

Thermal Performance Analysis of Nanoparticles Enhanced Phase Change Material (NEPCM) in Cold Thermal Energy Storage (CTES)


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ABSTRACT

Consideration on energy on energy saving in cooling has been voiced out lately. Cold Thermal Energy Storage (CTES) incorporating with phase change material (PCM) play an important role in cooling system as latent heat storage. Nevertheless, the nature of poor thermal conductivity and supercooling phenomena of PCM are the drawbacks that degrade the efficiency of CTES. A numerical and experimental work on phase change of PCM after dispersed with various types of nanoparticles is presented in this study. Nanoparticles with high thermal conductivity properties could be a good additive to enhance the thermal performance of PCM in latent heat thermal energy storage. The phase change rate of paraffin wax as PCM dispersed with three types of nanoparticles: Alumina (Al₂O₃), Copper oxide (CuO) and Zinc Oxide (ZnO) in a 25mm × 25mm square enclosure and the effect of heating side of the wall and the concentration of nanoparticles dispersed in PCM were investigated. ANSYS Workbench 17.0 that included mesh generation tools and FLUENT software was used to run the simulation. Enthalpy porosity method was applied in this numerical study. Results shown that heat transfer rate was improved by adding low volume fraction of nanoparticles. Heating from the side wall of the enclosure has better melting rate than heating from below.

Keywords:

Thermal Energy storage, Phase change material, Nanoparticles, NEPCM, CTES

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1. Introduction

Due to demand of people to live in a comfort life, new electronic devices and technologies advance tremendously nowadays. However, this trend has also voiced out the considerations on the energy conservation to save energy; cooling technique for overheated equipment and the list go on. Nevertheless, most of the challenges are related to the heat transfer of material and its thermal performance in applications. Thus, enhancement in thermal performance is significant in order for devices and systems to work in high efficient and consistently.

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In Malaysia, Cold Thermal Energy Storage (CTES) plays a vital role especially in building centralized air conditioning (AC) system to store the cooling energy as the energy consumption of AC system is the highest (57%) in office building [1]. The chart below (Figure 1) shows the total energy consumption by all equipment and their breakdown (%) in office of Malaysia.

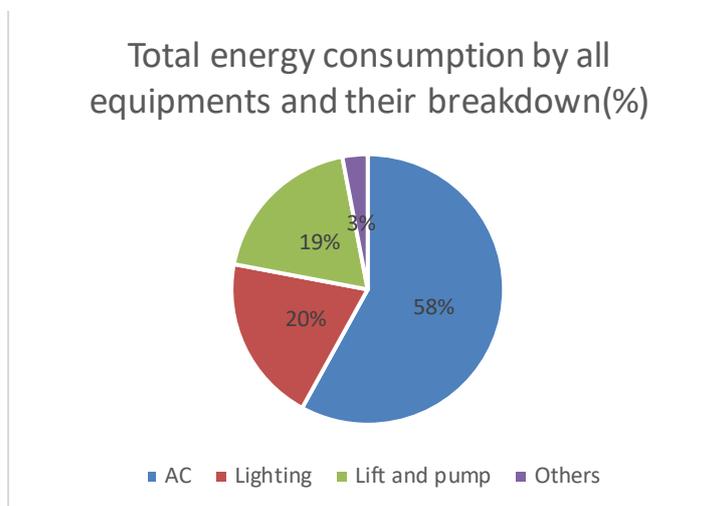


Fig. 1. Total energy consumption by equipment and their breakdown (%) in Malaysia office

CTES able to conserved the energy through shifting the entire on-peak load to off-peak hours [2]. During the daytime or on-peak hours, there is a lot of energy demand for cooling the building due to the risen environmental temperature. The main chiller system will work at a high burden condition in order to fulfill the high cooling demand especially in noon. On the other hand, the chiller system is at rest during night or off-peak hours. By installing CTES, it able to assist the main chiller system by storing cold energy at night/off-peak hours and releasing cold energy when it is needed in the time of peak load. Cold energy is stored and released through freezing and melting processes respectively [3].

In order to conserve the energy usage, CTES play an important role as a latent heat energy storage to store the abundance energy and supply energy when needed. By enhancing the heat transfer performance of PCM in CTES, more energy can be conserved as CTES can function at high efficiency when incorporating with NEPCM. CTES that incorporating with PCM as a latent energy storage is a viable option to achieve high energy efficiency as it can store 5-14 times higher latent energy in intensity compared to sensible heat [4]. Furthermore, cost such as maintenance cost can be reduced as lesser work and burden done by the main chiller system. as CTES reduces peak demand of cooling system and shifts electric energy usage from on-peak to off-peak hours, it can lead to significant electricity cost savings especially in areas with variable market price of electricity during daytime and nighttime. In additions, cooling system with high efficient CTES are more environmental friendly as less greenhouse gases will be generated by the chiller system due to reduction in consumption of energy.

Phase change material (PCM) is widely recognized in many engineering applications due to its superior properties. As PCM able to store and release thermal energy during the process of melting & freezing, PCM is an ideal product for thermal management solutions. Currently, PCM has been applied in Thermal Energy Storage Systems (TES), in heating, ventilation and air conditioning systems (HVAC) in modern building, as coolant for microelectronics such as Microchannel Heat Sink (MCHS) and even in production of smart textiles in purpose keeping human body temperature warm [5-7].

Water is a conventional PCM that used in many applications owing to its abundant availability and thermal conductivity.

The purpose of PCM is to work as a latent heat energy storage through melting & freezing processes. However, PCM itself unable to work at high efficiency due to poor thermal conductivity of pure PCM. Besides, supercooling phenomena can easily occur and caused the PCM inefficient in transfer heat. There are many studies and research have been done to improve the heat transfer performance of the thermal energy storage such as encapsulation of PCM [8-10], modify geometry/shape [11] of storage tank and adding fin [12-14]. Owing to the breakthrough of nanotechnology recently, the role of nanoparticles in improving the thermal properties is being reported as an alternative solution. Thus, enhancement of the thermal performance by introducing NEPCM through dispersion of nanoparticles into PCM is suggested in order to solve the problem stated.

Thermal conductivity of PCM are enhanced by dispersing nanoparticle into the heat transfer fluid (HTF) or PCM itself and become nanoparticles enhanced phase change material (NEPCM). The rate of solidification & melting tend to increases as the time taken is shorten [15]. The common factors of nanoparticle that influence the thermal properties improvement of PCM are found to be the nanoparticle size, volume fraction, temperature and geometry (shape) [16]. Khodadadi and Hosseinizadeh [17] were probably the earliest researchers that perform the investigation on enhancing the PCM thought dispersion of nanoparticles in year 2007. Inspired by the report of Mesuda [18] on the improvement of thermal conductivity after dispersed some nano-sized particles in liquids, Khodadadi and Hosseinizadeh conducted an computational study that highlight the potential of using NEPCM in thermal storage applications. Table 1 shown some researches carried out recently by other authors in enhancing PCM thermal properties.

Table 1
Study on enhancement of PCM by Nanoparticles

Authors	Nanoparticles	PCM	Findings
Sakr R.Y. <i>et al.</i> , [19].	Aluminum oxide (Al ₂ O ₃)	water	Freezing/melting time of NEPCM shorten by 19% with 2% nanoparticles
Chen J. &, Zhang P <i>et al.</i> , [20]	n-hexadecane n-octadecane / water (prepared by D-phase method.)		Enhanced total heat capacity, thermal conductivity Viscosity decreased at high temperature but increased with the large mass faction.
Li X. <i>et al.</i> , [21]	perlite		NEPCM performed better than microencapsulated PCM under certain conditions
Karimi G. <i>et al.</i> , [22]	Silver (Ag), Copper (Cu), Iron(III) Oxide (Fe ₃ O ₄)		Dispersion of metal nanoparticles in the PCM brought significant improvement in the effective thermal conductivity. Ag nanoparticles exhibited the best thermal performance.
Babapoor A. <i>et al.</i> , [23]	Silica Oxide (SiO ₂), Aluminum Oxide (Al ₂ O ₃), Iron(II) Oxide (Fe ₂ O ₃), Zinc Oxide (ZnO)	paraffin	Dispersion of nanoparticles can improve thermal conductivity by 150% at maximum but also lowered specific heat by 39% at maximum. 8wt% loading of ZnO nanoparticles exhibit the optimum thermal performance.
Nourani M, <i>et at.</i> , [24]	Aluminum Oxide (Al ₂ O ₃)		Sodium stearyl lactylate (SSL) was used as surfactant. Heating and melting times of NEPCM reduced by 27%. 10wt% of Al ₂ O ₃ enhanced the thermal conductivity by 31% in solid state and 13% in liquid state.
Warzoha R.J <i>et al.</i> , [25]	Herringbone style graphite nanofibers (HGNF)		Thermal conductivity of the NEPCM rise gradually in solid phase but not liquid phase. The latent heat of fusion declined with the increasing volume fraction of

			HGNF yet still able to retain 90% amount of original latent heat
Zhang X. and Han Z. [26]	Alumina (AlO ₂)		At 0.5wt%, NEPCM melted at 54.24°C with and freeze at 57.68°C after 50 cycles. Thermal conductivity increased by 72% but slightly decrement in latent heat occurred
Ma Z. <i>et al.</i> , [27]	Copper (Cu)	RT24	NEPCM shown higher melting and freezing rate compared to pure PCM where 8.3% more heat was charged and 25.1% more heat was discharged during the test.
Sharma R.K. <i>et al.</i> , [28].	Titanium Dioxide (TiO ₂)	palmitic acid	Melting point of NEPCM does not experienced significant change. Latent heat was dropped but thermal conductivity increased tremendously by 12.7, 20.6, 46.6, and 80% with respect of 0.5, 1, 3, and 5% weight fraction of TiO ₂ nanoparticles
Fan L.W. <i>et al.</i> , [29, 30]	Graphite nanosheets (GNSs)	1-dodecanol	Thermal conductivity of NEPCM improve up to 50% in comparison to pure PCM and the total melting rate is fastened by 10% with the assist of 0.5 wt.% GNS. The total solidification time reduced by 18.0%.

Nanoparticles can be concluded as a promising additive for PCM in order to enhance its heat transfer performance. However, there are still lack of numerical result on total energy stored and retrieved from the PCM and NEPCM in a continuous phase change cycle. The simulation on phase change of PCM and NEPCM in 3D and two phases methods are still limited. There is abundance investigation on paraffin wax as an organic PCM in CTES yet there is limited use of salt hydrate component as PCM. In this study, the enhancement effect of dispersing nanoparticles in pure PCM is determined through numerical and experimental study of melting process of NEPCM in a square enclosure as storage tank.

2. Methodology

2.1 Numerical Simulation

Defining the geometry and boundary condition are the first stage for CFD simulation. From coordinate and line forming, faces and body of the geometry are defined. The second stage will be defining the mesh. The grids are arranged based on tri/quad type and with mesh sizing/interval being size within the wall of faces. The higher the number of grids, the finer the simulation flow profile, converging and closer to the actual result, at the expense of computational power and time. Subsequently, mesh independent test are run until it reaches independency for optimal simulation where the result will not be affected by denser grids or nodes. The solver and model needed to be comprehended, selected with necessary condition/criteria activated such as energy, gravity and so forth.

In present numerical study, the integrated simulation system ANSYS Workbench 17.0 is used. The governing equations that related to the boundary and initial conditions are solved by the FLUENT software based on the finite volume method. The SIMPLE algorithm is applied for solving pressure–velocity coupling and the PRESTO scheme is used for the pressure correction equation. FIRST ORDER UPWIND differencing scheme is adopted on the momentum and energy equations. For all iterations, the time step for integrating the temporal derivatives was set to 0.01s. whereas for every time step, the maximum number of iterations is adjusted to 10 which is adequate with the convergence limit of 10^{-3} in the continuity and momentum equations; 10^{-6} in the energy equation. Also, for the under-relaxation factors for x-components and y-components, momentum equations, pressure correction equation, energy equation, and liquid fraction are fixed to 0.5, 0.3, 1 and 1 respectively.

2.1.1 Physical model & boundary condition for 2D simulation

The geometry applied was shown in Figure 2. It is a square enclosure with a dimension of 100 mm (L) × 100 mm (W). The cavity filled with pure PCM or PCM dispersed with numerous type of nanoparticles with different volume fraction. There are two case study where one of the hot wall are located at the left vertical wall and the other at the horizontal bottom wall. The temperature of the hot wall is at constant temperature of 330 K and the opposite wall, also known as cold wall is at a constant temperature of 300 K. The remaining two walls are adiabatic and the initial temperature of the PCM is 300K. The boundary condition in the study of melting process is prescribed as follow:

Hot Wall: $T = T_{\max}$

Cold Wall: $T = T_{\min}$

Adiabatic Wall: $K_{npcm} \Delta T = 0$

Initial Condition: $T_i = T_{\min}$

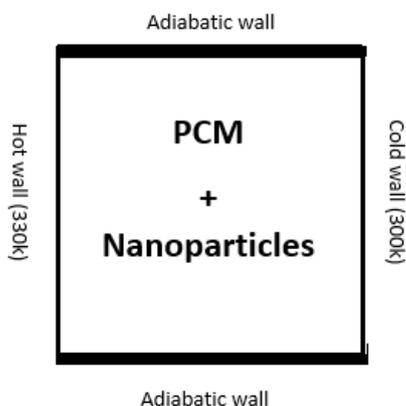


Fig. 2(a). Square cavity (100 mm × 100 mm) heating from left vertical side

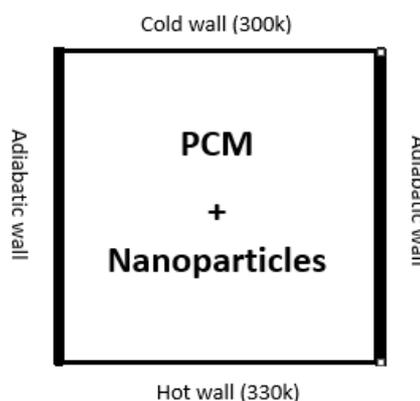


Fig. 2(b). Square cavity (100 mm × 100 mm) heating from bottom

2.1.2 Grid independence test

A mesh test is conducted in order to check the grid independence and refine the obtained results. A graph of liquid fraction over flow time is plotted as shown Figure 3 with 0 % of Al₂O₃. Grid sizes of 80 × 80, 100 × 100 and 110 × 110 are simulated. According to the Figure 3, there is negligibly small difference between the results of the 100 × 100 and 110 × 110 grid sizes. Hence, the grid with 100 × 100 cells is considered and selected for all the simulations and calculations in present work.

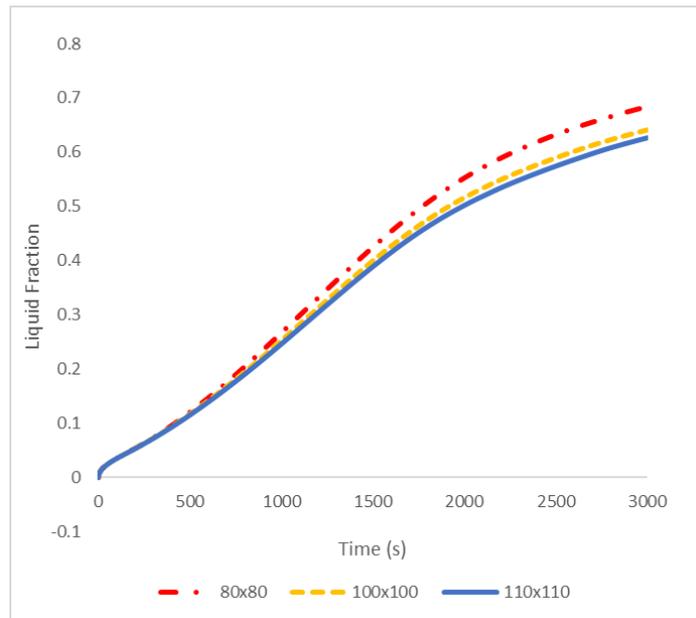


Fig. 3. Effect of Grid Size on Melting of Pure PCM

2.1.3 Governing equation

Enthalpy porosity method is used in present simulation on melting of a NEPCM in a square enclosure. The enthalpy porosity method can figure out the liquid fraction in each cell in the computational domain at any iteration based on enthalpy balance. During the phase change process, the value of liquid fraction changes between 0 and 1 where the values of 0 represent solid state and 1 represent liquid state respectively. Also, values lie between 0 and 1 are serve as mushy state. The governing conservation equations are as follows [31]:

Continuity equation:

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

Momentum equation:

$$\frac{\partial}{\partial t} (\rho \vec{U}) + \nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla P + \rho \vec{g} + \nabla \vec{\tau} + \vec{F} \quad (2)$$

where P represents the static pressure, $\vec{\tau}$ denotes the stress tensor, $\rho \vec{g}$ is the gravitational body force and \vec{F} is the external body force.

Energy equation:

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{U} H) = \nabla \cdot (K \nabla T) + S \quad (3)$$

where H is the enthalpy of NEPCM, T denotes the temperature, ρ represent density, K is thermal conductivity of NEPCM, \vec{U} stands for velocity and S is the source volumetric heat source term which is set for zero in present work. The total enthalpy H , of the PCM is considered as the sum of the sensible enthalpy, h and the latent heat, ΔH :

$$H = h + \Delta H \quad (4)$$

where

$$h = h_{ref} + \int_{T_{ref}}^T C_p dT \quad (5)$$

Here, T_{ref} and h_{ref} are the reference temperature and reference enthalpy respectively. C_p represents the specific heat at constant pressure. Also, the latent heat of the PCM is given by:

$$\nabla H = \beta L \quad (6)$$

where β is the liquid fraction and is defined as:

$$\beta = 0 \quad T < T_{solidus}$$

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad T_{solidus} < T < T_{liquidus}$$

$$\beta = 1 \quad \text{if } T > T_{liquidus} \quad (7)$$

There is a necessitate to have iteration between the energy Eq. (3) and liquid fraction Eq. (6) to solve temperature. In enthalpy porosity method, the mushy region (partially solidified region) is treated as a porous medium. The porosity in each cell is set equal to the liquid fraction in that cell. In fully solidified regions, porosity is set equal to zero, which excluded the velocities in these regions.

2.1.4 Thermal physical properties

The thermal physical properties of PCM and nanoparticles are listed in Table 2. The difference in the solidus and liquidus temperatures denotes the phase transition from solid to liquid state in the melting of PCM

Table 2
Properties of PCM, nanoparticles and operating parameters [32-34]

	Paraffin Wax	Al ₂ O ₃	CuO	ZnO
Density (kg/m ³)	$\frac{750}{0.001(T - 319.15) + 1}$	3600	6510	5606
Specific heat (J/kgK)	2890	765	540	514
Thermal conductivity (W/mK)	0.21 if $T < T_{solidus}$ 0.12 if $T > T_{liquidus}$	36	18	23.4
Dynamic Viscosity (Ns/m ²)	$0.001 \exp(-4.25 + \frac{1700}{T})$	-	-	-

Latent heat (J/kg)	173400	-	-	-
Solidus temperature (K)	319	-	-	-
Liquidus temperature (K)	321	-	-	-
d_{np} (nm)	-	59	29	50
λ_1	-	0.983	0.9197	0.904
λ_2	-	12.958	22.8539	14.8
β_1	-	8.4407	9.881	8.4407
β_2	-	-1.07304	-0.9446	-1.07304

2.1.5 Model validation

Similar simulation was reported by Arasu and Mujumdar [35] and Ebrahimi [36] on melting of NEPCM in a square enclosure using paraffin wax as PCM and mixing with 2 wt.% of Al_2O_3 nanoparticles. The results of liquid–solid interface at 1000 s and 3000 s is compared and shown in Figure 4 and 5. A reasonably good agreement is obtained.

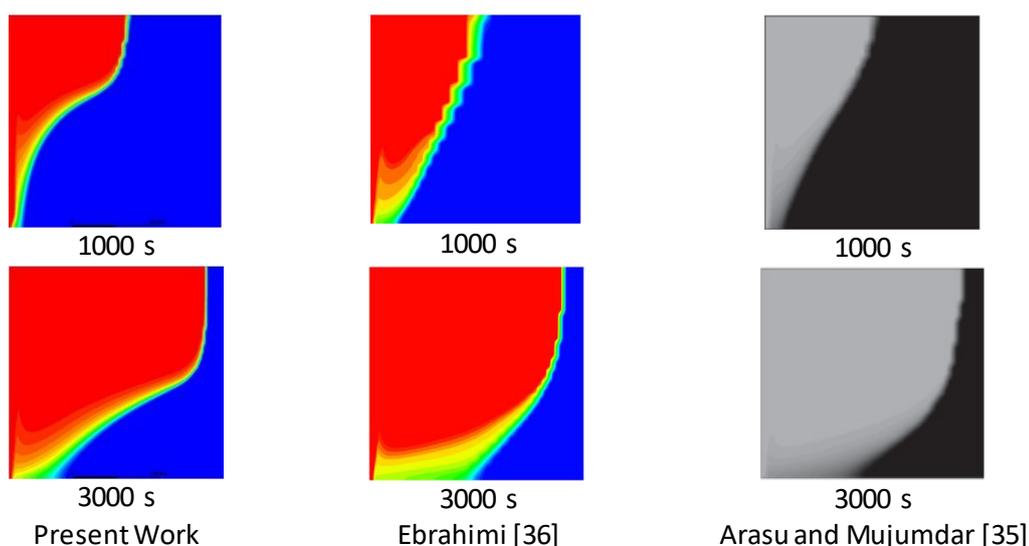


Fig. 4. Comparison on Melting of Paraffin Wax + 2 % Al_2O_3 Nanoparticles

2.1.6 Assumption for preliminary study

- I. The numerical studies on the heat transfer performance during phase change process of PCM and NEPCM are based on enthalpy porosity method. There are some assumptions that been made for the numerical study.
- II. The flow of NEPCM in liquid state is considered as an incompressible, unsteady, laminar and Newtonian.
- III. The thermal physical properties of PCM and NEPCM are temperature dependent.
- IV. Heat transfer is both conduction and convection controlled.
- V. The PCM or nanoparticles are assumed as continuous media and in state of thermodynamic equilibrium.

VI. There is no-slip boundary condition is applied between PCM and nanoparticles.

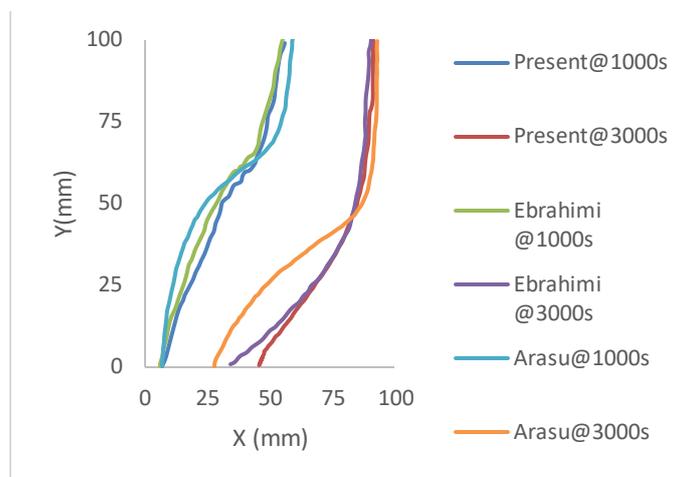


Fig. 5. Melting Front of Paraffin Wax + 2 % Al_2O_3 Nanoparticles at various Time

3. Results

3.1 Evolution of Melting Rate

The effect of mixing nanoparticles with PCM on its melting rate is examined and the result is plotted in Figure 6. The melting rate is indicated by the liquid fraction contained at certain time being. According to Figure 6, it is clear that the melting rate of PCM can be improved by adding 2 % of nanoparticles but only at low concentration. On the other hand, PCM melt slower when 5 % of metal oxide is added. This trend justifies that improvement in thermal conductivity can enhance the melting rate but high dynamic viscosity will degrade the heat transfer rate. In first 400 s, there is no significant difference in melting speed of all PCM/NEPCM as the conduction is dominant at the heat transfer rate at initial stage. Effect of dynamic viscosity becomes greater when dominant mechanism become convection during melting and may overweight the improvement in thermal conductivity. Thus, the heat transfer performance enhancement of NEPCM is only applicable at low volume fraction. In present study, greatest enhancement in melting rate is obtained by dispersion of 2 % Al_2O_3 nanoparticles in paraffin wax. On the other hand, adding 5 % CuO nanoparticles results in significant degradation in heat transfer.

3.2 Effect of Heating Source Orientation

According to Figure 7, the overall melting rate of paraffin wax heated from the vertical side is higher than that heated from below at 3000 s. However, during the melting period 1000 s to 1500 s, the melting speed of paraffin wax heated from below is faster compared with heated from the side. This melting trend is probably due to the formation of multi-cellular flow patterns when heating from below. In addition, the enhancement effect in melting rate is highest when 2 % of Al_2O_3 dispersed into paraffin wax for both heating surface.

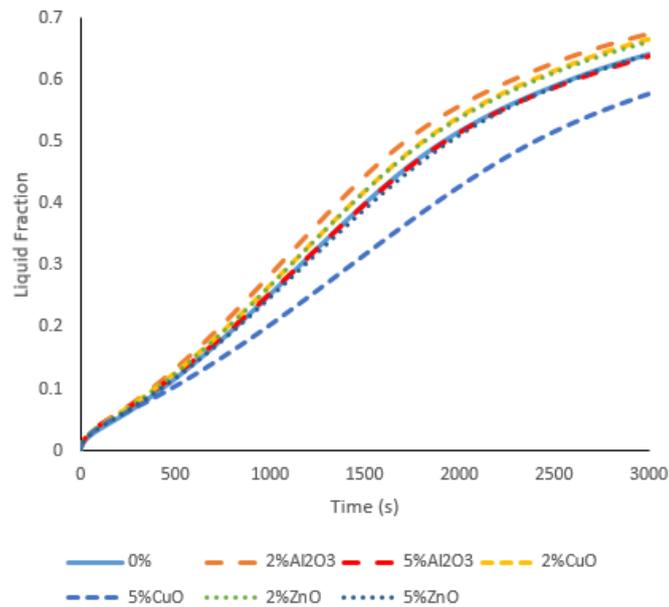


Fig. 6. Liquid Fraction of PCM/NEPCM

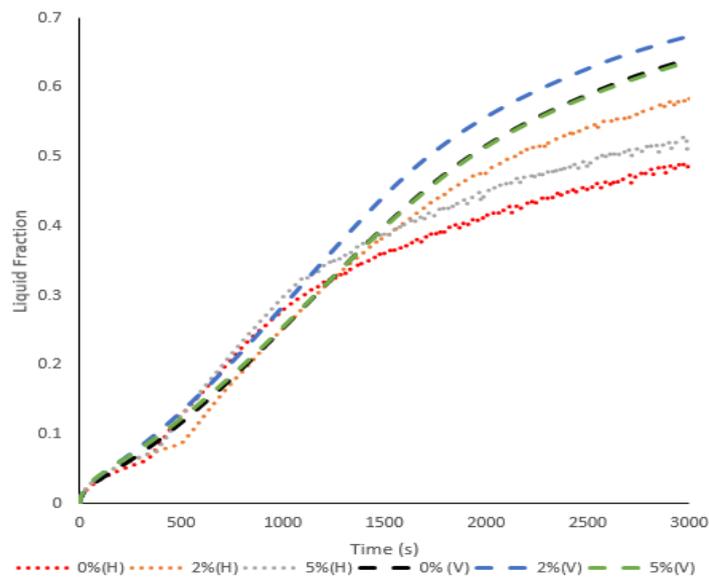


Fig. 7. Liquid Fraction of PCM/NEPCM Heated from Vertical side (V) and Bottom (H)

3.3 3D Temperature Contour

Figure 8 show the 3D temperature contour for the melting of Paraffin Wax + 2 % Al₂O₃ nanoparticles with vertical side heating. Red colour represented high temperature while blue colour indicated low temperature. For the melting with the heat source from vertical side, the temperature in the upper region of the cube storage is higher than that of the lower region as the time passed. This melting trend is similar to the 2D simulation in present work and also to the previous done by Bareiss and Beer[37]. During the melting process, natural convection of the liquid phase is occurred

and leads to the ascending of hot liquid PCM and the descending of cold liquid NEPCM. Thus, the the melting process in the upper part is faster than that in lower part [35].

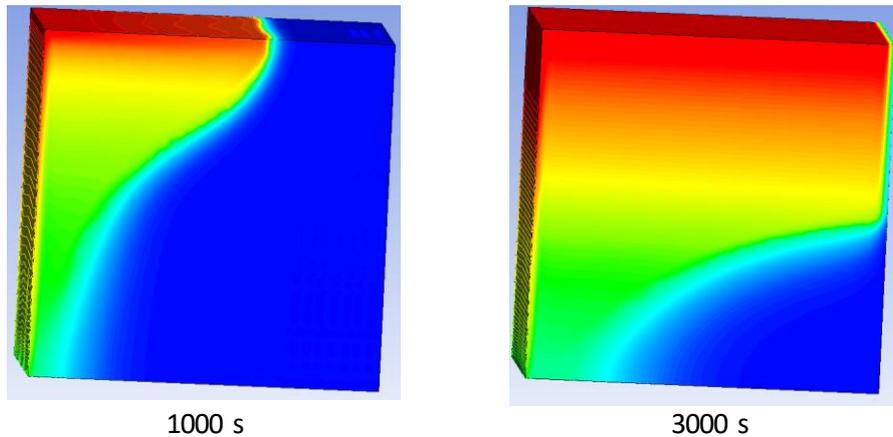


Fig. 8. 3D Temperature Contour of Melting of Paraffin Wax + 2 % Al₂O₃ Nanoparticles

4. Conclusions

The dispersion of nanoparticles can enhance the effective thermal conductivity but also increase the dynamic viscosity of the composites in the same time. Therefore, the heat transfer performance of PCM only can be enhanced by low volumetric concentration of nanoparticles. Too much nanoparticles loading may cause high viscosity and degrade the heat transfer rate. Besides, the best improvement in melting rate in present work was achieved by the combination of paraffin wax and 2 % Al₂O₃ nanoparticles which is around 5.15 %. In contrast, combination of paraffin wax with 5 % CuO nanoparticles slow down the melting speed of PCM by 9.98 %.

For the future works, the numerical simulation on solidification process of PCM and NEPCM can be done to obtain a phase change energy cycle diagram. The amount of energy stored or retrieved by the PCM and NEPCM will be recorded.

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