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Energy saving potential of phase change materials in major Australian cities

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ABSTRACT

The potential of phase change materials (PCM) in reducing the heating/cooling energy consumption of residential houses along with several factors influencing the effectiveness of PCM were investigated using EnergyPlus. Simulations were carried out using five different phase change temperature ranges at eight Australian cities which represent six climate zones. It was found that the effectiveness of PCM strongly depends on local weather, thermostat range, PCM layer thickness and surface area. The optimum PCM melting range for lowest energy consumption in each month of the year was found to be far from unique. Different PCM was found to be effective in different times of the year. Depending on local weather, the integration of PCM resulted in 17–23% annual energy savings in the studied house except hot and humid cities like Darwin. For a given amount of PCM, energy saving potential was found to improve further with the increase of applied surface area and decrease of PCM layer thickness up to certain limit beyond which the potential started to decline. The energy saving potential was also found to decrease when the PCM melting point was outside the thermostat range of the corresponding city. The paper also presented the potential effect of climate change on the effectiveness of PCM.

1. Introduction

The fast economic development around the globe and high standards of living imposes an ever increasing demand for energy. Over the period 1979–1980 to 2009–2010, there was a 90% increase in Australia's total energy use, from 3131 PJ to 5925 PJ [1]. Approximately, 95% of Australia's total energy consumption comes from fossil fuels (coal, oil and gas) [2] which results in harmful greenhouse gas emissions. In 2009–2010, the energy consumption of residential building was around 25% of total energy consumptions and contributed around 13% of total Australia national greenhouse gas emission [1,3]. In recent years, Latent Thermal Energy Storage (LTES) systems in buildings have received serious attention for reducing the dependency on fossil fuels and contributing to a more efficient environmentally benign energy use. Latent heat storage materials, also known as phase change materials (PCM's), absorb or release the energy equivalent to their latent heat when the temperature of the material undergoes or overpasses the phase change temperature [4]. PCM represent a technology that has the potential to shift peak load and reduce Heating Ventilation and Air-conditioning (HVAC) energy consumption in buildings. A large number of research studies on PCM application in buildings have been carried out during the last 30 years which resulted in considerable amount of literature about PCM properties, PCM impregnation methods, locations of application and effect of PCM on thermal energy storage, indoor temperature, energy consumption and peak load shifting of buildings.

PCM can be incorporated in wallboards, concretes, plaster, roof, underfloor and insulation of buildings [5–10]. From laboratory experiment, it was reported that the TES of the gypsum wallboard can be increased by ten times through the incorporation of PCM [11]. Oliver [12] observed that a 1.5 cm thick board of gypsum with PCM can store thermal energy equivalent to a 12 cm thick brick wall. Similar phenomenon was also observed by Kuznik et al. [13]. In case of concrete wall with PCM, 30% increase in TES was reported by Hawes et al. [14–16]. Hunger et al. [17] reported energy savings up to 12% through the inclusion of 5% microencapsulated PCM in self-compacting concrete mix. From theoretical investigation, Neeper [18] indicated that the maximum diurnal energy storage occurred when the PCM melting temperature was close to the average comfort room temperature.

After having studied PCM walls in the laboratory, several authors studied their performances in test rooms exposed to outdoor weather conditions. Athienitis et al. [19] observed 4 °C decrease in

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maximum room temperature in Montreal using gypsum board with 25% butyl stearate PCM. Kissock et al. [20] observed a 10 °C reduction in peak daytime temperature of Dayton, Ohio where wallboard imbibed with 30% commercial paraffinic PCM K18 was used. Shilei et al. [21] managed to decrease the room temperature by 1.02 °C in the northeast of China by incorporating a mixture of capric and lauric acid into the wallboard. Chen et al. [22] showed that energy savings can get to 17% or higher if phase transition temperature and enthalpy is set at 23 °C and 60 kJ/kg respectively during winter season in north China. Ahmed et al. [23] observed 20 °C decrease in the indoor temperature amplitude of the test cell through the application of a composite wallboard with vacuum insulation panel and PCM during summer in France. In addition to wall, several studies were carried out by incorporating PCM in roof, floor and plaster of the test room [24–28] and reductions in room temperature fluctuation were observed.

With the advent of more accurate computational method, numerical modelling is becoming increasingly popular to test the performance of PCM in buildings. In the numerical studies, the phase change effect has been taken into account through either enthalpy method [29–31] or heat capacity method [32–36]. Kuznik et al. [37] used building simulation software TRNSYS to simulate PCM wall where phase change process was taken into account through effective heat capacity method. The calculated internal wall surface temperature was found to be in good agreement with experimental data [38]. Heim et al. [39] modelled the behaviour of PCM in a three zone building using building simulation software ESP-r. Effect of phase transition was added to the energy equation through effective heat capacity method. Pederson et al. [40] used building simulation software EnergyPlus to simulate buildings with PCM wall in Minneapolis MN, USA. Effect of PCM was modelled through Enthalpy method in EnergyPlus. It was shown that the incorporation of PCM lowers the peak cooling load by 1000 W at that particular simulation environment. Using same software, Tardieu et al. [41] showed that PCM wallboards reduce the daily indoor temperature fluctuation by up to 4 °C on typical summer day in Auckland. Recently, after extensive verification and validation study Tabares-Valesco et al. [42] showed that EnergyPlus can accurately predict the thermal performance of buildings with PCM if several guidelines are met. Hence, “EnergyPlus v7.2” has been adopted as the investigation tool in the present study.

From the above literatures, it is evident that integration of PCM in building materials results in an increase in thermal energy storage of building which in turn reduces the indoor temperature fluctuation and energy consumptions of the buildings. It is also observed that efficiency of PCM depends on local climate, types of PCM, amount of PCM and location of application in buildings. The aim of the present study is to investigate the potential of PCM in reducing building energy consumptions and some parameters (i.e. PCM melting ranges, applied surface area, PCM layer thickness, local comfort range etc.) related to the effective application of PCM at different Australian cities. Finally, the potential effect of climate change on the effectiveness of PCM has been explored.

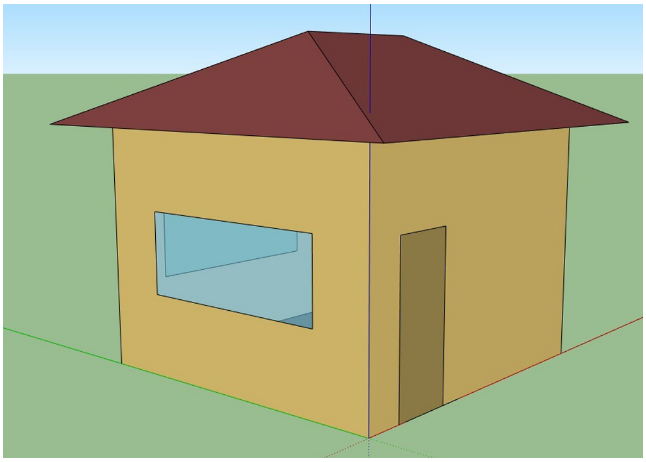

Fig. 1. Single room house for the simulation.

2. Methodology

2.1. Building description

A single room house was considered for the simulation as shown in Fig. 1. The house consisted of 2 zones: attic space and living area. The dimensions of the living area zone were 4 m × 4 m × 3 m (16 m^2 floor area) with one south facing door and one window on each of the west and north wall. The size of each window was 1 m in vertical direction and 2.5 m in horizontal direction and was placed 1 m above the floor surface. Although it was a single room house, all the walls, roof and window materials were selected according to Australian standards. Total window area was 25% of the total floor area which complies with the range recommended by Building Codes of Australia (BCA) [43]. The thickness of windows are 3 mm with solar transmittance = 0.45, visible transmittance = 0.7 and conductivity = 0.9 W/m K. The size of the south facing door was 2 m × 0.8 m and is positioned at an offset of 0.5 m from the left edge. The roof was of hip type with 23 degree pitch on north and south sides and 45 degree pitch on the other two sides and has 0.5 m long eaves on all four sides. The thermophysical properties of all building materials are given in Table 1. The detail constructions of building walls, roof, ceiling and floors are presented in Table 2. The standards described in ICANZ [44] were followed in the constructions. The roof was constructed following the R0100 system-*pithed tiled roof with flat ceiling* and the external walls were constructed according to W0100 system-*clay masonry veneer* [44]. Ground level concrete slab was used as floor. Only the living area zone of the building was conditioned to maintain the desired comfort range.

2.2. Simulation details

Simulations were carried out using building simulation software EnergyPlus v7.2 for eight different cities of Australia located in six different climate zones: Adelaide, Brisbane, Canberra,

Table 1
Thermophysical properties of building materials.

Name	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Resistance (m^2 K/W)
Brick veneer	0.110	0.547	1950	840	0.2
Insulation wall (glass fibre batt)	0.07	0.044	12	883	0.63
Insulation roof (glass fibre batt)	0.162	0.044	12	883	3.68
Plasterboard	0.01	0.17	800	1090	0.059
Timber	0.035	0.159	721	1260	0.22
Carpet	0.02	0.0465	104	1420	0.43
PCM	0.005	0.2	860	1970	0.025