CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 2

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Influence of Phase Change Material on Thermal Comfort Conditions Inside Buildings in Hot and Dry Climate of India

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Abstract

Phase change materials (PCMs) are known for storing thermal energy by the virtue of their inherent latent enthalpies. Careful introduction of PCMs as thermal mass along with external insulation is likely to increase thermal comfort hours in naturally ventilated buildings and reduce cooling energy consumption in air conditioned buildings. Form stabilized phase change materials integrated with building envelope promises to offer ease of construction without encroaching on valuable floor space occupied by building structure. This study evaluates influence of PCMs on thermal performance of buildings in hot and dry climate of India. In first phase, study relied on whole building energy performance simulation to determine potential benefits of phase change materials and to identify suitable thermal characteristics of PCMs. Based on simulation results, two PCM compositions were developed by manufacturer and characterized in the laboratory. Based on measured characteristics, one composition was selected to develop ceiling tile prototype for deployment in experimental setup. In second phase, PCM ceiling tiles were installed in externally insulated naturally ventilated room measuring 3.3 meter by 3.3 meter by 3.3 meter. Fully instrumented room capable of measuring various indoor and outdoor environmental conditions provided insights into PCM effectiveness. Study quantifies benefits of PCM on thermal comfort conditions inside naturally ventilated buildings using simulations and experimental setup. Study also provides guidance to determine most appropriate melting and freezing point of PCM, which helps in manufacturing. A collaborative approach between R&D institute and PCM manufacture provide valuable results leading to understanding of PCM performance in India.

Keywords – Phase Change Building Materials; High Performance Building; Buildings; Thermal Comfort;

1. Introduction

India, with population nearly 1.2 billion, is world's third largest green house has (GHG) emitter. It has pledged to reduce carbon emission per unit of gross domestic product ('emission intensity') up to 35% by 2030 from 2005 level [1]. The building sector is experiencing unprecedented growth in past decade. It is expected to grow about five times from 2.1 million square meter in 2005 to about 10.4 million square meter in 2030 [2]. As per study [3], India's residential sector will fuel energy consumption unless focused policy and market efforts provide 27% to 57% savings by 2050. Along with challenge to reduce energy consumption, reduction in peak demand is also necessary for India to focus on [4]. One of the best way to reduce energy consumption is to achieve energy efficiency in buildings. Reduction in demand to operate heating ventilation and air conditioning (HVAC) systems is possible to achieve by designing buildings suitable for climate, by operating buildings in mixed mode, and by designing buildings as per adaptive thermal comfort models [5],[6]. Out of five recognized climate zones in India, four climate zones, namely hot-dry, warm-humid, composite and moderate climate zone does offer an opportunity to operate building in temporal mixed mode over year. Such buildings may meet adaptive thermal comfort standard [7] to be adopted in India.

Climate responsive building envelop technologies will help reduce annual energy consumption, reduce peak demand, and also will help reduce operation hours of HVAC system. Traditionally, India have experienced high thermal mass walls by construction of thick brick or stone masonry walls with cement or lime plaster finish. Such construction provided sufficient thermal lag and internal thermal mass to keep indoor conditions comfortable. Due to high value of floor space, thick walls are not a desired approach. Hence, introduction of Phase change material (PCM) having latent capacity will help achieve desired thermal mass without encroaching on valuable floor space. Storing energy using appropriate strategy may result in longer shift of thermal load and lower energy demand [8].

Studies [9][10] suggest that PCMs are helpful in stabilizing indoor air temperature and increasing thermal energy storage. Number of studies have examined performance of PCM when encapsulated as part of masonry unit material [10], or as part of ventilated double skin façade [11], or hollow masonry blocks filled with PCM [12]. Investigations related to use of PCM in building has been conducted with the various approaches. Studies have attempted to understand PCM behavior with experimental setup in the field [13][14], with experimental setup in laboratory conditions [15][16][17], and with numerical methods [8][10][12][18][19]. Certain PCM categories, such as Bio based PCM, are advisable for application due to low embodied energy

[9] making them environmentally less harmful. This study evaluates influence of PCMs on thermal performance of buildings in hot and dry climate of India.

2. Methodology

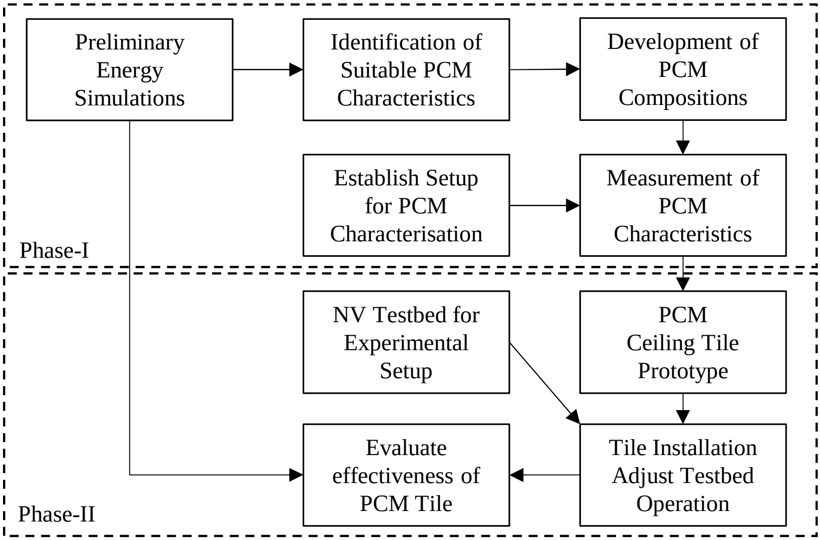

Fig. 1 Overview of Study Methodology

Figure 1 outlines overall methodology of this study. Initially, the study conducted preliminary energy simulation to understand the potential benefits of using PCM in envelope in hot and dry climate of India. Initial simulations were carried out using EnergyPlus for a simple single-zone naturally ventilated (NV) building in hot and dry climate of India. Ahmedabad (AMD) was selected as a representative city for hot and dry climate of India. Finite difference heat balance algorithm was used in the model to accurately simulate PCM and to better understand the temperature and heat flux at every construction layer of the envelope (node). The simulations were performed for two envelope characteristics representative of business-as-usual (BAU, Uninsulated wall and roofs) envelop and ECBC-compliant envelop (ECBC, Insulated walls and roof) prescribed for hot and dry climate of India. Table 1 presents envelope characteristics and inputs used in the simulation model in EnergyPlus:

Thermal conductivity of PCMs were measured using Transient plain source (TPS) method [20]. The conductivity measurements were conducted in liquid phase (after phase change) and in solid phase (before phase change). The temperature of PCM was modulated during measurements using a container in precision temperature liquid bath. The sensible and latent heat storage properties of PCM were measured using T-history Method [21, 22]. In T-history method, the temperature history of PCM gets measured against a reference material with known properties to derive latent heat storage curve of PCM.

Table 1. Building Inputs and Envelope Characteristics

Parameter	Input Values	
Total Floor Area (m^2)	158.8	
Climate	Ahmedabad	
Geometry Type	Single Zone Square Building	
Number of Floors	One	
Floor Height (m)	3.0	
Window-to-Wall Ratio	0.3	
	BAU Envelope	ECBC Envelope
Roof U-value	1.72	0.44
Wall U-value (W/m^2-K)	2.94	0.41
Window U-value (W/m^2-K)	5.80	3.30
Window SHGC	0.82	0.25
Window VLT	0.8	0.2

In second phase, a ceiling tile prototype using the selected composition were installed in an experimental setup for measurements. The experimental set up consisted of 3300 mm by 3300 mm by 3300 mm room. Wall assembly comprised of 12 mm external plaster, 50 mm extruded polystyrene insulation (XPS), 230 mm brick, and 12 mm internal plaster. Roof assembly comprised of 6 mm white glazed tiles, 25 mm mortar bedding, 60 mm XPS insulation, 100 mm reinforced cement concrete (RCC) slab, and 12 mm of internal plaster. The room contained double-glazed window on the north wall and partially glazed door on the south wall. The room also contained provision for supply and exhaust air fans for night time ventilation.

The surface temperatures, air temperatures, and globe temperature in room is monitored Onset ZW wireless sensors and loggers. The surface temperature between ceiling and PCM tile, temperature of materials inside the tile, and surface temperature of PCM tile (adjacent to room air) were monitored at five (5) locations (north, east, south, west corners of the room as well as and center of room) in the room. Air temperature sensors, relative humidity sensors and globe temperature sensors were installed at the midpoint of the room at two different heights (ceiling height and desk height) to monitor the indoor environment and room stratification. The installed temperature sensors have 0.21 ºC accuracy between operative temperatures of 0 to 50 ºC. The outdoor weather station was installed in nearby building (around 1 km from experimental set up) to record the outdoor weather conditions.

Throughout the experiment, the room was operated in naturally ventilation mode with ventilation fans operated during night time (from 7 pm to 9 am) to better recharge the PCM tiles. The measured results and simulation results provide understanding on effectiveness of PCM ceiling tile in naturally ventilated buildings.

3. Results and Discussion

Based on detailed review of the climatic conditions, heat flux, surface temperatures, and operative temperature from outputs of the simulation model, the suitable PCM characteristics were identified for use in naturally ventilated buildings.

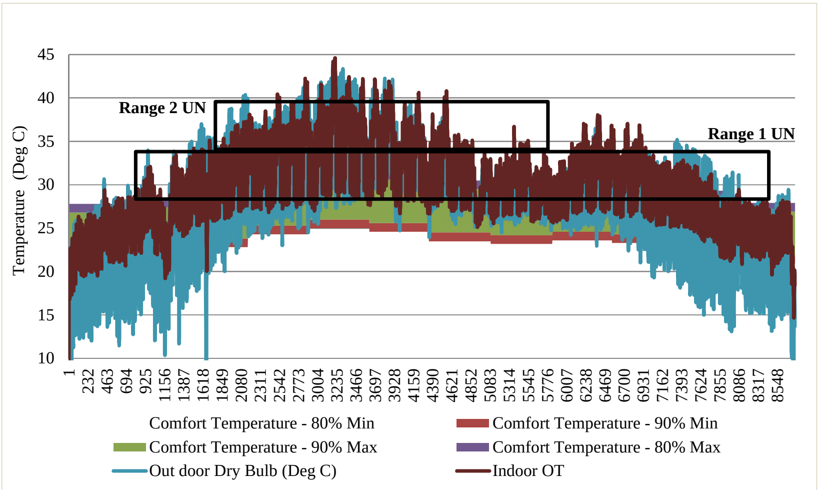

Fig. 2 Hourly Temperature Profiles of BAU (Uninsulated) Naturally Ventiated Building

Figure 2 demonstrates operative temperature inside the uninsulated naturally ventilated building with temperature ranges (bands) derived from adaptive model [7] developed for India. As shown in the figure, two ranges (Range 2 UN and Range 1 UN) were identified that would improve thermal comfort conditions inside the building. PCM with higher melting and freezing temperatures (Range 2 UN – 34 to 38 ºC) were found to be active during peak summer (April to June) but remained in frozen state during the rest of the year. The daily heat flux in uninsulated building during peak summer was found to be 50% higher than latent heat for fusion of typical PCMs (200 KJ/Kg). PCM with moderate melting and freezing (Range 1 UN/IN – 28 to 34ºC) temperature were active for longer period (August to October, February to March) and for multiple days without need for recharging. Due to lower daily heat flux, PCM with moderate range also increased comfort hours during the operating period. PCM in the moderate range (Range 1 UN/IN) showed 15% and 7% increase in comfort hours (using adaptive comfort model definition) for BAU (Uninsulated) building and ECBC (Insulated) buildings.

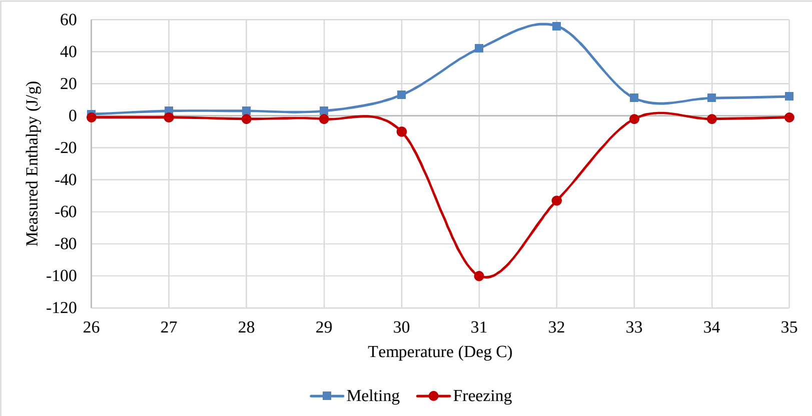

Fig. 3 Measured Enthalpy for PCM HS30 PCM using T-history Method

Table 2. Measured Properties for PCM HS30 and HS29

Property	HS30	HS29
Density (Kg/m^3)	1555	1550
Melting Point (ºC)	32.1	31
Freezing Point (ºC)	31	28
Melting Enthalpy (J/g)	154.9	153.7
Freezing Enthalpy (J/g)	174.1	165.2
Properties Below Melting Temperature (Solid)		
Thermal Conductivity (W/m-K)	2.55	2.74
Volumetric Specific Heat (MJ/m^{3}K)	2.31	2.29
Properties Above Melting Temperature (Liquid)		
Thermal Conductivity (W/m-K)	1.72	1.80
Volumetric Specific Heat (MJ/m^{3}K)	2.56	2.53

Using the identified melting and freezing point characteristics, two feasible fatty acid based PCMs (HS30 and HS29) were developed by manufacturer for characterization. Fatty acid compositions, categorized as Bio-based PCM, were primarily selected due to their extraction from natural products (palm kernel or coconut oil). Figure 3 shows measured enthalpy during melting and freezing for PCM HS30 using T history method. Table 2 shows the thermal properties measured for both PCM composition HS30 and HS29. PCM HS30 were found more suitable for experimental setup due to higher freezing temperature allowing opportunity to recharge PCM at higher air temperatures.

Figure 4 shows monitored ceiling inside surface temperature, outdoor temperature, and PCM temperature for a week in September 2015. As seen in the figure, PCM was melting on 9th to 11th September when inside ceiling surface temperature increases to 32ºC but PCM temperature stays below 30ºC. On 12th September, once the PCM was completed melted, the PCM temperature rose quickly and reached close to the ceiling inside surface temperature. Similarly, 1-2ºC temperature difference between ceiling inside surface and PCM was observed on 14th to 17th September.

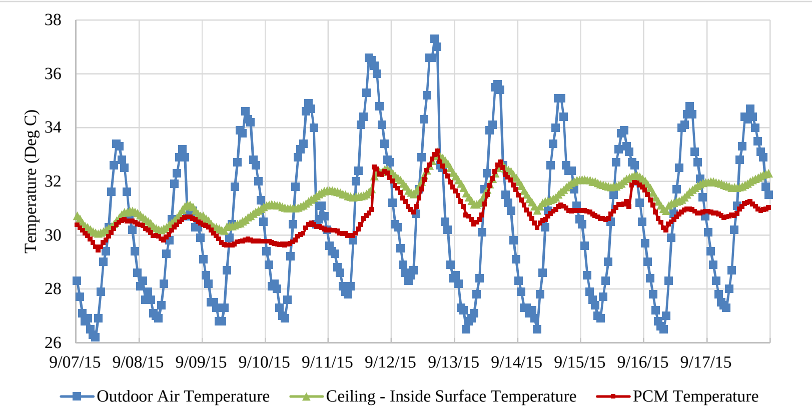

Fig. 4 Monitored Temperatures in Experimental Setup with PCM Ceiling Tiles

Figure 5 plots average and standard deviation of temperature difference between ceiling inside surface and PCM for various daily mean indoor air temperatures. On secondary axis, number of occurrences of daily indoor air temperatures was plotted to understand prevalent indoor air temperature conditions throughout the monitoring period. The temperature difference was found to be highest (1.28ºC±0.6ºC) for daily mean indoor air temperatures between 29.5-30ºC. Daily mean indoor air temperatures of 30-30.5ºC (29 days) and 30.5-31ºC (26 days) were found to be most prevalent where average temperature difference of 0.9ºC (±0.3ºC) and 0.75ºC (±0.26ºC) were observed between ceiling inside surface and PCM.

Figure 6 shows average, minimum, and maximum outdoor air temperatures, and PCM active days for every month. Based on earlier figures, temperature difference of 0.5ºC between ceiling inside surface temperature and PCM temperature was used to calculate PCM active days.

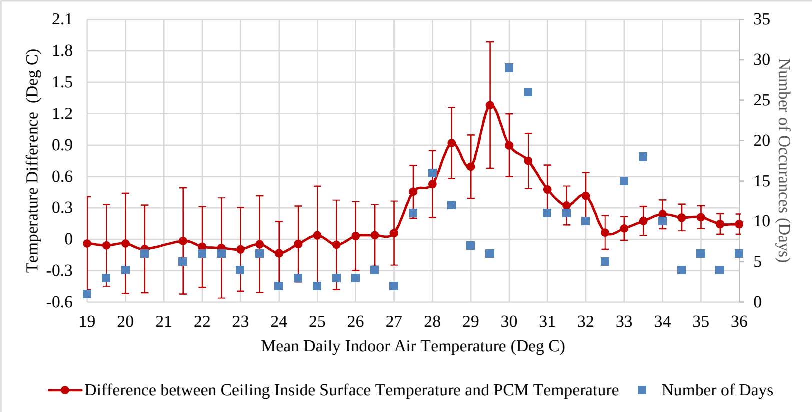

Fig. 5 Average (±Standard Deviation) Temperature Difference at Indoor Air Temperatures

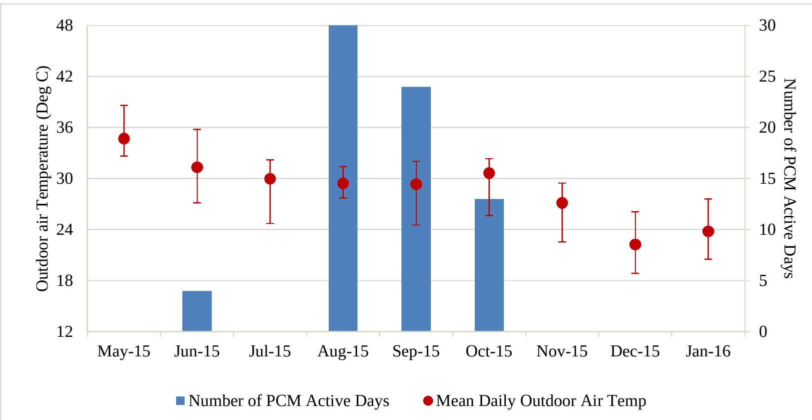

Fig. 6 Average Outdoor Air Temperatures and PCM Active Days for Montired Month

As seen in figure, PCM was found active from August to early part of October 2015 where mean daily outdoor air temperatures and diurnal variation allowed PCM to melt during the day and freeze during the night hours. Daily outdoor air temperatures have been below the freezing temperature from November 2015 to January 2016 and above the melting point in May 2015. In July 2015, while the outdoor air temperatures were favorable for melting and freezing, the indoor air temperatures inside naturally ventilated building during the night were consistently above the freezing temperatures. The increased night ventilation fan flow might have provided opportunity to take additional benefit of PCM operation during July 2015. Overall, sixty (60) PCM active days were observed through nine (276 days) months of monitoring of experimental setup. These observations aligned with the initial estimations based on simulation results where moderate temperature range for melting and freezing of PCM were selected.

4. Conclusions

The energy simulation of PCM demonstrated potential of 15% and 7% increase in comfort hours (using adaptive comfort model definition) for BAU (Uninsulated) building and ECBC (Insulated) naturally ventilated buildings in hot and dry climate of India. The study demonstrated that the detailed analysis of the heat flux of envelop and indoor temperatures was required to carefully design PCM melting and freezing temperature ranges (28 to 34ºC) for experimental setup. Close interaction between industry and researchers allowed development and characterization of bio-based PCM ceiling tiles with melting temperature of 32.1ºC and freezing temperature of 31ºC.

Monitoring of experimental setup validated the PCM operation and effectiveness as envelope component. PCM was able to create more than 0.5ºC temperature difference between ceiling inside surface and PCM during the active period. This temperature difference was found to be highest 1.28ºC (standard deviation of ±0.6ºC) for daily mean indoor air temperatures between 29.5-30ºC. From nine (9) months of monitoring, PCM was found active for sixty days (60) days (August to Mid-October) where outdoor and indoor conditions allowed PCM to melt during the day and recharge (freeze) during the night. A collaborative approach between R&D institute and PCM manufacture provide valuable results leading to understanding of PCM performance in India.

Acknowledgment

The U.S. Department of Energy (DOE) and the Department of Science and Technology (DST), Government of India (GOI) provided joint funding for work under the U.S.–India Partnership to Advance Clean Energy Research (PACE-R) program's "U.S.–India Joint Center for Building Energy Research and Development" (CBERD) project. The Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, of the U.S. DOE under Contract No. DE-AC02-05CH11231 supports the U.S. CBERD activity. The DST, GOI, administered by Indo-U.S. Science and Technology Forum, supports the Indian CBERD activity.

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