Thermal comfort enhancement of office buildings located under warm and humid climate through phase change material and insulation coupled with natural ventilation

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Abstract

Facilitating indoors with healthy and fresh air along with adequate thermal comfort using less energy is a true challenge in buildings located in hot climates. The present work aims to improve the thermal comfort of office occupants by incorporating phase change material (PCM)/insulation integration coupled with natural ventilation. Four building models integrated with various combinations of PCM and insulation were analyzed using DesignBuilder software with respect to Chennai climatic conditions. It was understood from the analysis that the PCM integration in the building roof and walls of Case 3 did not provide adequate thermal comfort for the considered climate. But the presence of insulation in Cases 2 and 4 maintained an average hourly operative temperature of 26.8°C and 26.6°C, including extreme summer. These temperatures are well within the tolerable temperature range of humans. Also, it is observed that Case 4 comparatively reduced the thermal comfort index by a maximum of 0.25 (reduction in warm sensation). Further optimization of Case 4 yielded an insulation and PCM thickness of 50 mm and 30 mm, respectively. The recommended building model was evaluated with a thermal comfort index not exceeding 1.7 until the end of office hours, throughout the year for Chennai climate.

Keywords: Sustainable energy; Energy storage; Thermal performance of buildings; Cooling load reduction; Thermal comfort;

Nomenclature

Abbreviations

ACH – Air Changes per Hour

ACS – Adaptive Comfort Standard

CondFD – Conduction finite difference

CTF – Conduction transfer function

PCM – Phase Change Material

PMV – Predictive Mean Vote

Symbols

α – Thermal diffusivity (m^2/s)

Δt – Time step (s)

Δx – Finite difference layer thickness (m)

i – Node being modeled

i-1 – Adjacent node to exterior of construction

i+1 – Adjacent node to interior of construction

j – Previous time step

j+1 – New time step

k – Thermal conductivity (W/m.K)

Q_{conv} – The amount of convection between the all of the surfaces in the zone and the zone air (kJ)

$Q_{convIntGains}$ – The amount of heat convected from internal gains such as people, lights, and equipment (kJ)

Q_{infil} – The amount of heat gained or lost due to infiltration (kJ)

Q_{sys} – The amount of heat added to or subtracted from the space due to a space conditioning system (kJ)

ρ – Density (kg/m^3)

T – Temperature (°C)

t – Time (s)

x – Element thickness (mm)

1. Introduction

Natural ventilation in buildings is preferred for its capability of providing healthy and fresh air, diluting the pollutants originating from the building structure, and requiring less energy consumption [1]. Natural ventilation could contribute positively to the passive cooling of buildings in hot and dry climates through night-time cross-ventilation strategies. These strategies reduce the peak indoor air temperature of a day by taking advantage of the low ambient temperature of the previous night [2,3]. Implementing night ventilation strategies has demonstrated a significant reduction in cooling/heating loads and an enhancement in thermal comfort [4]. However, due to low thermal mass and higher temperatures, this strategy is not enough to cool the entire space, though it has a favourable impact on the internal air temperature of the buildings [5]. Under this scenario, night ventilation strategies in combination with PCM techniques are encouraged [6]. PCM integration enhances the thermal mass of modern lightweight buildings [7]. PCMs with higher melting points are effectual during warm weather. However, extreme temperatures during summer prevents the PCM solidification at night, thus reducing its effectiveness [8], which could be overcome through insulation integration. The presence of an insulation layer prevents heat gain into the indoors while mitigating the thermal stresses developed in the building envelopes [9]. The type of insulation material, its thickness, and its position with respect to the building elements should be considered during the selection of insulation materials and will vary with respect to the building location and the climatic conditions [10].

1.1. Literature review

The literature review of the performance of buildings with insulation, PCM, and/or natural ventilation techniques are presented as follows: Lei et al. [11] investigated the application and positioning of PCM with respect to building elements. It was determined that PCM positioned on the building outer surface enhanced the thermal performance of the building. Also, it was observed that PCM with lesser melting temperature facilitates to achieve a full PCM melting/solidification cycle, while that with a higher melting temperature enhances its adaptivity to temperature variations, with a trade-off in the achievable energy savings of the PCM. PCM with phase transition temperature from 27^o to 29^o are appropriate for warmer and hot climates, while PCM with phase transition temperature range from 23 to 25 are appropriate for regions with cold climates [3,11,12]. Beemkumar et al. [13] experimentally analyzed the effect of applying PCM to the roof of a building which is situated in Chennai. It was determined that the building with a PCM roof reduced the indoor temperature fluctuations and mitigated the temperature by 1 - 2° C compared to that of the conventional building. Kim and Moon [14] investigated by applying insulation to the building elements including windows and analyzed its impact on building energy utilization through eQUEST software. The simulation was done for two climatic zones: Detroit, Michigan (cold climate) and Miami, Florida (hot climate). It was concluded that a minimal level of insulation is necessary for both climates, while multiple glazing of windows in hot climates is unnecessary and does not yield appreciable heating and cooling energy benefits.

Al-Yasiri et al. [15] analyzed the different window orientations and window-to-wall ratio towards enhancing indoor thermal comfort of buildings by employing PCM and natural night ventilation strategies. It was concluded that window orientation has less effect towards natural night ventilation of the room with PCM, irrespective of the wind direction under hot locations. Seyedehniloufar Mousavi et al. [16] studied the impact of various passive techniques such as PCM, insulation, reflective paint, etc., on three residential buildings located in Monterrey, Mexico (falls under semi-arid climate) using a building simulation software. Based on the annual energy saved and cost effectiveness, optimum configuration was recommended, which includes insulation, and reflective painting applied on the outer surface of the buildings, combined with low-E glazing and shading and it gave an annual energy reduction of more than 50% in all the analyzed cases.

Arumugam et al. [17] optimized the PCM and insulation positions with reference to the building elements so as to reduce the cooling energy demands of a commercial building located in India. Buildings with different PCM and insulation combinations were analyzed using DesignBuilder® software for five different locations in India. It was concluded that PCM and insulation selection should be made with reference to the external day and night temperatures of the geographical location where the building is actually situated. Arumugam et al. [6] analyzed the different PCM and insulation combinations combined with natural ventilation when applied to office buildings situated in various locations. Based on the five climatic types that exists in India, randomly five locations were selected and considered for analysis. They are Bangalore (temperate climate), Delhi (moderate climate), Pune (warm and humid climate), Jodhpur (hot and arid climate), and Guwahati (cold climate). The office building was investigated for the selected five locations. In all the analysis, more attention was paid towards achieving adequate thermal comfort in buildings through 100% natural ventilation, particularly in summer. Therefore, a PCM with melting temperature 27^{o}C was used for all the analysis. The investigation of the buildings under all the locations revealed the fact that natural night ventilation is not sufficient to cool the thermal mass in the different cases. Hence, the cool energy was generated through an air-conditioner during the night and stored in the building's thermal mass, which could be used up in the upcoming day. It was determined that the average temperature during the nighttime of summer was considered as a key factor in selecting the PCM and insulation combinations coupled with 100% natural ventilation during the daytime.

Summary of the literature review reveals that most of the studies have investigated the separate application of either PCM or insulation or night ventilation strategies applicable to buildings, while only few recent studies investigated the combination of different passive technologies. Applying PCM, insulation, and night ventilation techniques separately to buildings did not yield significant results for regions that has hot weather conditions. But, the positive results from the few recent studies that analyzed the combination of the above-mentioned technologies gave the confidence to proceed further with different combinations of passive technologies. Hence, it was decided to investigate and analyze different combinations of insulation and PCM coupled with natural ventilation applicable to buildings. The investigation was proceeded PCM types and thicknesses to improve the thermal performance of a building with enhanced air circulation in a warm and humid climate like Chennai.

1.2. Objectives

The objective of the present study is as follows:

1. This paper aims to confirm the capability of natural ventilation in combination with insulation and PCM techniques to provide adequate daytime thermal comfort and fresh air intake inside an office building in Chennai. However, Chennai has a hot and humid climate, and night cooling by natural ventilation is not that much effective due to higher temperatures in nighttime.
2. To circumvent the above problem, it is decided to store the cool thermal energy in the building elements by operating the air conditioner during night and then to utilize the stored cool energy through natural ventilation during office hours.
3. To assess and confirm the potential of the above-said concept when applied to a hot climate, simulation analysis was performed, and the results were discussed.
4. To recommend an optimised PCM/insulation technique for an office building located under Chennai climatic conditions.

The novelty of the present work lies in the application of the similar concept for a geometric location like Chennai, which is different from the previous work. Since level of adequate thermal comfort varies from region to region, investigations are necessary in this regard. Added to that, investigations are done with different PCM types, thicknesses, and insulation thickness. Also, recommendation of the optimised model for the considered building was done in this work.

2. Research motivation

The reasons that motivated the present research work are given as follows:

- ***Well ventilated indoors are necessary to avoid the spread of viral diseases.***

During the recent pandemic, the use of air conditioners was not recommended because closed spaces might increase the spread of the virus [18]. It was also confirmed that most of the virus spread happens in indoor spaces like hospitals, offices, and large community halls without proper ventilation. The amount of virus found to be low in the case of well-circulated indoor spaces [19]. Also, the preferred relative humidity level for humans is 40% to 70% to prevent problems from pathogens [20]. On a global scale, it is understood that corona spread is high in cold countries during the winter season and in hot countries during the summer season. This might be due to the operation of the air-conditioner to meet the occupant comfort during extreme climatic conditions, which in turn increases the virus concentration in the air [21].

- ***Modulating the energy supply/demand through PCM/insulation integration in building envelopes***

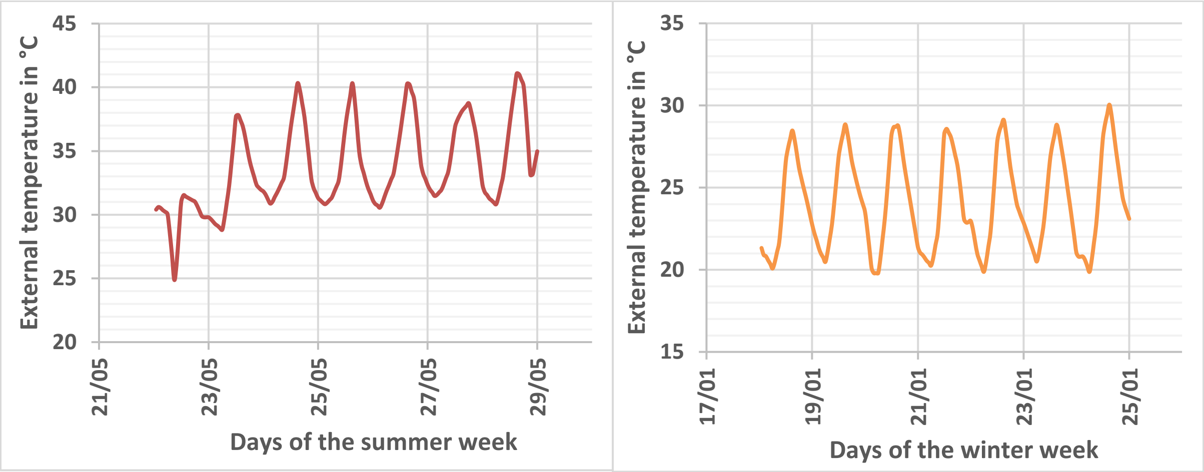
Overnight cooling of the building thermal mass acts as a heat sink; this in turn could be used up in the daytime [22]. The building's thermal mass and heat gain in indoors have a major effect on the cooling and comfort of the occupants [23]. Since the nighttime temperatures are comparatively lesser than that of the daytime temperatures, cooling PCM during the night using an air conditioner mitigates the energy used for cooling. Since this idea uses energy during the night, it in turn yields the benefit of using off-peak energy at lower cost.

- ***Adaptive principle***

"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" is the adaptive principle [24]. The thermal performance analysis of a naturally ventilated commercial building located in Quito-Ecuador showed that the office occupants reacted in such a way to match their comfortable temperature to some extent with reference to the prevailing external temperature. Also, the adaptive model EN15251 is an optimal approach to evaluate thermal comfort in buildings equipped with natural ventilation [25]. ACS is a model based on the mean outdoor air temperature, which shows acceptance levels of 80% and 90% of the total population in terms of indoor operative temperature [5,26,27].

3. Material and methods

The type of building selected for analysis is an office building. Since energy demand will be generally higher in office buildings, this type is selected for investigation purpose. The building size was selected randomly because the model represents a typical office building in a small scale, which operates with few office staffs and equipments such as computers, copiers etc. The dimension of the building and other data considered are kept as simple as possible because, more attention was paid towards the impact and analysis of the techniques towards the thermal performance of buildings.



(a) (b)

Fig. 1. External ambient temperature profiles of Chennai (a) summer week (b) winter week

The building considered for investigation was located in Chennai, Tamil Nadu, India, characterized by higher temperatures throughout the year except for two months in winter (December and January). However, heating is also not required for these two months as the weather is comfortable, whereas cooling is necessary for ten months of a year. The external ambient temperature profiles for the analyzed peak summer and winter weeks are shown in Fig. 1. It is proposed to stock the cool thermal energy in the building elements during the night and later use the stored cool energy to enhance the thermal comfort of the office occupants during the day. Since Chennai is reported to have a hot and humid climate with warmer nights, night cooling was achieved by operating the air conditioner during the early morning hours for 3 hours and allowing the building envelopes to store the cool energy. Operating an air conditioner between 3 a.m. and 6 a.m. is recommended for two reasons: Firstly, the external temperature will be comparatively lower than the other hours of the particular day. Secondly, the use of off-peak energy contributes to lower operating costs. However, during office hours, the air conditioner is not in operation. The stored cool energy in the building envelope will be used up gradually through natural ventilation and provide the required comfort. Since the energy is stored in the building wall and roof, the performance could be enhanced in two ways: (i) Adding insulation to the building surface reduces heat loss to the surroundings [28], and (ii) Improving the building thermal mass by adding PCM with phase transition temperature within the comfortable range [29]. To confirm the feasibility and potential of the above-said concept when applied to a city like Chennai, simulation analysis was performed and the results were analyzed. The investigation is presented in detail in the upcoming sections.

3.1. Building details

An office building of size 4.6 m (15’) X 6.1m (20’) X 3m (10’) [6] was modeled and simulated using DesignBuilder software. The building was modeled with a door on the north side, along with the parameters indicated in Table 1. Totally nine windows were added to the building, to have appreciable fresh air circulation. All the walls possess two windows each, except the wall on the south side, which has three windows. The internal heat loads considered for the analysis were ten employees with four computers, along with a natural ventilation of 5 ACH [30], an infiltration of 0.05 ACH, and lighting of 5W/m^2 – 100 lux. The characteristics of the proposed PCM and insulation materials are presented in Table 2. PCMs were incorporated into the building elements in layers with pouches for filling PCMs. In DesignBuilder software, PCM's phase change enthalpy contributions are added to the enthalpy resulting from the constant specific heat of the pouch material.

Table 1 Details of various parameters considered for building analysis

Sl. No.	Parameters	Details	Remarks
1.	Building purpose	Office building	Working hours 9 AM to 5 PM [with an assumption that part of the office staffs will stay morning hours (7 AM to 9 AM) and evening hours (5 PM to 7 PM)]
2.	Location	Chennai	13.0827°N, 80.2707°E

3.	Wall/roof specification	1.25cm plaster+11.25cm brick (wall)/10 cm RCC (roof) +1.25cm plaster	Bureau of Indian Standards [31]
4.	Window size	0.9m (3’) x 1.5m (5’)	9 windows [window to wall ratio of 17% and single glazing (Generic CLEAR 6 mm)]
5.	PCM	BioPCM®Q27 and BioPCM®Q29	Phase change temperature 27°C and 29°C
6.	Insulation material	XPS extruded polystyrene – HFC blowing	Upper deck insulation

Table 2 Characteristics of the building materials

Material	Thickness (mm)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Specific heat (J/kg.K)	Remarks
Cement/plaster, sand aggregate	1.25	0.72	1860	840	
Brick	11.25	0.62	1700	800	
Reinforce cement concrete (RCC)	10	2.5	2400	1000	
BioPCM®Q29	37.1	0.2	235	1970	Latent heat of PCM 210 – 250 J/g [32]
BioPCM®Q27	20.8	0.2	235	1970	Latent heat of PCM 210 – 250 J/g [33]
XPS Extruded polystyrene – HFC blowing	50/100	0.03	35	1400	Upper deck insulation

3.2. *Simulation*

DesignBuilder® software was used for simulation and analysis purposes. DesignBuilder® software (developed by DesignBuilder® Pvt. Ltd., United Kingdom) is a simulation software used to analyse the thermal performance of buildings by considering whole building simulation approach. The DesignBuilder® software is a graphical user interface for the EnergyPlus™ program (developed by the U.S. Department of Energy), where EnergyPlus™ is a simulation program used for energy and thermal load analysis. EnergyPlus™ does building simulations over specified time periods with fair computational time and resources.

The building under analysis is discretized into different thermal zones. Each zone can be a single or multiple rooms that have uniform state variables, e.g., temperature, pressure, and density. EnergyPlus™ is capable of predicting precise temperatures in spaces since it is based on an integrated simulation approach (loads determined at a specific time step are then transferred to the simulation module at the same time step) [34]. The various loads calculated are space load, system load, and central plant load, while the simulation module estimates the reactions of the heating/cooling systems and electrical systems. EnergyPlus™ accomplishes load calculations based on ASHRAE's preferred heat - balanced approach based on surface heat balance and zone air heat balance [35].

The basic assumptions made in the model are that every space inside the building has a uniform temperature as it is well mixed. Also, it is assumed that all room surfaces have (a) uniform surface temperature, (b) uniform long and short-wave irradiation, (c) diffuse radiating surfaces, and (d) one dimensional heat conduction. Also, the time step represents the interactive time between the heat zones and the surroundings and could range between 1 and 60 minutes. EnergyPlus™ software is used to compute the energy consumption, thermal load demands, and the dynamic change in energy consumption in buildings [36].

Fig. A (given in detail in the supporting information file) represents the work flow in DesignBuilder software. As a first step, the building location and appropriate weather file are to be given as input. Weather files are available in the database of the software, and they represent the hourly ambient conditions like temperature, humidity, air velocity, solar radiation, etc. for various geographical locations. The geometry of the building (could be developed in DesignBuilder software or the same can be imported from any CAD software), construction details, occupancy, lighting, window openings, and HVAC details are provided in the consecutive steps. The software correlates the given inputs and estimates the thermal load and occupant thermal comfort through the governing equations and hence presents the building thermal performance for the required period [37].

The building element was considered as a 1D element with convective heat transfer in an unsteady state and without internal heat generation. The heat balance equation is given through Equation (1) [35]. Solution methods such as sequential iteration and predictor-corrector for zone and system integration were used. The building elements are discretized into uniform nodes, and then appropriate heat transfer equations are solved for each node using the finite different scheme. Under the finite difference scheme, the fully implicit scheme was used to calculate the solution through Equation (2) [38]. Conduction through a wall can be calculated using the CTF or CondFD solution algorithm as selected by the user. CondFD can handle both phase change materials and materials with variable thermal conductivity. The condFD model is composed of a well-validated algorithm [39–41] and is used for the assessment of PCM performance in buildings. The algorithm is coupled with enthalpy-temperature function, and hence, any change in enthalpy would be converted into specific heat value of the PCM for a given phase change temperature. Therefore, Equation (2) includes the sensible heat of solid and liquid PCM and also latent heat of PCM during phase change.

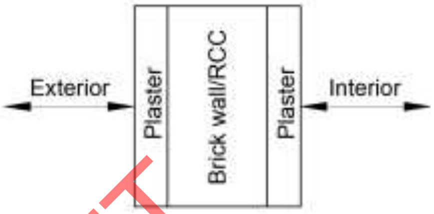
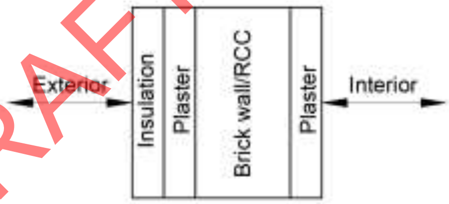
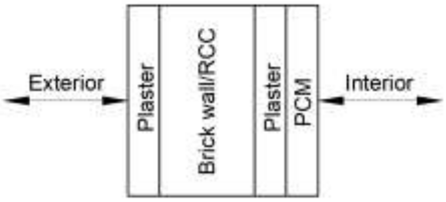
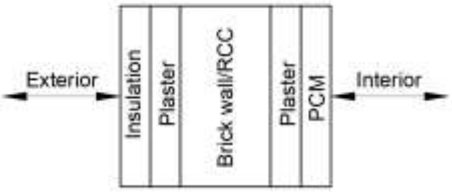
$$C\frac{dT}{dt} = Q_{conv} + Q_{convIntGains} + Q_{infil} + Q_{sys} \tag{1}$$

$$C\rho\Delta x\frac{T_i^{j+1}-T_i^j}{\Delta t} = \left[k_{int}\frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta x} + k_{ext}\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x}\right] \tag{2}$$

The number of time steps used in this work for calculating the solutions is 30 per hour, with a time step duration of 2 minutes [42]. Six warm-up days were used while carrying out the simulation to ensure the stability of the results. Input data to the software includes building geometry and construction, occupancy, and lighting details.

As per Table 3, four cases were analyzed to investigate the effect of insulation/PCM when integrated with the building elements. It is to be noted that the thickness of the insulation/PCM was determined through trial and error. To analyze the requirement under the worst weather conditions, the performance of all the cases was investigated on May 28th during peak summer and then for one week each of peak summer and peak winter. Historical weather data (an average of the previous weather data) for many locations is available inbuilt in the DesignBuilder software as weather files. The external air temperature on May 28th was around 40°C, which is the typical summer temperature in Chennai. The peak week weather data are used for cooling/heating load calculations and sizing the cooling/heating equipment. In all four cases, the air conditioner was operated between 3 a.m. and 6 a.m. to cool the building thermal mass, which has the impact of the earlier day's solar radiation.

Table 3 Details of the four cases analysed

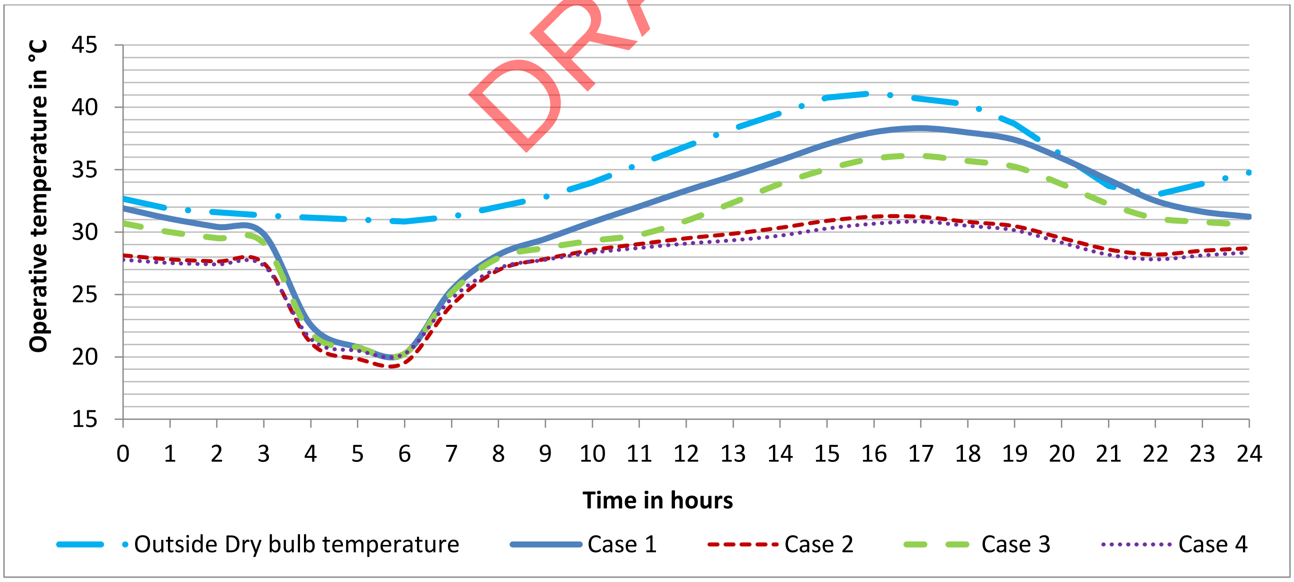
Case No.	Concepts investigated	Construction details	Cross section of the RCC/walls (figures not to scale)	Remarks
1.	No insulation and no PCM	Conventional building construction		
2.	With insulation	Upper deck insulation with 100mm thickness		Type/thickness of the insulation/PCM were arrived through trial and error for Cases from 2 to 4
3.	With PCM	BioPCM®Q29 with 37.1 mm thickness at the interior surface		
4.	With insulation and PCM	Upper deck insulation with 50 mm thickness and BioPCM®Q27 with 20.8 mm thickness at the interior		

3.3. *Data analysis*

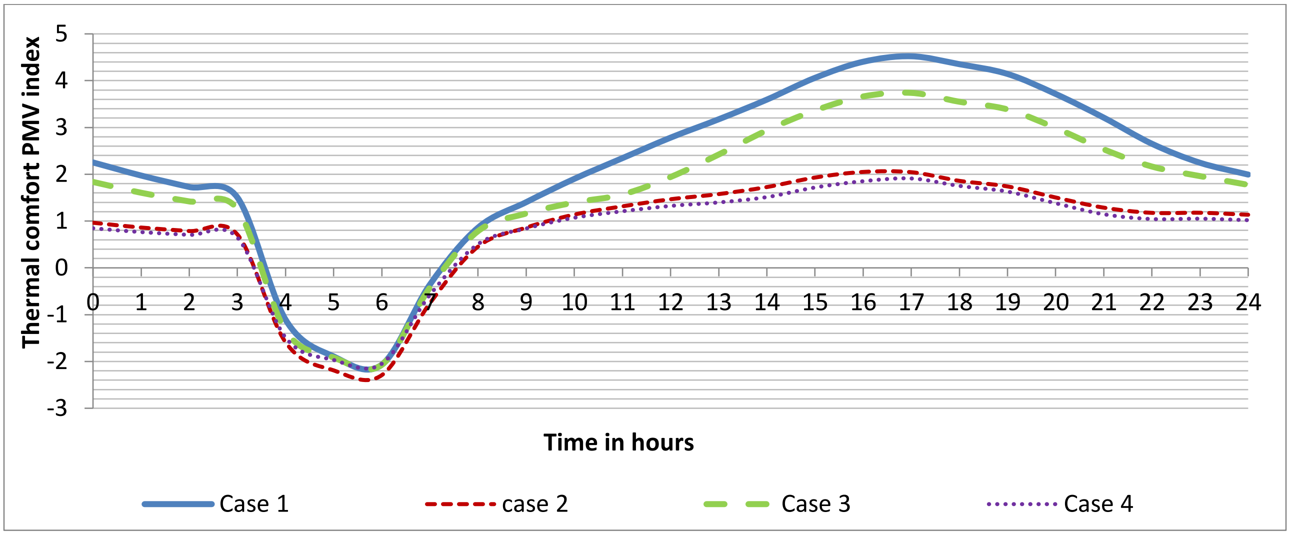
The results obtained from the analysis were interpreted based on the Fanger PMV index and the indoor operative temperatures recommended in the ACS model. Researchers have explored the thermal, physiological, and psychological responses of people to their environment and developed mathematical models to predict these responses. The PMV model developed by Fanger [43] is one such model that aids to assess the occupant comfort in the indoors. The PMV index, which was used here to interpret thermal comfort, was evaluated using indoor air temperature, thermal radiation, humidity, air speed, level of metabolic activities, and occupant clothing. The seven-point scale for PMV index is shown in Fig. B (given in the supporting information file), where -3 indicates the maximum sense of coolness, +3 indicates the maximum sense of hotness, and zero indicates no cool or warm sense. Even though the ACS model is an extension of the PMV met
ACS model of ASHRAE gave better results than the
ated buildings [44].

Fig. C (given in detail in th
acceptable indoor operative temperature range of the A
utdoor temperature for any location. The temperature
indicates the comfortable temperatures accepted by 9
nthly outdoor temperature, whereas the temperature range within the 80% acceptable limit gives the temperature values comfortable for 80% of the people. These temperatures will vary depending on the average monthly outdoor temperature of the location [45]. In this work, thermal comfort evaluation in terms of PMV indices and the ACS model is used to interpret the results of the analysis.

4.2. Effect on thermal comfort parameters



(a)



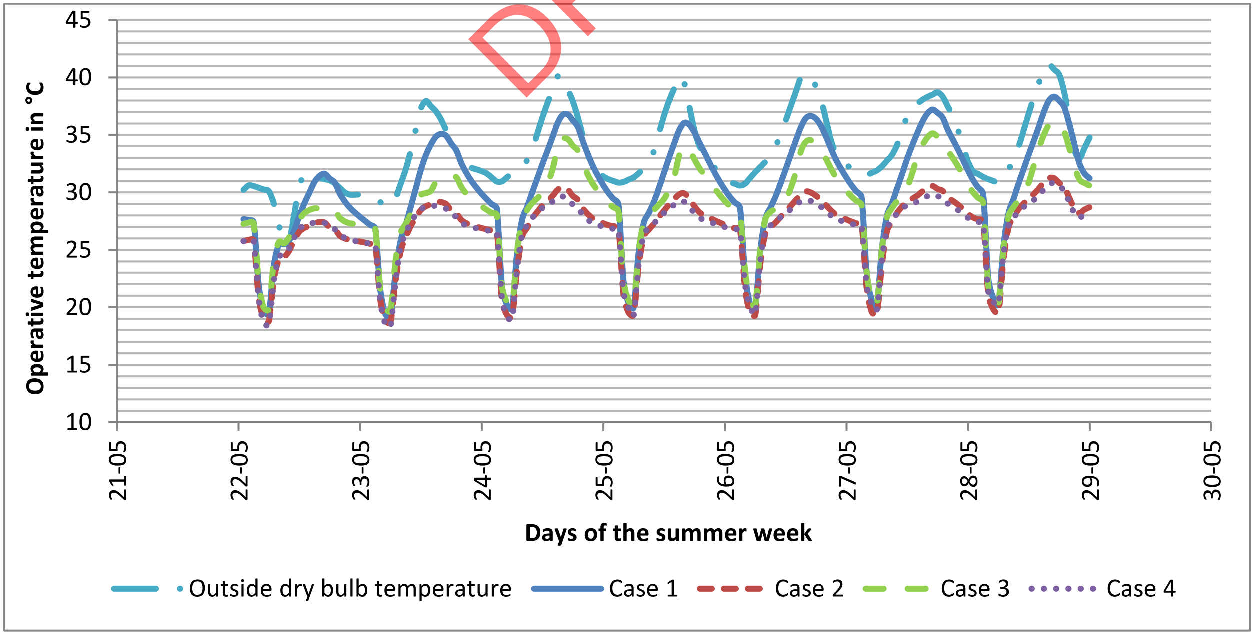
(b)

Fig. 3. Thermal comfort parameter variations on May 28th (worst summer day) (a) Operative temperature (b) PMV index

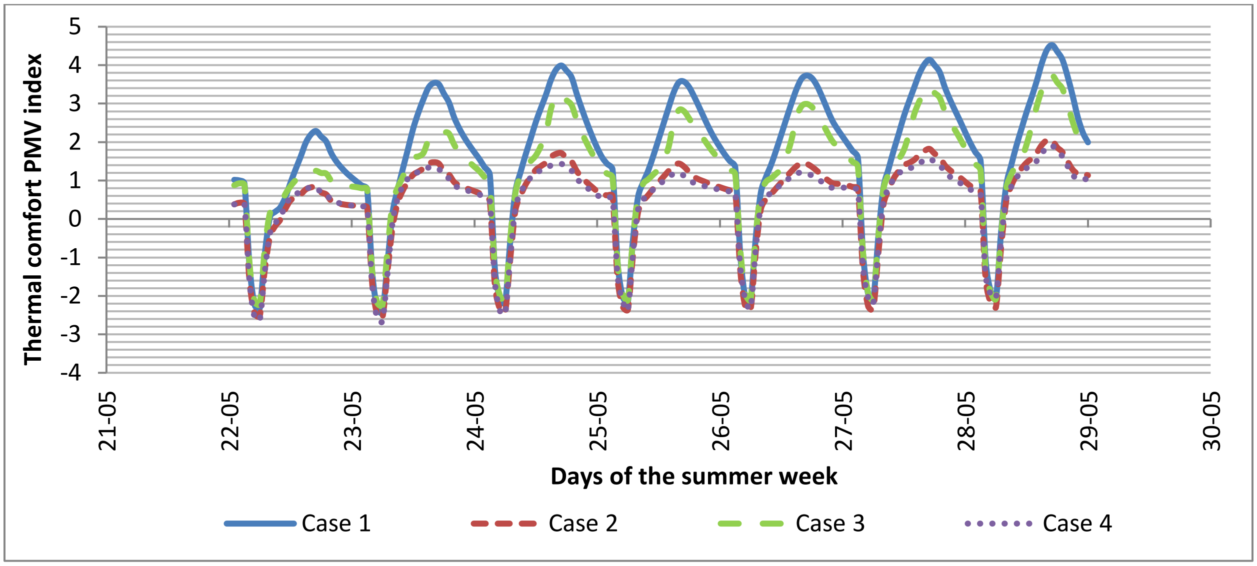
Fig. 3 (a) shows the hourly variations of the indoor operative temperature on May 28th. According to Fig. 3 (a), the hourly average outdoor temperature was 34.9°C, while the average hourly operative temperature for Cases 1 to 4 was 31.6°C, 27.8°C, 30.3°C, and 27.6°C, respectively. A peak temperature of 41.1°C, 38.4°C, 31.2°C, 36.1°C, and 30.8°C were noted, respectively, for the outer temperature and the indoor temperature for the four cases considered between 4 and 5 p.m. The building model in Case 1 showed a higher temperature than the other cases because of the lower thermal mass. In Case 3, from 8 a.m. to 11 a.m., it is noted that the slope of the operating temperature is minimal, thus showing the PCM effect. After 11 a.m., the operative temperature slope of the building in Case 3 (building with PCM) started to increase. This is mainly because the cool energy stored in the PCM got exhausted around 11 a.m. and hence, melted PCM will simply act as an added thermal mass to the building elements. Buildings in Cases 2 (with insulation) and 4 (with PCM and insulation) showed almost equal operative temperatures, which is mainly due to the addition of an insulation layer. The buildings in Cases 2 and 4 comparatively performed better than the buildings in the other two cases in terms of operative temperatures.

The same was confirmed through the graph, which shows the corresponding PMV indices (Fig. 3 (b)). Despite adding PCM, low performance in Case 3 is noted. Though PCM was frozen through mechanical cooling for three hours, it is understood that the entire PCM was not frozen because of its higher thickness, which led to an incomplete melting/solidification cycle. The same was confirmed by extending the air conditioner's operating time by a couple of hours. Also, proportional improvement was noted in the thermal comfort indices and operative temperature. However, mechanical cooling beyond three hours is not encouraged in this work because it will shoot up the building's operational cost. With respect to Cases 2 and 4, the presence of an insulation layer prevents heat gain into the indoors. On the other hand, it prevents the leakage of stored cool energy into the external environment. However, the stored cool thermal energy is used to regulate the indoor air temperature when it goes higher than the temperature of the stored energy. It is noted from Fig. 3 (b) that the PMV index for Cases 2 and 4 is 2 and 1.9, which confirms that both cases are capable of modulating the indoor operative temperature while maintaining the indoor spaces with a tolerable PMV index.

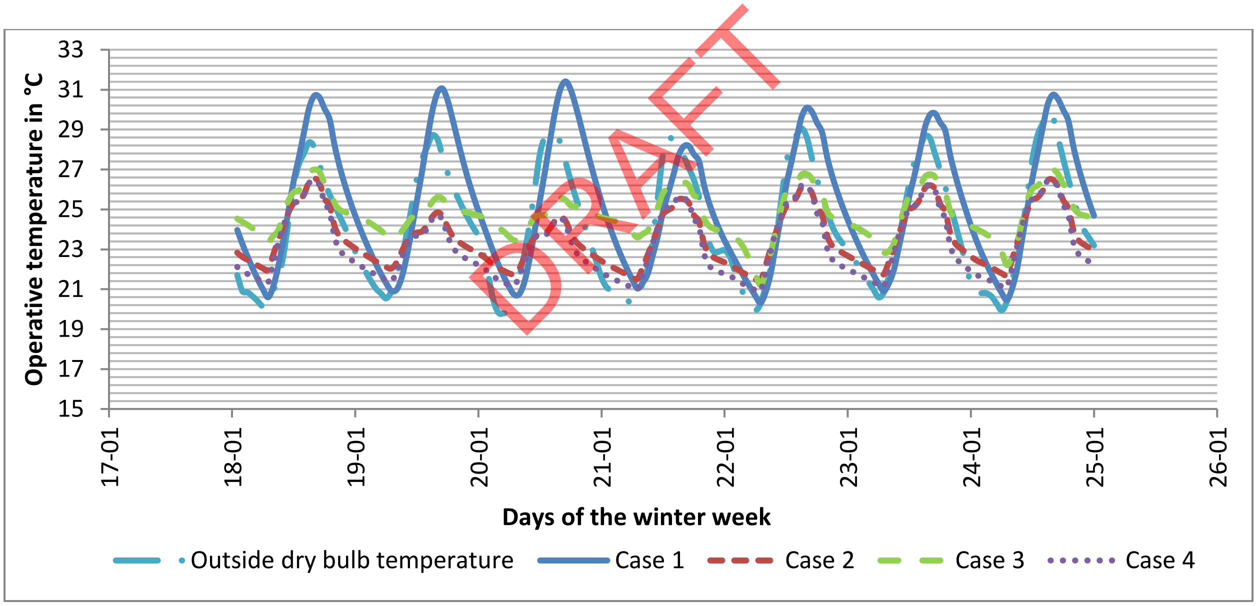
4.3. Thermal performance during summer and winter design weeks



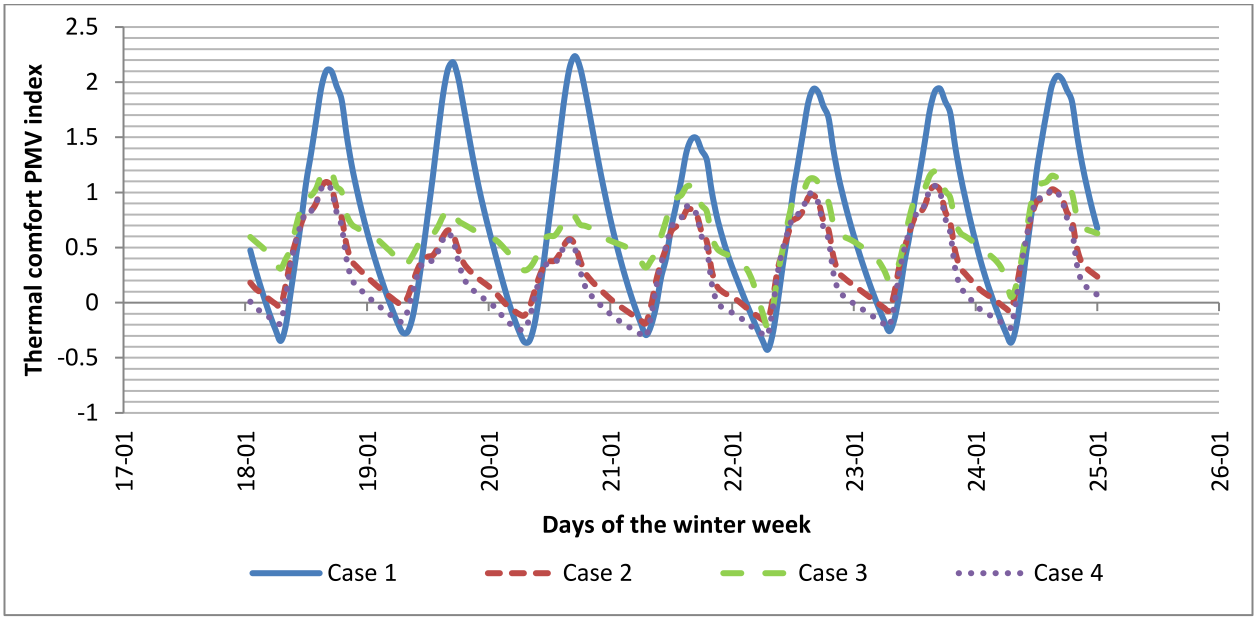
(a)


Thermal comfort PMV index
5
4
3
2
1
0
-1
-2
-3
-4
21-05
22-05
23-05
24-05
25-05
26-05
27-05
28-05
29-05
30-05
Days of the summer week
Case 1
Case 2
Case 3
Case 4

(b)


Operative temperature in °C
33
31
29
27
25
23
21
19
17
15
17-01
18-01
19-01
20-01
21-01
22-01
23-01
24-01
25-01
26-01
Days of the winter week
Outside dry bulb temperature
Case 1
Case 2
Case 3
Case 4

(c)



(d)

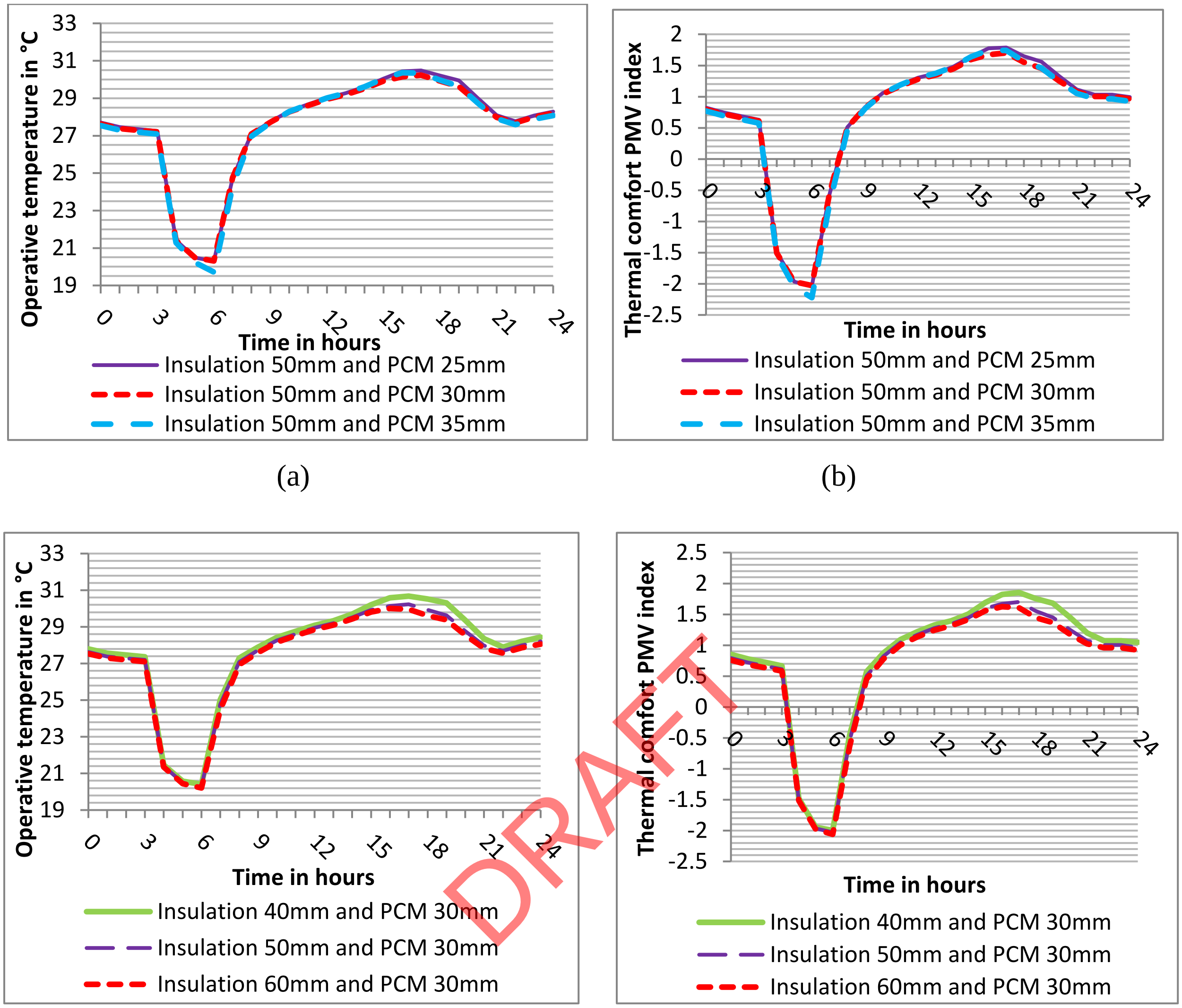
Fig. 4. Thermal comfort parameter variations (a) operative temperature for peak summer week (b) PMV index for peak summer week (c) operative temperature for peak winter week (d) PMV index for peak winter week

Extreme weather data is mainly considered for HVAC design in order to size the air-conditioner that is required to fulfil the comfort requirements of any building. Hence, the analysis was carried out for a peak summer week from May 22nd to May 29th. Figures 4 (a) and 4 (b) show the daily variations in the operative temperature and PMV index pertaining to the peak week of summer. The hourly outdoor temperature and building operative temperature for cases from 1 to 4 were noted as 33.6°C, 30.2°C, 26.8°C, 28.9°C, and 26.6°C, respectively. The average peak temperatures for the entire week for the outdoor and indoors were observed as 38.5°C, 36°C, 29.8°C, 33.5°C, and 29.3°C, respectively. Again, it is evident from Fig. 4 (a) that Case 2 and Case 4 were capable of providing better indoor operative temperatures with naturally ventilated spaces throughout the days of the summer week, despite the higher ambient temperature. Also, Case 4 was able to provide slightly better thermal comfort (reduced up to a maximum of 0.25 PMV index) than Case 2 (Fig. 4 (b)) due to the presence of PCM. However, the consideration of pure PCM in the walls and ceilings (Case 3) is not effective as it produces a negligible effect on the comfort index, as explained in the earlier section.

Similarly, Figures 4 (c) and 4 (d) show the indoor air temperature and thermal comfort index for the days of the peak week of winter. The external temperature ranged between 20°C and 30°C. In Case 1, the building's operative temperature shoots up more than the external temperature due to the internal heat gain in the room. In Case 2, the operative temperature was reduced by an average of 5°C compared to Case 1. This is because the presence of an insulation layer prevents solar gain, while internal heat gain is balanced by utilizing the cool thermal mass. The building's thermal mass gains cool energy from the air that enters through the open windows. In Case 3, PCM was activated whenever the temperature went beyond its phase transition temperature of 29°C and stored the available cool energy. Hence, a reduction in average operative temperature of around 4°C compared to Case 1 was observed in Case 3. Case 4 performed almost the same as Case 2 with respect to operative temperature and PMV index. This is because of the prevention of solar gain by the insulation and managing the internal heat gain through the combined effect of building thermal mass integrated with PCM. Hence, Case 4 is taken for further analysis due to the better comfort provided during the analysed weeks.

4.4. *Effect of insulation and PCM thickness on thermal comfort parameters*

Various combinations of insulation and PCM thicknesses with respect to Case 4 were analyzed during the worst summer day (i.e., May 28th). The insulation thickness was varied as 40 mm, 50 mm, and 60mm, while the PCM thickness was varied as 25 mm, 30 mm, and 35 mm. The resulting indoor temperature and thermal comfort index were used to interpret the results.



(a) (b)

(c) (d)

Fig. 5. Thermal comfort parameter variations on May 28th (a) Operative temperature for constant insulation and various PCM thicknesses (b) PMV index for constant insulation and various PCM thicknesses (c) Operative temperature for constant PCM and various insulation thicknesses (d) PMV index for constant PCM and various insulation thicknesses

Figures 5 (a) and 5 (b) indicate the operative temperature and thermal comfort variations on May 28th, for different combinations of constant insulation thickness (50 mm) and varying PCM thickness. The average hourly temperatures were noted as 27.6°C, 27.5°C and 27.4°C for the models with PCM thicknesses of 25 mm, 30 mm, and 35 mm, respectively. However, only a marginal improvement of about 0.1°C was noted when the PCM thickness varied from 25 mm to 30 mm and from 30 mm to 35 mm. On analysing the Fig. 5 (b), which shows the variations of thermal comfort indices of the analysed models, it is noted that the PMV index was reduced by 0.1 for the model with a PCM thickness of 30 mm, while it marginally increased in the case of PCM with a thickness of 35 mm. Since the analyzed day is the worst summer day, a reduction in the thermal comfort index of about 0.1 is considerable. Hence, the PCM thickness was fixed at 30 mm for further proceeding the analysis.

Figures 5 (c) and 5 (d) show hourly indoor air temperature and PMV index variations on May 28th for the models with constant PCM and varying insulation thicknesses. The average hourly operative temperature was noted as 27.7°C, 27.5°C and 27.3°C for the models with insulation thicknesses of 40 mm, 50 mm, and 60 mm, respectively. A reduction in the operative temperature of around 0.2°C was noted for an increase of 10 mm in the insulation thickness (i.e., from 40 to 50 mm and 50 to 60 mm). The PMV index for the above models was noted as 1.85, 1.7, and 1.62, respectively (Fig. 5 (d)). On analysing the performance of building models with an insulation thickness of 40 mm and 50 mm, the later one performed better in terms of PMV index. At the same time, when comparing the performance of building models with insulation thicknesses of 50 mm and 60 mm, the later one showed only a marginal improvement of around 0.08 in the comfort index. Based on the above analysis, optimized thickness values of 50 mm and 30 mm were obtained for the insulation and PCM layers.

4.5. Impacts on power consumption

Fig. E (given in the supporting information file) shows the monthly power consumption of the regular air-conditioned office building (with air conditioner set temperature of 26°C) and the building with the optimized configuration. The average power consumption was noted as 122 kWh and 47 kWh per month for the regular building with air conditioning and the recommended office building. It is understood that the total power consumed was 61% less than that of the regular office building with air conditioning.

As per the Fanger thermal comfort model, PMV index 2 indicates warm. Similarly, with respect to ACS model, an operative temperature of 30°C is recommended for 90% acceptability limits and 31°C is recommended for 80% acceptability limits based on the average monthly outdoor temperature of Chennai which is 32°C. Fig. F (given in the supporting information file) shows the year-round performance output of the recommended building configuration calculated through DesignBuilder software. The above figure shows the operative temperature, external temperature, relative humidity and PMV index for the entire year. It is seen in Fig. F, the thermal comfort index was limited to less than 2 for the entire year, indicating a bearable warm thermal sensation by most of the people. Also, operative temperature fluctuates between 25°C to 30°C during office hours. As per ACS model, this indicates a comfort level accepted by 90% of the population during summer and winter weather conditions. These were achieved by modulating the energy supply and demand in combination with insulation/PCM integration while complementing healthy fresh air.

5. Conclusions

The effectiveness of integrating insulation, PCM, and/or natural ventilation techniques into an office building located in Chennai, India, was investigated for the summer and winter weeks. The conventional building (Case 1) and three other buildings incorporating insulation (Case 2), PCM (Case 3), and insulation and PCM (Case 4) were analyzed through DesignBuilder software. Extruded polystyrene and BioPCM® with melting points 27°C and 29°C were used as insulation and PCM materials. The simulation results were interpreted using operative temperatures, the thermal comfort index, and adaptive comfort models.

On analysing the results, Case 2 and Case 4 showed more or less similar average hourly operative temperatures of 26.8°C and 26.6°C in comparison to 30.2°C in Case 1 during the summer. However, Case 4 showed a slight reduction in the thermal comfort index by a maximum of 0.25 (reduction in warm sensation) compared to Case 2. Also, during the winter week analysis, all the buildings except Case 1 were found to show acceptable comfort with no significant difference. Since Chennai is characterized by hot weather conditions for most of the year, Case 4 was found to be appropriate for the Chennai climate. The results obtained from the previous study were therefore confirmed. Further, parametric analysis and optimization of Case 4 yielded a final insulation thickness of 50 mm and a PCM thickness of 30 mm.

The recommended building configuration has a comfort level accepted by 90% of the population for the whole year, with a maximum PMV index of 1.7. The same comfort level was achieved throughout the year, including in extreme summer, without air conditioner during office hours (daytime in this case). The proposed model showed a power reduction of 61% in comparison to the traditional building with air conditioning during the day. The proposed method will provide a pathway for healthy comfort in buildings located in hot countries and could be applied to existing and new buildings.

Acknowledgment

The authors are highly thankful to the 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.

References

[1] Z. Tong, Y. Chen, A. Malkawi, Estimating natural ventilation potential for high-rise buildings considering boundary layer meteorology, Appl Energy. 193 (2017) 276–286. https://doi.org/10.1016/j.apenergy.2017.02.041.

[2] E. Kyritsi, A. Michael, An assessment of the impact of natural ventilation strategies and window opening patterns in office buildings in the mediterranean basin, Build Environ. 175 (2020) 106384. https://doi.org/10.1016/j.buildenv.2019.106384.

[3] P. Arumugam, V. Ramalingam, P. Vellaichamy, Effective PCM, insulation, natural and/or night ventilation techniques to enhance the thermal performance of buildings located in various climates – A review, Energy Build. 258 (2022) 111840. https://doi.org/10.1016/j.enbuild.2022.111840.

[4] S. Omrani, V. Garcia-Hansen, B. Capra, R. Drogemuller, Natural ventilation in multi-storey buildings: Design process and review of evaluation tools, Build Environ. 116 (2017) 182–194. https://doi.org/10.1016/j.buildenv.2017.02.012.

[5] J.P. Landsman, Performance, prediction and optimization of night ventilation across different climates, 2016.

[6] P. Arumugam, P. Vellaichamy, V. Ramalingam, S.A. Prakash, V.A.A. Raj, A pathway towards healthy and naturally ventilated indoor built environment through PCM and insulation techniques for office buildings in India, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 236 (2021) 555–574. https://doi.org/10.1177/09576509211056426.

[7] N. Artmann, Cooling of the building structure by night-time ventilation, 2008.

[8] F. Souayfane, F. Fardoun, P. Biwole, Phase change materials (PCM) for cooling applications in buildings : A review, Energy Build. 129 (2016) 396–431. https://doi.org/10.1016/j.enbuild.2016.04.006.

[9] D.G.L. Samuel, S.M.S. Nagendra, M.P. Maiya, Passive alternatives to mechanical air conditioning of building: A review, Build Environ. 66 (2013) 54–64. https://doi.org/10.1016/j.buildenv.2013.04.016.

[10] M.S. Al-Homoud, Performance characteristics and practical applications of common building thermal insulation materials, Build Environ. 40 (2005) 353–366. https://doi.org/10.1016/j.buildenv.2004.05.013.

[11] J. Lei, J. Yang, E. Yang, Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore, Appl Energy. 162 (2016) 207–217. https://doi.org/10.1016/j.apenergy.2015.10.031.

[12] M.E. Valencia-Solares, M. Gijón-Rivera, C.I. Rivera-Solorio, Energy, economic, and environmental assessment of the integration of phase change materials and hybrid concentrated photovoltaic thermal collectors for reduced energy consumption of a school sports center, Energy Build. 293 (2023) 113198. https://doi.org/10.1016/j.enbuild.2023.113198.

[13] N. Beemkumar, D. Yuvarajan, M. Arulprakasajothi, K. Elangovan, T. Arunkumar, Control of room temperature fluctuations in the building by incorporating PCM in the roof, J Therm Anal Calorim. 143 (2021) 3039–3046. https://doi.org/10.1007/s10973-019-09226-0.

[14] J.-J. Kim, J.W. Moon, Impact of insulation on building energy consumption, in: Eleventh International IBPSA Conference, Scotland, 2009: pp. 674–680.

[15] Q. Al-Yasiri, M. Alktranee, M. Szabó, M. Arıcı, Building envelope-enhanced phase change material and night ventilation: Effect of window orientation and window-to-wall ratio on indoor temperature, Renew Energy. 218 (2023) 119263. https://doi.org/10.1016/j.renene.2023.119263.

[16] S. Mousavi, M. Gijón-Rivera, C.I. Rivera-Solorio, C. Godoy Rangel, Energy, comfort, and environmental assessment of passive techniques integrated into low-energy residential buildings in semi-arid climate, Energy Build. 263 (2022) 112053. https://doi.org/10.1016/j.enbuild.2022.112053.

[17] P. Arumugam, V. Ramalingam, P. Vellaichamy, Optimal positioning of phase change material and insulation through numerical investigations to reduce cooling loads in office buildings, J Energy Storage. (2022).

[18] Coronavirus lingers in air of crowded, non-ventilated rooms; more evidence of aerosol spread, The Week. (2020).

[19] Aylin Woodward, You're most likely to catch the coronavirus in a poorly ventilated space. That makes offices very risky., Business Insider India. (2020).

[20] ISHRAE, COVID-19 Guidance Document for Air Conditioning and Ventilation, (2020).

[21] V. Raj, R. Velraj, F. Haghighat, The contribution of dry indoor built environment on the spread of Coronavirus: Data from various Indian states, Sustain Cities Soc. 62 (2020) 102371. https://doi.org/https://doi.org/10.1016/j.scs.2020.102371.

[22] N. Artmann, H. Manz, P. Heiselberg, Climatic potential for passive cooling of buildings by night-time ventilation in Europe, Appl Energy. 84 (2007) 187–201. https://doi.org/10.1016/j.apenergy.2006.05.004.

[23] N. Artmann, H. Manz, P. Heiselberg, Parameter study on performance of building cooling by night-time ventilation, Renew Energy. 33 (2008) 2589–2598. https://doi.org/10.1016/j.renene.2008.02.025.

[24] D. Clements-Croome, Naturally ventilated buildings: Buildings for the senses, economy and society, 1997. https://doi.org/10.4324/9780203476659.

[25] A. Gallardo, M. Palme, A. Lobato-Cordero, R.D. Beltrán, G. Gaona, Evaluating thermal comfort in a naturally conditioned office in a temperate climate zone, Buildings. 6 (2016) 1–20. https://doi.org/10.3390/buildings6030027.

[26] M.K. Singh, R. Ooka, H.B. Rijal, S. Kumar, R. de Dear, Adaptive thermal comfort in the offices of three climates of North-East India, Journal of Building Engineering. 75 (2023) 106843. https://doi.org/10.1016/j.jobe.2023.106843.

[27] M. Indraganti, R. Ooka, H.B. Rijal, G.S. Brager, Adaptive model of thermal comfort for offices in hot and humid climates of India, Build Environ. 74 (2014) 39–53. https://doi.org/10.1016/j.buildenv.2014.01.002.

[28] C. v Vo, F. Bunge, J. Duffy, L. Hood, Advances in thermal insulation of extruded polystyrene foams, Cellular Polymers. 30 (2011) 137–156.

[29] A. Waqas, S. Kumar, Utilization of latent heat storage unit for comfort ventilation of buildings in hot and dry climates, Int J Green Energy. 8 (2011). https://doi.org/10.1080/15435075.2010.529406.

[30] Guidelines on ventilation of residential and office buildings for SARS-CoV-2 virus version 2.0 (2022), 2022. https://www.csir.res.in/covid-19/guidelines-ventilation-sars-cov-2-virus-ver-20 (accessed May 23, 2022).

[31] SP 41 (1987) : Handbook on functional requirements of buildings (other than industrial buildings) - Bureau of Indian standards, 1988.

[32] BioPCM Q29 Technical data, n.d. https://phasechange.com/wp-content/uploads/2018/01/BioPCM-1.0-Data-Sheet-Q29.pdf (accessed May 23, 2022).

[33] BioPCM Q27 Technical data, n.d. https://phasechange.com/wp-content/uploads/2018/01/BioPCM-1.0-Data-Sheet-Q27.pdf (accessed May 23, 2022).

[34] D.B. Crawley, Linda K. Lawrie, Curtis O. Pedersen, R.K. Strand, Richard J. Liesen, Frederick C. Winkelmann, W. F. Buhl, Y. Joe Huang, Michael J. Witte, Robert J. Henninger, Jason Glazer, Daniel E. Fisher, Don Shirey, EnergyPlus: New, capable, and linked, J Archit Plann Res. 21 (2002). https://www.researchgate.net/publication/268390688.

[35] R.K. Strand, C.O. Pedersen, D.B. Crawley, Modularization and simulation techniques for heat balance-based energy and load calculation programs: The experience of the ASHRAE loads toolkit and EnergyPlus, in: Building Simulation , Rio de Janeiro, Brazil, 2001: pp. 43–50. https://www.researchgate.net/publication/238602692.

[36] EnergyPlus Essentials, 2021.

[37] T. Maile, M. Fischer, V. Bazjanac, Building energy performance simulation tools – a life-cycle and interoperable perspective, 2007. https://www.researchgate.net/publication/237621385.

[38] P.C. Tabares-Velasco, C. Christensen, M. Bianchi, C. Booten, Verification and validation of EnergyPlus conduction finite difference and phase change material models for opaque wall assemblies, National Renewable Energy Lab. (NREL). (2012) article no. NREL/TP-5500-55792.

[39] F. Kuznik, J. Virgone, Experimental assessment of a phase change material for wall building use, Appl Energy. 86 (2009) 2038–2046. https://doi.org/10.1016/j.apenergy.2009.01.004.

[40] F. Guarino, A. Athienitis, M. Cellura, D. Bastien, PCM thermal storage design in buildings : Experimental studies and applications to solaria in cold climates, Appl Energy. 185 (2017) 95–106. https://doi.org/10.1016/j.apenergy.2016.10.046.

[41] M. Auzeby, S. Wei, C. Underwood, J. Tindall, C. Chen, H. Ling, R. Buswell, Effectiveness of using phase change materials on reducing summer overheating issues in UK residential buildings with identification of influential factors, Energies (Basel). 9 (2016) 605. https://doi.org/10.3390/en9080605.

[42] D. Beltran, J. Martínez-Gómez, A. Lobato-Cordero, Effect of environment on the selection of phase change materials for building wallboards using multi-criteria decision methods and Building Energy Simulations, in: Proceedings of the 15th IBPSA Conference, San Francisco, USA, 2017: pp. 7–9.

[43] ISO 7730:2005(E) Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 2005.

[44] Z. Zhao, M. Houchati, A. Beitelmal, An energy efficiency assessment of the thermal comfort in an office building, Energy Procedia. 134 (2017) 885–893. https://doi.org/10.1016/j.egypro.2017.09.550.

[45] C.B. Ramspeck, ANSI/ASHRAE Standard 55-2004 Thermal Environmental Conditions for Human Occupancy, 2004.

[46] A. Tardieu, S. Behzadi, J.J.J. Chen, M.M. Farid, Computer simulation and experimental measurements for an experimental PCM-impregnated office building, in: Proceedings of Building Simulation, 2011.

Declarations

- **Funding**

This work has been funded by Department of Science and Technology, Govt. of India (Grant Ref. No. TMD/CERI/BEE/2016/039) to Anna University, Chennai, India, DST-IPHEE laboratory, Easwari Engineering College, Chennai, India and Meenakshi College of Engineering, Chennai, India