Theoretical study the effect of dispersion of nanoparticles on thermo-physical characteristics of PCM with micro-channel heat sink

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Abstract. Thermal performance of micro-channel heat sink (MHS) with different cooling mediums has been investigated numerically using 3D model of conjugated heat transfer. Four types of coolants have been used in this study starting with air as a baseline to compare its thermal performance with pure phase change material (PCM) which was paraffin wax and nanoparticles-enhanced phase change material (NEPCM) which were (Silicon carbide (Sic)-PCM and Diamond-PCM) with volume fraction values of (1, 3, and 5%). On the heat sink base, a constant and uniform heat flux of (8000, 10000, 12000, and 14000W.m⁻²) is applied. Numerical simulations have been performed to investigate the effect of nanoparticle material and concentration on cooling performance of heat sink. The findings elucidated the cooling performance of MHS is enhanced with PCM compared with air and suspension nanoparticles lead to improve the thermal conductivity of (NEPCM) comparing with pure PCM, that causing expedite the melting process and enhancement of cooling performance. Also, as the concentration of nanoparticles increased, the heat transfer rate for (NEPCM) enhanced and decreasing the time of the melting process.

1. Introduction
Micro-channel heat sinks have high cooling performance as compared with a conventional channel that makes it appropriate for cooling of electronics which have high heat-generating such as supercomputers, mainframe, and military radar system [1]. The hydraulic diameter of microflow channels ranging from 10 μm to 1000 μm. The rate of heat transfer using micro-channels affects by many factors including the surface roughness, geometry shape, solid and fluid materials used. Micro-channel heat sinks are either micro-channels heat sink putting on plates attached to the silicon chips or micro-channels heat sink that etched on the back of silicon wafers. High cooling performance of micro-channel heat sinks (MHS) is due to the large surface area of the micro-channel to volume ratio. Therefore the dimensions of micro-channel and the fluid flow properties influence the cooling capability of the micro-channel system. Many promising improvements that occurred with using phase change material (PCM) for cooling electronic devices.

Masuda et al. (1993) [2] reported the improved thermal conductivity of working fluid by additive ultra-fine (nano-size) particles. Then, the first definition of the “nanofluids” term as a new type of fluids with improving thermal properties was by Choi (1995)[3]. Khanafer et al. (2003) [4] investigated the thermal performance improvement in a 2D cavity integrated with nanofluids of different relevant parameters. Khodadadi et al. (2007)[5] were the first to scrutinize for enhancing PCM functionality with the suspension nanoparticles. Their findings indicated that nanoparticle-enhanced phase change materials (NEPCMs) show improved thermal conductivity as compared to the pure material. Anandan
et al. (2008)[6] performed a review on thermal management for electronic devices using various methods of cooling. Last years, researchers conducted many studies to find new methods for the advancement of the systems of energy storage. One method was nanotechnology to improve heat transfer displays a great opportunity for the energy storage system. Due to the low value of thermal conductivity for pure fluids coolants such as oil, water, and ethylene glycol mixture. Nanotechnology has been used for improving thermo-physical properties. The dispersion of nanoparticles into the conventional fluids increases the noticeably thermal conductivity of coolant fluid and so improves characteristics of heat transfer. Ganaoui et al. (2009) [7] qualified and developed a numerical scheme coupling finite volumes and lattice Boltzmann methods for checking phase change problem cases.

Shen et al. (2010) [8] introduced an investigation on the thermal managing for portable devices. Their research introduced experimental study about utilizing PCM for cooling of mobile devices and discussed cooling performance for transitory charging and discharging for portable devices with three different cases which were working a long duration calls, working phone frequently calls, and making occasional calls. Their findings indicated the mobile devices overheated at long duration calls.

A comprehensive numerical investigation is conducted by Sebti et al. (2013) [9] to study thermal performance improvement during the phase change process of paraffin-based nanofluid with different concentrations of Cu in a square cavity. They studied the effects of significant parameters, namely hot wall temperature, cavity size, and nanoparticle volume fraction on heat transfer features, fluid flow, and melting time. Their findings indicate that dispersion nanoparticles lead to enhance thermal conductivity for NEPCM as compared with pure PCM, so thus improvement of heat transfer rate. Besides, melting time for nanofluid decreased and the heat transfer rate increased as concentrations of nanoparticles increased. The higher difference in temperature between hot walls will expedite the phase change process of NEPCM.

In this study, the thermal performance of micro-channel heat sink (MHS) with various volume fraction values of two types of nanoparticle material of NEPCM were studied theoretically.

2. Physical model description
Micro-channel heat sink (MHS) represented in figure 1 and for simplifying a numerical solution a unit has been selected. This unit consists of one channel and two symmetrical halves. The 3D micro-channel heat sink unit model with rectangular channels as shown in figure 2. Heat sink unit (HSU) dimensions are heat sink unit height H=190µm, width W=260µm, and length L=1000µm. The dimensions of the rectangular channel were channel height H_{ch}=150µm, channel width W_{ch}=100µm, and channel length L_{ch}=1000µm. This model has been constructed to study the heat sink performance with different cooling mediums employed in this paper. The coolants have been treated as a Newtonian and incompressible fluid. The thermo-physical properties of coolants have been considered constant except density that handled with Boussinesq approximation to indicate the effect of the thermal buoyancy force. Gravity effect has been taken in y-direction toward the heat sink base. Properties of the heat sink material listed in table 1.

Table 1. Thermo-physical properties of air and heat sink material.

| Property     | Air   | Aluminium |
|--------------|-------|-----------|
| ρ (kg. m⁻³)  | 1.22  | 2719      |
| C_p (J. (kg. K)⁻¹) | 1006.4 | 871       |
| k (W. (m. K)⁻¹) | 0.0242 | 202.4     |
| μ (Pa. s)    | 1.7894×10⁻⁵ | -        |
Figure 1. Geometry of the micro-channel heat sink.

Figure 2. The geometry of micro-channel heat sink unit model.

3. Governing equations
Assuming NEPCM behaves as a continuum medium and thermal balance between pure PCM and nanoparticles, and steady-state condition, governing equations and properties of the NEPCM are [10]:

Continuity equation
\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

Momentum equations

X-direction:
\[ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = \frac{1}{\rho_{\text{NEPCM}}} \left[ -\frac{\partial P}{\partial x} + \mu_{\text{NEPCM}} \nabla^2 u + (\rho \beta)_{\text{NEPCM}} g_x (T - T_{ref}) \right] \]  

Y-direction:
\[
\begin{align*}
\frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &= \frac{1}{\rho_{NEPCM}} \left[ -\frac{\partial P}{\partial y} + \mu_{NEPCM} \nabla^2 v + (\rho \beta_{NEPCM}) g_y (T - T_{ref}) \right] \\
Z\text{-direction:} \\
\frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} &= \frac{1}{\rho_{NEPCM}} \left[ -\frac{\partial P}{\partial z} + \mu_{NEPCM} \nabla^2 w + (\rho \beta_{NEPCM}) g_z (T - T_{ref}) \right] \\
\text{Energy equation} \\
\frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} &= \frac{\partial}{\partial x} \left[ \frac{(k_{NEPCM0} + k_d) \partial T}{(\rho c_p)_{NEPCM}} \right] + \frac{\partial}{\partial y} \left[ \frac{(k_{NEPCM0} + k_d) \partial T}{(\rho c_p)_{NEPCM}} \right] + \frac{\partial}{\partial z} \left[ \frac{(k_{NEPCM0} + k_d) \partial T}{(\rho c_p)_{NEPCM}} \right] \\
The density of NEPCM is given by \\
\rho_{NEPCM} = (1 - C) \rho_{PCM} + C \rho_s \\
The heat capacity of NEPCM and the Boussinesq term can be written as \\
(\rho c_p)_{NEPCM} = (1 - C)(\rho c_p)_{PCM} + C(\rho c_p)_s \\
(\rho \beta)_{NEPCM} = (1 - C)(\rho \beta)_{PCM} + C(\rho \beta)_s \\
The viscosity of NEPCM can be expressed as \\
\mu_{NEPCM} = \frac{\mu_{PCM}}{(1 - C)^{2.5}} \\
Whereas effective thermal conductivity of NEPCM is \\
k_{eff} = k_{NEPCM0} + k_d \\
Thermal conductivity for NEPCM is \\
\frac{k_{NEPCM0}}{k_{PCM}} = \frac{k_s + 2k_{PCM} - 2C(k_{PCM} - k_s)}{k_s + 2k_{PCM} + C(k_{PCM} - k_s)} \\
And the improvement term for thermal conductivity due to thermal nanoparticles suspension is given by \\
k_d = D(\rho c_p)_{NEPCM} \sqrt{u^2 + v^2} \ C \ d_p \\
With D, dp represents the constant of an empirically determined that evaluated by work of Wakao and Kaguei [11] and diameter of nanoparticle respectively.
Latent heat of fusion for NEPCMs is obtained as

\[(\rho\lambda)_{NEPCM} = (1 - C)(\rho\lambda)_{PCM}\]  \hspace{1cm} (13)

Thermo-physical properties of PCM, nanoparticles materials, and NEPCM mentioned in tables 2 and 3.

**Table 2.** Thermo-physical properties of paraffin wax, Sic nanoparticles, and NEPCM.

| Property       | Pure PCM | Sic nanoparticle | Sic-PCM C=1% | Sic-PCM C=3% | Sic-PCM C=5% |
|----------------|----------|------------------|--------------|--------------|--------------|
| ρ (kg.m\(^{-3}\)) | 773      | 3160             | 796.87       | 844.61       | 892.35       |
| C\(_p\) (kJ.(kg·K\(^{-1}\))) | 2.3      | 0.675            | 2.23556      | 2.1176       | 2.01227      |
| k (W.(m.K\(^{-1}\))) | 0.215    | 490              | 0.221506     | 0.234921     | 0.2489       |
| μ (Pa.s)       | 0.0063   | -                | 0.00646      | 0.00679      | 0.00716      |
| λ (kJ. kg\(^{-1}\)) | 179.6    | -                | 172.4779     | 159.4414     | 147.799      |
| β (K\(^{-1}\)) | 3 \times 10\(^{-3}\) | -                | 2.7 \times 10\(^{-3}\) | 2.5 \times 10\(^{-3}\) | 2.3 \times 10\(^{-3}\) |

**Table 3.** Thermo-physical properties of pure paraffin wax, Diamond nanoparticles, and NEPCM.

| Property       | Pure PCM | Sic nanoparticle | Diamond-PCM C=1% | Diamond-PCM C=3% | Diamond-PCM C=5% |
|----------------|----------|------------------|------------------|------------------|------------------|
| ρ (kg.m\(^{-3}\)) | 773      | 3510             | 800.37           | 855.11           | 909.85           |
| C\(_p\) (kJ.(kg·K\(^{-1}\))) | 2.3      | 0.497            | 2.22094          | 2.07800          | 1.95227          |
| K(W.(m.K\(^{-1}\))) | 0.215    | 1000             | 0.221506         | 0.23493          | 0.248924         |
| μ (Pa.s)       | 0.0063   | -                | 0.00646          | 0.00679          | 0.00716          |
| λ (kJ. kg\(^{-1}\)) | 179.6    | -                | 171.7236         | 157.4836         | 144.957          |
| β (K\(^{-1}\)) | 3 \times 10\(^{-3}\) | -                | 2.7 \times 10\(^{-3}\) | 2.5 \times 10\(^{-3}\) | 2.3 \times 10\(^{-3}\) |

4. **Boundary conditions**

The boundary conditions which applied to the mathematical model to conduct numerical simulations are given as follows:

1- The top surface is exposed to mixed natural convection and radiation

At x=0 to W, y=H, and z=0 to L

\[h=6 \text{ W.m}^{-2}.\text{K}^{-1}\]

\[T_{amb}=293\text{K}\]

Where \(h\), \(e\), and \(T_{amb}\) denoted to the heat transfer coefficient of natural convection, external emissivity, and ambient temperature respectively.

2- Side surfaces at \(x=0, W, y=0\) to \(H\), and \(z=0\) to \(L\)
Symmetry condition (no heat flux, normal flow, and shear stress) is applied to reduce computational time.

\[
\frac{\partial T}{\partial x} = 0, \quad \frac{\partial u}{\partial x} = \frac{\partial u}{\partial y} = \frac{\partial u}{\partial z} = 0
\]

3- Front and back surfaces are treated as insulated surfaces.

At \( x= 0 \) to \( W \), \( y= 0 \) to \( H \), and \( z= 0 \) to \( L \)
\[ u = v = w = 0 \]

4- Bottom surface (heat sink base): A uniform and constant heat flux is applied

At \( x= 0 \) to \( W \), \( y=0 \), and \( z= 0 \) to \( L \)
\[ q \text{ (W.m}^{-2}\text{)} = \text{constant} \]

5. Solution methodology

Finite volume method (FVM) has been used to convert partial differential equations of continuity, momentum, and energy to algebraic equations based on Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm. Upwind scheme of Second-order has been used for discretized thermal convection terms. A numerical solution consisting of three main steps which were pre-processing, implementation of solver, and lastly post-processing. Pre-Processing is consisting of creating a geometry of the mathematical model and chose a suitable mesh for this model. Solver Implementation is the step of setting the numerical model and boundary conditions to start up solver. Post Processing is the part of the numerical solution which completing until solver running reaches to convergence then examined results. Iterations have been performed until the residual of the governing equation reach less than 10\(^{-6}\).

6. Results and discussion

The present model validated with experimental results of [12] to ensure the reliability of the model used in this study. The model presented in [12] is an unfinned heat sink unit with dimensions of (114×114×25mm\(^3\)). Air and paraffin wax have been used as coolants at a heat flux of 2.4 kW.m\(^{-2}\) which provide on the base of heat sink along 90 minutes. The results have been validated for comparison the effect of using PCM instead of air with a heat sink. Figure 3 represents the comparison of the present model results for air and paraffin wax with those of [12]. The obtained numerical results showed acceptable agreement with experimental data for both coolants along period time with an average error of (4 and 5.5%) for air and paraffin wax respectively which may be resulting from experimental conditions. Effects of different parameters, which were coolant type, concentration for NEPCM (1, 3, and 5%), heat flux values, and ambient temperature on temperature distribution of heat sink base have been investigated numerically.

Variation of the average base temperature of micro-channel heat sink (MHS) without and with PCM for heat flux values at constant ambient temperature is elucidated in figure 4. From this figure, it could be noted the average base temperature of micro-channel heat sink (MHS) rising with increasing the heat flux value for both coolants at constant ambient temperature because of increasing the amount of difference between the average temperature of base and ambient temperature (\( T_{\text{w}}-T_{\text{amb}} \)). Also, it can be observed that cooling performance for heat sink with paraffin wax is better than that with air at all heat flux values because of the paraffin wax has better thermo-physical properties as compared to air which characterized with higher density, thermal conductivity, specific heat, and latent heat of fusion that making paraffin wax absorbing an extra amount of heat from heat sink base as latent heat until completed melting process then rejected it to surrounding during the re-solidify process. Figure 5 clarifies variation of the average temperature of heat sink base with heat flux for air, PCM, and PCM enhanced with Sic nanoparticles with different volume concentrations. From this figure, it can be noted that cooling performance for MHS with NEPCM is best compared with air and paraffin wax due to improving the thermal conductivity of PCM after addition nanoparticle through it. This lead to absorb more heat than
conventional PCM. The figure also shows clearly that the cooling performance enhancement is increased continuously with an increase in the volume fraction of Sic nanoparticle until reach the maximum improvement at 5% volume fraction. Variation of the average temperature for MHS base with heat flux by using different types of coolants (air, PCM, PCM enhanced with a diamond of different volume concentrations) at constant ambient temperature is shown in figure 6. As illustrated in figure 5, the NEPCM integrated into the MHS has the best cooling performance among other coolants as a result of increase thermal conductivity and density that lead to modify the thermal properties of PCM and modify the melting process which means dissipated a large amount of generated heat from the electronic chip.

Increasing the concentration of diamond nanoparticle into the PCM leads to increase heat transfer performance enhancement for heat sink integrated by NEPCM to a maximum value at 5% concentration. To compare heat transfer rate enhancement between Sic-PCM and Diamond-PCM as coolants, simulation results of variation the average temperature of MHS base with thermal flux values at various values of volume concentrations of two types of nanoparticles are depicted in figures (7-9). These figures explained that the heat transfer rate of MHS with all nanoparticle material types is higher than air and paraffin wax since the base temperature is lower in two cases of NEPCM compared with air and pure PCM. Also, the base temperature in case of MHS with (Diamond-PCM) is lower than that with (Sic-PCM) at all volume concentrations due to the nanoparticles of diamond have higher thermo-physical properties than silicon carbide such as density and thermal conductivity. Figure 10 clarifies the variation of average base temperature of MHS with volume fraction at constant ambient temperature for diamond-PCM as NEPCM coolants with different values of heat flux. This figure explained that average base temperature for MHS reduced by increasing volume fraction of diamond at all heat flux values due to increase amount of heat absorbed due to increasing thermal conductivity.

The variation of average base temperature of MHS with the volume fraction of (Sic-PCM) at different heat flux values and same the ambient temperature is indicated in figure 11. This figure clarified that average base temperature will reduce with increasing the volume fraction of (Sic-PCM) as a result to continue the enhancement of thermal conductivity for NEPCM to reach the highest value at 5% volume fraction like the previous figure for diamond-PCM. Figures (12-15) show the variation of the average temperature of MHS base versus ambient temperature for air and paraffin wax at different selected values of heat flux. These figures indicated that the average base temperature increased with the ambient temperature rising for all values of heat flux due to decreasing the value of temperature difference which lead to a decrease in the heat transfer process.

From these figures, it can be noted clearly that for all values of heat flux, the average base temperature of MHS with paraffin wax is lower than air at all ambient temperature because the paraffin wax has higher thermo-physical properties than air and can absorb extra amount of heat as latent heat through melting process.
Figure 3. Variation the base temperature versus time at heat flux=2.4kW.m\(^{-2}\) as comparing present model and results of [12].

Num. results of air.
Exp. results of air [12].
Num. results of paraffin wax.
Exp. results of paraffin wax [12].

Figure 4. Variation the average base temperature versus heat flux values at ambient temperature=20°C.

Air.
Paraffin wax.

Figure 5. Variation the average base temperature versus heat flux values at ambient temperature=20°C.

Air.
Paraffin wax.
Sic C=1%.
Sic C=3%.
Sic C=5%.

Figure 6. Variation the average base temperature versus heat flux values at ambient temperature=20°C.

Air.
Paraffin wax.
Diamond C=1%.
Diamond C=3%.
Diamond C=5%.
Figure 7. Variation the average base temperature versus heat flux values at ambient temperature =20°C.

Figure 8. Variation the average base temperature versus heat flux values at ambient temperature =20°C.

Figure 9. Variation the average base temperature versus heat flux values at ambient temperature =20°C.

Figure 10. Variation the average base temperature versus heat flux values at ambient temperature =20°C.

Figure 11. Variation the average base temperature versus heat flux values at ambient temperature =20°C.

Figure 12. Variation the average base temperature versus heat flux values at ambient temperature =20°C.
Figure 11. Variation the average base temperature versus volume fraction values of paraffin wax-Sic.

Figure 12. Variation the average base temperature versus ambient temperature at heat flux=8000 W.m$^{-2}$.

Figure 13. Variation the average base temperature versus ambient temperature at heat flux=10000 W.m$^2$.

Figure 14. Variation the average base temperature versus ambient temperature at heat flux=12000 W.m$^2$. 
7. Conclusions
This paper offers a comprehensive numerical investigation for the heat distribution in a micro-channel heat sink filled with various cooling mediums which were air, conventional PCM, and NEPCM. The impact of nanoparticle material types and the effect of increasing concentration by volume of nanoparticles and heat flux values are simulated numerically to enhance the cooling performance and so increasing the efficiency of the electronic devices.

From the main obtained results, the following annotations can be summarized as:

1- Thermal performance of micro-channel heat sink (MHS) integrated by PCM is better than air as coolant with a percentage of 7.8% due to the high ability of PCM to absorb heat as latent heat during the melting process that dissipated it to ambient and re-solidify when the device is idle.

2- For all nanoparticles material types, the addition of nanoparticles to PCM results in enhanced thermal conductivity for PCM and so the rate of heat transfer for NEPCM coolant is better than that for conventional PCM.

3- Cooling performance for MHS enhanced with increasing nanoparticle volume fraction for NEPCM coolant that integrated with the heat sink.

4- At all heat flux values, the base temperature of MHS increasing with an ambient temperature rising.

5- The nanoparticle-enhanced phase change material (NEPCM) of (Diamond-PCM) integrated into heat sink configuration at 5% volume fraction showed the best performance among the other cooling mediums in this study.

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