Experimental study of a modified solar phase change material storage wall system

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Abstract: Aiming at satisfying demands of buildings in hot summer and cold winter regions, this work proposed a dual-channel and thermal-insulation-in-the-middle type solar phase change material storage wall system. The system has four independent functions: passive solar heating, heat preservation, heat insulation, and passive cooling, and it can agilely cope with requirements of climatization of buildings in different seasons throughout the year. The analysis of measured data from comparative tests on a hot-box test platform, shows that in summer, the daily average temperatures in the experimental room are 29.8°C, 30.9°C and 31.0°C respectively, while those in the reference room are 29.6°C, 30.7°C and 30.8°C, and thereby the difference is small. The south-facing wall with solar collector module shows reduction in peak temperature and delay phenomenon compared with that without solar collector module. These aspects highlighted by the results together indicate that effective prevention from summer overheating problem can be achieved by this system. In winter, by comparison with the ambient temperatures and those of the reference room, the air temperatures in the experimental room, both its maximum and average, raise greatly showing good heating effect. In addition, some distinct thermal characteristics of the system operated in summer or winter are obtained.

Keywords: Solar Energy, Building Energy Efficiency, Passive Cooling, Passive Heating, Phase Change Material.

1 Introduction

Nowadays, the world is facing the deep adjustment of energy distribution to globally cope with the challenge of growing issues in climate change. The main cause of climate change issues is producing and consuming manner excessively relying on fossil energy resources,

intrinsically an energy resource problem as well. According to the data of 2009 [1], 40% of fossil energy of EU and US is consumed in buildings. Solar energy is an important alternative to fossil resources, renewable and with environmental-friendly advantages. The efficient use of solar energy in buildings to reduce the final energy consumption of conventional energy by a significant percentage is an important approach to develop a low-carbon society. The way the phase change material (PCM) provides indirect heat storage is related to energy absorption, which turns into latent heat instead of self-temperature rise. Small volume, low temperature, and high heat storage are its strengths therefore PCM is a good and efficient heat storage material to be used in buildings climatization. Hence, the investigation of applying the combination of phase change material storage technology and solar energy utilization technology to energy efficient building emerges and receives more and more attention.

To date, composite PCM for energy efficient building has been deeply studied. Font et al. [2] investigated the performances of Polyol and its mixture and analyzed the prospect of getting their application in buildings. Hong and Xin-shi [3] investigated the structure and performance of shape-stabilized phase change material composed of paraffin and high-density polyethylene. In [4] the paraffin/expanded graphite composite PCM was prepared and its performance tested by X-ray diffraction, DSC, and scanning tunneling microscope (STM), and its faster phase change speed proved. Zhang et al. [5] prepared a novel heat-storage mortar by mixing conventional cement mortar and phase change material based on Octadecane and expanded Graphite, and experimentally proved its capability of reducing the energy consumption of buildings. Moreover, PCM's microencapsulation able to combine with building material more conveniently was investigated in [6-8].

Trombe wall, a heat-collecting system based on solar energy, is a high-efficiency simple structure that does not require maintenance. It combines solar energy utilization technology with conventional envelope structure of building; therefore, its broad application, improvement, and development have been implemented in the decades since it was proposed. By computational fluid dynamics (CFD) analysis based on experimental data, Koyunbaba et al. [9] proposed a BIPV Trombe wall model. The three-dimensional model for the shutter structure of Trombe wall was established in [10] and the comparison with experimental data and an optimal design scheme were conducted. With regard to the combination of solar energy application technology and PCM envelope structure, current researches and discussions mainly focus on PCM floor [11], PCM wall [12-15], and PCM roof [16, 17].

Soares et al. [18] demonstrated that the approach of combining solar energy utilization technology and PCM envelope structure can effectively reduce the room temperature fluctuation in solar energy building caused by lack of solar energy during the night or uncertain weather, and thus enhancing the in-room thermal comfort. However, some large areas of China are characterized by hot summers, cold winters and usually require more than

three months of air conditioning cooling. In winter, buildings need heating/heat preservation, while in summer they need heat cooling/insulation. Since solar energy is a thermal energy, it can be used conveniently for building heating in winter, but it can also cause overheating and heavy load of air conditioner in summer. Thus, in regions with hot summers and cold winters, current solar PCM storage technology cannot fully satisfy the application requirements.

Based upon the analysis above, this work proposes a novel solar PCM storage wall technology that combines Trombe-wall-like technology and phase change material storage technology, i.e. a dual-channel and thermal-insulation-in-the-middle type solar PCM storage wall (MSPCMW) system. This system has the following four independent functions: passive heating, heat preservation, heat insulation, and passive cooling. Therefore, it can easily cope with the requirements of different seasons throughout the year when applied to buildings in regions with hot summers and cold winters. By comparative tests conducted on hot-box test platform, the present work experimentally analyzed thermal characteristics of the proposed system and its influence on indoor thermal environment was investigated.

2 Principles of MSPCMW system and experiment introduction

MSPCMW system is based on a novel solar PCM storage wall technology with simple and compact structure, aiming at effective and reasonable use of solar energy in buildings located in regions with hot summers and cold winters. The system was installed on building's south-facing wall. Structural design of dual-channel and thermal insulation layer, appropriate design of vent opening switch, as well as the use of characteristics of PCM help achieving passive heating, heat preservation, heat insulation and cooling functions of buildings. A schematic of the system is shown in Fig. 1, mainly consisting of a MSPCMW module and a hot-box room with upper and lower vents. The module includes PCM wall, thermal insulation layer, interior and exterior flow channels, heat absorbing aluminum plate covered by selective absorption coating, indoor upper and lower vents, outdoor upper and lower vents, insulation layer upper and lower vents, glass cover board, and frame. The structure in which interior and exterior flow channels are separated by thermal insulation layer differs from the single-channel structure of conventional Trombe wall system. The detailed operation modes and functions are as follows:

Summer mode: (a) Heat insulation mode: in summer's daytime when building needs thermal insulation protection, indoor and middle layer upper and lower vents are closed, while outdoor ones keep open. Ambient wind pressure together with thermosiphon pressure would form a circular flow between exterior channels and outdoor air that takes the solar energy absorbed by aluminum plate back to environment. Meanwhile, thermal insulation layer prevents heat conduction into room, reducing building's absorption of solar energy. (b) Passive cooling mode: when needs insulation protection, such as summer's night, by taking

105 advantage of relatively low air temperature in the night, indoor upper and lower vents shut
106 while middle layer and outdoor ones keep open. Under the action of ambient wind pressure,
107 the formed circular flow among interior channels, exterior channels and relatively cool air
108 outdoors can cool down the PCM wall, reducing indoor temperature and storing PCM wall's
109 cold energy.

110 Winter mode: (a) Solar passive heating function: in winter's daytime needing heating,
111 the exterior upper and lower vents of system close, middle layer ones open, and interior ones
112 can open/close to implement the interactive adjustment between the indoor temperature rise
113 rate and the stored heat amount of PCM. Aluminum absorbing plate heats up the air of
114 exterior flow channel by absorbing solar radiation irradiated on it. Among the air in the
115 exterior channel, interior channel and indoor, the natural circulation due to thermosiphon
116 occurs and induces circular exchange and heating up of PCM wall and indoor air, eventually
117 achieving the solar passive heating in building. (b) Heat preservation function: in winter's
118 nights needing heat preservation, the indoor, outdoor and middle layer upper and lower vents
119 all close, and PCM wall transfers the heat stored during daytime into the room via heat
120 conduction to the neighboring building wall. In addition, the thermal insulation layer
121 composed of insulation material can block the heat loss toward outdoor as much as possible.

122 The experimental test of the system was carried out on a comparative hot-box test
123 platform located in Hefei City, Anhui Province, characterized by hot summer and cold winter
124 zone (Fig. 2). The test system included two hot-box rooms, proposed system module, vents,
125 and an experimental parameter measurement system. The experimental room was the hot-box
126 room installed with MSPCMW module, and the other one was the reference room. PCM wall
127 was made by orderly laying and pasting 11 PCM plates on building's south-facing wall using
128 thermal silicone grease. Each plate measured 0.45 m × 0.3 m × 0.01 m (L, W, H). Fig. 3
129 presents the array pattern of PCM plates and monitoring point distribution of thermocouples.
130 The plate was wrapped in aluminum and plated with anti-corrosive coating. Its interior
131 components are crystalline hydrate and organic PCM thus it benefits from both phase change
132 materials of hydrate and organic matter. The material properties of the PCM are listed in
133 Table 1.

134 Copper-constantan thermocouple with ice-point compensation (accuracy of ± 0.2 °C)
135 measured the temperature of experimental system. The position of main thermocouples is
136 shown in Fig. 1 and 3, where circles indicate their locations; along the height direction, for
137 each of interior and exterior channel, 5 nodes are placed for temperature monitoring; along
138 the height direction, 3 nodes – i.e. upper, middle, and lower - are placed for room air
139 temperature monitoring. Note that the only middle temperature probe was used to measure the
140 temperature of the indoor air in summer test, but in winter test the all three probes were used.
141 To measure the temperatures of PCM plates, at the centers of external and internal surfaces of

the three PCM plates, a measuring point is placed for each surface. Moreover, to study temperature distribution characteristics on a single PCM plate, 5 additional measuring points are placed on each of internal and external surfaces of the middle PCM plate (locations of measuring points are referred as circular marks in Fig. 3). The measuring system also included ambient temperature measurement and total solar radiation intensity of south-facing vertical surface obtained by TBQ-2 Pyranometer. All temperature data and radiation data were collected in real time by Agilent 34970A data collector.

3 Results and discussions

According to different operation modes in summer and winter, 3-day continuous experimental tests were conducted during Aug. 28-30, 2016 and Dec. 15-17, 2015, respectively. In the summer test, exterior vents kept open while interior vents kept closed; middle layer vents shut during daytime and opened during the night, and the switching time was around 7:00 and 17:30. In winter mode tests, exterior vents kept shut; middle layer vents and interior vents kept opened during daytime and shut during night, and the switching time was around 8:00 and 17:00. Tests were simultaneously conducted in experimental room and reference room.

3.1 Summer mode

Figure 4 shows the comparison of air temperature variation curves between experimental room and reference room, the variation curve of ambient temperature and the variation curve of solar radiation intensity radiated on south-facing vertical surface. Terms T_{E-Air} , T_{R-Air} , and $T_{Ambient}$ are air temperatures of experimental room, reference room and ambient, respectively. I_{Solar} is solar radiation intensity on south-facing vertical surface. During the 3-day test, the daily peak ambient temperatures were 40.5 °C, 41.9 °C and 41.8 °C, respectively and peak solar radiation intensities measured on south-facing vertical surface were 473.3 W/m², 518.2 W/m² and 585.0 W/m², respectively, meeting the requirement of high-temperature clear weather in summer mode. The comparison between temperature variations in experimental room and reference room together with the comparison of the mean and maximum temperatures in both rooms highlights that during the tested three days, air temperatures in both rooms are close to each other. This result demonstrates that overheating is avoided in experimental room, i.e. the building is not overheated. And, in experimental room it takes longer to reach the peak temperature than in reference room, revealing that certain change in heat transfer of envelope structure can be induced by the solar PCM storage wall system in summer operation condition.

Figure 5 compares temperature variations related to the area of experimental room's south-facing wall with solar collector module, the exterior surface of south-facing wall of experimental room without solar collector modules, and the exterior surface of reference

room south-facing wall, which show as $T_{E-SW-With}$, $T_{E-SW-Without}$, T_{R-SW} , respectively. The exterior surface of experimental room's south-facing wall without solar energy collecting modules and the exterior surface of reference room south-facing wall are similar in temperature, but the temperature variation of the area with solar energy collecting module is different, mainly characterized by reduction and delay of the peak value. For example, in the first day, the maximum temperature of the exterior surface of reference room south-facing wall is 46.2 °C at noon, whereas that of experimental room with solar collecting modules installed reaches its peak of 42.6 °C and the time is delayed to 15:42. Figure 6 compares the temperature variation of the three monitoring points of heat-absorbing plate (upper, middle and lower) and the center of back surface of thermal insulation plate, which show as T_{F-U} , T_{F-M} , T_{F-L} , T_{In-B} , respectively. Heat-absorbing plate shows clear temperature gradient along the height direction under solar radiation and the temperature rises from lower side to higher side sequentially. Besides, to compare temperature at the same height between the front surface of heat-absorbing plate and the back surface of thermal insulation plate, taking the results of the third day as an example, the center maximum temperature of frontal surface of heat-absorbing plate reaches 78.3 °C, whereas that of the back surface of thermal insulation plate at the same height is 50.8 °C. The comparison shows that the back surface temperature of thermal insulation layer greatly reduces. According to the principle of this work, when operating in summer mode, thermal insulation layer prevents most of solar thermal energy absorbed by plate from conducting to wall, and the small part of solar thermal energy conducting through thermal insulation layer is absorbed by PCM layer and released during the night. Building wall temperature can be kept relatively low to the greatest extent since temperature seldom rise during the phase change storage process of PCM layer. Based on the experimental results of reduction and delay of peak temperature of south-facing wall surface and the distinct reduction in back surface temperature of thermal insulation plate, this integrated approach is confirmed to be capable of avoiding the overheating issue of building and reducing obtaining solar heat.

Figure 7 compares the measured temperature variation curves of monitoring points at the exterior surface of center PCM plate during the third day, whose positions are shown in Figure 3. Vertical temperature gradient on the exact plate in the daytime is observed. The peak temperatures of the upper half and the lower half are 44.5 °C and 41.8 °C, respectively, with a temperature difference of 2.7 °C, while in horizontal direction the difference is very small. Figure 9 shows temperature comparison between the center positions of the middle three PCM plates (Monitoring points G, B and H). The surface temperature gradients of three PCM plates at different heights are also observed that higher temperature occurs at higher position and lower temperature occurs at lower position.

Figure 9 compares the temperature of interior flow channel and center PCM plate. The bigger node number of flow channel represents the higher position. For convenient comparison, the third day of test is selected as the target period for both, i.e. 48th-72th hour. As shown in the figure, temperature of interior flow channel increases with height, exhibiting a similar trend with that shown in Figure 6. In summer, because the summer exterior air flow induces temperature gradient in height direction on the heat-absorbing plate, the heat conduction leads to analogous temperature stratification phenomenon in interior flow channel. By comparing the temperatures of PCM plate and that at the third node of flow channel with the similar height, the peak temperature of phase change material plate is 43°C at 14:00 on the third day; whereas that of flow channel was 45.3 °C at 13:30. Moreover, at 6:12 and 16:06 on the third day, temperature differences are less than 0.1 °C. From heat transfer principles it can be derived that this duration corresponds to the period during which phase change plate absorbs heat from air, and the remaining time of the day heat releasing from heat-absorbing plate to air occurs .

3.2 Winter mode

Figure 10 compares the variation of air temperature measured in experimental room and reference room, as well as the ambient temperature, in winter mode, where $T_{E-Air-U}$, $T_{E-Air-L}$, T_{R-Air} , and $T_{Ambient}$ denote upper and lower air temperatures in experimental room, temperature of reference room, and ambient temperature, respectively. During the 3-day test, the daily averages of ambient temperature were 6.1 °C, 2.7 °C and 3.2 °C, respectively. And the daily maximums of solar radiation intensity on south-facing surface of building were 722.0 W/m², 816.9 W/m² and 837.6 W/m², respectively. Following Table 3 summarizes the analysis results of experimental data, in which T_{E-Air} is the mean value of $T_{E-Air-U}$ and $T_{E-Air-L}$. They demonstrate that for experimental room, both mean and maximum temperatures increase distinctly than the corresponding ones of ambient and reference room, and thereby the performance is excellent in winter mode. Furthermore, the different temperature stratification phenomenon in height direction, lower temperature at lower position and higher temperature at higher position, is also observed in the air of experimental room.

Figure 11 compares the temperature of 5 nodes at the same height of interior and exterior flow channels, distinguished as T_{IC} and T_{OC} . The temperature gradient along height exists in both interior and exterior flow channels, due to thermosiphon action. At the same height, comparing air temperatures of the channels, the air temperature of exterior flow channel is higher than the interior one. The maximum air temperatures of exterior and interior flow channels were 57.5 °C and 55.0 °C, respectively, so the difference is not large. Therefore, thermal insulation layer is not effective as a barrier of heat transfer in winter due to upper and lower vents in middle thermal insulation layer.

Figure 12 compares air temperature on the outer side of middle PCM plate and interior flow channel at the same height during 56th-80th hour. The flow channel temperature reaches its peak of 36.4°C at 13:36 on the third day; the temperature of PCM plate reached its peak of 30.1 °C at 15:54 on the third day; thus, the peak temperature of phase change material plate is relatively low and delayed. Between 16:00 and 5:24 on that day, temperature differences between them reach less than 0.1°C. During this period, the temperature of PCM plate is higher than that of air, so it can be regarded as the exothermic stage of PCM plate, namely the PCM plate heats its surrounding air. Moreover, by observing the temperature variation of phase change material plate in 67th-71.5th hour (corresponding to 7:00-11:30 in the night), temperature drop of phase change material plate is relatively moderate, and thereby this time corresponds to the release of latent heat of PCM plate.

Fig. 13 shows the temperature comparison for the outer center position of the middle three phase change material plates, and Fig. 15 compares the node temperature of center PCM plate. Temperature stratification phenomenon is also observed on the plate with height gradient owing to temperature gradient in interior flow channel. In addition, vertical temperature gradient exists on the same PCM plate, as is the case in summer mode.

4 Conclusions

The present work proposes a modified solar PCM storage wall technology that combines Trombe-wall-like technology and phase change material storage technology, i.e. the dual-channel and thermal-insulation-in-the-middle type solar phase change material storage wall system. By comparative tests on hot-box test platform, experimental tests and analyses are conducted on the system operating in summer mode and winter mode. From the experimental results, the following conclusions are addressed:

(1) This facility can effectively prevent building overheating in summer, the proof is that air temperature in experimental room is close to that in reference room, surface peak temperature of south-facing wall of building is lower and takes longer to reach the maximum, and back surface temperature of thermal insulation plate is distinctly reduced. The above show that this facility can prevent room from overheating problem.

(2) Both mean and maximum temperatures are obviously higher when comparing experimental room with ambient temperature or temperature in control room in winter, leading to excellent performance of the system in winter mode.

(3) In both summer and winter operating modes the system's PCM plates show similar temperature gradient phenomenon, lower temperature at lower position and higher temperature at higher position, but the horizontal temperature gradient is not obvious. Air in interior flow channel in summer mode and air in both interior and exterior flow channels in winter mode show the temperature gradient along height direction. In winter mode, at the

same height, the air temperature of exterior flow channel is higher than that of interior flow channel. In winter mode, a relatively longer releasing process of latent heat in the night is found by observing the smooth decline of PCM plate temperature during tests.

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Fig. 1 The structural principle of the proposed system and the arrangement diagram of thermocouples

Fig. 2 Exterior view of the test MSPCMW system

Fig. 3 Arrangement diagram of PCM plates array and thermocouples

Fig. 4 Air temperature variations in experimental room and reference room, ambient temperature variation, and solar radiation intensity variation on south-facing vertical surface

Fig. 5 Comparison of temperature between area of experimental room south-facing wall with solar collector module, exterior surface of experimental room south-facing wall without module and the surface of reference room south-facing wall

Fig. 6 Temperature comparison for upper, middle, and lower positions of heat-absorbing plate

Fig. 7 Temperature variation comparison for outer nodes at the exterior surface of center PCM plate during the third day

Fig. 8 Comparison of temperatures of outer center locations of middle three PCM plates

Fig. 9 Temperature comparison of air of interior flow channel and outer center location of center phase change material plate

Fig. 10 Air temperature variations in experimental room and reference room, ambient temperature, and the solar radiation intensity variation on south-facing vertical surface

Fig. 11 Comparison of air temperature between interior and exterior flow channels

Fig. 12 Comparison of temperatures at the middle of interior flow channel and at the center of central PCM plate

Fig. 13 Temperature comparison curves for the outer center positions of the middle three PCM plates

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Table 1 Material properties of the PCM

Properties	Unit	Number
Melt point	°C	25-27 (Standard 25)
Solid point	°C	22-24(Standard 22)
Latent Heat (18-33°C)	kJ/kg	160
Solid Density (20°C)	kg/L	1.43
Liquid Density (40°C)	kg/L	1.23
Volume expansion rate	%	13.98
Thermal conductivity	W/(m·K)	0.6
Viscosity (50°C)	mm ² /s	16.88

Table 2 Summary of main data of experimental room and reference room (summer time)

Day	Daily Avg T_{E-Air}	Daily Avg T_{R-Air}	Max T_{E-Air}	Time to reach max T_{E-Air}	Max T_{R-Air}	Time to reach max T_{R-Air}
1	29.8°C	29.6°C	35.1°C	16:24	35.1°C	15:42
2	30.9°C	30.7°C	36.7°C	16:30	36.7°C	15:48
3	31.0°C	30.8°C	36.3°C	15:36	36.3°C	15:12

Table 3 Summary of main data of experimental room and reference room in winter

Day	Daily Avg $T_{Ambient}$	Daily Avg T_{E-Air}	Daily Avg T_{R-Air}	ΔT	Max T_{E-Air}	Max T_{R-Air}	ΔT
1	5.9°C	16.4°C	11.0°C	5.4°C	34.2°C	17.6°C	16.6°C
2	2.7°C	14.5°C	8.4°C	6.1°C	33.5°C	16.0°C	17.5°C
3	3.2°C	16.6°C	9.8°C	6.8°C	38.4°C	18.7°C	19.7°C