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Modeling and simulation on the performance of a novel double shape-stabilized phase change materials wallboard

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ABSTRACT

The structure of a new wall system was that of a three-layer sandwich-type panel with external/internal layer consisting of shape-stabilized phase change material (SSPCM) wallboard and middle layer consisting of conventional concrete. The external layer was active in hot seasons and the internal layer was active in cold seasons. An office room integrated with the novel double SSPCMs wallboard with a splitting air-conditioner was used for modeling and simulation test platform. Studies were conducted to investigate the effects of the novel double SSPCMs and different parameters on the energy and thermal performance in typical climate area with hot summer and cold winter (Wuhan city, China). Test results showed that the recommended thicknesses of external and internal SSPCM wallboard were 30–60 mm. With the recommended thickness, the annual energy savings for cooling were 3.4–3.9%. The peak load reductions for cooling were 3.1–3.8%. The annual energy savings for heating were 14.8–18.8%. The peak load reductions for heating were 8.6–11.3%. The external layer was effective on reducing annual energy demand and peak load of cooling in hot seasons. The internal layer was effective on reducing the indoor temperature fluctuation in cold seasons.

1. Introduction

Envelope thermal physical properties have a significant weight in the overall energy balance contributing to a high extent to the cooling and heating load. The use of phase change materials (PCMs) in building elements with the purpose of increasing thermal mass is extensively studied. PCMs can be integrated into building materials or prefabricated building elements such as concrete, gypsum wallboard, plaster, etc. A substantial amount of studies [1–12] are available on the applications of PCMs in buildings to enhance their energy and thermal performance.

In recent years, the shape-stabilized phase change material (SSPCM) attracts the interests of the researchers [13–29]. The SSPCM consists of PCM as dispersed material and high-density polyethylene or other materials as supporting material. The mass percentage of PCM contains can be as much as 80% or so and the compound material keeps its shape as long as the operating temperature is below the melting point of the supporting material. This reduces the liquid PCM leakage danger and it can be used for thermal storage in buildings without encapsulation.

Xu et al. [30] developed a heat transfer model to analyze the thermal performance of SSPCM floor. The model was verified by experimental results. The influence of various factors (thickness, melting temperature, heat of fusion, thermal conductivity of PCM, etc.) on the room thermal performance was analyzed. Some recommended parameters were given and they were helpful for the application of SSPCM floor in solar energy buildings.

Zhou et al. [31] numerically investigated the thermal performance of a hybrid space-cooling system with night ventilation and thermal storage using SSPCM. A south-facing room of an office building in Beijing was analyzed, and the electrical COPs of night ventilation (the reduced cooling energy divided by fan power) were 7.5 and 6.5 for cases with and without SSPCM, respectively. The hybrid system could improve the indoor thermal comfort level and save 76% of daytime cooling energy consumption in summer in Beijing (compared with the case without SSPCM and night ventilation).

The exiting researches mainly concentrated on single layer SSPCM element which was active in hot seasons or cold seasons. They could not improve thermal comfort and reduce energy consumption over a year. Only a few studies [32,33] have been performed on double layers SSPCM integrated into constructions for year-round application.

Pasupathy et al. [32] studied the thermal performance of an inorganic eutectic PCM based on thermal storage system for thermal

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Nomenclature

c	specific heat (kJ/kg K)
C	capacitance (kJ/K)
D	thickness of materials (mm)
E	annual energy saving
H	latent heat (kJ/kg)
P	peak load reduction
Q	cooling/heating load or heat (kW)
R	resistance (K k/W)
T	temperature (°C)
t	time (s or h)

Greek symbols

λ	conductivity (W/m·K)
ρ	density (kg/m^3)
τ	time (s or h)

Subscripts

C	cooling
ex	external or outdoor
H	heating
in	internal or indoor
m	melting point of SSPCM
m1	melting point of external SSPCM wallboard
m2	melting point of internal SSPCM wallboard
oe	occupants and equipments
p	phase change material (pcm)
sol	solar
s	simplified model
w	concrete wall

management in a residential building with mathematical models. The system had been analyzed by theoretical and experimental investigation. A double layers PCM concept was studied in detail to achieve year round thermal management in a passive manner. The double layers PCMs were placed next to each other and regarded as a whole panel. It was found that the PCM could reduce the internal air temperature swing during the winter seasons, but it was not suitable for the summer seasons as the PCM remained in the liquid state at all the times during these months and hence the system cannot exploit the latent heat effect.

Diaconu et al. [33] proposed a new type of composite wall system incorporating PCMs and its potential for cooling/heating energy savings in continental temperate climate was evaluated. The middle layer was insulation panel (100 mm) and outer layer was PCM wallboards (50 mm). A year-round simulation of a room built using the new wall system was carried out and the effect of PCM presence into the structure of the wall system was assessed in this study. It was found that the new wall system contributed to annual energy savings (1% cooling energy saved in summer and 12.8% heating energy saved in winter) and reduced the peak value (24.3% for cooling and 35.4% for heating) of the air-conditioning/heating loads. But the author pointed out that the characteristics of the wall system were not optimized, and insulation as the main body of the wall was not the common envelope used in the actual buildings, therefore the actual value of the energy savings was of little relevance.

Meng et al. [34] studied on thermal characteristics of the composite PCM structure numerically and experimentally. Two different kinds of PCM were placed on the wall in different orientations. Results showed that this new type of PCM room can decrease the indoor air temperature fluctuation by 4.3 °C in summer and 14.2 °C in winter. Different arrangements of the two kinds of PCM in the room can cause an indoor air temperature difference to be 6.9 °C in summer and 2.7 °C in winter. Moreover, it was found that the selection of the phase change temperature and the thickness influenced melting speed and rate.

Jin et al. [35] put forward a new double layer PCM floor. The two layers PCMs had different melting temperature. The system was used to store heat or cold energy in the off-peak period and release them in the peak period during heating or cooling. The results showed that the optimal melting temperatures of PCMs exist. The fluctuations of the floor surface temperatures and the heat fluxes would be reduced and the system still can provide a certain amount of heat or cold energy after the heat pump or chiller had been turned off for a long time. Compared to the floor without PCM, the energy released by the floor with PCM in peak period will be increased by 41.1% and 37.9% during heating and cooling when the heat of fusion of PCM was 150 kJ/kg.

Peippo et al. [36] presented approximate formulae for optimum phase change temperature and thickness of the PCM wall. It showed that the optimal thickness was relevant on optimal phase change temperature and other parameters (latent heat of fusion, density, average heat transfer coefficient between wall surface and surroundings, discharging time and average room nighttime temperature). These formulae were very simple and cannot be used to optimize a PCM wall used in a building. Since the optimal thickness of the wall highly depends on the thermal diffusivity of the PCM composite [37].

Favoino et al. [38] proposed a facade integrating SSPCM. The main feature of this multifunctional facade module lies in the ability to change its thermo-physical behavior in order to suit different building requirements and to face several/contrasting boundary conditions. A prototype of the facade module was built and its performance investigated by means of an experimental analysis, performed during the winter (heating) season. The latent heat thermal energy storage coupled with the photovoltaic allows to manage in a better way heat gains and to reduce the mismatch between energy demand and solar energy availability (even if the energy inefficiency of the system revealed to be relevant).

While it was generally agreed that SSPCM integrated in building elements could improve indoor thermal comfort and reduce cooling/heating system energy consumptions. A novel SSPCMs wallboard for year-round application was proposed in this paper. Two different SSPCMs with different thermophysical properties were integrated into the common concrete wall in an air-conditioned room in Wuhan (30.52 °N, 114.32 °E), China. The influences of various factors (thickness, melting temperature, latent heat, thermal conductivity of PCM, etc.) on the energy and thermal performance were different. Influences of latent heat and thermal conductivity values on performance of the novel wallboard were relatively simple. But the influences of melting temperature and thickness values on wallboard performance were very complicate. Therefore the SSPCMs melting temperatures and thicknesses were the main considered factors in this paper influencing the energy and thermal performance of the novel SSPCMs wallboard. The recommended optimum thickness and melting temperature ranges of double SSPCM layers were analyzed and given in this paper. The annual energy savings and peak load reductions for cooling/heating were also analyzed by numerical study.

2. Mathematical models description

The SSPCM used in this study consists of paraffin as main part and high density polyethylene/expanded graphite as additives. The mass percentage of paraffin is 80%. The mass percentage of high density polyethylene is 15% and it could maintain the SSPCM in solid shape when melting and without leakage. The mass percentage of expanded graphite is 5% and it could improve the thermal