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Numerical Investigation of the Effect of Multi-Walled Carbon Nanotubes Phase Change Materials on Enhancing Thermal Performance of Electrical Equipment Heat Sink

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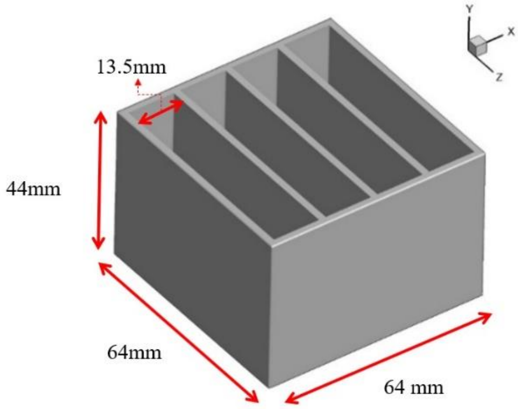
Abstract
Heat Sink play a crucial role in cooling electrical equipment. In this research, we have used a new approach to increase heat extraction from Heat Sinks by homogeneously dispersing multi-walled carbon nanotubes in paraffin as a phase change material. The phase change process was numerically investigated in a three-dimensional space using the enthalpy-porosity method and applying three heat fluxes of 10,000, 20,000, and 30,000 watts per square meter. Based on the results obtained during the phase change process, adding nanoparticles with volume percentages of 4, 6, and 8% showed better performance in reducing the phase change temperature. However, increasing the volume percentage of nanoparticles did not have a positive effect, and a 4% volume fraction of nanoparticles created a greater temperature reduction in the Heat Sink. Overall, adding 8% nanoparticles to the phase change material reduces the complete melting time by 15%.

Keywords: Heat Transfer, Melting Process, Numerical Simulation, Phase Change Materials, Multi-Walled Carbon Nanotubes

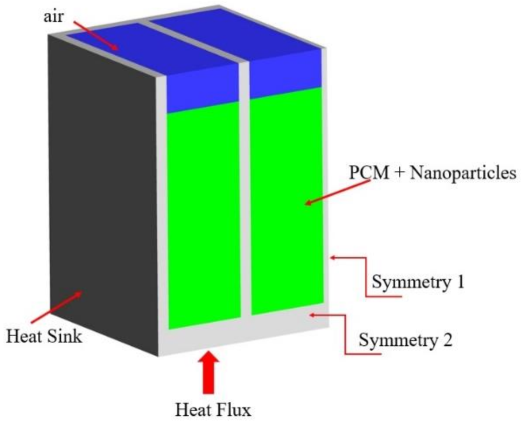
1. Introduction
The increase in computing speed and the reduction in the size of heat sinks result in excessive thermal loads and reduced lifetimes of these devices. In recent years, phase change materials (PCMs) have attracted special attention from researchers in the field of heat management in electronic equipment due to their high latent heat capacity and nearly constant solid-liquid phase change temperature [1]. Mohammad et al. conducted an experimental study on the thermal performance of a heat sink filled with PCMs. The results showed that the use of PCM improved the thermal performance of the heat sink by about 30% compared to heat sink without PCM [2]. Darzi et al investigated the effect of tube’s number and arrangements on PCM behavior in a three-tube heat exchanger. The results showed that increasing the number of inner tubes increased the melting rate of the PCM due to the increase in natural convection in the exchanger, resulting in an 80% reduction in melting time compared to the two-tube exchanger[3]. Hosseinzadeh et al numerically and experimentally investigated the thermal performance of a PCM-filled heat sink. The simulation results showed that increasing the height and number of fins had a significant effect on improving the thermal performance of the heat sink. However, increasing the thickness of the fins only slightly improved the performance [4]. Jalal et al studied the thermal performance of a PCM-filled heat sink with aluminum oxide nanoparticles. The results showed that the use of nanoparticles in PCMs can improve performance thermal of the heat sink [5]. Arshad et al. investigated a PCM-filled finned heat sink for cooling electronic equipment. According to the results, the PCM used in the heat sink keeps the base temperature of the sink low and uniformly melted at low temperatures [6]. Arshad et al. investigated the performance of a PCM-filled heat sink by adding copper nanoparticles and metallic foam made of copper, aluminum, and nickel. The results showed that the addition of nanoparticles to the PCM reduces the melting time and increases heat transfer due to the improved thermophysical properties of the PCM [7]. In this study, a new approach is taken to investigate the effect of adding multi-walled carbon nanotubes to paraffin for cooling a heat sink.

2. Problem Statement
Due to the symmetry present in the geometry of the problem, it is possible to divide the geometry into four parts to reduce numerical calculations. Figure 1 depicts the geometry of a heat sink and the boundary conditions of a phase-changing material. The heat sinjk, made of aluminum, has rectangular fins. The heat flux

uniformly enters the heat sink from the bottom.



1a) Heat sink



1b) Boundary Conditions

Figure1. Geometry and boundary conditions in the Heat Sink

3. Governing Equations and Numerical Simulation Method

3.1. Simulation of Phase-Changing Materials

As the phase-changing material melts, its volume increases, and the volume of air above it decreases. The volume of fluid (VOF) model of the two-phase mixture, which includes a movable but non-penetrating internal boundary between the two fluids, is used to simulate the combined system of the phase-changing material and air [8]. The enthalpy-porosity method is used to simulate the melting process of the phase-changing material [9].

The liquid fraction in each iteration is determined based on the enthalpy balance.

The energy equation is as follows:

H represents the enthalpy of the phase-changing material with nanoparticles (1) and is equal to the sum of the sensible enthalpy (h) and latent heat (ΔH):

$$H = h + \Delta H \tag{1}$$

For the melting or solidification problem, the energy equation (2) is as follows:

$$\frac{\partial(\rho H)}{\partial t} + \nabla.(\rho\vec{v}H) = \nabla.(k\nabla T) + S \tag{2}$$

In this equation, v ⃗ represents the fluid velocity, and S is the source term.

The continuity equation is:

In the enthalpy-porosity method, the melting region is assumed to be a porous medium, and the porosity in each cell is equal to the liquid fraction in that cell. In the completely solid region, the porosity is zero, which makes the velocity zero in this region. The momentum equation for laminar and unstable flows (3) is generally as follows:

$$\frac{\partial(\rho_n u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho_n u_i u_j) = \frac{\partial \mathrm{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_n\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \rho_n g_i + S \tag{3}$$

In this equation, the term "porous well" is defined as S, which is the decrease in porosity in the melting region and is defined as follows [10]:

$$S = \frac{(1-\gamma)^2}{\gamma^3 + \varepsilon} A_{mush}(\vec{v} - \vec{v_p}) \tag{4}$$

3.2. Thermophysical Properties of Materials

This study investigates the performance of a geo Heat Sink based on PCM containing nanoparticles. The thermophysical properties of the phase change material containing nanoparticles are determined using the following equations. The indices NP and PCM represent the nanoparticles and pure phase change material, respectively, and the index nPCM represents the phase change material containing nanoparticles.

Density [11]:

$$\rho_{nPCM}=\varphi\rho_{np}+(1-\varphi)\rho_{PCM} \tag{5}$$

Specific heat capacity:

$$C_{P,nPCM}=\frac{\varphi(\rho C_P)_{np}+(1-\varphi)(\rho C_P)_{PCM}}{\rho_{nPCM}} \tag{6}$$

The effective thermal conductivity coefficient (k_eff) is calculated using the following equation, which combines the Maxwell theory and the Brownian motion [6]:

$$K_{nPCM}=\frac{K_{np}+2K_{PCM}-2(K_{PCM}-K_{np})\varphi}{K_{np}+2K_{PCM}+(K_{PCM}-K_{np})\varphi}K_{PCM} + 5\times10^4\beta_k s\varphi\rho_{PCM}C_{P,PCM}\sqrt{\frac{\kappa T}{\rho_{np}d_{np}}}f(T,\varphi) \tag{7}$$

3.3. Numerical Simulation Method

To create the Design Modeler and Ansys Meshing, the commercial software ANSYS-Fluent was used in the ANSYS Workbench environment. The governing equations were solved using the finite volume method and ANSYS-Fluent software. To couple the pressure and velocity equations, the Pressure Implicit with Splitting of Operators (PISO) solver with segregated solver was used.

4. Independence from Meshing

In order to mesh the computational domain and select an appropriate time step, the meshing and solving environment of ANSYS was used. Results were obtained for four different mesh sizes to investigate mesh Independence. No changes in the results were observed with an increase in the number of mesh cells to more than 300,000 cells. Moreover, a suitable time step of 0.01 seconds was selected for the simulation based on the phase change process of the phase change material.

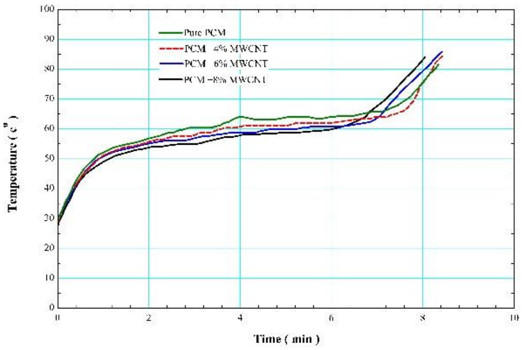
5. Discussion and results

5.1. Investigating the effect of heat flux on the performance of a heat Sink with a Phase change material

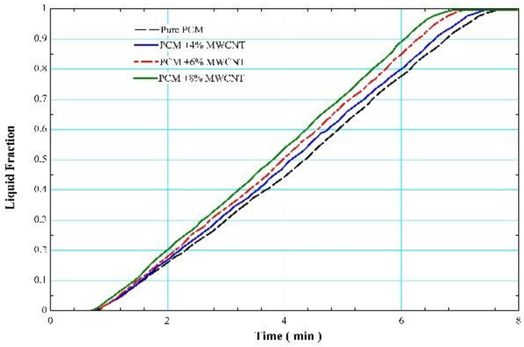
In this section, the performance of a Heat Sink with phase change material is studied for input Heat fluxes of 10, 20, and 30 kW/m2. It is observed that with decreasing Heat flux, the temperature of the Heat Sink also decreases. At 5 minutes after applying the Heat flux, the temperature of the heat sink for thermal fluxes of 10,000, 20,000, and 30,000 W/ m2 is 48, 56, and 64 degrees Celsius, respectively. The time for melting the phase change material also increases with decreasing thermal flux.

5.2. Effect of Adding Nanoparticles to Phase Change Material

In this section, a heat flux of 30 kW/m2 is used to study the effect of nanoparticles. Figure 2 shows the changes in temperature and the fraction of melted liquid in the heat sink for different volume percentages of nanoparticles. It can be observed from this figure that during the stage of increasing the temperature of the phase change material while it is still solid (up to 40 seconds), the temperature of the heat sink does not change much with the addition of nanoparticles. However, with the start of PCM melting, the effect of nanoparticles becomes evident. The changes in the temperature of the heat sink for different volume percentages of nanoparticles show different behaviors. The increase in temperature over time is due to viscosity reduction of the fluid.



2a) temperature changes



2b)The fraction of molten liquid

Figure 2) Changes in the temperature of the Heat sink and the fraction of the melted liquid of the PCM for different volume percentages of nanoparticle at a flux of 30 kW/m2

6. Conclusion

In this study, the performance optimization of a PCM heat sink with carbon multilayer nanotubes has been numerically investigated. Based on the results, the optimization of adding nanoparticles to the thermal performance of the heat sink, considering the thermophysical properties of the phase change materials, plays a crucial role. Excessive addition of nanoparticles results in the opposite effect, causing an increase in the temperature of the Heat Sink instead of decreasing it, due to the decrease in latent heat and faster melting of the phase change material. Therefore, an appropriate percentage of nanoparticles should be determined based on the type of cooling system. Base on results of this study adding nanoparticles to PCMs for heat sinks at temperatures lower than 60 degrees Celsius shows best performance.

7. Symbols, Signs, and Numbers

H	Enthalpy of phase change material	(J / kg)
h	Sensible enthalpy	(J / kg)
C_P	Specific heat capacity	$(jkg^{-1} k^{-1})$
L	latent heat	$(\frac{kj}{kg})$
$\overrightarrow{v_p}$	Solid velocity	$(m\, s^{-1})$
$\vec{v}$	Fluid velocity	$(m\, s^{-1})$
κ	Boltzmann's constant	$(m^{2} kg s^{-2} k^{-1})$

μ	Dynamic viscosity	(N s/m2)
K	Thermal conductivity coeficient	(W/m.K)
φ	Volume fraction of nanoparticles	(-)
ρ	Density	(kg/m3)
T_0	Reference temperature	(300K)
β	Thermal expansion coefficient	$^1/_k$
g	Gravitational acceleration	۹,۸۱ (m s^{-2})

8. References

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