Comparative assessment of thermal comfort with Insulation and phase change materials utilizations in building roofs and walls

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Abstract

Present study deals with estimation of thermal comfort of residential buildings for different scenarios. The three scenarios which are analysed for the present study are construction using brick wall and concrete roof, construction by utilization of insulation over walls and roof and construction by utilization of Phase Change Materials (PCM) over walls and roof. A building is simulated in EnergyPlus using conduction finite difference algorithm. The PCM is microencapsulated in plaster boards thereby restricting any chemical reactions with the building material. The assessment is carried out by calculating the hourly average room dry bulb temperature and average room relative humidity. This is then compared with the thermal comfort conditions provided in National Building Code of India 2005 and a percentage of hours within comfort range is worked out. The assessment is carried out between the months of March and October for three cities i.e. Bhubaneshwar, Jodhpur and New Delhi, all under different climatic conditions. The results indicate that PCM is performing comparatively better than insulation in improving the indoor conditions and that its performance can be greatly enhanced if the operating temperature is increased from 27°C to at least 30°C. Combined with the strategy of night ventilation and enhanced heat capacity storage, PCM could greatly enhance the thermal comfort levels. Copyright © 2017 VBRI Press.

Keywords: Phase change material, thermal comfort, buildings, microencapsulation, energy plus.

Introduction

It is estimated that almost 31% of the energy generated all over the world is utilised in the operation of buildings [**1**]. This demand for energy is increasing due to the changes in the living standards of the urban population and the increase in the usage of air-conditioners to provide thermal comfort inside buildings [**2**]. To reduce the energy consumption of the air-conditioners, several new technologies are being conceptualised. Some of them include providing insulation to the building envelop i.e. roof, wall and floor so as to reduce the amount of heat gain through the envelop [**3-9**]. Another technology which has gained prominence in the last decade is Phase Change Material (PCM). PCM has the capability to absorb and store massive amounts of heat during the phase change process and release this stored heat at a later stage [**10**]. PCM has been successfully integrated into the building envelop to reduce the heating and cooling load [**11-13**]. By microencapsulation of PCM into plaster, several problems of macro-capsules or direct immersion processes were eliminated [**14, 18**] and a reduction of peak indoor temperature of 2°C was achieved [**14**].

While studies have shown improvement in indoor temperatures for both cooling and heating seasons using PCM [**10-17**], it is the cooling season that is most significant in India as more than 90% of India is characterised by three types of climate zones: Hot & Dry, Composite and Warm & Humid synonymous with high temperature and high relative humidity levels (**Fig. 1**).

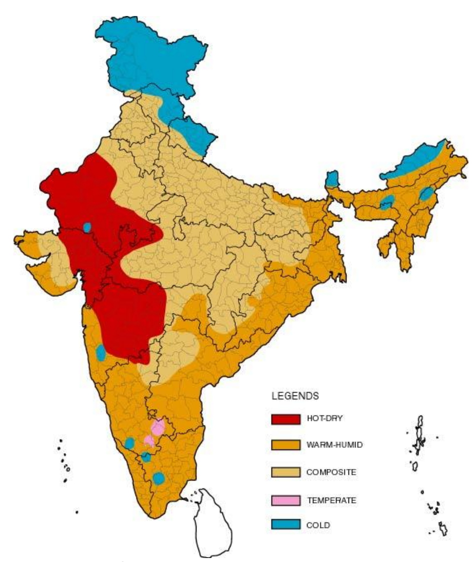


Fig. 1. Climate map of India.

Table 1 (available as supporting information from VBRI press) illustrates the conditions for classification of climate zones in India. Almost all the studies have assumed that a reduction in indoor temperature would lead to improved comfort levels within the room [**3-17**]. However other parameters like wind speed, and relative humidity also play a vital role in the determination of thermal comfort levels [**19**]. National Building Code of India (NBC) specifies a certain minimum desirable wind speed for achieving thermal comfort and just acceptable warm conditions at different temperatures and relative humidity [**20**] and are shown in **Fig. 2**. It is necessary to analyse the fabric heat gains along with the effect of thermal comfort conditions to fully justify the use of insulation or PCM and this study would play a key role in the future development of materials.

(a)

Dry Bulb Temperature, °C	Relative Humidity (Percentage)						
	30	40	50	60	70	80	90
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
28	*	*	*	*	*	*	*
29	*	*	*	*	*	0.06	0.19
30	*	*	*	0.06	0.24	0.53	0.85
31	*	0.06	0.24	0.53	1.04	1.47	2.10
32	0.20	0.46	0.94	1.59	2.26	3.04	**
33	0.77	1.36	2.12	3.00	**	**	**
34	1.85	2.72	**	**	**	**	**
35	3.20	**	**	**	**	**	**

* None

** Higher than those acceptable in practice.

(b)

Dry Bulb Temperature, °C	Relative Humidity (Percentage)						
	30	40	50	60	70	80	90
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
28	*	*	*	*	*	*	*
29	*	*	*	*	*	*	*
30	*	*	*	*	*	*	*
31	*	*	*	*	*	0.06	0.23
32	*	*	*	0.09	0.29	0.60	0.94
33	*	0.04	0.24	0.60	1.04	1.85	2.10
34	0.15	0.46	0.94	1.60	2.26	3.05	**
35	0.68	1.36	2.10	3.05	**	**	**
36	1.72	2.70	**	**	**	**	**

* None

** Higher than those acceptable in practice.

Fig. 2. Minimum Wind Speeds (m/s) for (a) Thermal Comfort Conditions (b) Just Acceptable Warm Conditions.

Experimental

To carry out the analysis, one city each is chosen from Hot & Dry, Composite and Warm & Humid climate zones. For Hot & Dry climate, the analysis is carried out for Jodhpur. New Delhi is chosen for Composite climate while analysis is performed for Bhubaneshwar as part of Warm & Humid climate. The locations are marked in **Fig. 3.** (available as supporting information from VBRI press).

Hourly weather data as provided by Indian Society of Heating, Refrigerating, and Air-Conditioning Engineers is obtained in EPW and DDY format for carrying out the analysis.

Numerical method

To study the effects of insulation or PCM on the thermal comfort, simulation was carried out using EnergyPlus software developed by U.S. Department of Energy and is one of the widely used software for numerical modeling of buildings. It uses conduction finite difference (CondFD) heat balance algorithm solved by either Crank-Nicholson or fully implicit finite difference scheme to simulate the performance of PCMs.

The CondFD method is coupled with an enthalpy-temperature function (**Equation 1**) that the user inputs to account for enthalpy changes during phase change. [**21**],

$$h=h\,(T) \tag{1}$$

The enthalpy-temperature function is used to develop an equivalent specific heat, C_p, at each time step. The resulting model is a modified version of the enthalpy method as per the equation:

$$C_p\,(T) = \frac{h_i^{\,j} - h_i^{\,j-1}}{T_i^{\,j} - T_i^{\,j-1}}$$

where, T is the node temperature, i is the modeled node, j is the actual simulation time step and j-1 is the previous one.

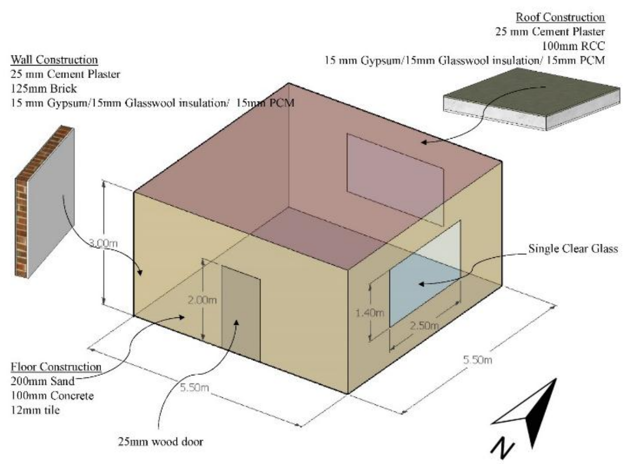


Fig. 4. 3D Model created in Sketchup.

Model description

A building of size 5.5m x 5.5m x 3m is modeled in Trimble Sketchup Make v2016 software (**Fig. 4**). Using OpenStudio v1.10.0 & OpenStudio plug-in for Sketchup softwares, the model is exported to Energy Plus v8.4.0.

The infiltration into the building is set to 0.000226568 m^3/s per m^2 of exterior surface area which is roughly equivalent to 1.15 air changes per hour. The ground temperature is maintained at a constant 18° C.

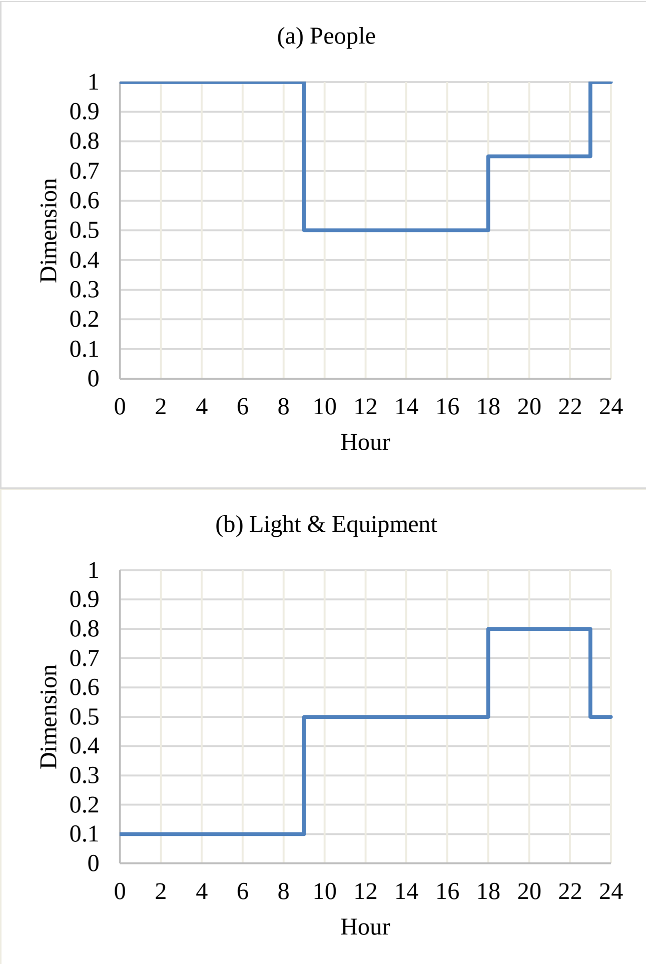


Fig. 5. Hourly profile used in simulation.

The lighting power density is set to 10 W/m^2 with a radiant fraction of 0.5. The equipment power density is set to 4 W/m^2 with a radiant fraction of 0.5. It is assumed that 5 people would be staying within the house and the radiant fraction is set to 0.3. The hourly profiles for the internal loads (people, lights and equipment) is shown in **Fig. 5**.

The construction build-up is considered as 25mm Cement Plaster + 125 mm clay brick + 15mm Gypsum/15mm Glasswool insulation/15mm PCM for external wall. For the roof, the construction build-up is considered as 25mm Cement Plaster + 100 mm Reinforced Cement Concrete (RCC) + 15mm Gypsum/15mm Glasswool insulation/15mm PCM. 200mm Sand + 100 mm concrete + 12mm floor tile is considered for the floor. The glass is considered as single clear 6mm thick float glass while the door is assumed as 25mm thick wood door. Glass is placed on north and east façade while the door is placed on the south façade. No openings is considered on the west façade.

Thus simulation is carried out for three types of construction build-up by modifying the wall and roof, while keeping the build-up of floor, glass and door constant. This is illustrated in **Table 2**.

Materials details

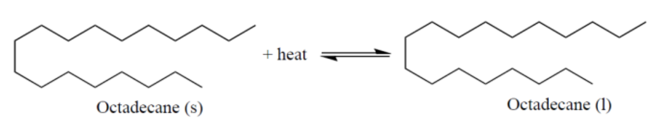
The materials used for carrying out the simulation along with their physical properties are listed in **Table 3** (available as supporting information from VBRI press). The PCM used for this study is Micronal PCM Smartboard developed by BASF. The melting and setting enthalpy to enter into Energy Plus are obtained using PCMexpress v1.0 (3) software and is illustrated in **Fig. 6** (available as supporting information from VBRI press)

Table 1. Construction build-up for simulation.

No.	Analysis Mode	Wall build-up	Roof build-up
1	Normal	25mm Cement Plaster + 125 mm clay brick + 15mm Gypsum	25mm Cement Plaster + 100 mm RCC + 15mm Gypsum
2	With Insulation	25mm Cement Plaster + 125 mm clay brick + 15mm Glasswool insulation	25mm Cement Plaster + 100 mm RCC + 15mm Glasswool insulation
3	With PCM	25mm Cement Plaster + 125 mm clay brick + 15mm PCM	25mm Cement Plaster + 100 mm RCC + 15mm PCM

Material reactions

The main chemical used in Micronal PCM Smartboard is paraffin wax or octadecane. It undergoes a phase change from solid to liquid by absorbing heat during the day time and this phenomenon is known as charging. During the night, when conditions permit, it then releases back heat and undergoes a phase change from liquid to solid and this is known as discharging[**22**]. Generally the currently available PCMs can last at least 2000 cycles. The general reaction can be represented as below:-



Characterizations

The analysis is carried out starting from March through October. Upon simulation, the room indoor hourly temperature and humidity levels are extracted from the output of the EnergyPlus result file. The obtained hourly temperature and humidity results are then compared with the upper limit of comfort and acceptable warm conditions of NBC of **Fig. 2.** The comparison is carried out by plotting the temperature v/s humidity chart for the upper limit and generating an equation of the form $R=f(T)$ where R is relative humidity & T is the temperature of that hour. Using the above equation, the relative humidity is calculated for the obtained temperature of that hour. If the calculated relative humidity is lower than the relative humidity generated in the EnergyPlus output, then it can be said that by providing the listed wind speed, thermal comfort will be achieved.

Results and discussion

The results obtained by carrying out the analysis is tabulated in **Table 3** and **Table 4** for Thermal Comfort conditions and Acceptable Warm conditions.

Table 3. Results obtained for Thermal Comfort conditions.

City	Climate	Analysis mode	Comfort Hours	%(out of 5880 hours)
Bhubaneshwar	Warm & Humid	Normal	3221	54.80%
		With Insulation	3588	61.00%
		With PCM	3780	64.30%
Jodhpur	Hot & Dry	Normal	2726	46.40%
		With Insulation	3090	52.60%
		With PCM	3182	54.10%
New Delhi	Composite	Normal	2716	46.20%
		With Insulation	3047	51.80%
		With PCM	3157	53.70%

Table 4. Results obtained for Acceptable Warm conditions.

City	Climate	Analysis mode	Acceptable warm Hours	%(out of 5880 hours)
Bhubaneshwar	Warm & Humid	Normal	4406	74.90%
		With Insulation	4842	82.30%
		With PCM	4935	83.90%
Jodhpur	Hot & Dry	Normal	3560	60.50%
		With Insulation	4008	68.20%
		With PCM	4063	69.10%
New Delhi	Composite	Normal	3573	60.80%
		With Insulation	4003	68.10%
		With PCM	4080	69.40%

All the construction materials not only offer some resistance to the transfer of heat but also store it, although their heat storage capacities are lower as compared to PCM or insulation. Time is considered as another parameter in the transfer of heat and this is known as transient heat transfer. This leads to the phenomenon known as time delayed heat transfer.

When the night temperatures are compared for Hot & Dry climate and Warm & Humid climate in **Table 1** (available as supporting information from VBRI press), it may seem that Hot & Dry climate would perform better.

However, the results indicate that among the three cities, the best indoor conditions are being achieved in Bhubaneshwar.

In normal analysis mode in Bhubaneshwar, 54.8% of analysis hours are in thermal comfort conditions while 74.9% of the analysis hours are in acceptable warm conditions. While in Jodhpur and New Delhi only 46.4% and 46.2% of the analysis hours are achieving thermal comfort conditions. For acceptable warm conditions, 60.5% and 60.8% of analysis hours are being satisfied for Jodhpur & New Delhi respectively.

Then insulation is added to the construction, Bhubaneshwar is still performing the best among the three cities. 61% and 82.3% of the analysis hours are in thermal comfort conditions and acceptable warm conditions respectively. An improvement of 6.2% and 7.4% is achieved by adding insulation for thermal comfort conditions and acceptable warm conditions respectively when compared to normal construction. While for Jodhpur, the comparative improvement by adding insulation is 6.2% and 7.7% for thermal comfort conditions and acceptable warm conditions respectively. For New Delhi, the figures stand at 5.6% and 7.4% for thermal comfort conditions and acceptable warm conditions respectively. This indicates that insulation is performing almost similar percentage improvements in performance across all scenarios.

If insulation is replaced by PCM, the percentage improvement over normal for thermal comfort conditions and acceptable warm conditions stand at 9.5% and 9% for Bhubaneshwar, 7.7% and 8.6% for Jodhpur and 7.5% and 8.6% respectively.

The results for Bhubaneshwar also indicate that acceptable warm conditions improve by 20.1% for normal, 21.3% for insulation and 19.3% for PCM in comparison to thermal comfort conditions. For Jodhpur the percentage improvement stands at 14.1% for normal, 15.6% for insulation and 15% for PCM when acceptable warm conditions are compared with thermal comfort conditions. The percentage improvement for New Delhi for acceptable warm conditions in comparison with thermal comfort conditions are 14.6% for normal, 16.3% for insulation and 15.7% for PCM.

Overall the results indicates that PCM is performing the slightly better when compared to insulation.

The results thus indicate that climate of Bhubaneshwar is providing the best indoor conditions among the three cities. This is partly because in Warm & Humid climate, the summer day time temperature stays between 30 and 35. This results in a lower fabric heat gain throughout the day. Additionally, Bhubaneshwar is about 100 km away from the coast. During the day the land mass is heated more quickly than the water body by the incoming solar radiation. The air over the land also gets heated and it starts expanding, decreasing the pressure over the land. This results in pressure difference across the land and the sea and air starts moving from the sea to the land during the evening and the night resulting in cool breeze with higher velocity.

A temperature pattern indicates that the room temperature stays above 30°C most of the time. The operating temperature of the PCM is 27°C. This indicates that the PCM is unable to completely discharge and regain solid form. Thus for the next cycle of charging, the heat storage capacity is not fully utilised. Therefore the operating temperature of PCMs should be at least 30°C for Indian climatic conditions.

Conclusion

In this study, a comparative assessment of thermal comfort with Insulation and PCM utilizations in building roofs and walls was made for three cities i.e. Bhubaneshwar, Jodhpur and New Delhi, all under different climatic conditions. It was also found that the city of Bhubaneshwar was performing the best in terms of indoor conditions for occupants. For Bhubaneshwar it was also found that PCM was preforming slightly better in improving the indoor conditions when compared to insulation. However the performance of PCM can be greatly improved if the operating temperature is increased to at least 30°C. Therefore PCM materials, which melt or set at not less than 30°C, have to be used. For Delhi and Jodhpur the performance of the existing PCM are comparable and makes an impression of not a great energy savings contributor.

Another way to improve performance further would be to enhance the heat storage capacity by increasing the thickness of the PCM and could lead to a better performance of PCM. Another strategy could be to ventilate during the night.

A combination of the above strategies could lead to PCM performing better than insulation for Indian climatic conditions.

Author's contributions

Conceived the plan: DR, KB; Performed the expeirments: KB; Data analysis: DR, KB; Wrote the paper: DR, KB. Authors have no competing financial interests.

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