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Impact of employing phase change material in building wall on energy consumption and thermal comfort level

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K E Y W O R D S

Energy Efficiency

Efficient Buildings

PCM Effect

Thermal Comfort Level

Energy Plus Software

A B S T R A C T

Energy crises are becoming a problem for the globe. Most of the energy being produced is utilized in buildings. Building design and materials that are used in buildings play a vital role in saving electricity. Sustainable cities are one of the eleventh goal of Sustainable Development Goals to be achieved and this study is in context of SDGs for developing tools to create this globe sustainable and efficient society for humans. Phase change material is a type of material that can absorb and release heat energy as it changes between solid and liquid states. This ability to store and release thermal energy makes phase change materials a promising material for use in building insulation, Heating Ventilation Air Conditioning Systems, and other energy-efficient applications. The use of PCM in buildings has the potential to significantly reduce energy consumption and improve thermal comfort levels. By incorporating PCM into building envelopes, such as walls, roofs, and floors, the material can absorb excess heat during the day and release it at night, helping to regulate indoor temperatures and reduce the need for heating and cooling systems. This study investigates the impact of using PCM in building envelopes. In this regard, office building rooms are modelled in computer-aided design software and are simulated in energy plus software. The simulation results are validated by considering the experiment and numerical study as a reference from the paper. The model room is simulated for Hyderabad, Pakistan. Building envelopes without PCM have a conduction rate of around 106.6 W/m2, whereas building envelopes with PCM have a conduction rate of around 42 W/m2. This shows that utilization of PCM reduced heat conduction up to around 40%. PCM reduced energy consumption by around 33.25 kWh/year/m2. Results show that without PCM air temperature was above the thermal comfort value. it reached 300C in hot months, it reduced up to 270C with the incorporation of Phase Change Material.

1. Introduction

The ability of Phase change material to absorb thermal energy in form of latent heat during phase change makes it one of the choices for thermal energy storage (TES)[1]. It tends to shift the cooling load from peak to off-peak hours by improving the system efficacy by decreasing the required capacity[2]. Heat energy-storage process has developed many applications and forms because of its several advantages in exploiting solar energy, reducing energy consumption, and ensuring environmental paybacks. Employing phase change materials (PCMs) with building elements is among the fast-growing technologies these days, thanks to their high potential for thermal energy storage and supple use to improve building energy-saving and thermal comfort[3]. Present energy crises around the globe are a sign of huge energy utilization and it will increase with increase in population and living standard of people, one of the major contributors is air conditioning system[4]. Approximately 40% of the total energy used by the building sector is used for cooling and space heating, respectively, and that will increase greenhouse gas emissions by around 25%[5]. Building inhabitants experience heat stress during the summer owing to indoor warming, which causes them to experience pain[6]. As a result, the residents' productivity at work declines. Therefore, it's crucial to design energy-efficient buildings that will lessen their environmental impact while also consuming less energy[7]. Passive cooling is one of the newest technologies that draws researchers[8]. There are two different kinds of cooling methods: the conventional method, which uses mechanical devices like air conditioners for cooling, and the non-conventional method, which uses passive cooling and thermal energy storage materials like Phase Change Materials (PCM)[9]. The introduction of phase change material ranks highly on the list of solutions that reduce heating and cooling load in building envelopes and produce energy-efficient buildings because it offers advantages in terms of thermal comfort and energy efficiency[10]. This is one of the methods that not only lowers energy consumption but also has a beneficial impact on greenhouse gas emissions[11]. Phase change materials, sometimes referred to as thermal energy storage devices, are frequently utilized in the construction of energy-efficient buildings and have a favourable effect on the rate of energy consumption[12]. By implementing this strategy, buildings can provide excellent interior air quality and thermal comfort while using less energy overall. Due to its enormous thermal energy storage capacity during the phase transition from solid to liquid, phase change materials (PCM) can be utilized to reduce the cooling and heating load in the building envelope while still maintaining a certain level of thermal comfort[11], [12]. In this view, the leaning in the direction of the function of passive cooling method have improved to be alleviate greenhouse gases emission[13], [14], [15], [16]. In the current scenario many studies have been carried out regarding the energy consumption and providing thermal comfort in buildings by using passive cooling approach. Passive cooling technique is a non-mechanical energy utilization of this technique not only reduces the energy consumption but also mitigates the adverse effects of building on the environment[6], [13], [17], [18]. Furthermore, passive cooling technique control the interior temperature variation along with maintain the air temperature of the building room near the comfortable range because of decrease in fossil fuel usage as well reduce the greenhouse gas emission[15], [19], [20], [21], [22], [23], [24], [25]. Different ways can be utilized for the incorporation of phase change material in building envelopes. Direct incorporation, immersion, and encapsulation[6], [26]. Out of these micro encapsulation combination with gypsum board proved to be a good arrangement for energy efficient design of a building[27], [28]. Because it prevents Leakage problem of PCM and provides larger heat exchange area as a result heat transfer rate is increase. For behaviour of PCM materials and its effectiveness on the local climate of Hyderabad, Pakistan is considered. World population is growing rapidly, and it pushes the demand of electricity including residential, business, and industrial purposes[7], [8], [29], [30], [31], [32], [33]. In a process, the conventional methods to produce power has been researched that its widespread ramification is harmful for the masses and has negative impact on eco system[10], [34], [35], [36]. As, a consequence researchers and engineers are trying new ways to explore technologies and smart materials that can mitigate energy usage along managing thermal comfort levels. One of such material getting attention is phase change materials. PCM is the material that can release and absorb thermal energy as it goes from solid and liquid phases. Ability to store and release energy enables PCM a material favourable for use in buildings insulations, Heating ventilation and air conditioning systems and many like energy-efficient applications[1], [4], [23], [34], [35], [38], [39], [40], [41], [42]. The PCM can potentially be significant in reducing consumption of energy and helps maintain thermal comfort level. By using PCMs in building walls, roofs, and floors the PCM absorbs heat during the day and at night releases it thus helping in regulation of indoor temperatures of buildings which in results reduces the need of Air-Conditioning systems[3], [5], [9], [12], [21], [43], [44], [45], [46] . Resulting in enormous energy savings, especially the areas with high diurnal temperature variations[32], [35], [37], [38], [38]. Due to reduction in temperature fluctuations, PCM aids to enable stable and convenient indoor environment, productivity and well-being thus is achieved. The effectiveness of PCM depends on various factors, which include type and amount in which PCM is used, Building design and surrounding climate. So, for this it needs to understand pros and cons of PCM in variety of applications. The main purpose of the research work is to investigate the effects of employing phase change material in building envelopes on cooling load energy demand and thermal comfort of occupants. The modelled room location is considered in Hyderabad Sindh, Pakistan.

The study's main objective is to determine how the building envelope would react thermally when integrated with phase change material. As was already mentioned, several wall arrangement options are also taken into consideration. Hyderabad, Pakistan is where the modelled room is located. Energy Plus Software contains a description of every important detail. The paper presents a case study of the building model in Hyderabad to see the change in indoor temperature when incorporating the PCM material and other various parameters which effects the thermal comfort for the occupants in the building in this region and is the policy tool to be considered when designing the building in this area.

2. Methodology and Description of Building Room

The work starts with the modelling of the single room in Sketchup software whose orientation is described and the material properties are shown in Table 1 and Table 2, the weather file which is the input to Energy plus software for Hyderabad Pakistan is acquired through the site called "white box technologies" after inserting both files and setting some parameter we obtain the required results and generate the graphs of the relations between the Parameters. Fig. 2 shows the conventional building composition and Fig. 3 show the PCM introduction in walls of the building and Fig. 4 introduces the gypsum and its effect on the energy consumption and other parameters. It is assumed in the paper that the system is homogenous, lighting, and other things are not considered in this paper. An envelope of a single room of a building having volume of 64 m^3 with one window, door directed south and north respectively is modelled in a CAD software and simulated in energy plus software as shown in Fig. 1. In energy plus software, for simulation an input data file is generated in which all necessary details of building envelope are described. Material and physical properties of an office room and Construction detail is described in Table 1 and in Table 2 respectively. The modelled office room is simulated for different cases. In the first case conventional construction material is used seen in Fig. 2 and in another case a phase change material is used within the conventional material. The arrangement of PCM with conventional material is shown in Fig. 3 and 4 and the properties of PCM are given in Table 1 Basically we are comparing the PCM and with no PCM material effect on energy consumption, results were validated with published work, results came from the energy plus simulation software with above mentioned material and validated with published literature results came from experimental results. To summarize, a room is taken to study in energy plus software, the weather file is inserted in IDF file with the below data like material Sdata and other properties, the CAD model is built on SKETCHUP, its results are simulated according to weather data which is an input in energy plus software and the results are generated in excel file. This study is carried out by considering the climate of Hyderabad Pakistan, to establish the SDGs in the region.

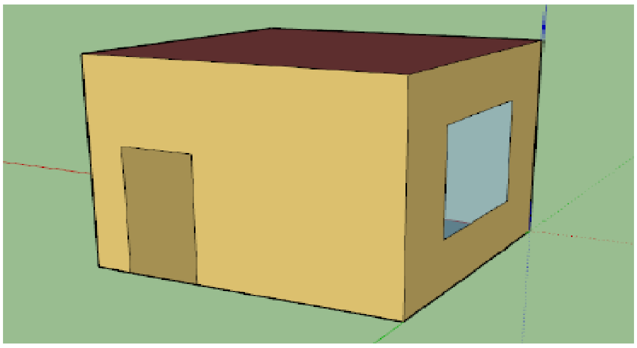

Fig. 1. An Envelope of a Single Room of An Office Model

Table 1

Material Physical Properties

Material	Thermal conductivity (w/m-K)	Melting temperature (K)	Specific heat (J/kg K)	Density (kg/m^3)	Phase change enthalpy (kJ/kg)	Thickness (cm)
Concrete	1.4	-------------	880	2300	--------------	3
Clay Brick	1.3	-------------	880	1460	--------------	15
Plaster	0.22	-------------	1085	1680	--------------	2
Gypsum	0.16	--------------	0.84	950	-------------	0.12
Paraffin C18 (PCM)	0.15	295 - 300	2500	814	243	10

Table 2

Construction detail of an office room(Conventional)

Layer (Outer to Inner)	Roof	Wall	Floor
1	Plaster	Cement	Acoustictile
2	Concrete	Clay brick	Plaster
3	Plaster	Plaster	Concrete
4	---------	---------	---------

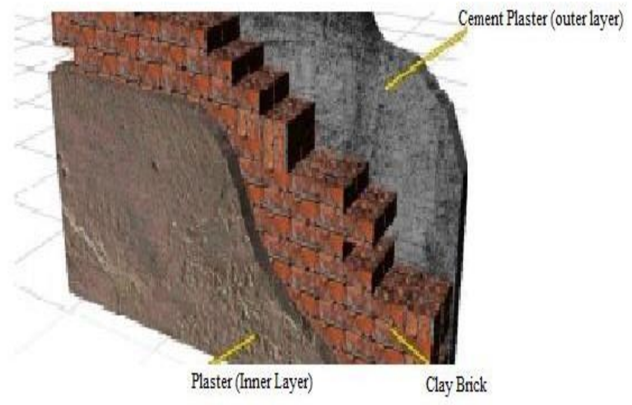

Fig. 2. Wall Conventional Construction of a Single Room Model[32]

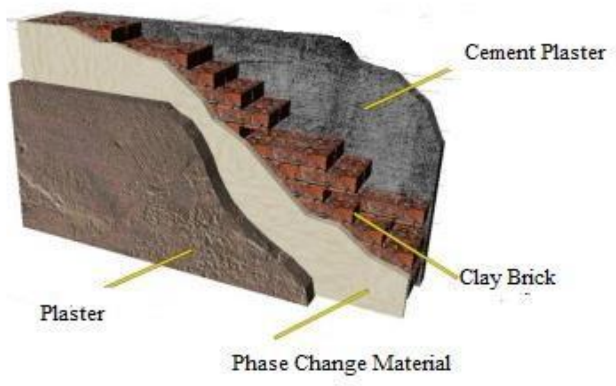

Fig. 3. Wall Non-Conventional Construction of a Single Room Model[32]

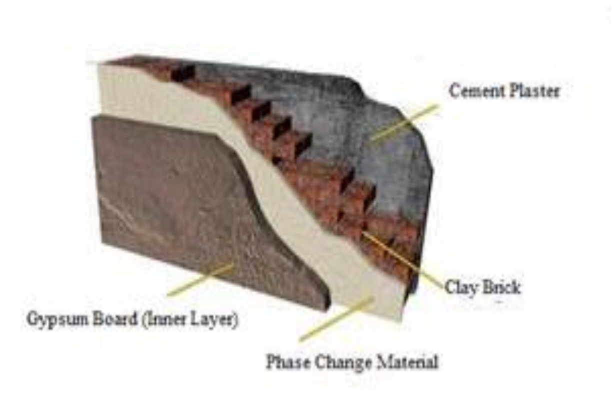

Fig. 4. Non-Conventional Wall Construction with Gypsum Board

3. Mathematical Modelling

The mathematical modelling includes the conduction heat equation working in Energy Plus Software, heat transfer reduction equation and cooling load reduction equation.

3.1 Conduction Heat Solution Algorithm

$$Cp * \partial * \Delta x * \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(K_W . \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + K_E . \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right) \quad (1)$$

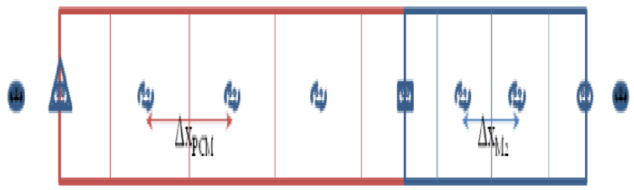

Fig. 5. Energy Plus Wall Conduction Model

3.2 Building Office Room Heat Conduction Analysis

According to the[14], [32], PCM utilization is effective. If the ratio of heat transfer reduction (HTR) is less than unity.

$$HTR = \frac{Q_{pcm} - Q_{without\ pcm}}{Q_{without\ pcm}} \quad (2)$$

3.3 Cooling Energy Saving

Cooling load reduction (%)

The reduction in cooling load (CLR) which is caused by Phase change material is calculated as follows.

$$CLR = \frac{C.L_{pcm} - C.L_{without\ pcm}}{C.L_{without\ pcm}} * 100 \quad (3)$$

Where Cooling load (C.L) in kWh.

Also, reduction in cooling load can be calculated as, Reduction of cooling load = cooling load of room without PCM – cooling load of room with PCM wall.

3.4 Data Validation

The simulation work for this study is carried out on energy plus software. The present study is validated by an experimental and numerical study done by [14], [32]. For validation of experimental work done previously done by researchers, a typical building model having a volume 64 m^3 and situated in Hyderabad was simulated. During the literature review, it was observed that the work done by researchers experimentally, which is validated with the simulation software and the results that were obtained are of the same pattern as shown in Fig. 6, Fig. 7, Fig. 8 shows the temperature of inner space measured experimentally by employing phase change material and to validate the outcome of simulations came out to be same thus validating the study. Fig. 7 shows the temperature during different hours of the day obtained through the simulations and comparison with experimental outcomes in one of the reviewed papers.

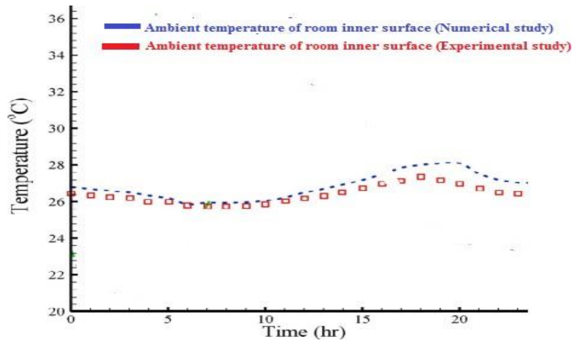

Fig. 6. Ambient Room Temperature (Present Study)

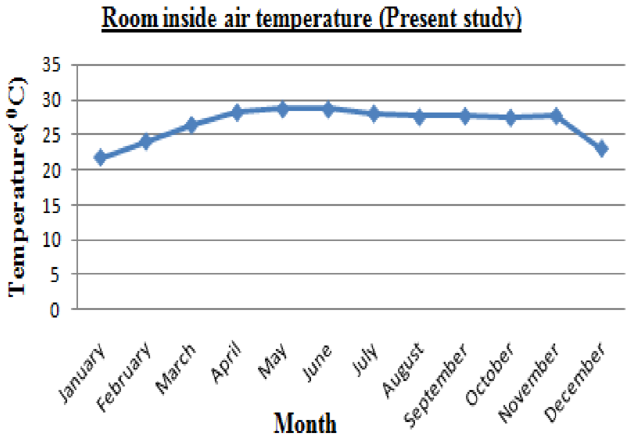

Fig. 7. Ambient Temperature of Room Inner Surface

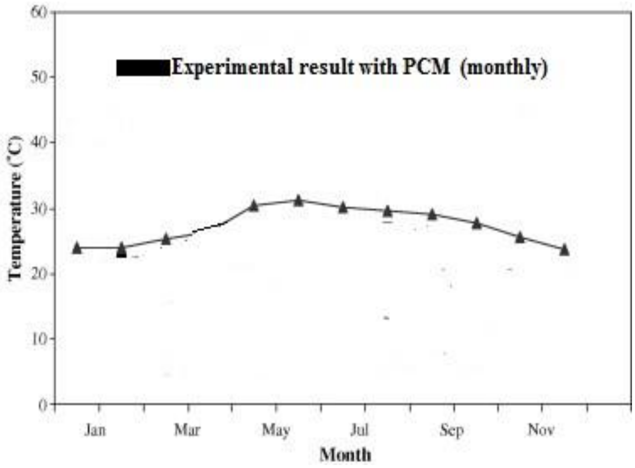

Fig. 8. Numerical and Experimental Study

4. Results and Discussion

1. The heat conduction rate in the overall analysis was high without using PCM materials which is the matter of concern, whereas the usage of PCM decreases the heat conduction rate through building walls.

2. The correlation of operating temperature with energy consumption and heat conduction rate was analysed in the paper, the results highlight that with the usage of PCM in a building the energy consumption is low which means less energy is consumed whereas the building without PCM has high consumption and it is seen in simulated results.

3. Co-relation of gypsum board with plaster and PCM was analysed in the paper.

Overall, the effect of PCM tends to decrease the energy required by the room and thus enabling the sustainable environment.

4.1 Case 1,2: Office Room Wall Heat Conduction Rate

Fig. 9 shows that integration of PCM with the envelope can effectively decrease heat conduction rate. In summer season temperature values reached their peak position due to high intensity of solar radiance which causes over heating of building envelope as can be seen in Fig.9. In June and July, the heat conduction rate of office room envelope is high which causes overheating of building, because of human discomfort level increase. Most of the office places utilized mechanical cooling systems for thermal comfort achievement. On other hand passive cooling approach also have a good potential as discussed here. Fig.9 shows that for Hyderabad region utilization of Phase change material is beneficial. Without PCM the room will have higher values of heat conduction rate as compared to room envelope having phase change material.

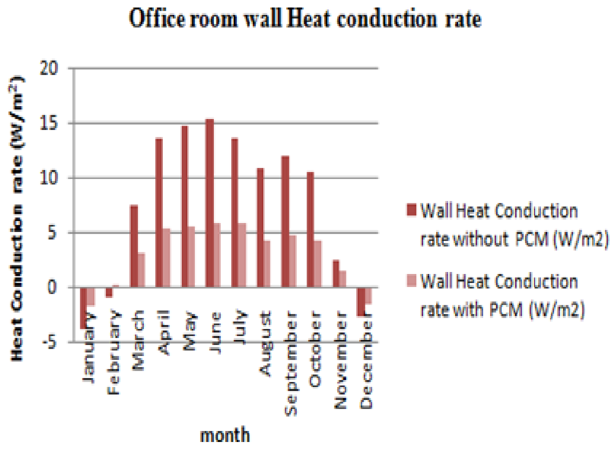

Fig. 9. Building Room Wall Heat Conduction Rate

There is a huge difference between these values, hence incorporation of PCM can not only reduce the cooling energy demand in hot months.

4.2 Cooling Energy Consumption (With and Without PCM)

Between March and October cooling energy demand increase gradually due to high intensity of global temperature around the buildings. Maximum demand in the months of May, June, July.

Hence passive cooling technique proved to be beneficial, it decreases the cooling energy demand in warm months. Building envelope without PCM cause maximum demand of cooling energy around the year, almost 531.75 kWh are required for maintaining thermal comfort level. On other side building envelope with PCM decrease the cooling energy demand, in a whole year consume cooling energy near 369 kWh and around 162 kWh of cooling energy will be saved.

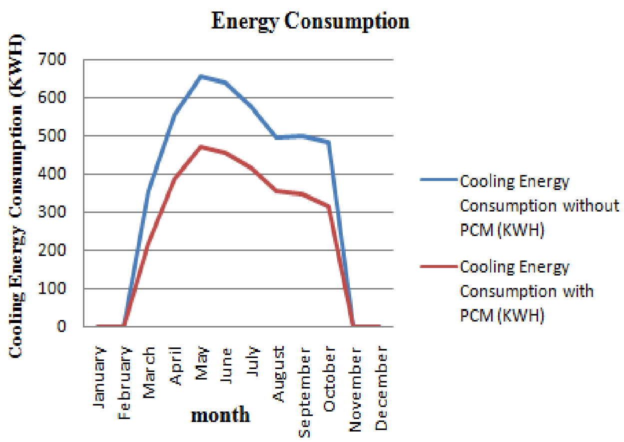

Fig. 10. Building Room Energy Consumption

4.3 Thermal Comfort Analysis of Office Room

Human thermal comfort condition depends upon the surrounding environment. Factors that influence the human thermal condition are air temperature and radiant temperature. According to the ASHARE standard 55-1992, the temperature range 24^0C to 26^0C a normal human feel thermally comfortable in winter and summer respectively. Fig 11 and Fig.12 illustrate that in June and July, air temperature and radiant temperature cross the thermal comfort temperature value in case of conventional construction and put load on cooling energy consumption for achieving thermal comfort level. But on other side utilization of thermal storage material decreases the air temperature and radiant temperature which is near to the thermal comfort temperature as can be seen in Fig.11 and Fig.12. As a result, demand for cooling energy also minimized which can save some amount of electricity.

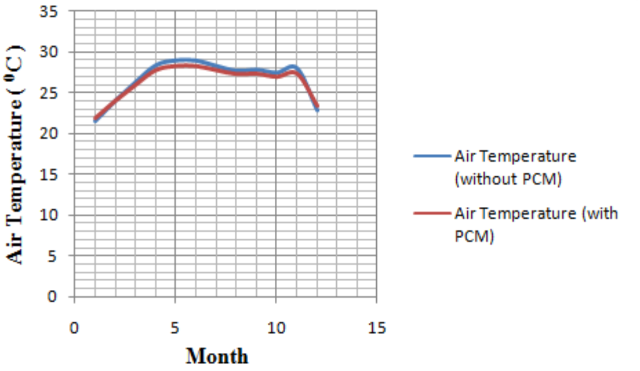

Fig. 11. Building Room Air Temperature

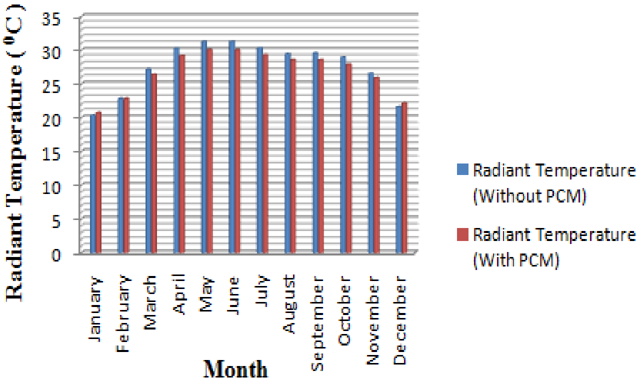

Fig.12. Building Room Radiant Temperature

4.4 Parameters That Influence the Cooling Energy Consumption of An Office Room

The following are the parameters that influence the cooling energy consumption of an office room.

4.4.1 Operative temperature

Fig. 13 shows that energy consumption increases as the operative temperature increases. It implies that energy consumption depends upon the operative temperature. As discussed earlier, operative temperature is used as an important factor for the evaluation of thermal comfort conditions. As the value of operative temperature reached maximum as shown in Fig.13 and Fig. 14, demand for cooling energy enhanced. Hence it is necessary to control operative temperature parameters for the purpose of energy saving. Therefore, there is need to adopt some new techniques that provide thermal comfort with minimum consumption of energy. One of the techniques already discussed in this work, passive cooling technique which now a days is an attractive technology for the design of energy efficient building and its utilization is so beneficial as can be seen in Fig.14, Operative temperature value decrease down near the thermal comfort value as a result cooling energy demand decrease. Hence for the energy efficient building it is necessary to control operative temperature parameter. One of the techniques discussed in this work is the passive cooling technique which has proved to be beneficial for considered region.

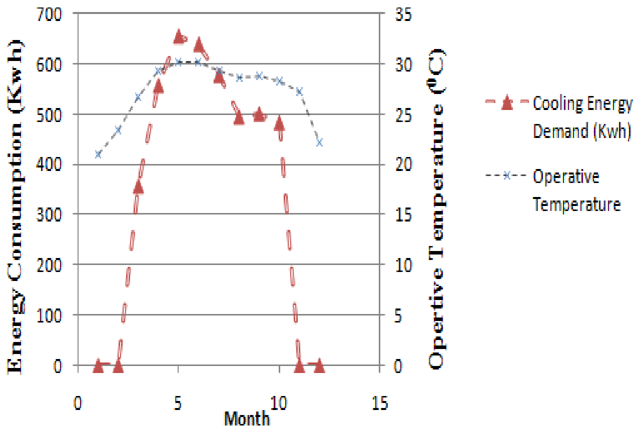

Fig. 13. Consumption Of Energy Against Operative Temperature (without PCM)

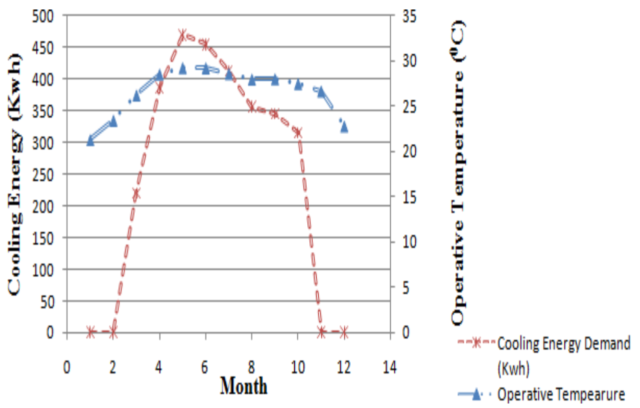

Fig. 14. Consumption of energy against Operative temperature (With PCM)

4.4.2 Heat conduction rate

Another factor that influences cooling energy consumption of an office room of a building is heat conduction rate. As can be seen in Fig.15, which elaborates that in warm months of summer rate of heat conduction of the office room of a building increase, demand for cooling energy also increases. Envelopes of a building directly exposed to the sunlight building envelopes get warm usually in March, April, May, June, July. In a middle of a day around after noon when intensity of irradiance reaches high envelop of building gets warm through conduction. As the time passes the conducted heat of the building envelope initiates toward the occupant space. As a result, people feel uncomfortable and try to maintain the temperature near to their comfort. Therefore, demand for cooling energy increases in peak hours of the day. Researchers use several techniques for that to minimize cooling energy demand in peak time of the day, some of them use insulation material. But in this research work passive cooling technique is utilized, and it effect on the heat conduction rate and cooling energy demand can see in Fig.16 which illustrate that incorporation of thermal storage material with office room building can not only reduce the heat conduction rate but also reduces the cooling energy demand in hot month of the year.

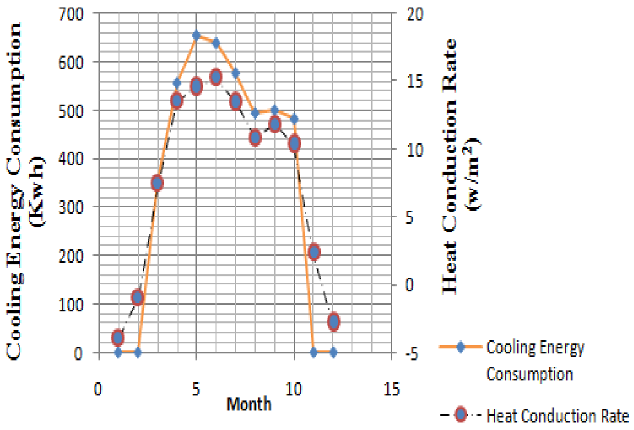

Fig. 15. Energy Consumption Against Heat Conduction Rate

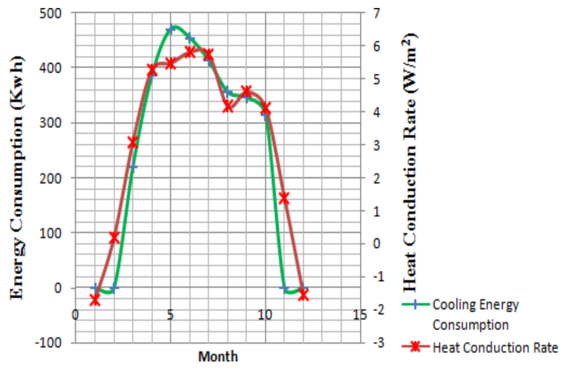

Fig. 16. Energy Consumption Against Heat Conduction Rate

4.5 Phase Change Material with Gypsum Board

Fig. 17 represents that replacement of plaster layer with gypsum board has not much effect on energy consumption as compared to the PCM and plaster arrangement in a building envelope. Further it shows that both settings with PCM give nearby results. One of the reasons can be illustrated as due to the thermal storage capacity of phase change material are so effective that it doesn't allow heat conduction to pass through its preceding layer. Hence performance of Phase change material when it employed near the interior side of the wall doesn't affect by its upper layer.

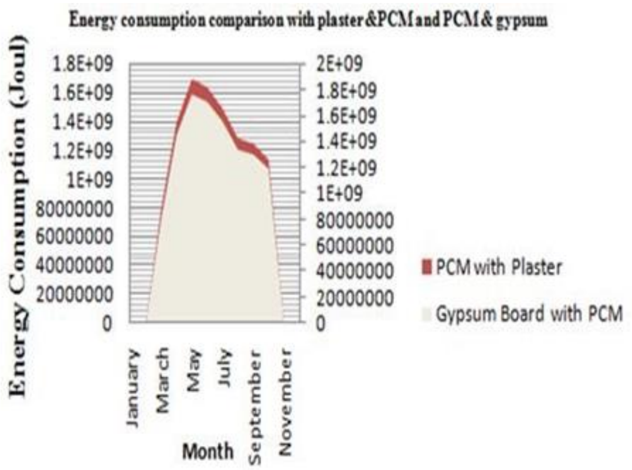

Fig. 17. Energy consumption with gypsum wall board and PCM and PCM and plaster

5. Conclusion

The Results show that the phase change material has huge impact on the decreasing energy needs and maintaining thermal comfort in the model room simulated in energy plus software.

Following are the key outcomes of the research.

1. It validates the experimental research performed by other researchers mentioned above. Further it validates the software like energy plus to be efficient and correct tool to use in modelling the building energy systems for the new buildings.
2. PCMs showed reducing cooling energy demands in the model room and is the guide for stakeholders to efficiently use it in the building so that by reducing energy requirements we can mitigate the global warming.
3. The use of PCM decreased the indoor room temperature from 1 to 1.5^{0}C.
4. The study highlights that when the conduction rate increases the energy will be lost and the system will require more energy.
5. It is shown that with same operative temperature in room with PCM material and without it, the energy required is high in conventional building orientation.
6. Heat conduction through walls can be greatly reduced using PCM.
7. PCM with plaster and PCM with gypsum board has no greater effect on energy consumption rate.

This study reveals that incorporation of phase change material in building room envelope provide exceptional results regarding thermal comfort and cooling energy consumption. In this research work a wall of a typical room model with different construction arrangement are simulated in an energy plus software. Room model location is in Hyderabad, Pakistan. It is clear from the results PCM proves to be beneficial for current region. Generally cooling energy demand increases in March, April, May, June and July. The reason is that excessive heat gain by the building envelope cause overheating of the building room, as a result indoor room air temperature increase which cause thermal discomfort. Therefore, for thermal comfort they utilized HVAC system which adds a considerable amount in monthly electricity bill specially in hot months. As discussed earlier in this research work passive cooling approach is a good technique to mitigate huge amount of cooling energy consumption as well as providing thermal comfort. The outcome of the study elaborates that envelopes with phase change material save 162 kWh of energy per year along with a reduction of 40% heat conduction rate of the wall as well. Phase change material is also capable of maintaining the room temperature near the thermal comfort temperature. Also, operative temperature and heat conduction rate are the two most important parameters that put load on cooling energy consumption. It is found that if the value of operative temperature remains within the thermal comfort level, demand for cooling energy may decrease. Specially in June and July in these two months when the temperature value touch above 30^0C value, demand for cooling energy gradually increases and reached up to 650 kWh. But on other hand when room temperature remains within the range of 26^0C to 28^0C, demand for cooling energy falls below and reached around between 400kWh to 450kWh. A considerable energy saving amount is attained, the temperature value falls within the comfort zone. The utility of this research is not limited to this region, but it can be studied in any location for achievements of SDGs.

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