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Thermal performance of buildings integrated with phase change materials to reduce heat stress risks during extreme heatwave events

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HIGHLIGHTS

- Building refurbishment with PCM is investigated numerically.
- PCM can effectively reduce the heat stress risks during heatwave periods.
- Phase change temperature, quantity of PCM and ventilation design are critical.
- Recommendation of the optimized PCM design is presented.

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ABSTRACT

Building refurbishment, through incorporating phase change materials (PCMs) into building fabrics, has been considered to be an effective way to reduce the energy consumption and related carbon emission of buildings. At the same time, it can also help to reduce the extreme heatwave risks in non-air-conditioned buildings. This study investigates the potential applications of PCMs to be integrated into buildings to reduce heat stress risks during extreme heatwave periods through numerical simulations. This study uses 2009 weather data of Melbourne, a city that regularly experiences heatwaves in summer. A detached single-storey house, without an active air-conditioning system, is refurbished with the installation of macro-encapsulated Bio-PCM™ mats as inner linings of walls and ceilings. Dynamic thermal simulations have been undertaken to reveal the performance of, and factors that influence, the adoption of PCM to reduce heat stress during heatwave periods. Discomfort index has been used as an indicator for measuring the indoor heat stress risks. The results showed that PCM refurbishment can effectively reduce the indoor heat stress risks, indicating a significant advantage in improving the occupant health and comfort. The selection of suitable phase transition temperature, and amount of PCM, is critical for this application to be effective. Appropriate selection of PCM with better ventilation design could reduce the severe discomfort period by 65% during extreme heatwave conditions. While the thermal energy storage of PCM reduces the indoor heat stress, night ventilation enhances the cool storage of PCM.

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1. Introduction

The rapid depletion of fossil fuels, and associated worsening environmental problems, has led to an increased demand for clean, versatile and efficient utilization of energy. Among various energy consumers, the building sector contributes to 30% of primary energy consumption [1,2]. Therefore, there has been a lot of effort in the field of building design to improve building energy efficiency and indoor thermal comfort. As a result, several building design standards and practices have emerged to aid the design and development of highly energy efficient buildings. The common themes in the energy efficient building design are effective space conditioning controls, better insulation performance [3], minimized infiltration [4] and high performance windows and doors [5]. As a result, the buildings can achieve up to 90% more energy efficiency than typical construction [6].

However, a common complaint about high energy efficient buildings is that, due to increased thermal insulation and airtightness, these buildings are more prone to be over-heated during hot days and heatwave periods. This resulted in increased level of thermal discomfort or energy demand [7,8]. While the energy

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Nomenclature

PCM	phase change material
DI	discomfort index
NV	night ventilation
ACH	air circulation per hour
ASHRAE	american society of heating, refrigerating, and air-conditioning engineers
ISO	international standards organization
CondFD	conduction finite difference
x	thickness (mm)
t	time

Greek letters

Δ	difference
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
γ	radiant factor

Subscripts

i	modeled node
$i+1$	adjacent node to interior of construction
$i-1$	adjacent node to exterior of construction
j	simulation time step
$j+1$	previous time step
W	interface between i and $i+1$ node
E	interface between $i-1$ and i node
OPE	indoor operative temperature (°C)
$drybulb$	indoor air drybulb temperature (°C)
MRT	mean radiant temperature (°C)
$comf$	optimum comfort temperature (°C)
a, out	mean monthly outdoor air temperature (°C)

efficiency in buildings has been the focus in many studies, there has been little consideration given to the effects on buildings and occupants during extreme heatwave events, which are characterized by prolonged high temperature exposure. It is anticipated that, extreme heatwave exposure has greater effects on indoor environment, occupant health and comfort [9–12].

During July and August 2003, European countries experienced its worst ever heatwave, where the temperatures recorded above 40 °C. In 16 European countries, more than 70,000 excess deaths occurred during the summer of 2003 [13]. France was particularly affected, where 15,000 excess deaths were observed. The greatest increase in mortality was due to heat related issues such as dehydration, hyperthermia and heat stroke [14]. The impact of heatwaves on buildings and occupants has also been reported in Australia. In February 2004, almost two-thirds of continental Australia recorded the temperatures above 39 °C. Brisbane in particular, recorded 41 °C and 42 °C for two consecutive days of 21–22 February 2004. This heatwave event caused 116 additional deaths in Brisbane, Australia [9,15]. During January 2009, south-eastern Australia (i.e. South Australia and Victoria) experienced an extreme heatwave event. During the period of 27–31 January, the majority of the Victorian weather stations recorded maximum temperatures; more than 12–15 °C above normal. On 30 January, the maximum temperature in Melbourne was recorded as 45.1 °C, which is the second highest on record. This heatwave event caused 374 additional deaths in Victoria [9,10].

The effect of heatwaves on mortality and morbidity has been studied by many researchers [12,16–18]. For instance, Santamouris [16] studied the effect of heat waves and increased summer heat stress in European cities and reported that heatwaves may seriously affect older adults and vulnerable populations and increase the risk of their lives in non-air-conditioned buildings. Furthermore, extreme events can result in power blackouts and brownouts and put at risk even buildings that are air-conditioned.

Although heat waves are attributable to extreme outdoor temperatures, efficient building design and refurbishment measures can reduce the effect of heatwaves by sheltering occupants and reducing the heat stress risks indoors. However, traditional ways of performance enhancement of buildings, such as increased thermal insulation and airtightness, could further exacerbate the overheating during heatwaves that could lead to even higher levels of heat-related health issues.

Over the past decade, the incorporation of phase change materials (PCMs) into the building envelope has been investigated as a potential technology to enhance building energy efficiency and indoor thermal comfort. This is due to the obvious merits of PCMs such as high energy storage density and narrow temperature variation during energy storage process [19–22]. Numerous studies have shown that the adoption of latent heat thermal energy storage with PCMs significantly reduces the indoor temperature fluctuations and cooling loads [23–28]. For example, studies have reported that PCMs can potentially reduce the daily maximum temperature by up to 2 °C and eliminate approximately 47% of peak energy use and 12% of energy consumption in winter for the climate zone of Beijing, China [29–31]. In another study, cooling load reductions of 15–17% was observed for PCM integrated brick walls in Spain [32]. In France, PCM integrated wallboards reduced the peak indoor temperature by 3.9 °C and 2.3 °C in summer and mid-seasons respectively and increased the minimum temperature by around 0.4–0.8 °C [33]. In addition to energy savings, isothermal energy storage nature of PCMs could also reduce the potential heat stress during extreme heatwave periods by reducing high indoor temperatures [24] which, in turn, can result in reduced heat related health issues.

In general, PCMs can be incorporated into building fabrics by either integrating them into construction materials or using them as a component. The former application is enabled via impregnating micro-encapsulated/granular PCM into building elements such as concrete/brick walls, wall plasterboards, ceiling, floor and roof. When PCMs are applied in this manner, the increased surface area facilitates a high heat transfer rate. However, these applications are costly and can adversely affect structural integrity [6,34,35]. Moreover, it would be difficult to incorporate PCMs into traditional buildings as a retrofitting measure. On the other hand, the application of PCMs as a component has recently been shown to be a promising technology due to easy installation, low cost, compatibility with any sort of surrounding environment, and reduced changes to external volume [6]. Examples of PCMs 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.

A kind of macro-encapsulated shape stabilized PCM (SSPCM), the so called Bio-PCM™, has been concerned in recent years, which consists of refined fatty acids in square pouches and produced as mat-form. The compound material contains as much as 90% of PCM and it remains stable during the operative temperature range. This reduces the liquid PCM leakage problems during the operational stage of buildings. Alam et al. [25] investigated the energy

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