THERMAL MANAGEMENT ANALYSIS OF PCM INTEGRATION IN BUILDING USING A NOVEL PERFORMANCE PARAMETER PCM Effectiveness Index

by

Arun Prakash SELVARAJU[a], Arivazhagan RANGANATHAN[b], Antony Aroul Raj VINCENT[a*], Pappu ARUMUGAM[c], and Velraj RAMALINGAM[c]

[a]Department of Mechanical Engineering, Easwari Engineering College, Chennai, India
[b]Department of Mechanical Engineering, Meenakshi College of Engineering, Chennai, India
[c]Department of Mechanical Engineering, Anna University, Chennai, India

Original scientific paper
https://doi.org/10.2298/TSCI200830208S

Integration of phase change material (PCM) in walls and roof of a building is done to augment human comfort at places where variation of local diurnal temperature of ambient air is extensive. An exhaustive tool to study on year-round thermal effect due to solar radiation falling on a building is generally required to identify the correct PCM and the portion of a year that warrants better thermal management. The transient behavior associated with PCM heat transfer through building roof and walls vary in accordance with location and orientation of the building and the prevailing seasons. Hence, it becomes necessary to carry out a detailed analysis with the integration of PCM layers and to collect information with suitable theoretical approach as experimental study on energy performance of a building is time-consuming and expensive. In this paper, a 3-D building model has been developed and analyzed using ANSYS FLUENT for performing CFD analysis for comparing two identical buildings with and without PCM located at Chennai. The PCM was integrated in roof and walls of the building and analysis was carried out for different days of the year. A novel concept of PCM effectiveness index is introduced to measure the thermal performance due to PCM integration in building. This novel concept is useful for building engineers to measure the effectiveness of PCM integration and to select the correct PCM for thermal management in buildings at any location and time of the year.

Key words*: CFD analysis, transient simulation, PCM, thermal comfort*

Introduction

Space cooling in buildings has gained priority in this modernized world in order to improve human productivity and services besides comfort. This cooling is generally achieved with the help of mechanical methods in which refrigerants are used to remove heat in living space. But most of the refrigerants are harmful to the environment due to their significant contribution to ozone depletion and global warming. Hence passive cooling with ventilation

---

[*]Corresponding author, e-mail: antonyaroulraj@gmail.com

has become a viable method to overcome environmental issues and to minimize the use of expensive electrical energy for running mechanical cooling systems [1-3]. Since solar radiation falling on roof and walls is a major source for heat gains in buildings, the thermal modulation arising due to sunshine and Sun-off cycle is to be moderated in passive cooling in accordance with requirements of commercial and residential buildings. This has paved ways for incorporation of PCM as layers to roof and walls. Further the application of PCM layers to roof and walls becomes inevitable when variation of local diurnal temperature of ambient air is extensive. The heat gained by buildings due to incidence of sun rays and the range of diurnal temperature depends on the location in terms of latitude and longitude, and orientation of buildings. Introduction of more PCM has been witnessed in the last few decades for charging and discharging thermal energy [4]. Subsequently, both theoretical and experimental studies have been carried out to identify effective utilization of PCM and to enhance phase change processes, viz., melting and solidification [5-9] in accordance with applications. However, the choice of correct PCM with suitable thickness is still a challenging task that requires meticulous investigations in line with the location, orientation and type of a selected building. Since the transfer of thermal energy through roof and walls is influenced by solar radiation that varies with time, the investigation becomes more meaningful if it involves transient analysis. It is a general observation that experimental studies to derive information from different types of buildings are time-consuming and expensive. Hence a theoretical investigation with suitable simulation technique and tool could always be a welcome approach to assess the performance and the effect of PCM integration in buildings.

The CFD analysis is found to be an effective method to study precisely the transient heat transfer through roof and walls of a building and the effect on its indoor temperature. With this perspective, many researchers have conducted numerical investigations on buildings with and without PCM integration using different computational tools. Rohdin and Moshfegh [10] have investigated numerically the thermal performance of a building using FLUENT. They have explored the benefit of CFD in predicting the conditions of indoor environment using three different turbulence models. Gomez *et al*. [11] have evolved a CFD model using ANSYS FLUENT to analyze the effect of PCM incorporation in walls of a cubicle. They have reported that the thermal modulation in the enclosure is moderated effectively with the integration of PCM. Gowreesunker and Tassou [12] have conducted an analytical study on PCM clay wall boards to bring down peak indoor temperatures of building envelope using ANSYS FLUENT. Their study has revealed that the thermal behavior of the envelope depends on the quantity of PCM used and thermal properties of building materials. Ahangari and Maerefat [13] have numerically investigated the improvement of energy efficiency and indoor thermal comfort of building integrated with a novel multi-layer PCM, located at Tehran, Iran. They performed the simulation for four days (between 14th and 17th of January) using ENERGYPLUS with CondFD scheme and TARP heat transfer algorithm. Xaman *et al*. [14] have conducted a theoretical study using a numerical code written in FORTRAN with a time step size of the 30 seconds for a concrete roof with PCM integration in a building located at Merida city in Mexico. They have considered three types of PCM for integration during the warmest day (7th April) and the coldest day (23rd January). They have concluded that buildings' thermal performance depends on the integration of appropriate PCM selected based on the location. Jin *et al*. [15] have developed a numerical technique for building wall with PCM layer integration and conducted a mathematical analysis using finite difference discretization scheme with a time step size of 20 seconds along with TDMA algorithm for a period of four days for determining the best location of PCM integration in the wall. They have concluded that the optimum location for PCM integration should be along the interior walls for achieving maximum thermal performance, which depends on the wall interior surface temperature variation throughout the day. Sovetova *et al.* [16] have evaluated the thermal behavior of a building integrated with PCM in walls, located in eight different cities worldwide at hot desert climatic conditions using commercial analysis software ENERGYPLUS. They have performed hourly simulations for a typical energy-saving day that is found to lie in summer months. They have concluded that the energy efficiency of building increases with increase in the exposed area and decreases with thickness of the PCM layer. They have also reported that the PCM that has higher transition temperature performed better in hot desert climatic conditions. Zhu *et al.* [17] have carried out a numerical investigation using ANSYS FLUENT on a light-weight building that involves incorporation of PCM suitable for the summer climate prevailing at Tianjin city in China. The simulation results obtained for 24 hours during a summer day have revealed that positioning of PCM layer close to the inner surface helps to reduce indoor temperature and yields better thermal comfort. Kong *et al.* [18] have also carried out a numerical study using FLUENT to validate their experimental outcome and reported that the PCM layer on the interior surfaces of walls and roof performs better than that on the outer surfaces. However, Li *et al.* [19] have reported that the PCM positioned close to the exterior absorbs and stores heat from the external sources and reduces the heat transfer into the interior space and thus acts as an insulation layer. They concluded that, for effective indoor thermal comfort, the optimal melting point of PCM has to be close to the average temperature of room air. Berardi and Soudian [20] have studied the integration of PCM in roofs and walls of high-rise apartments and analyzed the improvement in monthly thermal performance in a year-round cycle of operation using ENERGYPLUS. They have concluded that the percentage of energy savings with particular PCM depends on the city's location. A numerical investigation using ANSYS FLUENT has been carried out by Chen *et al.* [21] to study the heat transfer through the thermo-activated PCM composite wall. They have reported that the thermal activation during winter improves the thermal performance of a composite wall with PCM integration. The thermal behavior of a building with PCM integration in roof and walls has been investigated using a numerical model with MATLAB/SIMULINK for a summer day in Morocco by Kharbouch *et al.* [22]. It has been reported that the thermal performance is enhanced significantly with the use of PCM with suitable quality on facade and roof configurations. In general, it is observed from many literature that the outcome of the thermal analysis of a building depends on its location defined by the local latitude and longitude, besides the climatic conditions linked to seasons of the year. From the literature, it is understood that many researchers have carried out energy simulation using location-specific software with the weather data available at weather stations of particular locations as input. However, a simple parameter for measuring the effectiveness of PCM integration in buildings is not available. This paper details on CFD analysis carried out using ANSYS FLUENT for studying the integration of PCM layers to roof and walls of a building located at Chennai. In addition to the aforementioned analysis, a non-dimensional parameter called PCM effectiveness index (PEI) has been introduced and used for comparing the effectiveness of PCM and non PCM buildings.

Methodology

The outline of the methodology consists of: the geometrical modelling of the building walls and roof using ANSYS DESIGN MODELLER, incorporation of governing equations for 3-D heat transfer through walls and roof in ANSYS FLUENT, and the inclusion of phase change model for PCM integration The location of a particular place on the globe is identified using latitude, longitude and time zone, and date of the simulation has been given using the solar calculator in the radiation modelling of ANSYS FLUENT. The CFD analysis has been carried out to estimate the solar heat flux falling over the external wall/roof surfaces of the building and room temperature variation for 24 hours of the day. The scheme describing the methodology of simulation is shown in fig. 1 whereas the schematic sketch of geometry of building developed using ANSYS FLUENT is presented in fig. 2.

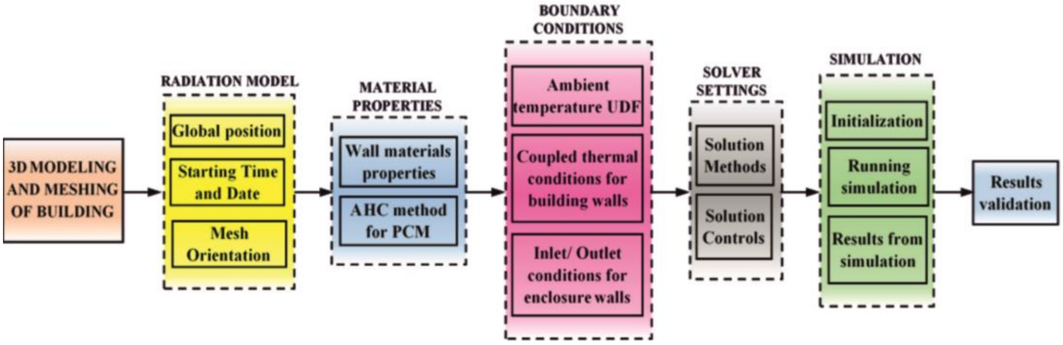

Figure 1. Scheme describing the methodology of simulation

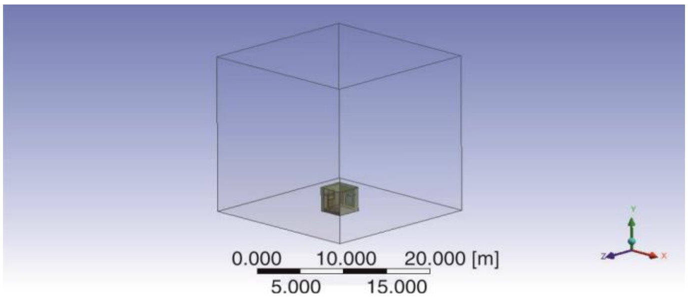

Figure 2. Schematic sketch of geometry model of building developed using ANSYS FLUENT

The 3-D model of the building has been developed using the DESIGN MODELER, inbuilt modelling software in ANSYS FLUENT Workbench 19.2. The building model is bounded by the outer enclosing domain for representing the surrounding atmosphere. Meshing was developed using ANSYS meshing software with tetra diagonal and hex dominant mesh type.

Geometrical features of the walls and roof of the model

The building's geometrical modeling with the dimensions of 3.048 × 3.048 × 3.048 m^3 has been used for the simulation. It is considered that the building has its main entrance placed in the north and includes windows each placed in the east and west faces of the building with the cross-sectional dimensions of 0.9144 × 1.2192 m^2. Every wall of the building without PCM has three layers; namely, two layers of plaster with the thickness of 0.0254 m applied on inner and outer surfaces of the brick layer having a thickness of 0.2286 m, whereas the roof consists of one layer of cast concrete with the thickness of 1.0466 m. The integration of a PCM layer of 0.0254 m thickness has been made on inner surfaces of the walls and bottom of the roof. The numerical investigation involves three different studies:

– the walls and roof of building without PCM integration,
– the roof alone integrated with the PCM layer, and
– all walls and the roof integrated with PCM layer.

The schematic view of the modeled building is shown in fig. 3.

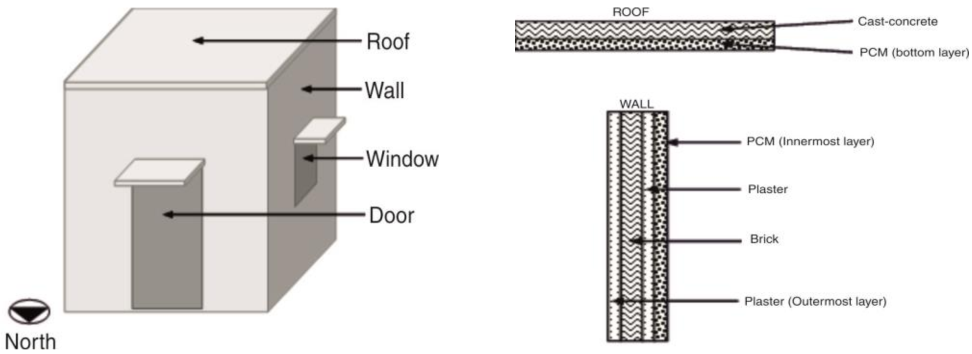

Figure 3. Schematic view of the modelled building; (a) building model and (b) layers in walls and roof

Modeling of the physical building model using ANSYS FLUENT

Governing equations for performing CFD analysis

In order to perform CFD analysis of building indoor environment, governing equations given in eqs. (1)-(5) are being solved for obtaining the solution. Boundary conditions such as, wall temperatures and inlet/ outlet conditions along with solar input data are set using the provisions in ANSYS FLUENT [23].

Continuity equation

$$\frac{\partial \rho}{\partial t}+\rho\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)=0 \tag{1}$$

Momentum equations

$$\rho\left[\frac{\partial u_x}{\partial t}+u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}+u_z\frac{\partial u_x}{\partial z}\right]=-\frac{\partial p}{\partial x}+\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}\right]+\rho f_x \tag{2}$$

$$\rho\left[\frac{\partial u_y}{\partial t}+u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}+u_z\frac{\partial u_y}{\partial z}\right]=-\frac{\partial p}{\partial y}+\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}\right]+\rho f_y \tag{3}$$

$$\rho\left[\frac{\partial u_z}{\partial t}+u_x\frac{\partial u_z}{\partial x}+u_y\frac{\partial u_z}{\partial y}+u_z\frac{\partial u_z}{\partial z}\right]=-\frac{\partial p}{\partial z}+\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right]+\rho f_z \tag{4}$$

Energy equation

$$\rho C_p\left[\frac{\partial T}{\partial t}+u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}+u_z\frac{\partial T}{\partial z}\right]=k\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right]+S_\phi \tag{5}$$

Solar radiation model (discrete-ordinate radiation model)

The ANSYS FLUENT provides various radiation models for implementing in building energy simulation. The solar radiation model provides a utility to calculate solar radiation in the solar calculator tab that consists of options to describe the location of Sun in sky for any particular day and time, geographical location. The solar ray tracing is mentioned by setting up the mesh orientation limits in north and east direction which is also provided in the modeling option of solar radiation. The discrete ordinate model considers the radiative transfer equation in the direction $\vec{S}$ as a field equation and is given:

$$\nabla\left[I\left(\vec{r},\vec{s}\right)\vec{s}\right]+\left(a+\sigma_s\right)I\left(\vec{r},\vec{s}\right)=an^2\frac{\sigma T^4}{\pi}+\frac{\sigma_S}{4\pi}\sum_0^{4\pi}I\left[\left(\vec{r},\vec{s}^{'}\right)\right]\phi\left(\vec{s}.\vec{s}^{'}\right)\mathrm{d}\Omega' \tag{6}$$

Modeling of wall heat transfer and PCM integration in building radiation model

The exterior surfaces of walls and roof are subject to unsteady but uniform heating of a constant area due to solar radiation, and hence it can reasonably be assumed that the conduction of heat through the wall and roof is 1-D. Accordingly, the governing equation for 1-D heat conduction at unsteady state can be expressed by:

$$\rho C_p\frac{\partial T}{\partial t}=k\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right]+S_\phi \tag{7}$$

where k is thermal conductivity of the wall material, ρ – the density of the wall material, and C_p – the specific heat of the wall material.

This method involves modeling of phase change by converting latent heat of PCM into apparent specific heat. Figure 4 shows the graphical representation of the variation of specific heat in PCM during its charging and discharging. Further improvement in accuracy is made by converting the area obtained below the span of transition temperature (latent heat) from the analysis with DSC to the area equaling to rectangle [5]. The mathematical expression, eq.(8), depicting the phase change phenomenon is given:

$$\rho_p c_{app}\frac{\partial T_p}{\partial t}=k\left[\frac{\partial^2 T_p}{\partial x^2}+\frac{\partial^2 T_p}{\partial y^2}+\frac{\partial^2 T_p}{\partial z^2}\right] \tag{8}$$

where c_{app} is the specific heat capacity relating to the solid, transition,and liquid region as per the fig. 4 shown.

The ambient air temperature has been measured experimentally at every hour by using resistance temperature detectors (RTD) sensor and is presented in fig. 5. This temperature profile has been included in the simulation using user-defined function.

Thermophysical properties of building materials employed in simulation

The building wall materials play an important role in the proper isolation of the room interior space from the surrounding environment, which may vary with seasons in a year. Some of the well-known building materials used in the construction of walls and roof and their thermophysical properties are listed in tab. 1. Based on the year-round weather report and daily temperature variation of indoor air, *savE*® OM30 Organic PCM manufactured by Pluss Polymers India Pvt. Ltd was chosen for incorporating in the the interior surfaces of the walls and roof. The thermophysical properties of the selected PCM are shown in tab. 2.

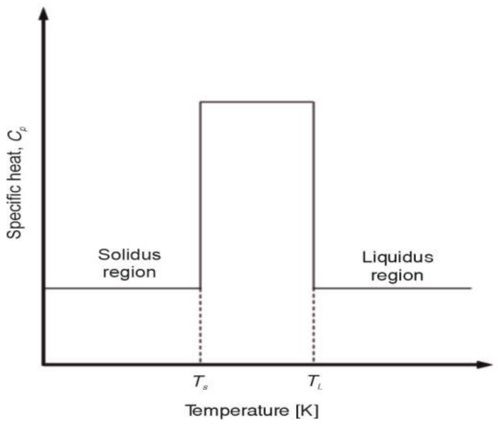

Figure 4. Graphical representation of the variation of specific heat with respect to temperature

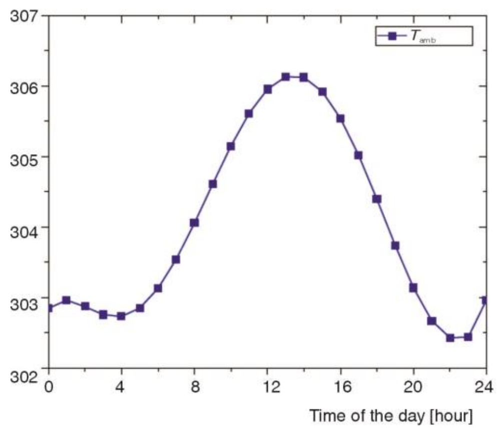

Figure 5. Ambient air temperature variations for Chennai on 2nd September

Table 1. Material property for building walls and roof

Name of the material	Thermal Conductivity, k [$Wm^{-1}K^{-1}$]	Density, ρ [kgm^{-3}]	Specific heat, C_p [$kJkg^{-1}K^{-1}$]
Plaster	0.72	1760	0.84
Brick	0.72	1920	0.84
Cast-concrete	1.13	2000	1

Table 2. Properties of *savE*® OM30 Organic PCM

Property	Values
Phase change temperature [K]	303-305
Density of solid phase [kgm^{-3}]	906 (Solid); 878 (Liquid)
Latent heat of phase change [Jkg^{-1}]	230
Thermal conductivity [$Wm^{-1}K^{-1}$]	0.185 (Solid); 0.123 (Liquid)
Specific heat capacity [$Jkg^{-1}K^{-1}$]	2600

Novel PCM Effectiveness index

In thermal management of building using any free cooling concept, the maximum deviation of the indoor temperature from the mean value during a day is an important parameter and the objective is to minimize the temperature fluctuation. In this context, a novel PEI is introduced to evaluate the thermal behavior of a building. This number presented in eq. (9) is used to compare the fluctuation in effective net indoor temperature of a building during the day with the introduction of a new concept for building thermal management while using conventional wall materials of the building. Here, the effect of PCM integration in building is assessed using PEI which is evaluated using the ratio of the relative indoor temperature integral (RITI) values of the indoor temperature fluctuation for the entire day without PCM and with PCM. The RITI value is calculated by subtracting the indoor temperature integral with the product of minimum room temperature and the time interval as given in eq. (10):

$$PEI = \frac{\text{RITI value of indoor temperaturevariation without PCM}}{\text{RITI value of indoor temperature variation with PCM}} \tag{9}$$

$$RITI = \int_0^{24*60*60} T\mathrm{d}t - \left(T_{\min}\Delta t\right) \quad (10)$$

where $T_{\min}$ is the minimum indoor temperature on a day comparing the buildings with and without PCM and Δt – the time interval of the numerical simulation.

Results and discussion

The solar radiation is transmitted through walls and roof of the building predominately by conduction with convective boundaries on the outer surface exposed to the atmosphere and the inner surface of the building space. Since solar radiation is a time-dependent phenomenon, transient heat conduction is considered for the thermal analysis of the walls and roof. The CFD analysis for studying the variation of indoor temperature of the building was carried out using the commercial software ANSYS FLUENT.

Contours of solar heat flux and indoor air temperature of the building

Solar radiation falling on Earth atmosphere gets reflected, refracted and part of it falls over the earth surface in two forms, namely, direct solar radiation and diffused solar radiation. The net solar heat flux falling over the building varies throughout day and almost tends to be negligible or zero during night hours. The contour of solar heat flux falling on building walls and roof on 11th June at 9 a. m. is shown in fig. 6(a). It is seen that the maximum amount of heat flux incident over the east wall and roof of the building, whereas, the shadow of the building is seen over ground surface near to the west-wall of the building. Gradual increase of solar heat flux falling over the building walls and roof is observed as time passes. The solar heat flux reaches to peak of the day of 651 W/m^2 at 12 noon with an increase in indoor temperature of 309 K which is seen in fig. 6(b). Thereon, the amount of solar heat flux falling over building walls and roof gradually decreases to zero at 6 p. m. The contour of solar heat flux falling over the building walls and roof at 3 p. m. and 6 p. m. is shown in figs. 6(c) and 6(d) respectively.

Indoor temperature variation of the building throughout the day

Variation of indoor temperature in the building on 2nd March is shown in fig. 7. It is noted that the building without PCM integration exhibits a gradual rise from mid-night and reaches a maximum temperature of 304.5 K around 2 p. m. Thereafter, the indoor temperature falls until the subsequent midnight. However, for the case with PCM in the roof alone (range: 303-305 K), the building's indoor temperature variation decreases comparatively for the 24 hour cycle. A similar trend in temperature variation is noted while integrating all the walls and roof with the integration of PCM layer but with further reduction in temperature variation of the indoor space. It is understood that the integration of PCM layers with the walls and roof reduces the indoor temperature significantly compared to the building without the integration of any PCM.

The indoor temperature variation of building on 2nd March shown in fig. 8. A decrease in indoor temperature is observed during the early morning for the building without PCM and afterward, there is a rise in this temperature till 2.00 p. m. The addition of PCM to the roof leads to a reduction in peak temperature and shifts to a later hour of the day. A further reduction in indoor temperature occurs when PCM is integrated to all walls and the roof of the building.

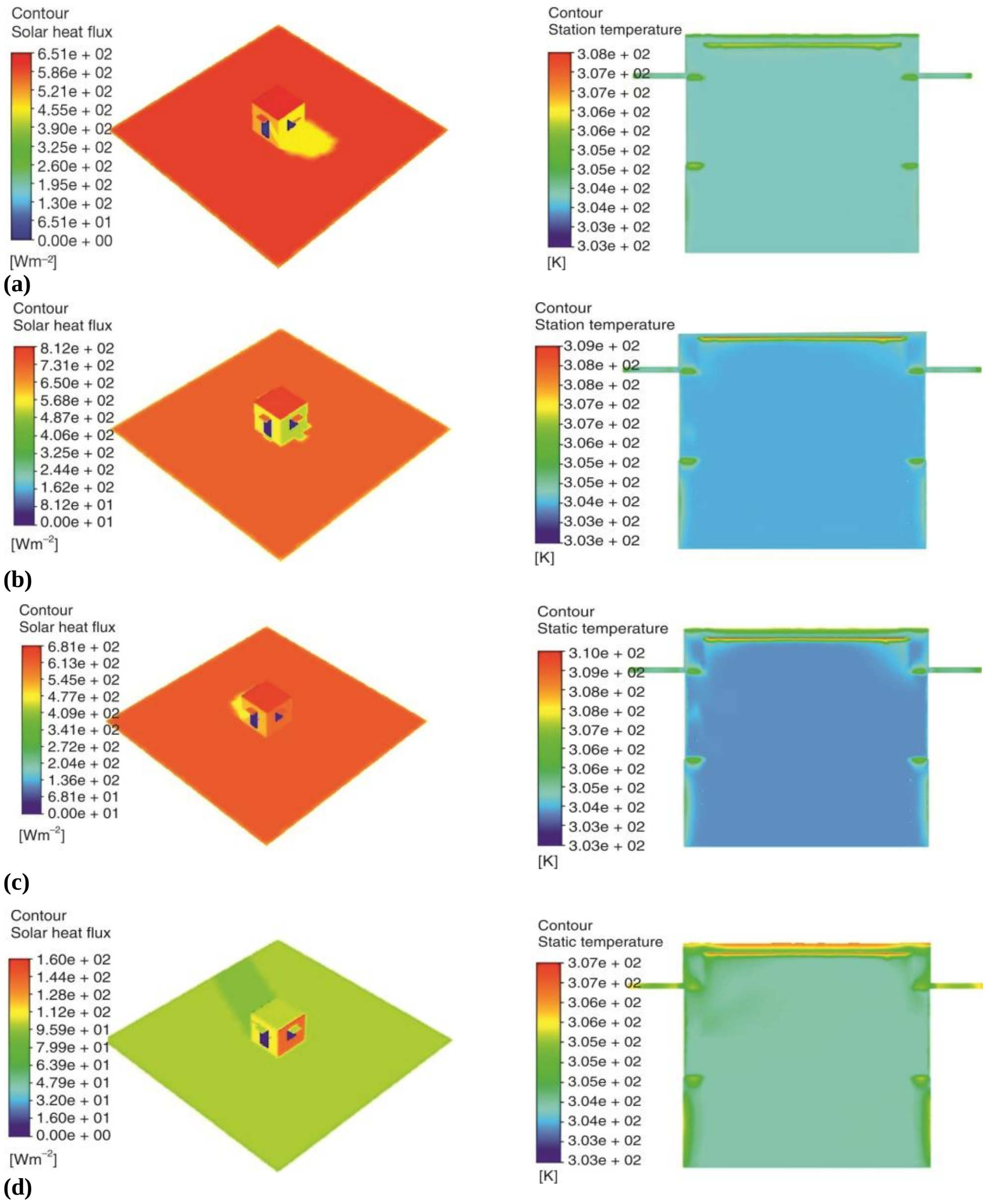

Figure 6. Contours of solar heat flux incident on building walls and roof and cross sectional view of building indoor temperature; (a) Solar heat flux and cross-sectional view of indoor temperature at 9 a. m., (b) solar heat flux and cross-sectional view of indoor temperature at 12 noon, (c) solar heat flux and cross-sectional view of indoor temperature at 3 p. m., and (d) solar heat flux and cross-sectional view of indoor temperature at 6 p. m.

Thermal performance analysis using the developed tool has been carried out further for 11th June and 26th December. The variation in indoor temperature for the respective months are shown in figs. 9 and 10. Though the values of the total heat flow and the indoor temperature at any respective time of the day are different, the trends of variation are similar to that of the months cited in figs. 7 and 8. It is construed that the heat flow variations and indoor temperature are being damped by PCM incorporation in the walls and roofs. During the night in December, the heat flow occurs from the building to the ambient. The presence of PCM prevents heat loss and maintains a uniform temperature and positive heat flow.

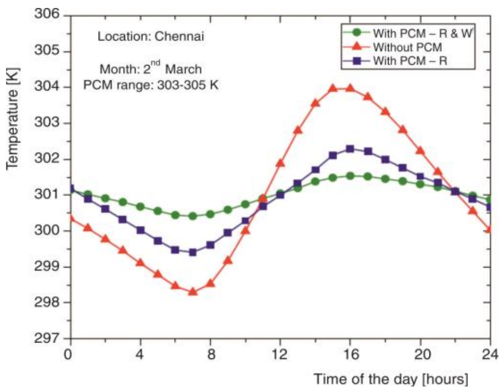

Figure 7. Indoor temperature variation in building on 2nd March

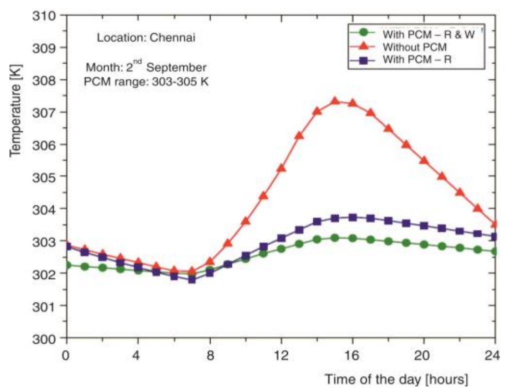

Figure 8. Indoor temperature variation in building on 2nd September

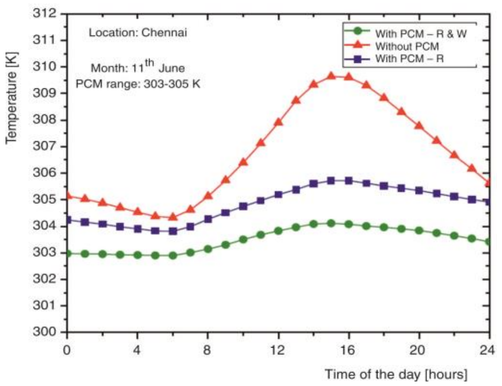

Figure 9. Indoor temperature variation in building on 11th June

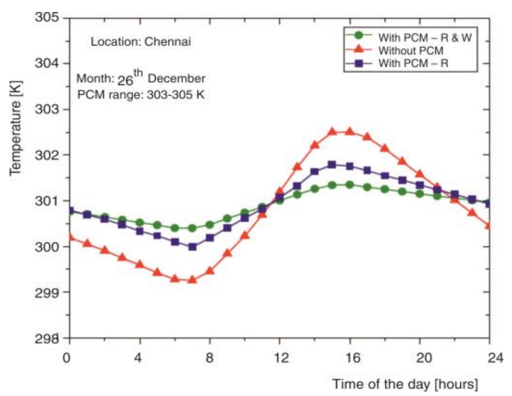

Figure 10. Indoor temperature variation in building on 26thDecember

Validation of simulated results with experimental data for Chennai

With an aim to adjudge the correctness of simulated results obtained from the CFD analysis in respect of indoor temperature, validation has been done with the experimental data. Two buildings of similar size, one building without PCM integration and the other one with the PCM integration in the roof, were constructed in Chennai (13.0827^{o}N, 80.2707^{o}E) as shown in fig. 11. The geometry of the building is 3.048 m length, 3.048 m breadth, and 3.048 m height. The PCM that has thermophysical properties, as mentioned in tab. 2, has been encapsulated into the high-density polyethylene panels (with the dimension $0.5 \times 0.25 \times 0.036$ m^3) for the incorporation into the roof. Experiments has been conducted for buildings with/ without PCM integration in the roof on 26th December. The PT-100 RTD (with an uncertainty of ± 0.5 ^{o}C) has been used to determine the hourly data of temperature of indoor air.

Figure 12 shows the evidence that the outcome of the CFD simulation is in good agreement with the experimental results. However, it is observed that the deviation between experimental and simulated results in respect of peak indoor temperature for the building without PCM integration is 0.1% while this deviation is only 0.03% for the building with the integration of PCM.

Figure 11. Photographic view of experimental building

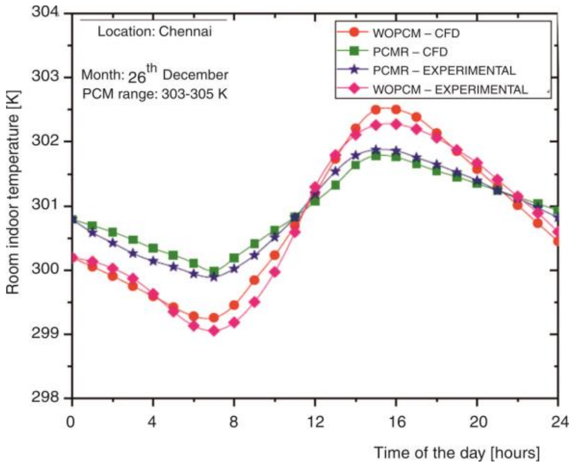

Figure 12. Validation of simulation results with experimental data

Thermal analysis using PCM effectiveness index

The performance of PCM in thermal management in building has been determined using a new PCM performance parameter called PEI, as described in eq. (9). The PEI evaluated for a building with PCM integration on the roof alone and the building with PCM integration on all walls and roof under Chennai weather conditions is given in tab. 3 and presented the same in fig. 13.

From this fig. 13, it is observed that PEI is not only indicating the effectiveness of PCM in terms of indoor temperature reduction but also describes the amount of moderation caused by the PCM integration for both cases, namely, integration of PCM to roof alone and integration of PCM to all walls and roof of the building. The PEI of 6.32 implies that, during the month of June, the temperature range of phase transition of PCM is positioned at the middle of variation of the diurnal temperature of indoor air, giving a large temperature gradient for heat transfer during PCM's charging and discharging cycle.

Table 3. The PCM performance parameter – PEI

Month	T_{min}	RITI without PCM	RITI with PCM – R	RITI with PCM – R and W	PEI with PCM – R	PEI with PCM – R and W
Mar.	298.29	234861	224005	235066	1.05	0.99
June	302.89	333202	166284	52723	2	6.32
Sept.	301.78	250746	97162	67238	2.58	3.73
Dec.	299.12	154533	156245	152751	0.98	1.01

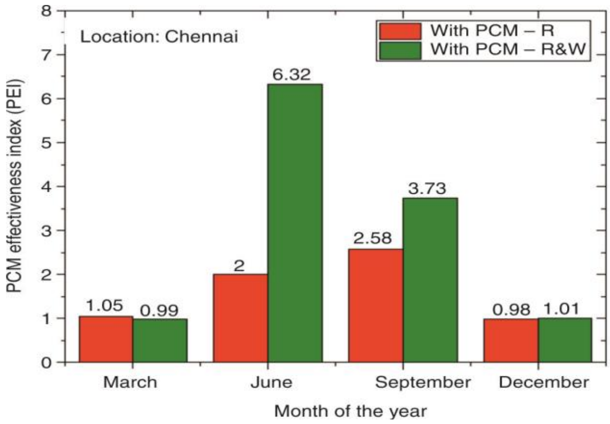

Figure 13. Comparison of PEI for four different months

Conclusions

- The thermal performance analysis of PCM integration in the building was carried out using ANSYS Fluent CFD software for the building located at Chennai.
- The solar heat load on the surfaces of walls and roof and indoor temperature variation for the building with and without PCM integration were investigated and reported.
- Experimental investigation of PCM performance on room indoor temperature has been carried out for the month of September for two buildings of identical dimensions (one without PCM integration and other with PCM integration) located at Chennai. The results obtained from the simulation were validated with the experimental results and found to vary by 0.1% for building without PCM and 0.03% for building with PCM.
- The non-dimensional parameter PEI introduced in this research has been found to be useful in evaluating the suitability of the PCM for a particular location, climate and time of the year. Higher value of PEI indicates that the selected PCM is more suitable for the simulated location and climatic conditions
- This non-dimensional parameter and CFD model can be used for year-round pre installation studies of PCM integration in building for a particular location which avoids costly and time-consuming experimental studies.

Acknowledgment

The authors are highly thankful to Department of Science and Technology, Govt. of India (Grant Ref. No. TMD/CERI/BEE/2016/039) for the financial support provided to Anna University, Chennai, India, DST-IPHEE laboratory, Easwari Engineering College, Chennai, India and Meenakshi College of Engineering, Chennai, India for the successful completion of the present work.

The authors are also thankful to the Department of Science and Technology, Govt. of India, for providing us the infrastructure under the scheme "Funds for Improvement of S&T Infrastructure (Grant Ref. No. SR/FST/College-2017/110) to performing theoretical analysis in buildings.

References

[1] Antony Aroul Raj, V., Velraj, R., Review on Free Cooling of Buildings Using Phase Change Materials, *Renewable and Sustainable Energy Reviews, 14* (2010), 9, pp. 2819-2829

[2] Pasupathy, A., *et al.*, Experimental Investigation and Numerical Simulation Analysis on the Thermal Performance of a Building Roof Incorporating Phase Chase Change Material (PCM) for Thermal Management, *Applied Thermal Engineering, 28* (2018), 5-6, pp. 556-565
[3] Bhamare, D. K., *et al.*, Passive Cooling Techniques for Building and their Applicability in Different Climatic Zones – The State of Art, *Energy and Buildings, 198* (2019), Sept., pp. 467-490
[4] Cabeza, L. F., *et al.*, Materials Used as PCM in Thermal Energy Storage in Buildings: A Review, *Renewable and Sustainable Energy Reviews, 15* (2011), 3, pp. 1675-1695
[5] Antony Aroul Raj, V., Velraj, R., Heat Transfer and Pressure Drop Studies on a PCM-Heat Exchanger Module for Free Cooling Applications, *International Journal of Thermal Sciences, 50* (2011), 8, pp. 1573-1582
[6] Antony Aroul Raj, V., *et al.*, Numerical Investigations of Outward Solidification in Cylindrical PCM Storage Unit, *Applied Mechanics and Materials, 787* (2015), Aug., pp. 177-181
[7] Rajagopal, M., *et al.*, Investigation on Phase Change Material-Based Flat Plate Heat Exchanger Modules for Free Cooling Applications in Energy-Efficient Buildings, *Advances in Building Energy Research, 11*(2016), 2, pp. 282-304
[8] Karthik, P., *et al.*, Enhancement in Free Cooling Potential through PCM Based Storage System Integrated with Direct Evaporative Cooling (DEC) Unit, *Energy, 144* (2018), Feb., pp. 443-455
[9] Karthik, P., *et al.*, Effect of Direct Evaporative Cooling during the Charging Process of Phase Change Material Based Storage System for Building Free Cooling Application – A Real Time Experimental Investigation, *Energy and Buildings, 152* (2017), July, pp. 250-263
[10] Rohdin, P., Moshfegh, B., Numerical Predictions of Indoor Climate in Large Industrial Premises. A Comparison Between Different k-ε Models Supported by Field Measurements, *Building Environment, 42* (2007), 11, pp. 3872-82
[11] GOmez, M. A., *et al.*, CFD Simulation of a Concrete Cubicle to Analyze the Thermal Effect of Phase Change Materials in Buildings, *Energies, 5* (2012), 7, pp. 2093-2111
[12] Gowreesunker, B. L., Tassou, S. A., Effectiveness of CFD Simulation for the Performance Prediction of Phase Change Building Boards in the Thermal Environment Control of Indoor Spaces, *Building and Environment, 59* (2013), Jan., pp. 612-625
[13] Ahangari, M., Maerefat, M., An Innovative PCM System for Thermal Comfort Improvement and Energy Demand Reduction in Building Under Different Climate Conditions, *Sustainable Cities and Society, 44* (2019), Jan., pp. 120-129
[14] XamAn, J., *et al.*, Thermal Performance Analysis of a Roof with a PCM-Layer Under Mexican Weather Conditions, *Renewable energy, 149* (2020), Apr., pp. 773-785
[15] Jin, X., *et al.*, Numerical Analysis for the Optimal Location of a Thin PCM Layer in Frame Walls, *Applied Thermal Engineering, 103* (2016), June, pp. 1057-1063
[16] Sovetova, M., *et al.*, Thermal Performance and Energy Efficiency of Building Integrated with PCMs in Hot Desert Climate Region, *Solar Energy, 189* (2019), Sept., pp. 357-371
[17] Zhu, L., *et al.*, Numerical Study on the Thermal Performance of Lightweight Temporary Building Integrated with Phase Change Materials, *Applied Thermal Engineering, 138* (2018), 25, pp. 35-47
[18] Kong, X., *et al.*, Numerical Study on the Thermal Performance of Building Wall and Roof Incorporating Phase Change Material Panel for Passive Cooling Application, *Energy and Buildings, 81* (2014), Oct., pp. 404-415
[19] Li, Z. X., *et al.*, Heat Transfer Reduction in Buildings by Embedding Phase Change Material in Multi-Layer Walls: Effects of Repositioning, Thermophysical Properties and Thickness of PCM, *Energy Conversion and Management, 195* (2019), Sept., pp. 43-56
[20] Berardi, U., Soudian, S., Benefits of Latent Thermal Energy Storage in the Retrofit of Canadian High-Rise Residential Buildings, *Building simulation, 11* (2018), Feb., pp. 709-723
[21] Chen, S., *et al.*, Numerical Study on the Winter Thermal Performance and Energy Saving Potential of Thermo-Activated PCM Composite Wall in Existing Buildings, *Building Simulation, 13* (2020), 2, pp. 237-256
[22] Kharbouch, Y., *et al.*, Thermal Performance Investigation of a PCM-Enhanced Wall/Roof in Northern Morocco, *Building simulation, 11* (2018), May, pp. 1083-1093
[23] ***, ANSYS FLUENT 15.0, *User's Guide*, FLUENT Inc., New York, USA, 2015

Paper submitted: August 30, 2020
Paper revised: February 12, 2021
Paper accepted: April 20, 2021