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# Numerical Investigation of Heat Transfer Performance of Phase Change Material Slurries in Micro channels for Cooling of High Power Electronic Devices

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***Abstract: This numerical study investigates the effect of using phase change material slurries (PCMs) on the thermal performance of micro channel used for cooling of high power electronic devices. The phase change material slurries composed of Lauric acid nanoparticles in water (carrier fluid) which is introduced into a rectangular micro channel of 100µm height and 10mm length, where bottom wall face a constant heat flux. Energy, momentum and mass equations are solved simultaneously using a carrier fluid with effective temperature dependent physical properties. Under specific conditions including mass flow rate of 1x10$^{-4}$ kg/s, heat flux of 0.7MW/m$^2$ and PCM nano-particles volume concentration (0-25%), results showed a remarkable increase in the wall temperature reduction, heat transfer coefficient and Nusselt number. Enhancement index is used to measure the efficiency of PCM slurries. Such study helps in understanding that at low pumping power, low and uniform temperatures across the electronic devices can be achieved, compared to using water only for effective heat removal.***
***Keywords: Microchannel, Phase Change Material, PCM Slurry, Heat Transfer, Laminar Flow***

## I. INTRODUCTION

Now a days functioning of electronic devices produce high heat flux of order 10$^5$W/m$^2$, which generate high temperature rise in the electronic devices. The high temperature rise and non-uniform temperature distribution in electronic microchips damages the electronic systems and devices. To prevent the malfunctioning of electronic systems and devices, it is very important to control the wall temperature rise and remove the generated heat quickly from the system. [1]

Many methods for cooling of small scale heat generating devices have been presented in previous few years.[1]-[9]. One latest method gaining importance is using Phase Change material particles with fluid in microchannels, this improve the heat storage capacity and helps in effective heat removal.[1]-[9]

The previous work performed on three dimensional numerical study of temperature dependent physical properties of PCM carrying fluid having melting range of 300-305K and inlet temperature 300K in rectangular microchannels and increase in heat transfer coefficient and temperature reduction with increase of PCM particles volume concentration recorded.[7]

The work presented in this paper is performed for 2D study of microchannel with Lauric acid nanoparticles, having melting range of 316.7-317.7K and inlet temperature 315K in carrier fluid (water) on different operating conditions. In addition the present work takes into account the enhancement in Nusselt number with increasing Lauric acid particles in carrier fluid (water). Table I summarize the properties of the PCM Nanoparticles [1]

Table Physical Properties of Lauric acid

| Lauric acid Particles | Density (kg/m3) | Specific heat (kJ/kg K) | Latent heat (kJ/kg) | Thermal conductivity (W/m K) |
|---|---|---|---|---|
| Solid | 1007 | 1.76 | 211 | 0.147 |
| Liquid | 862 | 2.27 | -- | 0.147 |

## II. MODEL FRAMEWORK

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Schematic diagram of microchannel used in this study, is shown in Fig.1. In this paper a microchannel of fixed height (H)100μm and length (L) 10mm is defined in FLUENT 15.0. The width (W) of the channel is considered to be 1mm for three-dimensional study. Lauric acid nano-particles carrying fluid is introduced to the inlet of microchannel at mass flow rate of $1x10^{-4}$kg/s and temperature of 315K below the melting temperature (317.2 K) of PCM particles. Pressure of 1atm is assumed at the outlet of microchannel. The bottom wall face a constant heat flux of 0.7MW/$m^2$and heat the slurry inside microchannel.

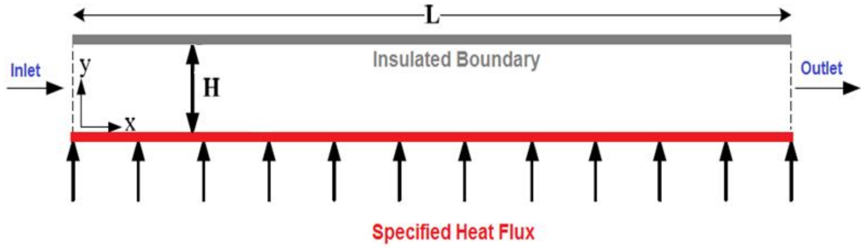


Fig.1 Schematic of microchannel used in this study, (H) Height of microchannel, (L) Length of microchannel, Bottom wall face constant heat flux.

### A. *Assumption*

1) Flow of the PCM slurry inside the microchannel is laminar, steady, viscosand incompressible. [1]
2) Physical properties (density, viscosity, specific heat capacity, thermal conductivity) of carrier fluid (water) are temperature dependent.[7]
3) PCM slurry properties are temperature dependent and also function of particles volume concentration.[7]
4) The effect of any external and internal forces are negligible.[7]
5) The effect of shell encapsulating nanoparticles is neglected.[8]
6) The nanoparticles and carrier fluid are moving with same velocity and temperature inside microchannel.[8]
7) The distribution of Nanoparticles are assumed to be homogeneous inside microchannel.[8]
8) Instant melting take place when PCM particles reached the melting temperature range.[8]

### B. *Governing Equations*

Energy, Momentum and Mass governing equations are solved simultaneously using temperature dependent physical properties of PCM slurries as shown below:

1) Conversation of Energy Equation: [1]

$$\nabla \cdot \left( \rho_{pcms} \vec{v} c_{ppcms} T \right) = \nabla \cdot \left( k_{pcms} \nabla T \right)$$

2) Conversation of momentum: [1]

$$\nabla \cdot \left( \rho_{pcms} \vec{v}\vec{v} \right) = -\nabla \rho + \mu_{pcms} \nabla^2 v$$

3) Conversation of mass: [1]

$$\nabla \cdot \vec{v} = 0$$

### C. *Temperature Dependent Physical Properties of PCM Slurry*

1) *Density:* PCM slurry (pcms) density is calculated as[7]

$$\rho_{pcms} = c\rho_p + (1-c)\rho_{cf}$$

2) *Specific Heat Capacity:* In this study the melting range of PCM nano-particles are assumed to be 316.7-317.7K and melting temperature 317.2 [1].PCM slurry (pcms) specific heat capacity is calculated as [7]

$$For\, T_p < T_{Solidus}:$$

$$c_{ppcms} = \frac{c\left(\rho c_{p,S}\right)_p + (1-c)\left(\rho c_p\right)_{cf}}{\rho_{pcms}}$$

$$For\, T_{Solidus} < T_p < T_{liquidus}:$$

$$c_{ppcms} = \frac{c\left(\rho\left(\frac{c_{ps}c_{pL}}{2} + \frac{L}{T_{liquidus} - T_{Solidus}}\right)\right)_p + (1-c)(\rho c_p)_{cf}}{\rho_{pcms}}$$

$$For\, T_p > T_{liquidus}:$$

$$c_{ppcms} = \frac{c(\rho c_{p,L})_p + (1-c)(\rho c_p)_{cf}}{\rho_{pcms}}$$

3) *Viscosity:* PCM slurry is composed of carrier fluid (water) and PCM (Lauric acid) nano-particles assume to have diameter of 50nm. The addition of PCM nano-particles rise the viscosity of the PCM slurry (pcms), which is calculated as[11]

$$\mu_{pcms} = \left(1 - c - 1.16c^2\right)^{-2.5} \mu_{cf}$$

4) *Thermal Conductivity:* PCM slurry (pcms) thermal conductivity is calculated as [10]

$$k_{pcms} = k_{cf} \frac{2 + k_p / k_{cf} + 2c\left(k_p / k_{cf} - 1\right)}{2 + k_p / k_{cf} - c\left(k_p / k_{cf} - 1\right)}$$

## III. NUMERICAL METHOD

A 2D geometry and Mesh is created in FLUENT 15.0. in order to discretize the governing equations control volume approach of Simple Algorithm, utilize the second order upwind scheme. For energy, momentum and mass equations residuals of $10^{-6}$, $10^{-3}$and $10^{-3}$ applied respectively.

### *A. Grid Independence Test*

Four different grid resolutions were created in FLUENT15.0 as 10x1000,15x4000, 20x8000 and 22x10000. The maximum difference between the Nusselt number results of grid resolution20x8000 and 22x10000 was 0.002 as shown in Fig.2. Therefore Grid 20x8000 used for simulations.

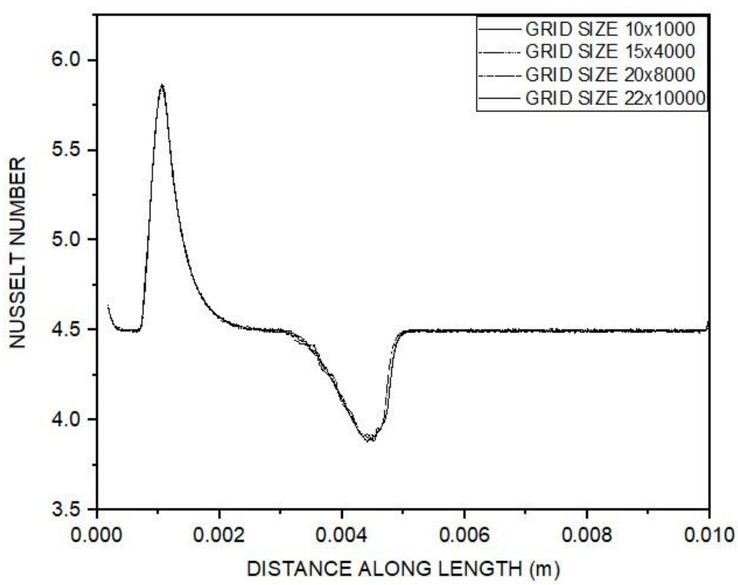


Fig.2 Grid independence test

### *B. Significance of Temperature Dependent Properties*

In this paper the physical properties of carrier fluid (water) especially density, specific heat capacity, viscosity and thermal conductivity are temperature dependent. Table II shows the importance of using temperature dependent physical properties rather than constant temperature physical properties. The percentage difference in outlet temperature is 0.03% where the percentage

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difference in pressure drop along the microchannel is 114%. The reason behind this huge difference in pressure drop is viscosity of carrier fluid (water), which is highly sensitive to temperature. So, on the basis of results in Table II, the simulations are performed with temperature dependent physical properties. [1] [7]

Table II
Significance of Temperature dependent physical properties

| Constant Properties | | Temperature dependent properties | | Percentage Difference | |
|---|---|---|---|---|---|
| $T_{outlet}$ (K) | ΔP (Pa) | $T_{outlet}$(K) | ΔP (Pa) | $T_{outlet}$(%) | ΔP (%) |
| 331.6471 | 16465.62 | 331.7607 | 7684.943 | 0.03 | 114 |
| Heat Flux=0.7MW/m$^2$, Mass Flow rate=1x10$^{-4}$kg/s, Inlet Temperture=315K | | | | | |

*C. Model Validation with Experimental Work*

Due to absence of experimental data of flow of PCM slurries in microchannels, experimental data presented in [4], was used to validate the homogeneous model presented in this paper. Numerical model was solved for flow of PCM carrying fluid of 10% PCM particles volume concentration, in circular pipe of diameter 3.14mm and length 0.3m for Stefan Number 2, same pipe geometry and PCM slurry as used in [4]. The results of wall temperature along the pipe length obtained from numerical model were compared with the experimental results of [4]as shown in Fig. 3, which shows a good agreement with maximum percentage difference of 0.12%.

Stefan number is a ratio of slurry sensible heat capacity to slurry latent heat capacity and defined as

$$Ste = \frac{C_{ppcms} q'' D_h \rho_{pcms}}{2k_{pcms} c L \rho_p}$$

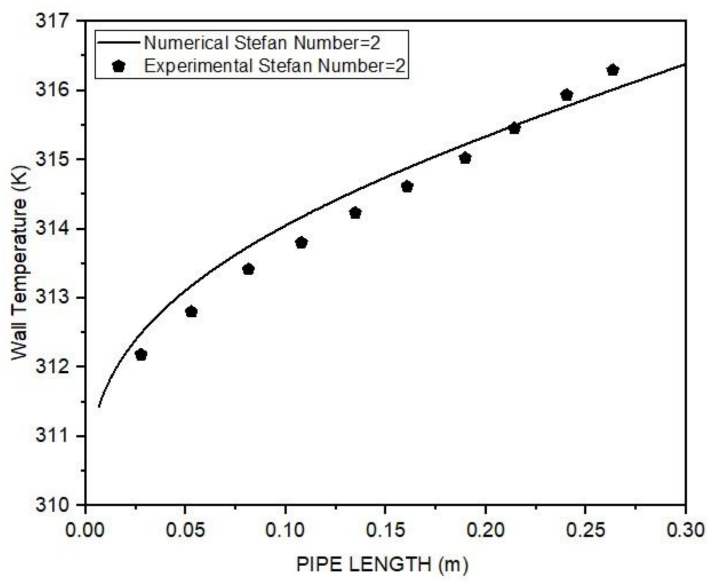


Fig.3 Comparison of homogenous numerical model with experimental data

## IV. RESULTS AND DISCUSSIONS

*A. Weighted Average Temperature*

The mass weighted average temperature is function of flow in x-direction, represented as [7]

$$T_{mass-weighted-average} = \frac{\int_{Ac} \rho v C_p T dA_c}{\int_{Ac} \rho v C_p dA_c}$$

Fig. 4 shows the mass weighted average temperature along the mirochannel length for PCM slurries of Particle volume concentration of 0% (water), 5%, 10%, 15%, 20% and 25% at inlet temperature of 315K , mass flow rate of 1x10$^{-4}$ kg/s and heat flux of 0.7 MW/m$^2$. The temperature decreases with the addition of PCM particles due to latent heat capacity of PCM particles.

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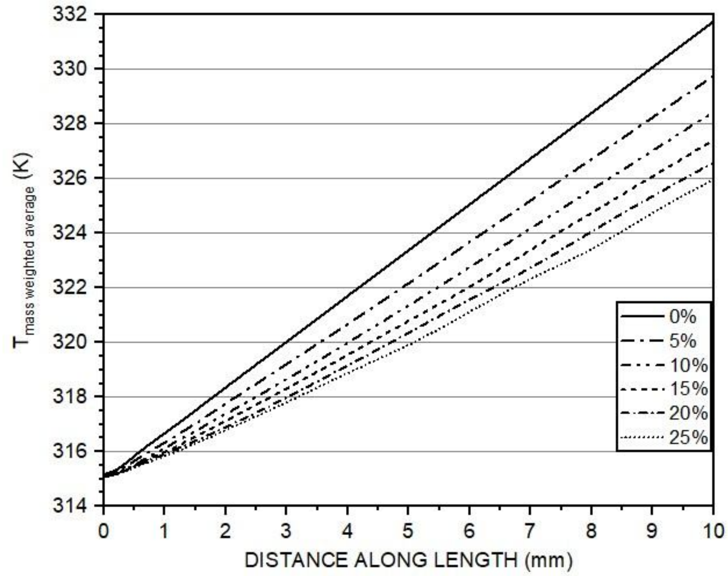


Fig. 4 Mass weighted average temperature along the microchannel length for PCM slurries of particle volume concentration (0-25%)

*B. Mean Flow Temperature Reduction*

Reduction in mean flow temperature measures the relative enhancement in reduction ofmicrochannel wall temperature by adding PCM particles in carrier fluid (water), represented as [7]

$$\theta_{reduction} = \frac{\theta_{water} - \theta_{pcms}}{\theta_{water}}$$

Fig. 5shows the reduction in mean flow temperature along the microchannel length for PCM slurries of particle volume concentration of 5%, 10%. 15% , 20% and 25% at inlet temperature of 315K , mass flow rate of 1x$10^{-4}$ kg/s and heat flux of 0.7 MW/$m^2$. The result shows that the temperature is reduced by 11-57% with the addition of PCM particles in water. The maximum temperature reduction of 57% is recorded for particle volume concentration of 25%. It is observed that the reduction in temperature increases at the initial section of microchannel near entrance and then slightly decreases along the microchannel length. This is because, 40-60% PCM particles melts in the initial 20% length of microchannel.

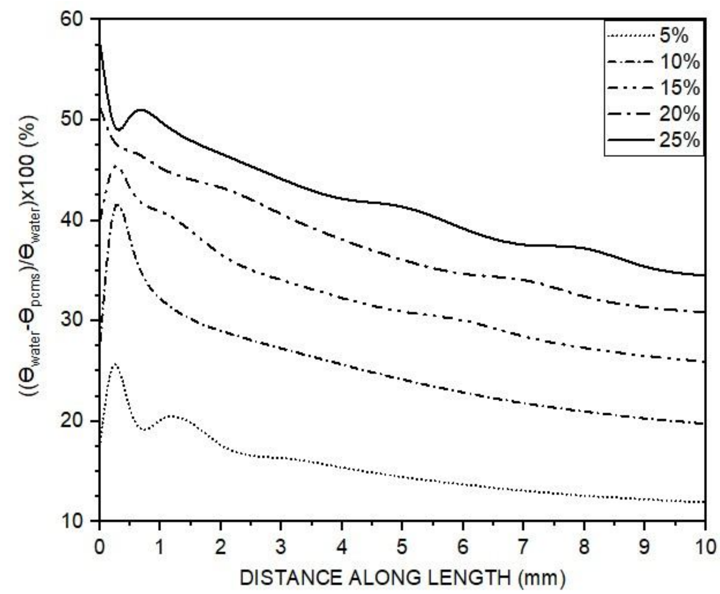


Fig. 5Reduction in Mean flow temperature along microchannel length for PCM Slurries (pcms) of particle volume concentration (0-25%)

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*C. Heat Transfer Coefficient Enhancement*

Heat transfer coefficient enhancement measures the relative enhancement in heat transfer coefficient by increasing PCM particle in carrier fluid (water), defined as[7]

$$h_{enhancement} = \frac{h_{pcms} - h_{water}}{h_{water}}$$

$$\text{Where } h = \frac{q''}{T_w - T_m}$$

Fig. 6 shows the enhancement in heat transfer coefficient along the microchannel length for PCM slurries of particle volume concentration of 5%, 10%. 15% , 20% and 25% at inlet temperature of 315K , mass flow rate of $1\text{x}10^{-4}$ kg/s and heat flux of 0.7 $MW/m^2$. The result shows that heat transfer coefficient increased by 13-135% with the addition of PCM particle volume concentration (0-25%). The highest enhancement in heat transfer coefficient of 135% is recorded for particle volume concentration of 25%. It is observed that heat transfer coefficient rises at the initial section of microchannel near entrance and then slightly decreases along the microchannel length. This is because 40-60% PCM particles melts in the initial 20% length of microchannel.

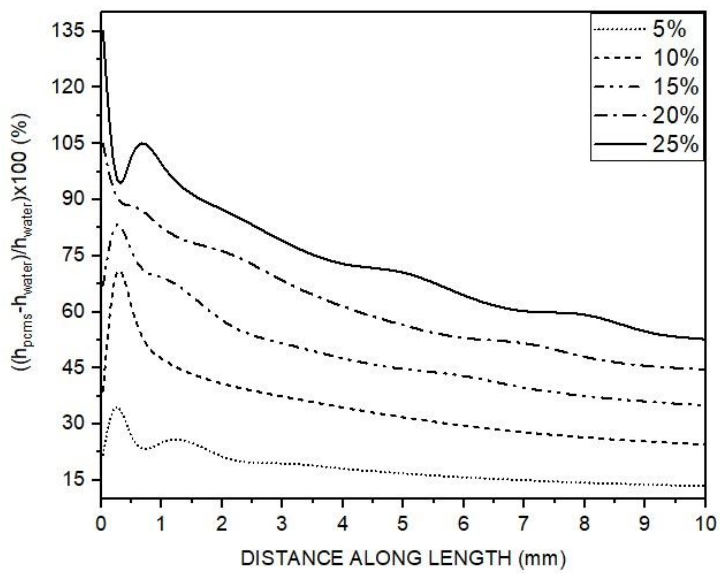


Fig. 6 Enhancement in heat transfer coefficient along microchannel length for PCM slurries (pcms)of particle volume concentration (0-25%)

*D. Local Nusselt Number Enhancement*

Enhancement in local Nusselt Number measures the relative enhancement in Nusselt number by increasing PCM particles in carrier fluid (water), defined as

$$Nu_{xenhancement} = \frac{Nu_{xpcms} - Nu_{water}}{Nu_{water}}$$

$$\text{Where } Nu_x = \frac{h_x D_h}{k_x}$$

Fig. 7 shows the enhancement in local Nusselt number along the microchannel length for PCM slurries of particle volume concentration of 5%, 10%. 15% , 20% and 25% at inlet temperature of 315K , mass flow rate of $1\text{x}10^{-4}$ kg/s and heat flux of 0.7 $MW/m^2$. The result shows that local Nusselt number increased by 19-207% with the addition of PCM particles in water. The highest increase, in local Nusselt number, of 207% is recorded for particle volume concentration of 25%. It is observed that local Nuseelt number rises at the initial section of microchannel near entrance and then slightly decreases along the microchannel length. This is because 40-60% PCM particles melts in the initial 20% length of microchannel.

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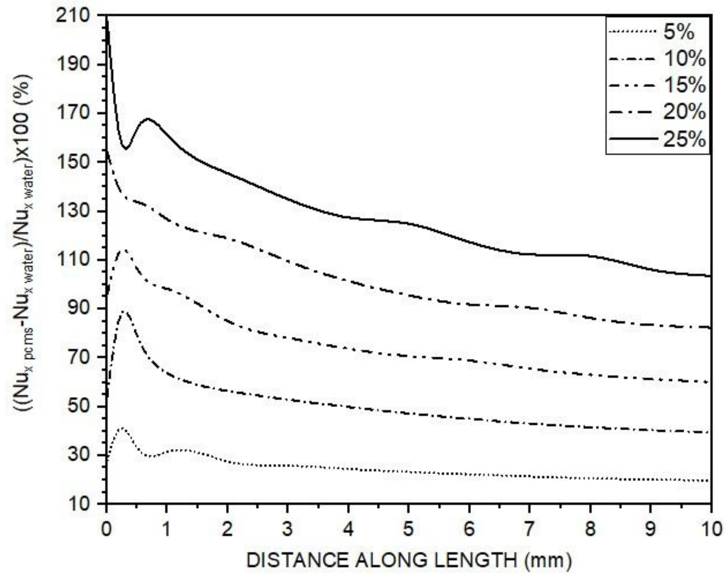


Fig. 7 Enhancement in local Nusselt number along microchannel length for PCM slurries (pcms) of particle volume concentration (0-25%)

*E. Overall Nusselt Number Enhancement*

The overall Nusselt Number is calculated by averaging the local Nusselt number $Nu_x$ over the length of microchannel represented as [12]

$$Nu_{overall} = \frac{1}{L}\int_0^L Nu_x dx$$

Fig. 8 shows the overall average Nusselt number as a function of particle volume concentration (0-25%) in microchannel at inlet temperature of 315K , mass flow rate of $1x10^{-4}$ kg/s and heat flux of 0.7 MW/m$^2$. The result shows that overall average Nusselt number increased by increasing PCM particles in carrier fluid. The highest enhancement of 181% in overall lNusselt number is recorded for particle volume concentration of 25%.

*F. Enhancement Index*

Enhancement index is a ratio of reduction in mean flow temperature to increase in pumping power, due to addition of PCM particles in carrier fluid, defined as [7]

$$\text{Enhancement index}=\frac{\theta_{water}-\theta_{pcms}}{\theta_{water}} / \frac{PP_{pcms}-PP_{water}}{PP_{water}}$$

As discussed in this paper that addition of PCM particles in carrier fluid (water)increase the performance of microchannel by increasing the heat transfer coefficient and Nusselt number and decreasing the wall temperature. But drawback of this method is that by increasing the PCM particles volume concentration in the slurry, viscosity of slurry also increases which in turn increase the pumping power demands. The second method for effective heat removal and reduction of microchannel wall temperature is, circulating water (0%PCM slurry) at higher mass flow rates.

Enhancement index is used in order to compare the efficiency of both methods. Fig. 10 shows the enhancement index along the microchannel length, for method I as PCM slurries of particle volume concentration of 5%, 10%, 15% , 20% and 25% at inlet temperature of 315K , mass flow rate of $1x10^{-4}$ kg/s and heat flux of 0.7 MW/m$^2$. And method II as particle volume concentration of 0%(water) at various mass flow rates of $1.5x10^{-4}$ kg/s, $2x10^{-4}$ kg/s, $2.5x10^{-4}$ kg/s, and $3x10^{-4}$ kg/s at inlet temperature of 315K and heat flux of 0.7 MW/m$^2$. The maximum enhancement index of 0.39 is recorded for 10% PCM slurry.

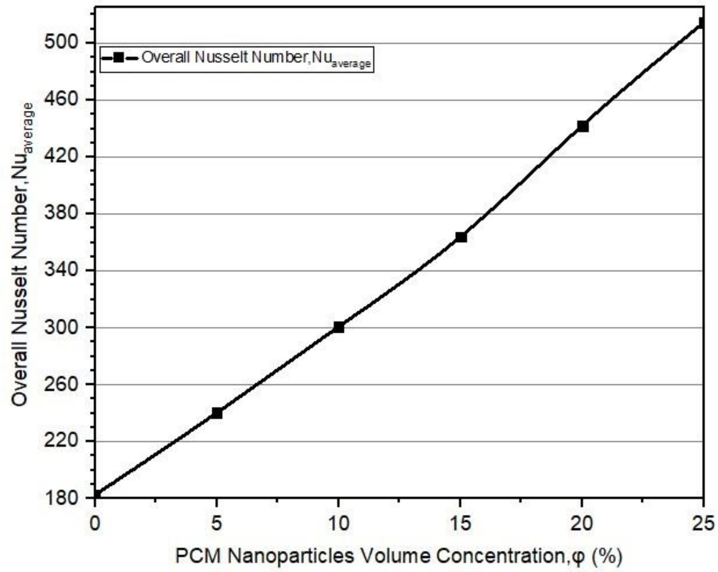


Fig. 8 Enhancement in overall Nusselt number as a function of particle volume concentration (0-25%)

Fig. 10 shows that enhancement index of 20% PCM particle volume concentration and water at mass flow rate of $1.5\times10^{-4}$ kg/s is almost equal. So, the method I is efficient for cooling of electronic devices below 20% particle volume concentration.

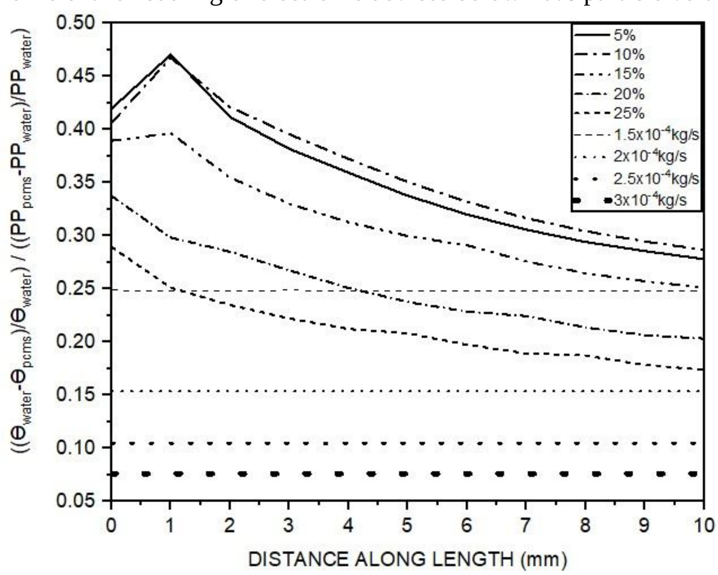


Fig.10 Enhancement index along microchannel length, comparison between PCM slurries (0-25%) and water at various mass flow rate ($1\times10^{-4}$-$3\times10^{-4}$ kg/s).

## V. CONCLUSION

A numerical two-dimensional model investigated the effect of using phase change material slurries (PCMs) on the thermal performance of microchannel used for cooling of high power electronic devices. Under specific conditions including mass flow rate $1\times10^{-4}$ kg/s, heat flux 0.7MW/m$^2$ and PCM nano-particles volume concentration (0-25%).It is found that the reduction in mean flow temperature was more than 10% for all the cases and reached the maximum value of 57% for particle volume concentration of 25%. The Enhancement in heat transfer coefficient and Nusselt number was more than 13% and 19% for all the cases and reached the maximum value of 135% and 207% respectively for Particle volume concentration of 25%.The maximum enhancement index of 0.39 is recorded for 10% PCM slurry. This means that 10% PCM slurry reduce more temperature with less pressure drop along the microchannel as compared to other slurries.

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## VI. ACKNOWLEDGMENT

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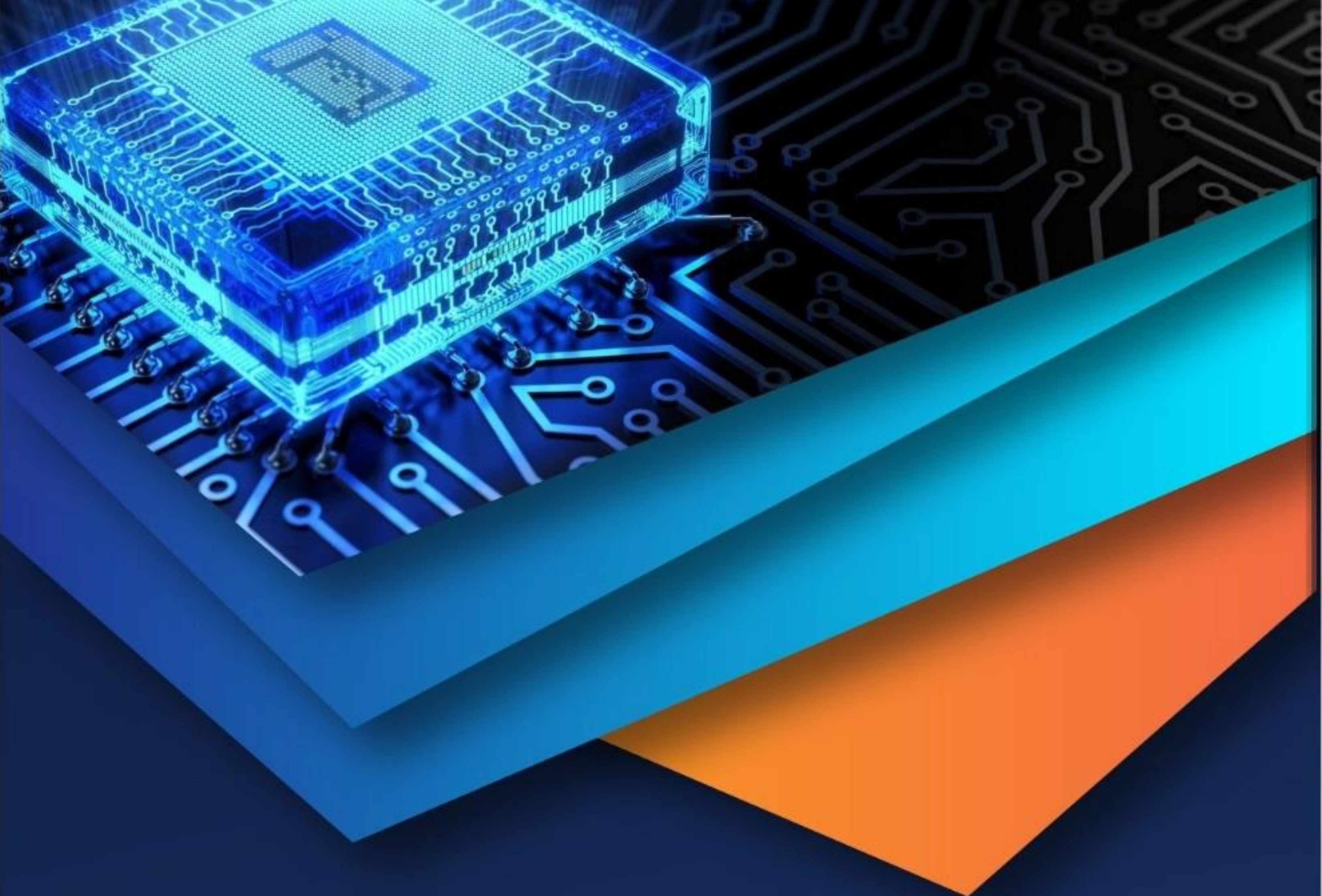


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