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Experimental and Numerical investigation to Maintain the inside temperature of wooden Transport/storage box by incorporating Phase Change Material

Bhargava Srusti¹, Rajat S², Amar K², Daksh S² & M.B. Shyam Kumar^{3,*}

¹Research Scholar, School of Mechanical Engineering, VIT Chennai

²B.Tech Student, School of Mechanical Engineering, VIT Chennai

³Associate Professor, School of Mechanical Engineering, VIT Chennai

*Corresponding Author Email - shyamkumar.mb@vit.ac.in

Abstract. Transport/storage box is to be used for storing the inorganic material under control environment. The main aim of this storage box is maintain the inside temperature during the transport in the production plant or customer place for the short duration of 1 to 2hrs. In general, during day or night times the interior temperature of storage box increases or decreases than the ambient temperature. This change in temperature can make the stored inorganic materials hazardous. A latent heat based storage system plays a major role in removing unwanted heat & maintaining the inside temperature of the storage box. Numerical and experimental studies were conducted to investigate the role of PCM in maintaining the temperature inside the wooden storage. Storage box is made by plywood and avoid the heat transfer from ambient. the sides and bottom walls are insulated by pasting the thermocol. Experimentation is carried out on the wooden box with no PCM and then with PCM. The operating conditions like solar radiation and ambient temperature is same for both the cases. PCM is placed horizontally on the Aluminium mesh, which is seated above the thermocol padding on top side. The experimental results showed that the box air temperature in the case of without PCM could be raised 42°C depending on how long the box is exposed to sunlight. In case of the wooden box with PCM the inside temperature of 37°C could be maintained for nearly one hour. Considering the same boundary conditions employed in experiments like sun radiation, ambient temperature, a 3D transient numerical simulation is carried out using ANSYS FLUENT. HYPERMESH is used for meshing the solid and fluid domain. Inside air and outside air is considered as fluid domain in the simulation. Both the experimental and numerical results were in variation with 1°C.

1. Introduction

The need for maintaining the inorganic material, salts below the acceptable temperature, during their Transport/storage in production plant or customer place for the short duration of 1 to 2 hours arises. Therefore, the interest in investigating the inside physics of storage box has increased. The storage box is eminently sensitive to climatic conditions during their storage, where it is often subjected to either very high temperature and low temperature areas during the summer and winter periods. In order to maintain the inside temperature of storage box, the room should either to be of fully air conditioned which increases the energy consumption or the side walls should be properly insulated. For the thermal comfort of inorganic material in storage box, the inside air temperature is the important



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ambient variable. Incorporation of phase change materials (PCM) is the possible solution to control and maintain the storage box internal air temperature.

Through experiments conducted on M20 grade concrete cubes [1], better thermal storage in concrete cubes was reported, by incorporating optimized percentage of PCM. From their results it conveys that the thermal comfort improves on reduction in temperature. PCM helps in maintaining the temperature of steering surface and cabin air [2] thereby increasing the thermal comfort of the passenger. Many theoretical design of PCM encapsulation have been reported. Bigger structures showed a better phase change performance, when PCM is encapsulated [3]. Moreover, Thermal energy storage systems (TES) is important component in solar thermal power plant, TES consists of heat transfer fluid (HTF) and thermal energy storage material. For improving the performance of PCM different methods have been used like HTFs such as molten salts and synthetic oil, $\text{NaNO}_3 + \text{Expanded Graphite (EG)}$, pure NaNO_3 [4]. The solidification and liquidification time can be reduced by 14%, with the use of composites and extended fins. Scope of PCM is wide enough such that many numerical studies have been reported. Three different modules like pure CF20, CF-20 plus RT-65 and CF20 plus Nano carbon is tested Numerically for different porosities of carbon foam [5]. There are much wider scope of application using PCM, in ground combat vehicles [6]. Manila and Gian [7] using direct synthesis method different nano fluids, which have phase change behavior are generated by mixing nanoparticles and molten salts. In buildings, PCMs were used to maintain the indoor temperature and store thermal energy [8]. By adding PCMs in concrete, gypsum boards, sandwich panel or other wall covering materials, it becomes an important material of the building structure. Murat and Khamid [9] investigated the effects on organic phase change material by graphite and copper oxide and aluminum oxide. As per the supporting materials, graphite has max crystallite size and min porosity. Tamme et. al. [10] carried out a numerical analysis to find the effect of fin geometry and outer tube conductivity on melting process of PCM, further examined the effect of free convection on the horizontal sleeve-tube unit. Multi objective Pareto method of optimization of solar system was investigated using Particle Swarm Optimization (PSO) method by Sadafi et. al. [11]. They numerically simulated the net energy stored and discharging time of PCM with the geometrical parameters and mass flow rate. It was found that such model gives better simulation results with high accuracy. To test the effects of thermal and geometric parameters on cyclic heating of phase change system Adami [12] developed a 2D time dependent axi symmetric model. Enthalpy method was used to investigate a shell and tube configuration where annulus was contained with phase change material.

The main objective is to study numerically and experimentally the performance of PCM in maintaining the interior temperature of a storage box when placed under the sun or higher ambient temperature for a period of time.

2. Experimental Setup

2.1. Description of the storage box

The experimental setup consists of a wooden box of outer dimensions (505 x 480 x 450 mm). Wood of 15mm thickness is used to make the bottom and side walls of the storage box. Additionally, the inner walls of the wooden storage box were pasted with 40 mm thermocol (Figure 1), to make sure that there is low heat flow from outside through these side and bottom walls. The top surface of wooden box is covered with 2 mm Wooden sheet. The setup ensures that the heat transfer from the solar radiation into the wooden box is only through the top surface. PCM is placed between the aluminum mesh and the wooden sheet as shown in Figure 2. This setup is employed to carry out experiments to check the behavior of Phase Change Material. To measure the box inside temperature two holes are made in the side face of the wooden box for inserting a Pt – 100 (1/5 DIN class B) Temperature sensor. Temperature sensors were calibrated from 10 to 80°C in MICROCAL T100 equipment with 0.1°C accuracy. Solar radiation is measured using Standard Pyranometer, which is manufactured by TENMARS ELECTRONICS CO., LTD. and as accuracy of $\pm 10\text{W/m}^2$.

2.2. PCM Description

In this experiment, a commercial PCM OM 37 purchased from PLUSS ADVANCED TECHNOLOGIES and is employed without any further processing. PCM is already encapsulated in a 30 μm multilayer Nylon Pouches, which is the most flexible method of encapsulating PCM. Multilayer nylon provides good strength, durability and thermal properties equivalent to that of aluminum. The dimensions of 1 nylon pouch comprising of 3 sachets is 495 X 157 X 17 mm thick sheet and weighs 0.6 kg. A total of 3 nylon pouches is used in this experiment, which is almost weighing 1.8 kg together and occupies only 10% of the total inner volume. The Physical characteristics of OM 37 PCM inner is provided in Table 1

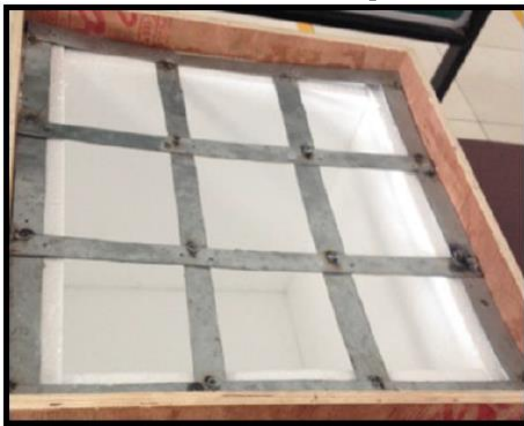


Figure 1. storage box with mesh and thermocol paddings



Figure 2. Storage box with PCM.

2.3. Experimental Procedure

Based on the storage temperature of inorganic material the melting temperature PCM was decided. In the first case, the storage box without PCM and in the second case the storage box with PCM is carried out. PCM pouch is placed over the aluminum frame. Full assembly were placed in the open terrace. Both the above experiments were started from 12:30 PM and continued for almost 2.5 hours. Before starting the above experiments the PCM should be in solid state and the storage box should be at homogenous temperature. This is achieved by placing the box in an air-conditioned room maintained at a room temperature of 27°C. Then the box is immediately placed in the open terrace where solar radiation falls on the box. The inside air temperature is noted for every 20 min by a thermal sensor, placed in the central space of the box. The other sensor is placed outside to measure the ambient temperature. A radiation meter and anemometer were also employed to measure the solar radiation and wind velocity respectively during the experiments.

3. Numerical Simulation

In order to study the performance of PCM numerically, CFD analysis is carried out. A computational domain representing the outside air is selected, where the size is three times of that of the storage box. The void space within the storage box represents inside air. The Fluid domain and structural domain like Wood, thermocol aluminum are FE Modelled using 3D hex & Penta elements (Structured) in ALTAIR HYPERMESH 14, which can be seen in Figure 3. Once the mesh generation is completed, it is imported into ANSYS FLUENT V18. For considering the PCM solidification or melting effects, the solidification module is activated. The solar radiation is calculated by software with the help of date, time, latitude & longitude for the location. Thus the solar radiation obtained from software is same as that of the measured solar radiation. Energy equation is activated for calculating the heat transfer. Laminar viscous model is activated; Domains are defined with gravity to get the air buoyance effect. Fluid (Air) is assumed to be compressible i.e. its density varies with respect to temperature.

As all the solar problems are time varying, a transient simulation is carried out with a time step of 0.1s. The software thus takes almost 1 day of solving time for marching 1200 time steps. Parameters in Table 2 are activated in ANSYS FLUENT.

Table 1. Physical Properties of OM37 PCM.

Physical Properties	Values
Density at 37°C	960 kg/m ³
Density at 38°C	860 kg/m ³
Fusion Temperature range	37°C -38°C
Latent Heat	210kJ/kg
Specific Heat capacity	2.3 kJ/kg-°C
Thermal Conductivity	0.145 W/mK

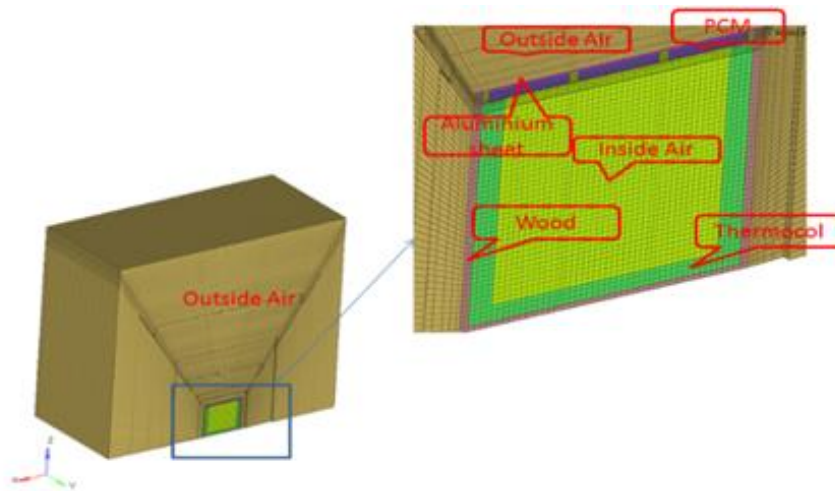


Figure 3. Sectional view of FE model.

Table 2. Simulation Methods.

Physics	Models
Radiation Model	DO Model
Phase Change Model	Solidification and Melting Mushy Zone - 10000
Turbulence Model	Laminar
Simulation Type	Transient (60 min)
Discretization Method	Solver – SIMPLE Algorithm Pressure – Body Weighted Average Velocity – Second Order Energy – Second order DO radiation – First order
Gravity	-ze direction
Convergence Criteria	Continuity /Momentum/Velocity – 1e-04 Energy – 1e-06

3.1. Problem Formulation

Equation (1) is for Heat Transfer in fluids, right hand terms represents the energy transfer due to species diffusion, conduction, source term and viscous dissipation. Specific enthalpy is given by Equation (2), where Y_j – mass fraction of species j.

$$\frac{\partial}{\partial t} [\rho E] + \nabla \cdot [\vec{v}[\rho E + p]] = \nabla \cdot [k_{eff} \nabla T - \sum_j h_j \vec{J}_j + [\bar{\tau}_{eff} \cdot \vec{v}]] + S_h \quad (1)$$

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \quad (2)$$

k_{eff} - Effective thermal conductivity, S_h - Volumetric heat source, ρ - Density, E - Energy, v - Velocity
 T - Temperature, $\bar{\tau}_{eff}$ - Viscous stress tensor

When a fluid is heated its density decreases, due to gravity acting on the density a buoyancy force is induced which can be determined by the ratio of Grashoff number and a Reynolds number, mentioned in Equation (3). If this ratio exceeds 1, then there is a strong contribution of buoyancy effect to the flow.

$$\frac{Gr}{Re^2} = \frac{g\beta\Delta TL}{\nu^2} \quad (3)$$

In case of pure natural convection, the strength of the buoyancy-induced flow is determined by Rayleigh's number mentioned in Equation (4), Thermal expansion β and Thermal diffusivity α are determined through equations (5) and (6). If Rayleigh's number is less than 10^8 then this indicates buoyancy is induced in laminar flow. The energy inside solids is given by Equation (7). As the radiation is included, the Source term S_h in the energy equation includes the heat load from radiation. The Radiative Transfer Equation(RTE) for an absorbing, emitting and scattering medium \vec{r} in direction \vec{S} is given by equation (8), where

$$Ra = \frac{g\beta\Delta T\rho L^3}{\mu\alpha} \quad (4)$$

$$\beta = -\frac{1}{\rho} \left[\frac{\partial \rho}{\partial T} \right]_p \quad (5)$$

$$\alpha = \frac{k}{\rho C_p} \quad (6)$$

$$\frac{\partial}{\partial t} [\rho h] + \nabla \cdot [\vec{v}h] = \nabla \cdot [k\nabla T] + S_h \quad (7)$$

$$\frac{dI[\vec{r},\vec{s}]}{ds} + [a + \sigma_s]I[\vec{r},\vec{s}] = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I[\vec{r},\vec{s}'] \phi[\vec{S},\vec{S}'] d\Omega' \quad (8)$$

\vec{S}' - Scattering direction vector, S - Path length, a - Absorption coefficient, n - Refractive index, σ_s - Scattering coefficient, σ - Stefan-Boltzmann constant, I - Radiation intensity, which depends on position \vec{r} and direction \vec{S} , T - Local temperature, ϕ - Phase function, Ω' - Solid angle

4. Results and Discussions

4.1. Experimental Results

Storage box without PCM is initially maintained at a homogeneous temperature of 27°C by keeping in air conditioned room. At 12:30 PM the storage box without PCM is exposed to solar radiation for a duration of 2.5hrs. Ambient temperature reported is 38°C at 12:30PM and the end of experiment it is reduced by 10.5% as shown in Figure 4. Storage box interior air temperature is observed to be increasing to 42°C from 27°C as shown in Figure 5, which is greater than the ambient temperature.

This change in temperature is due to solar radiation entering the box and the low heat transfer rate to ambient due to the insulation walls.

Similar to initial experiment, the storage box with PCM is maintained at room temperature of 27°C by keeping in air conditioned room. PCM is observed to be solid as it is maintained at 27°C, which is much lower than the melting temperature of PCM i.e. 37°C. Keeping the same ambient conditions as in 1st experiment, the box with PCM is exposed to solar radiation. Interior temperature of box is observed to be increased to 36°C in 60min and then maintained the same temperature for another 60min, which can be seen in Figure 5. This shows that the PCM can maintain the box interior temperature by undergoing phase change from solid to liquid at 36°C.

Results from the experiments of storage box with PCM & without PCM conveys that incorporating PCM will reduce the box interior temperature by 7°C.

4.2. Simulation Results

Simulation is carried out for a computational time of 70 mins. The interior temperature of Storage box has reached to 37°C in 50 mins and remains unchanged for 20min, this is due to the PCM. Figure 6 contains the Contour plots of Box Interior Temperature, which is extracted at the Mid plane. The Air temperature is observed to be increasing as the time passes and also observed that hot air is top & cold air is in the bottom, this is due to the buoyancy effect. Figure 7 conveys that Initially the liquid mass fraction of PCM is 0 i.e. solid. After 30 mins, it can be seen that the top surface of PCM has changed its phase from solid to liquid. At 50 mins it can be seen that the PCM inside layer also starts to become liquid. As heat passes through the space between the PCM packets, a high temperature is observed here.

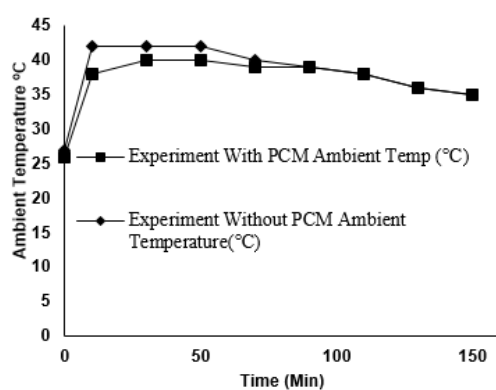


Figure 4. Ambient Temperature

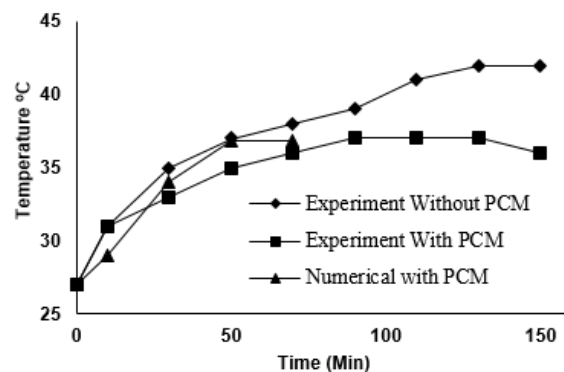


Figure 5. storage box interior air Temperature.

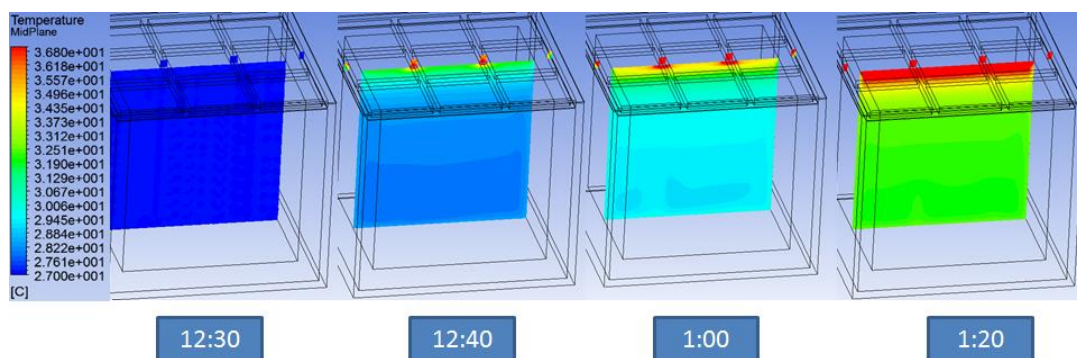


Figure 6. Contours of Air Temperature distribution along a plane at different intervals of time.

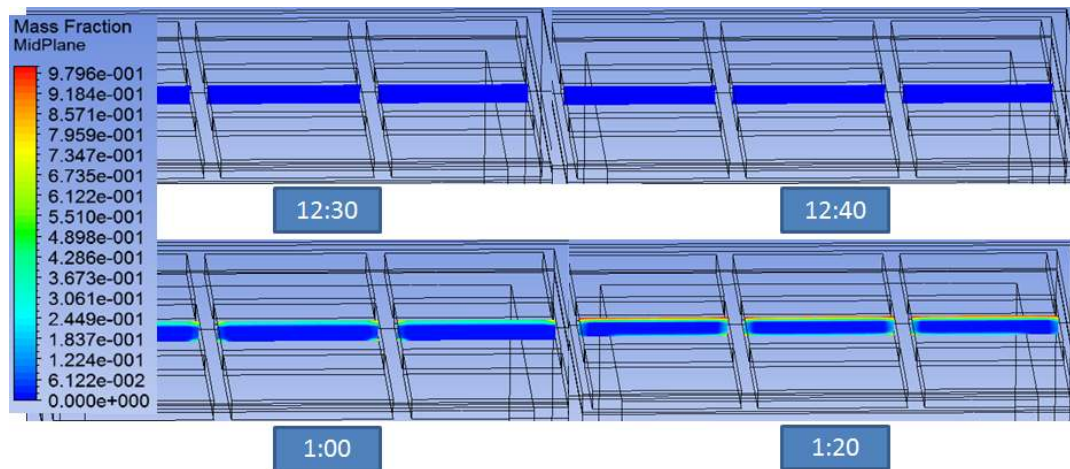


Figure 7. Liquid Mass fraction of PCM

5. Conclusion

The air temperature inside the storage box will increase very fast during the summer when transported, thus causing damage to the inorganic storage material. As a measure to reduce this effect, it is suggested to incorporate the PCM on top side, which absorbs the energy and changes its phase there by maintaining the storage box interior temperature for more than 70min. Experimental and CFD were carried out and the results were deviating by 1°C. By this a benchmarking between Numerical & experimental is established, so many no of Numerical analysis can be carried out by changing PCM Melting temperature.

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