

Numerical simulation study on heat transfer characteristics and parameter optimization of solar phase change energy storage fresh air preheating system

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Abstract. In cold regions, indoor fresh air preheating in winter has received much attention. An improved fresh air preheating system using solar energy and phase change energy storage technology is proposed in this study to solve the problem of insufficient fresh air supply in cold regions. This study establishes two-dimensional mathematical model for air-type phase change energy storage device, and compares the error between them and the experimental results. The results show that the comparison between the simulated and experimentally measured is in good agreement. This study explores the effects of velocity of hot air, temperature of fresh air and temperature of hot air during simultaneous heat storage and discharge conditions by using numerical simulation method. The results show that the designed system has the ability to preheat fresh air at 4.5°C for more than 4 hours under the condition of outdoor average temperature of -10°C at night, and has practical promotion value. All three parameters affect the thermal performance of the system. When the hot air velocity increases from 1.5 m/s to 2.25 m/s , the liquid fraction increases by 5.16 %, 10.11 % and 14.52 % respectively. Different fresh air temperatures determine the heat storage capacity of the system under the condition of simultaneous heat storage and heat release.

1 Introduction

The preheating of fresh air in residential buildings has attracted increasing attention. Previous studies have shown that preheating outdoor fresh air can improve indoor environment[1,2]. At present, the main ventilation way of residential buildings in China is window opening. However, in winter, the challenge is the human discomfort of the occupants caused by the temperature difference between indoor and outdoor, especially in cold regions in northern China[3]. Therefore, preheating fresh air is an important measure to improve the indoor environment of residential buildings in winter. Residential buildings in China mainly uses electric heating device or heat recovery device to heat fresh air, which will increase cost and cause energy waste[4].

Solar energy is commonly used for drying, heating, or dehumidification[5,6]. In order to solve the problem of discontinuity in solar energy utilization, some studies combine solar energy with energy storage technology, which can also be used in low solar radiation or cloudy days[7,8]. However, few scholars pay attention to the

problem of ventilation in winter residential buildings in severe cold areas.

To solve the problem of indoor ventilation in cold regions, this study proposes a fresh air preheating system using solar energy combined with phase change energy storage technology. The system can not only meet the needs of fresh air preheating at night and in cloudy days, but also realize the simultaneous heat storage and heat release when solar energy is sufficient. The mathematical model of the system was established and the experimental platform was built to verify the accuracy of the model. Then, influence of different factors on thermal performance of system under the condition of simultaneous heat storage and heat release was discussed by numerical simulation method.

2 Establishment of system model

2.1 System principle

The system is composed of solar air collector, phase change energy storage device and fan, as shown in Fig. 1. The phase change energy storage device is designed

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as a dual-channel S-type, which can prolong the contact time between air and phase change material and make the heat storage and heat release process independently. During the heat storage, air in the solar collector absorbs solar radiation and its temperature rises, then enters the phase change energy storage device and contacts with the phase change material. After heating the phase change material, the hot air returns to the collector through the heat storage outlet for the next cycle. Similarly, in cloudy days or nights, the cold outdoor fresh air enters the fresh air channel, transfers heat with phase change materials, and enters the room through the fan after raising the temperature to realize the preheating of fresh air. Under the condition of high solar radiation, phase change materials can be melted or maintained in a high liquid rate state in a short time. At this time, the heat storage and heat release channels can work at the same time. The system can realize the simultaneous heat storage and release process.

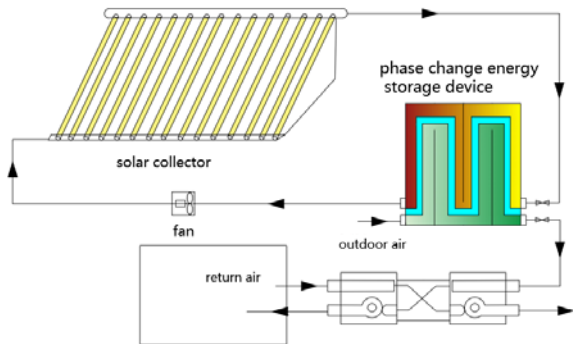


Fig. 1. System working principle

2.2 System mathematical model

According to the previous research[9], mathematical model of two-dimensional unsteady heat transfer phase change energy storage device is established and simplified. The simplified model is as follows :

The energy balance equation of heat transfer fluid is :

$$\frac{\partial T_f}{\partial \tau} + \frac{m_f}{\rho_f A_f} \frac{\partial T_f}{\partial x} = \frac{hP}{\rho A} (T - T_f) \quad (1)$$

where T_f is air temperature ; m_f is air quality flow ; ρ_f is air density ; A_f is duct section, h is convective heat transfer coefficient ; P is the section perimeter of airflow channel ; ρ is the density of phase change material ; A is the cross-sectional area of phase change material contacting with air.

The two-dimensional energy balance equation of phase change materials expressed by enthalpy method is :

$$\frac{\partial H}{\partial \tau} = \frac{k}{\rho} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{hP}{\rho A} (T_f - T) \quad (2)$$

The total enthalpy $H(T)$ is calculated as follows:

$$H(T) = h(T) + \rho f_i(T)L \quad (3)$$

The apparent enthalpy $h(T)$ is calculated by the following equation:

$$h(T) = \int_{T_m}^T \rho c_f dT \quad (4)$$

The expressions of convective heat transfer coefficient under heat storage and heat release are as follows :

$$h = \frac{0.023 \times \left(\frac{4A_f u}{P \cdot v} \right)^{0.8} \times pr^{0.4} \times k_f \times P}{A_f} \quad (5)$$

$$h = \frac{0.023 \times \left(\frac{4A_f u}{P \cdot v} \right)^{0.8} \times pr^{0.3} \times k_f \times P}{A_f} \quad (6)$$

2.3 Experimental installation

The experiment was completed in the laboratory of a school in Shenyang. As shown in Fig.2, the experimental equipment includes industrial hot fan, which is used to replace the solar collector , energy storage device, exothermic fan and so on. The experimental equipment is placed on a movable experimental platform with a double-layer plate bracket, and the experimental equipment is insulated and sealed. The energy storage device is composed of stainless steel container, phase change material packaging structure and stainless steel baffle. The stainless steel baffle separates the inner wall of the stainless steel container into two equal width air channels for heat storage and heat release. Phase change materials used low melting point paraffin with phase change temperature of 14.4°C - 19.6°C . In the experiment, PT100 sensor was used to test the temperature and humidity values of the four measuring points installed inside the phase change energy storage device, judge the degree of the phase change process, and compare them with the value.



Fig. 2. Experimental device.

3 Results and discussion

3.1 Experimental results analysis and model validation

Fig.3 shows the comparison between the experimental data and the simulation results of the system heat storage. It can be seen from the trend of the curve that in the heat storage stage, because the inlet hot air temperature is high, the inlet temperature of the device will rapidly rise to a certain value. Since then, the inlet temperature is gradually stable, which corresponds to the transformation of phase change material at the entrance of the device from sensible heat storage to latent heat storage. From the change trend of the outlet temperature curve, it can be analyzed that the heat storage of the system is roughly divided into three stages. The second

stage is the latent heat storage stage, and the temperature changes little during this period.

Fig.4 shows the comparison between the experimental data and the simulation results when the system is exothermic. The initial period of time is the sensible heat release stage, the device inlet temperature in a certain period of time quickly dropped to near outdoor fresh air temperature. About half an hour later, the device enters the latent heat release stage, and the system can preheat the air at a certain temperature stably. With the continuous solidification of phase change materials, the preheating ability of the system to the fresh air decreases gradually, until the end of the experiment, the system still has the effect of preheating the fresh air. The experimental results show that the proposed system has the ability to preheat outdoor fresh air at an average night temperature of -10 °C for an average of 4.5 °C for 4 hours in a regenerative and exothermic cycle.

The comparison shows that the simulation results are in good agreement with the experimental data. The main reason for the error in the initial stage of heat storage may be that the initial temperature of the phase change material is set to be uniform in the simulation, but in the actual process, the internal temperature of the phase change material may be uneven.

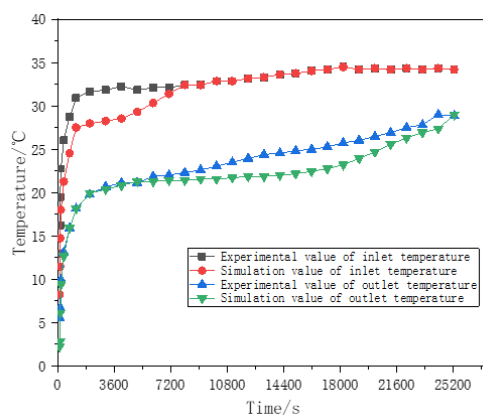


Fig. 3. Comparison of experimental data and simulation results under heat storage condition.

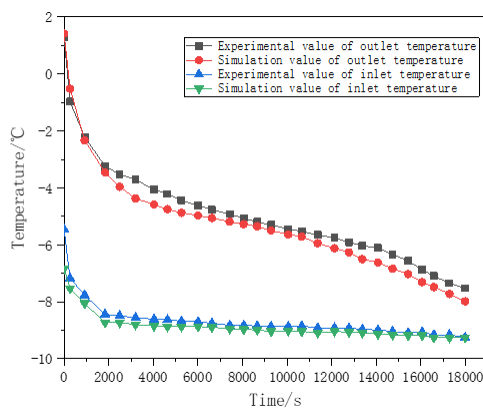


Fig. 4. Comparison of experimental data and simulation results under heat storage condition.

3.2 Influence factors of system performance under simultaneous heat storage and release process

Based on the verified model, the influence of different parameters on the thermal performance of the system under the condition of simultaneous heat storage and discharge is numerically simulated. Simulation conditions are shown in table 1.

Table 1 Calculation results of simulated operating conditions

Working condition of simulated	Hot air temperature (°C)	Hot air flow rate (m/s)	Fresh air temperature(°C)
Condition1	45	1.5	12
Condition2	50	1.5	12
Condition3	55	1.5	12
Condition4	60	1.5	12
Condition5	50	1.75	12
Condition6	50	2.0	12
Condition7	50	2.25	12
Condition8	50	1.5	6
Condition9	50	1.5	8
Condition10	50	1.5	10

3.2.1 Influence of different hot air temperaturer

Fig. 5 shows the influence of different hot air temperatures on the liquid fraction of the system under the simultaneous heat storage and release conditions. The pure heat storage process lasted until 14400 s, and then the simultaneous heat storage and release process was carried out. In the process of heat storage, with the increase of hot air temperature, the growth rate of liquid fraction increases. The liquid fractions of the four conditions were 0.7694, 0.8024, 0.8356 and 0.8878 at the end of the pure heat storage process, respectively. After 14400 seconds, the increase rate of liquid fraction in four conditions decreased significantly, and the liquid fraction in condition 1 was almost equal, indicating that the heat stored in the system was roughly equal to the heat consumed by the preheating fresh air. The liquid fraction of condition2,3 and 4 showed different upward trends. The higher the hot air temperature, the faster the liquid fraction increased.

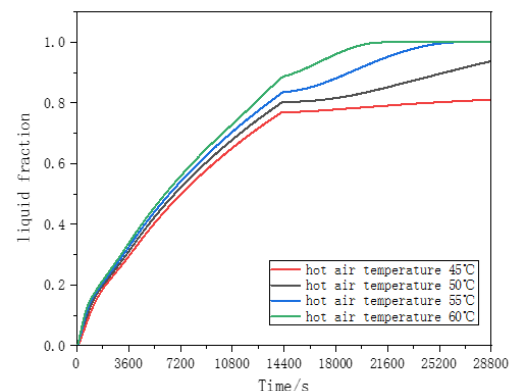


Fig. 5. Liquid fraction at different hot air temperatures in simultaneous heat storage and release proces.

3.2.2 Influence of different hot air velocity

Fig. 6 shows the change of liquid fraction of the system under different hot air flow rates (working conditions1、5、6 and 7). After simultaneous heat storage and

release mode started, the influence of hot air flow rate on the liquid phase rate of phase change materials became larger. Based on condition 2, the increase of hot air flow increases the liquid phase rate by 5.16 %, 10.11 % and 14.52 % on average. In a certain range, under the condition of simultaneous heat storage and discharge, increasing the flow rate will greatly improve the heat storage rate, but the increase rate will decrease slowly with the increase of flow rate. The main reason is that the increase of hot air flow makes the melting speed of phase change materials faster, but the increase of hot air flow means that the heat transfer time of hot air contact with phase change materials is shortened, which will affect the melting speed of phase change material.

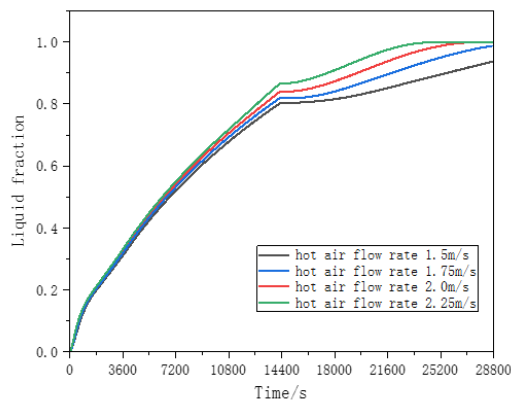


Fig. 6. Liquid fraction at different hot air flow rate in simultaneous heat storage and release proces.

3.2.3 Influence of different fresh air temperatures

Fig. 7 shows the heat storage of the system under different fresh air temperatures (Condition 2、 8、 9 and 10). After the beginning of simultaneous heat storage and release mode, the heat storage of condition 8、 9 and 10 have different degrees of decline, because the fresh air temperature is low, as time goes on, the heat transfer of the system gradually enters a stable state. Among them, the heat storage of condition 8 and 9 is maintained in a balanced state, and the heat storage of condition 10 shows an upward trend due to the weak heat transfer between fresh air and phase change material.

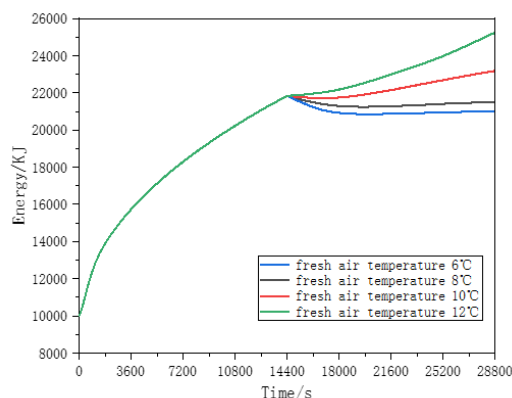


Fig. 7. Enegy at diffenert fresh air temperatures in simultaneous heat storage and release proces.

4 Conclusion

- (1) The proposed system has the ability to preheat fresh air at 4.5 °C for more than four hours at the outdoor average temperature of – 10 °C at night;
- (2) The increase of hot air temperature and hot air flow rate within a certain range will improve the system heat storage speed, which is more obvious in the simultaneous heat storage and release process;
- (3) When the flow rate of hot air increased from 1.5 m / s to 2.25 m / s, the liquid fraction under the simultaneous heat storage and release process increased by 5.16 %, 10.11 % and 14.52 % on average ;
- (4) After the simultaneous heat storage and release process starts, the overall heat storage of the system will have a decline process, then it may increase again or enter a balance state, which depends on the fresh air temperature.

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