Numerical Analysis of Melting Percentage of Paraffin Wax with Al_2O_3 & Fe_2O_3 Nanoparticles in Rectangular Enclosure

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Abstract - This study is based on variations of thermo-physical properties of Phase Change Material (PCM) due to dispersion of nanoparticles. Dispersed metal oxide nanoparticles in paraffin wax might be a solution to improve latent heat thermal storage performance. Thermo-physical properties such as thermal conductivity and latent heat could be changed for different concentration of dispersed nanoparticle. This paper focuses on numerical investigation of the melting of paraffin wax dispersed with two different metal oxide Alumina (Al2O3) & Ferric oxide (Fe2O3) that is heated from one side of rectangular enclosure of dimensions of 20 mm × 20 mm. The integrated simulation system ANSYS Workbench 15.0 for the numerical study was used including mesh generation tool FLUENT software. In FLUENT, the melting model with Volume of Fluid (VOF) that includes the physical model to disperse nanoparticles in the PCM and their interactions is applied. During melting process, the enhancement of heat transfer is considered. For each nanoparticle analyzed, two different volume fractions are considered and compared. Dispersed nanoparticles in smaller volumetric fractions show a rise in the heat transfer rate. The melting percentage is slightly greater using Fe2O3 as compared to Al2O3 nanoparticles.

Keywords: Phase Change Material; Paraffin Wax; Melting Percentage; Metal Oxide Nanoparticles; Thermal Storage System.

I. INTRODUCTION

The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process. PCMs have been widely used in latent heat thermal storage systems for heat pumps, solar engineering, and spacecraft thermal control applications. The uses of PCMs for heating and cooling applications for buildings have been investigated within the past decade. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications. This paper also summarizes the investigation and analysis of the available thermal energy storage systems incorporating PCMs for use in different applications.

The continuous increase in the level of greenhouse gas emissions and the climb in fuel prices are the main driving forces behind efforts to more effectively utilize various sources of renewable energy. In many parts of the world, direct solar radiation is considered to be one of the most prospective sources of energy. The scientists all over the world are in search of new and renewable energy sources. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. The storage of energy in suitable forms, which can conventionally be converted into the required form, is a present day challenge to the technologists. Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy.

II. PHASE CHANGE MATERIALS

A phase change material (PCM) is a substance with a high heat of fusion melting and solidifying at a certain temperature with capability of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units

In thermal energy storage systems, the melting of phase changing materials in the enclosure has significant consideration. Melting temperature, heat capacity, thermal conductivity and density are crucial properties to define a material suitable for such applications. Ideally, the required qualities of PCM would be high latent heat of fusion per unit mass, high heat capacity, high density, to be not toxic, not expensive and not corrosive.

A large heat flow for this material can be achieved by increasing the effective thermal conductivity. Nanoparticles added in PCM considerably increase the effective thermal conductivity of the fluid and thus enhance the heat transfer characteristics. In the present work, a numerical investigation of the melting is carried out to estimate the effect on melting percentage of paraffin wax due to the dispersion of nanoparticle of metal oxide (Al2O3 & Fe2O3) with paraffin wax. The effect of volumetric fractions of two different nanoparticles on the melting performance are presented and discussed.

Fig. 2.1 Phase change material (PCMs)

Physical Model

The geometry used, shown in Figure 2, is a rectangular box of size 20 mm × 20mm. It contains paraffin wax or paraffin wax dispersed with 1% and 3% by volume of two different nanoparticles Al_2O_3 & Fe_2O_3 The initial temperature of the Nano PCM is 300 K, the hot wall side is at a variable temperature of 327-400 K (Tmax) and the cold wall, opposite the hot wall, is at 300 K (Tmin) in order, the other two walls are adiabatic.

Assumptions made:

- The flow is Newtonian, incompressible and laminar
- The viscous dissipations are negligible.
- The physical properties of PCM are temperature dependent.
- Heat transfer is both conduction and convection controlled.
- The volume variation resulting from the phase change is neglected.
- 2D model is used, neglecting 3D convection. With this hypothesis, the results may be considered almost real because the 3d convection duration is very short as compared with the whole melting process.

III. GOVERING EQUATION

PCM Storage System: Fluid flow, heat transfer and phase change of the PCM processes with nanoparticles are regarded in the storage system. The governing conservation equations are as follows.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{U}) = 0 \qquad (1)$$

Momentum equation:

$$\partial / \partial t (\rho \bar{U}) + \nabla . (\rho \bar{U} \bar{U}) = -\nabla . P + \rho \bar{g} + \nabla . \bar{\tau} + \bar{F} \qquad (2)$$

Where P is the static pressure, → τ is the stress tensor, and ρ→g& →F are the gravitational body force and external body forces, respectively.

Energy equation:

$$(\partial (\rho H)) / \partial t + \nabla . (\rho \bar{U} H) = \nabla . (K \nabla T) + S \qquad (3)$$

Where H is the enthalpy, T is the temperature, ρ is density, K is the thermal conductivity, U is the velocity and S is volumetric heat source term and is equal to zero in the present study. The total enthalpy H of the PCM is computed as the sum of the sensible enthalpy, h and the latent heat, ΔH. The latent heat content, in terms of the latent heat of the PCM, L is:

$$\nabla H = \beta L \qquad (4)$$

where β is liquid fraction and is defined as:

$$\beta = 0 \quad \text{if } T < T_{solidus}$$
$$\beta = 1 \quad \text{if } T > T_{liquidus}$$
$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad \text{if } T_{solidus} < T < T_{liquidus} \qquad (5)$$

The solution for temperature is essentially an iteration between the energy Eq. (3) and the liquid fraction Eq. (5). The enthalpy-porosity technique treats the mushy region (partially solidified region) as a porous medium. The porosity in each cell is set equal to the liquid fraction in that cell. In fully solidified regions, the porosity is equal to zero, which extinguishes the velocities in these regions.

IV. THERMAL PHYSICAL PROPRIETIES

The thermo- physical properties of paraffin wax, Al_2O_3 & Fe_2O_3nanoparticles, are listed in Table 1. The Difference in the solids and liquids temperatures defines the transition from solid to liquid phases during the melt¬ing of PCM. The density, specific heat capacity and latent heat of the nano PCM are defined as follows.

$$\rho_{npcm} = \varphi \rho_{np} + (1 - \varphi) \rho_{pcm} \qquad (6)$$

$$C\rho_{npcm} = \frac{\varphi (\rho C_p)_{np} + (1 - \varphi)(\rho C_p)_{pcm}}{\rho_{npcm}} \qquad (7)$$

$$L_{npcm} = \frac{(1 - \varphi)(\rho L)_{pcm}}{\rho_{npcm}} \qquad (8)$$

Where φ is volumetric fraction of nanoparticle. The dynamic viscosity and thermal conductivity of the Nano PCM are given by the following

$$\mu_{npcm} = 0.983 e^{(12.958 \varphi)}$$

TABLE 1.PARAMETERS

	Paraffin Wax	AL_2O_3	Fe2O3
Density(kg/m3)	750/[.001(T-319.15)+1]	3600	5240
Specific heat(J/kgK)	2890	765	650.6
Conductivity(W/mk)	0.21 if $T<T_{solid}$ 0.12 if $T>T_{liquidus}$	36	0.27
Viscosity (Ns/m2)	0.001 exp [-4.25+(1700/T)]		
Latent Heat (J/kg)	173400		
Solid Temperature (K)	319		
Liquid Temperature (K)	321		
Tref (K)	298.15		
dnp (nm)		59	

The effective thermal conductivity of the nano PCM, which includes the effects of particle size, particle volume fraction and temperature dependence as well as properties of the base PCM and the particle subject to Brownian motion is given by:

$$K_{npcm} = \frac{K_{np} + 2K_{pcm} - 2\left(K_{pcm} - K_{np}\right)\varphi}{K_{np} + 2K_{pcm} + 2\left(K_{pcm} - K_{np}\right)\varphi} K_{pcm} + 5\times10^4 \beta_k \varsigma \varphi \rho_{pcm} C_{p_{pcm}} \sqrt{\frac{BT}{\rho_{np} d_{np}}} f(T,\varphi) \quad (10)$$

Where Tref is the reference temperature. The first part of

where:

B is Boltzmann constant, 1.381×10−23 J/K

$$\beta_k = 8.4407 * \left(100\varphi\right)^{-1.07304} \quad (11)$$

$$f(T,\varphi) = \left(2.8217\times10^{(-2)}\varphi + 3.917\times10^{(-3)} T/T_{ref}\right) + \left(-0.669\times10^{(-2)}\varphi - 3.91123\times10^{(-3)}\right) \quad (12)$$

Eq. (10) is obtained directly from the Maxwell model while

TABLE 2.PERCENTAGE COMPOSITION FOR ANALYSIS

Melting	%(Volume)
PCM = Paraffin Wax	100%
PCM + Al2O3	1% & 3%
PCM + Fe2O3	1% & 3%

The second part accounts for Brownian motion, which causes the temperature dependence of the effective thermal conductivity. Note that there is a correction factor ς in the Brownian motion term, since there should be no Brownian motion in the solid phase. Its value is defined as the same as for liquid fraction, b in Eq. (5).

V. BOUNDARY AND TEST CONDITIONS

In this section conclusion of the research work should be explained.

The boundary and test conditions (Table 2) are prescribed as follows:

Hot wall $T = T_{max}$

Cold wall $T = T_{min}$

Adiabatic walls $(Kn_{pcm}\ \Delta T) = 0$

Initial condition $T_i = T_{min}$

For the numerical study, the integrated simulation system ANSYS Workbench 15.0 is used. The platform includes meshgeneration tool FLUENT software.

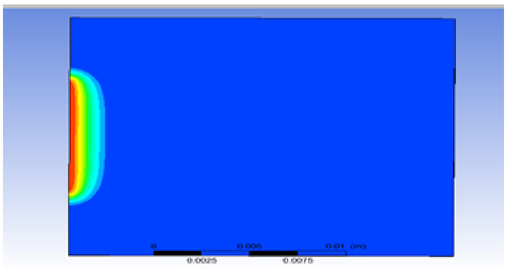
RESULTS

Liquid fraction

The contour of liquid fraction in melting process at various times for different volume fractions is shown in the below mentioned figures.

Results for 1% of Al_2O_3 & Fe2O3

PCM+Al_2O_3(1%)



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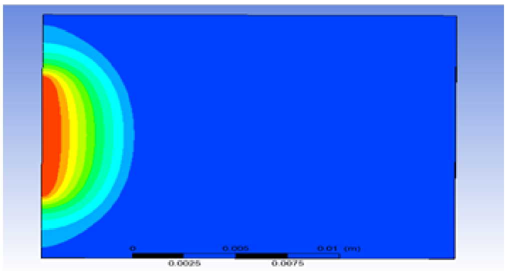

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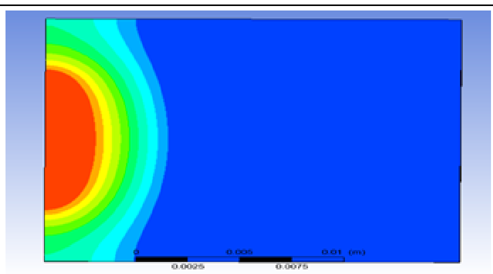

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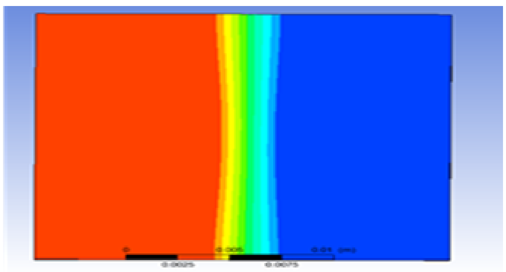

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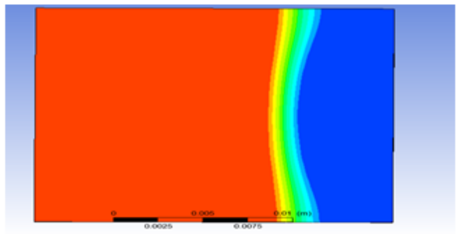

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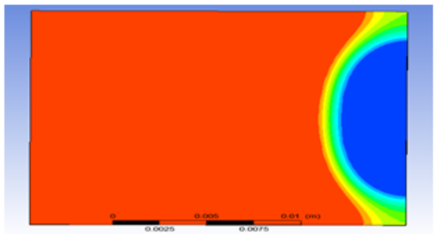

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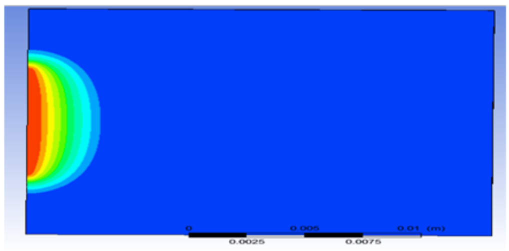
PCM+Fe_2O_3(1%)



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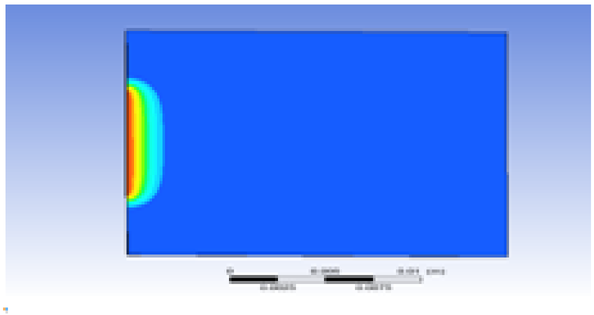
PCM+Al_2O_3(3%)



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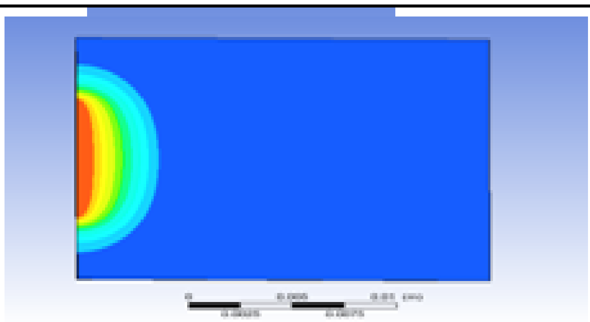

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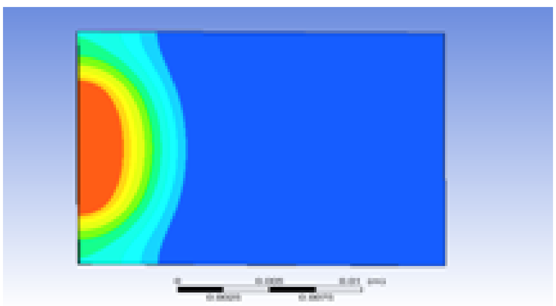

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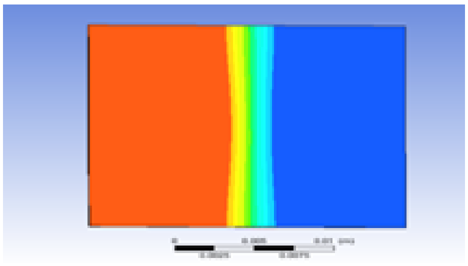

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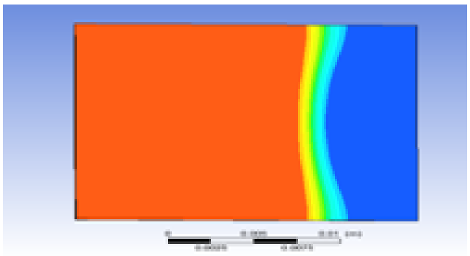

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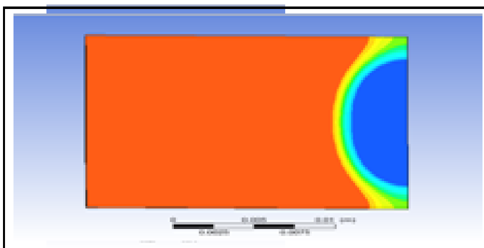

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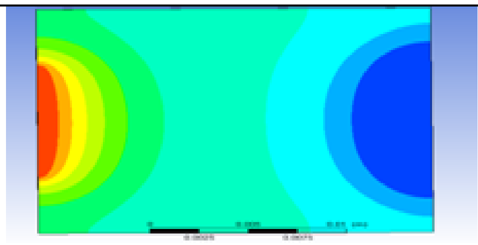
PCM+Fe_2O_3(3%)



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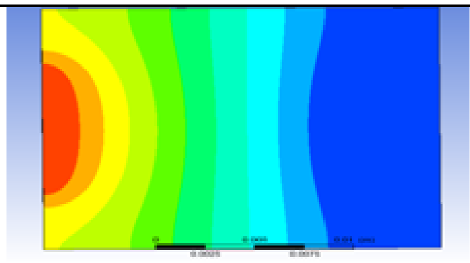

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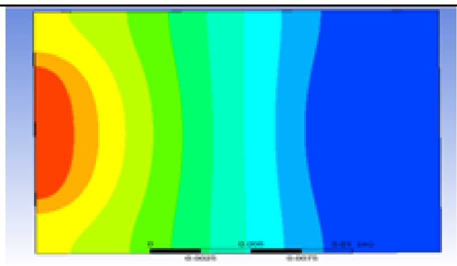

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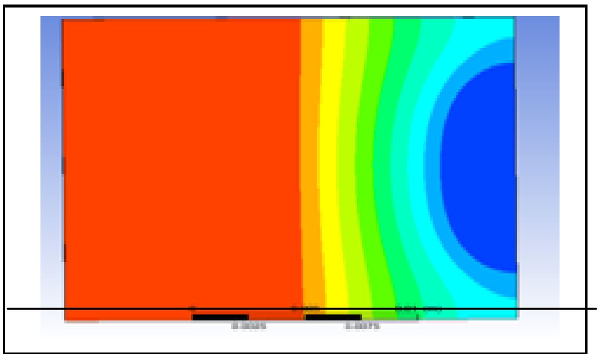

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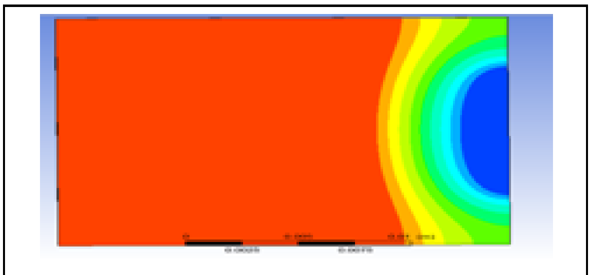

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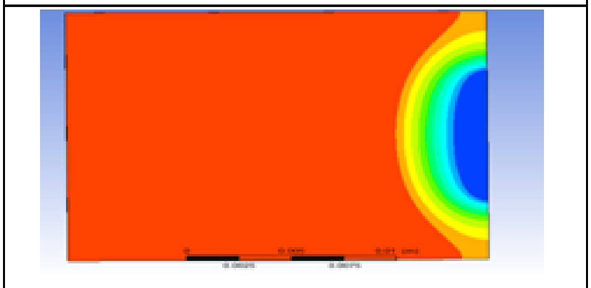

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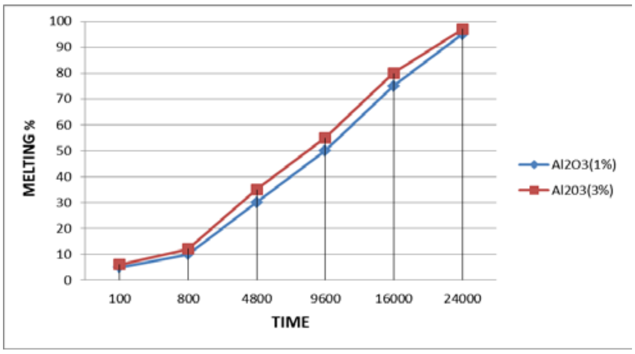
Results for 3% of Al2O3 & Fe2O

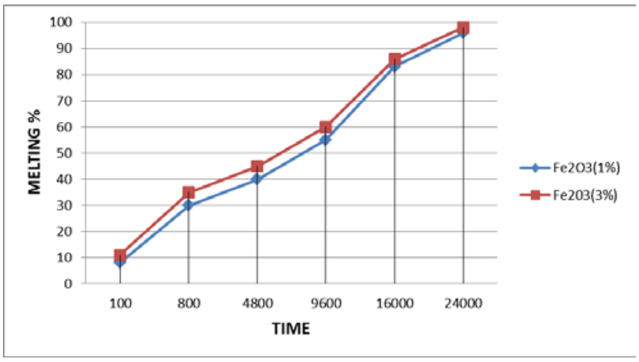
Liquid fraction distribution for different volume fractions of PARAFIN WAX with different nanoparticles.

Heat Transfer Performance

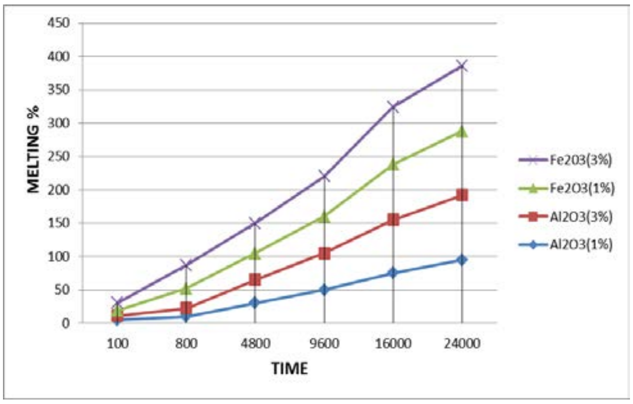
The melting rate of Al2O3 and Fe2O3 nanoparticles enhanced paraffin for two volumetric concentrations 1%, and 3% wax is examined.



Thermo-physical properties of Al2O3 at different volumetric concentration.



Thermo-physical properties of Fe2O3 at different volumetric concentration



Thermo-physical properties of Al2O3 and Fe2O3 at different volumetric concentration

VI. CONCLUSION

In this study on variations of melting properties of phase change material (PCM) due to dispersion of nanoparticles is presented. We focused on investigation of the melting of paraffin wax dispersed with two different metal oxide ((Al2O3 & Fe2O3) with different concentration is heated from one side of rectangular enclosure of dimensions of 20 mm×20 mm. From the results mentioned in the previous chapter following conclusion can be drawn:

For all Nano PCM considered at 1% and 3% volumetric concentration, results confirm that:

- The melting percentage increases with the increase in the volumetric composition of adding nanoparticles.
- The thermal performance of paraffin wax is enhanced only marginally with the dispersion of Al2O3 &Fe2O3 nanoparticles.
- The melting percentage for Al2O3 with 1% concentration is more than for nanoparticle concentration of Al2O3 with 3 %.
- The melting percentage for Fe2O3 with 1% concentration is more than for nanoparticle concentration of Fe2O3 with 3 %.

- In the early stages of the melting process the heat transfer take place mainly by conduction process and after further heating it changes to natural convection.
- It requires 6.6 hours for paraffin wax + Al2O3 (1%) to fully melt while in case of paraffin wax + Fe2O3 (1%) 1.3 hours are needed for the fully melting of the PCM wall.
- It requires 2.6 hours for paraffin wax + Al2O3 (3%) to fully melt while in case of paraffin wax + Fe2O3 (3%) ½ hour are needed for the fully melting of the PCM wall.

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