NUMERICAL STUDY ON THE EFFECT OF PHASE CHANGE MATERIALS (PCM) IN THERMAL MANAGEMENT OF BUILDING

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Term Project Proposal for MAE-7430 Computational Fluid Dynamics and Heat Transfer

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Abstract

Building is one of the largest consumers of energy and is a major contributor to greenhouse gases emissions. With the global climate change toward extreme mean, the demand for HVAC system is also rising. Effective insulation with layers of different materials is considered as an efficient way for thermal insulation of a building. In this study, the insulation capability of phase change materials (PCM) is evaluated numerically and compared with wood and sand. PCM is found to be more effective to conserve the thermal condition inside conditioned space. PCM closed to the heat source is found to be better position for the thermal management.

1. Introduction

The need for energy worldwide is gradually increasing. Finding substitutes for traditional fossil fuels that will minimize CO_2 emissions is a challenge for scientists and engineers. Buildings consume 70% of the nation's electricity, and they are also responsible for 39% of the nation's carbon emissions, according to estimates from the US Department of Energy [1] and [2]. It is essential to design buildings that are both affordable and effective in terms of energy use because fossil fuel supplies are finite, and energy is expensive. The thermal comfort of buildings that integrate a thermal energy storage system (TESS) based on phase change material (PCM) is raised while energy consumption is decreased [3].

One of the most potential substitutes for traditional energy sources is a thermal energy storage system (TESS). Depending on how heat is stored, there are primarily three forms of TESS: thermochemical, sensible, and latent. In comparison to sensible storage systems, latent heat storage systems have a higher energy storage density and can absorb and deliver heat at practically constant temperatures.

High specific heat, high latent heat of fusion, and minimal volume changes during phase change are benefits of PCM for thermal management [4]. During power operation, PCM absorbs heat and then releases it at later time. Because PCM absorbs heat from a high temperature source while it melts, and because it can solidify once it can release heat to a low temperature sink, the phase change of PCM is significant.

Despite the fact that natural convection occurs during the PCM melting and charging process, Chiu and Martin's [5] numerical results were consistent with their experimental findings even though they did not represent natural convection. This result shows that the characteristics and thickness of PCM affect how natural convection behaves during melting and solidification.

The purpose of the study is to measure the time lag in the heat transfer from the indoor conditioned building zone to the cold outdoor through the walls with or without the integration of PCM. The amount of heat loss through the wall will also be calculated numerically using ANSYS Fluent 2022. The effect of temperature variation and location of PCM sandwiched between two layers of building materials will also be measured. We will also numerically explore the effect of different building materials for the thermal insulation of a building.

2. Model Description

We'll use the ANSYS design modeler to create a two-dimensional model. Because it is easier to construct and measure, the planar mode should be considered. The model will have dimensions that are identical to the experimental set-up described in the literature. After a predetermined number of time intervals, the results will be taken one after the other. It will be compared against the outcomes of the experiment to see how the numerical analysis performed. The two-configuration depending on the position of PCM are shown in Figure 1. For the simplicity of the study and faster heat transfer through the walls, we used copper as the materials. Copper has higher order of heat conductivity than either PCM, wood or sand.

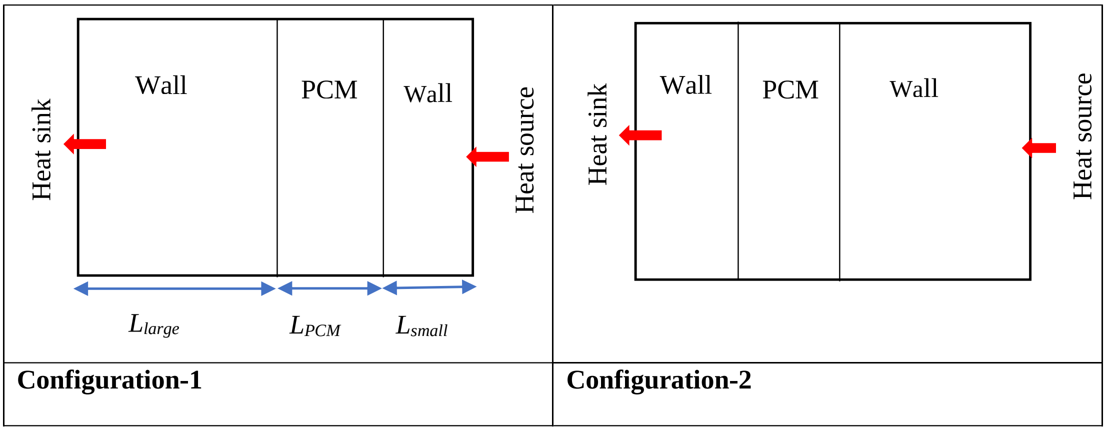

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Figure 1. Design model considered for simulation

Study [5] shows that we can model the CFD simulation of 3-D annular problem as 2-D without any compromise of the results. In our study, 2-D planar model is used to numerically simulate the melting process in ANSYS fluent. The SIMPLE method was used for the pressure-velocity coupling in the continuity equation, second-order upwind schemes were used for the mass, momentum, and energy equations. PRESTO was used for pressure correlation equation. The relaxation factors were used as default: 0.3 for pressure, 0.7 for momentum, 0.9 for the melt fraction, and 1 for energy.

The convergence criteria for continuity and three momentum equations were 10^{-6} and 10^{-9} for energy equation.

Table 1. Thickness of different layers.

L_{large} (mm)	L_{pcm} (mm)	L_{small} (mm)	H (mm)
76.2	10	15.2	50.8

For this CFD simulation a suitable meshing is necessary. In our study, quadrilateral mesh of element size 8,800 was used. ANSYS fluent uses pressure-based solver for the numerical calculation of solidification/melting.

Table 2. Thermophysical properties of PCM (P56-58), sand and wood.

Property	**PCM**	**Wood**	**Sand**
Latent heat of fusion, ΔH_f [kJ/kg]	250		
Solidus temperature, T_{sol} [K]	329		
Liquidus temperature, T_{liq} [K]	331		
Thermal conductivity, k [W/m-K]	0.25	0.17	0.25
Specific heat, c_p [J/kg-K]	1840	700	800
Density, ρ [kg/m^3]	900	2310	1600
Dynamic viscosity, μ [N-s/m^2]	0.004		

3. Mathematical formulation

In our CFD problem, PCM is the fluid domain, but wood and sand are solid domain. The governing equations of conservation of mass, momentum, and energy used for fluid domain are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\, \bar{u}) = 0 \qquad (1)$$

$$\frac{\partial \rho \bar{u}}{\partial t} + \nabla.(\rho \bar{u}\bar{u}) = \nabla(\rho) + \nabla(\bar{\tau}) + \rho\bar{g} + F \qquad (2)$$

$$\frac{\partial(\rho h)}{\partial t} + \nabla.\,(\rho\bar{u}h) = \nabla(k\ \nabla T) \qquad (3)$$

Where, ρ is the density, $\bar{u}$ is the velocity vector, T is the temperature, P is the static pressure, and t is the time. F, $\bar{\tau}$, $\rho\bar{g}$ are the momentum source term, stress tensor, and gravitational body force respectively. In our case unidirectional flow was considered, so $\bar{\tau}$ is equal to ∞. The “solidification and melting” model in ANSYS is based on enthalpy-porosity method. In this method, a porous region called “mushy zone” [6] represents a zone where both sold and liquid phases coexist. The porosity of each meshing element in mushy zone is described by the liquid mass fraction (f). The value of f is described as follow:

$$f = \begin{cases} 0 & if\quad T < T_{sol} \\ \dfrac{T - T_{sol}}{T_{liq}\text{-}T_{sol}} & if\quad T_{sol} < T < T_{liq} \\ 1 & if\quad T > T_{liq} \end{cases} \qquad (4)$$

In equation (4), T_{sol} *and* T_{liq} are the solidus and liquidus temperature of PCM. The source term F is expressed as,

$$F = \frac{(1-f)^2}{f^3+\epsilon} A_{mush}\bar{u} \quad (5)$$

In equation (5), ϵ is a small numerical constant (usually the value is 10^{-3}) used to avoid floating point error during division. A_{mush} is mushy zone constant. A_{mush} value of 10^{-9} was chosen for our study. The specific enthalpy h_{en} of PCM is the sum of latent enthalpy h_{lat} and sensible enthalpy h_{sen} which is given by, $h_{en} = h_{sen} + h_{lat}$.

Sensible heat is the amount of energy required to increase the temperature of a material as follow:

$$h_{sen} = \int_{T_{ref}}^{T} c_p dT, \text{ and} \quad (6)$$

$$h_{lat} = fL_{fusion} \quad (7)$$

Where, L_{fusion} stands for the latent heat of fusion that is energy required to change the phase from solid to its liquid state.

4. Results

The walls of the building function as the insulation for heat transfer to and from inside of the building. In our study, we have used three layers of different materials to form a compact wall. Both the walls from Figure 1 are made of copper but we use PCM sandwiched between these two copper walls. We have studied the best position of PCM based on thermal behavior using numerical simulation. We have considered that the inner conditioned wall (heat sink) is at 298 K and the outer wall (heat source) is at 352 K with convective boundary conditions (convection coefficient, h = 13 W/m^2-K).

Figure 2 shows the evaluation of temperature with time for both Configuration-1 and Configuration-2. We can see that after 10 minutes temperature for configuration-1 rises to almost 300 K and for configuration-2 it rises to almost 306 K.

Figure 3 represents the melt fraction of PCM with the passing time. Melt fraction of PCM for configuration-1 is initially higher that the configuration-2 and thus configuration-1 absorbs more heat which is the reason behind the lesser temperature rise compared to configuration-2. These results depict that when PCM is closed to heat source it can function better as the thermal insulation.

We further study the effect of different materials on heat transfer. We use configuration-1 as our based simulation model and changed the PCM to either sand or wood to study the effect of materials as insulation. Figure 4 shows that the percentage of heat flow is lower for PCM than both sand and wood. We have used temperature boundary conditions for our study and therefore, amount of heat flux through the wall varies with time also different for different materials.

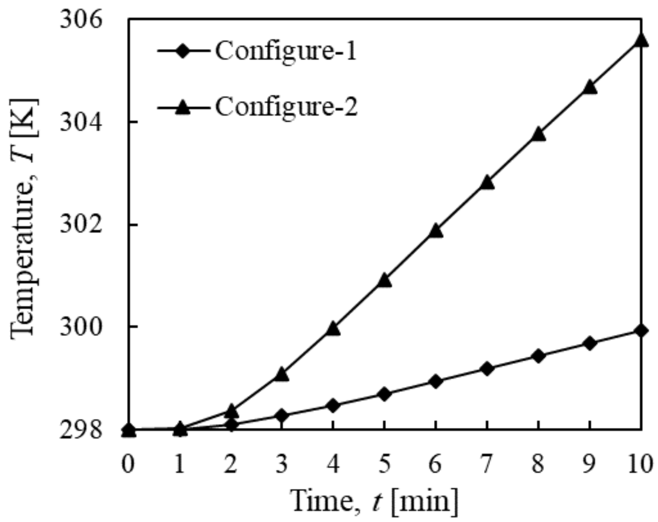

Figure 2. Temperature rises of PCM for configuration-1 and configuration-2

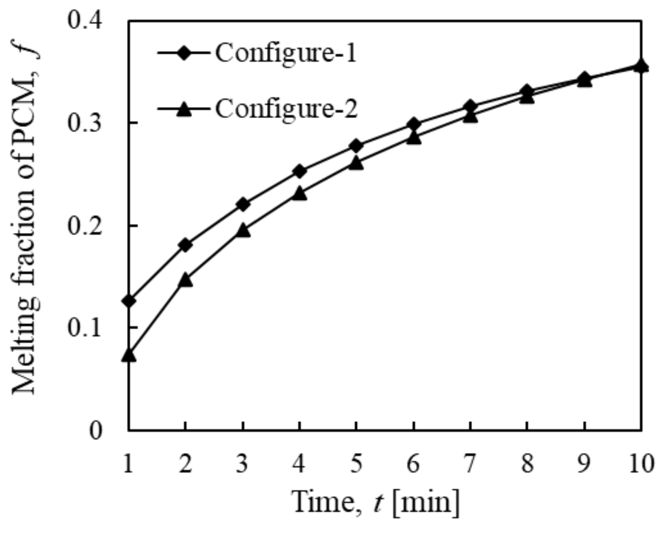

Figure 3. Melt fraction of PCM for configuration-1 and configuration-2

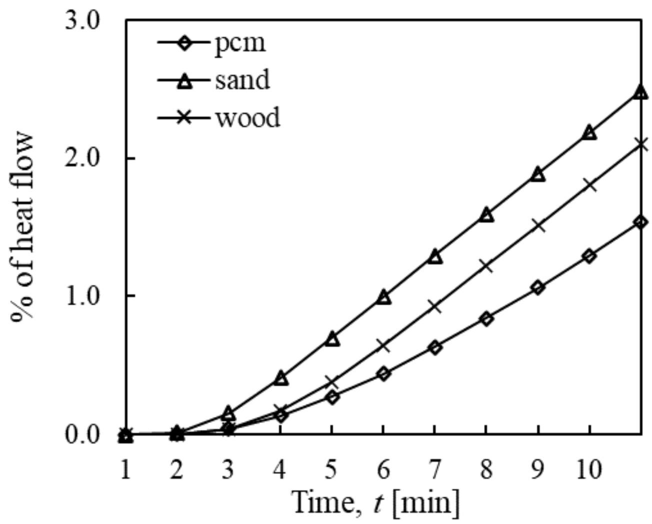

Figure 4. Percentage of heat flow from heat source to heat sink with time.

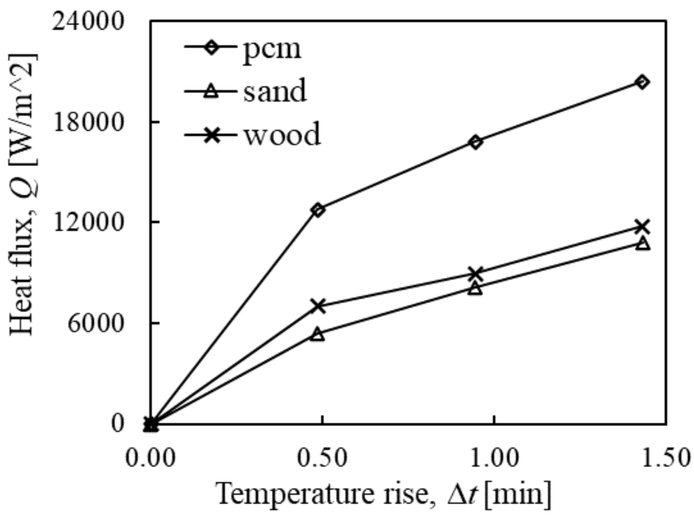

Figure 5. Required heat flux for temperature rise to the heat sink

Figure 5 shows that for the inner wall (heat sink) temperature to rise by the same amount using PCM, roughly twice as much heat from the outside heat source is needed as compared to both sand and wood. This result tells the effectiveness of PCM to condition the inner space of building and how can we store energy using PCM.

5. Conclusion

PCM absorbs huge enthalpy during its melting process. This energy will be driven out during solidification process. TESS can be used as insulation for building envelope to absorb heat energy and later this absorbed energy can be utilized for other purposes. We have run our CFD simulation for different materials and different positions. In this work, the insulating and energy absorbing capacity of phase change materials (PCM) is quantitatively assessed and contrasted with that of wood and sand. It has been discovered that PCM is more successful in preserving the thermal environment inside conditioned space. PCM is discovered to be better positioned for heat sources when it is close to them.

6. Acknowledgement

I would like to thank Dr. Chen to give me the opportunity to complete the project with some satisfying results.

7. References

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