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Thermal behavior of a novel vertical coaxial geothermal ventilation system under different operating conditions: An experimental study

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ABSTRACT

With the increasing energy consumption in buildings, developing efficient and low-energy ventilation technologies has become essential. The earth-to-air heat exchanger (EAHE) systems utilize relatively stable soil temperatures to precondition outdoor air and reduce building cooling and heating loads. However, conventional horizontal EAHE systems suffer from limitations such as large land occupation, condensate drainage difficulties, and shallow pipe burial depth. To address these issues, a novel vertical coaxial pipe earth-to-air heat exchanger (VCP-EAHE) is proposed and experimentally investigated using a scaled sandbox setup under different soil moisture contents and seasonal conditions in Changsha. The results show that under summer conditions, the system provides stable precooling performance with a maximum inlet–outlet temperature difference of 1.68 °C. Higher soil moisture enhances thermal buffering capacity, reducing the standard deviation of the temperature difference from 0.190 to 0.158. During the transition season, the system exhibits bidirectional thermal regulation, achieving a maximum cooling of 1.31 °C and heating of 0.78 °C. Overall, the VCP-EAHE demonstrates effective thermal regulation and stable operation, providing experimental support for the design and application of vertical geothermal ventilation systems.

Nomenclature

Ar	Archimedes number
c_p	Specific heat capacity of air at constant pressure, J kg^{-1} K^{-1}
Fr	Froude number
k	Rate of soil temperature change,°C day^{-1}
l	Characteristic length, m
$\dot{m}_a$	Air mass flow rate, kg s^{-1}
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}_{soil}$	Heat exchange between air and soil, W
U_{x_i}	Uncertainty of measured variable x_i
$U_{\Delta T}$	Uncertainty of temperature difference, °C
v	Air velocity, m s^{-1}
We	Weber number
x_i	Independent measured variable

Greek symbols

η	Heat exchange efficiency
υ	Kinematic viscosity, m^2 s^{-1}
ΔT	Temperature difference between inlet and outlet, °C

Subscripts

(*continued on next column*)

(*continued*)

$\dot{Q}_o$	Heat transfer between outer pipe air and soil, W
$\dot{Q}_i$	Heat transfer between inner pipe air and outer pipe air, W
R	Calculated result
Re	Reynolds number
T_{in}	Inlet air temperature, °C
T_{out}	Outlet air temperature, °C
$T_{soil,avg}$	Average soil temperature around the system, °C
U_R	Uncertainty of calculated result

i	inner pipe
in	inlet
m	model system
o	outer pipe
out	outlet
p	prototype system
soil, avg	Soil average

1. Introduction

Against the dual backdrop of global climate change and energy structure transformation, the issue of energy scarcity has become increasingly prominent [1]. Building energy consumption, especially

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that of ventilation and air conditioning systems, accounts for a relatively high proportion, reaching 32% of global total energy consumption [2], and has become an important area that in urgent need of optimization. Traditional ventilation and refrigeration systems generally rely on electric drive, resulting in high energy consumption, high operating costs, and certain environmental impacts. Therefore, the development of green, energy-saving, and efficient ventilation systems has become a research hotspot in the field of building environments. Against this backdrop, renewable energy has emerged as a new solution to energy problems [3]. As a clean energy source, geothermal energy is characterized by large reserves, wide distribution, environmental friendliness, and renewability [4], and has been widely applied in building energy efficiency technologies [5]. Soil exhibits significant thermal inertia: at a certain burial depth, the impacts of variations in solar radiation intensity and atmospheric temperature fluctuations on soil temperature are nearly negligible [6]. Specifically, soil temperature is lower than the seasonal average ambient temperature in summer and higher than that in winter. This naturally formed temperature difference can be effectively utilized for building heating in winter and cooling in summer, making geothermal energy a crucial potential resource for building energy conservation [7].

Within the framework of geothermal energy utilization technologies, geothermal ventilation systems have garnered more attention than traditional ventilation systems due to their core advantages of simple structure, easy operation, and low operating costs. They have been widely applied in scenarios with abundant land resources, such as rural areas and greenhouses [8]. As a core form of shallow geothermal ventilation systems, the earth-air heat exchanger (EAHE) preconditions outdoor air by leveraging the relatively stable soil temperature via underground buried ventilation pipes [9], ultimately achieving the goals of reducing building cooling loads and improving indoor thermal comfort [10]. Current research on EAHE is extensive, with scholars verifying its feasibility across different climatic conditions and building types [11], confirming its broad application prospects in new green buildings and energy-saving retrofits of existing buildings. For instance, Fatih Taşdelen et al. [12] compared the performance of EAHE with different buried pipe layouts using CFD, and obtained the performance analysis under various Reynolds numbers. Experiments conducted by Yang et al. [13] in the hot-summer and cold-winter regions of China showed that the cooling or heating potential of the EAHE system can reach 3 kW. Ascione et al. [14] evaluated the system under the Mediterranean climate of Palermo, Italy, and found that it achieves 29% energy savings in winter, 36%–46% in summer, and 24%–38% annually. Benhammou et al. [15] studied the summer parameters of EAHE in the Sahara Desert region of Algeria and pointed out that pipe length, diameter, and air flow velocity significantly affect the outlet temperature and COP of EAHE: increasing pipe length reduces the outlet temperature, while increasing pipe diameter and air flow velocity have the opposite effect; additionally, adjusting the air flow velocity inside the pipe in summer can achieve an energy saving rate of 16%. Furthermore, Inalli and Esen [16] investigated the EAHE system in Elazığ, Turkey, and found that its average cooling COP is 2.01. Agrawal et al. [17] confirmed that pipe length and winter soil moisture content significantly influence system thermal performance, with variations in soil moisture content directly affecting heat exchange efficiency. Overall, existing studies have extensively explored the thermal performance of EAHE systems from perspectives such as climatic conditions, structural parameters, and operating conditions, and verified the application potential of this system in the field of building energy efficiency.

Research on optimizing EAHE performance has also advanced continuously. For example, Qi et al. [18] proposed a hybrid mode combining EAHE with Return Air, verifying that this configuration reduces thermal interference with the surrounding soil and exhibits better durability than open-loop EAHE systems. Bulut [19] conducted experiments in which the soil surrounding the EAHE system was humidified via irrigation lines, demonstrating that soil with high moisture content can effectively enhance system efficiency. Li et al. [20] combined the EAHE system with an enhanced solar chimney equipped with solar collectors to construct a passive air conditioning system; by synergistically utilizing geothermal and solar energy, this system achieves significant building energy savings and reduces peak summer electricity demand. Ahmadi et al. [21] developed an integrated system combining EAHE system with water spray channels; an evaluation in Tehran, Iran, demonstrated that its cooling efficiency exceeds 100%, which can satisfy indoor comfort requirements and shows the potential to replace traditional evaporative coolers. However, the above studies mainly focus on the traditional horizontal buried-tube EAHE system and its combined application forms, and there remains a lack of systematic experimental research on the heat transfer characteristics and operation laws of the new vertical structure geothermal ventilation system.

However, with the widespread application and in-depth research of EAHE systems, several issues have limited their largely application, such as difficulties in condensate water treatment [22], large land occupation [23] and low system efficiency caused by shallow pipe burial depth [24]. These problems have restricted their application in the construction sector to a certain extent. To address the aforementioned shortcomings of EAHE systems, Liu et al. [25] proposed a vertical earth-air heat exchanger (VEAHE) system, and established a mathematical model to investigate its application under different scenarios [26]. Compared with traditional EAHE systems, the VEAHE system adopts a vertical pipe design, significantly reducing land occupation; its U-tube structure greatly increases the pipe burial depth, and a condensate drainage system is integrated. Nevertheless, the VEAHE system still faces challenges in practical application, such as complex construction and high costs, which limit its popularization in economically underdeveloped regions. Therefore, it is necessary to further explore new geothermal ventilation systems with simpler structures, lower construction difficulty, and excellent heat transfer performance.

To address the above problems, this paper proposes a vertical coaxial pipe earth-to-air heat exchanger (VCP-EAHE) system and conducts research on its structural design and experimental validation. The system is optimized based on the VEAHE system, with the air duct arranged between the inner and outer tubes. It adopts a vertical structure in which air enters through the outer tube to the bottom and flows upward through the inner tube. Compared with conventional vertical buried tube systems, it occupies less land, achieves higher heat exchange efficiency [27], and exhibits stronger adaptability, especially suitable for scenarios with limited land resources [28]. The main research objectives of this paper are as follows: to evaluate the heat transfer performance of the VCP-EAHE system under different soil moisture content conditions; to analyze the temperature response and energy-saving potential of the system under typical operating conditions in summer and the transition season; and to investigate the influence of the soil thermal buffer on the operational stability of the system. In terms of research methods, a sandbox scaled experimental platform is adopted in this study. By setting typical working conditions in summer and the transition season, and conducting comparative analyses under low and high soil moisture content conditions, the thermal performance of VCP-EAHE is systematically investigated. The research scope mainly focuses on the variations in system air temperature, soil temperature, and heat exchange efficiency under different soil moisture content and typical seasonal conditions. The rest of this paper is organized as follows: Section 2 introduces the experimental system, measuring point layout, and experimental condition settings; Section 3 presents the variations in air and soil temperatures and the analysis of system heat transfer performance under different working conditions; Section 4 discusses the effects of soil moisture content on the system operational characteristics and thermal buffer effect, and points out the research limitations; Section 5 summarizes the main conclusions of the full paper and proposes future research directions.

2. Experimental system and equipment

2.1. The VCP-EAHE system

Fig. 1 shows the system schematic diagram of the VCP-EAHE system, presenting the parameters and all components of the full-scale system. During system operation, the fan is activated to draw air into the system. After being preliminarily purified by the air filtration equipment, the air enters the air inlet duct and undergoes the first heat exchange with the surrounding soil inside the outer tube. It then flows into the air supply duct through the lower end of the inlet duct, rises vertically along the air supply duct to the horizontal air supply duct, and is finally delivered into the building by the fan. To investigate the efficiency characteristics of the VCP-EAHE system, a test bench was constructed for experimental research. The test site was located in Changsha, Hunan Province, which has a hot-summer and cold-winter climate [29].

Under high temperature and high humidity conditions, outdoor fresh air exchanges heat with the low-temperature pipe wall and surrounding soil after entering the system, resulting in a gradual decrease in air temperature. When the local air temperature drops below the dew point, water vapor condenses on the inner surface of the outer tube and the outer surface of the inner tube, forming condensate. The generated condensate collects in the water storage tank under gravity. When the water level in the tank reaches the preset high level, the built-in water pump is activated to discharge the condensate from the system. Compared with the conventional horizontal buried-tube EAHE, the vertical coaxial tube structure proposed in this paper has obvious advantages in condensate management: on the one hand, condensate can naturally flow down along the vertical pipe wall under gravity, avoiding the local water accumulation commonly found in horizontal pipes; on the other hand, since both the inner and outer tubes are arranged around the same vertical axis, condensate can be collected intensively at the bottom of the system, facilitating the integrated design of a water collection tank and drainage device, thereby reducing the complexity of drainage design and later maintenance.

It should be noted that the working conditions described in this study are indoor scaled-down simulated conditions constructed based on the typical ambient temperature characteristics of Changsha in summer and the transition season, rather than outdoor full-scale measured conditions. Accordingly, the air-side boundary conditions in this study are mainly the indoor ambient temperature. The typical ambient temperature curves of Changsha in summer and the transition season measured indoors are shown in Fig. 2. As the experiment was conducted indoors, the soil surface was not affected by outdoor meteorological factors such as solar radiation, rainfall, and wind speed fluctuations. Thus, the upper boundary of the soil mainly exhibits convective heat exchange with air under the indoor environment. The side walls of the sandbox were covered with thermal insulation material and aluminum foil to minimize interference from lateral heat transfer.

Considering cost and time constraints, this study adopted a scaled-down model for sandbox simulation experiments (Fig. 3). The test bench mainly comprises a sandbox, soil layer, vertical coaxial pipes, and an axial flow fan. The vertical coaxial pipes are made of stainless steel, with an outer pipe diameter of 100 mm and an inner pipe diameter of 50 mm. Literature research [30] indicates that when the distance between buried pipes is greater than 2D (where D refers to the outer pipe diameter), the maximum difference in the ratio of annual heat exchange rates is less than 2.1%. To ensure sufficient heat exchange between the coaxial pipes and the soil, the sandbox was designed with dimensions of 700 × 700 × 1500 mm. To simulate the real underground environment and avoid interference from lateral air convection, the perimeter of the test bench was wrapped with 30 mm thick thermal insulation material, and an aluminum foil layer was attached to its outer surface to reduce the impact of radiant heat transfer on the experimental results.

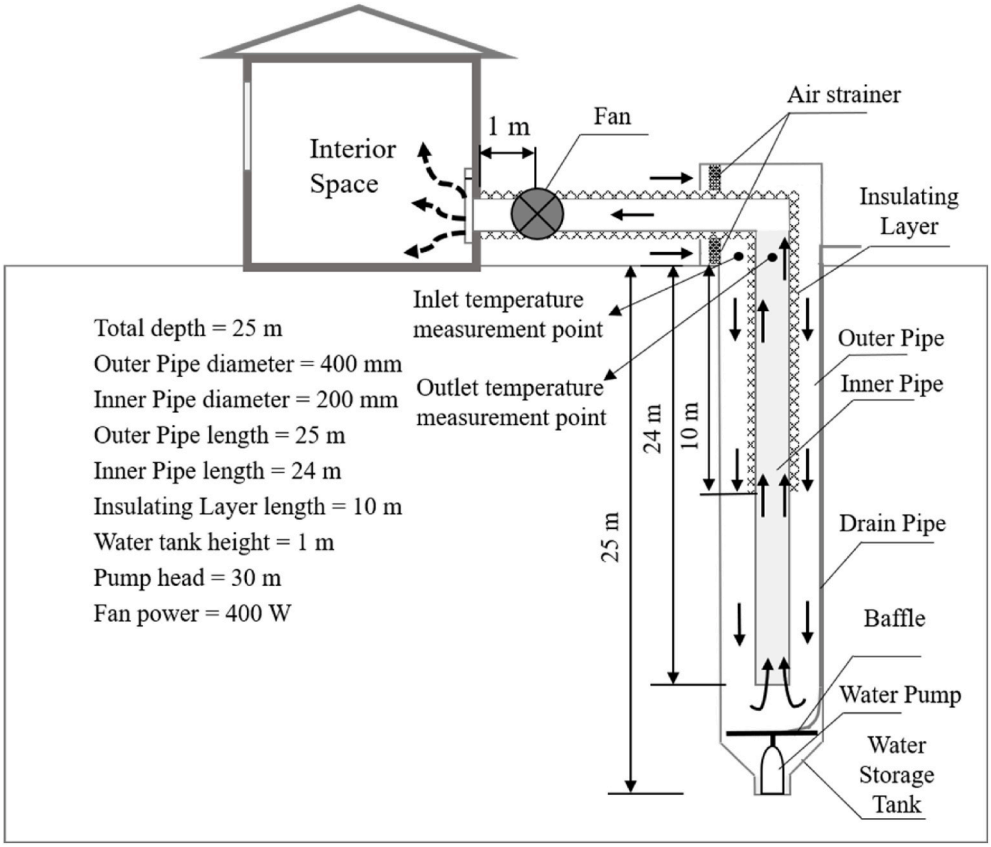


Fig. 1. Schematic diagram of the system.

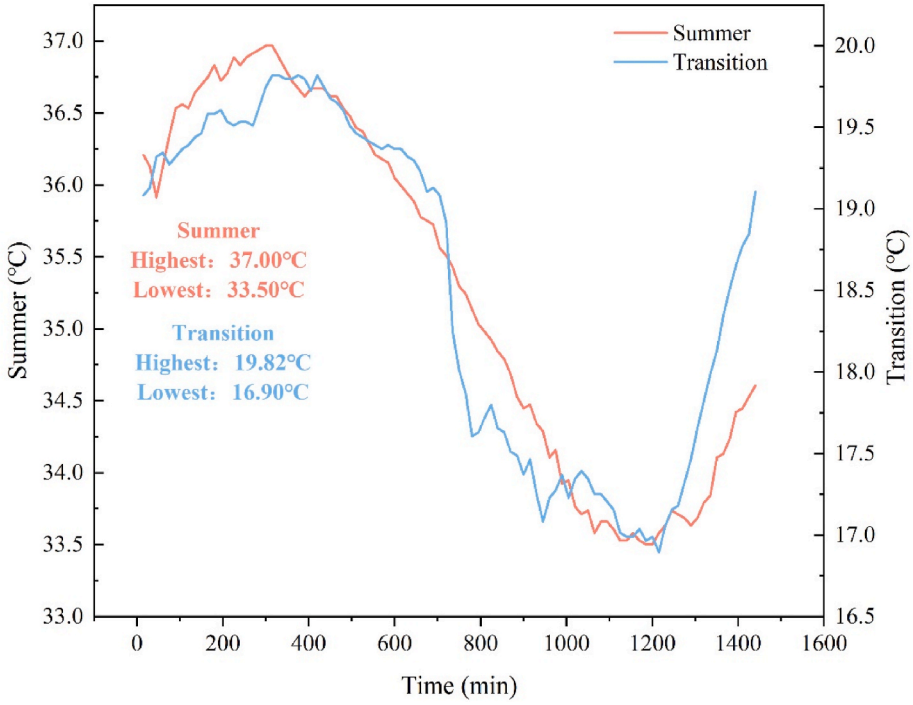


Fig. 2. Environmental temperature variation during summer and transition seasons.

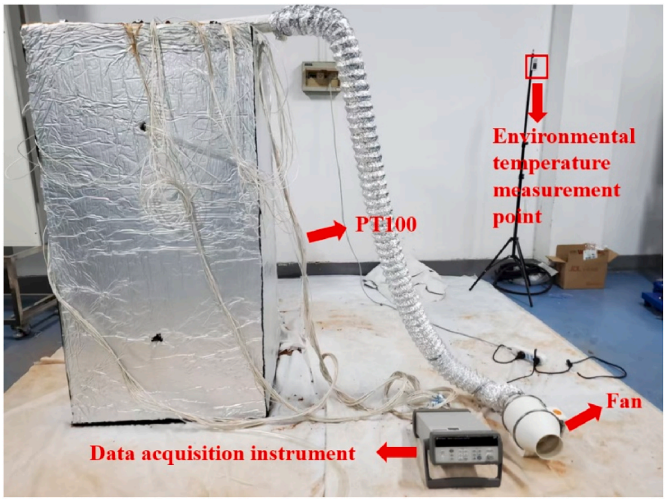


Fig. 3. Schematic diagram of the system setup.

In this study, PT100 temperature sensors were used to monitor the temperature changes of air and soil, with a measurement accuracy of ±0.15 °C. All sensors were calibrated using an ice-water mixture. The temperature acquisition system consisted of an Agilent 34972A data logger, which could collect temperature data from each measurement point in real time. Air velocity was measured using a testo Universal Air Velocity and Temperature Recorder, with an accuracy of ±0.05 m/s + 3% of the reading, for real-time monitoring of outdoor air velocity. This paper also quantitatively describes the main thermophysical parameters of the soil used in the sandbox experiment. The relevant parameters include thermal conductivity, specific heat capacity, density and moisture content, with their specific values listed in Table 1. All instrument specifications are shown in Table 2. The system details, PT100 calibration diagram and soil thermophysical property test diagram are presented in Fig. 4.

Table 1
Thermophysical parameters of the tested soil.

Parameters	Value	Unit
Thermal conductivity	0.66	$W \cdot m^{-1} \cdot K^{-1}$
Thermal diffusivity	0.93	$mm^2\ s^{-1}$
Specific heat capacity	590	$J \cdot kg^{-1} \cdot K^{-1}$
Density	1650	$kg \cdot m^{-3}$
Moisture content	12/25	%

2.2. Experimental condition setup

To systematically explore the effects of seasons (summer, transition season) and soil moisture content (low, high) on the heat exchange performance of the VCP-EAHE system, this study designed four groups of comparative experimental conditions. The operating conditions are shown in Table 3, and the detailed design concept is as follows:

Summer conditions: Including Condition 1 (summer, low soil moisture content) and Condition 2 (summer, high soil moisture content), simulating the typical meteorological characteristics of Changsha in summer (June–August), with the inlet temperature controlled at 31−34.5 °C.

Transition season conditions: Including Condition 3 (transition season, low soil moisture content) and Condition 4 (transition season, high soil moisture content), simulating the meteorological characteristics of Changsha in transition season (April–May, September–October), with the inlet temperature controlled at 14−22 °C.

Under all conditions, the air velocity inside the pipes was uniformly controlled at 2 m/s, achieved via closed-loop control of a stepless speed-regulating fan combined with an air velocity recorder, with a fluctuation range of ±0.1 m/s, to eliminate the interference of air velocity on heat exchange and focus on the effects of season and soil moisture content.

Each condition was continuously operated for 72 h, and data collection started uniformly at 12:00 noon every day—this time period is close to the daily maximum temperature in summer/transition season in Changsha, enabling more accurate capture of the system's heat exchange performance during high-temperature periods. During the

Table 2
Specifications of instruments.

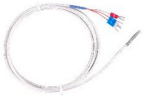
Instrument	Model	Accuracy	Image
Data Logger	34972A		
Air Velocity Recorder	testo	±0.05 m/s + 3% of reading	
Soil Temperature Sensor	PT100	±0.15 °C	
Ambient Temperature Sensor	HOBO UX100-003	±0.5 °C	
Fan	Stepless Speed-Regulating Axial Fan	75W	



Fig. 4. System details, PT100 calibration and soil thermal property tests.

Table 3
Experimental conditions.

Condition	Season	Soil Moisture Content	Air Velocity
1	Summer	Low	2 m/s
2	Summer	High	2 m/s
3	Transition Season	Low	2 m/s
4	Transition Season	High	2 m/s

experiment, an Agilent data logger was used to continuously monitor parameters such as inner pipe air temperature, outer pipe air temperature, and multi-layer soil temperature, with a data collection interval of 3 min to ensure the capture of dynamic temperature change details (e.g., sudden temperature rises in summer afternoons, diurnal temperature fluctuations in transition season).

To avoid the impact of soil thermal disturbance from the previous condition on subsequent experiments, after completing one group of conditions, the system was shut down for 72 h to allow the soil temperature to naturally recover to its initial state before conducting the next group of experiments.

3. Experimental results and analysis

3.1. System efficiency

In this study, the heat exchange efficiency η is adopted as the main performance evaluation index. This index characterizes the ratio between the actual temperature drop achieved by the air during its flow through the system and the theoretical maximum possible temperature drop, thereby reflecting the utilization degree of the system for geothermal energy. Its calculation formula is as follows [31]:

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_{soil,avg}} \times 100\% \quad (1)$$

Where T_{in} representing the heat input temperature of the system (°C); T_{out} representing the heat output temperature of the system (°C); $T_{soil,avg}$ representing the average temperature of the soil surrounding the system

(°C).

The numerator $T_{in} - T_{out}$ is the actual temperature drop of the air, reflecting the actual heat exchange effect of the system; the denominator $T_{in} - T_{soil,avg}$ is the theoretical maximum temperature drop of the air (i.e., the temperature difference when the air is cooled from the inlet temperature to the average soil temperature), representing the theoretical upper limit of heat exchange. Therefore, η directly reflects the alignment between the actual heat exchange amount and the theoretical maximum heat exchange amount—the closer η is to 100%, the higher the efficiency of the system in utilizing soil thermal energy.

3.2. Analysis of air temperature variation law under summer operating conditions

Fig. 5 shows the dynamic variation laws of the system's inlet temperature, outlet temperature, soil temperature, temperature difference, and heat exchange efficiency (η) over time under typical summer conditions.

During the experiment, the inlet temperature reached a maximum of approximately 34.8 °C and a minimum of about 31.1 °C, consistent with the diurnal variation trend of outdoor air temperature in summer. However, the outlet temperature remained lower than the inlet temperature, and the diurnal variation amplitude was significantly smaller, with a certain lag. Observation shows that the diurnal variation amplitude of the outlet temperature was significantly smaller than that of the inlet temperature, with a certain lag in variation.

During summer operation, the system exhibited excellent cooling performance during the daily noontime high-temperature period (14:00–16:00), with the temperature difference between the inlet and outlet generally maintained at 1.0~1.5 °C and a maximum temperature difference of up to 1.68 °C. Since the soil can be approximated as a relatively constant-temperature heat sink, the larger the temperature difference between the inlet air and the soil, the higher the theoretical heat exchange efficiency of the system.

As shown in the figure, during the daily high-temperature period, η was generally around 0.5. However, abnormal values of η far exceeding 1 appeared in some periods, concentrated during times when the inlet temperature was relatively low.

This abnormal occurs because the experiment used a sandbox to simulate the soil environment, which cannot fully replicate the relatively constant temperature characteristics of soil at a 20 m burial depth in practical engineering. Although the soil temperature in the experiment showed minimal overall fluctuation, the inlet temperature exhibited periodic diurnal changes; when the inlet temperature approached the average soil temperature, the denominator of the heat exchange efficiency formula ($T_{in} - T_{soil,avg}$) approached zero, causing the calculated η to increase sharply and deviate from its physical meaning.

3.3. Analysis of air temperature variation law under high-moisture-content conditions in summer

By comparing Figs. 5 and 6, it can be observed that under high moisture content conditions, the inlet air temperature exhibits more frequent small fluctuations, while the outlet air temperature becomes significantly more stable. The standard deviation of the temperature difference decreases from 0.190 °C under low moisture content to 0.158 °C under high moisture content (a reduction of 16.8%), indicating an enhanced thermal buffering capacity of the soil.

This improvement is mainly attributed to the higher volumetric heat capacity and thermal inertia of moist soil. As the specific heat capacity of water is significantly higher than that of dry soil, soil with higher moisture content experiences smaller temperature variations under the same heat input, thereby smoothing fluctuations in outlet air temperature.

Under high moisture content conditions, the inlet air temperature ranges from 31.02 °C to 34.74 °C, which is similar to that under low moisture content. However, the system exhibits improved heat exchange performance, with the maximum inlet–outlet temperature difference increasing from 1.40 °C to 1.68 °C (approximately 20% enhancement). This demonstrates that higher soil moisture content not only strengthens air–soil heat transfer but also improves the cooling performance of the system.

In addition, soil temperature rises more rapidly under high moisture content due to the increased thermal conductivity and heat storage

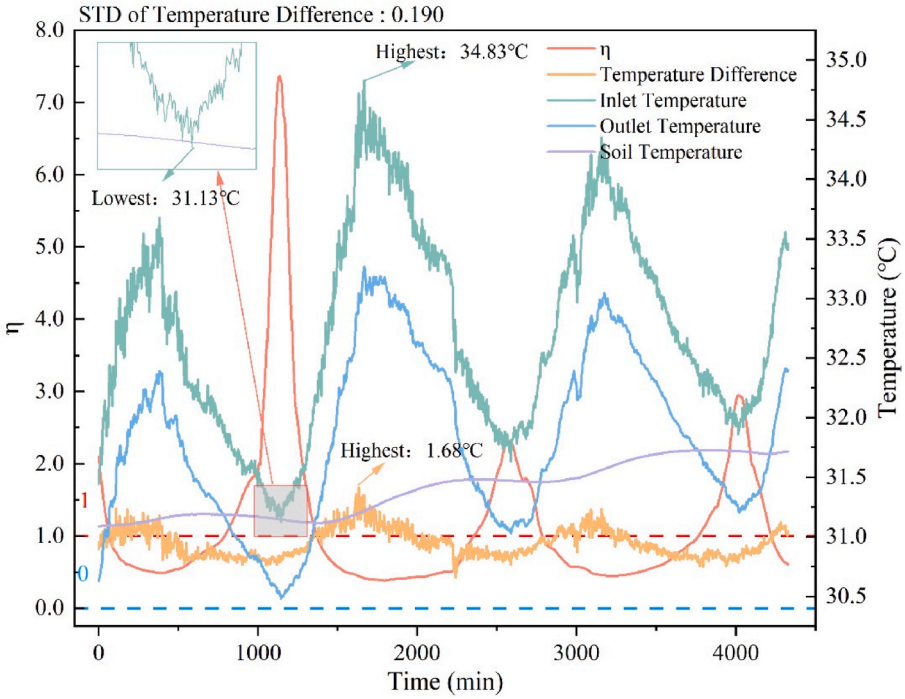


Fig. 5. System efficiency under summer low-moisture-content soil condition.

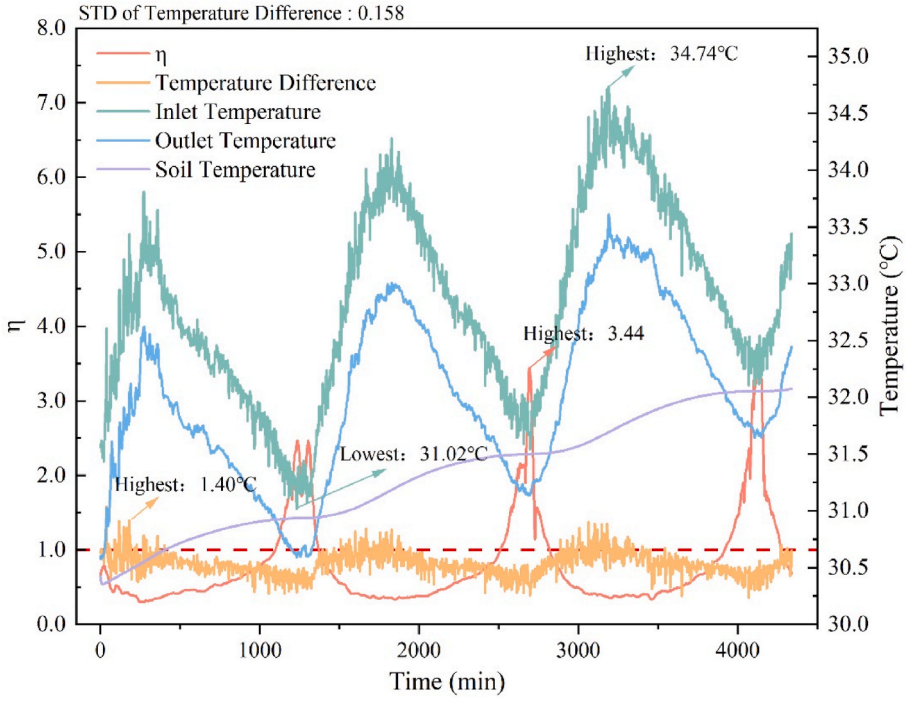


Fig. 6. System efficiency under summer high-moisture-content soil condition.

capacity. As a result, soil temperature variations become more synchronized with the inlet air temperature. In contrast, low-moisture-content soil shows slower heat transfer and weaker thermal response.

Regarding heat exchange efficiency, the occurrence of abnormal peak values is significantly reduced under high moisture content. This is because the stabilized temperature difference between inlet air and soil avoids calculation distortion when the denominator approaches zero. Meanwhile, the combined effects of enhanced thermal conductivity and heat capacity lead to a more physically consistent and stable efficiency performance.

In terms of heat exchange efficiency, the outliers of η in Fig. 6 was significantly lower than that in Fig. 5. This is because the stronger thermal buffer capacity of high-moisture-content soil stabilizes the temperature difference between the inlet air and the average soil temperature; at the same time, under high-moisture-content conditions, the synergistic effect of improved thermal conductivity (promoting heat transfer) and high heat capacity (enhancing heat storage) makes the ratio of actual heat exchange amount to theoretical maximum heat

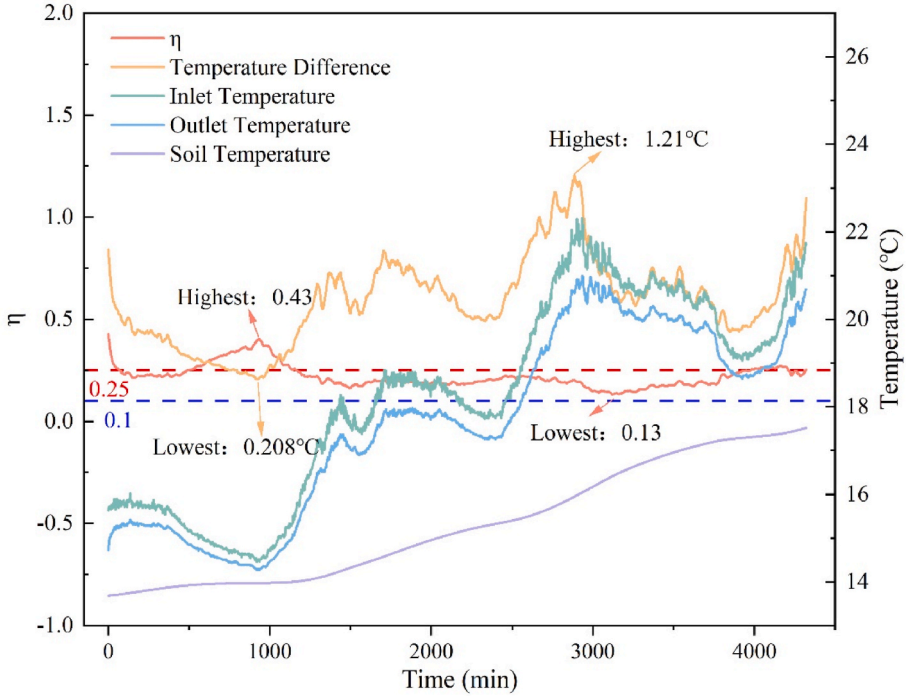


Fig. 7. System efficiency under low-soil-moisture condition in transition season.

exchange amount (i.e., η) more in line with physical laws.

3.4. Analysis of air temperature variation law under high and low moisture content conditions in transition seasons

As can be seen from Figs. 7 and 8, under transition season conditions, regardless of soil moisture content, the system's inlet temperature showed obvious diurnal fluctuations. Under the low-moisture-content condition, the outlet temperature was generally lower than the inlet temperature, and the system still had a certain cooling regulation capacity, but the spacing between the temperature curves was smaller and the temperature difference was relatively weaker; under the high-moisture-content condition, the system's heat exchange process exhibited more significant bidirectional thermal regulation characteristics.

In the early stage of the transition season with high soil moisture content, the inlet temperature is higher than the soil temperature, presenting cooling-type heat exchange, with a maximum heat exchange temperature difference of up to 1.31 °C. As time elapsed, the ambient temperature gradually decreases, and the inlet temperature becomes lower than the soil temperature. At this point, the underground soil with relatively stable temperature acts as a heat source, supplying heat to the low-temperature inlet air. The system shifts from cooling to heating, with a maximum heating temperature difference of 0.783 °C, which verifies the bidirectional thermal regulation potential of VCP-EAHE. Meanwhile, in the later stage of the high-moisture-content condition, the magnitude of small fluctuations in the temperature curve increases significantly, and multiple curves even tend to approach or partially overlap. This is due to the fact that moisture infiltration and accumulation enhance the soil's thermal conductivity and specific heat capacity: the increased thermal conductivity makes the soil more sensitive to temperature fluctuations, while the high heat capacity enables the soil to act as a buffer, maintaining the relative stability of the outlet temperature by smoothing temperature variations and releasing stored heat.

Compared with the low-moisture-content condition, the high-moisture-content soil not only enhances the system's response sensitivity to ambient temperature fluctuations but also improves its thermal buffering capacity. In contrast, under low moisture content, the soil's thermophysical properties are relatively weak; coupled with the inherently limited temperature difference between the inlet air and soil in the transition season, the overall heat exchange efficiency and the dynamics of temperature regulation are both weaker than those under the high-moisture-content condition. Although the maximum heat exchange temperature difference reaches 1.21 °C, the overall heat exchange temperature difference remains at a relatively low level compared to the summer condition, with a minimum temperature difference of only 0.208 °C. This indicates that soil moisture content is a key factor affecting the system's thermal performance in the transition season.

In the low-moisture-content condition of the transition season, since the inlet temperature is consistently much higher than the soil temperature, no abnormal phenomena occur in the heat exchange efficiency η. As shown in Fig. 7, the heat exchange efficiency η is basically maintained at approximately 0.13–0.25. In the high-moisture-content condition, except for abnormal values caused by sudden drops in ambient temperature, the heat exchange efficiency η is entirely maintained within the range of 0–0.25.

3.5. Mechanism of soil temperature variation during operation and recovery phases

Fig. 9 shows the variation of soil temperature with time at different burial depths under summer conditions. The period of 0–4350 min corresponds to system operation, while 4350–9000 min represents the natural recovery stage after shutdown. Soil temperature variation is mainly influenced by heat exchange between the air in the outer tube and the surrounding soil.

During operation, soil temperature at all depths increases gradually, with clear depth dependence. Shallow soil (e.g., 0–0.1 m) exhibits a faster and larger temperature rise, while deeper soil (e.g., 0.9–1.1 m) shows smaller variations and a noticeable time lag. This is because air first exchanges heat with shallow soil, where the temperature difference is larger, leading to stronger heat transfer. As air flows deeper, its temperature decreases, reducing the heat transfer driving force and resulting in weaker temperature changes in deeper soil.

After system shutdown, soil temperature continues to rise briefly and

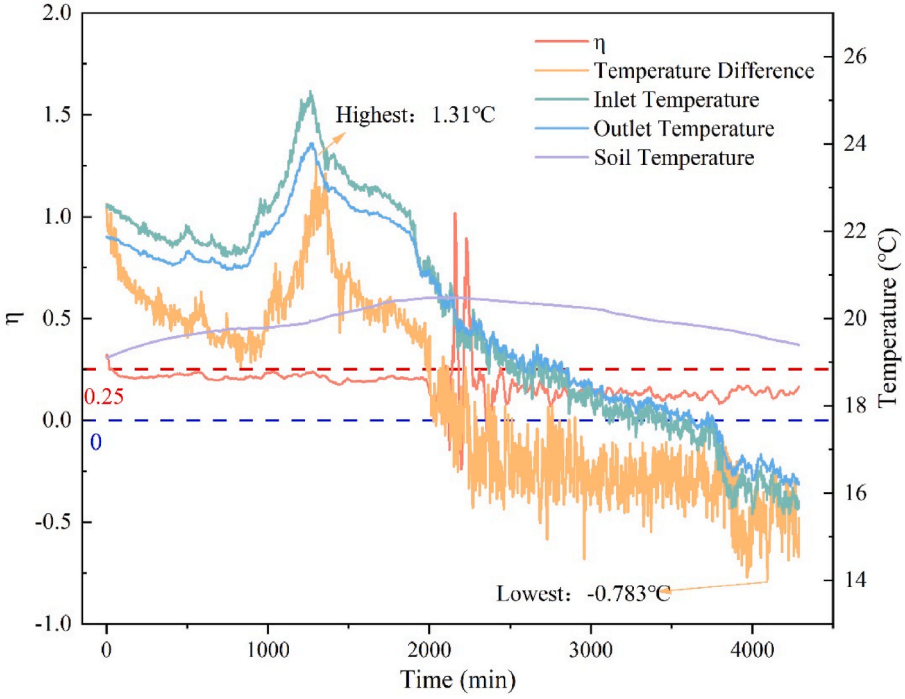


Fig. 8. System efficiency under high-soil-moisture condition in transition season.

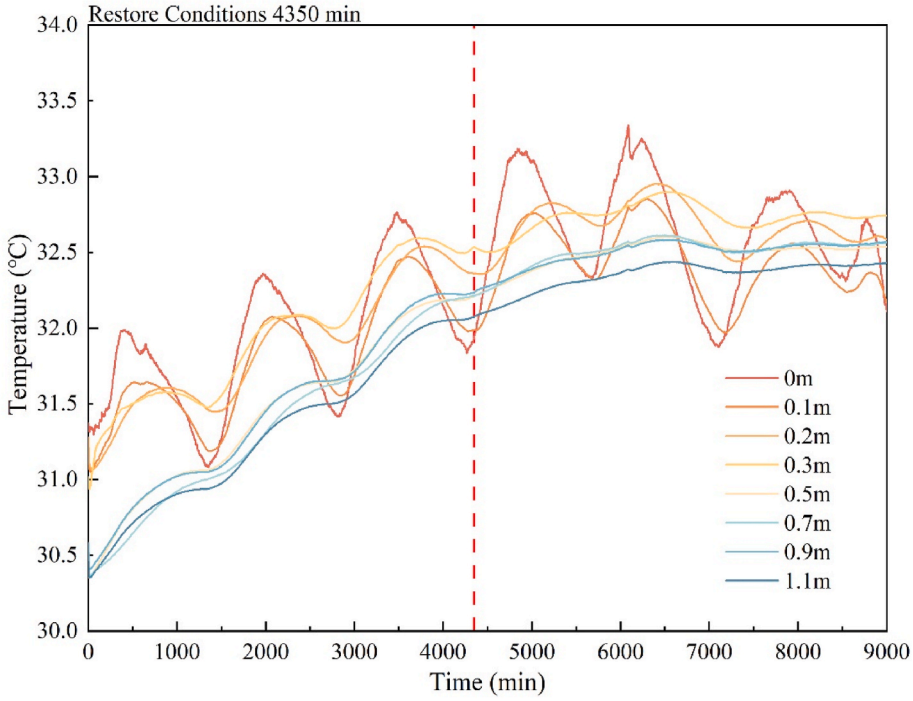


Fig. 9. Soil temperature variation during system operation and recovery phases.

reaches a peak at approximately 6090 min, indicating that the heat accumulated during operation continues to diffuse within the soil. Subsequently, soil temperature gradually decreases and stabilizes, reflecting the release of stored heat through natural heat diffusion.

To quantify soil thermal recovery capacity, the temperature change rate is defined as:

$$k = \frac{T_2 - T_1}{t_2 - t_1} \tag{2}$$

where k is the soil temperature change rate (°C/day). The calculated heating and recovery rates are approximately 0.3417 °C/day and 0.3371 °C/day, respectively, indicating comparable time scales for heat storage and dissipation. This suggests that the soil has a good thermal recovery capacity under the experimental conditions.

However, under prolonged continuous operation in summer, heat accumulation may still occur. Based on the measured heating rate, the soil temperature is estimated to increase by about 2.4 °C after 7 days and 3.4 °C after 10 days under ideal linear conditions. Although the actual

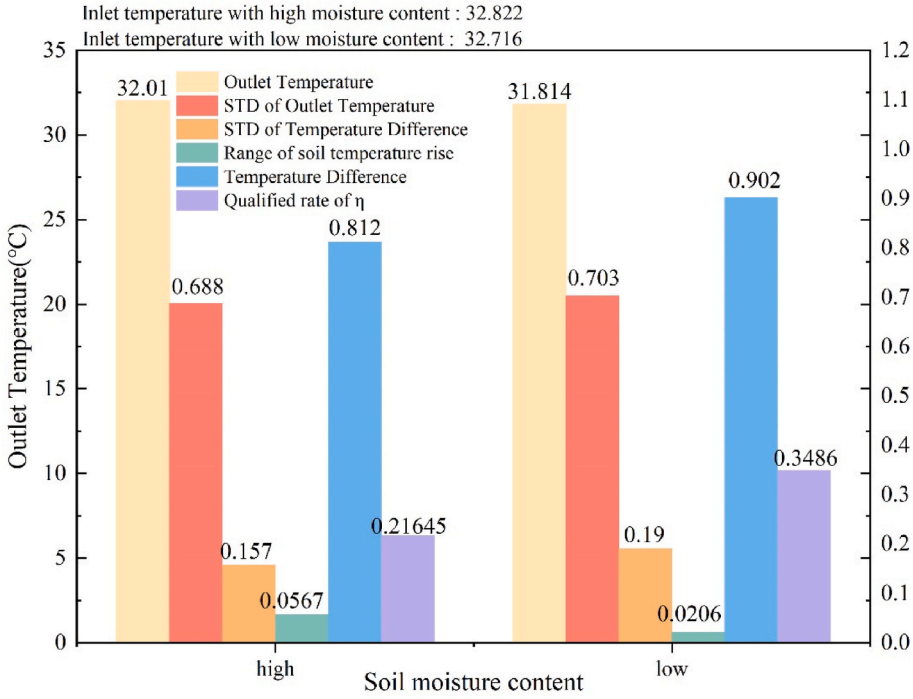


Fig. 10. Data comparison of different moisture contents under summer condition.

temperature rise rate may decrease as the temperature difference diminishes, these results indicate the potential risk of thermal saturation near the pipe region.

Therefore, in practical applications, strategies such as optimizing operation cycles, extending recovery periods, and adjusting burial depth should be considered to mitigate heat accumulation and ensure long-term stable operation.

4. Discussion

4.1. Influence of moisture content on system efficiency

Fig. 10 illustrates the effect of soil moisture content on system performance under summer conditions. From a microscopic heat transfer perspective, increasing soil moisture content modifies the heat transfer pathways within the porous medium, thereby affecting the overall air–soil heat exchange process. At low moisture content, heat transfer mainly occurs through limited particle contacts with air-filled pores, resulting in high thermal resistance and weak heat transfer.

As moisture content increases, pore air is gradually replaced by water, forming continuous or semi-continuous water films between particles. These water films enhance heat conduction and reduce contact thermal resistance, while the higher volumetric heat capacity of moist soil improves its ability to store and release heat. As a result, temperature fluctuations are effectively dampened, leading to a more stable outlet air temperature and a smoother air–soil temperature difference. Therefore, increased soil moisture content enhances both heat transfer efficiency and thermal buffering capacity, enabling the VCP-EAHE system to maintain more stable heat exchange performance.

4.2. Temperature difference advance effect

Under summer conditions, both inlet and outlet air temperatures exhibit clear diurnal variations. The peak temperatures are nearly synchronized, but the outlet temperature rises more slowly, resulting in a delayed response. Notably, the peak temperature difference occurs earlier than the temperature peaks of both inlet and outlet air.

This phenomenon is primarily attributed to the combined effects of air transport delay and soil thermal inertia. As ambient temperature rises, inlet air responds rapidly, while the outlet air experiences a time lag due to finite residence time within the pipeline. Meanwhile, soil temperature remains relatively stable in the early stage because of its low thermal diffusivity, maintaining a large air–soil temperature difference and a strong heat transfer driving force.

In addition, the two-stage heat exchange process in the VCP-EAHE system (outer tube downward flow and inner tube upward flow) further prolongs the thermal response time. As a result, the inlet temperature increases rapidly while the outlet temperature lags behind, causing the temperature difference to reach its peak earlier. Subsequently, as the outlet temperature gradually increases, the temperature difference decreases accordingly.

4.3. Comparison with conventional EAHE efficiency

To evaluate the thermal performance of the proposed VCP-EAHE system, this study compared the experimental results with existing laboratory-scale EAHE research.

First, Zhao et al. [32] conducted experiments using a conventional EAHE scale model with a burial depth of 2 m at a wind speed of 2 m/s. The results showed that the system efficiency decreased slightly with increasing pipe diameter. However, at a burial depth of 2 m and a smaller pipe diameter, its temperature extraction efficiency was still close to that of the VCP-EAHE system in this study. Notably, the pipe diameter of the proposed VCP-EAHE was significantly larger and the burial depth shallower, yet it achieved comparable temperature extraction efficiency at the same wind speed. This indicates that the VCP-EAHE can maintain effective heat transfer performance under relatively unfavorable geometric conditions.

Second, Alkrush et al. [33] investigated EAHE under laboratory-simulated conditions. At an inlet air temperature of 35 °C, a pipe diameter of 0.0254 m, an air-soil temperature difference of approximately 20 °C, and a wind speed close to 2 m/s, the efficiency of the conventional EAHE system was only about 45%. In contrast, the VCP-EAHE achieved a comparable efficiency under similar wind speeds, despite having a larger pipe diameter and a smaller soil-air temperature difference. This further demonstrates that the vertical coaxial pipe structure improves the heat exchange utilization per unit pipe length, allowing the system to retain high efficiency even under unfavorable conditions.

Based on the comparison with the two references, it can be concluded that the VCP-EAHE system maintains heat transfer performance equivalent to that of conventional horizontal-buried EAHE under unfavorable conditions such as reduced land occupation, larger pipe diameter, and smaller soil temperature difference.

4.4. Research limitations and future outlook

Although this study investigated the heat exchange characteristics of the VCP-EAHE system under multiple operating conditions through sandbox experiments, it still has certain limitations due to experimental constraints, which also pointing out directions for future research.

The current experiment has two main limitations. First, sandbox simulation cannot fully reproduce the actual unsteady thermal environment underground, where soil properties have a significant impact on system efficiency. For example, soil moisture content can be altered by the operation of EAHE [34], which in turn affects the system. Cuny et al. [35] pointed out that modifying or replacing the soil around EAHE pipes can significantly improve thermal performance. In practical engineering, the actual underground environment involves dynamic thermal processes such as annual periodic variations in soil temperature and heat migration induced by groundwater flow—these processes cannot be fully reproduced by sandbox experiments, which may lead to deviations between the thermal properties of the soil in the experiment and actual conditions, affecting the accurate evaluation of the system's long-term operational performance. Second, there are differences between the indoor sandbox experimental environment and the actual outdoor scenarios. Outdoor meteorological factors such as solar radiation, wind, and rain directly affect processes such as the system's inlet temperature and soil surface heat exchange, which cannot be fully replicated in the indoor environment—thus influencing the reflection of the system's performance under actual outdoor conditions.

Based on these limitations, future research can be carried out in the following directions. First, enhance the realistic simulation of the soil thermal environment: improve the sandbox experimental setup and introduce more precise soil temperature control methods. For example, during summer experiments, use a chiller to inject cold water into the sandbox soil to lower the soil temperature to the actual summer soil temperature level in Changsha; during winter experiments, insert heating tubes into the sandbox to raise the soil temperature to the actual local winter soil temperature. This will more realistically simulate the annual variations in soil temperature and improve the guiding value of experimental results for practical engineering. Second, conduct outdoor field tests: bury the system directly in the soil at an actual site, exposing the system to the natural outdoor environment. Fully consider the impact of outdoor factors such as solar radiation, natural wind, and precipitation on processes such as system air intake and soil heat exchange, and obtain system performance data that is more consistent with engineering practice. Furthermore, in recent years, aiming at performance improvement of complex thermal systems, existing studies have begun to introduce multi-objective optimization methods such as machine learning and genetic algorithms into system modeling and optimization processes to improve parameter optimization efficiency

and thermal performance analysis capability [36]. On the other hand, some studies have further realized the screening of key design variables and the optimization of overall system performance by combining parameter sensitivity analysis, machine learning prediction and multi-objective decision-making methods [37], which provide referable methodological approaches for the subsequent numerical optimization and engineering design of novel geothermal ventilation systems.

Therefore, in future work, based on the establishment of a numerical model for VCP-EAHE, the internal heat and mass transfer processes of the system can be simulated with computational fluid dynamics software FLUENT or building thermal system simulation software TRNSYS. Furthermore, parameter sensitivity analysis, machine learning prediction and multi-objective optimization methods can be introduced to systematically investigate the influences of key parameters such as burial depth, pipe diameter, air velocity inside the pipe and operation strategy on the heat exchange efficiency, energy consumption and operational stability of the system. In this way, the optimal combined design of parameters can be achieved, providing theoretical support for the efficient and economical application of the system in practical engineering.

5. Conclusions

In this paper, a VCP-EAHE system is proposed and its thermal performance and temperature response characteristics of the system under different seasons and soil moisture content conditions are investigated experimentally using a sand-box scaled-down setup. Based on the experimental results, the main conclusions are drawn as follows.

(1) The VCP-EAHE system responds significantly to changes in ambient temperature and exhibits stable thermal regulation capability. Under summer conditions, the system provides stable pre-cooling during high-temperature periods, with an inlet-outlet temperature difference of up to 1.68 °C.
(2) The system demonstrates obvious dual-direction thermal regulation under transition-season conditions. When the inlet air temperature is higher than the soil temperature, the air is cooled during the underground heat exchange process, with a maximum temperature drop of 1.31 °C. When the inlet air temperature is lower than the soil temperature, the soil acts as a heat source and releases heat to the air, achieving a maximum temperature rise of approximately 0.78 °C.
(3) Soil moisture content is an important factor affecting the thermal performance of the system. Experimental results show that soil with high moisture content, due to its higher thermal conductivity and specific heat capacity, can enhance the thermal buffer capacity of the system and stabilize the outlet air temperature fluctuations. Statistical results indicate that the standard deviation of the inlet-outlet temperature difference is 0.158 under high moisture content conditions, compared with 0.190 under low moisture content conditions.
(4) Compared with conventional horizontal-buried EAHE systems, the VCP-EAHE system adopts a vertical coaxial pipe configuration, which reduces land occupation while increasing effective burial depth and improving heat exchange efficiency between air and soil. Experimental results confirm that the system presents favorable thermal regulation and operational stability under various soil conditions and seasonal scenarios.

CRediT authorship contribution statement

Zhitong Meng: Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Zhengxuan Liu:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zhangfan Zhou:** Methodology, Investigation, Formal analysis. **Zhengtao Ai:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2026.125706.

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