Heat Transfer Enhancement in Composite Building Wall using Phase Change Material

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Abstract. Phase Change Materials (PCMs) are capable of reducing the thermal load transfer rate between outdoors and indoors and maintain stability in the indoor temperature when used in building applications. In this study, a variation of layers of two Bio-PCMs integrated with layers of general construction material and insulation have been analysed discretely as well as in combination. The observations from various models have been compared to draw the result and perceive the best model of a Bio-PCM wall for constructing thermally efficient buildings. The wall models have been created and analyzed through Computer Aided Design (CAD) modeling and simulation techniques using Transient Thermal module in ANSYS software. Coconut fat and Palm fat being highly efficient and easily available Bio-PCMs, are used in this study and attractive results have been obtained from them.

1. Introduction

The world is currently facing a climate crisis. Earth’s average temperature is on a steady rise. Human activities have already raised earth’s average temperature by 1°C and there is a high certainty that the 2°C mark will also be breached soon. The rising temperatures are abominable for human comfort. Current HVAC systems used for maintaining the indoor environment comfortable for humans have not solved the problem but only added to the severity of the scenario. The Phase Change Materials have the properties of reducing the rate of thermal load transfer. Several studies have been conducted on the Inorganic PCMs using them in making the buildings thermally efficient and reduce fluctuations in indoor temperatures and have obtained mesmerizing results. The most promising results were obtained from Paraffin based PCMs. But, the paraffin based PCM is a petroleum based commodity. Petroleum reserves are already over consumed and are about to extinguish soon. Thus, PCM based technology would be sustainable only if the supplies for the PCM are easily replenishable. This draws the interest of this study towards the highly available and replenishable type of PCM i.e. Bio-PCMs. Bio-PCMs are phase change materials derived from natural sources such as bi-products of trees, animal fat and even organic wastes like vegetable peels and feed stock. Bio-PCMs also have the property of absorbing the heat and using it in changing its state like the various other paraffin based PCMs. Among the Bio-PCMs, Coconut fat and Palm fat attain most of the merits required for a PCM to be used in thermally efficient building applications. They both have a melting point near the human comfort temperatures and have a source which has a high availability and are replenishable. Palm tree and Coconut tree can be grown easily near coastal areas and the use of their products as PCM can generate a new source of income for farmers and will generate employment in the PCM processing plants. Not many studies have been conducted on the utilization of Bio-PCMs in the building application. Some of the studies and their results are stated. [1-4] studied the application of different types of PCMs in the roofs of buildings and focused on the implementation of various design of the
roof for better latent storage. The following implementations showcased the reduced heat flux through the roofing complex. [5, 6] tested the PCM equipped wallboards for the use in thermally efficient building applications. These studies provide us with an understanding that how PCM technology can be transformed into an enhanced commercial model in the form of ready to install wallboards. Researchers have incorporated the PCM into hollow bricks and blocks and simulated the latent storage characteristics of the model [7-9]. These types of design proved to be beneficial in lightweight construction along with the efficient performance of the PCM. Advanced models of composite walls with PCM blended into the composition of construction materials, provided the PCM composite with a shape stability, mechanical strength and latent storage characteristics [10, 11]. The simulations on the models concluded that the model sticks well with the latent storage characteristics of the PCM blended in it. [12-14] Researchers have conducted various experiments using the wall models having the PCM as an integral layer. It was observed that the PCM performed most efficiently in this setup. [15, 16] experimentally analyzed scaled down constructed models of a room with walls and ceiling integrated with PCM layers. The analysis was carried out considering the directions of the wall i.e. North, East, West and South along with a time variable for 24 hours of recorded data of the performance of the setup. This type of analysis presents an impressive practical approach. [17] compared the bio-based PCMs as a substitute to paraffin PCMs and stated that Bio PCMs can absorb, store, and release large quantities of latent heat, comparable to conventional paraffin’s, and are equally suitable for microencapsulation. [18] Performed a numerical study to investigate the behaviour of the melting process of Coconut fat based PCM under convection heat transfer condition. The investigation concluded that coconut fat has a melting range around the comfortable temperatures and can be used as a PCM. [19] developed macro-encapsulated palm oil based PCM solution for latent heat storage and compared the solution with the present PCM based solution available in the market. The results of the Palm oil based solution was found to be more attractive for thermal storage in building applications. [20] performed a multipurpose investigation on thermal behaviour and life cycle assessment on expired palm oil from food industry as a Phase Change Material for thermally efficient building applications. This study revealed that the expired palm oil can perform efficiently at temperatures near human comfort and can be used as PCM in building applications for latent heat storage. [21] followed an experimental procedure on various types of palm fruit to determine the thermal characteristics of the oil produced from them. A comparison among the thermal properties of various palm oils was produced as a result of this experimental analyse. It has been very helpful to analyse how PCMs fit into building applications based on the above-mentioned properties and optimization techniques, which have been documented by numerous research studies and articles. In response to this perception, we developed a virtual model of PCM fused in working as a wall-layer material. This study compares different b-PCM thicknesses in order to evaluate the thermal performance of composite building walls. Same-sized composite walls ANSYS transient tool is used to analyse different b-PCM for thermal conditions. A multi-layered wall’s air cooling and temperature distribution has been studied. This is a case in which palm fat & Coconut fat is used as b1-PCM and b2-PCM. As the temperature rises above a desired level, heat is absorbed, and heat is released when the temperature falls below that level. This study also present the heat reduction rates throughout the day and energy savings resulting from the multi-layered composite wall.

2. Description of the model

Four models of wall with (1m x 1m) cross-section area have been designed using geometrical design module in ANSYS WORKBENCH. The models designed are identical to an extent such that the basic design of a conventional wall is common in all the models, while the models distinguish by the combination of Bio-PCM used in them. The combination of layers used in the wall models are displayed in the Fig.1. along with the orientation.
2.1. Mathematical Modeling

The Prototype walls for the PCM integrated room in addition another room type are used as composite panels. The outer layer of the wall is exposed to the air, which is the goal of convective heat transfer and through the air. In this work, it is assumed that the ambient temperature is equal to the temperature of the outer layer of the composite wall, which shows that the convection is not considered due to heat loss. The heat transfer process between the different layers of the composite wall due to heat conduction is determined by the one-dimensional heat transfer equation based on Fourier's law[22].

\[ Q = -kA \frac{dT}{dx} \]  

(1)

Where Q is the heat flow, k is the thermal conductivity of a single layer of material, A is the cross-sectional area, dT is the temperature difference between the opposite ends of the wall, dx is the wall thickness. The process is unsteady and the ambient air temperature changes with time. The same is true for the temperature of walls and their corresponding layers, so the process takes the equation that controls time as a variable there is no heat source can transfer heat between the walls, inside the wall can be regarded as one-dimensional. The equation gives a one-dimensional form of the diffusion equation in the unstable state and without internal heat release which can be used for the initial value problems (I.V.P) are given by the eq.(2).

\[ \frac{d^2T}{dx^2} = \frac{1}{\alpha} \times \frac{dT}{dt} \]  

(2)

The initial and boundary conditions for eq.(2) asre as follows:

Initial condition, at 12:00 AM, \( T_{wall} = 36 \, ^\circ C \)

Boundary conditions, at \( X=0 \), \( T_{wall} = T_{amb} \)

where \( X=L \), \( T_{wall} \) represents the temperature of the wall surface, \( T_{amb} \) represents the ambient temperature and \( L \) represents the thickness of the wall.
2.2. **Standard wall model**
This model defines a conventional wall setup of brick and cement-mortar combined with an insulation setup of aluminium and gypsum wallboard. The standard wall model is a reference for comparing the results obtained from analyzing the various other wall models.

2.3. **b1 wall model**
A layer of Palm fat (stated as b1) of 10 mm thickness enclosed in an aluminium container having thickness 0.7 mm is combined with the standard wall model to form a b1 PCM wall model.

2.4. **b2 wall model**
The b2 PCM wall model is designed by using Coconut fat (stated as b2) having thickness of 10 mm enclosed in an aluminium container of 0.7 mm thickness along with the conventional wall layers and insulation.

2.5. **b1-b2 combined wall model**
As suggested by its name, the b1 and b2 PCM wall models are blended to develop a combination of Palm and Coconut fat layers separated by a 0.7 mm thick aluminium sheet and contained in an aluminium envelope having 0.7 mm thickness. The conventional layers of brick (100 mm thick), cement-mortar (15 mm thick) and gypsum wallboard (12 mm thick) still play their part in the design of this model. Both the PCM layers used are 10mm thick each. Materials used in simulations had specific properties, which are listed in Table 1. Material assignment module receives these properties before meshing has been completed as an input to the material assignment module. Since the behaviour of a material in a process is highly dependent on its properties, these properties are crucial for input. Depending on the type of mesh selected, the number of nodes and elements will be distributed differently. Elements and nodes are generated by the solver according to the model's structural requirements. The chosen mesh is a quad type with a maximum edge length of 5 millimetres (mm). Due to the fact that the walls are symmetrical and have no complex features, the mesh used is a structured mesh. To calculate the results efficiently, the structured mesh is preferred over the unstructured one. A coarse, medium and 4 mm element-sized fine mesh have been generated using all three meshing types. For medium and fine meshing, however, the simulation fails. Interior and exterior layers of the wall model are represented by the diagrams' top and bottom layers, respectively. There are minimum and maximum temperatures developed at different layers of the model over a certain time period, and these temperatures are shown as a temperature contour. On the diagram, the maximum temperature is represented by the dark red layers, while the minimum temperature is shown by the dark blue layers.

| Material          | Density (kg/m^3) | Conductivity (W/m K) | Specific heat (J/kg K) | Material          | Density (kg/m^3) |
|-------------------|------------------|----------------------|------------------------|-------------------|------------------|
| Aluminium         | 2689             | 237.5                | 951                    | Aluminium         | 2689             |
| Brick             | 1536             | 0.75                 | 523                    | Brick             | 1536             |
| Cement-mortar     | 1406             | 0.3505               | 1050                   | Cement-mortar     | 1406             |
| Coconut oil       | 920              | 0.166                | 3750                   | Coconut oil       | 920              |
| Palm oil          | 885              | 0.1717               | 1875                   | Palm oil          | 885              |

3. **Results & Discussions**
PCM were subjected to a convection-based heat transfer process that moved heat from the air to the outermost layer. Through conduction, the heat was exchanged in the inner layers. Air temperature was consistently
considered in general recreation as a factor in fluctuating time. The temperature of the air and the temperature of the model's deepest layer were taken into account over a period of hours. This is done using the ANSYS Transient Thermal Module (TTM). This is a heat transfer measure administered by the numerical condition of time-dependent heat transfer. In the temperature contours, the wallboard layer at the interior is the coldest layer, while the brick layer at the exterior is the hottest.

![Thermal contours across the walls](image)

**Fig. 2.** Thermal contours across the walls

The Fig.2. displays four different temperature contours with a rainbow style colour distribution across the layers of the model walls. The rainbow style colour distribution depicts the temperature variation among the layers. Red colour depicts the hottest layer, then the colour band varies to orange, yellow, green, light blue and finally reduces to dark blue, which depicts the coldest layer among the various layers of the wall model. The model without PCM have contours varying from 40.159°C to 36.48°C, b1 PCM model temperature contour varies from 40.091°C to 35.714°C, b2 PCM model contours varies from 40.058°C to 35.348°C and the temperature contours of b1&b2 combined wall model has achieved a variation from 40.056°C to 34.967°C. This shows the increasing performance in reducing temperature of the topmost layer shown in the fig.2, as the setup is optimized from no PCM to b1 PCM to b2 PCM to both b1&b2 PCM combined. An increased overlap of dark blue contour over light blue contour can also be observed in the contours of the models having PCM. This interprets the increased heat reduction due to PCM when compared with model without PCM.
3.1 The effect of b1 PCM

Fig. 3. Inner temperature of the composite building wall with b1-PCM and without b1-PCM

The graph in the Fig. 3 displays the simulation results of the b1 PCM wall model. The line joining the squared points describes the behavior of environmental conditions stated as ambient temperature. The ambient temperature stands at 34°C initially at 12:00 AM. There is a continuous fall in ambient temperature till 4:00 AM after which the ambient temperature starts to rise. The time step of 4:00 AM can be stated as the sunrise. Further the temperature rises till it reaches its peak of 42°C at 2:00 AM that is when the sun is at the top, after which the temperature falls continuously till the end of the observation time period at 12:00 AM. The behavior of the wall model without B1 PCM is comparative to the ambient temperature characteristics as it falls and rises along with the ambient temperature. The temperature differences between them are due to the higher initial temperature of the wall models and the insulation due to the presence of aluminum and gypsum wallboard layers. The behavior of the wall model with b1 PCM layer, depicted in form of line joining circular points shows a similar behavior as the wall without PCM but, it provides an extra smoothening of the curve which is the effect produced solely by the b1 PCM layer. When the temperature of the wall without PCM drops from 36°C to 32.59°C in the time steps ranging from 12:00 AM to 6:00 AM, the wall with B1 PCM layer drops with a smaller slope from 36°C to 33.172°C along the same time steps. After 6:00 AM, the temperature of the wall without PCM starts rising till its peak of 39.34°C and the PCM wall shows a smaller rise in slope than the wall without PCM and thus depicts a lower fluctuation in temperatures.

3.2 The effect of b2 PCM

Fig. 4. shows that the graphical result of the simulation performed on wall model with b2 PCM. The behavior of the ambient temperature is presented by the line joining squared points, the behavior of the wall without PCM is represented by line joining triangulated points and the line joining the circular points depicts the behavior of the wall with B2 PCM.
The process under observation begins at 12:00 AM at which the ambient temperature is 34°C and the initial temperatures of the wall models being 36°C. In the beginning, the temperature of wall without PCM falls to 33.714°C from 36°C as there is a fall in ambient temperature in the time steps ranging from 12:00 AM to 4:00 AM. After 4:00 AM, there is a sharp rise in ambient temperature but, the temperature of the wall without PCM has not fallen as much. Thus, an intersection is observed at 6:00 AM. Further, the temperature of the wall without PCM rises along with the ambient temperature and drops along it. On the other hand, the temperature of the wall with PCM wall falls along with the temperature of the wall without PCM but maintains a significant difference in temperature. By the time step of 6:00 AM, the temperature of the wall without PCM drops to 32.59°C, the temperature of the wall with B2 PCM has only dropped to 33.595°C. This point depicts the behavior of the PCM. While the temperature of wall falls below the ambient temperature, the temperature of the wall with B2 PCM stays above the ambient temperature at this time step. This shows that the PCM slows down the heat transfer rate at sufficiently differentiable rates. The same phenomenon can be observed at the time step of 6:00 PM, the temperature of the wall without PCM has reached 39.359°C, the temperature of the wall with PCM is at 38.093°C only. A reduction in fluctuation of temperature is observed in this simulation.

3.3 The effect of b1 & b2 PCM

The Fig.5. is a graphical representation of the results obtained by simulation on the model having both b1 and b2 PCM layers in combination. The ambient temperature curve and the temperature curve of wall without PCM is same as described in the B1 PCM and b2 PCM simulation graphs. The combination of the b1 and b2 PCM layers has further enhanced the fluctuation reduction which can be observed at the bottom peak of the temperature of wall without PCM, where it reached 32.59°C but the temperature of the wall with b1 and b2 PCM has dropped only to 34.093°C from 36°C. This creates a 1.503°C temperature difference between them. Similarly at the upper peak of temperature curve of wall without PCM at 39.359°C, the temperature of the wall with b1 and b2 PCM remains cooler at 37.444°C creating a 1.915°C temperature difference.
4. Conclusion
In this study Different b-PCM has been used in a composite wall to analyse the thermal insulation properties of the material. The PCM wall maintains its thermal inertia for longer periods of time, even as the ambient air temperature decreases. As a result, walls with PCM were found to be more thermally stable than walls without PCM. Due to the addition of PCM, temperature variations are reduced in intensity and their amplitudes are reduced significantly. PCM is most effective from 2 PM to 10 PM. The intersection of the temperature curve of wall without PCM and wall with b1 PCM is observed slightly before 10:00 AM, the intersection of the temperature curve of wall without PCM and wall with b2 PCM is observed exactly at 10:00 AM and the intersection of the temperature curve of wall without PCM and wall with B1 and B2 PCM combined is observed slightly after 10:00 AM. This shows that the b2 PCM produces a higher time delay in temperature change than b1 PCM and the combination of b1 and b2 PCM produces even higher delay than b2 PCM alone. On comparison with the wall without PCM, the difference at the bottom and top peaks of b1 PCM was 0.582°C and 0.696°C respectively, of b2 PCM was 1.005°C and 1.266°C respectively and of b1-b2 PCM combined was 1.503°C and 1.915°C respectively. This clearly derives towards the conclusion that b2 PCM i.e. Coconut fat is a better PCM than b1 PCM i.e. Palm fat and the combination of the two performs the best among them and reduces considerably high amount of temperature fluctuation loads.

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