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Application of Phase Change Materials to reduce heat related risks during extreme heat waves in Australian dwellings

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Abstract

This study investigates the effect of phase change materials (PCMs) in reducing potential heat stress risks in non-air-conditioned buildings during heat wave periods, such as that occurred in Melbourne, 2009. A residential house is refurbished with the installation of shape-stabilized phase change material as inner linings of walls and ceiling. Dynamic thermal simulations were performed in EnergyPlus for the heat wave period in Melbourne, Australia. Discomfort Index (DI) has been used as an indicator for the heat stress evaluation. From the simulation, it was observed that the incorporation of PCM in combination with night ventilation could reduce the hours of severe heat stress risks by up to 32%. Therefore, it is foreseeable that the application of PCM would have potential for minimizing the effect of heat waves on the occupant health and comfort in non-air-conditioned buildings. However, proper building design such as night ventilation is essential for the efficient utilization of phase change materials during heat wave period.

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Keywords: Phase change materials (PCMs); heatwave; heat stress; mitigation; building energy efficiency.

1. Introduction

Global warming is widely perceived as one of the important issue facing the world today, with increasing effects in the extreme temperatures such as heat waves. Especially, in Europe and Australia, much effort has been dedicated to reduce heatwave effects due to increasing public health concerns and heat related mortalities.

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During the summer of 2009 (27-31 January 2009), Melbourne, Victoria region experienced an extreme heat wave, causing 374 heat related mortalities in Victoria [1, 2]. This indicates that the extreme heat exposure can increase the health related issues. Although extreme heat exposure can occur both outdoor and indoor, efficient building design can reduce the effect of heat wave by sheltering occupants and reducing heat related impacts in indoor [3].

Over the past decade, incorporation of PCMs into building envelope has been investigated as a potential technology to reduce the building energy consumption and to increase indoor thermal comfort [4-7]. In addition, isothermal energy storage nature of PCM could also reduce the potential heat stress during extreme heat waves by cutting down the peak indoor temperature which, in turn, will result in reduced heat related mortalities [8].

A kind of shape-stabilized PCM, the so-called macro-encapsulated BioPCM^{TM} has been recently concerned, which consists refined fatty acid in square poaches produced as mat-form. Alam et al. [9] investigated the energy saving potential of Bio-PCM^{TM} in Australian residential buildings and reported that the integration of Bio-PCM^{TM} into building fabrics can provide 17-23% of annual energy savings.

Although several studies reported that the incorporation of PCM into building envelope can increase building energy efficiency and improve indoor thermal comfort, there is lack of studies available to investigate the efficiency of PCM during extreme events such as heat waves. Based on this concern, this study focuses on investigating the effects of PCM to reduce heat related impacts in residential buildings during heat wave period in Australia.

Nomenclature

PCMs	phase change materials
NV	night ventilation
NatHERS	Nationwide house energy rating system
ACH	air circulation per hour
DI	discomfort index

2. Methodology

2.1. Description of the residential building

In order to evaluate the effect of PCM incorporation in reducing heat wave effects in dwellings, a detached single storey house is considered (see Fig. 1). Detached houses represent approximately 80% of the Australian residential housing stock [10]. The house has a gross floor area of 289.6 m^2 and it has a two star energy rating according to NatHERS house rating scheme. The detailed construction elements and properties are given in Table 1.

The house was refurbished by installing Bio-PCM^{TM} as the inner linings of ceiling and walls. Based on the practical consideration, no PCM is included in the floor of the house. The Bio-PCM^{TM} considered here has a melting temperature and latent heat of 27^{o}C (26-29^{o}C) and 219kJ/kg respectively. The enthalpy-temperature variation of Bio-PCM 27 is shown in Fig. 2.

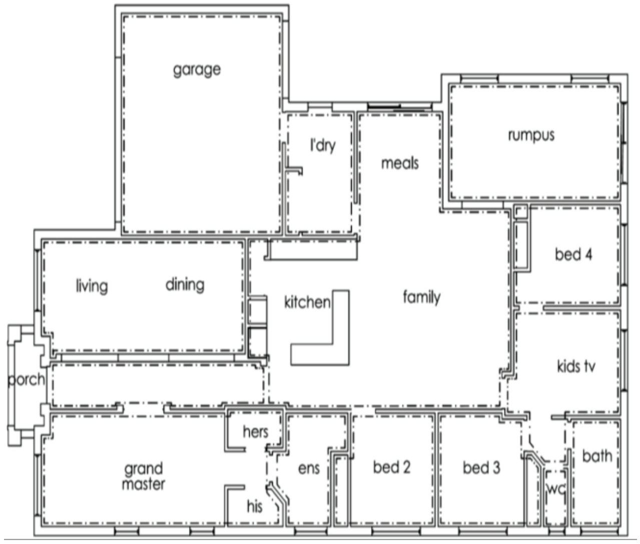

Fig. 1. Thermal zones of the house

Table 1. Specification of house design

Surface	Description
Exterior walls	Brick veneer construction, No insulation to the cavity and 10 mm wall plasterboard to internal surface. SSPCM are installed into the cavity
Floor	Concrete slabs on ground and carpeted
Roof	Pitched roof with concrete roof tiles
Ceiling	Flat ceiling having 13 mm ceiling plasterboard and R1.0 insulation; PCM installed between insulation and plasterboard
Windows	Single glazed aluminium framed windows
Doors	Timber doors (50mm thickness)

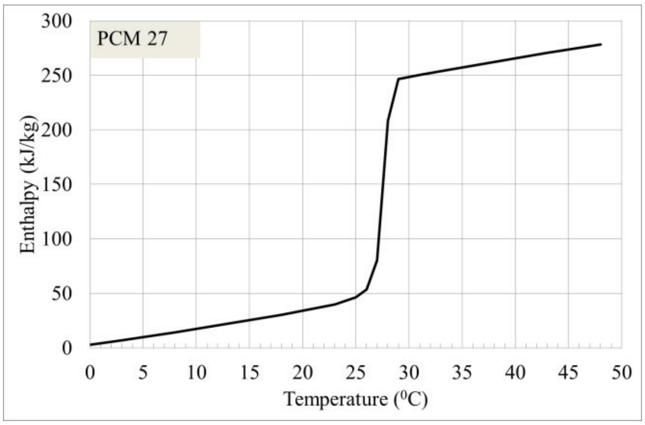

Fig. 2. Enthalpy-temperature relationship for Bio-PCM 27

2.2. Theory/calculation

The case study was defined to measure the discomfort level in a living zone (in this case: living dining in Fig. 1) under different scenarios including (i) building without refurbishment, (ii) building refurbished with PCM and (iii) PCM refurbishment with night ventilation. Discomfort index (DI) is used as a measure of heat stress [1]. The risk of heat stress evaluated by Discomfort Index (DI) can be calculated as follows:

$$DI = 0.5 \times T_w + 0.5 \times T_a \tag{1}$$

Where, T_w and T_a are the wet bulb temperature (°C) and dry bulb temperature (°C) respectively. The risk of heat stress is experienced as mild or no discomfort for DI below 24°C, a moderate level of discomfort is experienced for DI in the range of 24-28°C and DI above 28°C considered as severe level of discomfort.

Dynamic thermal simulations have been performed by building energy and thermal load simulation software EnergyPlus for Melbourne, Australia. The hourly climate data used was 2009 weather file for Melbourne. All the simulations were carried out through conduction finite difference (CondFD) approach provided in EnergyPlus [11]. The degree of night ventilation considered here is 8 air changes per hour (ACH) during a time period of 22:00 to 07:00.

3. Results and discussions

3.1. Risks of heat stress during the heatwave period (27-31 January 2009)

Fig. 3 demonstrates the discomfort level in the living/dining area for five consecutive days (27-31 January, 2009) of Melbourne heat wave period. Fig. 4 also illustrate the period of different discomfort levels (mild, moderate and severe) in terms of total period of 120 hours (five days). It can be seen that, without refurbishment, occupants exposed to high risk levels during heat wave period (36 hours of severe discomfort). Refurbishment of house with the application of PCM significantly reduces the severe discomfort period and peak discomfort level for first two days due to cool storage at night. For example, a reduction of 3°C in peak discomfort level and approximately complete elimination of severe discomfort level can be observed for the first day. However, the effect of PCM refurbishment in reducing the discomfort levels is negligible in the following days. The possible reason is that the cool storage for these days is very small due to high night temperature, so that the SSPCM is in fully liquid state without phase transition during daytime and it acts as a sensible storage layer. Furthermore, it is also evident that the PCM refurbishment increases the discomfort level during night time. This is due to the fact that the solidification process of PCM releases the heat during night, which would result in increased level of discomfort. Thus, it is clear that the incorporation of PCM had potential benefits in reducing the heat wave impacts to indoor and occupants, however, effectiveness of PCM should be improved.

In the attempt of improving the cool storage of PCM at night and concerning above mentioned disadvantages, mechanical night ventilation is introduced. The results obtained for the case of combined application of PCM and night ventilation are also reported in Fig. 3 and Fig. 4. Here it is possible to say that the cool storage of PCM was well improved with the activation of night ventilation, as it is further reducing the discomfort period and peak discomfort. On the other hand, Fig. 4 clearly indicated that the combined application of PCM and night ventilation largely reduced the high discomfort levels occurring at night, when the building refurbished with PCM

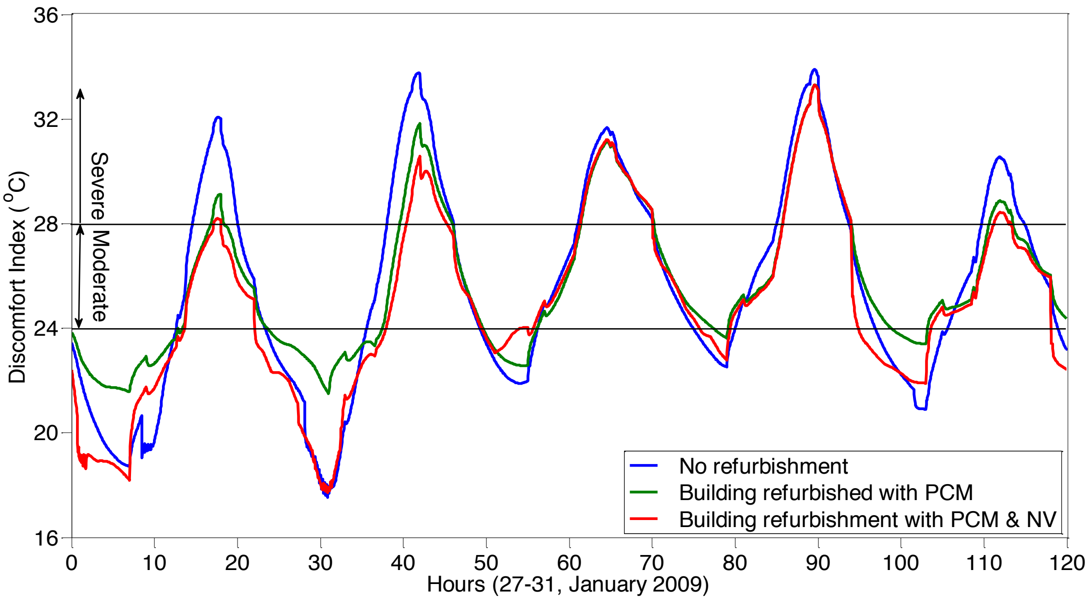

Fig. 3. Discomfort level at living/dining space for various refurbishments

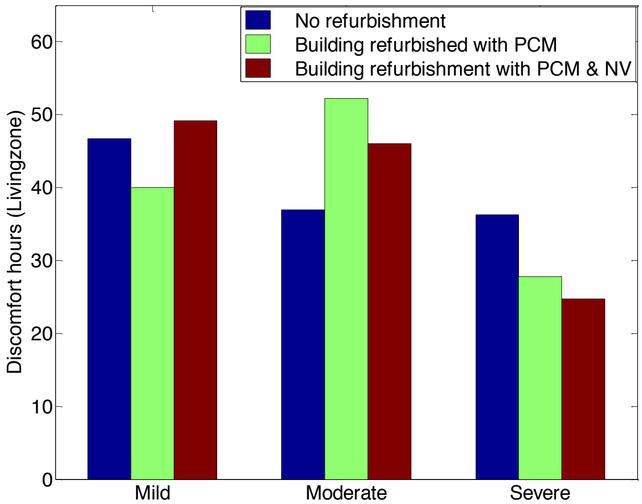

Fig. 4. Discomfort levels and periods based on the heat wave period (5 days)

On this basis, the results shown in Table 2 also allow the detection of discomfort hours for different refurbishment scenarios. From Table 2, it can be seen that the PCM refurbishment could reduce the severe discomfort hours by 23%. However, such reductions are largely shifted to moderate level of discomfort due to poor cool storage of PCM at night (moderate discomfort hours increased by 41% for the case of building refurbished with PCM). Thus, by improving the night cool storage of PCM with the application of night ventilation, the reduction of severe discomfort hours can be further increased to 32%, allowing the increased level of mild or no discomfort level.

Table 2. Risk of heat stress level for various refurbishments

Discomfort level	Discomfort hours (DI): Living/dining		
	No refurbishment	Building refurbished with PCM	Building refurbishment with PCM & NV
Mild	46.75	40	49.2
Moderate	36.95	52.2	46.05
Severe	36.3	27.8	24.75

4. Conclusions

In this study, effect of macro-encapsulated shape stabilized phase change material combined with night ventilation to reduce heat related risks in residential buildings is investigated. A commercially available macro-encapsulated Bio-PCM^{TM} mat is installed as inner linings of walls and ceiling of a non-air-conditioned building in Melbourne. Dynamic thermal simulations were performed during the heat wave period of 27-31 January 2009 to investigate the potential reduction of heat stress risks due to PCM incorporation and night ventilation. Discomfort Index (DI) has been used as a heat stress indicator which has three different categories: Mild, Moderate and Severe. The results revealed that the building refurbishment with the application of PCM could reduce the severe discomfort period by up to 23%. However, such reductions are largely shifted to moderate discomfort level, due to poor night cool storage during hot days. The introduction of night ventilation improves the cool storage of PCM, which would result in further reducing the severe discomfort period to 32%.

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Biography

Sayanthan Ramakrishnan is a PhD candidate at the centre for sustainable infrastructure of Department of Civil engineering in Swinburne University of Technology. He received his BSc Eng (Hons) in Civil Engineering from University of Moratuwa in 2013. He has active research interests in building energy performance and energy efficiency, energy storage and sustainable construction materials.