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Experimental investigation and numerical simulation analysis on the thermal performance of a building roof incorporating phase change material (PCM) for thermal management

A. Pasupathy [a], L. Athanasius [a], R. Velraj [a,*], R.V. Seeniraj [b]

[a] *Department of Mechanical Engineering, College of Engineering, Chennai 600 025, India*
[b] *Department of Mechanical Engineering, Sri Venkateswara College of Engineering, Sriperumpudur, Tamilnadu, India*

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Abstract

Thermal storage plays a major role in a wide variety of industrial, commercial and residential application when there is a mismatch between the supply and demand of energy. Latent heat storage in a phase change material (PCM) is very attractive, because of its high-energy storage density and its isothermal behavior during the phase change process. Several promising developments are taking place in the field of thermal storage using phase change materials (PCM) in buildings. It has been demonstrated that for the development of a latent heat storage system (LHTS) in a building fabric, the choice of the PCM plays an important role in addition to heat transfer mechanism in the PCM. Increasing the thermal storage capacity of a building can enhance human comfort by decreasing the frequency of internal air temperature swings, so that the indoor air temperature is closer to the desired temperature for a longer period of time. This paper attempts to study the thermal performance of an inorganic eutectic PCM based thermal storage system for thermal management in a residential building. The system has been analyzed by theoretical and experimental investigation. Experiments are also conducted by circulating water through the tubes kept inside the PCM panel to test its suitability for the summer months. In order to achieve the optimum design for the selected location, several simulation runs are made for the average ambient conditions for all the months in a year and for the various other parameters of interest.

Keywords: Latent heat thermal energy storage; Space heating and cooling; Building energy conservation; Phase change material; Encapsulation

1. Introduction

Scientists all over the world are in search of new and renewable energy sources. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. Thermal energy storage systems provide the potential to attain energy savings, which in turn reduce the environment impact related to non-renewable energy use. In fact, these systems provide a valuable solution for correcting the mismatch that is often found between the supply and demand of energy. Latent heat storage is a relatively new area of study although it previously received much attention during the energy crisis of late 1970's and early 1980's where it was extensively researched for use in solar heating systems. When the energy crisis subsided, much less emphasis was put on latent heat storage. Although research into latent heat storage for solar heating systems continues, recently it is increasingly being considered for waste heat recovery, load leveling for power generation, building energy conservation and air conditioning applications.

As demand for air conditioning increased greatly during the last decade, large demands of electric power and limited reserves of fossil fuels have led to a surge in interest with regard to energy efficiency. Electrical energy consumption

* Corresponding author. Tel.: +91 44 22203008; fax: +91 44 22300916.
E-mail addresses: pasu1967@gmail.com (A. Pasupathy), Athanasius@sify.com (L. Athanasius), velrajr@annauniv.edu (R. Velraj), seenirajr@hotmail.com (R.V. Seeniraj).

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Nomenclature

C_1, C_3	specific heat of roof top slab and concrete slab (kJ/kg K)
c_{pl}	specific heat of liquid PCM (kJ/kg K)
c_{ps}	specific heat of solid PCM (kJ/kg K)
f	implicit factor
Gr_L	Grashof number
h_i	inside heat transfer coefficient (W/m^2 K)
h_o	outside heat transfer coefficient (W/m^2 K)
k_1, k_2, k_3	thermal conductivity of roof top slab, PCM panel and bottom concrete slab (W/m K)
L_1, L_2, L_3	thickness of roof top slab, PCM panel and bottom concrete slab (m)
Nu_L	Nusselt number
Pr	Prandle number
q_{rad}	radiation flux (W/m^2)
Re	Reynolds number
T	temperature (°C)
T_∞	ambient temperature (°C)
T_i^0	previous time step temperature at ith volume cell (°C)
T_i	current time step temperature at ith volume cell (°C)
T_{in}	initial temperature (°C)
T_{room}	room temperature (°C)
T_s	surface temperature (°C)
T_{sky}	sky temperature (°C)
α	absorptivity
$\in$	emissivity
h_{sl}	solid–liquid enthalpy change (kJ/kg)
σ	Stefan Boltzmann constant
ρ_1, ρ_2, ρ_3	density of roof top slab, PCM panel and bottom concrete slab (kg/m^3)
Δt	time step (s)
δx_1, δx_2, δx_3	nodal distances (m)
Δx_1, Δx_2, Δx_3	control volume length of roof top slab, PCM panel, bottom concrete slab (m)

varies significantly during the day and night according to the demand by industrial, commercial and residential activities. In hot and cold climate countries, the major part of the load variation is due to air conditioning and domestic space heating, respectively. This variation leads to a differential pricing system for peak and off peak periods of energy use. Better power generation/distribution management and significant economic benefit can be achieved if some of the peak load could be shifted to the off peak load period. This can be achieved by thermal energy storage for heating and cooling in residential and commercial building establishments.

There are several promising developments going on in the field of application of PCMs for heating and cooling of building. Zalba et al. [1] performed a detailed review on thermal energy storage that dealt with phase change materials, heat transfer studies and applications. Farid et al. [2] also presented a review on the analysis of phase change materials, hermetic encapsulation and application of PCMs. Mehling and Hiebler [3] summarized the investigations and developments on using PCMs in buildings. Murat Kenisarin1and Khamid Mahkamov [4] presented a review of investigations and developments carried out during the last 10–15 years in the field of phase change materials, enhancing heat conductivity, available fields of using PCM, and clarifying typical questions.

Arkar and Medved [5], Stritih and Novak [6] designed and tested a latent heat storage system used to provide ventilation of a building. The results of their work, according to the authors, were very promising. Phase change dry wall or wallboard is an exciting type of building integrated heat storage material. Several authors investigated the various methods of impregnating gypsum and other PCMs [7–12] in wallboards. Limited analytical studies of PCM wallboard have been conducted, but few general rules pertaining to the thermal dynamics of PCM wallboard are available.

Lee et al. [13] and Hawes et al. [14] presented the thermal performance of PCM's in different types of concrete blocks. They studied and presented the effects of concrete alkalinity, temperature, immersion time and PCM dilution on PCM absorption during the impregnation process. Wood lightweight concrete is a mixture of cement, wood chips or saw dust, which should not exceed 15% by weight, water and additives. This mixture can be applied for building interior and outer wall construction. For integration in wood lightweight concrete, two PCM materials Rubitherm GR40, 1–3 mm and GR 50, 0.2–0.6 mm were investigated by Mehling et al. [15]. Meng Zhang et al. [16] presented the development of a thermally enhanced frame wall that reduces peak air conditioning demand in residential buildings. Ismail et al. [17] proposed a different concept for thermally effective windows using a PCM moving curtain.

UniSA (University of South Australia) [18] developed a roof-integrated solar air heating/storage system, which uses existing corrugated iron roof sheets as a solar collector for heating air. Kunping Lina et al. [19] put forward a new kind of under-floor electric heating system with shape-stabilized phase change material (PCM) plates. Hed [20] investigated PCM integrated cooling systems for building types where there is an over production of heat during the daytime such as offices, schools and shopping centers. Free cooling was investigated at the University of Zaragoza/Spain by Zalba [21]. The objective of the work was to design and construct an experimental installation to study PCMs with a melting temperature between 20 and 25 °C.