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Melting Characteristics of Hybrid Nano Enhanced Phase Change Material in a Finned Circular Tube

Sunkara Venkata Satyanarayana Rahul[1], Busireddy Dinesh Reddy[1], Vegu Himasurya Teja[1], Harish Rajan[1,*]

[1] School of Mechanical Engineering, Vellore Institute of Technology, Chennai, Tamil Nadu 600127, India

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ABSTRACT

In this study, the melting characteristics of hybrid nano-enhanced phase change material in a finned circular tube were studied by using the Finite volume method. This setup of circular tubes with a phase change material is used as cooling systems in automotive industries, air-conditioning, refrigerators, and other applications of cooling systems. There is a need for enhancing the specific heat capacity of this system to ensure that the system works even at high temperatures. As the current problem includes many design parameters and boundary constraints, the finite volume method has been performed to obtain a detailed report and data to examine the deformation of the hybrid nanoparticles and heat transfer rate on the corresponding surface. The current paper reviews and focuses mainly on the high-temperature PCM. And the suitable PCM has been selected based on its limitations and properties. To ensure the increased specific heat capacity, a salt-based phase change material, i.e., a mixture of $NaNO_3$-KNO3 (60:40 ratio) binary salt. This PCM could hold a temperature up to 334°C before melting to change its phase. In addition to spherical-shaped nanoparticles of silica (SiO_2) in this binary salt, it tends to have a significant potential for enhancing the thermal storage characteristics of the $NaNO_3$-KNO3 binary salt. On an extended surface, **Finns** are used on the peripheral of the circular tube to increase the surface area, which leads to an increase in frictional resistance resulting in a reduced airflow rate in the vicinity of the finned surface. From case studies, it has been found that the optimum fork-shaped fin array with two branches gives higher heat dissipation than the optimum rectangular fin. In the majority of the cases, the optimum fork-shaped fin array gives a 59.9% higher heat transfer rate compared to the rectangular fin array. Thus, the melting characteristics of the hybrid of $NaNO_3$- KNO_3 with nanoparticles of silica are studied when placed in a circular tube containing fork-shaped fins.

1. Introduction

The thermal properties of phase-changing materials in thermal convection have been widely used for many engineering and industrial purposes. Due to their extraordinary thermal properties and heat dissipation abilities, they play a key role in the functioning and working of various heat convection

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[*] *Corresponding author.*
E-mail address: harish.r@vit.ac.in

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processes [1]. By using this ability of the phase-changing material a finely defined and calculated setup has been modeled with certain boundary conditions, which contains tuning fork-shaped Finns, which are implemented to attain a better heat dissipation during the convection. The shape of the fins is designed with such geometrical aspects, which gives a greater surface of contact as compared to the other geometrical scenarios. Which leads to efficient heat convection [2]. The position of the Finns is decided in an isometric manner, which totally contains four fins with two branches each and placed every 90 degrees on the out surface of the inner cylinder which is located at the region between the inner surface of the outer cylinder and outer surface of the inner surface. The Finns in the particular region are surrounded by phase-changing material and nanoparticles. The nanoparticles are used to catalyze the convection process which will undergo between the Finns and the phase-changing material [3]. The nanoparticle shape also plays a significant role in the heat transfer process, Different shapes have different rates of heat transfer ability. In the studies with sub-100-nm nanoparticles, spheres show an appreciable advantage over rods. In fact, at this size range, increasing the aspect ratio of nanoparticles leads to considerable change in the heat transfer rate. Thus, the combination of the phase-changing material and the nanoparticles in the spherical shape ratio will be an efficient composition to obtain an efficient heat flow [4]. There are various forms and types of the phase changing material, but there are three main types organic (paraffin and non-paraffin), inorganic (salt hydrates and metallic alloys), and eutectic (mixture of two or more PCM components: organic, inorganic, and both). The hybridized molten salts have been used as a phase-changing material in the following setup. Which are $NaNO_3$ and KNO_3 [5]. The nanoparticles of SiO_2 have been used in spherical size. The whole composition is placed and packed around the Finns in a measured amount. Totally three major compositions have been tested and analyzed for the keen examination of the results and heat dissipation in the region of the PCM. The percentage of SiO_2 has varied in three different cases. Which is 1%,3% and 5% [6]. It will let us get a detailed and in-depth understanding of the heat dissipation in the required region.

The main motive of the investigation is to study the influence of nanoparticles in the convection process. This simulation will help to improve various types of heating issues in the different engineering applications and various industrial sectors [7]. Heat stabilization will also help in the semiconductor industry which is one of the major advantages of heat stabilization and heat optimization. Thus, it will help to increase the life scale of the particular product or subsystem. This study will help to understand the melting characteristics of the PCM with the influence of the solid nanoparticles.

Advancements in aerodynamics and power production have been one of the most developing and leading industries in the current world. The field of research particularly in this sector is very needed and helpful. The current study deals with the heating issues and cooling subsystems which are implemented in various industrial applications. Resolving the heating issues and advancing the various industrial machinery that deals with power production, propulsion engines, nuclear-powered systems, and many automobile sectors will make the systems perform more efficiently and it will increase the lifetime of the heat bearing subsystems [8]. There are various research and development in the field of finned nanotubes with phase-changing material, but enhancing the existing study with silicon-based nanoparticles in a spherical-shaped geometry will make the system dissolve the heat transfer more rapidly as compared to the existing case study. The excellent thermal properties of the silicon dioxide will modify the existing composition of the phase changing material and increase the latent heat of the phase changing material. There are various types of phases changing material with different thermal properties, molten salts are implemented in the current study as the phase changing material. Two different salts have been hybridized to get extraordinary thermal performance.

2. Methodology

A three-dimensional model with a calculated geometrical configuration of the Finns which is mapped in Figure 1. The hot fluid flowing through the inner cylinder will act as a heat source and undergo convection. The outer cylinder is in an adiabatic state. The hybridized molten salt $NaNO_3$ and KNO_3 with the composition of the measured percentage of SiO_2 nanoparticles is used as a Phase changing material [9]. The nanoparticles are added in spherical-shaped geometry to generate efficient heat convection.

The outer surface of the inner cylinder is employed with four Fins in Figure 1. The diameter of the inner cylinder is 50mm and the diameter of the outer cylinder is 100mm.

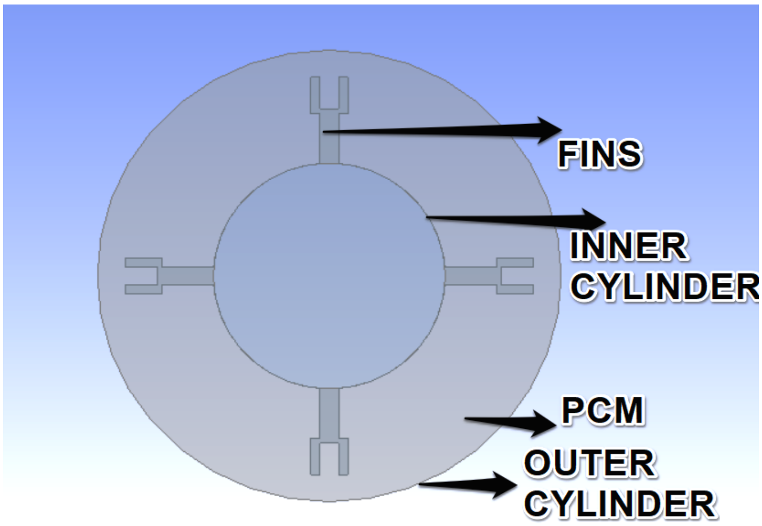

Fig. 1. Schematic diagram of front view of the geometry

The entire modelling is defined to obtain an efficient and detailed visualization of the heat transfer throughout the system. The pre-processing step is to define the geometry of the inner and outer cylinders (Figure 1). The Finns are planted on the outer surface of the inner cylinder Figure 1 and Figure 2. The Finns are fixed with a thickness of 4mm [10]. To obtain a detailed overview of the heat dissipation throughout the surface, meshing with a scale of 3mm has been implemented. The entire simulation is analysed under fluent circumstances. As per the required need and accuracy governing equations have been taken undercount, Within the influence of gravity of -9.81 m/s^2, the model should be simulated in the transient state. The specified boundary conditions and cell conditions for convection are initiated to run the simulation.

The finite volume method is used to process heat convection and the melting process [11]. To model this phenomenon, certain governing equations are taken into consideration.

The different volume fractions of silicon dioxide nanoparticles have been taken into the case to understand the influence of nanoparticles in addition to the composition of phase-changing materials [12].

Finite volume method is involved in the modelling of the melting process. To model this phenomenon, below PDEs can be noticed

$$\frac{\partial T}{\partial t} + \vec{V} \bullet \nabla \mathrm{T} = - \frac{\partial(\rho L\lambda)_{nf}}{\partial t} + \frac{k_{nf}}{(\rho C_p)_{nf}} \nabla^2 T \quad (1)$$

$$\frac{\partial u}{\partial t} + \nabla u \bullet \vec{V} = \frac{1}{\rho_{nf}} \left(- \nabla P + \mu_{nf} \nabla^2 u\right) + C\, u \frac{(1-\lambda^2)}{\lambda^3 + \varepsilon} \tag{2}$$

$$\frac{\partial v}{\partial t} + \vec{V} \bullet \nabla v = \frac{1}{\rho_{nf}} \left(\mu_{nf} \nabla^2 v - \nabla P\right) + C\, v \frac{(1-\lambda^2)}{\lambda^3 + \varepsilon} + g(T-T^{ref})\,(\rho\beta)_{nf} \tag{3}$$

Boussinesq estimation is considered for buoyancy terms. C=10^5, ε = 10^{-3} are mushy zone constants and small numbers. Density, $(\rho\beta)_{nf}$ and $(\rho C_p)_{nf}$ have been calculated as [13]:

$$\rho_{nf} = \rho_f\,(1-\varphi) + \varphi\,\rho_s (\rho\beta)_{nf} = \varphi\,(\rho\beta)_s + (1-\varphi)\,(\rho\beta)_f \tag{4}$$

$$(\rho C_p)_{nf} = \phi(\rho C_p)_s + (1-\phi)\,(\rho C_p)_f$$
$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{5}$$

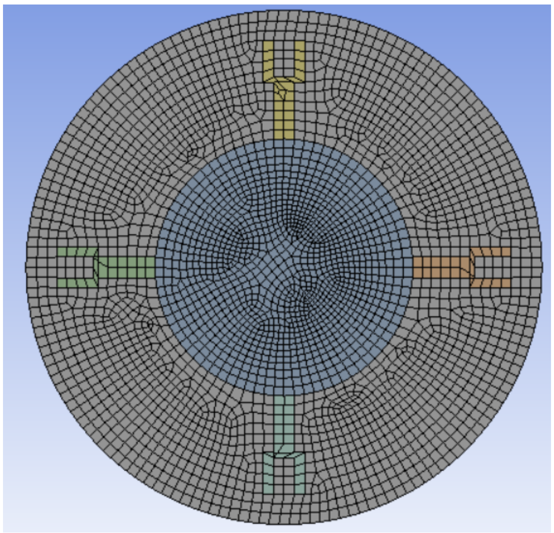

Fig. 2. A meshing of 2 millimetres

3. Result and Discussion

Three different concentrations of silicon dioxide nanoparticles are used to demonstrate the melting of PCM. Numerical examinations have been employed to reach the outcomes which are temperature, pressure, and velocity-based contours.

Figure 3 shows that when hot fluid passed through the inner cylinder with a certain initial temperature, the heat from the hot fluid started flowing through the surface of the cylinder. The Finns on the surface started exhibiting heat transfer throughout the phase-changing material present under that region. As the heat started flowing, the temperature of the phase-changing material started increasing, and the increment in temperature led to a decrease in the density of molten phase-changing material, the decrease of density is the factor that shows that heat convection is taking place.

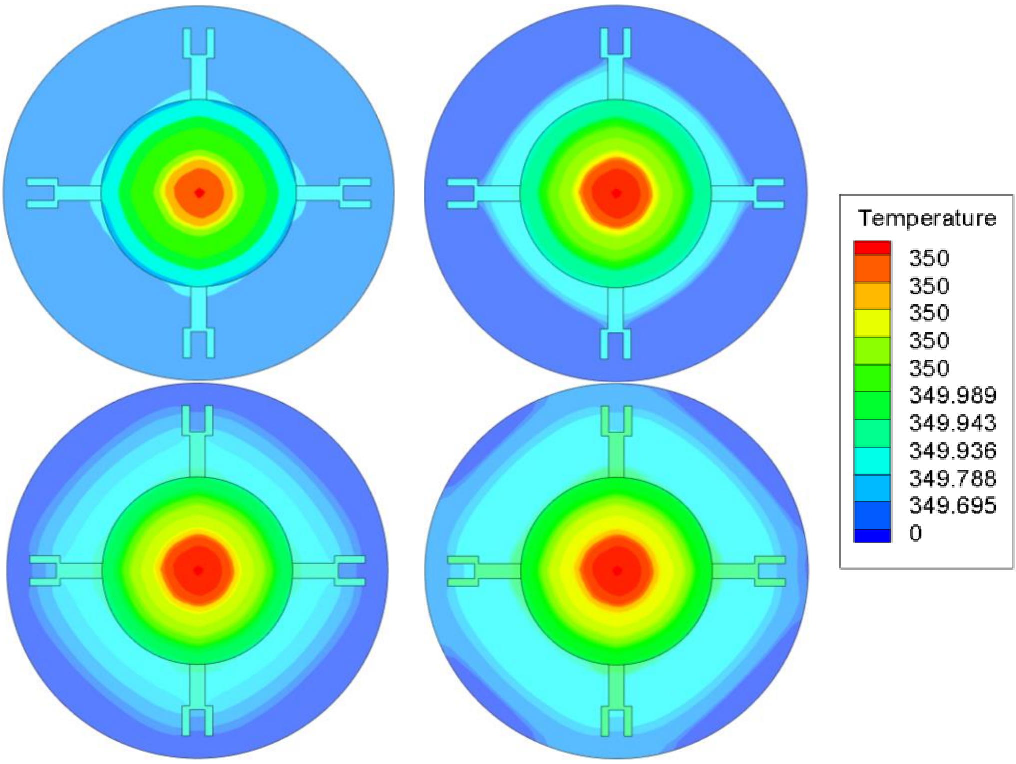

Fig. 3. Temperature contours of Phase change material with 1% volume fraction of silicon dioxide nanoparticles

Figure 4 shows that as the hot fluid flows through the inner cylinder, due to an increase in temperature the variation of pressure is encountered within the region. The decrease in pressure leads to an increase in temperature.

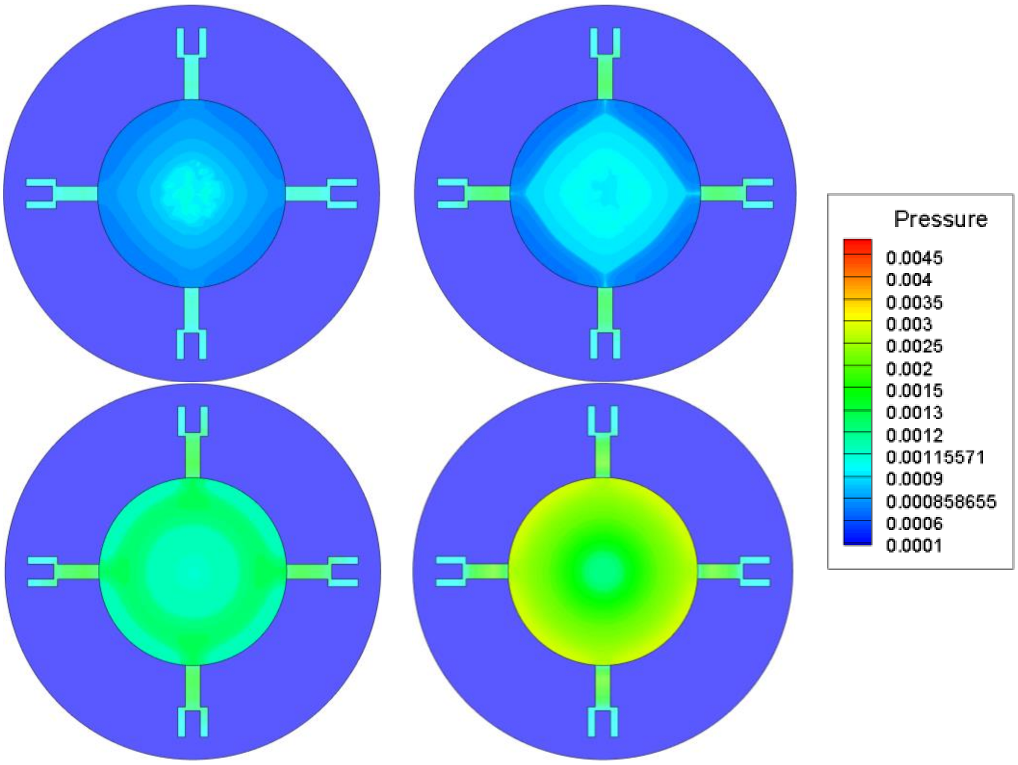

Fig. 4. Pressure contours of phase-changing materials with 1% volume fraction of silicon dioxide nanoparticles

In Figure 5, Velocity distribution in the region, the velocity is gradually decreased as the heat transfer increases. As time passes, the entire portion starts to turn blue, which is a sign of decrement in the velocity concerning time.

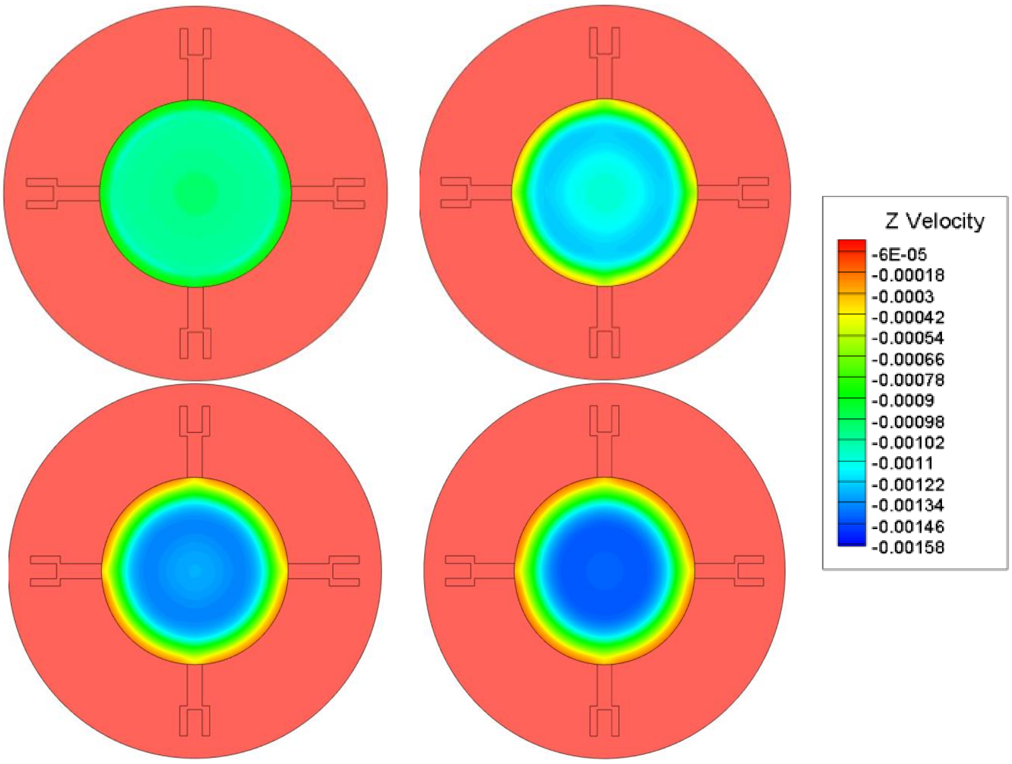

Fig. 5. Velocity contours of phase-changing materials with a 1% volume fraction of silicon dioxide nanoparticles

In Figure 6, there is a significant change in the heat transfer as compared to the volume fraction of 1%. As the heat started flowing, the temperature of the phase-changing material started increasing. The increment in temperature led to a decrease in the density of molten phase-changing material, the decrease of density is the factor that shows that heat convection is taking place. Most of the region inside the contour has turned into faded blue color as time passed.

In Figure 7, the variation of Velocity contours of phase-changing materials with a 3% volume fraction of silicon dioxide nanoparticles is noted and the contours show that with the increase in time the velocity rises and the area outside the hot fluid path always the velocity remains constant.

In Figure 8, it has been noticed that the velocity and temperature are tending to be in better condition and pressure is tending to reduce and that can be shown here.

The results for phase change material for 1% volume fraction of nanoparticles are shown in Figure 3 to Figure 5. In the beginning, the mode of heat transfer is due to convection so it has been observed that the temperature rise is less, and gradually when we go closer to the inner region the temperature is rising and the same trend continues for pressure and velocity as well Figure 6 to Figure 8.

In Figure 10, the variation of Pressure contours of phase-changing materials with the 5% volume fraction of silicon dioxide nanoparticles is noted and the contours show the variation of pressure with respect to time and also the pressure outside the hot fluid path remains constant only the inner portion the variation of pressure taking place.

As compared to the previous case scenarios, Figure 11 shows that the volume fraction of 5% has been the efficient case which shows better results in the cases of the addition of nanoparticles in the hybridized molten salts PCM.

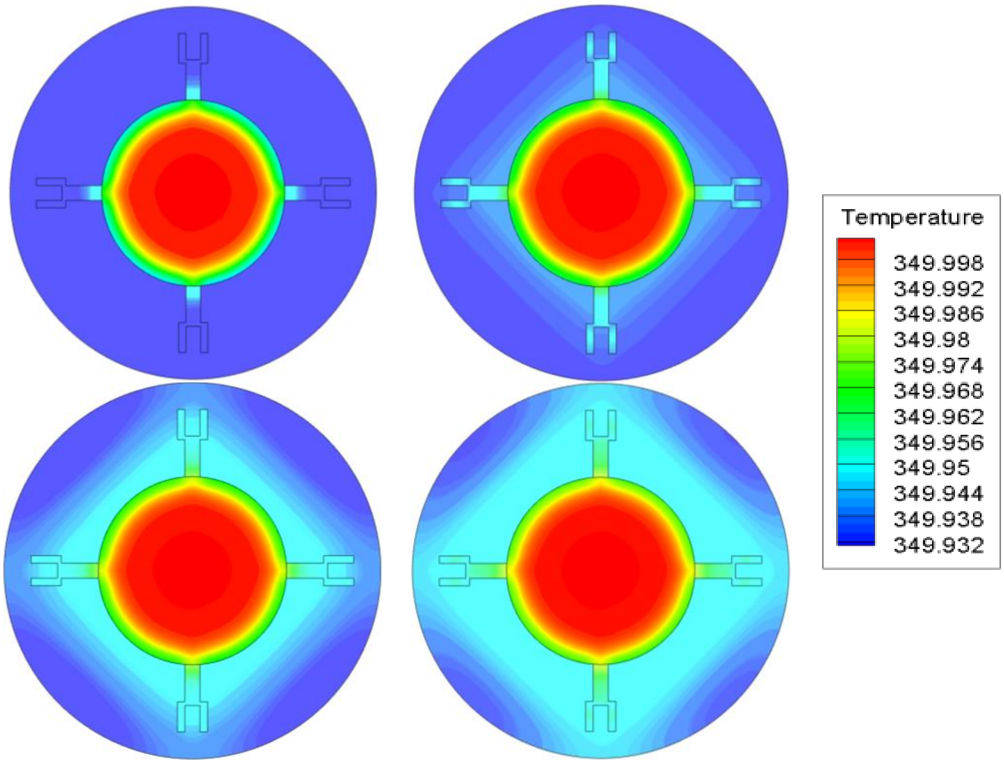

Fig. 6. Temperature contours of phase-changing materials with a 3% volume fraction of silicon dioxide nanoparticles

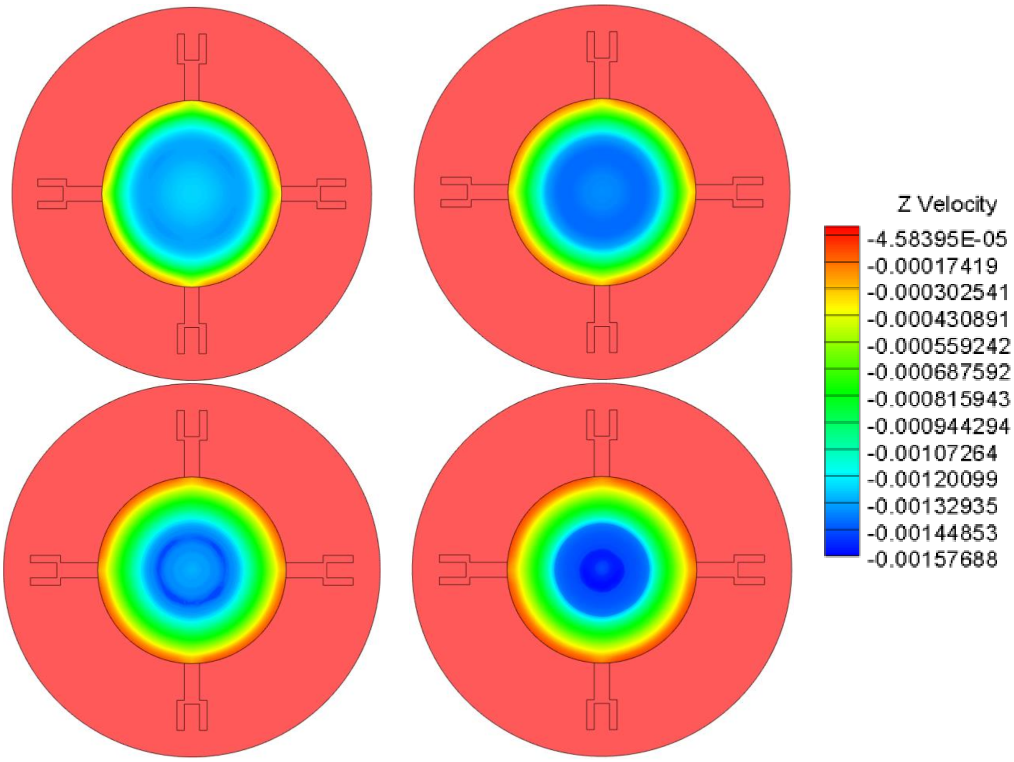

Fig. 7. Velocity contours of phase-changing materials with a 3% volume fraction of silicon dioxide nanoparticles

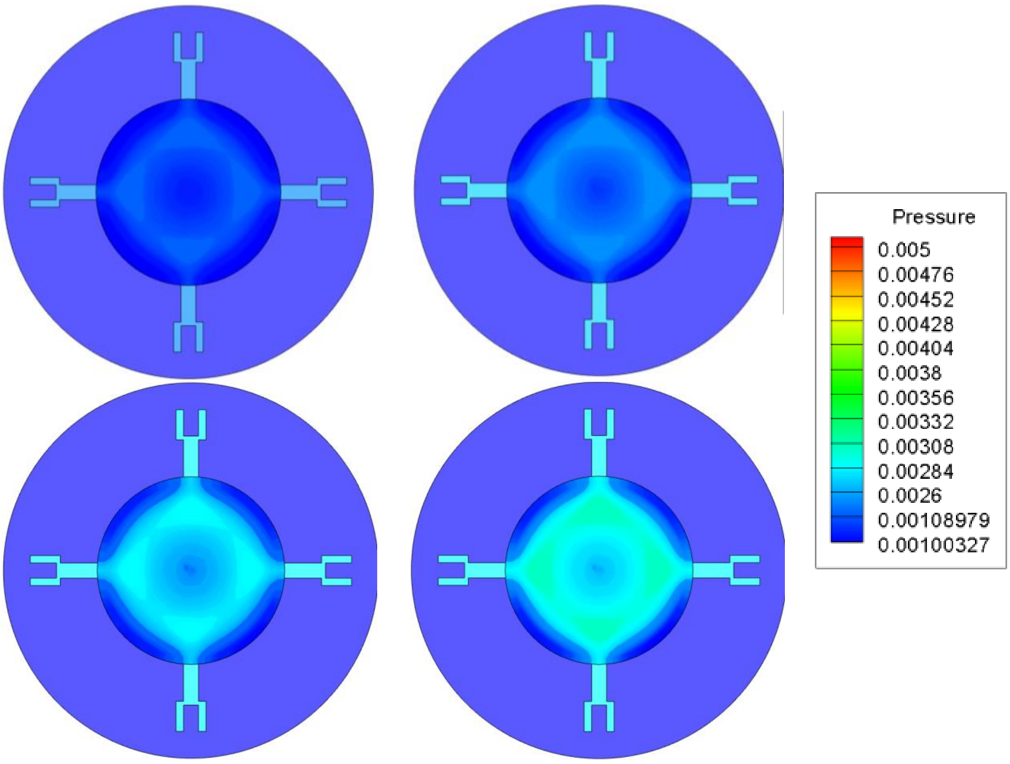

Fig. 8. Pressure contours of phase-changing materials with a 3% volume fraction of silicon dioxide nanoparticles

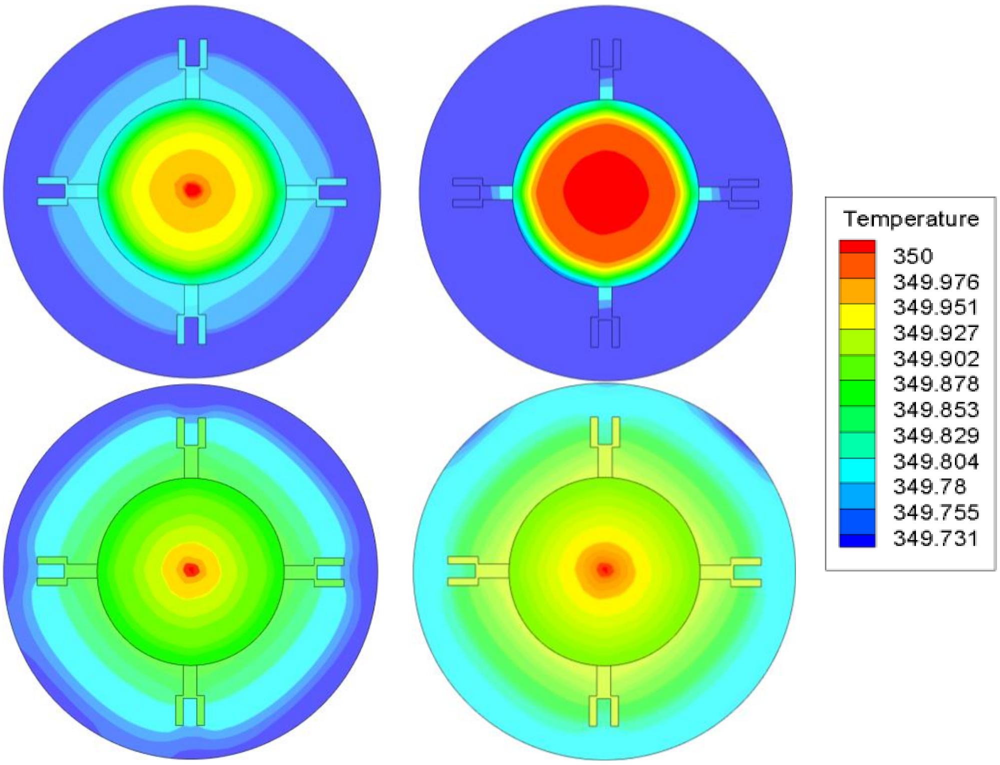

Fig. 9. Temperature contours of phase-changing materials with the 5% volume fraction of silicon dioxide nanoparticles

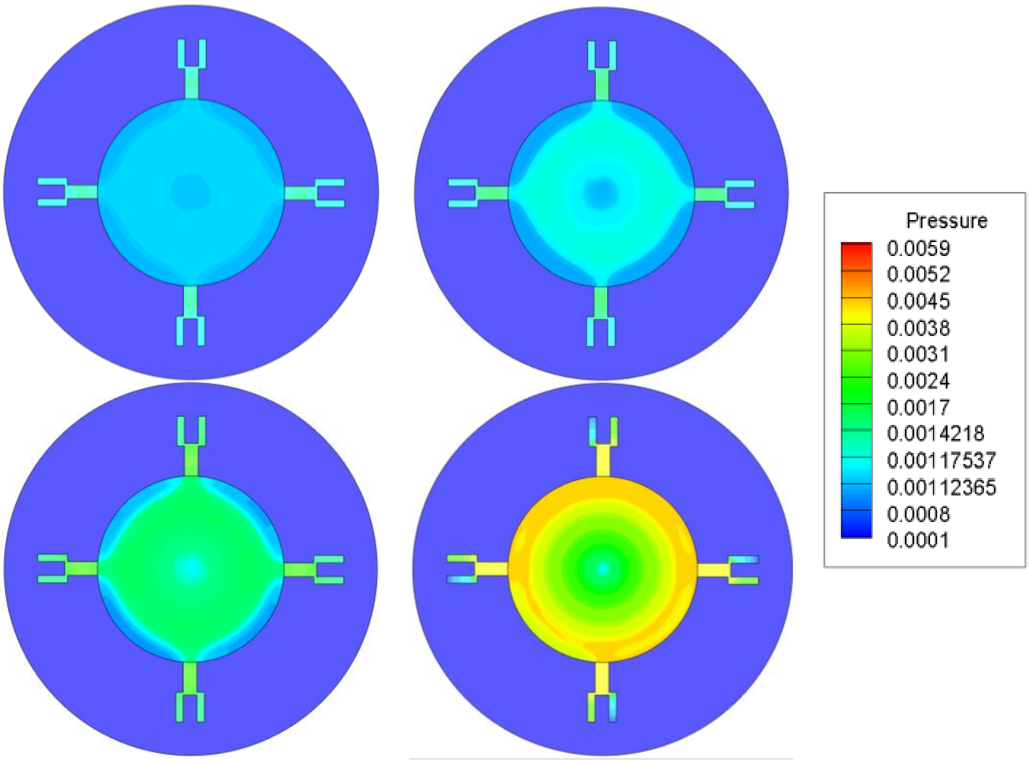

Fig. 10. Pressure contours of phase-changing materials with the 5% volume fraction of silicon dioxide nanoparticles

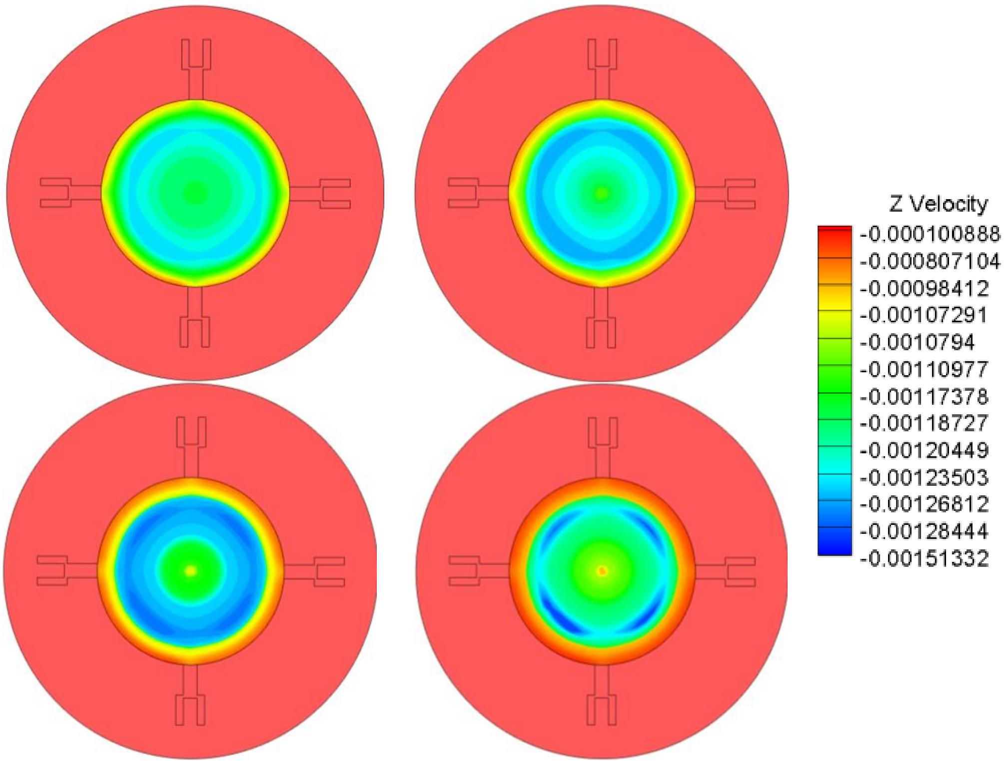

Fig. 11. Velocity contours of phase-changing materials with a 5% volume fraction of silicon dioxide nanoparticles

The combined Specific heat of hybridized molten salts with 0.01, 0.02 and 0.05 concentration of silicon dioxide nanoparticle Table 1. Cp_f(KNO$_3$,n) and $Cp_f(NaNO_3$,n) are calculated from the required PDEs.

Table 1
Specific heat of hybrid molten salts PCM enhanced with silicon dioxide nanoparticles [14]

φ	ρ_s (Kg/m^3)	Cp_s (J/Kg K)	ρ_f (Kg/m^3)	Cp_f (KNO$_3$) (J/Kg K)	Cp_f $(NaNO_3)$ (J/Kg K)	ρ_{nf} (Kg/m^3)	Cp_f (KNO$_3$,n) (J/Kg K)	Cp_f (NaNO$_3$,n) (J/Kg K)
0.01	2533	680	1817	953.5	1093	1824.16	949.7022	1087.2651
0.03	2533	680	1817	953.5	1093	1838.48	942.1954	1075.9294
0.05	2533	680	1817	953.5	1093	1852.8	934.8046	1064.7689

Table 2 reports the cumulative density of the phase-changing material when the 0.01, 0.02, and 0.05 concentrations of silicon dioxide nanoparticles are dropped in the hybridized molten salts.

Table 2
Density of hybridized salt PCM enhanced with 1%,3%, and 5% silicon dioxide nanoparticles

ρ_f (Kg/m^3)	φ	ρ_s (Kg/m^3)	ρ_{nf} (Kg/m^3)
1817	0.01	2533	1824.16
1817	0.03	2533	1838.48
1817	0.05	2533	1852.8

Table 3
Viscosity of PCM enhanced with 1%, 3% and 5% silicon dioxide nanoparticles

μ(KNO$_3$) (MPa/s)	μ(KNO$_3$) (MPa/s)	φ	$\mu_{nf}(NaNO_3)$ (MPa/s)	μ_{nf}(KNO$_3$) (MPa/s)
2.7	2.5	0.01	2.7686	2.5636
2.7	2.5	0.03	2.9136	2.6978
2.7	2.5	0.05	3.0694	2.8420

Table 4
Thermal conductivity of PCM enhanced with 1%, 3% and 5% silicon dioxide nanoparticles

K_f (W/m K)	φ	K_f(W/m K)	K_f(W/m K)
0.49	0.01	1.4	0.4937
0.49	0.03	1.4	0.5013
0.49	0.05	1.4	0.5091

By using commercial software, the Finite Volume Method has been executed on the designed model and simulated within the fluent conditions [15]. To examine the results, the data collected from the simulation is discretized into plotted graphs. This shows the distribution of pressure, velocity, and temperature to rough out the cross-section of the contour within the selected percentage of silicon dioxide volume fraction.

The initial stage of heat transfer is convection, so the temperature pressure and velocity are very minute in the initial stages.

In Figure 12, the comparison of temperature variation for three different volume fractions of nano-particles with PCM is plotted in graphs and the graphs show the 1% volume fraction of nano-particle has higher temperature than the remaining two volume fraction this is due to the 1% has less density whereas with the increase in volume function also increases the overall increase in density of PCM which results in reduction in the temperature.

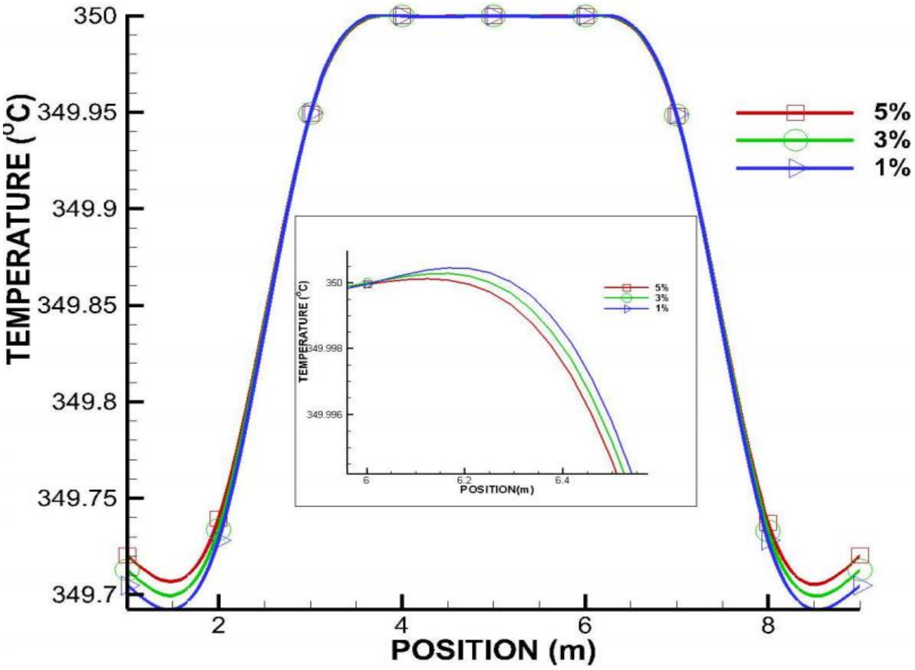

Fig. 12. Temperature variation for three different volume fractions of nanoparticles with PCM

In Figure 3, it has been keenly monitored in the pressure curves for the different volume fractions of nanoparticles that the major volumetric fraction of nanoparticles has an increment in pressure when compared to the lower volumetric fraction of nanoparticles Figure 13 [16].

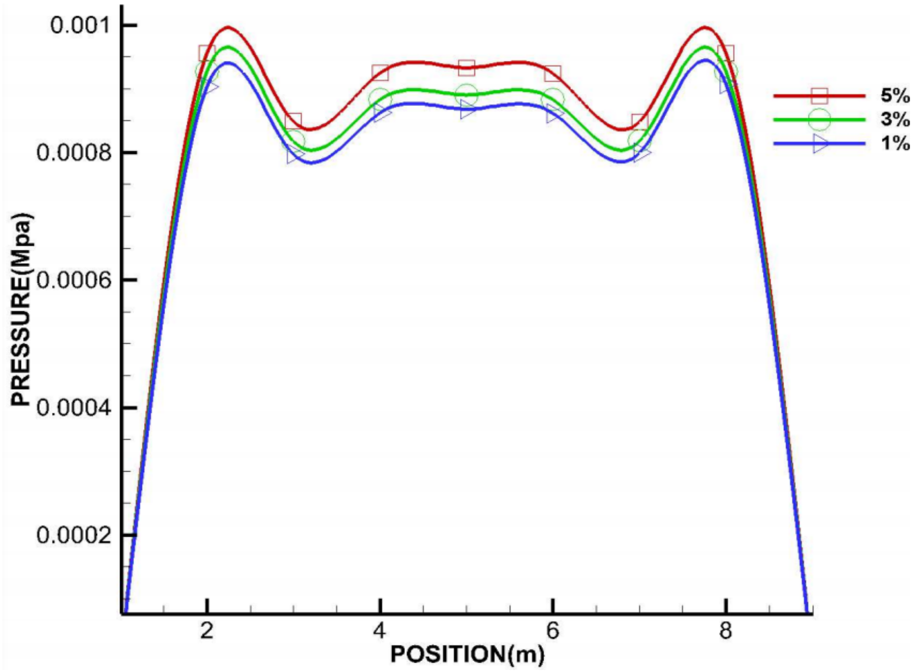

Fig. 13. Pressure variation for three different volume fractions of nanoparticles in PCM

The velocity-changing plot has been plotted to understand the velocity at different positions of contours for three different volumetric ratios of nanoparticles. According to the peaks and variations in the plot, the one having a lower volumetric concentration of nanoparticles has more velocity Figure 14.

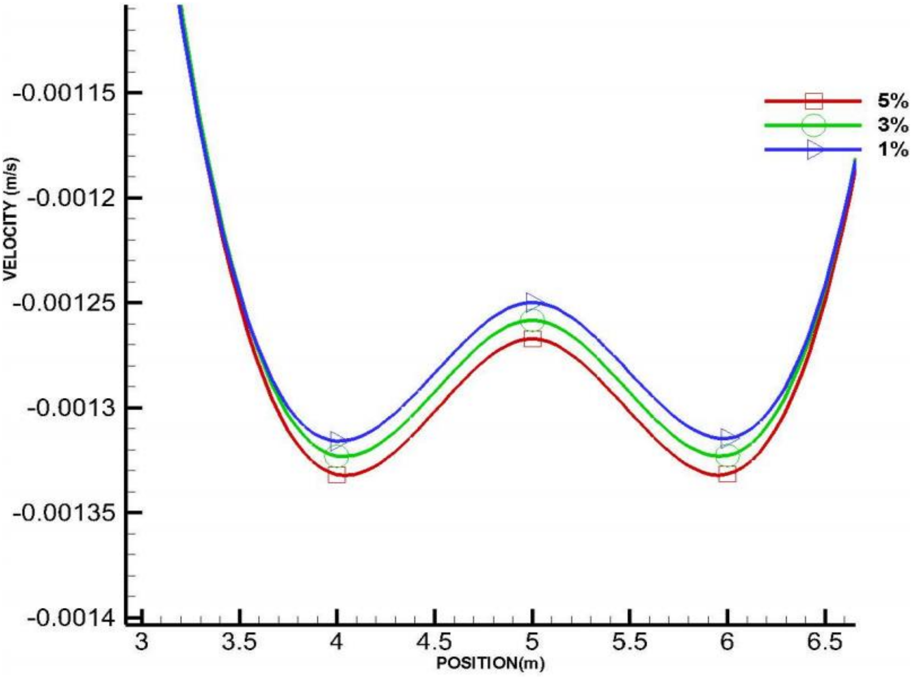

Fig. 14. Velocity variation for three different volume fractions of nanoparticles in PCM

4. Conclusion

In the present investigation, the melting characteristics of hybridized molten salts $NaNO_3$, KNO_3 phase-changing material through a heat exchanger containing various compositions of SIO_2 nanoparticles with tuning forked-shaped Finns have been simulated. A detailed analysis has been numerically investigated using an in-house code based on the finite difference method. The impact of nanoparticles on the transient melting behaviour and melt pool temperature distribution are compared between various concentration nanoparticles inside a circular enclosure. The following significant conclusions are reported from the present study.

The major volumetric concentration of 5 % reflects the most efficient heat transfer throughout the time span when compared to the other volume fraction of nanoparticles. This is due to the increment in density, as the density increases, the convection rate decreases, which results in a decrease in temperature. It has been observed that composition of phase-changing material with a high volumetric ratio of silicon dioxide nanoparticles disputes a major amount of heat in a limited time. The composition of phase-changing material with a 5% of nanoparticle, which is the major volumetric concentration of silicon dioxide nanoparticles in the compared and depicted scenarios. As the density increases, the convection rate decreases, which results in a decrease in temperature, So the concentration of the silicon dioxide enhances the thermal properties of phase-changing material. Optimizing the heat transfer can enhance the performance of the heat engines and it will also help to last its life for a longer period. Various industries face tremendous problems due to heat leaks and overheating while operating in extreme conditions, which leads to hazardous accidents and losses. As the world is switching to various alternative fuels, such as electric, Biogas, Helium based power generation. While producing and consuming these alternative fuels, a huge amount of heat will be released. So further study of this simulation will help to resolve the heat tempering issues of the subsystems operated. It will also help aerospace industries to optimize the propulsions and heat combustions, which will decrease fuel consumption. Hence the following study will build a great impact on many industries.

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