150	—	Ghafoor [25]
2020	China	12	—	0.100	—	2.5	—	70.7	—	Lu[27]

Compact shape is required for urban areas due to space constraints. There should be uniform flow in all parallel pipes as non-uniform flow leads to decreased thermal efficiency. There are very few reported studies for concrete material pipes. Some composite materials should be investigated to improve thermal efficiency, and side-by-side, be economical and environment friendly.

3 Results and Discussion

Considerable experimentation has been done on EAHEs to investigate applicability and performance in different aspects worldwide. The researchers have concluded that it is a promising technique to reduce the electrical energy consumption used by Heating, Ventilating, and Air conditioning systems. Many refrigerants being used in these systems are very harmful to the environment as they cause Global warming and Ozone layer depletion. So the use of EAHE should be promoted from high energy consumption and environmental safety point of view. The output of the EAHE is measured in the form of Temperature difference achieved (Fig. 5), the system's effectiveness (Chart 8), cooling potential, energy savings, and CO_2 emission savings. It is found that temperature difference improves by an increase in the length of pipes, decrease in velocity, and increase in depth. The cost of the system increases as the length, diameter, and depth of EAHE increases. As the length increases, the benefit derived from increased length decreases, so a balance needs to be achieved between cost and benefits.

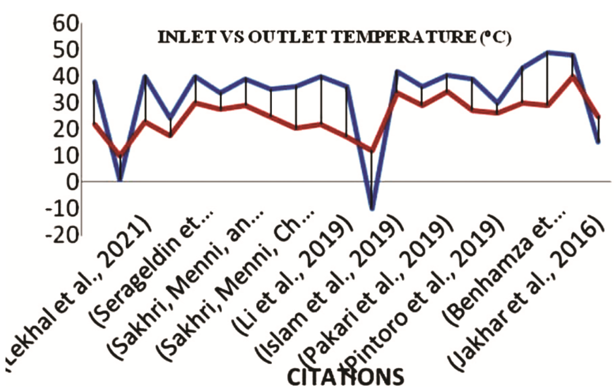

Fig. 5 — Inlet temperatures vs. outlet temperatures as reported by various researchers in their papers.

The effectiveness has been calculated as

$$\frac{T_i - EUT}{T_i - T_o}$$

Where T_i is the inlet temperature T_o is the outlet temperature

Moreover, EUT is Earth's undisturbed temperature.

The effectiveness value has been calculated for the citation where the values of inlet temperature, outlet temperature, and EUT have been reported by experimenters and plotted on a graph (Fig. 6). Wherever the value of effectiveness is more than one, it is indicated that some additional equipment has been used along with EAHE to increase its effectiveness, i.e., solar chimney or solar duct.

As shown in chart 8, the use of EAHE is quite effective in reducing ambient air temperature in summer and increasing the same in the winter season, thus reducing the energy load on air conditioning equipment.

The various output performance parameter values reported by the researchers in their papers are given in Table 2. As evident from Table 2, the energy efficiency ranges between 35.41% to 76%.

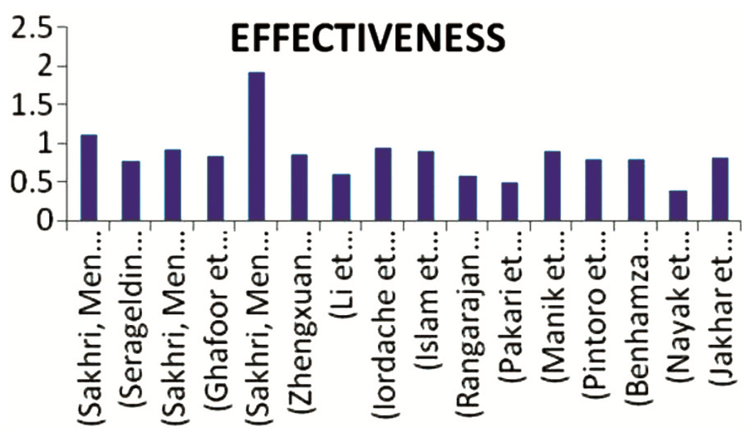

Fig. 6 — Calculated values of effectiveness.

Table 2 — Performance parameters reported by various researchers

COOLING PERFORMANCE	ENERGY SAVINGS	PAYBACK PERIOD (Years)	CO2 SAVINGS	MOISTURE REDUCTION	OPTIMUM LENGTH (m)	OPTIMUM DEPTH (m)	OPTIMUM DIA (m)	Citation
35.41 % for ZN and 58.42% for PVC	—	—	—	—	25	3-5		Namgial[4]
—	—	—	—	—	25, 30	3	0.18, 0.24	Lekhal[9]
—	—	—	—	—	—	—		Rangarajan[11]
Sensible cooling of 60-80% and latent cooling 17-40 %, 2987.4 W	—	—	—	7.41 g/kg	—	3	0.16	Romanska[14]
3-20 watts per hour	—	—	—	Increased or decreased by 45-46 %	—	—	—	Bertermann[17]
133375 W, 20134 W, 24080 W for hot and humid 5643 W, 7375 W, and 8939 W for hot and dry for 15 m,30 m, and 45 m length	—	—	—	—	—	—	—	Xia[19]
—	—	8.2	7170.42 Kg	—	—	—	—	Sakhri[24]
8972 W	—	—	—	—	—	—	—	Ghafoor [25]

4 Conclusion

EAHE (earth-air heat exchanger) can effectively reduce energy load by up to 50%. The system has achieved high levels of effectiveness of up to 0.9 when used alone and up to 2 when combined with a coupled system. Its performance can be further enhanced using smart technologies that can determine when the system should switch on or off, leading to optimized performance.

During the winter season, the performance of EAHE can be improved by using solar heating ducts. Additionally, when used in moist soil, a vertical configuration, or soil with higher thermal conductivity, EAHE achieves better results. The material of EAHE pipes has no effect on the system's performance.

To improve its cooling potential and temperature difference achieved, the velocity and diameter of the pipes should be decreased, while their length and depth should be increased. Installing EAHE can result in CO_2 savings of approximately 7,000 kg per annum, promoting an environmentally friendly approach.

EAHE installation costs have a payback period of approximately 7-8 years. The ideal length for EAHE ranges from 25-30 m, and the optimal range for diameter depth is 2-3 m, with a preferred diameter of 0.16-0.20 m.

In conclusion, EAHE is a promising technique that supports energy efficiency in the building sector for heating, cooling, and ventilation. However, future research needs to be focused on developing smarter and more efficient EAHE systems that utilize computerized control systems or the Internet of Things. Research must also strive to identify composite, environmentally friendly, and cost-effective materials for EAHE.

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