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Thermal performance of nanoparticle enhanced phase change material in a concentric cylindrical enclosure

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Thermal performance of nanoparticle enhanced phase change material in a concentric cylindrical enclosure

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Abstract. This paper presents the flow and heat transfer characteristics of melting behavior of phase change material (PCM) in the presence of nanoparticles. The melting process occurs in a concentric cylindrical enclosure filled with PCM (ice) and aluminum oxide (Al_2O_3) nanoparticles. The inner and outer walls of the concentric cylinder are considered as hot and cold walls and maintained at a constant wall temperature. The problem is modeled as unsteady, two-dimensional turbulent multiphase flow using the Eulerian multiphase model and SST k-ω turbulence model. The numerical simulation is performed using Ansys Fluent 19.2. The primary and secondary phases are specified with thermo-physical properties of ice and aluminum oxide. The transient melting behavior of PCM is investigated for different nanoparticle volume concentrations by varying the temperature difference between the hot and cold walls of concentric enclosure. The results are analyzed by plotting the streamline, velocity and temperature contours. The results indicate that the dispersion of aluminum oxide nanoparticles into phase change material increases the heat transfer rate and decreases the melting temperature of PCM. The results also indicate that the melting rate and thermal performance are significantly enhanced with increase in volume concentrations and temperature difference.

1. Introduction

The melting and solidification of phase change material dispersed with nanofluids have wide applications in thermal management of batteries, energy storage applications, nuclear and chemical reactors. Huan et al.[1] examined the heat transfer attributes of phase change materials used in batteries for thermal management and found significant improvement in the thermal performance of phase change materials [1]. It was further found that employing nanofluid augments the regular discharging rate of PCM thereby obtaining the best performance [2]. Yousef et al. [3] found that increasing the mass fraction of the particles helps expedite the melting rate and also, reducing the particle size accelerates the melting process. When the heat source and sink are placed on two vertical sidewalls alternatively, liquid fraction is highest; whereas, when sources are placed above sinks, liquid fraction is the lowest [4,5]. Ebrahimi [6] identified that detecting the heat pipe around a heat storage system, reduces the melting time by up to 91%. It was also found that for double and triple tube cases, melting times are almost the same and also, melting time reduces with increasing angle of the HTF [6]. Feng et al. [7] observed that the initial melting phase is deformed due to convection heat transfer that is caused by dominant conduction and by adding particles, the melting process and heat transfer efficiency can be improved. The increase in volume fraction results in the increase of melt fraction [7]. Hosseinizadeh et al. [8] found that increasing the thermal conductivity causes an enhancement in the melting rate of NEPCM in contrast with the conventional PCM due to the increase of thermal conductivity and reduction of latent heat of fusion. The temperature difference and Reynolds Number affect the melting time and smaller temperature difference can be compensated by increasing the Reynolds number significantly. Junior et al. [9] observed that the positional influence decreases with Reynolds Number augmentation. Li et al. [10] identified that the liquid fraction of NEPCM in an air heat exchanger reduces with increase in time and full solidification is indicated when liquid fraction is zero. Ng et al. [11] noticed that the increase in Rayleigh number results in the increase of melting rate and further investigations indicated that the surface temperature has the most deterministic effect on the melting time, melting rate and the rate of heat transfer [12]. Wang et al. [13] found that using PCM in aluminium heat sink, gives a more stable temperature for the functioning of electronic packages. and also, using PCM helps in controlling the operation temperature and using fin hybrid heat sink, longer melting time can also be recorded [13]. Their results also indicated that the maximum calculation error between numerical and experimental simulations were just 16.58%. Similar investigations were performed on the heat transfer behavior of various phase change materials used for cooling applications [14,15]. The previous investigations in literature have not reported the heat transfer characteristics of phase change materials and nanoparticles for high temperature applications such as nuclear and chemical reactors. This has been the motivation for this study. The present study focuses on the thermal performance of nano enhanced phase change materials in a concentric cylindrical enclosure with uniformly heated and cooled inner and outer walls. The parametric study is conducted by varying the difference in temperatures between the inner and outer walls of the cylindrical enclosure and by varying the volume fractions of nanoparticles.

2. Formulation and boundary conditions

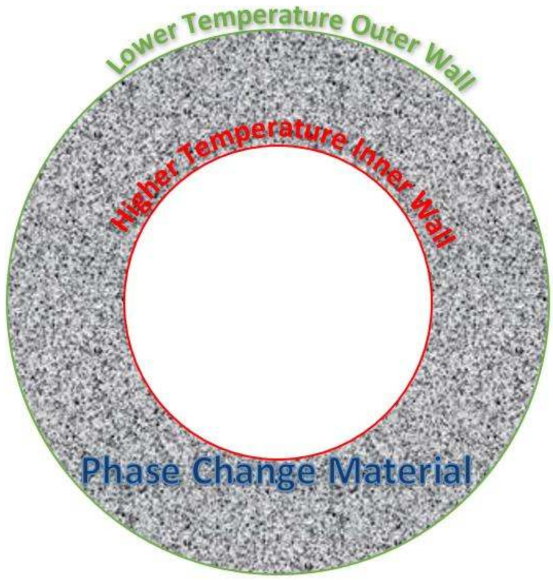

Figure 1: Schematic of Concentric Cylinder containing PCM

Figure 1 indicates the schematic diagram of the concentric cylinder considered in this study and is filled with phase change material dispersed with aluminum oxide nanoparticles. Phase change material melting in a concentric cylindrical domain is simulated using ANSYS Fluent software 19.2. Pressure-based type solver with absolute velocity formulation along with transient time is considered. Two-dimensional turbulent multiphase flow using Eulerian multiphase mode and SST k-ω turbulence model is used to model the turbulence and multiphase characteristics. The results are reported for different volume concentrations, by varying the temperature difference between the higher and lower temperature walls and the transient melting behavior of the PCM is analyzed. The primary phase used is water (solid) and Aluminium oxide nanoparticles is used as a secondary phase and dispersed into the_PCM. The inner wall is at a higher temperature whereas the outer wall is at a lower temperature, having both walls as stationary and roughness model is used as standard. The results are analyzed by plotting velocity and temperature contours along with XY plots for comparing them. In calculating, we have used 3000 time steps with a time step size of 0.1 and with a maximum of 4 iterations per time step. The heat transfer characteristics are analyzed by plotting the contours for each temperature differences of 100K, 250K and 500K respectively. The results are presented for nanoparticle volume fraction of 2% dispersed in phase change material.

3. Results and Discussions

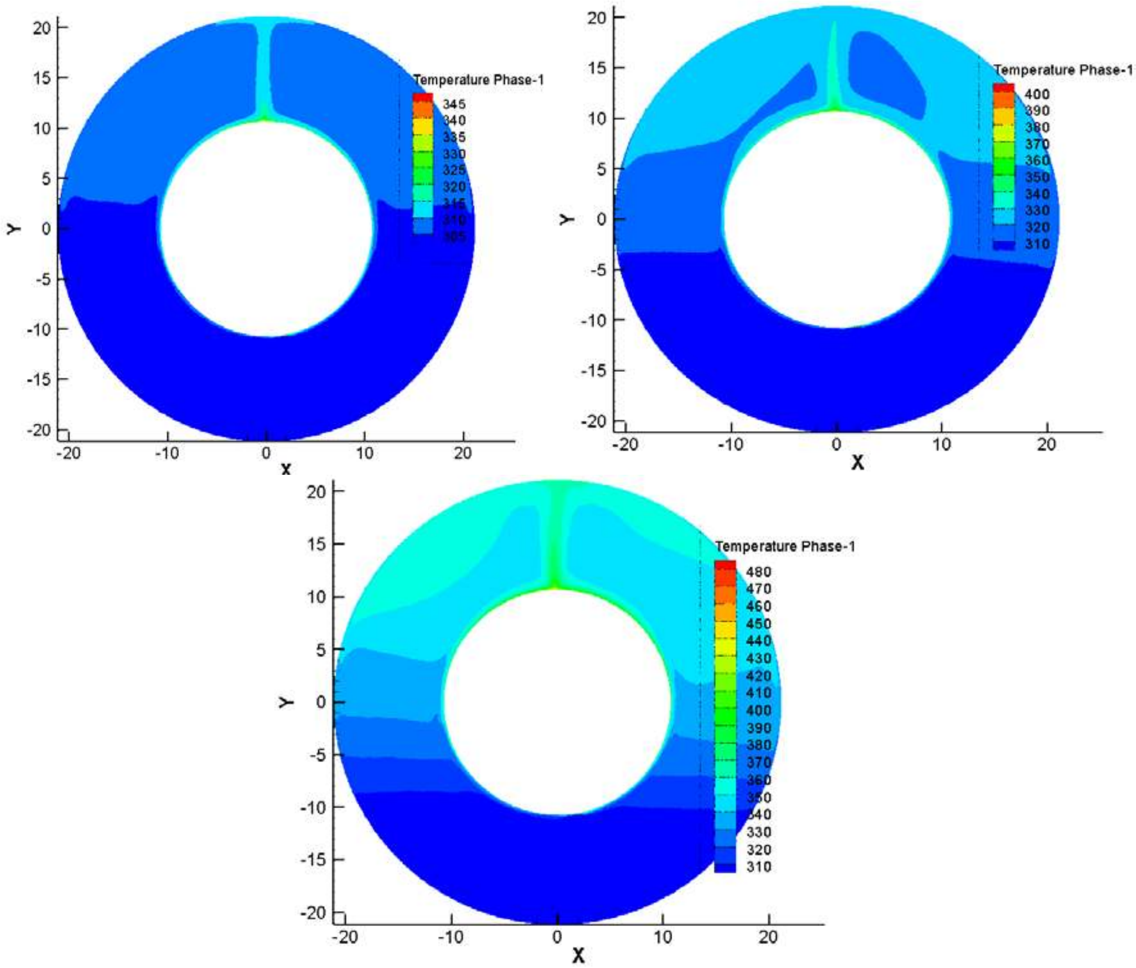

Figure 2: Temperature contours at temperature differences of 100k, 250k and 500k respectively

Figure 2 indicates the thermal convection patterns of PCM dispersed with 2% volume fraction of aluminum oxide nanoparticles inside the concentric cylinders for three different temperature differences of 100 K. 250 K and 500 K. It is seen that the thermal plume rises in the vertical direction and accelerates towards the outer wall of the concentric cylinder. The thermal convection increases the melting rates of the phase change material and a hot layer of thermal plume is seen propagating inside the concentric cylindrical enclosure. It is also observed that the intensity of temperature distribution and the acceleration rate of thermal plume increases with increase in the temperature difference between the higher temperature and the lower temperature walls of the concentric cylinder. The higher temperature difference increases the thermal buoyancy force and higher temperature zones are visualized inside the enclosure for a temperature difference of 500 K when compared to 250 K and 100 K.

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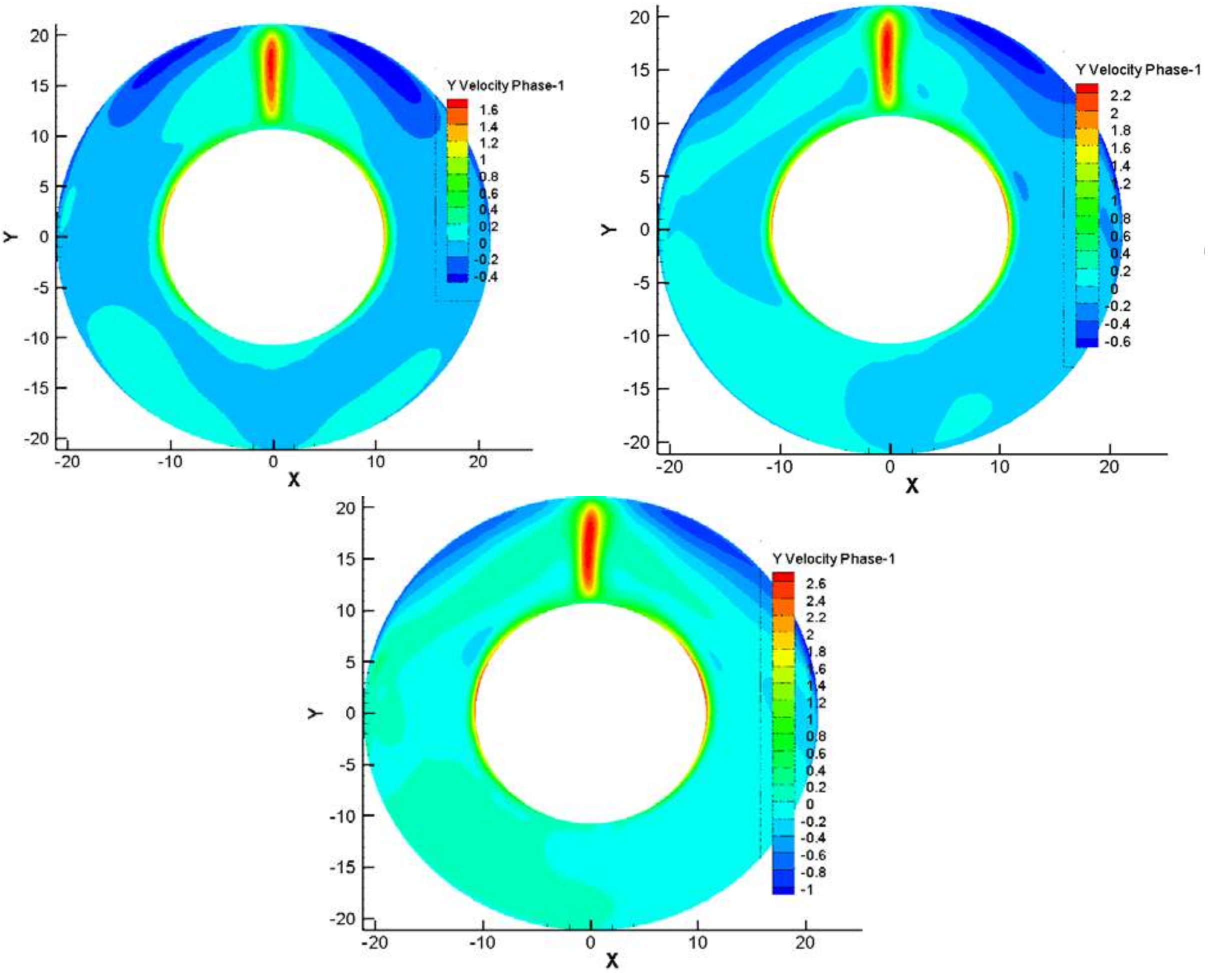

Figure 3: Normal velocity contours at temperature difference of 100k, 250k and 500k respectively

Figure 3 indicates the normal velocity distributions of phase change material and aluminium oxide nanoparticles inside the concentric cylinder. The red zone in the contour plots indicates that the normal velocity is higher as the thermal plume propagates in the vertical direction its intensity increases with increase in temperature difference. The hot layer of melt zone mixes with the surrounding melting layer and thermal stratification is visualized inside the concentric cylinder for a higher temperature difference of 500 K.

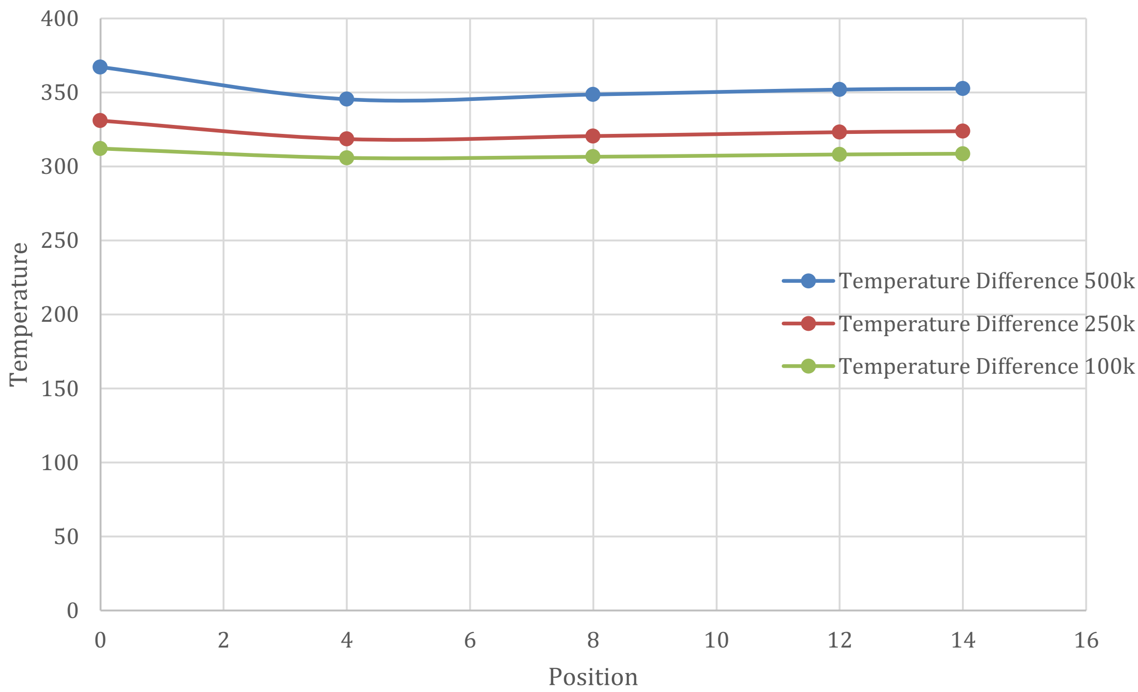

Figure 4: X-Y plot of comparison of Temperature (K) for different vertical location

Figure 4 indicates the variation of temperature distribution of NEPCM in the normal direction for different temperature differences. The uniform temperature distribution indicates the thermal stratification behavior inside the enclosure and the temperature distribution increases with increase in the temperature difference between the hot and the cold walls. The temperature distribution of NEPCM in the normal direction is increased by 47% and 69% for temperature differences of 250 K and 500 K in comparison with 100 K.

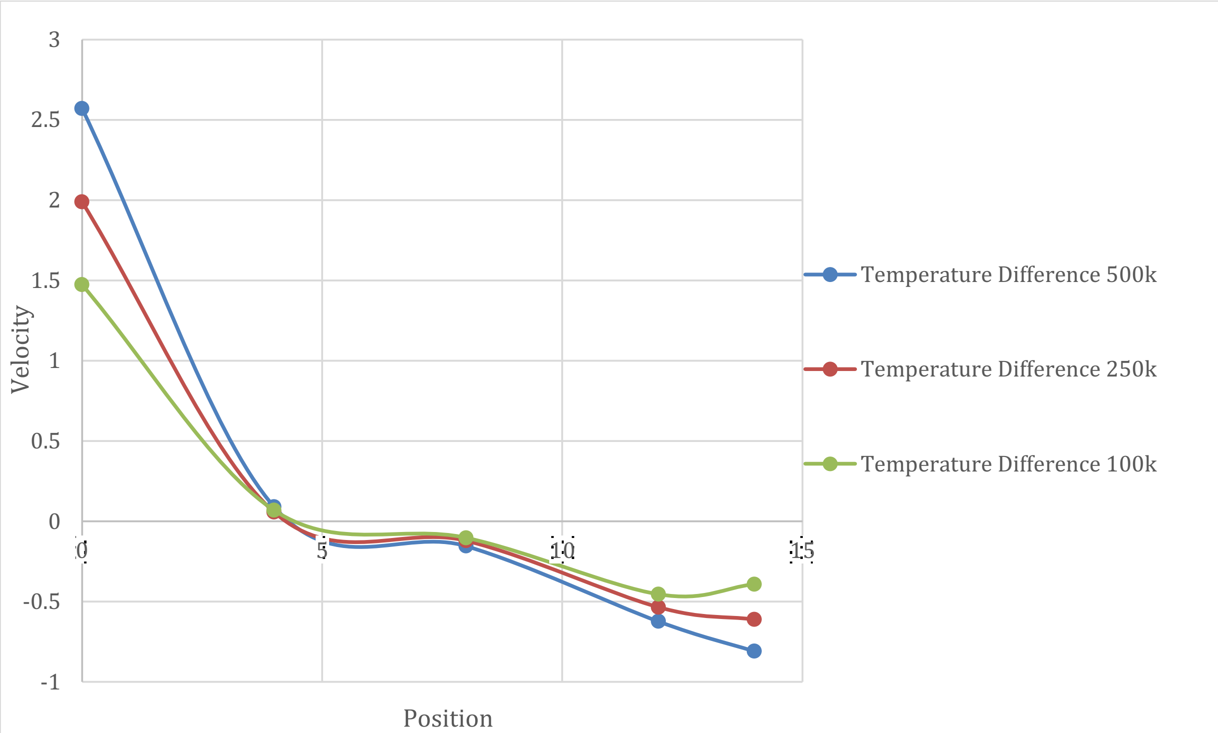

Figure 5: X-Y plot of comparison of Velocity (m/s) for different vertical location

Figure 5 indicates the variation of normal velocity of the melt zone for temperature differences of 100 K, 250 K and 500 K. The positive and negative values in the velocity profiles indicate the hot and cold melt zones inside the concentric enclosure. It is also observed that the velocity values increase linearly with increase in the temperature difference. The normal velocity distribution of NEPCM in the normal direction is increased by 38% and 54% for temperature differences of 250 K and 500 K in comparison with 100 K.

4. Conclusion:

The numerical investigation is performed to understand the flow and heat transfer characteristics of melting behavior of phase change material (PCM) in the presence of aluminum oxide nanoparticles. The melting process occurs in a concentric cylindrical enclosure filled with PCM (ice) and aluminum oxide (Al_2O_3) nanoparticles. The inner and outer walls of the concentric cylinder are considered as hot and cold walls and maintained at a constant wall temperature. The thermal convection increases the melting rates of the phase change material and a hot layer of thermal plume is seen propagating inside the concentric cylindrical enclosure. It is also observed that the intensity of temperature distribution and the acceleration rate of thermal plume increases with increase in the temperature difference between the hot and cold walls of the concentric cylinder. The higher temperature difference increases the thermal buoyancy force and higher temperature zones are visualized inside the enclosure for a temperature difference of 500 K when compared to 250 K and 100 K. The temperature distribution of NEPCM in the normal direction is increased by 47% and 69% for temperature differences of 250 K and 500 K in comparison with 100 K. It is also observed that the velocity values increase linearly with increase in the temperature difference. The normal velocity distribution of NEPCM in the normal direction is increased by 38% and 54% for temperature differences of 250 K and 500 K in comparison with 100 K. The results from the present study will be useful in designing effective thermal storage devices using nano enhanced phase change materials.

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