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SECTION 2. Applied mathematics. Mathematical modeling.

NUMERICAL ANALYSIS OF ENTROPY GENERATION AND PRESSURE DROP PERFORMANCE OF PHASE CHANGE MATERIAL SLURRIES IN MICROCHANNELS OF HIGH HEAT GENERATING ELECTRONIC DEVICES

Abstract: *This numerical study investigates the effect of using phase change material slurries (PCMs) on the hydraulic performance of microchannel. The phase change material slurries composed of Dodecanoic acid (PCM nanoparticles) in water (carrier fluid) which is introduced into a rectangular microchannel 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/m2 and PCM nano-particles volume concentration (0-25%), results showed a remarkable increase in the effectiveness ratio, pressure drop, pumping power and entropy generation. Effectiveness index is used to measure the effectiveness of PCM slurries.*

Key words: *Microchannel, Phase Change Material, PCM Slurry, Pressure Drop, Entropy Generation*

Language: *English*

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INTRODUCTION

Many methods for cooling of small scale heat generating devices have been presented in previous few years [1]. 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 [1-11]. The 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 and entropy generation [2].

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 [3].

The work presented in this paper is performed for 2D study of microchannel with Dodecanoic acid nanoparticles, having melting range of 316.7-317.7K and inlet temperature 315K in carrier fluid (water) on different operating conditions [1]. The present work takes into account the enhancement in pressure drop, pumping power and entropy generation with increasing Dodecanoic acid particles in carrier fluid (water). Table 1 summarize the properties of the PCM Nanoparticles [4]

Table 1

Physical Properties of Dodecanoic acid [4]

Dodecanoic 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

Materials and methods

Fig.1 shows the schematic diagram of microchannel used in this study. In this study a microchannel of fixed height (H)100μm and length (L) 10mm is defined in ANSYS-FLUENT 15.0. For three-dimensional study the width (W) of the channel is considered to be 1mm. PCM slurry introduced to the inlet of microchannel at mass flow rate of 1x10^{-4} kg/s and inlet temperature of 315K below the melting temperature (317.2 K) of PCM nano-particles. At outlet of microchannel the pressure of 1atm is assumed. A constant heat flux of 0.7MW/m^2 is generated at the bottom wall of microchannel which heats the PCM slurry flowing in microchannel.

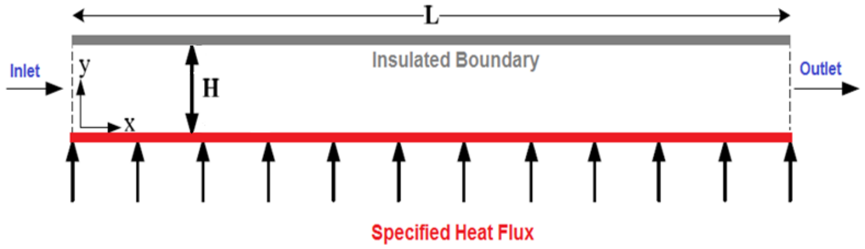

Figure 1- Schematic of microchannel used in this study. [1]

Assumption:

- PCM slurry flowing inside the microchannel is steady, viscos, incompressible and laminar [1].
- Physical properties (density, viscosity, specific heat capacity, thermal conductivity) of carrier fluid (water) are temperature dependent [3].
- PCM slurry physical properties are function of particles volume concentration and temperature dependent [3].
- Shell encapsulating nanoparticles has no effect of PCM slurry performance [5].
- The carrier fluid and PCM particles are flowing with same temperature and velocity [5].
- Homogenous distribution of Nanoparticles are assumed [5].
- When PCM particles reached the melting temperature range, they melts instantly [5].

Governing Equations

Energy, Momentum and Mass governing equations are solved simultaneously using temperature dependent physical properties of PCM slurries given 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]

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

Temperature Dependent Physical Properties of PCM Slurry

1) *Density: Density of* PCM slurry (pcms) is calculated as [3]

$$\rho_{pcms}=c\rho_{p}+\left(1-c\right)\rho_{cf}$$

2) *Specific Heat Capacity:* Melting temperature of 317.2K and melting range of 316.7-317.7K for Dodecanoic acid nano-particles is assumed in this study [1]. Specific heat capacity of PCM slurry (pcms) is calculated as [3-4]

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

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

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

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

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

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

3) *Viscosity:* The viscosity of PCM slurry increases with the addition of PCM particles, which is calculated as [12]

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

4) *Thermal Conductivity:* Thermal conductivity of PCM slurry (pcms) is calculated as [13]

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

Numerical Method

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

Grid Independence Test

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

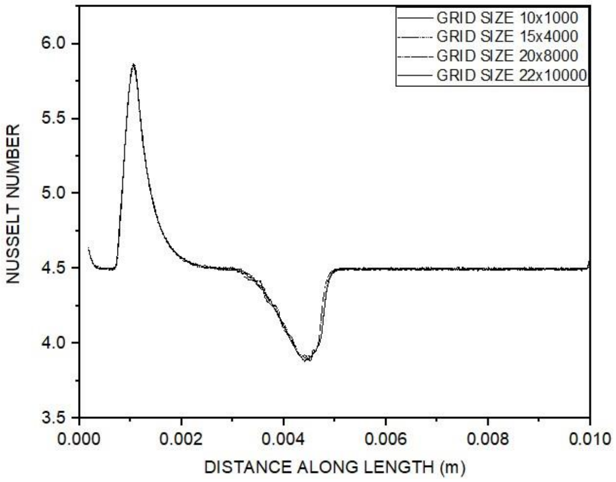

Figure 2 - Grid independence test

Significance of Temperature Dependent Properties

Temperature dependent physical properties for carrier fluid (water) are used in this study. Importance of using temperature dependent physical properties rather than constant temperature physical properties is shown in Table 2 [3]. The percentage 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 2, the simulations are performed with temperature dependent physical properties.

Table 2

Significance of Temperature dependent physical properties [3]

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					

Model Validation with Experimental Work

Due to absence of experimental data of flow of PCM slurries in microchannels, experimental data presented in [6], 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 [6]. The results of wall temperature along the pipe length obtained from numerical model were compared with the experimental results of [6] 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 [6]

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

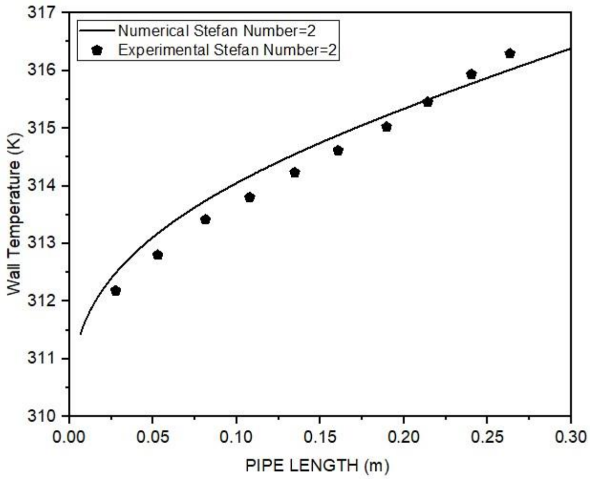

Figure 3 - Comparison of homogenous numerical model with experimental data

Results and Discussions

Effectiveness ratio

Effectiveness ratio measures the relative enhancement in heat transfer by adding PCM particles in carrier fluid (water) compared to using water only, defined as [1]

$$\varepsilon_{ff} = \frac{Q_{pcms}}{Q_{cf}}$$

Where, Q_{pcms} and Q_{cf} are PCM slurry and carrier fluid heat transfers respectively.

$$Q_{pcms} = Length \times Width \times q''$$

$$Q_{cf} = mc_{pcf} \Delta T_{cf}$$

Fig.4 shows the effectiveness ratio 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 results show that effectiveness ratio increased by increasing PCM particle volume concentration, but not going up with the addition of PCM particles. As relative percentage increase of 13% in effectiveness ratio is recorded for 5% PCM slurry compared to 0% PCM slurry, where the relative percentage increase of 8% in effectiveness ratio is recorded for 25% PCM slurry compared to 20% PCM slurry. This is because with the addition of PCM particles the viscosity of the fluid increases and slows down the fluid flow [1]. The effectiveness ratio of 1.13, 1.24, 1.34, 1.44 and 1.52 is recorded for 5%, 10%, 15%, 20% and 25% Particle volume concentration. This means that for the same temperature rise, 5%, 10%, 15%, 20% and 25% PCM slurry can store up to 13%, 24%, 34%, 44% and 52% more heat respectively, as compared to 0% PCM slurry (water).

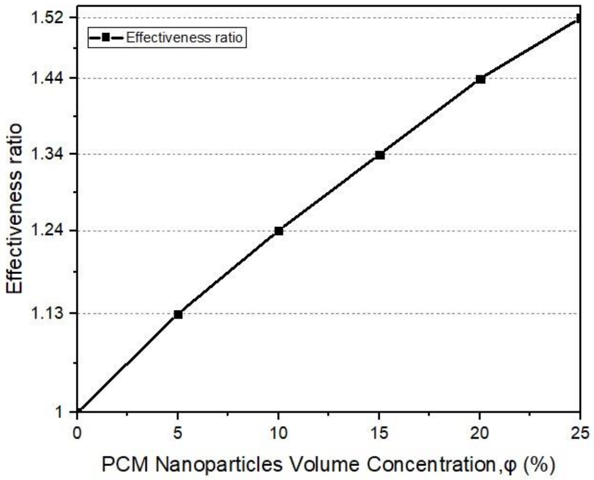

Figure 4 - Effectiveness ratio as a function of particle volume concentration (0-25%)

Enhancement in Pumping Power

Pumping power measures the power required to pump the coolant in microchannel, defined as

$$PP = VA_{flow}\Delta P$$

Fig.5 shows the Pumping power 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. Addition of PCM particles in carrier fluid increase the heat transfer coefficient and reduce the wall temperature in turn improves the performance of microchannel and helps in effective heat removal but drawback of using PCM particles in carrier fluid is that with the addition of PCM particles viscosity of slurry increases and rise the pressure drop [1-3], as shown in Fig 5, which in turn increase the pumping power demands. It is observed that the pumping power is increased by 42%, 68%, 102%, 150% and 197% for 5%, 10%, 15%, 20% and 25% PCM slurry respectively, as compared to water (0% PCM slurry).

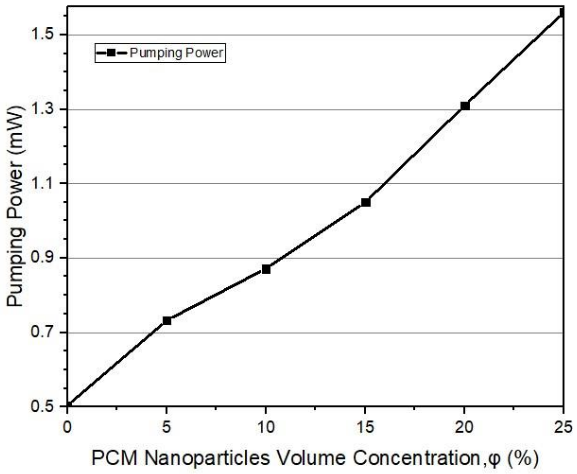

Figure 5 - Pumping power as function of particle volume concentration (0-25%)

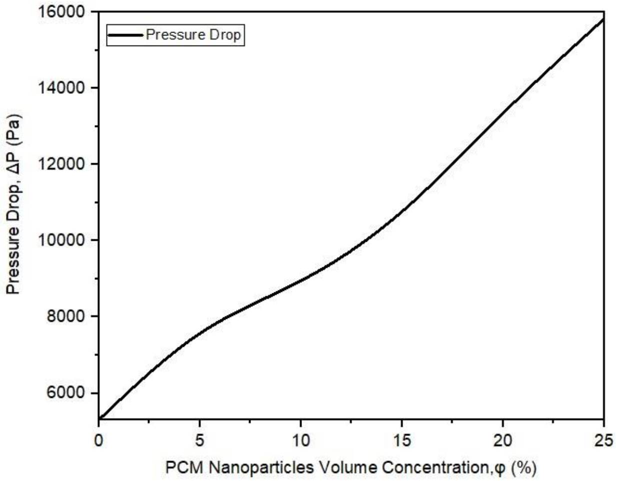

Figure 6 - Pressure drop as function of particle volume concentration (0-25%) at inlet temperature=315K , mass flow rate=1x10^{-4} kg/s, heat flux= 0.7 MW/m^2

Volumetric Entropy Generation Rate due to Heat Transfer

The volumetric entropy generation rate due to heat transfer is defined as [4]

$$S'''_{generation\_heat\_transfer} = \frac{k_{pcms}}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right]$$

Fig.7 shows the volumetric entropy generation rate due to heat transfer 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.We observed that addition of PCM nano-particles decreases the mean flow temperature of PCM slurry, decreases the thermal conductivity of PCM slurry and increases the temperature gradient along height which leads to increase volumetric entropy generation rate due to heat transfer [4]. It is found that the volumetric entropy generation rate due to heat transfer is increased by 7%, 11%, 15%, 19% and 21% for 5%, 10%, 15%, 20% and 25% PCM slurry respectively, as compared to water (0% PCM slurry).

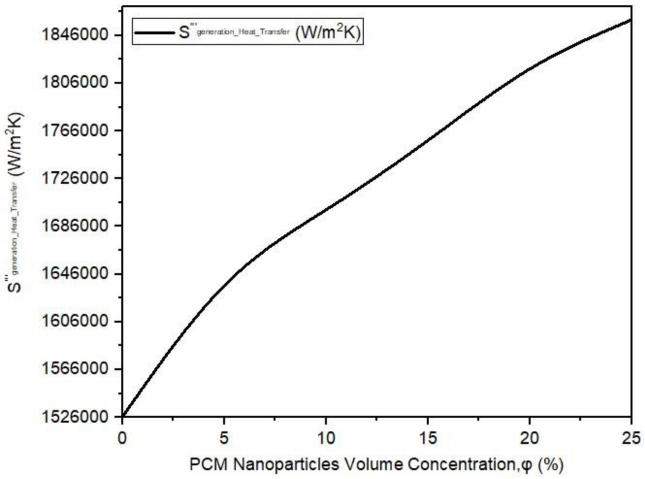

Figure 7 - Volumetric entropy generation rate due to heat transfer as a function of particle volume concentration (0-25%)

Volumetric Entropy Generation Rate due to Fluid Friction

The volumetric entropy generation rate due to fluid friction is defined as [4]

$$S'''_{generation\_fluid\_friction} = \frac{\mu_{pcms}}{T}\left(\frac{\partial u}{\partial y}\right)^2$$

Fig.8 shows the volumetric entropy generation rate due to fluid friction 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.Addition of PCM particles reduces the mean flow temperature and increases the viscosity which leads to increase volumetric entropy generation rate due to fluid friction [4]. It is found that the volumetric entropy generation rate due to fluid friction is increased by 12%, 34%, 63%, 104% and 143% for 5%, 10%, 15%, 20% and 25% PCM slurry respectively, as compared to water (0% PCM slurry).

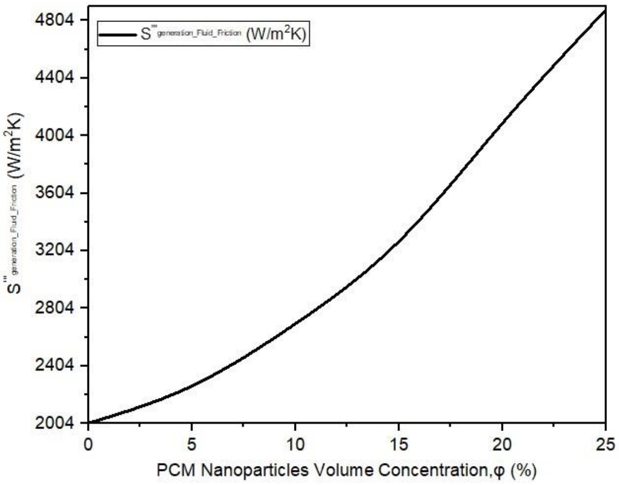

Figure 8 - shows the volumetric entropy generation rate due to fluid friction as a function of particle volume concentration (0-25%)

Effectiveness Index

Effectiveness index is ratio of enhancement in heat transfer to increase in pumping power due to the addition of PCM particles in carrier fluid, defined as

Effectiveness index=

$$\frac{Eff_{pcms}-Eff_{water}}{Eff_{water}} / \frac{PP_{pcms}-PP_{water}}{PP_{water}}$$

Fig. 9 shows effectiveness index 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 effectiveness index increases by increasing PCM particle volume concentration below 11% after 11% the effectiveness index decreases. This is because with the addition of PCM particles the viscosity of the PCM slurry increases which in turn increase the pumping power requirement and gain in effectiveness is compensated by demands of pumping power. The highest effectiveness index of 0.36 is recorded for Particle volume concentration of 11%.

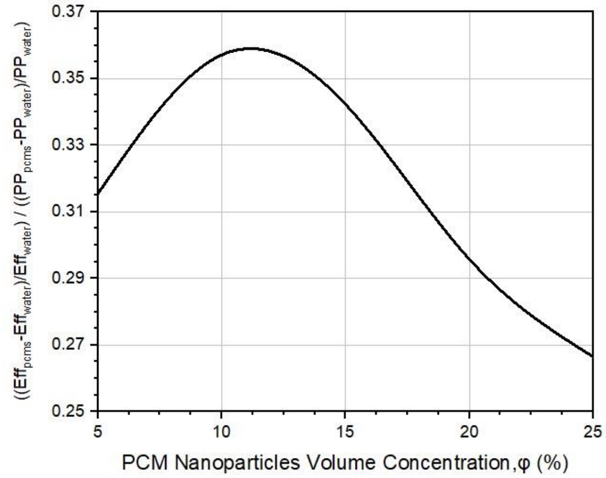

Figure 9 - Effectiveness index as a function of particle volume concentration (0-25%)

Conclusion

Numerical model investigated the effect of using phase change material slurries (PCMs) on the hydraulic performance of microchannel used for cooling of high heat generating small scale devices. Under specific conditions including mass flow rate $1x10^{-4}$ kg/s, heat flux $0.7MW/m^2$, inlet temperature of 315K and PCM nano-particles volume concentration (0-25%).It is found that for the same temperature rise, 25% PCM slurry can store up to 52% more heat as compared to 0% PCM slurry (water). The maximum relative increase of 197%, 21% and 143% in pumping power, volumetric entropy generation rate due to heat transfer and volumetric entropy generation rate due to fluid friction respectively is recorded for 25% PCM slurry, as compared to water (0% PCM slurry). The maximum effectiveness index of 0.36 is recorded for 11% PCM slurry. This means that 11% PCM slurry stores more heat with less pressure drop along the microchannel as compared to other slurries.

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References:

1. Awad B.S. Alquaity, Salem A. Al-Dini, Evelyn N. Wang, Bekir S. Yilbas (2012) “Numerical investigation of liquid flow with phase change nanoparticles in microchannels” International Journal of Heat and Fluid Flow 38, pp. 159–167, Nov. 2012.
2. Lalit Roy, M. A. R. Sharif (2017) “Numerical analysis of electronic substrate cooling by pumping nanoencapsulated phase change material slurry through micro-channels etched on the substrate” AIP Conference Proceedings 1851, 020028, 2017.
3. Rami Sabbah, Mohammad M. Farid, Said Al-Hallaj (2008) “Micro-channel heat sink with slurry of water with micro-encapsulated phase change material: 3D-numerical study” Applied Thermal Engineering, pp. 445–454, Mar. 2008 .
4. Awad B.S. Alquaity, Salem A. Al-Dini, B. S. Yilbas (2012) “Entropy generation rate in microchannel flow with phase change particles” Journal of Thermophysics and Heat Transfer, Vol. 26, pp. 134-140, 2012.
5. Kuravi, S., Kota, K.M., Du, J., Chow, L.C. (2009) “Numerical Investigation of Flow and Heat Transfer Performance of Nano-Encapsulated Phase Change Material Slurry in Microchannels” Journal of Heat Transfer, pp. 62901–62907, Mar. 2009.
6. Manish Goel, S. K Roy, S. Sengupta (1994) “Laminar forced convection heat transfer in microencapsulated Phase Change Material suspension” Int. J. Heat Mass Trasfer, vol. 37,pp.1593-604, 1994.
7. Binjiao Chen, Xin Wang, Ruolang Zeng, Yinping Zhang, Xichun Wang, Jianlei Niu, Yi Li, Hongfa Di (2008) “An experimental study of convective heat transfer with microencapsulated phase change material suspension: Laminar flow in a circular tube under constant heat flux ” Experimental Thermal and Fluid Science 32, pp. 1638–1646, May 2008.
8. Roy, S.K., Avanic, B.L. (1997) “Laminar forced convection heat transfer with phase change material emulsions” Int. Commun. Heat Mass Transfer 24, pp. 653–662, 1997.
9. Xing, K.Q., Tao, Y.X., Hao, Y.L. (2005) “Performance evaluation of liquid flow with PCM particles in microchannels” J. Heat Transfer 127,pp. 931–940, 2005.
10. Yutang Fang, Shengyan Kuang, Xuenong Gao and Zhengguo Zhang (2009) “Preparation of nanoencapsulated phase change material as latent functionally thermal fluid” J. Phys. D: Appl. Phys. 42, pp. 035407 (8pp), 2009.
11. Satyanarayana Kondle, Jorge L. Alvarado, Charles Marsh (2013) “Laminar Flow Forced Convection Heat Transfer Behavior of a Phase Change Material Fluid in Microchannels” Journal of Heat Transfer, pp. 052801,1-052801,11, 2013.
12. Vand, V. (1945) Theory of viscosity of concentrated suspensions. Nature (London) 155, pp. 364–365, 1945.
13. Maxwell, J.C. (1954) A Treatise on Electricity and Magnetism, third ed. Dover, New York, vol. 1, pp. 440–441, 1954.