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Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore

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HIGHLIGHTS

- PCM can effectively reduce building cooling load in tropical climate.
- Selection of phase change temperature, location, thickness, and enthalpy curve of PCM is critical.
- Optimum phase change temperature is influenced by location, thickness, and enthalpy curve of PCM.
- Recommendation on the optimized use of PCM in tropical climate is provided.

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ABSTRACT

Phase change materials (PCMs) are capable to absorb massive heat during a phase transition in a narrow temperature range, which have great potential to be incorporated into building envelopes to prevent heat penetration into buildings and reduce cooling loads. The efficiency and selection of PCMs, however, are highly subject to the climate where they are applied. This study focused on the energy performance of building envelopes integrated with PCMs for cooling load reduction in tropical climate through numerical simulations. Studies were carried out to reveal the efficacy and factors that govern the performance of the PCM addition for cooling load reduction in Singapore. The results showed that PCM can effectively reduce heat gains through building envelopes throughout the whole year, indicating the significant advantage of the use of PCMs in tropics over other regions where PCMs are only effective in certain seasons. The selection of PCM with suitable phase change temperature is critical. PCMs applied to the exterior surfaces of walls showed better performance and the optimum phase change temperature is the lowest temperature allowing the full melting–solidification cycle of the entire PCM layer. A larger phase change temperature range improves the adaptivity of the PCMs to temperature variations, but may compromise the largest energy savings that the PCMs can achieve. While thicker PCM layer reduces heat gains through building envelope, thinner PCM layer shows higher efficiency and cost benefits.

1. Introduction

Building, one of the largest energy consumers in modern society, is responsible for around 30–40% of the world primary energy consumption, of which a substantial proportion is consumed by heating, ventilation, and air conditioning (HVAC) systems to enhance indoor thermal comfort [1]. It is projected that the world primary energy consumption may continue to grow because of the climatic change and the rising living standard [2]. Reduction of building energy consumption and design of energy efficient building, therefore, have become critical topics nowadays owing to increased concerns on the diminished fossil fuel reserves and the environmental impacts of greenhouse gas emission.

A building envelope is what isolates the indoor environment of a building from the variable outdoor conditions. It is a key factor that influences the heating and cooling loads of a building and therefore presents an opportunity to significantly reduce the energy demands. One such method is to increase the thermal mass of building envelopes. The addition of thermal mass attenuates indoor temperature swings by absorbing heat and progressively releasing it when ambient temperatures drop down, leading to a reduction and a shift of the peak indoor loads [3].

Phase change materials (PCMs) are capable to absorb and to release massive latent heat during phase transition in a narrow temperature range and function as thermal mass. The advantages

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Nomenclature

C_p	specific heat capacity (J/kg K)
h	specific enthalpy (J/kg)
h_c	interior surface convection coefficient (W/m^2 K)
L	latent heat of fusion (kJ/kg)
Q	total envelope heat gains (MJ/m^2)
q''_{conv}	convective heat flux to zone air (W/m^2)
Q_{PCM}	total envelope heat gains of the building with PCM (MJ/m^2)
Q_{No_PCM}	total envelope heat gains of the building without PCM (MJ/m^2)
T	temperature (°C)
T_a	indoor air temperature (°C)
T_m	melting temperature (°C)
T_s	interior surface temperature of the wall (°C)

Greek symbols

Δ	difference
η	envelope heat gain reduction rate (%)
τ	phase change range (K)

Subscript

i	modeled node

Superscripts

j	actual simulation time step
$j-1$	previous time step

of incorporating PCMs into building envelopes are twofold: the heat capacity of PCMs is order-of-magnitude higher than traditional building materials and the melting and freezing cycles are almost isothermal [4]. PCMs have been successfully incorporated into building envelopes to enhance indoor thermal comfort and reduce heating and cooling loads [5]. For example, studies have reported that PCMs can potentially save 10–30% of the annual cooling and heating loads for buildings in various climate zones in the US [6,7]. An experimental study carried out in Arizona, USA showed energy savings of 10–26% were achieved by using PCMs in assembly walls in summer months [8]. A heating load reduction of 15% was recorded by using PCM gypsum boards as interior lining of a building envelope in Montreal, Canada [9]. In German, plaster incorporating PCM micro-capsules coated on interior walls reduced the indoor peak temperature by 2 K and maintained the temperature within the thermal comfort zone for longer periods [10].

Building envelopes integrated with PCMs have been extensively studied in temperate countries including China, European countries and the US [6–17]. However, very few studies reported the applications of PCMs to building envelopes in tropical climates. The tropical climate of Singapore is characterized with uniformly high temperatures throughout the year with no distinct seasons due to its geographical location and maritime influence. It has a diurnal temperature range between a minimum of 23–27 °C and a maximum of 30–34 °C [18]. Space heating is therefore not required and space cooling is crucial for indoor thermal comfort throughout the whole year.

Relevant studies on building envelopes incorporating PCMs for space cooling during summer months in temperate climates are listed in Table 1. The location, the climatic condition (diurnal temperature range and minimum outdoor temperature) in summer, the type and performance of PCMs are summarized in the table. As can be seen in Table 1, the addition of PCMs shows good performance to lower the peak indoor temperature or reduce the cooling loads in summer months. In those regions, the diurnal temperature range is much larger (10–20 °C) and the temperature at night is relatively lower (12–22 °C) as compared to those of Singapore (diurnal temp. range: 5–7 °C; min. outdoor temp.: 23–27 °C).

While these studies may be relevant to the current study, they were all conducted in temperate climate zones. The performance of building envelopes incorporating PCMs in the tropical climate could be very different. First, the limited diurnal temperature variation implies high potential of the incomplete melting–freezing cycle of PCMs which compromises the heat absorption of the PCMs in the following cycle. It was pointed out the diurnal ambient temperature variation should exceed 10 K to ensure effective thermal storage of PCM as passive cooling strategy [3]. Hence, the small diurnal temperature variation in Singapore may significantly reduce the efficacy of PCMs applied to buildings. Another factor is the relatively high temperature at night. The heat gains from the solidification of PCMs during the night may cause energy penalties since additional cooling and/or ventilation may be needed to remove the undesirable heat or indoor thermal comfort may be compromised at night. Therefore, with the year-round hot tropical climate, the adoption of PCMs for buildings in Singapore faces unique challenges.

On the other hand, tropical climate may actually provide opportunities for more effective design and use of PCMs. Unlike other climatic regions where PCMs are only effective in a certain season, the uniform tropical climate may allow PCMs to be effective throughout the whole year if proper PCMs are selected and designed. According to these reasons, it is essential to evaluate the performance of PCMs for building applications in tropical Singapore and to investigate suitable strategies for the effective use of PCMs.

Two papers investigated building envelopes integrated with PCMs in tropical climate [19,20]. The PCMs were incorporated in the building roof as a passive cooling strategy where no mechanical cooling was utilized in both studies. The building roof with a double layer PCMs was tested in Chennai, India [20], where the climatic pattern was similar to Singapore in terms of the diurnal temperature variation and the night-time temperatures. The results showed PCMs with a total thickness of 6 cm are required to maintain a comfortable temperature. To the best of the authors' knowledge, no published literature studied PCM building envelope in air-conditioned building in tropical climate and no data is available about potential cooling load reduction by using PCMs in such climate.

This paper investigated the energy performance of building envelopes integrating PCMs for cooling load reduction in Singapore through numerical simulations. The influences of the phase change temperature, location, temperature range of phase change, shape of enthalpy curve, and amount of PCMs on building envelope heat gain reduction in air-conditioned building were studied and reported.

2. Numerical method and model descriptions

2.1. Numerical method

EnergyPlus developed by the U.S. Department of Energy (US DOE) is one of the most commonly used programs for whole building energy simulations. The one-dimensional conduction finite difference (CondFD) solution is employed as the heat balance algorithm in EnergyPlus to simulate the thermal performance of