International Journal of Thermal Sciences 126 (2018) 105–117

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Thermodynamic analysis of directionally influenced phase change material embedded building walls

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ARTICLE INFO

Keywords:
Phase change material
Heat gain
Orientation
Temperature fluctuation
Latent heat

ABSTRACT

The study focuses on assessing the thermal performances of two phase change materials (PCMs) when they are embedded in a concrete wall. The ambient condition is that of a hot and dry climate of South-East Asia region. Incorporation of PCM in concrete wall reduces the heat gain and temperature fluctuations inside the building by virtue of the latent heating property of the PCM, which occurs at a constant temperature. When the orientation of the wall is changed, the incident solar radiation on the wall varies and it affects the thermal performance of the PCM. Numerical simulation of transient heat transfer has been carried out to evaluate the variation in the thermal performance of a PCM wall in terms of reduced heat gain and temperature fluctuations inside the building due to different orientations of the PCM wall. Finally, an optimum orientation of the PCM wall is determined for each of the two PCMs studied under the given geographical conditions. Also, a comparison is drawn between the overall performances of the two PCMs to select the better PCM out of the two for the given geographical conditions.

1. Introduction

Building being a foundation element in human civilization urges extreme importance in its design and construction. From thermodynamic point of view, building is one of the most common elements where macro scale heat transfer phenomena can be observed. Although heat transfer is prevalent in industrial processes and equipment, the most common experience of “heat” is felt inside buildings where thermal comfort is always a major concern. Heat transfer is experienced by each and every human being as the interior temperature of a house fluctuates. Therefore heat transfer in buildings is a major topic of practical heat transfer scenarios. One significant endeavour for optimizing building heat transfer is the application of phase change materials (PCMs) in building walls and roofs.

The latent heating property enables the PCMs to store a large quantity of heat at constant temperature. The isothermal response of PCM to varying heat flux makes these materials suitable to be used as thermal energy storage medium. Implementation of PCMs for thermal energy storage ranges from microelectronic components to large scale buildings, wherever there is a fluctuation in heat flux which needs to be stabilized.

The realization of PCM's potential for achieving thermal comfort inside buildings led to many studies on the methods of installing PCM in building walls [1–6]. These studies were accompanied by research on the thermal performances of different types of PCM impregnated building walls with different quantities of PCM [7–10]. Cylindrical and conical holes containing PCMs have been incorporated in building roofs. Experiments carried out by Alqallaf & Alawadhi [11,12] showed a potential reduction in heat flux through the roof by 17.26% with cylindrical PCM holes and 39% with conical PCM holes. The results of the study conducted by Ravikumar et al. [13] showed a further reduction in heat gain through the PCM impregnated roof by 56%. Pasupathy et al. [14] conducted a theoretical and an experimental investigation involving utilization of a PCM panel embedded roof demonstrating its importance as roof insulation in the warm and humid region of India (Chennai).

The potential of PCM for inducing thermal comfort has also been tested by incorporating PCM in building floors and windows. Ismail et al. [15] conducted a study focussing on the incorporation of a moving PCM curtain in the windows of buildings. In an experiment performed by Barzin et al. [16], PCM was installed in the floor of a building with an electrical heating instrument placed underneath. The floor and room temperatures were maintained within the comfort zone by solar radiation during day time in the cold climate. At night when solar radiation was not available, the electrical heater was turned on which supplied heat to the floor and melted the PCM. In the morning hours, when the electricity demand was high, the heater was switched off and the molten PCM kept the floor temperature within the comfort

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https://doi.org/10.1016/j.ijthermalsci.2017.12.029
Received 9 November 2016; Received in revised form 22 December 2017; Accepted 26 December 2017

zone by liberating heat while undergoing solidification. A similar investigation on PCM incorporated underfloor heating was performed by Lin et al. [17]. These studies reveal another useful aspect of PCM where it can be used to increase the thermal inertia of buildings. A PCM can shift the cooling or heating load of buildings from high electricity demand hours to low electricity demand hours by acting as a thermal energy storage medium. A detailed investigation of this aspect of changing the thermal inertia of different types of buildings by using PCM has been performed by Hed [18].

PCM is used to enhance the thermal insulation of buildings in both hot and cold climates. The studies conducted by Waqas & Kumar [19,20] investigated the utilization of PCM for achieving thermal comfort both in hot and cold climatic conditions. From their studies, the prime factors influencing the performance of a PCM were identified as the melting point of the PCM, the mass of the PCM and the air flow rate. The PCM results in maximum performance when the melting point of the PCM is within the thermal comfort temperature range.

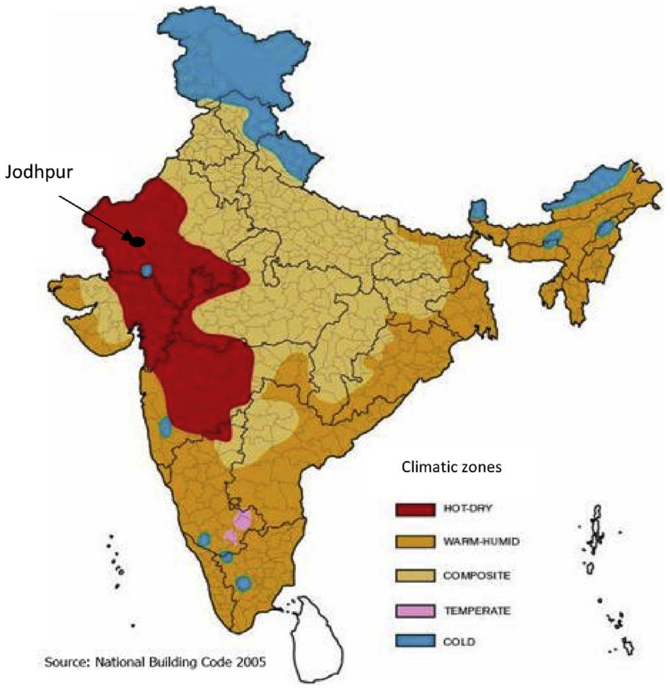
The concept of using multiple layers of different PCMs was used by Vakilaltojjar and Saman [21]. They developed a latent heat storage system comprising of two different PCMs which can be utilized for inducing thermal comfort during summer and winter months. The research carried out by Hamza et al. [22] focussed on finding the optimum thickness and locations of two different PCM layers to be installed in building roofs for achieving thermal comfort inside buildings.

In addition to the studies on engineering applications of PCM, extensive research has also been carried out dealing with complex physical and chemical phenomena related to PCM. The natural convection in the liquid phase of PCM, which is set up by the buoyancy force results in a curved solid liquid interface as the PCM melts. This phenomenon has been studied in detail by Kylili & Fokaides [23]. The research conducted by Hou et al. [24] emphasized three-dimensional heat transfer analysis in a PCM based canister used for storing thermal energy. The study focused on circumferential asymmetric heat flux and heat transfer by radiation and conduction across vapour voids formed inside a PCM.

The material properties of concrete also play a significant role in determining the thermal performance of a PCM wall. Hawes et al. [25,26] studied the effects of concrete properties, such as immersion time, alkalinity, immersion temperature etc., on the thermal performance of a PCM wall.

Waqas and Kumar investigated the utilization of PCM in hot and dry climate of South East Asia by conducting research in Islamabad [19]. In this study, a PCM based heat exchanger was used to convert the hot ambient air into cold air to be fed into buildings for maintaining thermal comfort. The molten PCM was charged back to the solid state by the cold ambient air at night. The study provided useful insight into the parameters of the PCM based heat exchanger for the efficient working of the setup. This study was concerned with the performance of a PCM installed in a heat exchanger without considering the effects of building elements such as building wall material, wall orientation etc. Therefore, further investigation is required which will encompass the thermal performance of PCM installed in building walls (rather than being used in heat exchangers) in hot and dry climate and also the effect of structural feature (orientation in particular) of the wall on the performance of PCM. This is the prime focus of the present study. The location for the present study has been chosen as Jodhpur (India) which is a nearby location of Islamabad and represents the typical hot and dry climatic condition prevailing in India and South East Asia (Fig. 1).

The present study aims at evaluating the thermal performances of two phase change materials (PCMs) when they are embedded in a concrete wall. The variation in the thermal performance of the PCM wall in terms of reduced heat gain and temperature fluctuations inside the building due to the different orientations of the PCM wall is also evaluated. Finally, an optimum orientation of the PCM wall is determined for each of the two PCMs studied under the given geographic conditions. Also, a comparison is made between the overall performances of the two PCMs to select the better PCM out of the two, for the given geographical conditions.



Source: National Building Code 2005

Fig. 1. Climatic zones of India.

2. Problem statement and modelling method

The mathematical model and the numerical solution methodologies for a PCM embedded concrete wall system are presented in this section.

2.1. Problem statement

When solar radiation is incident on the PCM wall, it absorbs heat. At the same time, the PCM wall exchanges heat with the ambient and room interior by convection. If the heat input to the PCM is more than the heat lost by the PCM, then there is an accumulation of heat in the PCM. This accumulated heat serves to change the phase of the PCM from solid to liquid at a constant temperature. If the heat accumulation proceeds further, the whole PCM melts and after that sensible heating (superheating) of the liquid occurs.

If the heat input to the PCM is less than the heat lost by the PCM, then there will be a reduction in the net heat stored in the PCM. This will facilitate phase change from liquid to solid. If the whole PCM solidifies and still the input radiation is less than the heat lost by the PCM, there will be a sensible cooling (sub cooling) of the solid PCM.

It is desirable to minimize the sensible heating and cooling of a PCM, as the aim of incorporating a PCM in concrete walls is to keep the inside temperature constant. Once the sensible heating or cooling of the PCM begins, its thermal behavior becomes similar to that of the concrete material and it ceases to serve its purpose of latent heat storage.

Upon changing the orientation of the wall, the incident solar radiation on the wall varies and it also affects the thermal performance of the PCM. Therefore, directional influence on the thermal performance of PCM is studied in the present work.

2.2. Model geometry

The schematic of the geometry is presented in Fig. 2. The concrete properties are typically those of a reinforced concrete [27]. The