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Numerically Investigation on Heat Transfer and Pressure Drop Behavior of MWCNT Nanofluid in MCHS

Sushil Kumar Singh[1]*, Harkirat Sandhu[2] and Gurpreet Singh Sokhal[1]

[1]Mechanical Department, Chandigarh University, Mohali – 140413, Punjab, India;
Sushilsingh782@yahoo.in, singh.gurpreet@thaper.edu
[2]Chemical Department, Chandigarh University, Mohali – 140413, Punjab, India;
harkiratsandhu86@gmail.com

Abstract

Background/Objectives: To find the best method for nanofluid stability or increment in heat transfer enhancement and terminating pressure drop. **Methods/Statistical analysis:** Nanofluids have big problem regarding its own preparation or stability. Here is details which can prevent both of problem. This paper based on a work which is able to prevent nanofluids stability problem or pressure drop problem in MCHS. **Findings:** MCHS vary from 2 cm to several feet or meter because its depends on the requirement of work. The design procedure is complex because of its diameter vary in micro-meter, but it can be designed for our requirement easily. Traditionally we utilized water, ethylene-glycol & some special kind of oils. But, with the large demand in obligation of working efficiency nanofluids were produced which are colloidal mixture of base fluid with nanoparticles. Nanofluids have truly developed the heat transfer characteristics of base fluids & hence are great base to overall working efficiency of the system. But along with advantages it also has quite a few disadvantages to which are stability, limitation to the volumetric concentration addition process of manufacturing and most of all economics of production. **Improvements/Applications:** They can also be used for wide range of applications such as in the chemical industry, food processing industry, refrigeration industry, computer technology industry, automobile industry, aerospace industry, power plant, mechanical industry etc.

Keywords: Heat Transfer, Micro Channel Heat Sink, Pressure Drop, MWCNT'S

1. Introduction

Minimizing of electronic devices has become importance of today worlds. In last two periods researcher devoted countless efforts in developing or minimized micro devices. Reducing size of devise caused increment in the heat flux density which causes overheating of devices became big challenge for researchers. Here is a necessary to grow high performance cooling technology and heat discharge process which is meet our current requirements for secure, safety and stable operation for Micro-Electro Mechanical System (MEMS)[1–4].

The easy preparations basically used to this effect are microchannel. In microchannels fluids can used to carry remove heat from the small hot surface by forcefully through it passages consuming hydraulic diameters vary between 10 μm to 200 μm. Microchannel has high heat transfer surface area compare than fluid volume ratio, so it gives high heat transfer coefficient for convective heat transfer. But, this thick channel faced very high pressure drops[5–11].

From the time when the pioneer effort by Tuckerman and Pease the microchannel heat sink has usual wide-ranging study because of its capabilities to drive away big quantity of heat from major area[12–14].

Mostly used coolants are air, water, and floro chemicals. Recent interest as well mine based on this concept which is dedicated on heat transfer enrichment using Nano fluid in which Nano scale size base fluid by appropriate dispersion agent. There has be located some inves-

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**Author for correspondence*

tigation on Nano fluid flow and heat transfer method for pure fluid and traditional fluid [6,7,15].

Researchers noted that by way of the hydraulic diameter of the channel drops cause increase in heat transfer coefficient. This landmark work paved the door for further research in the area of microchannels heat transfer. There subsequently lot of hard work have been added in improving the heat transfer abilities concluded microchannel heat sinks for eliminating heat produced by electronic chips. Heat transfer competences of these fluids are having limitations due to fluctuating transport properties. In micro channels, comparatively air has been used to cool electronic gears. However, when heat fluxes going further than 100 W/cm^2, air cooling system approaches have become insufficient for maximum applications then liquid cooling achieves better[16–20].

Microchannel is a narrow grove passage made for the fluid to flow through it. In today's era microchannel is being widely used in the following are: heat exchanger devices, micro-fluidic devices. Cooling components, heat sink, etc. these are some major areas where microchannel is rummage-sale to expand the rate of heat transfer by minimizing the pressure drop. There are various profiles and shape of microchannel. The various profile includes linear, array of linear, serpentine, fractal, P, S, U type etc. The shape of microchannel includes rectangular, triangular, square, semi-circular, trapezoidal, etc. By using the microchannel the rate off heat transfer can be augmented thus reducing the energy consumption and significantly improve environmental performance[21,22].

All of this has been made possible by increasing understanding of laws of physics governing the universe. Then the next step was to make certain theories and mathematical equations that summarize those theories. This led to the formulation of most significant law the law of conservation of mass and energy. This tells us that both mass and energy that exists can neither be created nor be destroyed but can only be converted from one form to another. It's the significance of this law which became the base of evolution of our civilization[23,24].

But heat generation is not always fruitful especially if its unwanted or being wasted during transition through space or matter. So far to understand these situations and conditions in better and efficient way a new primary field is required i.e. Thermal Management[25,26].

So, the next development stage was introduction of Nano sized particles in base of fluid. These additives are called Nano particles and together they are called Nano-fluids i.e. those fluids with Nano-particles. This greatly enhanced the heat transfer capabilities. The motive of this rises are the overall increase in thermal conductivity of fluids because of these solid Nano-particles in them. Some of these nano-particles are as follows: metal oxides, such as Al_2O_3, CuO, TiO_2, Fe_2O_3 etc. Usually, we prefer metal oxides over others because of their low cost as compared to metals, also they are easily available naturally as oxides already but some of researcher tries to test different nano particles like carbon nano tubes. The nano -fluids are applicable in many areas like electronics, power generation, automotive, air-conditioners and nuclear power plants[27–35].

Nano fluids can be employed in almost any field where heat transfer is involved. But, while selecting the field of experiments we do need to consider the cost of final setup of the system. Since, the manufacturing of nanofluids is very difficult and expansive. To understand this let us take a look at manufacturing process[36–40].

2. Computational Model

2.1 Geometry of the Problem

The experimental study on microchannel in collected works was inspired in this work so to authenticate the suggested numerical method with the investigational and numerical data of works. The geometry shown in Figures 1,2, the material used in microchannel heat sink is aluminium. The microchannel heat sink has 20 channels;

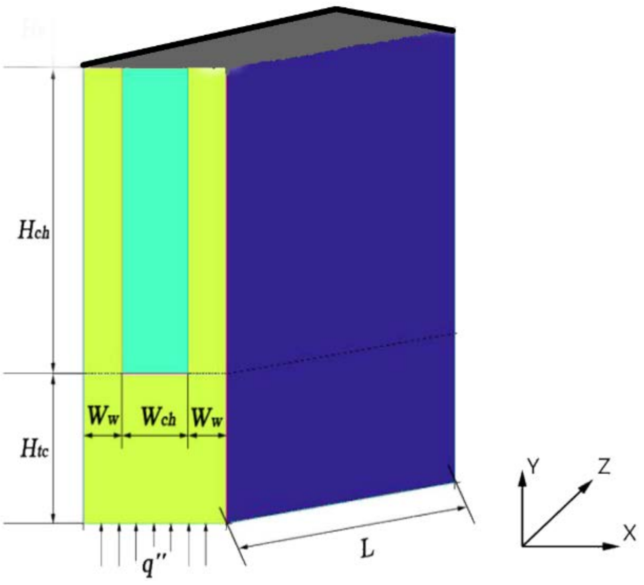

Figure 1. Schematic diagram for one channel.

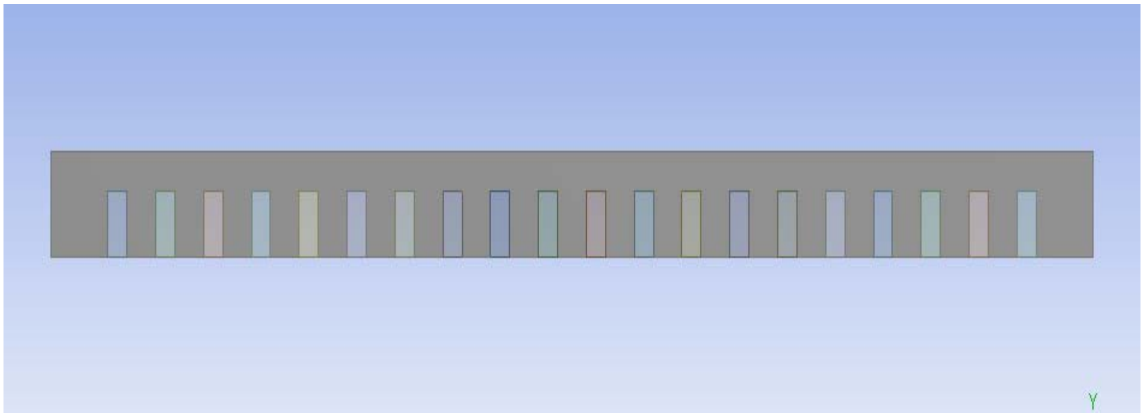

Figure 2. Front section of geometry.

the width of micro channel heat sink is 5450 μm, and the height of microchannel heat sink is 400 μm, and the length of microchannel heat sink is 40000 μm. Now, width of channels is 100 μm, and height of the channel is 250 μm and distances between two channels are 150 μm. A constant heat flux *q*” applied on the bottom surface of microchannel heat sink is 6.54 W, and rest of walls are assumed insulated[10,17,23].

Flow is laminar flow because of the Reynolds number less than 100. Whole geometry shows in Figure 2.

2.2 Governing Equation

In case to observe the effect of nanofluids operation in the MCHS cooling performance, expectations parameters are completed[10,17,20,23,25,27,28].

The continuity, momentum and energy equations for the current problems written as:

Continuity:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}+\frac{\partial W}{\partial Z}=0 \tag{1}$$

X-momentum:

$$(U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}+W\frac{\partial U}{\partial Z}=-\frac{dP}{dX}+\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right) \tag{2}$$

Y-momentum:

$$(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}+W\frac{\partial V}{\partial Z}=-\frac{dP}{dY}+\frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Z^2}\right) \tag{3}$$

Z-momentum:

$$(U\frac{\partial W}{\partial X}+V\frac{\partial W}{\partial Y}+W\frac{\partial W}{\partial Z}=-\frac{dP}{dX}+\frac{1}{Re}\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right) \tag{4}$$

Energy:

$$(U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}+W\frac{\partial \theta}{\partial Z}=\frac{1}{Re.Pr}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}+\frac{\partial^2 \theta}{\partial Z^2}\right) \qquad 5)$$

The Dimensionless parameters are:

$$X=\frac{x}{D_h},Y=\frac{y}{D_h},Z=\frac{z}{D_h},U=\frac{u}{u_{in}},V=\frac{v}{u_{in}},and\,W=\frac{w}{u_{in}} \tag{6}$$

2.3 Boundary Conditions

Boundary conditions are simply a quantified for simulations dormant at the microchannel inlet section, the inlet temperature are taken at 25° C and the inlet fluid velocities are calculated by the help of mass flow rate. The fluid distributed equally in all microchannels. The heat flux which is applied on the bottom of surface is 6.54 watt and rest of all wall assumed as slip boundary.

2.4 Thermal Physical Properties

Thermal conductivity by Hamilton and Crosser model in Table 1:

$$k_{nf}=\frac{k_{eff}}{k_m}=\frac{\alpha+(n-1)-(n-1)(1-\alpha)*\varphi}{\alpha+(n-1)+(1-\alpha)*\varphi} \tag{7}$$

where, $$\alpha = \frac{k_p}{k_m} \tag{8}$$

kp = Thermal conductivity of solid particles
km = Thermal conductivity of liquid medium
keff = Effective thermal conductivity of slurry
ϕ = Particle volume fraction
n = Shape factor [for sphere = 3, for cylinder = 6]

Einstein with an assumption of particle volume fraction less than 1 %.

$$\mu_r = (1 + 2.5\phi) \tag{9}$$

where, μ_r is the relative viscosity which is the ratio of the nanofluids viscosity μ_n to the base fluid viscosity μ_{bf} and ϕ is the volume fraction of nanoparticles in base fluid.

$$\rho_{nf} = \rho_p \varphi + \rho_{bf}(1-\varphi) \tag{10}$$

where, ρnf is the density of nanofluids, ρbf is the density of base fluids, ρp is the density of nanoparticles used, and ϕ is the volumetric concentration of nanoparticles.

Most of the researchers preferred to use mixture model based on mass fraction basis to calculate specific heat of nanofluids which can be represented as

$$c_{pnf} = \frac{\varphi(\rho c_p)_p + (1-\varphi)(\rho c_p)_{bf}}{\rho_{nf}} \tag{11}$$

3. Numerical Methods

The simulation analysis is approved by the resolving of governing equation lengthwise with the boundary condition solid and fluid phases are calculated by conjugate heat transfer problem finite volume method (FVM) shown in Figure 3 was used in discretization of governing equation for the fluid and solid region[10,17] the numerical model was design in physical domain or dimension-less factor was calculated by the help of calculated velocity and 25^0 inlet temperature. Where the simulation is prepared by assuming the area of pressure and Momentum equation help to understand the velocity behavior and continuity equation help to understand the pressure updates. The distribution of orthogonal cells in computational modal was described from series of test and altered number of cells. $0.9{*}10^5$, $1.0{*}10^5$, $1.5{*}10^5$ Grids were used in independence test and best result occurs on $1.0{*}10^5$.

Table 1. Thermal Physical Properties for Water or MWCNT

Thermal Physical Properties for Water				
	Thermal Conductivity (W/m ° C)	**Density (Kg/m³)**	**Viscosity (Kg/m-s)**	**Specific Heat (J/Kg ° C)**
WATER	0.618	995.7	0.000798	4180.1
MWCNT 0.10%	0.621706	997.3043	0.0008	4171.132
MWCNT 1.00%	0.6554	1011.743	0.000818	4091.696

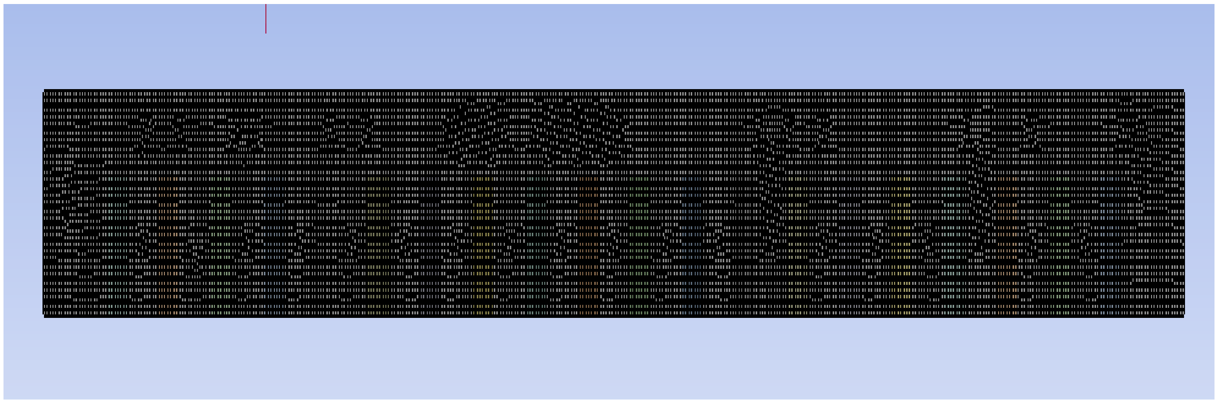

Figure 3. Front section meshing.

4. Results and Discussion

4.1 Temperature Profile

In the cases of microchannel heat sink study, the supreme temperature which is used to calculate the thermal resistance of MCHS engendered on bottom of the wall where heat flux applied and near the outlet region and less temperature occurs on the near of inlet region. Figures 4,5 represent the bottom wall temperature of MCHS[17,24,29,30].

The dimensionless temperature giving at each channel of MCHS at different flow rate for the various fluids with different inlet temperature are shown in Figures 6,7.

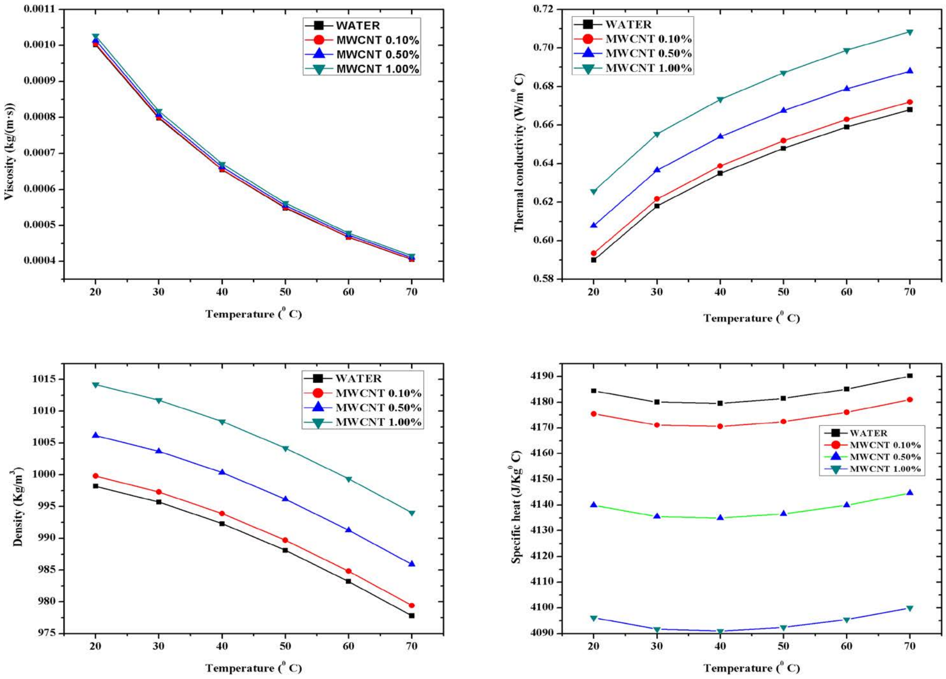

Figure 4. Thermal physical properties of water and multi wall carbon nanotube with volume concentration (ϕ= 0.1%, 1%) at different temperature.

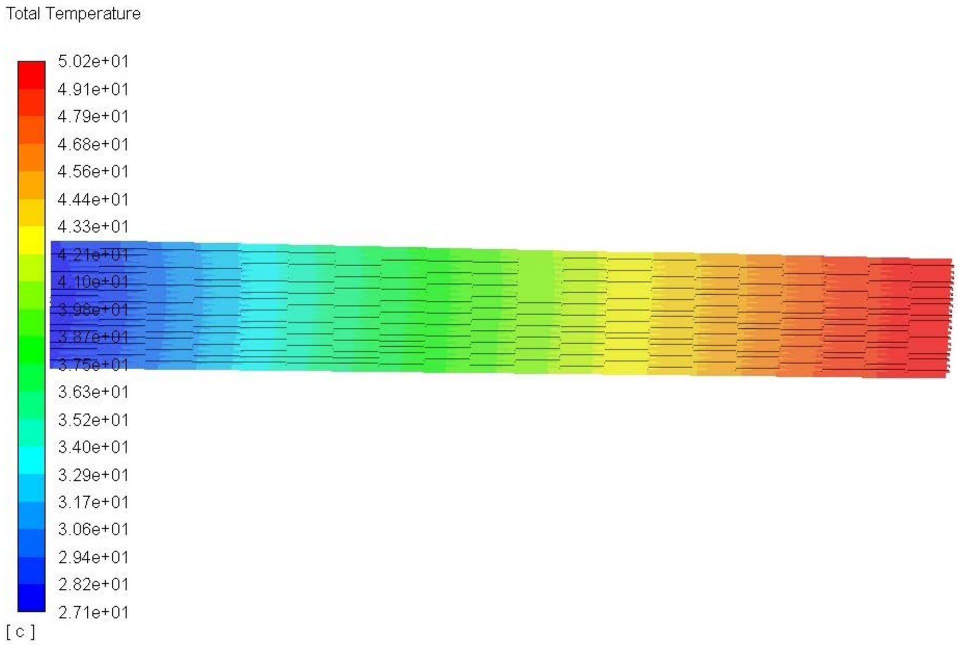

Figure 5. Temperature profile on the top plate of MCHS.

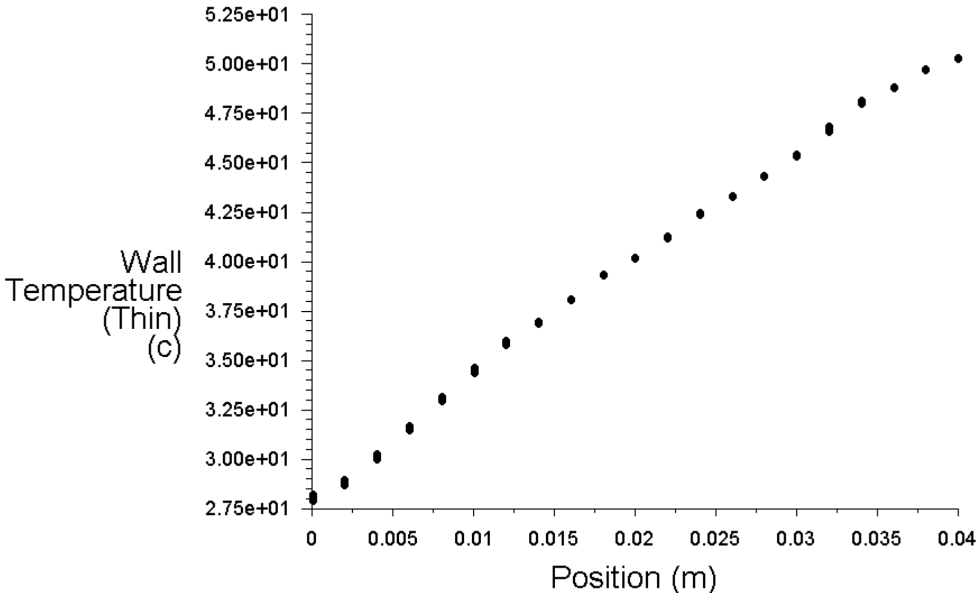

Figure 6. Dimension-less temperature along with the position for water.

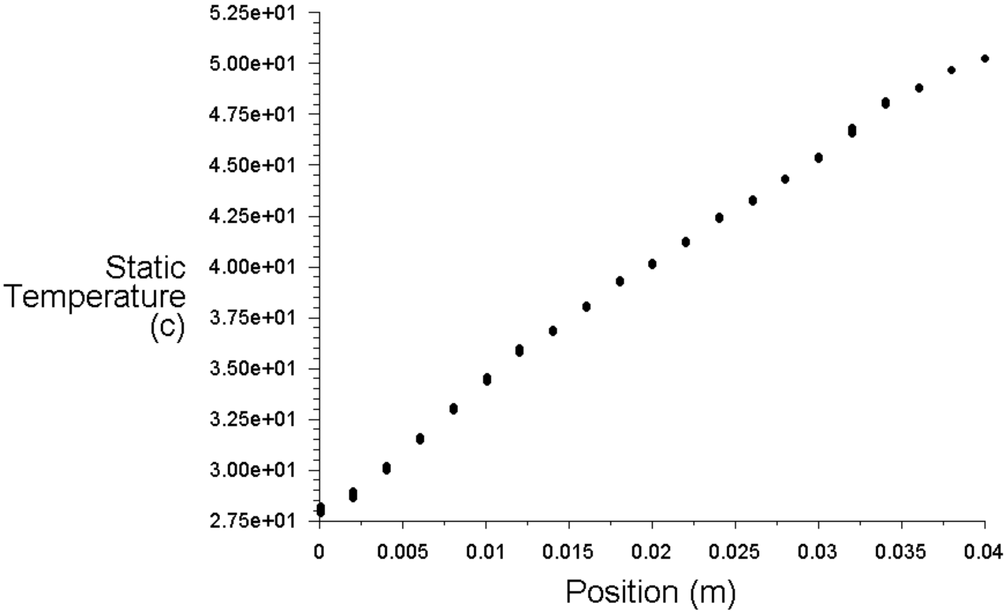

Figure 7. Dimension-less temperature along with the position for MWCNT 1%.

The dimension-less temperature can be defined as:

$$\theta = \frac{Tf - Ti}{Tw - Ti} \tag{12}$$

Where *Tf* indicates the fluid temperature, *Ti* indicates inlet temperature, and *Tw* indicates the wall temperature. Figure 6 Dimensionless temperature along with the position for water and Figure 7 Dimensionless temperature along with the position for MWCNT 1%. Therefore, in the existence of nanoparticles could increase cooling of MCHS under the high heat flux situation.

4.2 Pressure Drop

The pressure drop behavior is calculated by the help of this equation

$$\dot{P} = \frac{\Delta P}{\rho U_{in}^{2}} \qquad (13)$$

where, ΔP is the pressure drop which obtained from simulation, p is density and U_{in} is the inlet velocity.

The pressure circulation of the MCHS for water and nanofluid by the flow rate. It is shown in Figure 8, that increase in flow rate causes increase in pressure drop. This is for the reason that the investigational data is fully developed flow, but simulation data is in developing flow. The numerical results indicate that there is big pressure drop in developing flow shown in Figure 8. The numerical data of pressure drop seeing is in a decent promise than the experimental data. There is slitter change in water and

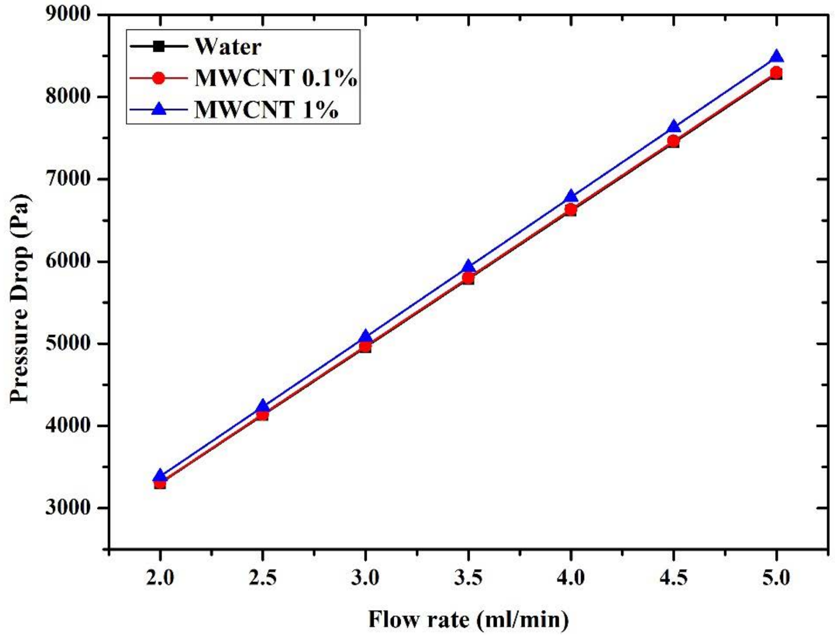

Figure 8. Dimension-less pressure drop variation versus Flow rate.

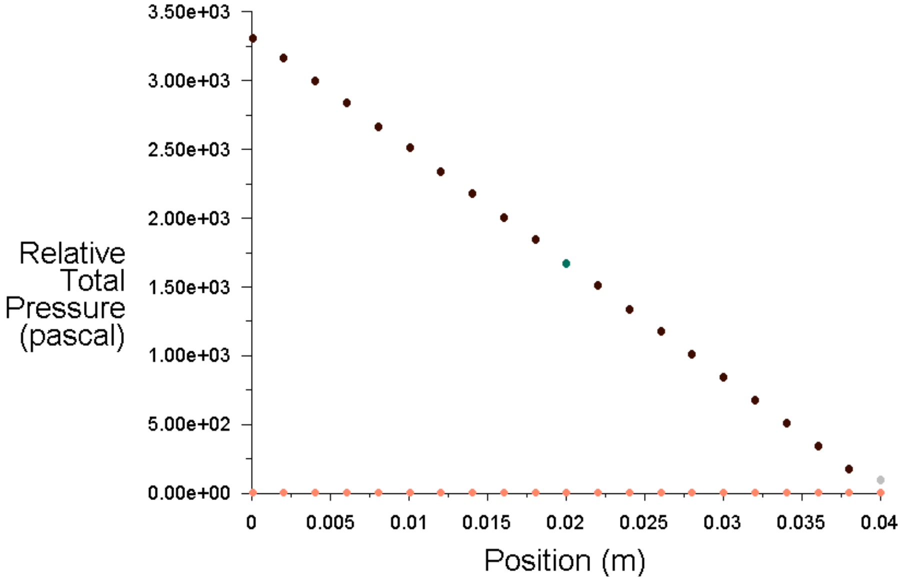

Figure 9. Dimension-less pressure along with the position for water.

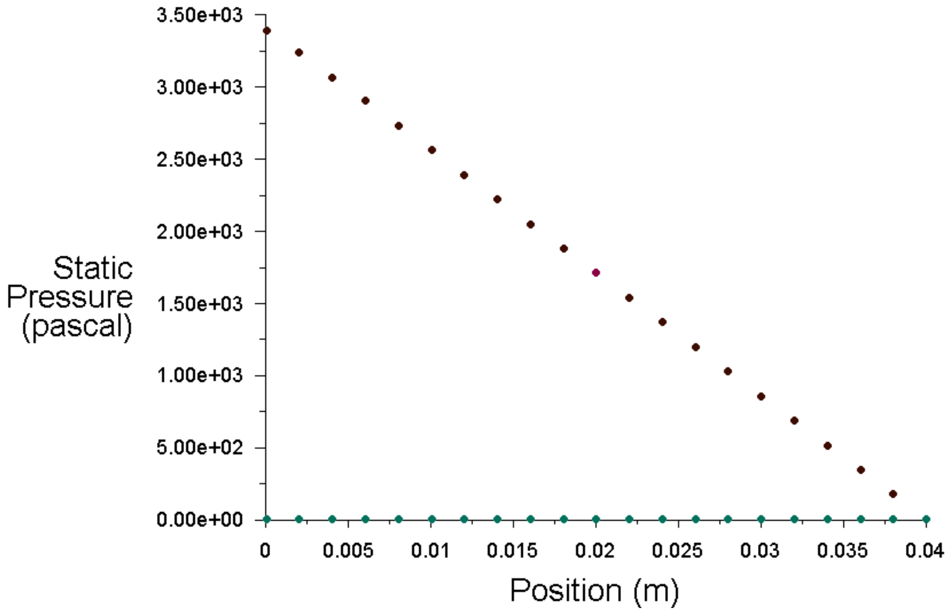

Figure 10. Dimension-less pressure along with position for MWCNT 1.00 %.

MWCNT 0.1% but compare to MWCNT1% its change. Figures 9,10 represent Dimensionless pressure along with the position for water and MWCNT 1%[17,24,29,30,38–40].

4.3 Heat Transfer Coefficient

The heat transfer enactment in rectangular MCHS using water and MWCNT as nanofluid at 0.1% & 1% volume concentration are analyzed by the outcome of heat transfer coefficient along the flow rate shown in Figure 11. It's that MWCNT nanofluid has more enhancement than water in cooling of MCHS. The water based nanofluid contain 0.1% and 1% MWCNT particles have higher heat transfer coefficient then the water. It is also noted that heat transfer coefficient decreasing along to the length or increasing with the Reynolds flow rate. Figure 12 represents Dimensionless Surface heat transfer coefficient along with the Position for water and Figure 13 represents Dimensionless Surface heat transfer coefficient along with the Position for MWCNT 1%.[1–3, 38–40]

$$h = \frac{q''}{\Delta T} \tag{14}$$

q'' is the heat flux which is acquired from the simulation results, ΔT is the (outlet temperature- inlet temperature). It is strong-minded that nanofluids could increase the heat transfer coefficient of MCHS as its volume concentration increases from 0.1% to 1%.

4.4 Friction Factor

Since the study of laminar fluid flow in MCHS has become more important than other aspects. The friction factor is calculated by Darcy equation is shown in Figure 14.

$$f = \frac{2Dh\Delta P}{\rho u^2 Lc} \tag{15}$$

where, D_h indicates hydraulic diameter, ΔP indicates the pressure drop which is obtained by simulation pressure (Pa), ρ is density of fluids, u_{in} is inlet velocity, Lc represent length of MCHS. The simulation indicates friction factor does not fluctuate with particle volume fraction but friction factor is decreasing with increasing in the Reynolds number[3-4,6,9,17,25,29,31,38–40].

5. Conclusion

In the case of nanofluids MWCNT has better properties then others, and the water is perfect base fluid in the case of nanofluids.

- This study has accomplished on MCHS's with MWCNT's to study the impact of the nanofluids on microchannels.
- The experiment is carried out at inlet temperature 25^0 C at MWCNT particle concentration 0.1% and 1%.

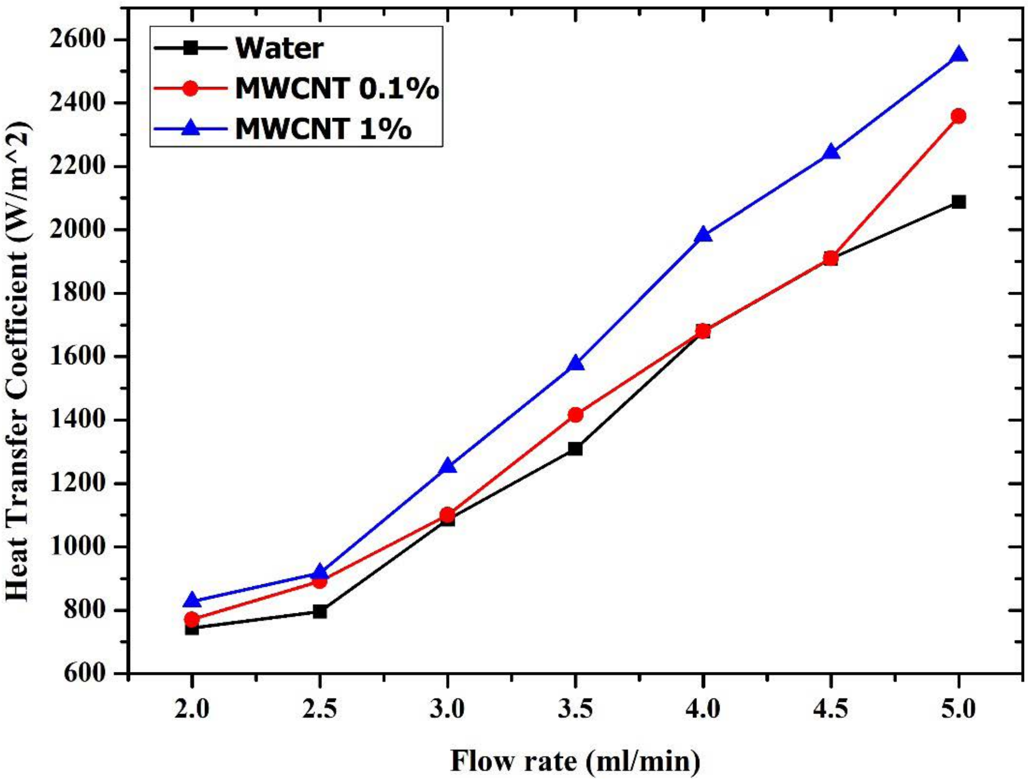

Figure 11. Dimension-less heat transfer coefficient for water and MWCNT's at 25^0 C temperature.

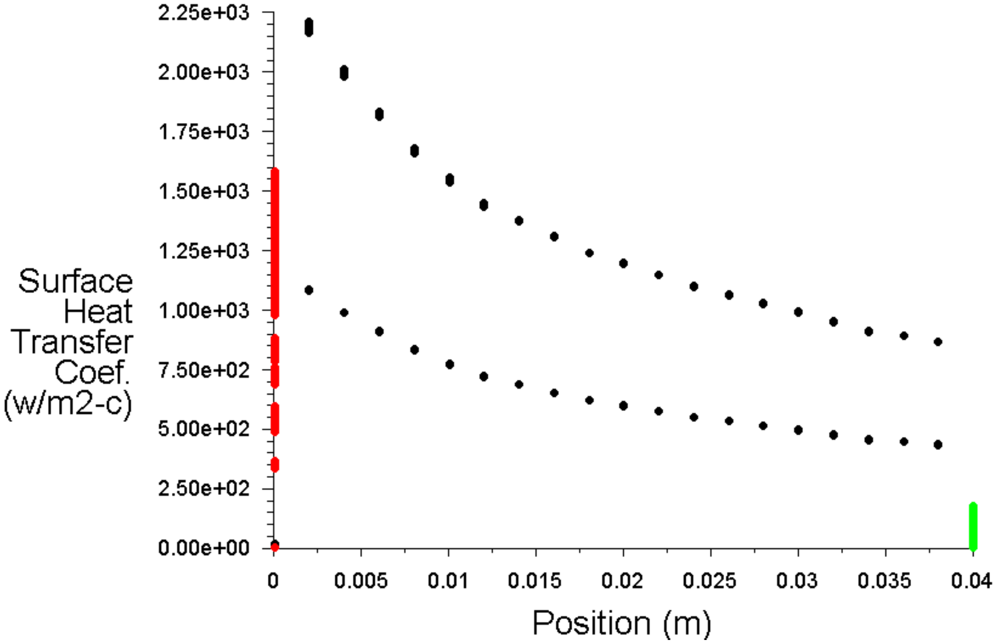

Figure 12. Dimension-less Surface heat transfer coefficient along with the Position for water.

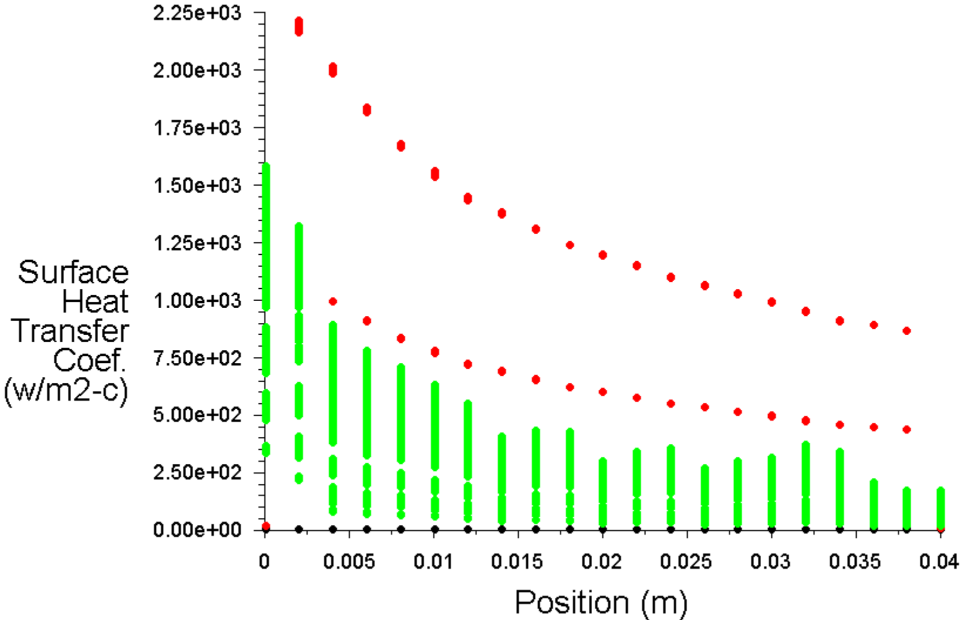

Figure 13. Dimension-less Surface heat transfer coefficient along with the Position for MWCNT 1%.

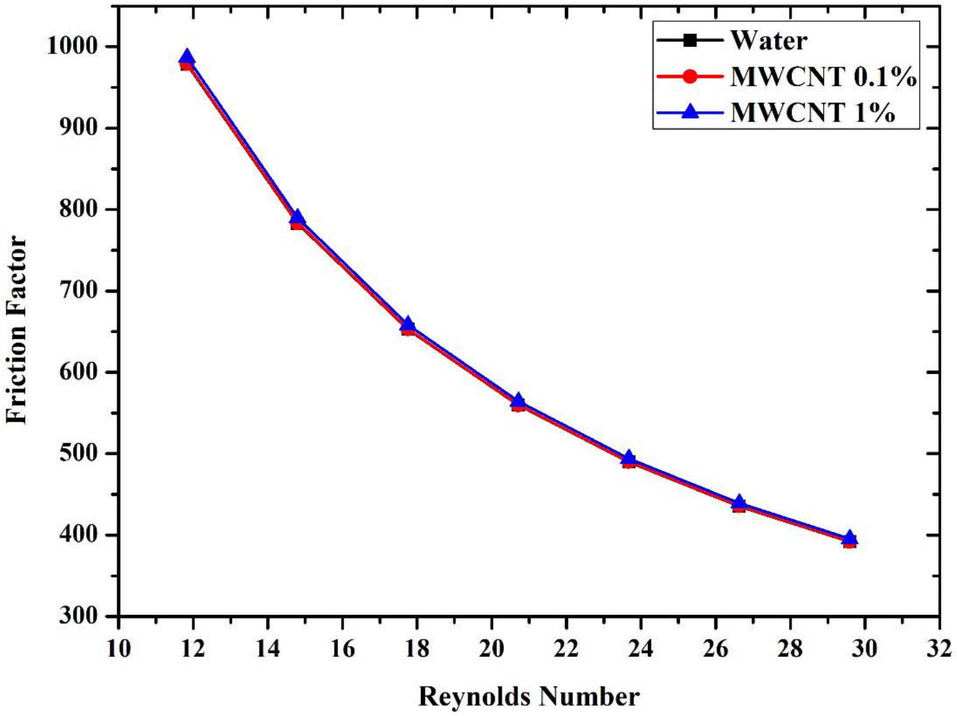

Figure 14. Variation between Friction factor and Reynolds number ranged from 10 to 30.

- The specific heat was noted to be incremented with rise temperature and further declines with rise in nanoparticle concentration.
- The density declines with rise in temperature with increasing nanoparticle concentration also increases.

Viscosity also increased with rise in temperature and decreases with an increment in MWCNT's concentration in nanofluids.

6. References

1. Wu J, Zhao J, Lei J, Liu B. Effectiveness of nanofluid on improving the performance of microchannel heat sink. Applied Thermal Engineering. 2016; 101:402–12. https://doi.org/10.1016/j.applthermaleng.2016.01.114
2. Manay E, Sahin B, Yilmaz M, Gelis K. Thermal performance analysis of nanofluids in microchannel heat sinks. World Academy of Science, Engineering and Technology. 2012; 6(7):87–92.
3. Mnădăş M, Manea A. Design and fabrication of the microchannels for microfluidics applications. UPB Scientific Bulletin, Series C. 2009; 71(4):1–10.
4. Harirchian T, Garimella SV. The critical role of channel cross-sectional area in microchannel flow boiling heat transfer. International Journal of Multiphase Flow. 2009; 35(10):904–13. https://doi.org/10.1016/j.ijmultiphaseflow.2009.06.005
5. Lajvardi M, Sabbaghzadeh J, Ebrahimi S, Hadi I. Analysis of microchannel heatsink performance using spherical nanofluids. 7th IEEE Conference on Nanotechnology (IEEE NANO); 2007. p. 541–4.
6. Jang SP, Choi SUS. Cooling performance of a microchannel heat sink with nanofluids. Applied Thermal Engineering. 2006; 26:2457–63. https://doi.org/10.1016/j.applthermaleng.2006.02.036
7. Koo J, Kleinstreuer C. Laminar nanofluid flow in microheat-sinks. International Journal of Heat and Mass Transfer. 2005, 48 (13):2652–61. https://doi.org/10.1016/j.ijheatmasstransfer.2005.01.029
8. Chein R, Huang G. Analysis of microchannel heat sink performance using nanofluids. Applied Thermal Engineering. 2005; 25(17):3104–14. https://doi.org/10.1016/j.applthermaleng.2005.03.008
9. Kandlikar SG. High flux heat removal with microchannels: A roadmap of challenges and opportunities. Heat Transfer Engineering. 2005; 26(8):5–14. https://doi.org/10.1080/01457630591003655 https://doi.org/10.1080/01457630490519772
10. Shi X, Li S, Wei Y, Gao J. Numerical investigation of laminar convective heat transfer and pressure drop of water-based Al2O3 nano fluids in a microchannel. International Communications in Heat and Mass. 2018; 90:111–20. https://doi.org/10.1016/j.icheatmasstransfer.2017.11.007
11. Wang H, Peterson RB. Performance enhancement of a thermally activated cooling system using microchannel heat exchangers. Applied Thermal Engineering. 2011. https://doi.org/10.1016/j.applthermaleng.2011.05.026
12. Mohammed HA, Bhaskaran G, Shuaib NH, Saidur R. Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids: A review. Renewable and Sustainable Energy Reviews. 2011; 15(3):1502–12. https://doi.org/10.1016/j.rser.2010.11.031
13. Farsad E, Abbasi SP, Zabihi MS, Sabbaghzadeh J. Numerical simulation of heat transfer in a micro channel heat sinks using nanofluids. Heat and Mass Transfer. 2011; 47(4):479–90. https://doi.org/10.1007/s00231-010-0735-y
14. Wang L, Wu J. Flow behavior in microchannel made of different materials with wall slip velocity and electro-viscous effects. Acta Mechanica Sinica. 2010; 26(1):73–80. https://doi.org/10.1007/s10409-009-0286-y
15. Wu X, Wu H, Cheng P. Pressure drop and heat transfer of Al2O3 -H2O nanofluids through silicon microchannels. Journal of Micromechanics and Micro engineering. 2009; 19:1–11. https://doi.org/10.1088/0960-1317/19/10/105020
16. Avsec J. Nanofluid and Ferrofluid Slip flow in rectangular and circular microchannels. 7th EUROMECH Solid Mechanics Conference; 2009. p. 1–3867.
17. Vageswar A. Extending flash thermography method for thermal diffusivity measurements using finite pulse widths. QIRT10, 10th International Conference on Quantitative InfraRed Thermography; 2010. p. 1–5. https://doi.org/10.21611/qirt.2010.142
18. Mohammed HA, Gunnasegaran P, Shuaib NH. Heat transfer in rectangular microchannels heat sink using nanofluids. International Communications in Heat and Mass Transfer. 2010; 37(10):1496–503. https://doi.org/10.1016/j.icheatmasstransfer.2010.08.020
19. Chein R, Chen J. Numerical study of the inlet / outlet arrangement effect on microchannel heat sink performance. International Journal of Thermal Sciences. 2009; 48(8):1627–38. https://doi.org/10.1016/j.ijthermalsci.2008.12.019
20. Gunnasegaran P, Mohammed H, Shuaib NH. Pressure drop and friction factor for different shapes of microchannels. 3rd International Conference on Energy and Environment (ICEE); 2009 Dec. p. 7–8. https://doi.org/10.1109/ICEENVIRON.2009.5398611
21. Chakraborty S. Numerical study of conjugate heat transfer in rectangular microchannel heat sink with Al2O3 / H2O nanofluid. Heat and Mass Transfer. 2009; 45(10):1323–33. https://doi.org/10.1007/s00231-009-0510-0
22. Shokouhmand H, Ghazvini M, Shabanian J. Performance analysis of using nanofluids in microchannel heat sink in different flow regimes and its simulation using artificial neural network. Proceedings of the World Congress on Engineering. 2008; 3:4–9.

23. Li J, Kleinstreuer C. Thermal performance of nanofluid flow in microchannels. International Journal of Heat and Fluid Flow. 2008; 29(4):1221–32. https://doi.org/10.1016/j.ijheatfluidflow.2008.01.005
24. Kamali R, Jalali Y, Binesh AR. Investigation of multiwall carbon nanotube-based nanofluid advantages in microchannel heat sinks. IET Micro and Nano Letters. 2013; 8(3):319–23. https://doi.org/10.1049/mnl.2012.0803
25. Wang X. Heat transfer enhancement in microchannel heat sinks using nanofluids. International Journal of Heat and Mass Transfer. 2012, 55 (9-10):2559-2570. https://doi.org/10.1016/j.ijheatmasstransfer.2012.01.004
26. Singh PK, Harikrishna PV, Sundararajan T, Das SK. Experimental and Numerical investigation into the heat transfer study of nanofluids in microchannel. Journal of Heat Transfer. 2011; 133(12):1–9. https://doi.org/10.1115/1.4004430
27. Seyf HR, Keshavarz S. Thermal and hydraulic performance of counterflow microchannel heat exchangers with and without nanofluids. Journal of Heat Transfer. 2011; 133(8):1–9. https://doi.org/10.1115/1.4003553
28. Hasan MI, Muhsin A, Rageb AR, Yaghoubi M. Investigation of a counter flow microchannel heat exchanger performance with using nanofluid as a coolant. Journal of Electronics Cooling and Thermal Control. 2012; 2:35–43. https://doi.org/10.4236/jectc.2012.23004
29. Solovitz SA, Mainka J. Manifold design for micro-channel cooling with uniform flow distribution. Journal of Fluids Engineering. 2014; 133(5):1–11.
30. Mohammed HA, Gunnasegaran P, Shuaib NH. The impact of various nanofluid types on triangular microchannels heat sink cooling performance. International Communications in Heat and Mass Transfer. 2011; 38(6):767–73. https://doi.org/10.1016/j.icheatmasstransfer.2011.03.024
31. Lu X, Nnanna AGA. IMECE2008-6 7932. 2008.
32. Chein R, Chuang J. Experimental microchannel heat sink performance studies using nanofluids. International Journal of Thermal Sciences. 2007; 46(1):57–66. https://doi.org/10.1016/j.ijthermalsci.2006.03.009
33. Rimbault B, Tam C, Galanis N. Experimental investigation of CuO e water nano fluid flow and heat transfer inside a microchannel heat sink. International Journal of Thermal Sciences. 2014; 84:275–92. https://doi.org/10.1016/j.ijthermalsci.2014.05.025
34. Kumar R, Islam M, Hasan MM. A review of experimental investigations on heat transfer characteristics of single phase liquid flow in microchannels. International Journal of Advanced Mechanical Engineering. 2014; 4(1):115–20.
35. Song K, Zhang W. Design of a microchannel system using axiomatic design theory for size-controllable and monodispersed microspheres by enhanced perturbation. The International Journal of Advanced Manufacturing Technology. 2013; 64(5-8):769–79. https://doi.org/10.1007/s00170-012-4059-6
36. Ramiar A, Ranjbar AA. Two-dimensional variable property conjugate heat transfer simulation of nanofluids in microchannels. Journal of Nanoscience. 2013, pp. 1–10.
37. Mirzaei M, Dehghan M. Investigation of flow and heat transfer of nanofluid in microchannel with variable property approach. Heat and Mass Transfer. 2013; 49(12):1803–11. https://doi.org/10.1007/s00231-013-1217-9
38. Swati S, Gurpreet S, Amit S. Experimental Studies on heat transfer performance of double pipe heat exchanger with using Baffles and nanofluids. Indian journal of science and technology. 2016 Oct, 9 (40):1-7.
39. Gurpreet PS, Sarao TPS. Experimental investigation of heat transfer characteristics of plate heat exchanger using alumina - water based nanofluids at different orientations. Indian Journal of Science and Technology. 2016 Dec; 9(48):1–14.
40. Abhisek N, Gurpreet S. Experimental studies on heat transfer performance of shell and tube heat exchanger with Air bubble injection. Indian Journal of Science and Technology. 2016 Sep; 9(36):1–6.