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NUMERICAL STUDY OF VELOCITY AND PRESSURE DROP IN A MICROCHANNEL USING WATER AND AL_2O_3 NANOFLUID

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ABSTRACT

This paper present a numerical simulation of velocity and pressure drop in a single flow square shape microchannel. The ANSYS Fluent 2015 was used to predict the flow in the microchannel. The simulations were undertaken to inform on how the fluid flow within the microchannel using water, 1% Al_2O_3 nanofluid and 2% Al_2O_3 nanofluid in water. The microchannel was model using Solidwork 2014 with 0.5mm wide and 0.5mm height which is in square shape. The temperature inlet was constant at 303K and uniform heat flux used at bottom of microchannel was 100 W/m^{-2}. The results show significant difference between working fluid used on velocity, pressure drop and the change of temperature. Comparisons also were made on velocity and pressure drop with previous study to validate present results. It has been observed the velocity was increased due to increase of Reynolds number. However, the pressure drop results show there is no much different at lowest Reynolds number (*Re=0.1*) for both fluid used but when increase at *Re=100*, water has high pressure drop. The velocity and pressure drop affected the temperature value in microchannel. This present analysis shows that the addition of nanoparticles to water leads to increasing of temperature and pressure drop compare to water.

Keywords: nanofluid, pressure drop, velocity.

INTRODUCTION

Microchannel heat sinks constitute an innovative cooling technology for removal amount of heat from a small area. The heat sink usually made from a high thermal conductivity solid such as copper, aluminum or silicon. The dimensions for each channel is in ranging from 1.0 millimeter to 100 millimeter and serve as flow passages for cooling liquid. The microchannels has very potential of wide applications in cooling high power density microchips in CPU system, micro power systems and many other large scale thermal systems requiring effective of cooling capacity. This is a result of the micro size of the cooling system which not only significantly to reduces the weight load but also enhances the capability to remove much greater amount of heat than any large scale cooling systems. As the size of channel reduces to micron (μm), the heat transfer coefficient can increase the drastically from the original value [1].

Many researchers have studied about single phase-flow of microchannel. Significant of their study is to understand the transport phenomena of hydrodynamics, especially pressure drop and velocity through microchannels. They have determined that the microchannel offer advantages due to their high surface-to-volume ratio and their small volumes. Most of published studies have been observed the temperature of fluid at the outlet of microchannel is maximum when pressure drop is low [2]. The previous study have predicted pressure drop along the microchannel, as well as the pressure losses associated with the abrupt contraction and expansion at microchannel. While for a fluid with constant properties flowing through a rectangular channel, expectation a linear relationship between pressure drop and Reynolds number. There are several reasons for changes pressure drop in microchannel. Firstly, for constant power input and water inlet temperature, the outlet water temperature should decrease with increasing Reynolds number. Secondly, the inlet and outlet pressure losses are proportional to the square of velocity. The previous studies also have observed that the measured pressure drop is in good agreement with the predicted values.

Velocity field can be determined by using analytically using formula or by numerical analysis. The numerically determined velocity field developed has been compared with theoretical. The comparison of the result indicates that while the numerical code accurately represents the general trend of results. There is some disparity between the theoretical and numerical results especially in the maximum value and the overall distribution around this maximum value. The previous studies have compared using temperature of 293 K. This is because the thermo physical properties are temperature dependent, particularly the liquid viscosity, the velocity and consequently the Reynolds numbers are different under the same pressure drop conditions [3].

Besides water or gas, nowadays small particles mixed with water were chosen as coolant in microchannel flow. The solid particles generally possess far greater thermal conductivity than common heat transfer liquids. Mixing those solid particles in the liquid will enhance the cooling potential of liquid by increasing the concentration. Recently, developments in nanotechnology have made the production of far smaller nano-size particles. Nanofluids are solid-liquid composite materials consisting of solid nanoparticles with sizes typically of 1 to 100 nm suspended in liquid. The most important criterion of nanofluid is agglomerate-free stable suspension for long durations without causing any chemical changes in the based fluid. One of the nanofluids type is aluminum oxide

(Al_2O_3). The past researchers have observed enhancement of thermal conductivity for Al_2O_3 is not consistent. However, the reason for this enhancement is not clear in the available literature. Generally, the thermal conductivity for Al_2O_3 increases with increasing volume fraction, decreasing of particle size and the shape of particles. Based from the past study, the researchers have observed that the nanofluids have greater potential for heat transfer enhancement and suitable for application in practical heat transfer processes [4]. The past numerical study for nanofluid flow in microchannel shown that the addition of nanoparticles to water leads to significantly increasing the temperature but slightly increase in pressure drop [5].

Other researchers have done experimental work on finding effectiveness of nanofluids in microchannels that been performed to explore the microchannel cooling benefits of water based nanofluids containing small concentrations of Al_2O_3. The high thermal conductivity of nanoparticles relative to common pure fluids enhances the single-phase heat transfer coefficient for fully-developed laminar flow. The previous researchers have measured pressure made in the inlet and outlet plenums. Their measured pressure drop have shown that Al_2O_3 nanofluid is higher than pure fluid [5]. Besides experimental results, the simulations results have been compared by using same dimension model. It has proven that at the same Reynolds number, the simulation results agreed with experimental results. The pressure drop increases as Reynolds number increases. Normally, the simulation values are higher than experimental [6].

The findings state using nanofluid have more effectives than water in laminar flow regime (Re<2300). This is because of thermal conductivity and viscosity of fluid. Therefore, in this present study, the pressure drop and velocity in microchannel are investigated numerically and compared between pure water, 1% Al2O3 nanofluid and 2% Al2O3 nanofluid. According to the thermal conductivity of fluid, temperature is analyze at low Reynolds number ($Re=0.1$ ~ $Re=100$) to show the different of temperature in microchannel. The main focus of this study is to understand more about velocity and pressure drop in microchannel based on working fluid used for this simulation.

NUMERICAL METHOD

The three dimensional (3D) computational domain of microchannel is represented. A microchannel heat sink was modelled and simulated using Computational Fluid Dynamics code ANSYS Fluent. The channel has been design in single flow square shape model using SolidWorks 2014 as seen in Figure-1. The model included fluid and solid region. This present study was used square shape microchannel. The dimension is 0.5 mm wide, 0.5 mm height and the channel's length is 28.0 mm. The heat flux was considered to be at the bottom of the heat sink. In order to get accuracy result, mesh independence was carried out by varying the cell density of model for the same set of boundary conditions. The grid size was decreased in order to increase the element numbers. The meshed have been done between 54432, 98978 and 162071 elements. The simulations have been done to find velocity in the microchannel. The result shows for first mesh level was suitable to use since no appreciable change in the value of velocity. Hence a mesh level with 54432 elements was chosen for the rest analysis. Figure-2 shows meshing process conducted. High resolution scheme was selected as the solver option while double precision has been activated to improve accuracy.

The model has been set to two domains which is solid and fluid domain. At fluid domain, material used was water, 1% and 2% concentration of Al_2O_3 nanoparticles in water. The properties of this type of fluid are shown in Table-1. The table show thermal conductivity, density, viscosity and specific heat of fluid at 303 K. For this study, several assumptions were incorporated before establishing governing equations for fluid flow. The steady fluid flow was selected with pressure-based type. The energy equation was selected with laminar flow for fluid model. The radiation heat transfer was negligible. A uniform heat flux (100 W/m^{-2}) was applied at bottom of heat sink surface. The top of the microchannel heat sink was considered as adiabatic cover while at top of fluid domain was set as symmetry. The temperature was set at 303 K. The inlet velocity was set in range of 0.00016 m/s to 0.16 m/s. Copper with constant thermal conductivity of K_{cu}= 387.6 W/mK was used as solid material. The specified solver in ANSYS Fluent uses a pressure correction based iterative SIMPLE algorithm with first order upwind scheme for discretizing the transport terms. The convergence criteria for all the dependent variables are specified as $1x10^{-6}$. At the microchannel sections, the fluid temperature was taken as 303K and the inlet velocity was calculated by using following equation,

$$Re= (\rho VD_h)/\mu \quad (1)$$

where Re is defined as Reynolds number; ρ is density, V is velocity flow in microchannel, D_h hydraulic diameter and is μ viscosity of fluid used as coolant for this study. The cross-section of microchannel, hydraulic diameter, D_h is calculated using the equation,

$$D_h= 4.A=(2H_{ch} . W_{ch}/H_{ch}+W_{ch}) \quad (2)$$

where A is area, H_{ch} is height and W_{ch} is width of microchannel. Pressure drop has been calculated based on data at inlet and outlet using equation,

$$\Delta p = p\text{in} - p\text{out} \quad (3)$$

where ΔP is the pressure drop while P_{in} is pressure inlet and P_{out} is the pressure outlet.

Table-1. Properties of water and Al_2O_3 nanofluid.

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Type of fluid	***k*** (W/mK)	***ρ*** (kg/m^3)	***μ*** (kg/ms)	***C_p*** (J/kgK)
water	0.600	995.7	0.000798	4182
1% Al_2O_3 nanofluid	0.620	1021.7	0.000817	4149
2% Al_2O_3 nanofluid	0.638	1047.7	0.000838	4115

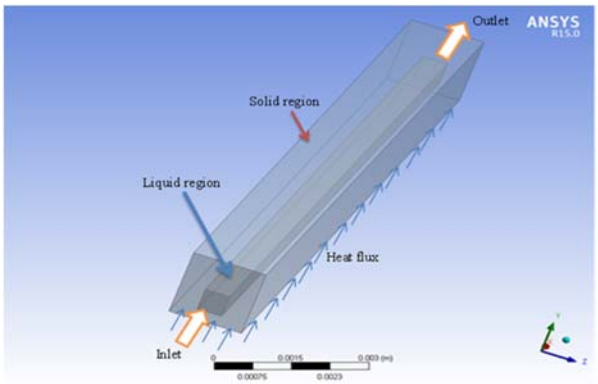

Figure-1. Model of square microchannel.

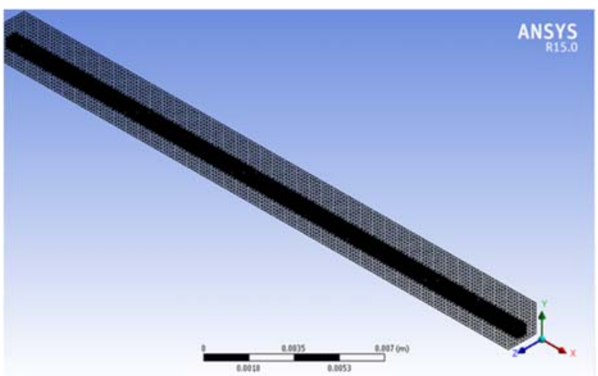

Figure-2. Meshing.

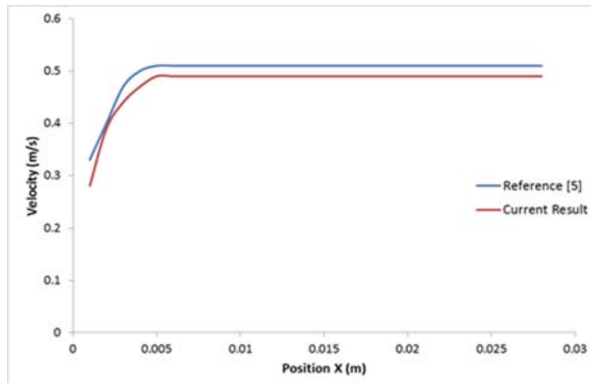

Figure-3. Comparison velocity in microchannel.

RESULT AND DISCUSSIONS

Validation data

The variation of velocity along microchannel has been validated with simulated results by previous researcher [6]. Figure-3 shows comparison of velocity along microchannel between present and previous study. Both model were compared at same Reynolds number (*Re*=140) but different model shape. The previous researcher use rectangular shape while present study uses square shape. However, the figure shows both result agreed by velocity increases along the microchannel. The different value for both simulated data is 4.4%. Based on both results, the velocity increases the maximum value at position 0.05 m.

Streamline velocity and contour pressure

Present numerical analysis has focus on laminar flow ($0.1 \leq Re \leq 100$) in a square shape microchannel. Based on the results, both water and Al_2O_3 nanofluid react to the heat flux produce at bottom of heat sink. As the channel being heated, fluid viscosity and thermal conductivity have changes. Therefore, velocity and pressure of fluid flow in microchannel affect the temperature. Figure-4 presents the streamline for velocity in microchannel. The velocity increases start from inlet region. However, the change of velocity is depending on Reynolds number set for this study. Meanwhile pressure recorded decrease at the outlet region. Figure-5 illustrates the contour for pressure drop in microchannel. The drop in pressure occurs as well as the pressure losses associated with abrupt contraction at the inlet and expansion at outlet of microchannel. This is corresponds to decreasing pressure in the direction of flow. As in internal flow, the fluid body is confined by the channel wall. At the inlet of microchannel, the fluid develops a boundary layer next to the walls. This is happen due to change of dimension size at piping system to microchannel.

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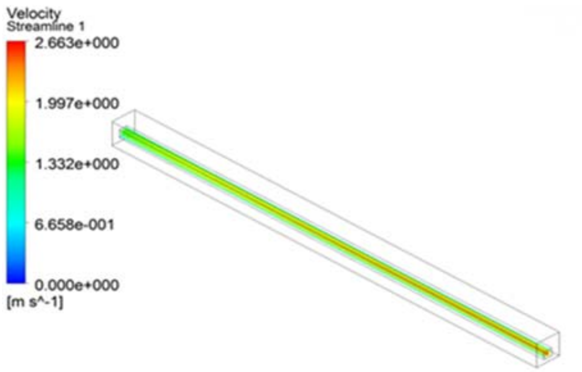


Figure-4. Streamline for velocity in microchannel.

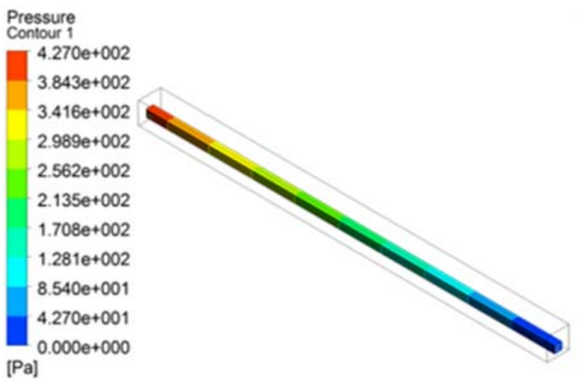


Figure-5. Contour for pressure in microchannel.

Comparison velocity and pressure drop between water and Al_2O_3 nanofluid

Generally, velocity is increase according to size of microchannel. Figure-6 shows comparison velocity of water and Al_2O_3 nanofluid based on its concentration at *Re=1278*. The present study was compared with previous study with same fluid properties [7] to prove the result. Since the design of microchannel is different, the variation of velocity is almost same for both studies.

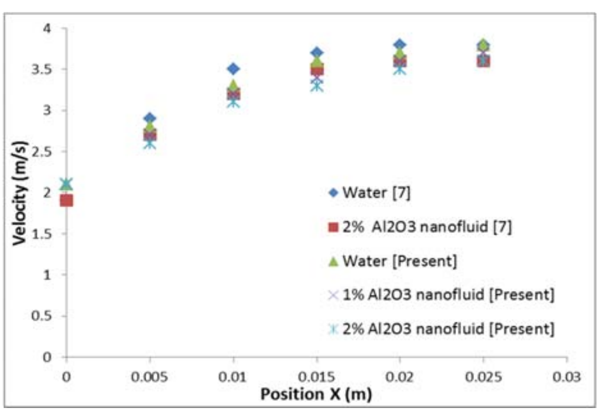


Figure-6. Variation of velocity of water and Al_2O_3 nanofluid at *Re=1278*.

The previous study used circular shape while present study used square shape microchannel. Comparison was made to velocity of water, 1% Al_2O_3 nanofluid and 2% Al_2O_3 nanofluid. The figure shows velocity of water is higher than Al_2O_3 nanofluid for both studies. This is due to density and viscosity of nanofluid increases with increase in nanoparticles concentration. Thus, the velocity at any axial position decreases by increase the nanoparticles concentration. Another comparison has been made with lower Reynolds number. Figure-7 shows comparison velocity of water and Al_2O_3 nanofluid at *Re=140* with different microchannel shape. This present study has compared with previous model that used rectangular shape. Based on the figure, it is also shows velocity of water is higher than Al_2O_3 nanofluid. It is observed at the entrance velocity of all types of fluids got fully developed. The difference for both graphs is velocity at lower Reynolds number become constant when it reach the highest value while at higher Reynolds number, the velocity continuously increase to the outlet of microchannel. While the fluid flow was in laminar regime, the lower velocity has contact more with the high heat flux produced at bottom surface of microchannel. This is attributed to the thin thermal boundary layer at microchannel region. The result proved that viscosity of fluid affect the velocity along microchannel.

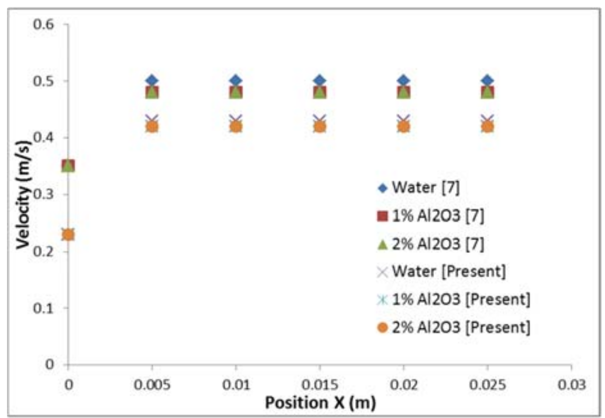


Figure-7. Variation of velocity of water and Al_2O_3 nanofluid at *Re=140*.

Next analysis is about pressure drop in microchannel. Usually pressure is decrease at outlet region. This present study computed pressure drop for water and Al_2O_3 nanofluid at different Reynolds number (0.1, 1, 10, 100). The result was compared with previous study (experimental) that using water with same heat flux produce at bottom of microchannel (100 W/cm^2). Figure-8 shows pressure drop along microchannel based on Reynolds number for water, 1% and 2% Al_2O_3 nanofluid compared with previous study [8].

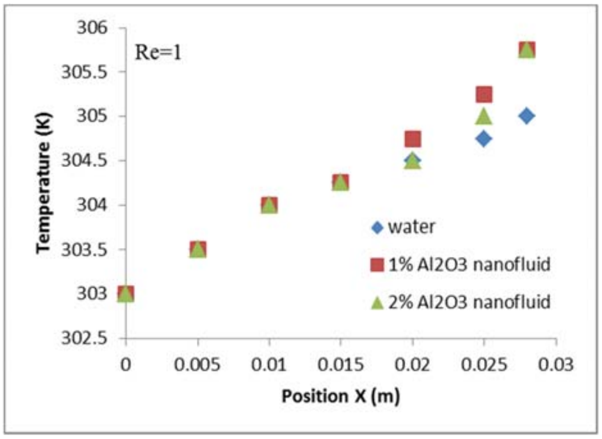


Figure-8. Comparison pressure drop of water, 1% Al_2O_3 nanofluid and 2% Al_2O_3 nanofluid.

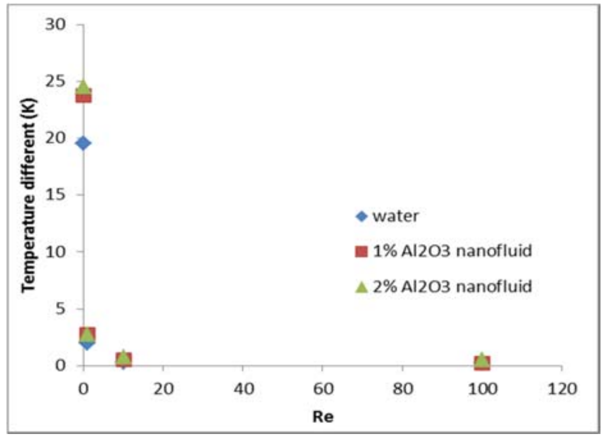
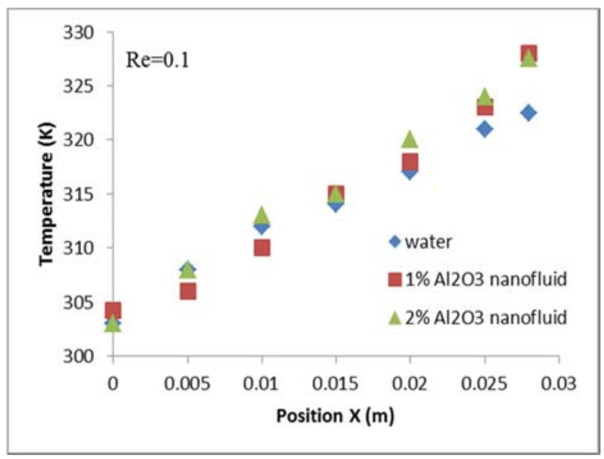


Figure-9. Temperature different for working fluid used based on Reynolds number.

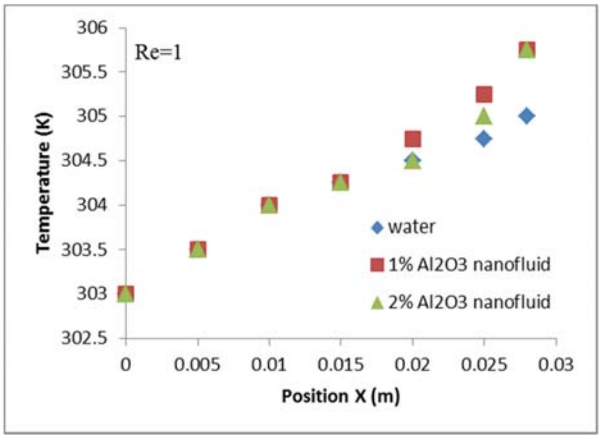
The figure shows pressure drop increase as well as Reynolds number increase. Furthermore, pressure drop is high when nanoparticles concentration is increase. This is because of suspending nanoparticles in water generally increases dynamic viscosity. The result also shows pressure drop increase linearly to the increasing of Reynolds number as same as previous study. It is shows good agreement of predicted pressure drops across the microchannel. The fluid flow across the square shape microchannel has been expected a linear relationship between pressure drop and Reynolds number. The gradient of graph for both studies are similar even the previous study use rectangular microchannel. The pressure drops slope change because of constant heat flux and inlet temperature. The inlet and outlet pressure losses are proportional to the Reynolds number. Therefore, increasing Reynolds number produces a more pronounced increase in the inlet and outlet pressure losses.

Based on velocity and pressure drop results, another comparison was made to prove the effect of thermal conductivity and viscosity to the working fluid use for this study. Figure-9 show temperature different in microchannel based on Reynolds number. The figure shows temperature different decrease due to the increase of Reynolds number. Thus, change of termperature in microchannel is high when the drop in pressure is low. The lower pressure drop is record at lower Reynolds number. The comparison also has been made based on fluid properties. This present study show 2% Al_2O_3 nanofluid has larger temperature different. The thermal conductivity of 2% Al_2O_3 nanofluid is higher than others. Therefore, it is proved that concentration of nanoparticle affect the temperature results. Meanwhile, temperature is increase when the loss of pressure is decrease along microchannel. Besides, the temperature increases when velocity of fluid is lower.

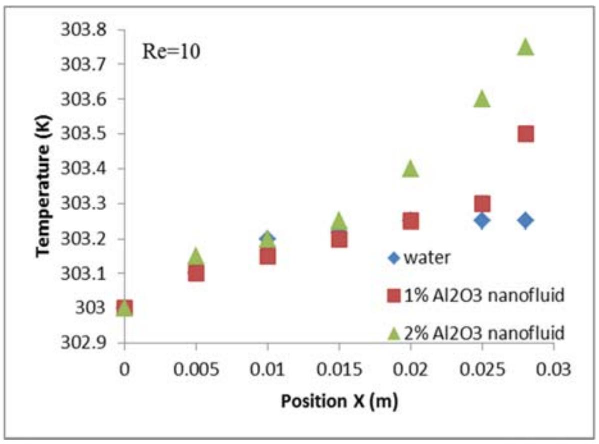
Figure-10 shows variation of temperature along microchannel based on Reynolds number (*Re*=0.1, *Re*=1, *Re*=10 and *Re*=100) at constant heat flux (100 W/m^{-2}). The previous study expected while constant heat flux boundary condition, the temperature increase linearly in the fully developed region. This is because of the wall thickness was assumed to be zero. Therefore, there is no conjugate effect. The temperature highly increase when *Re*=0.1 while it is slightly increase at *Re*=100.



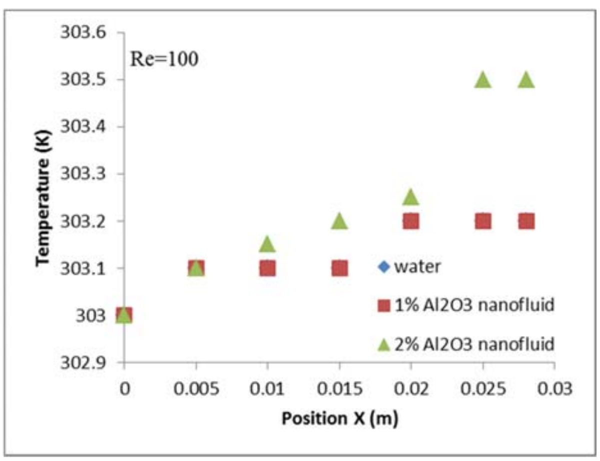
(a)



(b)



(c)



(d)

Figure-10. Temperature of working fluid along microchannel (a) at *Re=0.1*, (b) *Re=1*, (c) *Re=10* and (d) *Re=100*

Based on the results, it is prove that heat is absorbing more during lower velocity of fluid along the microchannel. This is because fluid has more contact to the heat flux produce at bottom of the microchannel. The increasing temperature is different according to the concentration of fluid. Figure-10 show comparison temperature along microchannel. The results shows high temperature rise while using 2% Al_2O_3 nanofluid compared to water. Simulation results have proved the thermal conductivity of fluid affect the temperature. Based on Table-1, thermal conductivity for 2% Al_2O_3 nanofluid is highest compared to others. As discussed by previous study, the increasing nanoparticle concentration increases the thermal conductivity of fluid especially for laminar flow. On the other hand, when increase the concentration of nanoparticle also degrades specific heat and resulting in larger axial rises in temperature compared to water.

CONCLUSIONS

The present study is a numerical analysis of square shape microchannel heat sink in three dimensional computational domains. Comparison was made with previous study based on velocity and pressure drop. The model uses by previous researchers are circular and rectangular.

Based on present analysis, velocity is increase along microchannel as well as the increase of Reynolds number. It is similar to pressure drop. However, the changes of temperature in mircrohannel decrease as well as the increasing Reynolds number. This present study conclude that the lower velocity of fluid with lower pressure drop increase the temperature in microchannel. Other than that, this present analysis shows that the addition of nanoparticles to water leads to increasing of temperature and pressure drop compare to water. This phenomenon caused by high thermal conductivity and viscosity of nanoparticles relative to water. As using laminar flow (2300≤*Re*), the pressure drop and temperature is increase due to increase of Reynolds number.

This present study has validated the results with circular and rectangular shape from previous researchers. Thus, the further study need to analysis more for square shape microchannel based on different materials and various types of fluid.

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