E3S Web of Conferences **356**, 03030 (2022) https://doi.org/10.1051/e3sconf/202235603030
ROOMVENT 2022

The combination of earth-to-air heat exchanger (EAHE) and phase change material (PCM) for indoor thermal environment regulation

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Abstract. The research and application of energy-saving technologies in buildings is receiving increasing attention. Phase change materials (PCM) is an effective passive cooling technology in the regulation of indoor thermal environment. However, in hot-summer and cold-winter regions, the high ambient air temperature makes it difficult to reduce PCM temperature to the phase change temperature in summer. Earth-to-air heat exchanger (EAHE), as an effective energy-saving ventilation technology, in combination with PCM can improve indoor thermal comfort. We performed full-scale experiments to investigate the combination of EAHE and PCM for indoor thermal environment regulation in a typical hot-summer and cold-winter region of China. After 24 hours of continuous operation in summer, variations in ambient and EAHE outlet air temperature range from 28.50 to 44.52 °C and from 22.78 to 24.78 °C respectively. EAHE can effectively precool fresh air, and its average cooling capacity and coefficient of performance (COP) are 1823.03 W and 16.6. The combination of EAHE and PCM has positive impacts on the regulation of indoor thermal environment. The indoor air temperature is in the 22-28 °C range for 69.0 % of the 24 h, and peak indoor air temperature is 31.14 °C. The hybrid system has a TDR of 0.84.

1 Introduction

With rapid population and economic growth, the consumption and depletion of fossil fuels are exacerbated, leading to pollution and damage of the environment. Therefore, innovative low-energy approaches are being developed and promoted to improve indoor thermal environments; One such approach is the earth-to-air heat exchanger (EAHE), which employs geothermal energy. EAHE pipes are buried at a depth of 2 to 3 m underground, using soil as a heating or cooling source, and ventilation air in the pipes as a heat exchange medium. The ambient air is directed into the pipes to exchange heat with the soil and then pumped into the building, thus reducing the indoor air temperature and improving indoor thermal environment.

The regulation of the indoor thermal environment by the EAHE is closely connected to the thermal performance of the EAHE. Hollmuller et al [2] carried out a theoretical analysis of the heat transfer process between soil and air, and derived an analytical solution for a theoretical model at a constant airflow. The model is based on the boundary conditions of an adiabatic or constant temperature of a finite large cylinder, while taking into account the periodicity of air temperature fluctuations. Al-Ajmi et al. [3] and Benhammou et al. [4] used theoretical thermal models to analyse the cooling potential of the EAHE in summer in Kuwait desert climates and in Saharan desert climates respectively.

And in the research on the coupling of EAHE ventilation with the thermal storage of the building, Yang et al. [5,6] propose an evaluation model for the coupling of EAHE and the thermal mass contained in a building, using the appropriate combination to achieve indoor thermal comfort in hot-summer and cold-winter regions, and further propose a demand-oriented reverse matching method to reverse the parameters of EAHE with goals of indoor thermal comfort [7]. Wei et al [8]. evaluated the coupling effects of EAHEs and the buoyancy generated inside a building through a theoretical model, and the simultaneous supply of fresh air and natural cold/heat energy to the room was achieved in a purely passive ventilation. Subsequent full-scale experiments in hot-summer and cold-winter regions were performed to investigate the effect of EAHE on the regulation of indoor thermal environment [9]. And EAHE decreased the average building cooling and heating loads by 55.4 W/m^2 and 40.43 W/m^2 in summer and winter respectively. However, it is difficult to maintain a comfortable indoor air temperature using an independent EAHE system.

In previous work, the combination of EAHE and building thermal mass was mainly considered in terms of sensible heat. Due to the large amount of sensible thermal mass materials in the building, sensible heat can be replaced by latent heat from the phase change process

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of the phase change material (PCM) [10]. The integration of PCM into the envelope of buildings can store the cooling capacity which is wasted by EAHE during the night, and increase the thermal storage capacity of the building. While EAHE ventilation system can enhance the cooling storage capacity of PCM. This study experimentally investigates the performance of the proposed combination of EAHE and PCM in summer for a typical hot–summer and cold–winter region of China. The temperature and humidity of the ambient, EAHE outlet and indoor air are mainly measured. The cooling capacity and coefficient of performance (COP) of the EAHE are obtained, and the ability of the combination of EAHE and PCM to regulate the indoor thermal environment is evaluated.

2 Experiments

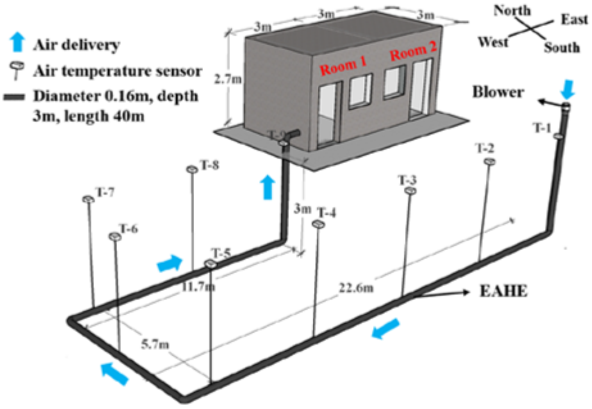

Fig. 1. Schematic of the full-scale test apparatus.

The experimental platform was located in Chongqing, a typical hot-summer and cold-winter region of China. The experimental platform consisted of two parts: an EAHE and a testing building, and schematic of the full-scale test apparatus was shown in Fig. 1. As shown in Fig. 1, the EAHE pipes consist of three parts: a vertical inlet component, a horizontal pipeline and a vertical outlet component. The vertical inlet component is connected to blowers and delivers ambient air into the horizontal pipeline, where the air exchanges heat with the soil; The horizontal pipeline is buried at a depth of 3 m underground and consists of a 40 m long, 0.16 m diameter PVC pipe, which is set at an inclination of 5° to enable the collection and removal of condensate from the heat exchange in the pipe; The vertical outlet component is connected to room and delivers fresh air, pre-cooled by EAHE, to the building. To reduce the thermal interaction between the air in the vertical components and the surrounding soil, the vertical inlet and outlet components are wrapped in 0.02 m thick polystyrene, so that only the horizontal pipe exchanges heat with the soil.

The test building has two rooms, numbered Room 1 and Room 2, each with dimensions of 3.0m×3.0m×2.7m. PCM is integrated into the envelope of Room 1, and experimental site map is shown in Fig. 2. Room 1 is used for experiments, and located in the west side, directly connected to the EAHE ventilation system. To ensure the cleanliness of the indoor air, the EAHE delivers fresh air at a speed of 4.2 m/s, corresponding to an air change rate per hour (ACH) of 12.5. The value of ACH was relatively high in our experiments, because it is beneficial to enhance the EAHE cooling/heating performance according to previous test results [11]. Room 2 is located in the east side and is only used for the recording and collection of experimental data. To avoid any thermal disturbance, the two rooms are insulated with 0.02 m thick rubber and plastic and 0.05 m thick glass fiber adjacent to each other.

Fig. 2. Experimental site map of PCM integrated into the envelope

3 Results and discussion

To investigate the regulation ability of the combination of EAHE and PCM on the indoor thermal environment in hot-summer and cold-winter region, the experiments were carried out in the hot summer and continuously for 24 h on 4 August 2021.

3.1 Air parameters for ambient, EAHE outlet and indoor

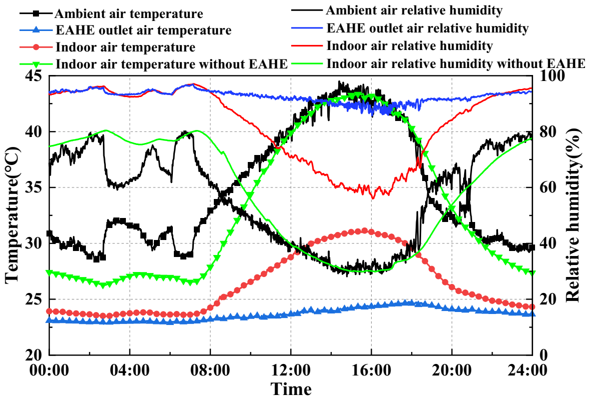

Fig. 3. Temporal profiles of ambient, EAHE outlet and indoor air temperature and relative humidity.

Fig. 3 shows the temporal profiles of ambient, EAHE outlet and indoor air temperature and relative humidity. The ambient (EAHE inlet) air temperature varies between 28.50 and 44.52 °C (average of 34.88 °C), while the EAHE outlet air temperature varies between 22.78 and 24.78 °C (average of 23.63 °C). EAHE effectively decreases the ambient air temperature, by a maximum of 20.44 °C and a minimum of 5.53 °C. And when the ambient air temperature varies widely, the EAHE outlet air temperature varies less and is more stable.

The ambient (EAHE inlet) air relative humidity varies from 28.1 % to 80.2 % (average of 56.6 %), while the EAHE outlet air relative humidity varies from 85.7 % to 96.9 % (average of 92.6 %). It is clear from the figure that the relative humidity of the EAHE outlet air is higher in 24 h. This is due to the fact that the EAHE cools the air effectively during the summer period, and the relative humidity decreases as the air temperature increases.

The indoor air temperature varies between 23.45 and 31.14 °C (average of 26.41 °C), and the peak indoor air temperature is 31.14 °C. When without EAHE, the indoor air temperature varies between 26.26 and 43.42 °C (average of 33.20 °C), and the peak indoor air temperature is 43.42 °C. The combination of EAHE and PCM prevents the room from overheating when regulating the indoor thermal environment, and decreases the average indoor air temperature by 6.79 °C. The indoor air relative humidity varies from 55.9 % to 97.1 % (average of 82.6 %). When without EAHE, the indoor air relative humidity varies from 29.85 % to 80.40 % (average of 58.50 %). When using EAHE ventilation, the average indoor air relative humidity is slightly high, which is caused by the reduction of indoor air temperature.

3.2 Cooling performance of EAHE

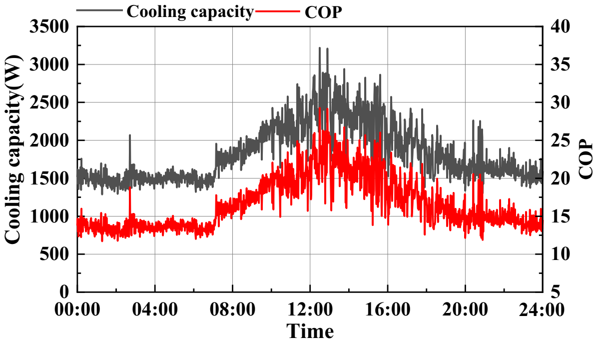

Fig. 4. The variation in cooling capacity and COP of EAHE.

The cooling capacity of EAHE Q is calculated using Eq. 1.

$$Q = \rho q_v (h_1 - h_2) \tag{1}$$

where q_v is the volume of air delivered per unit time (m^3/s). h_1 and h_2 are the enthalpy of the air at the EAHE inlet and EAHE outlet, respectively (kJ/kg), which is calculated by Eq. 3. ρ is the air density (1.29 kg/m^3).

$$q_v = Av \tag{2}$$

where A is the cross-sectional area of the EAHE pipe outlet (m^2), v is the average air velocity of outlet (m/s).

$$h = 1010T + (2501 + 1.85T)d \tag{3}$$

where d is the air moisture content (g/kg), obtained from the relative humidity [11]. T is the air temperature (°C).

The coefficient of performance for EAHE, COP is calculated using Eq. 4.

$$COP = Q/W \tag{4}$$

where W is the energy consumption of EAHE (W).

Fig. 4 illustrates the variation in cooling capacity and COP of the EAHE. The variation in cooling capacity provided to the room by the EAHE ranges from 1287.43-3219.43 W, with an average cooling capacity of 1823.03 W. The EAHE provides a more substantial cooling capacity, which is influenced by changes in ambient air temperature. However, at night (0:00-7:00) the EAHE still provides a cooling capacity of 1287.43-2070.15 W. When the EAHE cooling capacity is excessive, the excess cooling capacity can be stored by the PCM, and used in the regulation of the indoor thermal environment during the day.

The measured energy consumption of the EAHE blower is 110W. From Eq. 4, the COP of EAHE varies from 11.7—29.3, with an average of 16.6. EAHE provides almost 16 times more cooling energy than the electrical energy consumed by the EAHE system. Therefore, it can be concluded that the combination of EAHE systems and PCM is a more economical technology, which uses lower energy consumption to regulate the indoor thermal environment.

3.3 Assessment of the use of EAHE and PCM for indoor thermal environment regulation

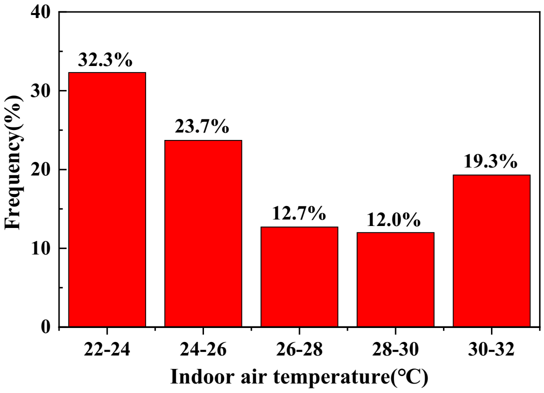

Fig. 5. Occurrence frequency of the indoor air temperature in different temperature ranges.

Fig. 5 shows the occurrence frequency of indoor air temperature in different temperature ranges. As shown in figure, the indoor air temperatures are largest in the 22-24 °C range at 32.2 % of the 24 h period. In contrast, indoor air temperatures are in the range of 24-26 °C and 26-28 °C for 23.7 % and 12.7 % of the 24 h period respectively. In summer cooling operation, the comfortable range of indoor air temperature in residential buildings is 22-28 °C. With the combined effects of EAHE and PCM, 69.0 % of the time at 24 h is in the comfort temperature range.

In summer more attention is paid to the overheating of buildings. The indoor air temperatures are in the 28-30 °C and 30-32 °C range for 12.0 % and 19.3 % of the 24 h respectively. The indoor air peak temperature is 31.14 °C. When the ambient air temperature is too high, the combination of EAHE and PCM enables the indoor air temperature to be greater than 28°C for only 31.3 % of the 24 h, without causing the building to overheat. It has a positive impact on the regulation of the indoor thermal environment.

The temperature difference ratio (TDR) was introduced by B. Givoni in 1992 [12], and was calculated by Eq. 5.

$$\mathrm{TDR}=\frac{T_{\mathrm{o,max}}-T_{i,\max}}{T_{o,\max}-T_{o,\min}} \tag{5}$$

where $T_{o,max}$ is the maximum ambient air temperature (°C). $T_{i,max}$ is the maximum indoor air temperature (°C). $T_{o,min}$ is the minimum ambient air temperature (°C).

The TDR represents the variation in the ambient air temperature, while the numerator represents the difference between the maximum ambient air temperature and the maximum indoor air temperature. The higher the value of TDR, the greater the temperature difference between the ambient and indoor air, which indicates a better cooling performance of the system. The TDR standardizes the capabilities of decreasing maximum indoor air temperatures. When regulated by EAHE combined PCM, the TDR of the hybrid system is 0.84. This demonstrates the effective cooling performance of EAHE in combination with PCM.

4 Conclusions

In the present work, field experiments were performed to evaluate the performance of the proposed combination of EAHE and PCM in summer for typical hot-summer and cold-winter climates. According to the experimental results, the main findings can be summarized as follows:

(1) The EAHE ventilation system provides pre-cooled fresh air to the room in summer. When the ambient air temperature varies between 28.50 and 44.52 °C, the temperature of fresh air provided by the EAHE varies between 22.78 and 24.78 °C and is relatively stable. EAHE can reduce the air temperature by a maximum of 20.44 °C.

(2) The combination of EAHE systems and PCM is a more economical technology, and hybrid system has a TDR of up to 0.84. While the average cooling capacity and COP of the EAHE are 1823.03 W and 16.6 respectively.

(3) The use of EAHE and PCM has a positive impact on the regulation of the indoor thermal environment. The indoor air temperature varies between 23.45 and 31.14 °C, while the indoor relative humidity varies between 55.9% and 97.1 %. And the indoor air temperature is in the 22-28°C range for 68.7 % of the 24 h, while the peak indoor air temperature is only 31.14 °C.

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