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Analysis of the effect of phase change material on indoor temperature in subtropical climate region

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ABSTRACT

Efficient use of energy is a need of time. The extravagant use of energy has caused depletion of energy resources which has raised concerns in scientific community. Past studies revealed that among different applications that consume energy, buildings are the major consumers of energy. In some countries, 50% of the total energy is consumed by buildings. Most of energy in buildings is used for heating, ventilating and air conditioning (HVAC) purpose. One of the methods to conserve energy and reduce the amount of energy required for HVAC purposes is modification in building envelope. Incorporation of phase change materials (PCM) in building envelope is one of such modifications. This paper reports the analysis of the use of PCM in prototype residential building. The results suggested that PCM can store considerable heat while undergoing phase change. This was shown by very stable indoor temperatures over 24 hours. A maximum of 2°C temperature variation was recorded in the room with PCM incorporated in walls and slab. While the variation of temperature over the day and night for a reference room without PCM was 7°C to 8°C. This suggested that PCM can be helpful in shifting the peak load hours.

Keywords:
Phase Change Material; Subtropical climate; Buildings; Thermal comfort; Thermal Performance

1. Introduction

Buildings consume a significant amount of energy mainly due to the insufficient insulation systems. There is growing desire for higher comfort level and luxurious lifestyle [1]. A major portion of energy is used for acquiring thermal comfort in a built environment [2]. Among different factors that contribute in building energy consumption, HVAC systems are the main consumer of energy. Around 50% of energy is utilized by space conditioning systems to maintain the indoor environmental conditions at comfortable and acceptable range [1]. This enormous amount of energy consumption by buildings is one of the reasons behind problems such as energy shortages, climate change and environmental pollution [3]. To address these issues, researchers around the globe are investigating new technologies and proposed different solutions including use of phase change materials (PCM). The efficacy of these materials comes from their phase changes. These materials absorb energy thus

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change their phase from solid to liquid and release energy to convert from liquid to solid. During this process of phase changes these materials maintain near constant temperature. By maintaining temperature, they control temperature fluctuations inside building and thus reduce energy usage [4].

Researchers have investigated the effectiveness of integrating PCM in buildings numerically and experimentally. Zalba *et al*., [5] reviewed and summarized 230 papers on the topic of PCM and their heat transfer characteristics. Many different PCMs were studied in those papers. Different methods were analyzed for determining their thermal properties. Problems related to their stability and encapsulation was discussed. Lamberg *et al*., [6] compared enthalpy method and effective heat capacity method for simulating phase transition of phase changing materials. Their results revealed that though both numerical methods work well but effective heat capacity method gives more accurate results. Chen *et al*., [7] applied heat capacity method to simulate a 1D, non-linear model of heat conduction for a wall board integrated with PCM. Their focus was to find the most appropriate location for placing PCM wall board. Results of their study revealed that north wall is the suitable location to fix PCM wall board. A one-dimensional model of stainless steel panel roof filled with PCM was developed and numerically studied by Pasupathy and Velraj [8]. They analyzed the effect of ambient condition and heat transfer coefficient on outer roof surface and panel thickness. Their theoretical and experimental results were in close agreement. Cho *et al*., [9] found that PCM enhanced building can provide thermal insulation. Authors [11-12] investigated 2D models of PCM heat transfer using different software's like COSMOS/M and CFD Fluent. Temperature-enthalpy and enthalpy-porosity models were used in these simulations. All these simulations showed that PCM helps in controlling heat flux and works as insulator. The simulated roofs consisted of concrete slabs with holes that were filled with PCM reported in [13, 14]. The model was based on heat capacity method and employed finite element method to simulate heat transfer through roof. Their results showed that for a specific type of PCM and for conical geometry of PCM container, the heat flux at indoor surface can be reduced up to 39%.

Experiments done by Chhugani *et al*., [15] showed that a gypsum wallboard thermal resistance increase when PCM was added in wall board. Macro-encapsulation of PCM is more suitable than microencapsulation and direct incorporation because it provides containment for PCM which prevents leakage and chemical reactions which are caused by direct mixing of PCM and building structure material. Heat transfer through building walls covered with PCM filled polymeric bags were studied by Lee *et al*., [16]. Their results showed that south facing wall experienced 51.3% reduction in heat flux and west wall showed 29.7% reduction in heat flux. Gounni and El Alami [17] investigated the impact of covering wall with PCM filled panel. There results showed 2oC reduction in temperature of internal wall surface. Xiaoqin *et al*., [18] used two pipes of different diameters to study the effect of incorporating PCM pipes at different depths. They found that the position referred to as "next to wall board" reduced peak heat flux by 22.5% and "middle depth configuration" by 36.5% as compared to walls that were not integrated with PCM.

Navarro *et al*., [19] studied the impact of PCM by constructing three rooms of equal dimensions. The reference room was made of bricks and no insulation was applied. Polyurethane insulation was applied in second room. Third room contained insulation as well as PCM. The energy consumption of all three cubicles was measured and the researchers reached to a conclusion that the energy consumption of rooms having PCM and insulation was less than the other two rooms. It was examined by [4] that the potential of PCM in controlled indoor temperature reduces heat gain. Two rooms of equal dimensions were constructed and were exposed to similar outdoor conditions. Results revealed that PCM aid in lowering inside temperature of room. Inside air temperature of room containing PCM was reduced by up to 0.6°C. Double layer shape stabilized PCM (SSPCM) wallboards were used by Na zu *et al.*, [20]. SSPCM works both in summer and winter. The experimental study was conducted in Wuhan city of China. To get real time data, two rooms were constructed. Both rooms had same dimensions and same material properties. The only difference was the addition of double layer SSPCM on south wall of one room. Tests were conducted in summer and winter. Outdoor temperature, indoor air temperature, surface temperatures and heat flux was recorded and compared for both rooms to evaluate the effect of PCM. Comparison of indoor air temperature of two rooms revealed that the indoor temperature of PCM room was 0.6°C less than reference room in summers. Comparison of surface temperature revealed that exterior and interior wall surface of reference room was higher than PCM room. The experimental results showed that PCM room has the ability to prevent overheating in summer and undercooling in winter as compared to the reference room.

This study focuses on using vegetable ghee as phase changing material in building. Two identical rooms referred to as: reference room and PCM room, hereinafter, were constructed. Prior to use, the thermal analysis of PCM was performed in order to ensure its suitability for use in building envelope. Temperature data of both the rooms was collected and compared to find the effectiveness of PCM in controlling inside temperature.

2. Materials and Methods

2.1 Thermal Analysis Approach

The Vegetable ghee and animal fats were acquired from the local market and analyzed with differential scanning calorimeter (DSC; DSC-8000, PerkinElmer) and thermal gravimetric analyzer (TGA; TGA-Q500, TA instruments. A 10mg sample, each of vegetable ghee and fat was heated from 0°C to 100°C at a heating rate of 5°C/min. Liquid Nitrogen was used to lower the temperature of system from ambient room temperature. A 10mg sample, each of the above mentioned materials was also tested with TGA over a temperature range of 0°C to 100°C. Moreover, thermal constants of the vegetable ghee were also analyzed with the help of thermal constant analyzer (TPS 2500s, Hot disk Instruments). Kapton insulated sensor was used to provide heat during measurement. It is very much important that the sample should be in proper contact with the sensor to get acceptable results. Sample holder containing ghee sample was fixed inside a 'silicon oil bath'. Oil bath contained silicon oil and had inbuilt heater and chiller. The working temperature range of oil bath was -30°C to 200°C. At the time of test, the room temperature was 25°C. To test a sample at lower or higher temperature than the room temperature, silicon oil bath is used. Therefore, sample was placed inside oil bath. The inbuilt heater and chiller heat and cool the silicon oil to a set temperature which in turn heat and cool the sample inside sample holder. All this is controlled by a program that can be set in software that comes with the equipment.

Six target points were set for the testing of ghee sample. The thermal conductivity and diffusivity of sample were measured at 0°C, 10°C, 20°C, 30°C, 40°C and 50°C. At each target point, a stabilization time was set to stabilize the oil bath temperature. At 0°C, 10°C, 20°C, 40°C and 50°C the stabilization time was set to 30 minutes. The phase of ghee material changes between 25°C to 30°C. For this reason, the stabilization time was increased to 60 minutes at this temperature so that PCM can melt completely. The measurement time was set to 3 seconds, 5 seconds and 10 seconds and 3 measurements were taken at each set temperature.

2.2. Construction of Model Rooms

Two rooms of equal dimensions were constructed. The rooms were 10ft long, 11ft wide and 12ft high. Building was constructed from hollow concrete blocks, having dimensions of 8”x8”x16”. Steel pipes of square cross section having area of 4”x4” were fitted in these hollow concrete blocks. The steel pipes were arranged in such a way that they passed through the cavities of the blocks throughout the height. Pipes were fixed in the walls and roof of one room while other room, which was the reference room, had no PCM filled pipes in its walls and roof. As shown in Figure 1., PCM was filled in these pipes in melted form and pipes were covered from top to prevent any type of dust and contamination from entering into the pipes. Figure 2 shows the full scale rooms constructed in this research work.

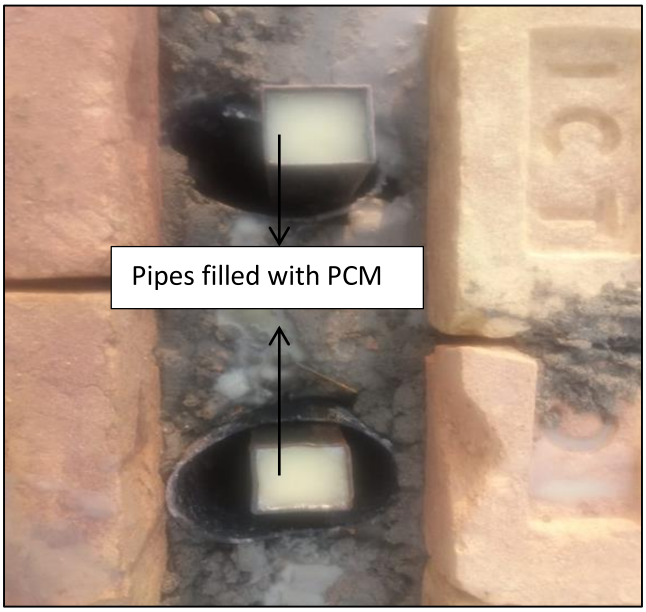

Fig. 1. Steel pipes filled with PCM

Fig. 2. Pictorial representation of the full scale room model

The test rooms were built in Peshawar, Pakistan located at 34.0151°N, 71.5249°E. The climate of Peshawar varies throughout the year. In summers the weather is very hot and humid. In winters it is dry and very cold. To observe the conduct of PCM in both climates, temperature data was recorded for the month between October and January.

The LM35 temperature sensors were attached on the interior and exterior surfaces of all the walls and roofs of both the rooms. Sensors were also fixed with PCM pipes to record temperature of pipes. These sensors were connected with a 32-channel data logger. Temperature data from all the sensors were continuously recorded and saved. Figure 3 shows the data logger system connected with laptop.

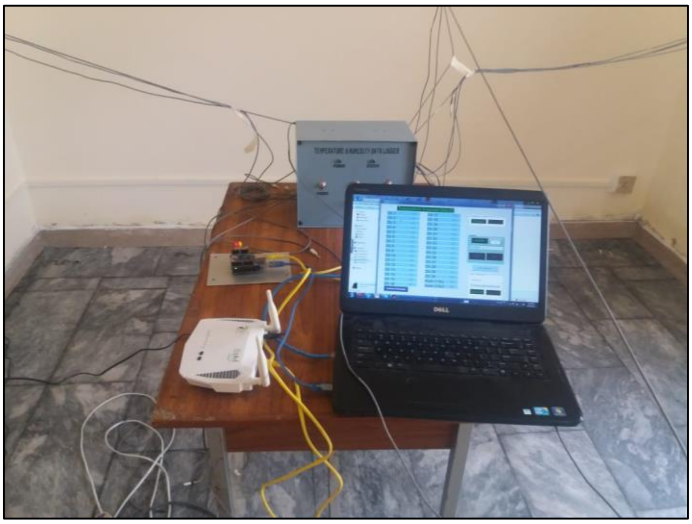

Fig. 3. Data logging system

3. Results and Discussions

3.1 Thermal analysis

The DSC results of vegetable ghee and animal fats are compared in fig 4. As shown in Fig. 4, melting of vegetable ghee starts at 20°C and it continues till a peak point reaches at 27°C, while it can be observed that for fats, melting starts at inflection point of 38°C and continues until 50°C.

The comparison of both the curves shows that Ghee is a better option to be used as PCM in buildings because its melting range is near the optimum temperature range of human thermal comfort. Also, noting the daily temperature range, i.e. the maximum and minimum temperature of the day reveals that ghee is a better option because at night when temperature drops down, it will start to solidify easily as compared to fats.

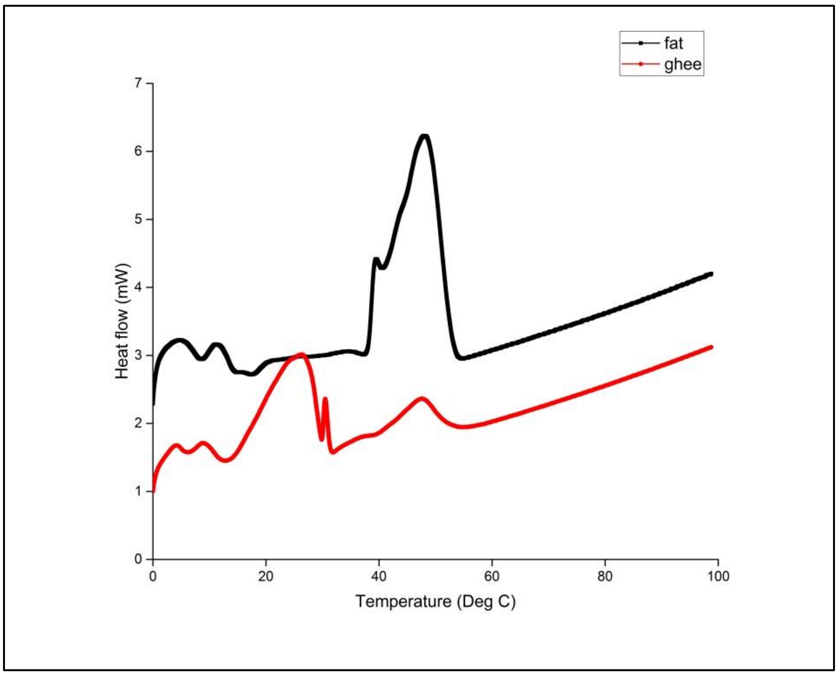

Fig. 4. Comparison of DSC curves of vegetable Ghee and animal fat

The TGA analysis of vegetable ghee and fat is shown in Fig. 5. The results show that both of these materials are thermally stable to a very high temperature. There is no decrease in weight of sample till 300°C. Further increasing temperature from 300°C to 350°C causes slight reduction in samples' weight. A significant weight loss can be notice when temperature rises from 350°C to 450°C.

Since these materials are supposed to be used in a temperature range not higher than its stable temperature ranges, therefore, both could be a good choice for heat storage.

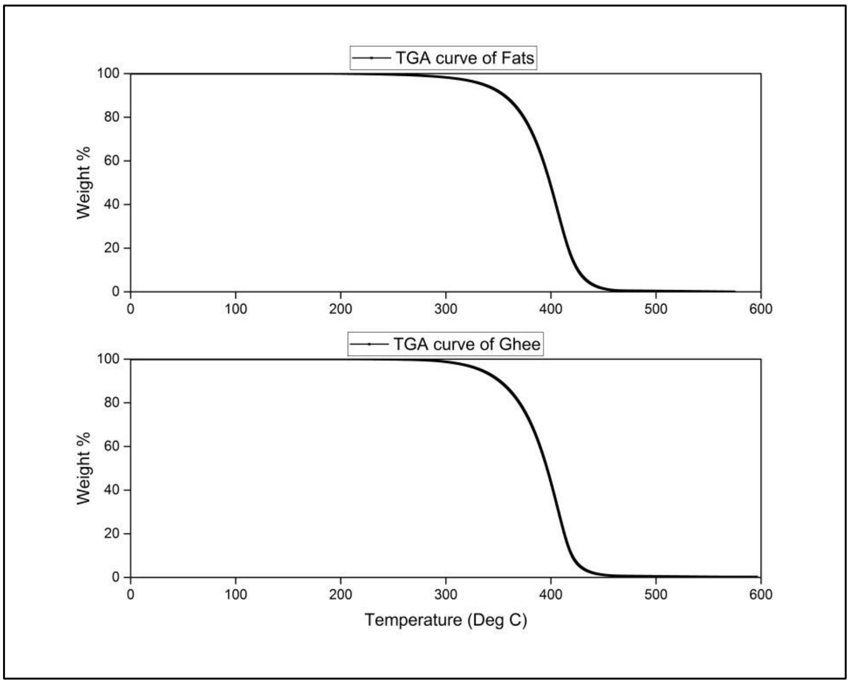

Fig. 5. TGA curves of Fat and Ghee Sample showing material's weight loss at high temperatures

However, as the melting temperature of the vegetable ghee is closer to the indoor comfort temperatures, therefore, it was selected for use in buildings. The thermal conductivity of the vegetable ghee was also analyzed at different temperatures. The results showed that the thermal conductivity of Ghee decrease with increase in temperature. As the temperature increase, PCM changes from solid to liquid state and its conductivity decreases. Table 1, tabulates the thermal conductivity of Ghee sample at different temperatures. The difference in thermal conductivity at 10°C and 50°C is 20%. These results also signify that PCM has more potential to conduct heat in solid form as compared to liquid form.

Table 1
Thermal Conductivity values of vegetable Ghee at different temperatures

Average Temperature	Thermal Conductivity ($Wm^{-1}K^{-1}$)
10ºC	0.265
20ºC	0.262
30ºC	0.252
40ºC	0.216
50ºC	0.210

3.2 Building Indoor and Outdoor Data Analysis

The indoor and outdoor temperature data was thoroughly measured and recorded in both of the two building structures (rooms). A custom-built data acquisition system was used to acquire and record the inside and outside temperature data. Figures 6- 9 show a comparison between the inner and outer roof surface temperatures of PCM and reference room. Data was recorded for 24 hours, and are presented in Figs. 6-9, on hourly basis. The data show a visible difference in the temperatures of the envelope with and without PCM. It is evident from the data of the PCM room that temperature of the external surface of roof varied significantly throughout the day but inside temperature remained almost constant.

During night when temperature falls, the outside surface temperature also drops significantly. Due to stabilizing effect of PCM, the roof inside temperature remained higher at night as compared to outside temperature.

In day time, temperature started increasing gradually. The peak temperature was recorded between 2 pm and 3 pm, as shown in Fig. 6. Though the external temperature increased considerably, not much variation was recorded at inside surface of the PCM room, which can be clearly attributed to the PCM.

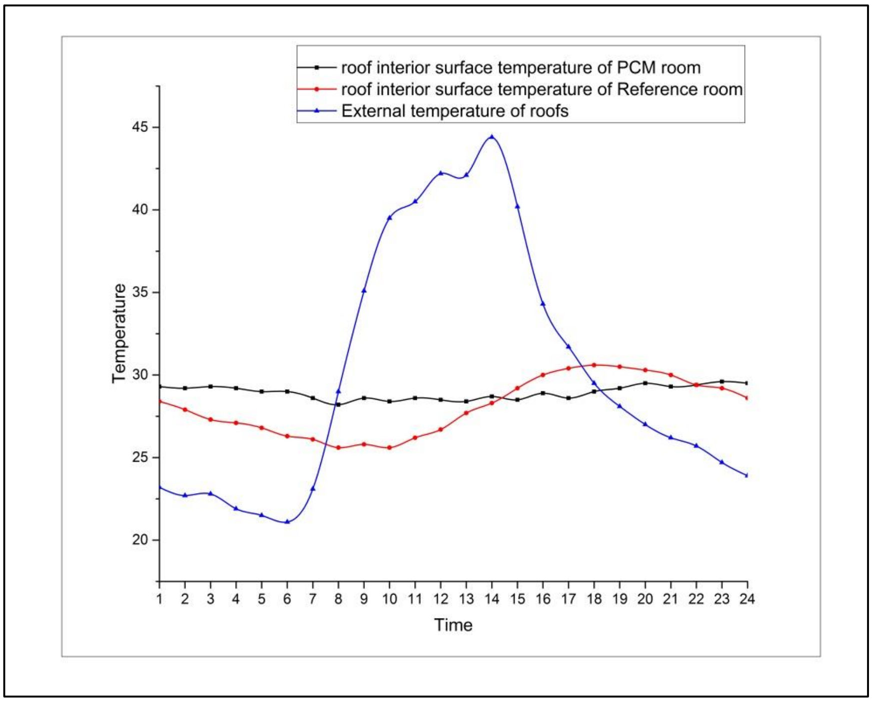

Fig. 6. Comparison of roof's inner and outer surface temperature of PCM Room and Reference room for 11th October

The results suggested that inner surface of reference room experiences variation between 4°C and 5 °C in 24 hours. Contrarily, the variation in inner surface temperature of PCM room is maximum 1 °C in 24 hours. This shows that PCM act as temperature regulator and helps in maintaining constant temperature throughout the day. The temperature data from the wall surfaces was also collected as shown in Fig. 8 and Fig. 9. Fig .8 shows the 'North' wall temperature data of PCM room and reference room. From the data recorded it can be seen that the pattern is similar to the roof data recorded for PCM room. Outer surface temperature varies significantly as compared to inner surface temperature.

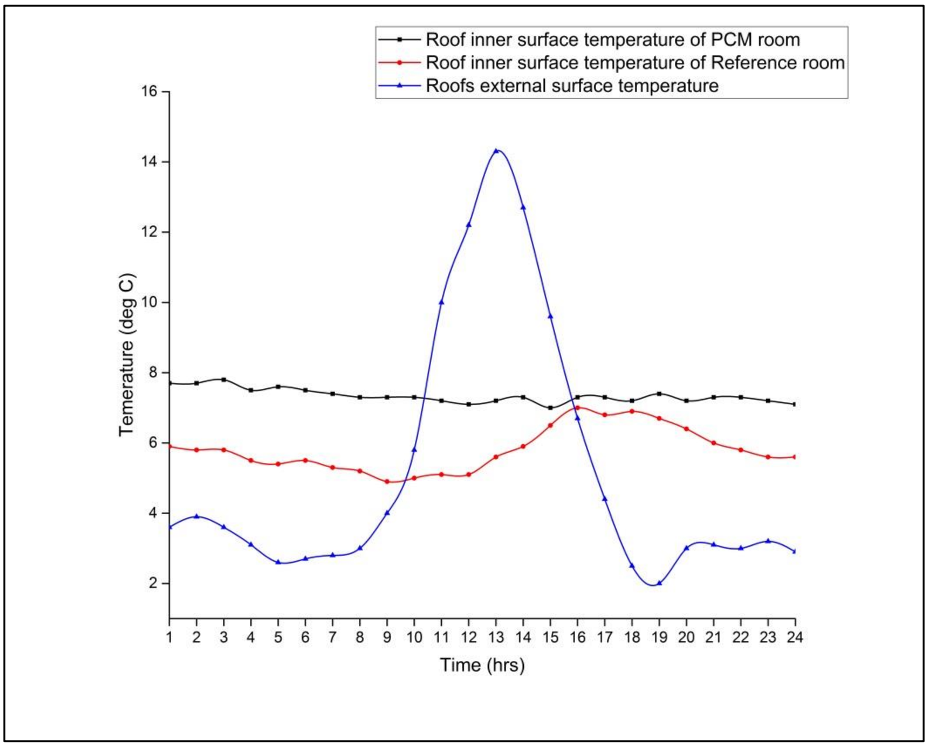

Fig. 7. Comparison of roof's inner and outer surface temperature of PCM Room and Reference room for 30th December

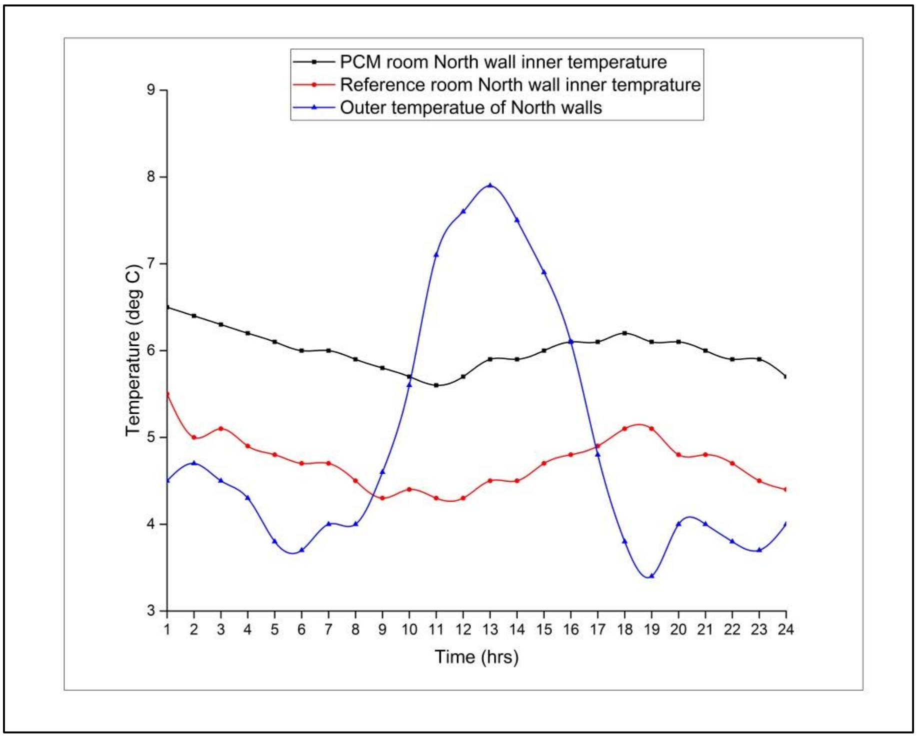

Fig. 8. Comparison of North wall's inner and outer surface temperature of PCM Room and Reference room for 30th December

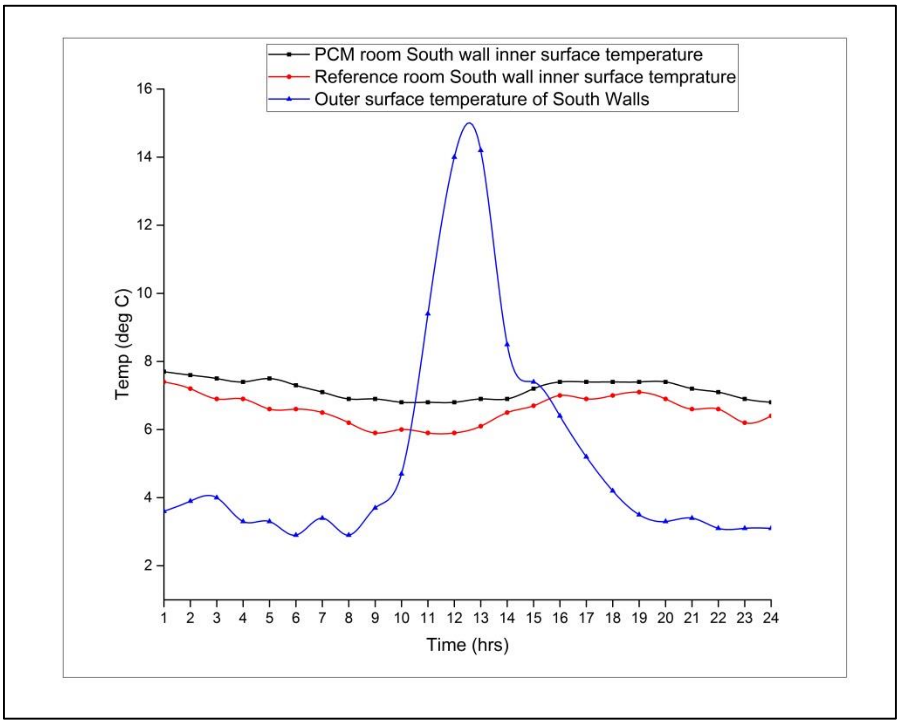

Fig. 9. Comparison of South wall's inner and outer surface temperature of PCM Room and Reference room for 30th December

In reference room the difference between outdoor and indoor temperature is due to thermal mass of concrete. A similar trend can also be observed in Fig. 9, which shows the data collected from the south facing wall. Overall, there is a clear difference in the temperature profiles of the building envelope of both the PCM and reference rooms. This suggests that PCM can help in heat storage and could also be used for shifting the peak load hours in hot summer seasons.

4. Conclusions

This paper reports the analysis of PCM used for heat storage in building envelope. Two materials were selected i.e. vegetable ghee and animal fat and thermal analysis was performed. Based on DSC results it was found that vegetable ghee with melting in the range of 20°C to 27°C is suitable PCM that can be used in buildings. The TGA results showed that Ghee is stable at higher temperature up to 400°C. The comparison of the indoor and outdoor temperature profiles of the two rooms showed that the indoor temperature of the PCM room is relatively stable with 1°C or less variation. On a contrast the indoor temperature variation in the reference room (without pcm) ranges up to 5°C. The results also showed that the outdoor surface temperature went as high as 50°C while the indoor remained in between 33°C to 35°C in relatively hot season. The data from relatively colder season suggested an outdoor variation from 2°C to 15°C. Contrarily the indoor temperature showed a variation of 2°C or less, over the 24 hours duration. The results also suggested that the PCM can hold for longer time, which could be attributed to its low thermal conductivity and relatively high latent heat.

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