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Designing and evaluating a new earth-to-air heat exchanger system in hot summer and cold winter areas

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Abstract

Energy demand for space cooling and heating in buildings is a primary contributor to the total building energy consumption. Its rapid increase calls for an urgent need to utilize renewable energy sources and associated energy-efficient technology in the building sector. Among different renewables, geothermal energy has been widely adopted due to its easy access and low impact on the environment. In this study, a new earth-to-air heat exchanger (EAHE) system with vertically buried tubes was proposed. Compared to the conventional EAHE systems, its advantages mainly include high geothermal energy utilization efficiency and ease of condensate water discharge. To evaluate the thermal performance and cooling capacity of this system, an experimental set-up was established and a series of tests were conducted in Hunan, China. The results show that the outlet air temperature of this system ranged from 22.4°C to 24.2°C as the air flow velocity set at 1.0 m/s, enabling it to be used as an energy efficient technology for summer cooling of buildings. Meanwhile, both inlet air temperature and air flow velocities have an important influence on the system's cooling capacity.

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Keywords: Earth-to-air heat exchanger; Experiment; Vertical; Performance; Cooling capacity

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1. Introduction

Energy demand for space cooling and heating in buildings is a primary contributor to the total building energy consumption. Its rapid increase calls for an urgent need to utilize renewable energy sources and associated energy-efficient technology in the building sector [1]. Among different renewables, geothermal energy has been widely adopted as a heat sink in summer and a heat source in winter due to its easy access, low impact on the environment [2] and almost constant soil temperature at a certain depth (i.e. 2–4 m [3, 4]) throughout the year, and this soil temperature is lower and higher than ambient temperature in summer and winter, respectively [5–7]. The earth-to-air heat exchanger (EAHE) as an important technology by utilizing the geothermal energy has received increasing attention during the past few decades. It consists of a network of buried tubes and the outdoor air through these tubes is transported by a fan [8]. Being energy-saving and environment-friendly, the EAHE system is considered as an energy efficient method for cooling the outside air by ventilating to a building in summer [3, 9].

In this study, a new earth to air heat exchanger based on U-type and vertical buried tube system was proposed. Compared to conventional EAHE systems, its advantages mainly include high geothermal energy utilization efficiency and ease of condensate water discharge. Specifically, it can take advantage of low soil temperature in deep soil with annual stability, thereby improving the energy utilization efficiency. This is useful especially for those areas with relatively high shallow soil temperature. Meanwhile, its vertical tube enables it to discharge condensate water timely since condensate water can flow to the bottom of the tube. To evaluate the thermal performance and cooling capacity of the proposed vertical earth to air heat exchanger (VEAHE) system, an experimental set-up was established and a series of tests were conducted in high summer in Hunan, China. This paper provides details of the experimental set-up and results of its performance evaluation.

2. Experimental set-up and cooling capacity calculation

2.1. Experimental set-up

The experimental setup is designed and illustrated in Fig.1. It is consisted of filter, air valve, fan, U-type buried tube. The U-type buried tube can be divided into heat exchanger part, insulation layer part and bypass structure. The diameter of U-type buried tube is 219 mm, and the center distance between the two legs of U-tube is 681 mm. The material of tube is stainless steel and the insulation layer is polyurethane with thickness of 50 mm. A bypass structure is designed at the bottom of the U-type tube for condensate water collection and drainage. Fig.1 (b) presents the details of the bypass structure.

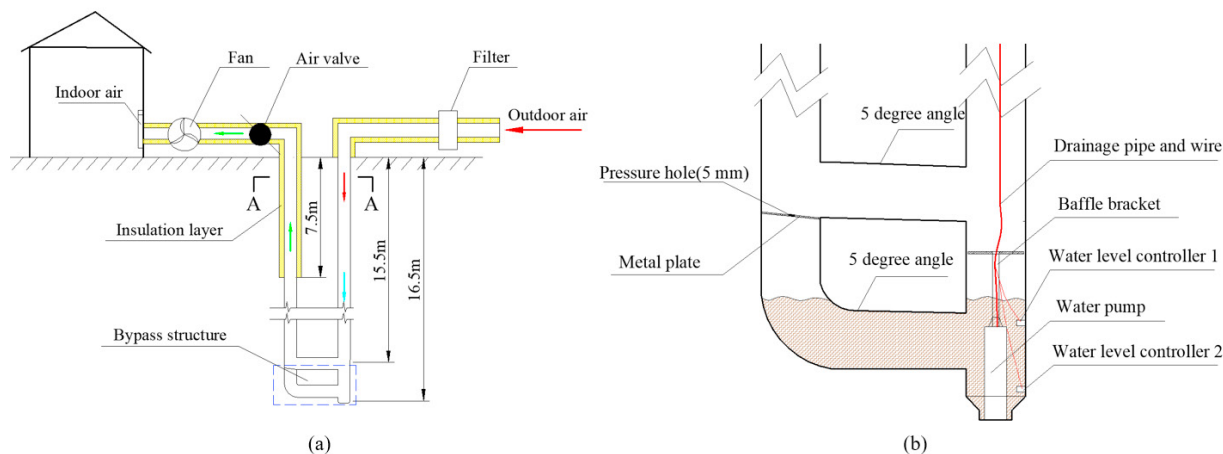


Fig.1. (a) Operation schematic diagram of the VEAHE system; (b) The bypass structure in the VEAHE system

The test location of the VEAHE system is in Changsha city, where the outdoor air temperature is often higher

than 30°C in summer [10]. The temperature of air inside the tube at different depths were measured using PT 100 thermocouple with a permissible error is ± 0.15 °C. All these sensors were calibrated and connected to the data loggers (Agilent 34972A). The velocity of inlet and outlet air is measured with a vane probe type anemometer (TSI-9555) having range of 0-50m/s with an accuracy to $\pm 3\%$ of reading.

2.2. Cooling capacity calculation

The variation of cooling capacity for VEAHE system is determined by the ventilation flow rate and air temperature at the inlet and outlet, and they can be calculated by the following equations [11].

$$Q_c = \dot{m} \times C_p \times (T_{in} - T_{out}) \quad (1)$$

where \dot{m} , C_p , T_{in} and T_{out} are the mass flow rate, specific heat, air temperature at the inlet and outlet of the tube, respectively.

The mass flow rate of air in tube can be formulated as follows:

$$\dot{m} = \frac{\pi}{4} \times d^2 \times \rho \times v \quad (2)$$

where d is the inner diameter of the tube, ρ and v are the air density and flow velocity, respectively.

Substituting Eq. (2) into Eq. (1), the equation for cooling capacity can be expressed as follows:

$$Q_c = \frac{\pi}{4} \times d^2 \times \rho \times v \times C_p \times (T_{in} - T_{out}) \quad (3)$$

3. Results and discussion

3.1. Variation of outlet and inlet air temperature

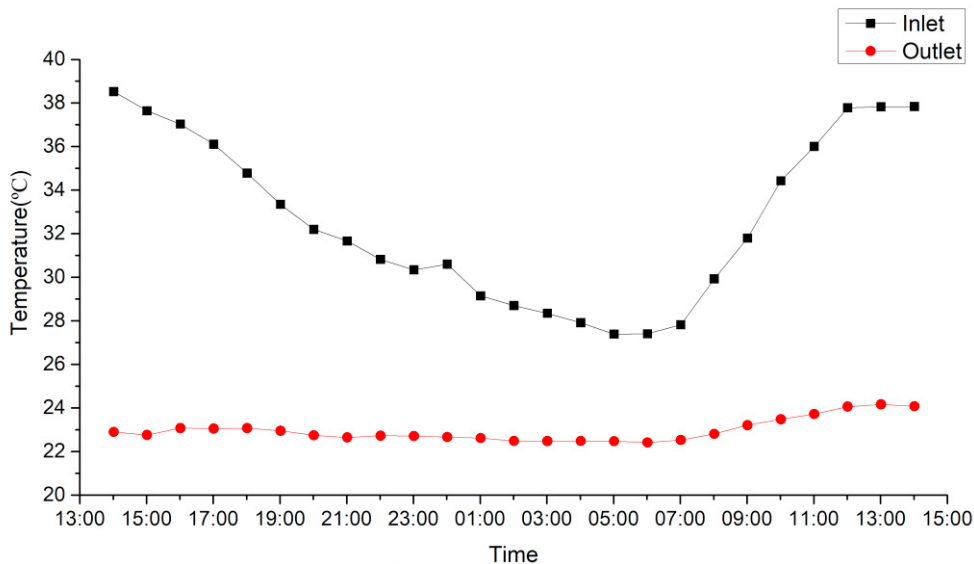


Fig. 2. The variation of inlet and outlet air temperature with time in summer

Fig. 2 shows the variation of inlet and outlet air temperature with the 24 hours of system operation as the air flow velocity set to 1 m/s. During the whole monitoring period, the outlet air temperature ranges from 22.4°C to 24.2°C in summer, with an average temperature of 23.0°C. This indicates that the outlet temperature remains relatively stable regardless of the ambient temperature. These values also demonstrate the effectiveness of the VEAHE system

in terms of making use of geothermal energy to cool air for building ventilation in summer. The maximum difference between inlet and outlet air temperature occurred when the inlet temperature was at its highest (38.5°C), while the minimum temperature difference occurred with the inlet temperature being at its lowest value (27.3°C). In addition, a slight increasing trend can be observed at the end of the operation. This trend is likely to be related to the inlet air temperature increase and the system’s heat transfer efficiency decrease. Further studies will be conducted to identify the main reason for this trend.

3.2. Variation of cooling capacity with time

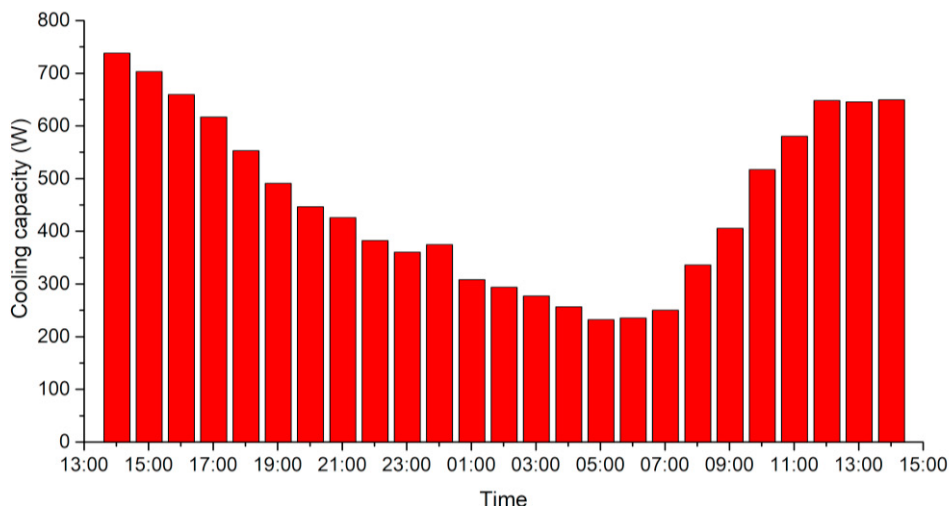


Fig.3. Variation of cooling capacity of the VEAHE system with time

Fig. 3 shows the variation of cooling capacity of the VEAHE system with time as the air flow velocity set to 1m/s. As shown in Fig. 3, the cooling capacity fluctuates during the 24 hours of system operation and it ranges from 232.1 W to 738.1W, with an average capacity of 466.2 W. The maximum cooling capacity is achieved at 14:00 with the highest inlet air temperature, and the minimum cooling capacity occurs at 5:00 with the lowest inlet air temperature. Clearly, the oscillation of cooling capacity is mainly determined by the inlet air temperature, given that the outlet air temperature remains relatively stable.

3.3. Variation of cooling capacity with inlet air velocity

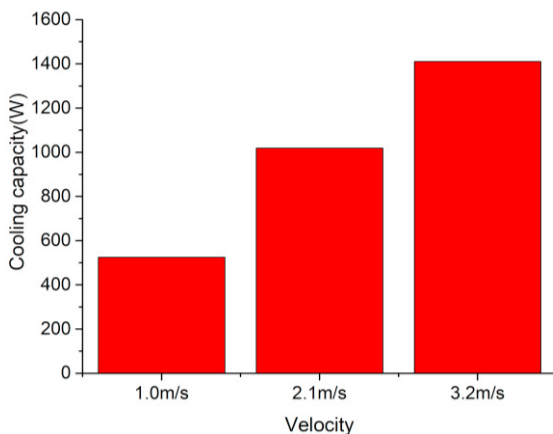


Fig. 4 Variation of cooling capacity of VEAHE system with different inlet velocities

Fig. 4 shows the variation of the cooling capacity of VEAHE system with different inlet air flow velocities in summer. As shown in Fig.4, the cooling capacity rises with the increase of inlet air flow velocities. For example, it increases from 524.6 W to 1410.4 W as the air flow velocity increases from 1.0 m/s to 3.2 m/s. It is noted that the relationship between cooling capacity and air flow velocities is not linear. The main reason is that the cooling capacity is determined not only by air flow rates that are linear with air velocities, but also by the inlet and outlet air temperature differences that are non-linear with air velocities. Indeed, as the air flow velocity rises, the outlet air temperature decreases even though the inlet air temperature remains the same. In addition, the rising rate of cooling capacity becomes gentler with the increase of air flow velocities. For example, the percentage increase of cooling capacity is 94.1% as the air flow velocity is increased from 1.0 m/s to 2.1 m/s, whereas the percentage increase is 38.5% as the air flow velocity is increased from 2.1 m/s to 3.2 m/s.

4. Conclusions

A new earth to air heat exchanger system with vertically buried U-tubes was proposed in this study. Compared to the conventional EAHE systems, its advantages mainly include high geothermal energy utilization efficiency and ease of condensate water discharge. In order to evaluate the thermal performance of the proposed VEAHE system, an experimental set-up was established and a series of tests were conducted. The experimental results show that the outlet air temperature of this system ranged from 22.4°C to 24.2°C as the air flow velocity set at 1.0 m/s, enabling it to be used as an energy efficient technology for summer cooling of buildings. Meanwhile, both inlet air temperature and air flow velocities have an important influence on the system's cooling capacity.

Our future studies will focus on the establishment of the mathematical model of VEAHE systems. Based on the model, the influence of different diameters, depths and materials of tubes on heat transfer of VEAHE system will be analyzed, and their optimal design parameters will be identified. Different design alternatives to recover soil temperature for optimum system performance will be investigated, and its combination with other systems will be explored such as solar chimneys, night ventilation and PCM system.

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