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Research paper

Investigation on soil thermal saturation and recovery of an earth to air heat exchanger under different operation strategies

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H I G H L I G H T S

- We investigated the soil saturation and recovery of an EAHE.
- The model is constructed with numerical transient control volume method.
- The numerical result is validated by testing data from an experimental facility.
- The soil has recovery capability in the intermittent operation mode.
- The cooling capacity is higher with low temperature in the intermittent operation.

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A B S T R A C T

A great portion of the primary energy is consumed by space heating and cooling in buildings. The need for utilizing more renewable energy in the building sector remains critical for ensuring the energy and environment sustainability. Geothermal energy is one of the renewable energy sources that we have an easy access to for supplying low grade thermal energy with a low impact on the environment. The methods of utilizing geothermal energy for buildings include such as ground source heat pumps and earth to air heat exchangers (EAHEs). Understanding the thermal saturation and recovery of soil around the heat exchangers is of great importance to ensure the successful and efficient use of a geothermal energy based system. This study addresses two dimensional dynamic heat transfer mechanism of EAHE through a transient control volume method. The soil computing domain is divided into control units along the axial and radius directions. A thermal balance of each unit is built to calculate the whole soil domain temperature based on a sequential method. The numerical result is validated by testing data based on an existing experimental facility. In order to analyze the self-recovery ability during the nonworking time, the performance of EAHE under both continuous and intermittent operation conditions is discussed. The research suggests that the soil temperature and the cooling capacity can recover during the nonworking time in an intermittent operation mode. The recovery capability of soil gradually reduces along the axial of the tube away from the inlet with the soil temperature increasing. The supply air temperature and the cooling capacity in the intermittent operation mode are more powerful than that of continuous operation mode. The research can be utilized for the design and operation management of EAHE.

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1. Introduction

Building sector is one of the biggest non-renewable energy consumers that are not utilizing much of the renewable energy. Buildings consumed nearly 40 percent of total energy use. About 50 percent of this energy is used for heating, cooling, and ventilating

buildings [1]. At the same time, about 86 percent of energy used in buildings is from the combustion of fossil fuel. An earth to air heat exchanger (EAHE) system has often been used to achieve free cooling/heating for energy saving [2]. An EAHE is an underground heat exchanger through burying pipes in the ground that can cool or warm air by dissipating heat to or capturing heat from the ground. It can free supply fresh pre-heated or pre-cooled air or even 100% cooling or heating when the capacity is enough.

In order to understand the thermal performance of an EAHE, many mathematic models, computing methods or tools were

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Nomenclature*Roman letter symbols*

<i>a</i>	time constant
<i>c</i>	specific heat, J/kg K
<i>d</i>	diameter, m
<i>h_c</i>	convective heat transfer coefficient, W/m ² K
<i>k</i>	soil heat conductivity, W/m K
<i>m</i>	mass flow rate of air flow, kg/s; mass of control unit, kg
<i>p</i>	perimeter of pipe, m
<i>r</i>	radius, m
<i>t</i>	time
<i>C</i>	thermal capacitance, J/K
<i>E</i>	energy storage, J
<i>M</i>	total node number in radial direction
<i>N</i>	total node number in horizontal direction
<i>P</i>	perimeter, m
<i>Q</i>	heat transfer, J
<i>R</i>	thermal resistance, W/K
<i>T</i>	temperature, °C

Subscripts/Acronyms

air	air
<i>c</i>	convective
<i>i</i>	node number in <i>x</i> direction
in	inlet
<i>j</i>	node number in <i>r</i> direction
out	outer
pip	pipe
<i>s</i>	soil
undis	undisturbed
EAHE	earth to air heat exchanger
<i>Nu</i>	Nusselt number
<i>Pr</i>	Prandtl number
<i>Re</i>	Reynolds number

Greek letters

Δt	time step, second
Δx	step length, m
Δr	step length, m
λ	heat conductivity, W/m K
θ	temperature, °C
ρ	specific density, kg/m ³

greatly applied. Krarti and Kreider considered the EAHE heat transfer problem as a transient one and proposed an analytical model assumes the EAHEs system reached a steady and periodic state after a few days of operation [3]. Hollmuller proposed a complete analytical solution for the heat diffusion of a cylindrical air/soil heat exchanger with isothermal boundary condition. The air flow with harmonic temperature signal at input was assumed constant. The analytical results were numerically validated with hourly data over one year. Amplitude-dampening and phase-shifting calculated based on the analytical solution were analyzed [4]. Paepe and Janssens proposed a one-dimensional analytical method to analyze the influence of the design parameters of the heat exchanger on the thermo-hydraulic performance. The specific pressure drop and linking thermal effectiveness with pressure drop of the air inside the tube were derived to obtain design-map finally [5]. In general, an analytical solution is difficult to achieve and is only gained with lots of assumptions. For the convenience of computer calculation, a numerical approach is widely used. Su developed a numerical simulating model for a deeply buried air-earth -tunnel system. A one-dimension implicit transient convection-diffusion sub-model described the air temperature and humidity, and a one-dimension transient explicit heat conduction sub-model computed the rock temperature. A sequential computing algorithm was used to calculate the model. At last, the numerical result was verified by the testing data [6]. Badescu developed a simple and accurate ground heat exchanger model based on a numerical transient bi-dimensional approach that allows computing of the ground temperature at the surface and at various depths. The heating and cooling potential of a system under real climatic conditions was investigated [7]. Vaz conducted the experimental and numerical analysis of EAHE. The turbulent flow of air inside the ducts of EAHE was considered in the numerical analysis. In order to analyze the interaction between multiple ground-buried heat exchangers, a calculation method for heat extraction or injection via multiple ground heat exchangers was developed [8]. A modification coefficient, used to multiply the ideal ground heat exchanger radius of an infinite line heat source for calculation of average temperature of a finite line heat source, is investigated in order to correct a heat source of infinite length.

Beside the analytical and numerical methods, computing tools especially computational fluid dynamics (CFD) were widely adopted to calculate the thermal performance of EAHE. A transient and implicit model based on numerical heat transfer and CFD was explored for evaluating the effects of operating parameters (i.e., the pipe length, radius, depth and air flow rate) on thermal performance and cooling capacity of earth–air–pipe systems [9]. A very useful review paper on applications of CFD in the field of heat exchangers was published. It is concluded that CFD is an effective tool for predicting the behavior and performance of a wide variety of heat exchangers [10]. Misra et al. used CFD software to study the effect of soil thermal conductivity, duration of continuous operation, pipe diameter and flow velocity on the thermal performance of EAHE based on a parametric method. Transient operating conditions greatly affected the thermal performance of EATH [11]. With the methods mentioned above, the performance of EAHE is greatly evaluated from various perspectives. Pfafferott proposed the evaluation way to calculate energy efficiency of EAHE with a standardized method. Both dynamic temperature behavior and energy performance were used to define the thermal efficiency [12]. Bojic et al. evaluated the technical and economic performance of an EAHE coupled to a system for heating and cooling of a building. Steady-state energy equations were used for each divided soil layer in each time step. It was found that the EAHE system was more energy and cost efficient in summer than in winter [13]. Bansal et al. proposed a derating factor for evaluating thermal performance of earth to air heat exchanger. It was determined by temperature drops obtained under steady-state condition and transient condition. The thermal performance of EAHE was analyzed under different soil thermal conductivity through CFD software. The result suggested that the soil situated in the immediate vicinity of the EAHE pipe should have higher thermal conductivity and at the same time a derating factor should be taken into account while optimizing the thermal performance of EAHE [14,15].

From the literature review, we found that the majority of calculation methods used only very limited EAHE configurations. Few efforts were paid to the real operation situation, especially in the regard of soil thermal saturation and recovery of EAHE. A soil thermal saturation refers to the situation when the soil and air

temperature difference becomes so close as to no energy obtaining from soil by heat transfer between soil and air. Therefore, a soil thermal saturation and recovery is an important factor that determines whether an EAHE system can successfully and efficiently work or not [16,17]. In addition, previous research ignored the dynamic effect between the air and earth. This study is the first to address the two dimensional dynamic heat transfer mechanism of EAHE through a transient control volume method. The soil computing domain is divided into a set of torus as control units. The thermal balance of each unit is built to calculate the whole soil domain temperature based on a sequential method. The numerical result is validated by testing data from an existing experimental facility. In the real application, an EAHE-assisted heating and cooling system usually does not need to work continuously over 24 h. In order to analyze the self-recovery ability during the nonworking time, the performance of EAHE under both continuous and intermittent operation conditions were discussed firstly. The research can be utilized to improve EAHE operation management.

2. Mathematic modeling

2.1. Soil temperature modeling

Ground soil is the energy resource of EAHE which supplies cooling or heating energy to the air inside the tube. In the mean time, the ground soil temperature is affected during the heat transfer process between the air and soil when the air flows continuously from the outside into the tube. In order to analyze the effect of heat transfer on the ground soil temperature, the soil temperature distribution and variation are calculated during the heat transfer process. The heat transfer of EAHE is considered in a cylindrical coordinate system. Heat transfer governing equations can be established based on energy balance. A transient temperature analysis method based on a control volume thermal network approach is performed [18,19].

The soil around a tube is divided into a number of torus control units. The thickness of the tube is far thinner than each unit. Therefore, the tube along radial direction is considered as one control unit. Fig. 1 shows the structure of control units. Each unit has its own thermal capacitance C_{ij} and is connected to its adjacent units.

This study focuses on the investigation of soil thermal properties under different operation strategies in short term when the soil temperature has generally very small variation [20]. The assumptions made in this research are listed as follows:

- (1) Initially, both air and ground soil temperatures are undisturbed;

- (2) The effect of depth on the soil temperature is ignored and the process of heat transfer along circumferential direction is considered symmetric;
- (3) Air inside an EAHE mixes evenly within each segment along the tube without stratification;
- (4) The effect of convection and radiation on the soil surface on the heat transfer process of EAHE is ignored;
- (5) The soil heat conductivity is assumed to be uniform [21];
- (6) Air is incompressible and its thermal properties are constant.

The tube along with x direction (horizontal) is divided into N elements and the length of each element is Δx . The temperature along the radius r and at the axis distance x at time t is $T(r, x, t)$. It can be obtained by using the transient control volume method to the governing equation:

$$\Delta \dot{E} = \dot{Q}_{in} - \dot{Q}_{out} \quad (1)$$

where the heat transfer rate of each control unit is:

$$\Delta \dot{E} = mc_s \frac{dT}{dt} \quad (2)$$

As indicated in Fig. 1, thermal energy transferring in (as \dot{Q}_{in}) and out (as \dot{Q}_{out}) of the control unit (i, j) is through the heat conduction from the adjacent axis units $(i-1, j)$, $(i+1, j)$ and adjacent units $(i, j-1)$, $(i, j+1)$.

The radius of number j element along the radial direction can be calculated as follow:

$$r_j = r_{j-1} + (j-1)\Delta r \quad (3)$$

The temperature at the midpoint of control unit (i, j) at time step t is denoted as T_{ij}^t . The thermal resistance associated with control unit (i, j) in x direction is equal to the reciprocal of one-dimensional conductance multiplied by the area of control unit as:

$$R_{ij}^x = \frac{\Delta x}{\pi k (r_j^2 - r_{j-1}^2)} \quad (4)$$

The thermal resistance in r direction is in cylindrical shape and should be calculated as:

$$R_{ij}^r = \frac{\ln(r_j/r_{j-1})}{2\pi k \Delta x} \quad (5)$$

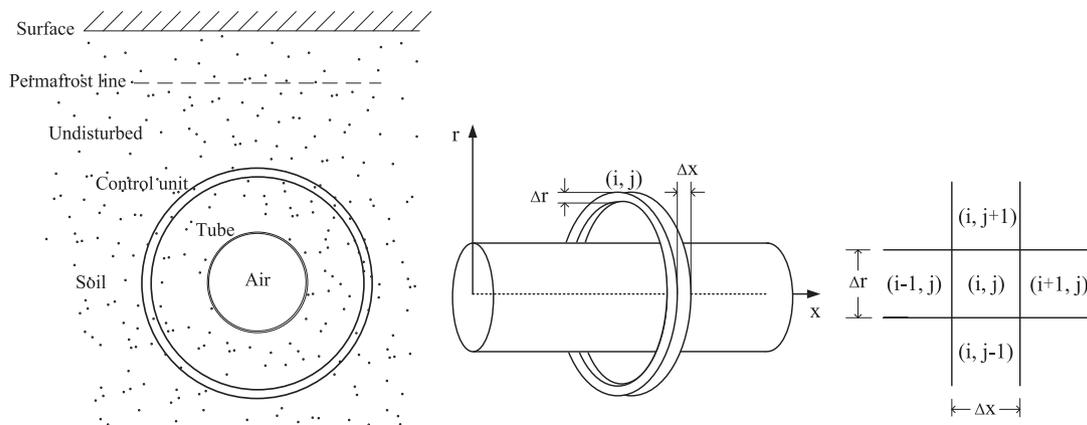


Fig. 1. The structure of governing unit.

The overall thermal resistance between two adjacent units takes the mean of the two along the two dimensions. The sum of the heat conduction through the soil unit (i, j) is:

$$\dot{Q}_{in} - \dot{Q}_{out} = \left(\frac{T_{i+1,j}^t - T_{i,j}^t}{\left(\frac{R_{i+1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i-1,j}^t - T_{i,j}^t}{\left(\frac{R_{i-1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i,j+1}^t - T_{i,j}^t}{\left(\frac{R_{i,j+1}^r + R_{i,j}^r}{2} \right)} + \frac{T_{i,j-1}^t - T_{i,j}^t}{\left(\frac{R_{i,j-1}^r + R_{i,j}^r}{2} \right)} \right) \quad (6)$$

The thermal capacitance C_{ij} is calculated as follow:

$$C_{ij} = \pi \cdot \Delta x \left[(r_j)^2 - (r_{j-1})^2 \right] \rho c_s \quad (7)$$

The energy change rate in control unit (i, j) is:

$$\Delta \dot{E} = \frac{(T_{ij}^{t+1} - T_{ij}^t) \cdot C_{ij}}{\Delta t} \quad (8)$$

Combine the previous equations, we can obtain the differenced governing equation for the temperature in control unit (i, j):

$$T_{ij}^{t+1} = \frac{\Delta t}{C_{ij}} \times \left(\frac{T_{i+1,j}^t - T_{i,j}^t}{\left(\frac{R_{i+1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i-1,j}^t - T_{i,j}^t}{\left(\frac{R_{i-1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i,j+1}^t - T_{i,j}^t}{\left(\frac{R_{i,j+1}^r + R_{i,j}^r}{2} \right)} + \frac{T_{i,j-1}^t - T_{i,j}^t}{\left(\frac{R_{i,j-1}^r + R_{i,j}^r}{2} \right)} \right) + T_{ij}^t \quad (9)$$

2.2. Heat transfer at the boundary

To solve the numerical equations, the boundary of the soil temperature should be defined. In total, there are four thermal balance governing equations of the boundary due to four surfaces in the whole computing domain. Currently, the main treatment method on the soil boundary in a numeric simulation generally assumes a thermal isolation condition [4,6,13]. In order to improve the accuracy, we introduce the saturated soil model in this study.

The governing equation at the inlet node $i = 1$ unit is:

$$T_{ij}^{t+1} = \frac{\Delta t}{C_{ij}} \times \left(\frac{T_{i+1,1}^t - T_{i,1}^t}{\left(\frac{R_{i+1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{undis} - T_{i,j}^t}{R_{i,j}^x} + \frac{T_{i,j+1}^t - T_{i,j}^t}{\left(\frac{R_{i,j+1}^r + R_{i,j}^r}{2} \right)} + \frac{T_{i,j-1}^t - T_{i,j}^t}{\left(\frac{R_{i,j-1}^r + R_{i,j}^r}{2} \right)} \right) + T_{ij}^t \quad (10)$$

The governing equation at the end node $i = N$ unit is:

$$T_{ij}^{t+1} = \frac{\Delta t}{C_{ij}} \times \left(\frac{T_{undis} - T_{i,j}^t}{R_{i,j}^x} + \frac{T_{i-1,j}^t - T_{i,j}^t}{\left(\frac{R_{i-1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i,j+1}^t - T_{i,j}^t}{\left(\frac{R_{i,j+1}^r + R_{i,j}^r}{2} \right)} + \frac{T_{i,j-1}^t - T_{i,j}^t}{\left(\frac{R_{i,j-1}^r + R_{i,j}^r}{2} \right)} \right) + T_{ij}^t \quad (11)$$

The governing equation at the innermost node $j = 1$ unit is:

$$T_{ij}^{t+1} = \frac{\Delta t}{C_{ij}} \times \left(\frac{T_{i+1,j}^t - T_{i,1}^t}{\left(\frac{R_{i+1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i-1,j}^t - T_{i,j}^t}{\left(\frac{R_{i-1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i,j+1}^t - T_{i,j}^t}{\left(\frac{R_{i,j+1}^r + R_{i,j}^r}{2} \right)} + \frac{T_{air,i}^t - T_{i,j}^t}{R_{i,j}^x} \right) + T_{ij}^t \quad (12)$$

The governing equation at the end node $j = M$ unit is:

$$T_{ij}^{t+1} = \frac{\Delta t}{C_{ij}} \times \left(\frac{T_{i+1,j}^t - T_{i,j}^t}{\left(\frac{R_{i+1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{i-1,j}^t - T_{i,j}^t}{\left(\frac{R_{i-1,j}^x + R_{i,j}^x}{2} \right)} + \frac{T_{undis} - T_{i,j}^t}{R_{i,j}^x} + \frac{T_{i,j-1}^t - T_{i,j}^t}{\left(\frac{R_{i,j-1}^r + R_{i,j}^r}{2} \right)} \right) + T_{ij}^t \quad (13)$$

2.3. Modeling the earth to air heat exchanger

During heat transfer process, tube is intermediate between earth and air heat transfer. Through the boundary analysis above, heat transfer between the soil and tube is introduced. Heat transfer model between the still tube and the moving air inside the tube is developed as follows.

$$m c_{air} dT_{air} = Ph_c (T_{pip} - T_{air}) dx \quad (14)$$

$$a \frac{d\theta}{dx} + \theta = 0 \quad (15)$$

where a , time constant, $a = m c_{air} / Ph_c$; h_c , convective heat transfer coefficient, $h_c = \lambda_{air} Nu / d$; $\theta = T_{air} - T_{pip}$, temperature difference.

Within the equation, Nu is a Nusselt number; λ_{air} is the thermal conductivity of air. They can be calculated as follows [22], respectively:

$$\begin{aligned} Nu &= 0.023 Re^{0.8} Pr^{0.4} \quad (\text{for heating mode}) \\ Nu &= 0.023 Re^{0.8} Pr^{0.3} \quad (\text{for cooling mode}) \end{aligned} \quad (16)$$

$$\lambda_{air} = 0.02442 + 10^{-4} \times (0.6992 T_a) \quad (17)$$

Air temperature can be calculated by the following equation:

$$T_{air}(x) = T_{pip} - (T_{pip} - T_{in}) \exp(-x/a) \quad (18)$$

3. Model validations

3.1. Introduction of existing experimental facility

The field testing data from an existing facility in Omaha, U.S. is used to verify the model. The schema and picture of the facility are shown in Figs. 2 and 3. A culvert steel EAHE with 57 m length, 0.45 m diameter, and buried at a depth of about 3 m underground is installed. It starts with a slanted inlet of 8.53 m, then penetrates the ground for 3 m and curves to a horizontal portion of about 45.7 m, finally bends upwards for 3.65 m at a right angle to enter the facility through its concrete slab near the south side of the building. The data logging system was programmed to record, average, and log the weather data over a 15-min span during the whole testing period. The main measurements that have been recorded for the

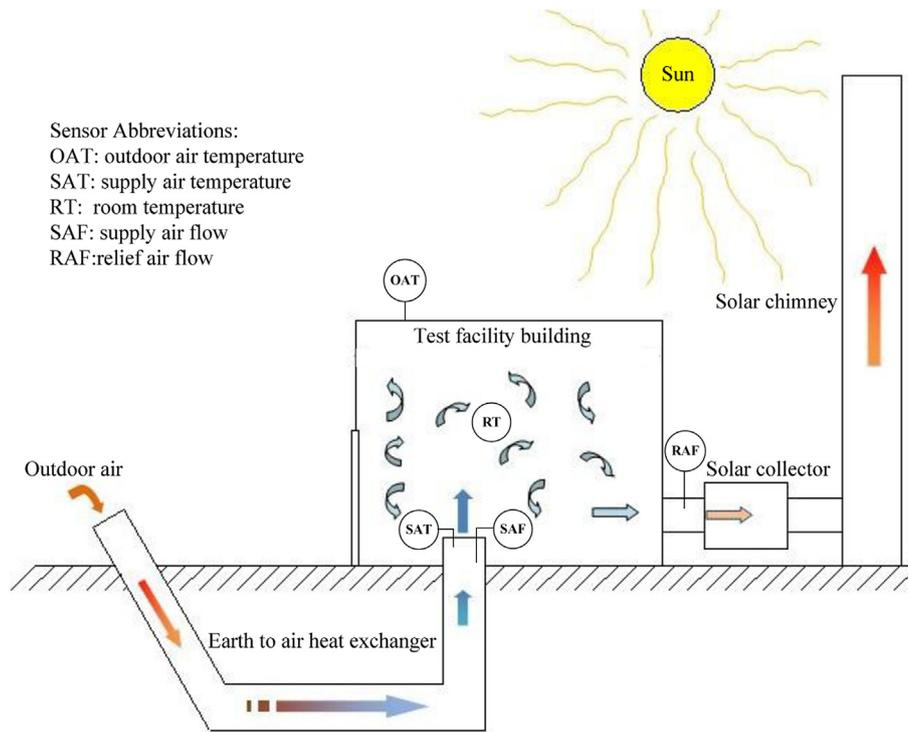


Fig. 2. Schematic diagram of the existing experimental facility [23].

purpose of analyzing the cooling capacity of the naturally driven coupled system are: time and date, supply air flow rate (m^3/s), the supply air temperature ($^{\circ}\text{C}$), and the outdoor air temperature ($^{\circ}\text{C}$). The system thermal performance during this testing period is presented based on the tested dates. Table 1 collects the main information about the experiment sensors, locations, type, and the corresponding accuracy.

3.2. Validation

The simulation program is developed using Matlab 8. The testing data from August 6th 2009 to August 16th 2009 was collected through the existing facility. Fig. 4 shows the tested outdoor air temperature, supply air temperature and simulated supply air temperature from the simulation program based on the aforementioned model. It can be seen from the figure that the supply air

temperature has the similar trend as the outdoor air temperature. When the outdoor air temperature increases, the supply air temperature increases, and vice versa. The supply air temperature is in the range of 18–27 $^{\circ}\text{C}$ during the period. According to the comparison between the tested and simulated supply air temperature, the error at the beginning phase is a little big. During the simulation process the initial ground soil temperature in computing domain is assumed the same; while in the real testing, the ground soil temperature in the whole computing domain is uneven and continuously affected by previous time condition all the time. Therefore, there is a little big error at the beginning phase. After three days operation, the effect of initial condition almost fades out. The match of experimental and simulated result is very well.

In order to analyze the effect of heat transfer between the air and soil on different thickness, the soil temperatures in different locations are tested and simulated. Figs. 5–7 show the soil temperatures at the location next to the tube surface 0, 0.15 and 0.3 m, respectively. It can be seen from Fig. 5 that the soil temperature next to the tube surface 0 m fluctuates in the range of 18–27 $^{\circ}\text{C}$ except the initial phase. The amplitude of the temperature is about 2.5 $^{\circ}\text{C}$. As seen from Fig. 6 the soil temperature fluctuates more gently than Fig. 5 which is in the range of 18–24 $^{\circ}\text{C}$. The amplitude of soil



Fig. 3. Picture of the existing experimental facility [23].

Table 1
List of experiment sensors.

Variable	Measurement	Location	Type	Accuracy
Temperature	a. Soil temperature	a. 0, 0.15, 0.30 m next to tube surface	Type "T" thermocouples	± 0.3 $^{\circ}\text{C}$
	b. Outdoor temperature	b. At the EAHE tube inlet		
	c. Supply air temperature	c. At the EAHE outlet		
Air flow rate	a. Supply air flow	a. EAHE outlet inside the house	Dwyer air velocity transmitters	$\pm 3\%$

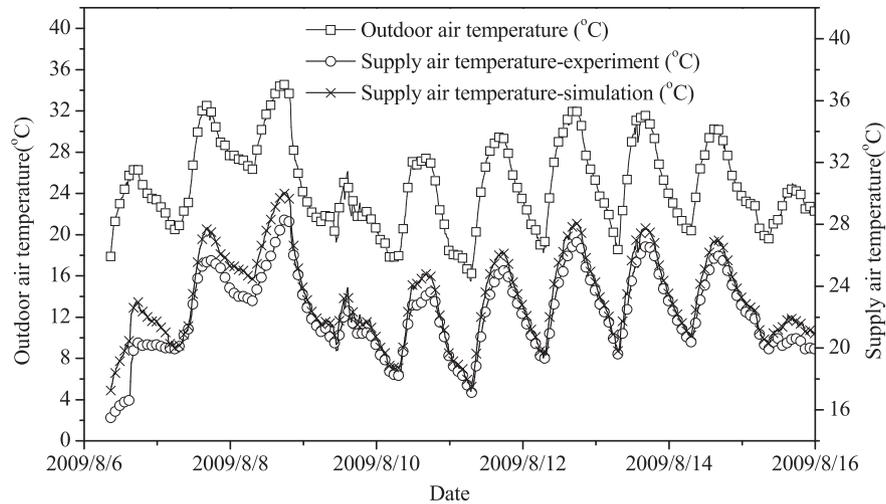


Fig. 4. The outdoor air and supply air temperatures.

temperature reduces to about 2 °C. Fig. 7 shows the soil temperature at the location next to the tube surface 0.3 m. The soil temperature barely fluctuates. The amplitude of the soil temperature is only 0.2 °C. According to the three figures some points can be obtained. First, the supply air temperature has the same changing trend as the outdoor air temperature. The soil temperature close to the tube surface fluctuates more sharply than that of far away from the tube surface. In addition, the amplitude is also much bigger. The simulation program can well predict the soil temperature. Except the initial phase, the error between the experimental and simulated data is small, which is acceptable for most engineering applications.

4. Analysis and discussions

4.1. Soil temperature analysis in axial and radial directions

The soil temperature has a great impact on the performance of EAHE. Therefore, the analysis of soil temperature distribution in the computing domain can be utilized to investigate the effect for the design and real operation management of EAHE. Based on the validated simulation program, more comprehensive soil thermal performance analysis is conducted. Fig. 8 shows the temperature of

soil 0.3 m away from the tube surface along with the length of tube. The initial soil temperature is set as 16 °C; the air flow rate and the air temperature at the inlet of EAHE are selected as 340 m³/h and 30 °C, respectively. As seen from the figure, after one day, the soil temperature close to the inlet of EAHE climbs up to 16.7 °C. This soil temperature along with length of tube decreases gradually to 16.25 °C. The decreasing rate of soil temperature is 0.0108 °C/m. After two days, the soil temperature close to the inlet of EAHE reaches 17.3 °C. The soil temperature along with length of tube decreases to 16.55 °C. The decreasing rate of soil temperature is 0.0184 °C/m. The results indicate that, after the use in days, the soil temperature close to the inlet of EAHE becomes much higher than that of close to the outlet of EAHE. Meanwhile, the decreasing rate of soil temperature along with the length of EAHE becomes higher and higher when time lapses. The air inside the EAHE is cooled down along with length, reducing the heat transfer and consequently absorbing less thermal energy from the soil. Therefore, the temperature difference between the air and soil at the inlet of EAHE is bigger than that of EAHE outlet.

Along with the inlet air temperature, the air flow rate is one of the most import influence factors on an EAHE. Therefore, the decreasing rate of soil temperature along with the length with

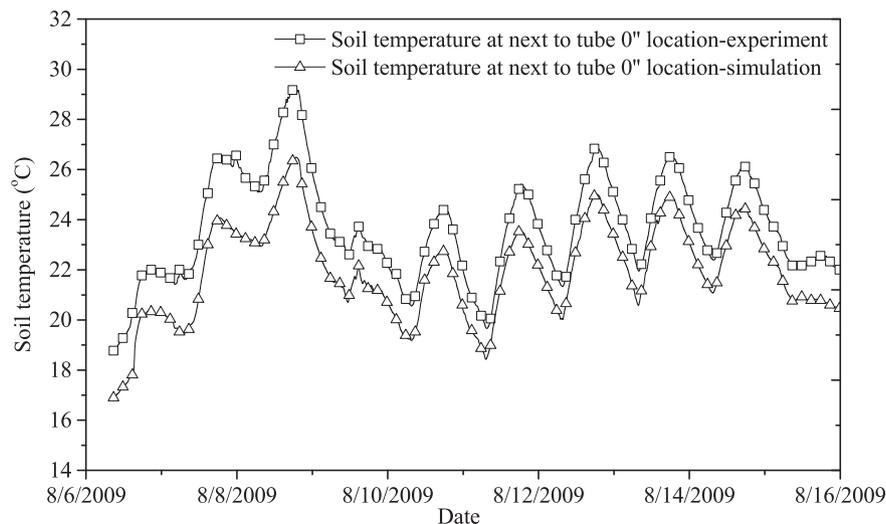


Fig. 5. The soil temperature next to tube surface 0 m location.

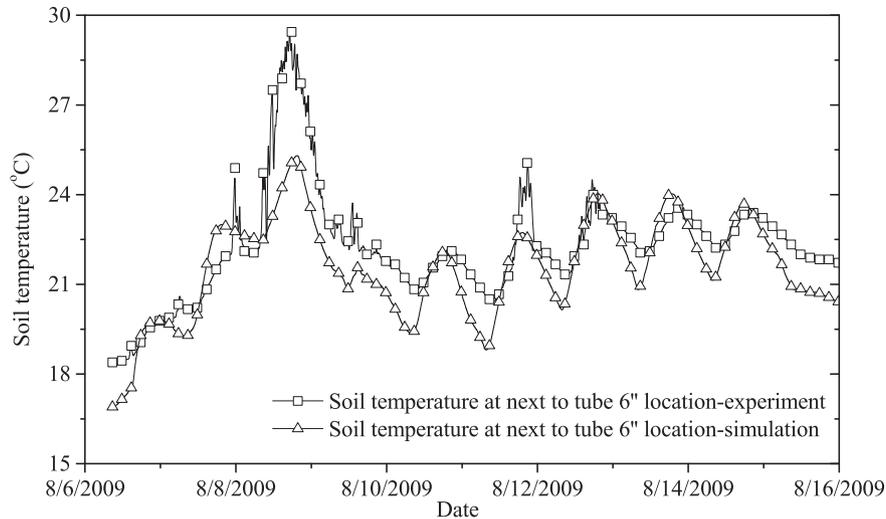


Fig. 6. The soil temperature next to tube surface 0.15 m location.

different air flow rates is analyzed, shown in Table 2. Two air flow rates of 340 and 3060 m³/h are selected (selection according to natural and mechanical ventilation with this EAHE [16]). The air temperature at the inlet of EAHE is kept as 30 °C for emulating a typical summer. Under the same air flow rate condition, the analysis on the decreasing rates of soil temperature at the different distance away from the EAHE surface of 0.3, 0.6 and 0.9 m are also conducted. With a low air flow rate, the decreasing rate gradually increases from Day 1 to Day 9. The soil at the inlet can continuously provide the cooling thermal energy. When it is operated with the air flow rate 3060 m³/h, the decreasing rate of soil temperature along with the length increases at the beginning, and then decreases after reaching the peak value. The reason is that the ability of heat transfer close to the inlet of EAHE is strong due to the big temperature difference and the air velocity between the air and soil at the beginning. The heat capacity in the soil dissipates gradually and the dissipation propagates toward the end of the tube. Along with the heat transfer ability decreasing close to the inlet of EAHE the decreasing rate of soil temperature along with the length will reach the peak; then the rate will start to decrease and becomes flat. For the different air flow rates, it indicates that when the air

flow rate increases the soil temperature difference at the inlet and outlet of EAHE becomes small. Therefore, a proper increase of the air flow rate could be beneficial to the overall thermal energy gain from the EAHE.

In order to analyze the effect of the distance away from the tube surface on the soil temperature, the soil temperature profiles at the different distance from 0 m to 1 m away from the tube surface are simulated and plotted in Fig. 9(a) and (b). The initial soil temperature is set as 16 °C, and the air flow rate and air temperature at the inlet of EAHE are selected as 340 m³/h and 30 °C, respectively. It can be seen from Fig. 9(a) that the soil temperature decreases quickly along with the increase of the distance away from the EAHE surface. However, the decreasing rate drops with the increasing distance. When the distance is far enough the soil temperature is equal to the soil initial temperature. Fig. 9(b) indicates how much soil thickness will be affected with time in hours. After the first 2 h, the soil temperature at the distance of 0.35 m far away from the EAHE surface begins to increase. It means that the air has affected 0.35 m thickness of soil within 2 h. Six hours later, the soil thickness of 0.6 m is affected. The soil thickness of 0.85 m is affected within 24 h. The analysis results indicate that, with the operation, the affected

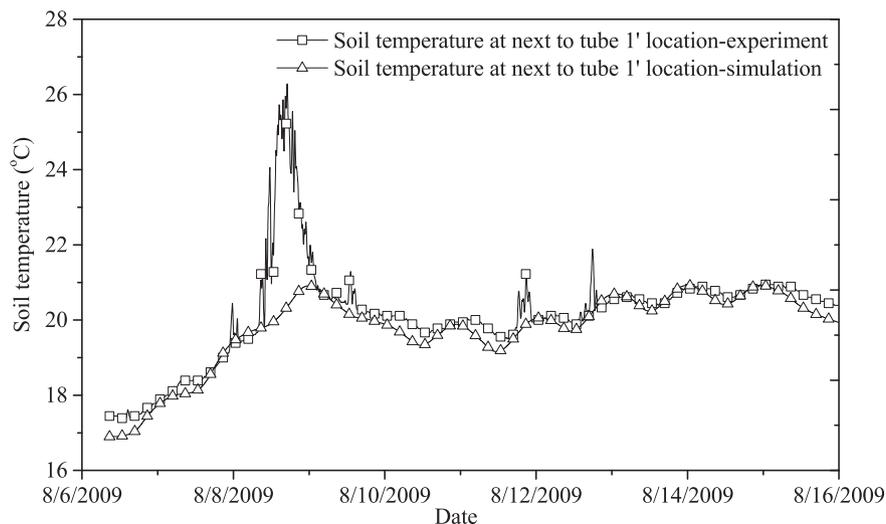


Fig. 7. The soil temperature next to tube surface 0.3 m location.

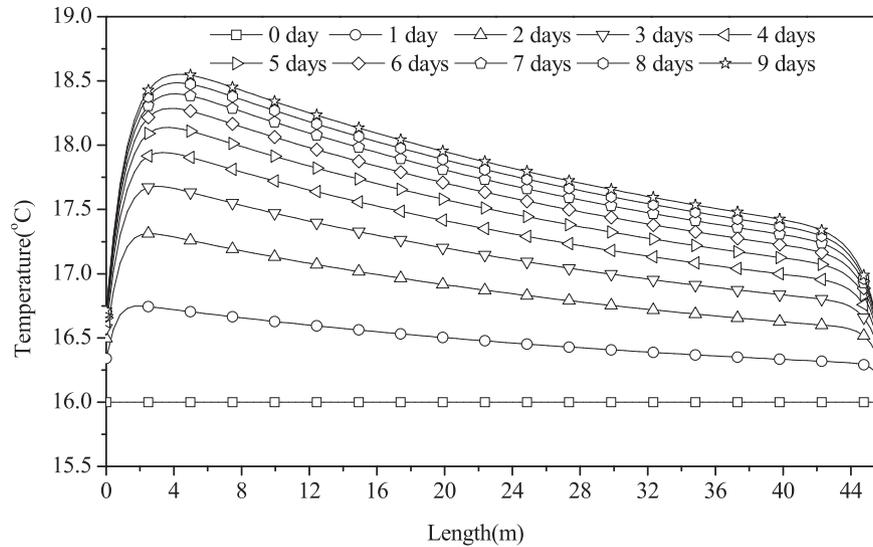


Fig. 8. The soil temperature at the location of next to tube surface 0.3 m.

soil thickness keeps growing, however, the increase gradient slows down gradually. Meanwhile, the effect of air on soil temperature close to the tube surface is greater than that of far away from the tube surface.

Fig. 10 shows the soil temperature rise with time at the different distance away from the EAHE surface. As shown in the figure, the soil temperature rise increases quickly at the beginning and then gradually slows down. The soil temperature rise of the distance away from the EAHE surface of 0.2 m reaches to 2.0 °C after 5 days. However, the temperature rise is just 2.3 °C after 9 days; the temperature changing is only 0.3 °C within 4 days. The soil temperature rise decreases when the distance from the EAHE surface increases; after 9 days, the soil temperature 1 m from the tube remains unchanged.

4.2. Soil temperature under continuous and intermittent operation conditions

Because of the difference of thermal capacity and heat transfer characteristics between the soil and air, the soil temperature distribution varies with the dynamic supply air conditions, including the air physics, flow rate, and pattern. The energy storage and cooling ability change all the time. In the real application, the indoor environment control system may not work 24/7. In general, the system is in operation during the office hour from 8:00 am to 18:00 pm, and is turned off during the nighttime. For the earth to air heat exchanger system, the nighttime is perfect to recover its energy

storage and cooling ability. In order to analyze the effect of the continuous and intermittent operation on the performance of EAHE system, the soil temperature, the supply air temperature and the cooling capacity of both modes are simulated and plot in Figs. 11–14. The initial soil temperature is set as 15 °C. The air is supplied at 340 m³/h and the air temperature at the inlet of EAHE is 30 °C. In the intermittent operation mode, the EAHE system works from 8:00 am to 18:00 pm, totally 10 h, and the recovery time is from 18:00 pm to 8:00 am, totally 14 h Fig. 11 shows the soil temperature under the continuous operation mode. It can be seen from the figure that the soil temperature 0.05 m away from the tube surface increases quickly at the beginning. Then the soil temperature increase becomes slow with time. After 96 h, the soil temperature reaches 18 °C. The soil temperatures at locations away from the tube surface 0.15 m, 0.30 m, 0.50 m, and 0.75 m climb to 17.25 °C, 16.35 °C, 15.6 °C, and 15.2 °C after 96 h, respectively. The temperature of soil 1.0 m away from the tube surface shows almost no change after 96 h with this operation mode. The effect of the air on the soil temperature close to the tube surface is greater than that of far away from the tube surface in terms of magnitude and variation.

Fig. 12 shows the soil temperature with time in the intermittent operation mode. It can be seen from the figure that the soil temperature can recover during the nonworking time. At the location 0.05 m away from the tube surface, the soil temperature increases from 15 °C to 16.5 °C during the first half cycle from 8:00 am to 18:00 pm. Since then, the soil temperature begins to recover. After 14 h from 18:00 pm to 8:00 am, the soil temperature drops 1.1 °C, from 16.5 °C to 15.4 °C. At the location 0.15 m away from the tube, the soil temperature increase has smaller amplitude, about 0.75 °C from 8:00 am to 18:00 pm; then the soil temperature begins to recover. After 14 h from 18:00 pm to 8:00 am, the soil temperature decreases 0.4 °C from 15.75 °C to 15.35 °C. The recovery ability decreases along with the distance and time. The simulation results are in consistency with our previous experimental results in terms of soil saturation and recovery [16]. In this case, the soil temperature does not recover to the original state. The soil temperature falls from the peak value every day. However, the low and high soil temperatures remain increasing in a long time. A full recovery of the soil can be achieved with proper operation condition and schedule to keep the EAHE system a good working condition.

Fig. 13 shows the supply air temperature in continuous and intermittent operation modes. As seen from the figure, the supply air temperature increases all the time from 19.5 °C to 21.7 °C in 96 h

Table 2
Decreasing rate of soil temperature with different air flow rates (°C/m).

	340 m ³ /h (200 CFM)			3060 m ³ /h (1800 CFM)		
	0.3 m	0.6 m	0.9 m	0.3 m	0.6 m	0.9 m
0 day	0	0	0	0	0	0
1 day	0.0108	0.0011	0.0000	0.0161	0.0019	0.0001
2 days	0.0184	0.0042	0.0006	0.0205	0.0056	0.0008
3 days	0.0230	0.0070	0.0013	0.0215	0.0076	0.0015
4 days	0.0258	0.0091	0.0019	0.0213	0.0082	0.0018
5 days	0.0276	0.0105	0.0023	0.0206	0.0082	0.0019
6 days	0.0287	0.0115	0.0026	0.0198	0.0079	0.0018
7 days	0.0295	0.0121	0.0028	0.0189	0.0074	0.0017
8 days	0.0299	0.0125	0.0029	0.0182	0.0069	0.0015
9 days	0.0301	0.0127	0.0030	0.0175	0.0065	0.0014

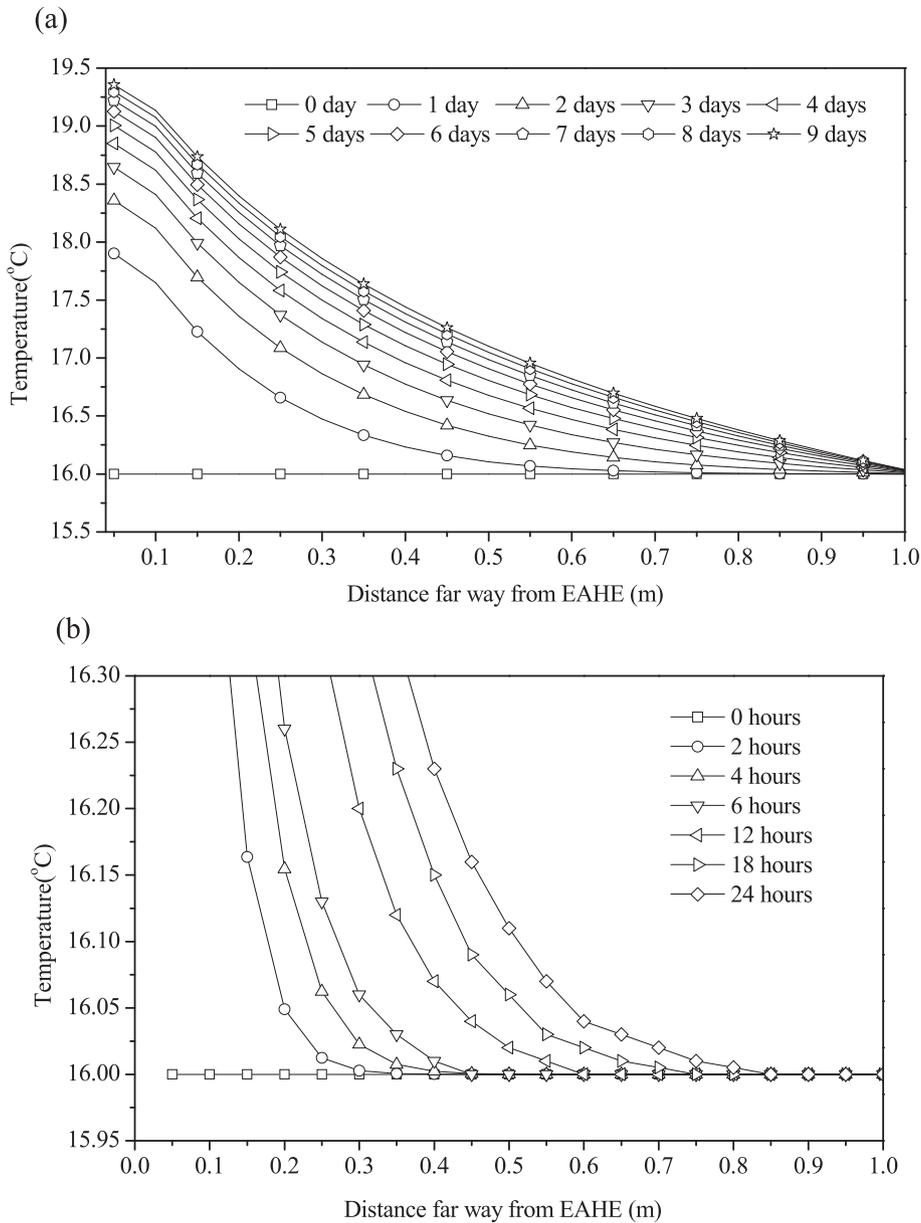


Fig. 9. The soil temperature at the different distance away from the tube surface.

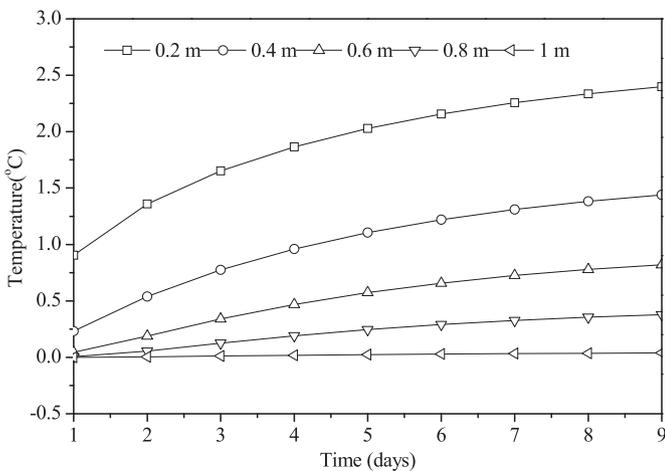


Fig. 10. The soil temperature rise at the different distance far away from the EAHE surface.

for the continuous mode. However, in the intermittent mode the supply air temperature increases slower than that of the continuous operation mode. The supply air temperature difference between the continuous and intermittent operation modes becomes wider over time. At 8:00 am in the simulated days, the supply air temperature differences between the continuous and intermittent operation modes are 0.72 °C, 1.06 °C, 1.21 °C and 1.52 °C, respectively. However, just in one day, the air temperature difference gets smaller and smaller. Meanwhile, in Day 1, the supply air temperatures difference is 0.72 °C at 8:00 am, and the difference becomes 0.26 °C at 18:00 pm. The similar pattern can be observed for the following days. In the intermittent operation mode the lowest supply air temperature happens at 8:00 am. The supply air temperature increases gradually in the day due to the cooling power loss of the soil. Through the soil temperature recovering during the nighttime, the similar pattern comes out again in the next day. Fig. 14 shows the cooling capacity in the continuous and intermittent operation modes. It can be seen from the figure that the cooling capacity of the continuous operation mode reduces all the

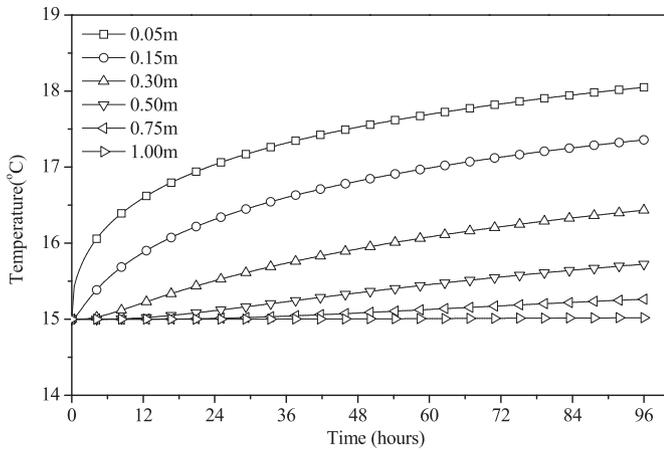


Fig. 11. The soil temperature in the continuous operation mode.

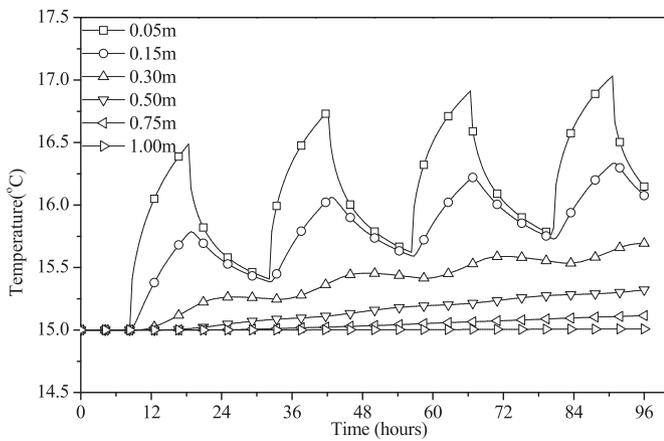


Fig. 12. The soil temperature in the intermittent operation mode.

time. It drops 240 W from the initial 1180 W–940 W within four days. The cooling capacity of the intermittent operation mode can be recovered in the nonworking time. The overall cooling energy of the intermittent operation condition is 1.64 MJ more than that of continuous operation condition in the first day, and the trend increases over time.

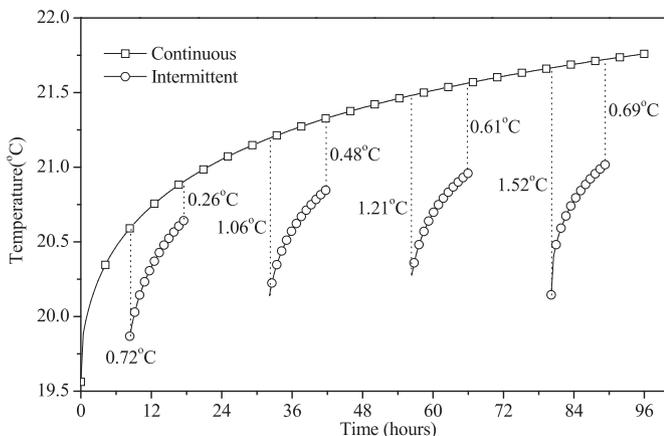


Fig. 13. The supply air temperature in and the difference between the continuous and intermittent operation modes.

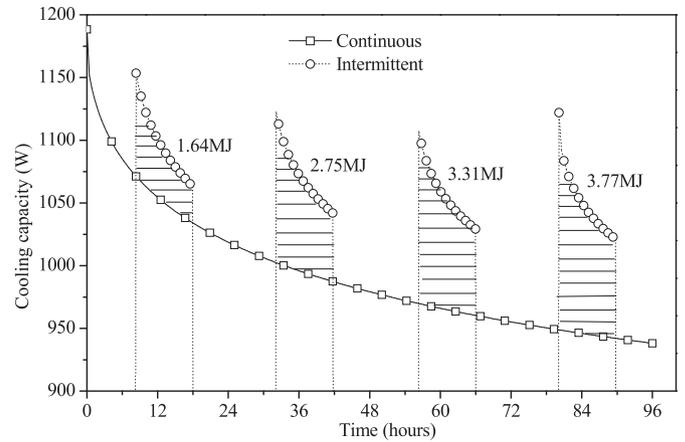


Fig. 14. The cooling capacity in and the cooling energy difference between the continuous and intermittent operation modes.

5. Conclusions and future works

While the soil can be considered as a great thermal energy source, there are temporal limitations in real applications due to the saturation issue. Understanding the soil thermal saturation and recovery of an earth-to-air heat exchanger (EAHE) system under different operation modes provides us valuable insights on how we may bypass the limitations and make full use of an EAHE system for heating and cooling. This research established a numerical simulation model for an EAHE system and validated it with real trended data. We addressed two dimensional dynamic heat transfer mechanism of EAHE through a transient control volume method. The computing domain of the soil consists of torus control units. The thermal balance of each unit was built to calculate the whole soil domain temperature based on the sequential method. The numerical results were validated by testing data based on an existing experimental facility. The performance of EAHE under both continuous and intermittent operation conditions was discussed. The research can be utilized to instruct the operation management of EAHE with the following observations:

- (1) The decreasing rate of soil temperature along with the length increases at the beginning, and then decreases after reaching the peak value. Increasing air flow rate can improve the heat transfer close to the outlet of EAHE. When the distance between the soil and the tube surface is far enough, the soil temperature is almost not affected by the air in the tube.
- (2) The analysis on the soil temperature indicates the affected soil thickness keeps on increasing along with the heat transfer between the air and soil. The effect of air on the soil temperature close to the tube surface is greater than that of far away from the tube surface.
- (3) In the intermittent operation mode, the soil temperature and the cooling capacity can recover during the nonworking time. The impact decreases with the distance increasing away from the tube. The supply air temperature and the cooling capacity in the intermittent operation mode are more powerful than that of the continuous operation mode.

In order to deeply understand the performance of EAHE, further aspects such as influence of surface (i.e., ambient temperature, rain), ice-formation in winter different and ground thermal conductivities will be investigated in the future work.

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