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# Parametric analysis for performance enhancement of phase change materials in naturally ventilated buildings

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ABSTRACT

This paper presents a design optimization related to the application of phase change materials within buildings, which aims to maximize the utilization of latent heat capacity to improve indoor thermal comfort during summer season. Two performance indicators are developed: efficiency coefficient (a representation of the effective utilization of latent heat storage capacity) and effectiveness coefficient (a representation of improvement of indoor thermal comfort). A series of parameters which influence the efficiency coefficient and effectiveness coefficient are identified and then formulated to quantify those coefficients for optimal design. With the performance indicators defined, a case study is performed in a typical standard Australian residential house to derive the optimized design of PCM refurbishment utilizing the developed performance indicators. Results reveal that the performance indicators are effective in the selection of optimum PCM configurations so that the resultant PCM storage efficiency and indoor thermal comfort are optimized. This is particularly demonstrated by the significant enhancement of storage efficiency and effectiveness of optimized PCM compared to non-optimized cases for each climate conditions. Furthermore, an optimized PCM condition is found to be more cost-effective than the non-optimized conditions.



## 1. Introduction

In recent decades, the significant attention has been given to the use of latent heat thermal energy storage (LHTES) applications for energy efficiency and indoor thermal comfort in buildings. A LHTES system or phase change materials (PCMs) enhance the thermal energy storage (TES) of the building envelope by storing or discharging large amounts of heat energy in a narrow temperature range [1–3]. PCMs can either be incorporated into building materials or can be used as a prefabricated building component. A substantial amount of studies are available on the use of PCMs in the building envelope to reduce energy consumption and to improve indoor thermal comfort [4–16].

In recent years, the application of PCM as a component has been found to be a promising technology due to easy installation, low cost, compatibility with any sort of surrounding environment and reduced volume changes [13]. Examples of PCM as a component include macro-encapsulated PCM mats installed between insulation and interior layer in walls and ceiling and PCM panels installed below floor finishes. Bio-PCM$^{TM}$ is a commercial grade macro-encapsulated PCM available in a mat form, in which refined fatty acids are filled in square pouches. Bio-PCM$^{TM}$ provides the versatility of installation, such as fastening to wood or metal studs between insulation and interior layer in walls and ceiling [13]. However, the thermal performance of such PCMs largely depends on the heat transfer rate between indoor air and PCM [17].

The thermal performance of PCM applications in a naturally ventilated building can be measured by different criteria. Obviously, well-defined thermal comfort theories can be used to evaluate the improvement in indoor thermal comfort, representing the enhancement of thermal performance of a building incorporating PCMs compared to the case without PCM [18]. Campbell and Sailor [19] studied the effect of Bio-PCM$^{TM}$ on thermal comfort and reported a reduction of 93% of zone hours and 98% of zone-degree-hours outside the ASHRAE-defined thermal comfort in Portland,

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**Nomenclature**

| | |
|---|---|
| LHTES | Latent heat thermal energy storage |
| TES | Thermal energy storage |
| CE | Cooling efficiency coefficient |
| HE | Heating efficiency coefficient |
| $L_C$ | Latent charge fraction |
| $L_{DC}$ | Latent discharge fraction |
| $T_C$ | Charging duration |
| $T_{DC}$ | Discharging duration |
| e | Effectiveness coefficient |
| $T_{comf}$ | Optimum comfort temperature (°C) |
| $T_{a,out}$ | Mean monthly outdoor air temperature (°C) |
| $T_{Ind}$ | Indoor operative temperature (°C) |
| $T_a$ | Indoor air temperature (°C) |
| $T_r$ | Mean radiant temperature (°C) |
| $\eta$ | Effective latent storage |
| $\Delta H$ | the latent enthalpy of BioPCM |
| $H(T_0)$ | Specific enthalpy at lower transition temperature |
| $H(T_i)$ | Specific enthalpy at the $i^{th}$ node |
| $\eta_{max:day}$ | Maximum effective latent storage during day time |
| $\eta_{min:day}$ | Minimum effective latent storage during day time |
| $\eta_{max:night}$ | Maximum effective latent storage during night time |
| $\eta_{min:night}$ | Minimum effective latent storage during night time |

Oregon. Lauck and Sailor [13] performed an experimental and simulation study in a super-insulated residential building in Portland and reported a reduction of overheated zone hours by 50% for floor PCM and 60% for PCM at the interior wall surface compared to the case of without PCM.

In addition to thermal comfort theories, some researchers have developed indices to evaluate PCM performance. Indices such as energy saving equivalent (ESE) and energy saving index (ESI), based on hypothetical energy input required to maintain a passive room at the same state by incorporating PCM, were developed by Ye et al. [20] to evaluate the PCM performance. Pisello et al. [21] proposed 'thermal deviation indexes' (TDI) based on the distance between the target thermal condition and the existing condition in terms of intensity and frequency. In another study [22], time lag and decrement factors were used as indicators to measure the peak load shift and peak load reduction respectively. Zhang et al. [23,24] also developed approaches to improve the building energy efficiency by proposing ideal parameters to thermal conductivity and specific heat capacity.

Evola et al. [18] introduced novel indicators based on PCM behavior in a micro-encapsulated PCM wallboard. They determined the latent energy gain rate based on the difference between positive heat fluxes entering from both sides of the wall. From the latent energy storage behavior, they introduced set of indicators to represent PCM effectiveness and indoor thermal comfort. However, the wallboard they investigated contained only 60% of micro-encapsulated PCM and the heat flux difference would include the sensible energy stored in non-PCM materials. Further, in a typical building construction which features multilayers, this approach cannot be used to isolate the energy stored in the PCM.

## 2. Research context

This research presents more comprehensive evaluation of thermal performance of PCM in naturally ventilated buildings. As also pointed out by various researchers [7,18], even if several criteria are used for evaluation of the thermal performance of PCMs, there is still a lack of proper indicators to optimize the thermal performance of PCM in buildings. Moreover, previous researches have primarily focused on the performance enhancement of PCMs in improving indoor thermal comfort and/or energy savings in buildings, whilst the storage efficiency of PCMs has not been adequately addressed. In order to optimize the PCM application in buildings, thermal performance of PCM should be evaluated in terms of the latent heat storage efficiency of PCM and effectiveness in improving the indoor thermal comfort.

The latent storage efficiency of PCM materials should be studied in terms of its diurnal charge and discharge capability. More precisely, an integrated PCM that stores a lower amount of energy compared to its capacity or that discharges energy poorly is not useful. Therefore, amount of daily energy storage and discharge become as factors of PCM efficiency. Another factor is the PCM operational period during the daily cycles. Indeed, a PCM layer that reaches its capacity in a relatively shorter period is not suitable, as it is not utilized for the whole day. Moreover, integrated PCM layers that stay in the solidified stage or completely melted stage are not preferred. A PCM layer that stays at the partially melted stage for a long time means that it operates efficiently in daily cycles. Therefore, operational period of charge and discharge become as another set of factors of PCM efficiency. Although these factors were addressed by Evola et al. [18], separate consideration of their effect would not represent the real efficiency of PCMs. It is necessary to develop an indicator by combining these factors in order to optimize the storage efficiency of PCM.

Optimal storage efficiency of PCM does not necessarily indicate that indoor thermal comfort is at an optimal level. It is necessary to propose an indicator to evaluate the effectiveness of PCM in improving indoor thermal comfort, in addition to PCM storage efficiency.

Finally, there is a lack of studies that evaluate the latent energy storage of PCM in a multilayered construction element. Such study would be an interesting way to propose a more accurate methodology to determine latent energy storage or discharge, hence providing more accurate predictions.

From these concepts, it emerges that the thermal performance of PCM in buildings should be evaluated considering both the latent energy storage efficiency of the PCM layer and improvement in indoor thermal comfort. Therefore, the aim of the present research is to present a novel design optimization method of PCM application in buildings considering both of these factors. In the present study, PCM storage efficiency and effectiveness will be calculated using the developed indicators. Parametric analysis will be carried out to identify the influence of thermo-physical properties of PCM and night ventilation on the PCM storage efficiency and effectiveness indicators. Furthermore, the study will be carried out for the entire cooling season (December-February) in four major cities of Australia: Melbourne, Sydney, Perth and Brisbane.

## 3. Methodology

### 3.1. Development of performance indicators

As explained in the Introduction, the factors that are influencing the efficiency of PCM in building applications is the diurnal latent energy storage and period of operation. Therefore, four different variables were formulated to represent the cooling and heating efficiency coefficients, as shown in Table 1. Here, *cooling efficiency coefficient (CE)* and *heating efficiency coefficient (HE)* are defined as how efficiently PCM works during charging and discharging operations respectively. In addition to efficiency, the PCM effectiveness in the indoor environment is measured by the ASHRAE Adaptive ther-