Study on a Solar Heating System with Phase Change Energy Storage in Cold Region

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Abstract. Although solar energy is one of the most promising renewable energy sources at present, the access to solar energy is unstable and discontinuous, so more advanced energy storage is needed. This paper designs and studies a phase change material (PCM) solar heating system which integrates heat storage and heat removal. In order to evaluate the system performance under actual operation, an experimental system is built. According to the experimental measurement results of the heat charging process, the COP of the system is between 1 and 5.5, which is higher than that of the general household electric heating system (COP=1). According to the system heat release process, the average temperature of the room without heating system is about 6 ℃ higher than the room temperature, and the room with heating system is also about 6 ℃ higher than the room without heating system. When the outdoor temperature is 5-10 ℃, the minimum temperature of the heating chamber is about 16 ℃, indicating that the heating effect is good. Although the new phase-change material (PCM) solar heating system, which integrates heat storage and heat removal, shows relatively good heating effect, further research is needed on the mass flow rate control strategy of the solar energy collection cycle, the filling quality of the phase-change material and the matching of the heat exchanger structure.

Keywords: solar heating; heating technology; heating power; PCM; energy-saving

1. Introduction

The main pastoral areas in Qinghai Province are located in the south with an average altitude of more than 3500m. The climatic environment in the pastoral areas is characterized by insufficient heat, great temperature difference between day and night, and large heating demand for buildings in the pastoral areas. Due to the special geological conditions, there are very few fossil energy that can be developed, and conventional energy such as coal, oil and natural gas are scarce. However, Qinghai has the richest solar energy resources in China [1]. Therefore, solar heating technology has broad application prospects in Qinghai, replacing traditional combustion heating [2].

Due to the simplicity and sustainability of obtaining heat sources, solar heating technology is currently one of the best utilization options for space heating. However, due to the instability and discontinuity of solar energy, solar heating technology requires the use of thermal storage units to achieve thermal matching between space and time [3]. Initially, the water tank was used as the heat storage unit of the solar system to store solar heat [4]. However, with the progress of technology, phase-change materials with high storage capacity are applied to heat storage units to gradually replace the water tank heat storage method in some areas [5]. Most of the current research is to fill phase change materials into different types of heat exchangers and studying their melting and solidification performance [6-8]. Due to the poor thermal conductivity of phase change materials, some scholars have improved the heating effect by strengthening the structure of heat exchangers [9, 10]. However, few phase change materials are used in the field of heat dissipation terminal.

Because the traditional water-filled flat radiator has the advantages of comfort, health, noiseless and energy saving, it is still one of the most widely used heating equipment in domestic, commercial and industrial environments [11]. Therefore, in this paper, a kind of heat storage and release integrated heat exchanger is designed, which can meet the demand of indoor heating, greatly solve the instability of solar energy utilization and reduce building energy consumption.

2. Experimental approach

2.1 System description

The section headings are in boldface capital and lowercase letters. Second level headings are typed as part of the succeeding paragr In general solar heating systems [12], the heat of the sun is stored in the water tank first, and the room is heated at night through the heat dissipation end. Because the electric energy and heat energy of the pasture in the pastoral area are hard to come by, this paper uses phase-change materials to design a phase-change heat storage and heat release integrated heat exchanger to reduce the water pump at the heat dissipation end. The schematic diagram of solar heating system suitable for buildings in Qinghai pastoral area is shown in Figure 1(a). It is mainly composed of flat solar collector, heat storage and heat release integrated heat exchanger, hot water pump and connecting pipe. In order to study the heat storage effect of phase change heat exchanger (PCHE), K-type thermocouples are set at the inlet and outlet water temperatures. In order to explore the heat release effect of PCHE, three K-type thermocouples T1, T2 and T3 are installed indoors. The installation height of indoor thermocouple is 1.1m, and the specific plane position is shown in Figure 1 (b).

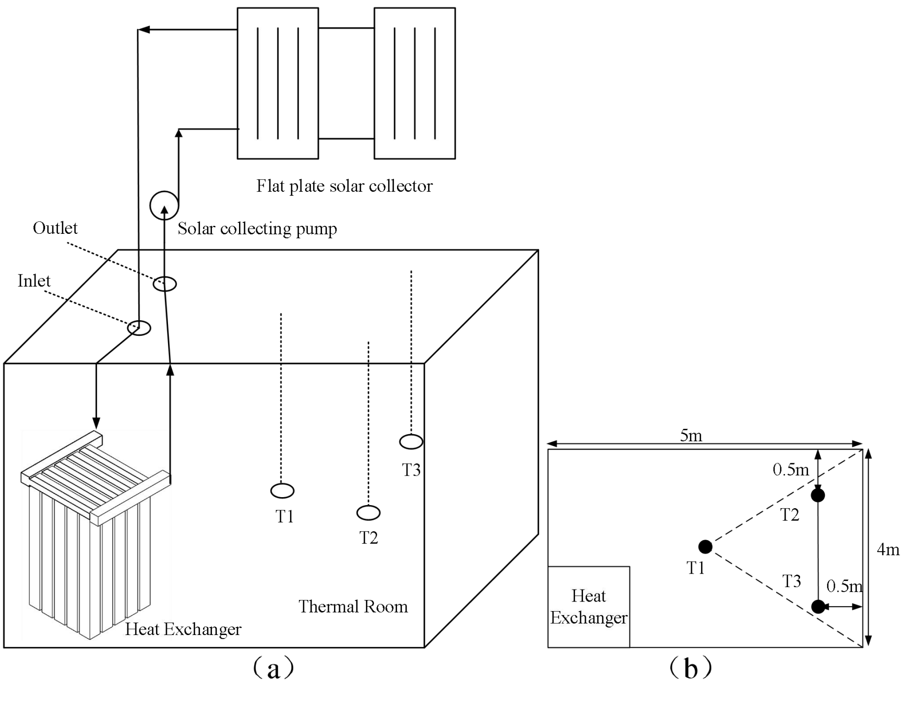

Fig. 1 (a)Schematic diagram of the solar heating system with PCHE and (b)Layout of temperature measuring points

This solar heating system with PCHE switches between two modes during operation：

Storage and release mode: When the hot water temperature in the solar system reaches the set temperature, the water pump starts, and the heat storage medium in the solar system transfers heat to the heat exchanger through circulation. Meanwhile, the PCHE releases heat into the room through natural convection, while the excess heat is stored in phase change materials.

Release heat mode: Usually at night or on continuous cloudy days, the conditions for heating system circulation are not met, and the water pumps in the solar system are in a closed state. The PCHE releases heat into the room through natural convection.

Technical parameters of the main components of the solar heating system with PCHE are listed in Table 1.

Table 1. Technical parameters of the main units.

Name	Technical parameters
Hot water pump	$L_{pump} = 7.8\text{m}^3/\text{h}$, $N_{pump} = 150\text{W}$
solar collector	$A_{sc} = 7.2\text{m}^2$, $F_R = 0.9$, U_L=5W/(m$^2\cdot$℃)
PCHE	$L_{HE} = 0.5\text{m}$, $W_{HE} = 0.5\text{m}$, $H_{HE} = 1\text{m}$
Room	L=5m, W=4m, H=2.8m,

The thermophysical properties of disodium hydrogen phosphate dodecahydrate/expanded perlite composite PCM prepared in this experiment are shown in Table 2.

Table 2. Thermo-physical properties of the PCM.

Property	unit	PCM
Density of PCM	kg/m^3	1690
Specific heat of PCM	J·kg^{-1}·K^{-1}	2000
Latent heat of fusion	J/kg	170000
Melting temperature	°C	35.5
Thermal conduction	W/(m·°C)	0.6
Thermal expansion coefficient	1/K	0.001
Dynamic viscosity	kg/(m·s)	0.025

In order to study the heating effect of the experimental device, this experiment used a mode of heat storage and release for a day of experimental simulation. As shown in Figure 2, the heat exchanger is located in Room 1, and Room 2 serves as the control group to detect temperature changes in both rooms under the same external conditions. Although the appearance of the room is different, its insulation performance and structure are the same.

Fig.2 Experimental and control group rooms：Room 1 (left) and Room 2 (right)

2.2 Experimental Procedure

The system will operate from 09:00 on December 18, 2022 to 09:00 on the next day. The solar collector provides heat to the phase-change heat exchanger from 09:00 to 15:00. PCHE releases heat in the form of natural heat dissipation during the whole operation time of the system. For the inlet of phase-change heat exchanger, the water temperature is approximately replaced by the wall-mounted measurement of K-type thermocouple, and the water flow is measured by electronic flowmeter. The thermocouples are attached to the upper, middle and lower parts of a single heat exchange column of the PCHE to measure the temperature distribution of the PCM. Using handheld detection instruments to monitor hourly solar radiation and outdoor temperature. Monitor the PCHE wall temperature and indoor temperature with data acquisition instrument every five minutes. Measure the flow and power of the water pump every hour. The temperature and humidity at the center of the two rooms are measured by the portable thermocouple. All instruments are pre-calibrated.

3. Experimental Results

3.1 Performance analysis of experimental device

The starting time of the whole system operation is 9:00. At this time, the temperature of water and PCM in the PCHE is basically the same. The water mass flow rates of 0.3 kg/s. The temperature of water inlet, PCM center and water outlet is shown in Figure 3. Figure 4 shows the solar radiation and ambient temperature in this the typical day.

From Figure 3, it can be found that the PCM has a super cooling of about 3.5 ℃, but its effect on space heating is small, and there is no non-solidification phenomenon. At the same time, it can also delay the heat release rate to a certain extent, and postpone the latent heat release to the beginning of the night as far as possible, which is more in line with the needs of room heating. The figure shows that the phase change latent heat release for nearly 8 hours starts from 19:30 to 3:00 the next day, which helps to improve the comfort level at night. The maximum temperature at the inlet of the phase change heat storage device is 46.5 ℃ at 14:00, and the maximum temperature difference at the inlet and outlet reaches 0.9 ℃ at 12:40. The maximum inlet temperature of the PCHE device is far lower than the vaporization temperature of water (100 ℃), but the temperature difference between the inlet and outlet is very small, which indicates that the heat collection flow is relatively large, so more reasonable operating parameters need to be further developed to achieve the minimum operating energy consumption.

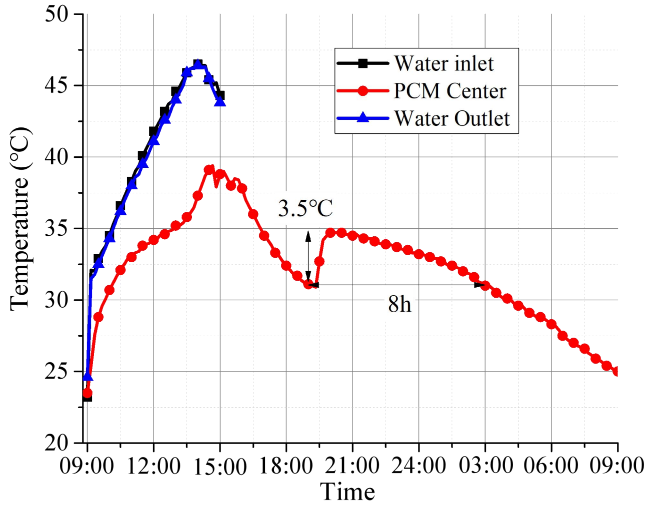

Fig. 3 The temperature of water inlet, PCM center and water outlet.

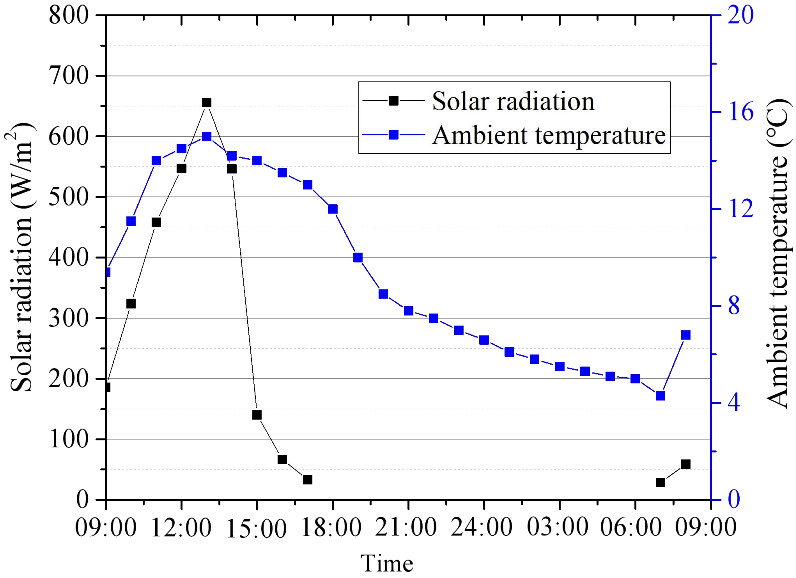

Fig. 4 Solar radiation and ambient temperature.

3.2 System heat storage characteristics

The detection indicators of thermal storage characteristics should include not only the temperature difference between inlet and outlet water, but also the total heat storage and thermal power. From Figure 5, it can be seen that the total heat storage increases over time, but the increase becomes smaller and smaller. This is because the inlet temperature of the circulating water pump is always higher than the outlet temperature. It is worth considering that when the radiant intensity is insufficient, the water inlet temperature will be lower than the temperature of the internal PCM. At this time, the water will take away the heat of the phase change material, thus reducing the total heat storage of the heat exchanger. Therefore, it is necessary to formulate the operation rules of the pump. When the inlet temperature is lower than PCM, the hot water pump will stop to avoid reducing the total heat storage of the heat exchanger.

The thermal power of PCHE is mainly affected by the difference of inlet and outlet water temperature and mass flow. Combining Figure 3 and Figure 5, it can be observed that comparing the thermal power of one hour starting from 9:00 and one hour starting from 13:00, it can be found that the biggest impact on the thermal storage power of PCHE is the temperature difference between the inlet and outlet

The COP of the system is defined as the ratio between the heat supplied by the solar collector to the PCHE and the energy consumption of the water pump. The COP of a general household electric heating system is 1.0, but according to the data in the figure 5, the COP of this system is calculated to be between 1 and 5.5, which is higher than that of an electric heating system. Therefore, it can be considered that this system can effectively improve energy utilization efficiency.

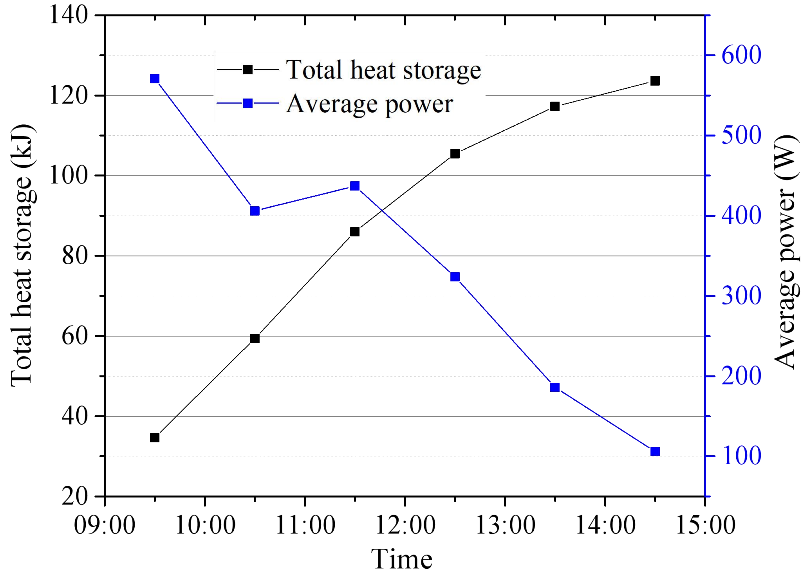

Fig. 5 System heat storage characteristics over time.

3.3 System heat release characteristics

To investigate the system heating effect at night, Room 1 and Room 2 are used respectively, which represent the heating and non-heating conditions. Compared with the ambient temperature, the changes of the two room temperatures with time from 00:00 to 9:00 are shown in Figure 6. It can be observed that room 1 and room 2 have the same temperature change trend. The room without heating is about 6 ℃ higher than the outdoor temperature, and the Room1 with heating is about 6 ℃ higher than the Room 2 temperature. At the same time, the temperature fluctuation of the two rooms is small, which indicates that the thermal insulation effect of the room is good. For room 1 with heating, the average temperature is more than 16 ℃ and the maximum temperature is close to 18 ℃. The results show that the solar heating system with PCHE under the Storage and release mode has a good heating effect and can maintain the indoor temperature at night at a comfortable level.

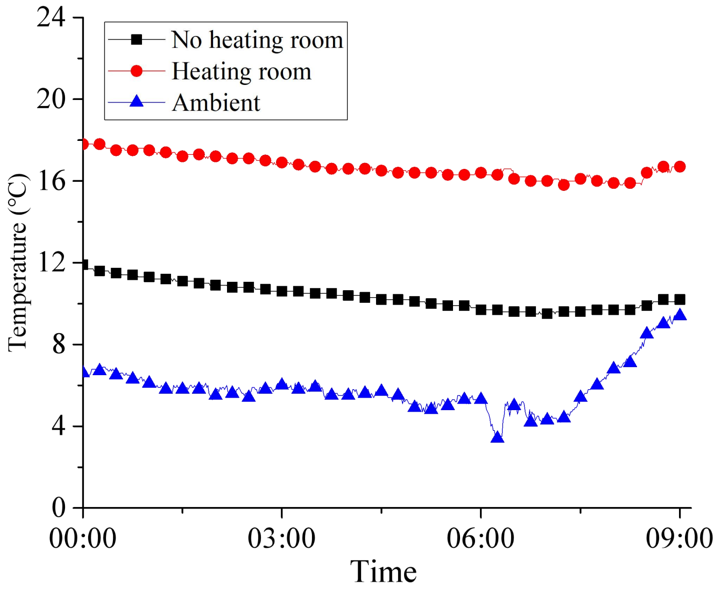

Fig. 6 Indoor and outdoor temperature changes at night.

In order to study the effect of phase change heat exchanger on indoor air temperature distribution, three temperature and humidity sensors are arranged in the indoor space from 0:00 to 9:00. The setting position of thermocouple is shown in Figure 1. Figure 7 shows the curve of temperature change with time at three different locations. It can be seen from the figure that the temperature of the measuring point close to the phase change heat exchanger is higher than that far from the measuring point, but the temperature difference between the measuring points is small, and the maximum temperature difference is less than 3 ℃. Therefore, the temperature of the room can be considered to be uniformly distributed.

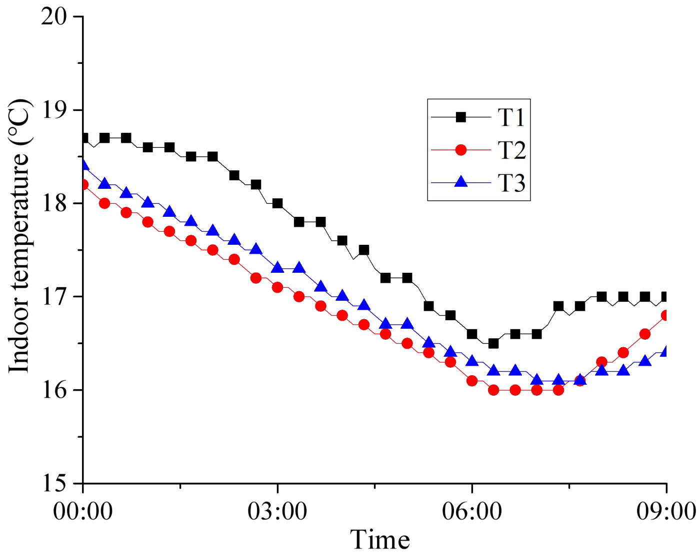

Fig.7 Temperature changes at different locations in the 1.1m high plane with time

4. Conclusion

A PCM solar heating system integrating heat storage and heat removal is designed and verified by experiments. It is found that the undercooling of PCMs is not entirely a negative effect. In this study, the main conclusions are as follows:

(1) When the undercooling is within a reasonable range, it can not only reduce the manufacturing cost, but also delay the latent heat release time to a certain extent, so that it can release the latent heat at night to maximize the heating of the room temperature.

(2) When the inlet temperature is lower than PCM, stop the hot water pump to increase the total heat storage of PCHE.

(3) The COP of this system is between 1 and 5.5, which is higher than that of general household electric heating system (COP=1).

(4) The biggest impact on PCHE heat storage power is the temperature difference between the inlet and outlet.

(5) For rooms with good thermal insulation effect, when the outdoor temperature is 5 ℃, the phase change heat exchanger can basically keep the indoor temperature at 16 ℃ without other heating measures.

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