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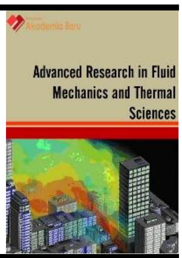

Numerical Analysis of Aluminium Oxide and Silicon Dioxide Nanofluids in Serpentine Cooling Plate of PEMFC

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ABSTRACT

Proton Exchange Membrane Fuel Cell (PEMFC) is an alternative energy application for vehicular power sources and is a strong contender for clean and efficient power generation. However, the heat generated by the PEMFC need to be taken care of efficiently as to avoid damage to fuel cell component especially membrane due to overheat. Excessive heat can also lead to performance deterioration of PEMFC. In this study, the heat transfer performance of Aluminium Oxide (Al_2O_3) and Silicon Dioxide (SiO_2) in water with low concentration value of 0.1 %, 0.3 % and 0.5 % volume were adopted as cooling medium in PEMFC. The simulation software used was ANSYS Fluent in laminar flow condition. The nanofluids studied were applied in a carbon graphite serpentine cooling plate of PEMFC which was subjected to a constant heat flux of 300 W. The heat flux mimicked the heat received during actual reaction in PEMFC. The result shows that maximum improvement was at 2.14 % improvement in Al_2O_3 and 1.15 % improvement in SiO_2 in term of heat transfer coefficient of 0.5 % volume concentration as compared to water. This is due to the superior thermal conductivity of nanofluids as compared to base fluid. The improved Brownian motion has enabled such excellent heat transfer. However, the improvement was also accompanied by the pressure drop increment as compared to base fluid water.

Keywords:
Aluminium Oxide (Al_2O_3); nanofluids; PEMFC; serpentine; Silicon Dioxide (SiO_2)

1. Introduction

The earth's atmosphere produce greenhouse gases (GHGs) which are in the form of water vapor containing small amount of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O). The greenhouse gases (GHGs) work as a thermal blanket for the planet by absorbing heat from the sun and keeping the surface warm on average 15°C to support life [1]. This is natural causes of global warming in life. The global warming is an important environmental issue that may affect humans and other living organisms. In order to overcome the problems, renewable energy resources are being

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discovered to minimize demand for fossil fuel. Therefore, alternatives energy sources are discovered in order to reduce pollution and depletion of the natural fuel resources. The hydrogen energy has been investigated and the device which utilizes hydrogen as fuel is called fuel cell. Hydrogen has a significant role in future low-carbon economies [2-4] with the versatility to provide power system, mobility, heat, industrial services and electricity. Therefore, hydrogen can be one of future promising solution to world's energy needs [5].

Among the power generation technologies that are rapidly developed for greater energy sustainability is the Proton Exchange Membrane Fuel Cell (PEMFC). The PEMFC uses hydrogen as fuel which reacts with oxygen to change hydrogen-bound chemical energy into electricity [6]. The PEMFC is gaining popularity due to its rapid start-up with low operating temperature between 60 °C and 80 °C while high operating temperature between 100 °C and 200 °C [6]. Heat is generated during the chemical reaction between oxygen and hydrogen hence need to be removed efficiently as to avoid the fuel cell component from causing damage due to overheat. The damage or breakdown of fuel cell component will eventually decrease the stack performance of PEMFC.

Effective cooling is crucial for a safer and more efficient operation of PEMFC especially when handling with higher power of fuel cell stack as reported by Zakaria *et al.,* [7]. A better performance of PEMFC is produced from an effective thermal management of a fuel cell as high temperature can result in membrane degradation while lower temperature will result in the kinetic reaction degradation and it will cause flooding issues to membrane [8-10]. The PEMFC cooling plate works to remove the reaction heat by circulating the coolant. In a cooling system of PEMFC, the cooling plate is placed between several unit cells in the fuel cell stack. Currently, the cooling medium that commonly used are liquid and air coolant. Liquid cooling is more efficient than air cooling since it enables higher heat transfer capability as compared to air.

A new technology is discovered to improve the thermal properties of cooling fluids termed as nanofluids. Nanofluids are nanoparticles suspended in base fluid with its particle size ranging between 1 to 100 nm. The addition of nanofluids coolant to the base fluid can increase and augment the thermal conductivity of the base fluid since the thermal conductivity of a metal is many orders of magnitude higher than the base fluid [11]. Islam *et al.,* [12] has reported that the thermal conductivity increases with the increase of nanofluids concentration while decrease with increasing temperature.

The fundamental heat transfers and fluid flow characteristic of nanofluids in mini channel is thoroughly reviewed by Muhammad *et al.,* [13] whose discussed on the current works done on nanofluids in mini channel. Among them are investigation by Sohel *et al.,* [14] and Khaleduzzaman *et al.,* [15]. They have investigated nanofluids in mini channel for electronic heat sink and automotive exchangers. Sohel *et al.,* [14] also investigated that the effect of volume fractions of Al_2O_3 in water, and reported that there is 18 % increment of heat transfer for 0.25 % volume concentration at Reynolds number 1000 as compared to base fluid.

Cooling plate design also influences the heat transfer and pressure drop of PEMFC. Various cooling plate designs including parallel, distributor and serpentine type has been studied by Ramos-Alvarado *et al.,* [16]. He has reviewed several key performance criteria of a cooling plate including the temperature distribution uniformity as well as pressure drop. Sainan *et al.,* [17] also investigated inlet outlet ratio effect to serpentine type cooling plate performance which regarded as the most commonly used flow channel for PEMFC.

In this study, Computational Fluid Dynamic (CFD) software (ANSYS FLUENT) was used to simulate thermal behaviour of nanofluids coolant in serpentine cooling plate. The nanofluids used were Aluminium Oxide (Al_2O_3) and Silicon Dioxide (SiO_2) in three different volume concentrations dispersed in base fluid of water. At the end of the study, a comprehensive finding on heat transfer improvement and pressure drop effect on Aluminium Oxide (Al_2O_3) and Silicon Dioxide (SiO_2) in water is reported.

2. Methodology

2.1 Properties of Fluid Used in Analysis

The properties of both Aluminium Oxide (Al_2O_3) and Silicon Dioxide (SiO_2) simulated were referred from experimental values of Zakaria *et al.,* [7] and Talib *et al.,* [18]. These nanofluids were chosen due to its excellent thermal conductivity, stable, cost advantage, commercially available, and less chance of sedimentation. Table 1 shows the thermo-physical properties of nanoparticles and based fluid used in the analysis.

Table 1
Properties of nanoparticles and based fluid used in the analysis

Nanoparticle/ Base Fluid	Density ρ, kg/m^3	Thermal conductivity K, W/m.K	Specific Heat Cp, J/kg.K	Viscosity μ, Kg/m.s	Reference
Distilled Water	999	0.615	4180.0	0.00085	[7]
Al_2O_3	4000	36	765.0	-	[7]
SiO_2	2220	1.38	745.0	-	[18]

2.2 Mathematical Formula and Governing Equations

Few assumptions were made in order simplify the analysis. Assumption made were as below:

I. The flow is laminar, steady state and incompressible
II. Viscous dissipation is neglected and remain constant the fluid properties.
III. Zero relative velocity in thermal equilibrium for fluid phase and nanofluids. The resultant mixture is considered as a conventional single phase
IV. Free convection heat transfer and radiation is negligible
V. Heat transfer and fluid flow characteristic for all mini channels are identical.

Below are the governing equations for the above assumption simulation [19].
Continuity equation:

$$\nabla.(\rho_{nf}.V_m) = 0 \tag{1}$$

The above equation is principle of mass conservation for a steady, one dimensional flow with one inlet and outlet. In this study A1= A2 because mass comes in A1 are same goes out to A2 since there is no flow go through the side walls of duct. Where, A = Area of duct

Momentum conservation equation:

$$\nabla.(\rho_{nf}.V_m.V_M) = -\nabla P + \nabla.(\mu_{nf}.\nabla V_m) \tag{2}$$

Energy equation for coolant:

$$\nabla.(\rho_{nf}.C.V_m.T) = \nabla.(k_{nf}.\nabla T) \tag{3}$$

The heat conduction through the solid wall:

$$0 = \nabla.(k_s.\nabla T_s) \quad (4)$$

At the wall no slip boundary:

$$\vec{V} = 0 \text{ (at Walls)} \quad (5)$$

At channel inlet the boundary conditions were assumed as:

$$\vec{V} = V_m \text{(at channel inlet)} \quad (6)$$

$$P = \text{atmospheric pressure (at channel outlet)} \quad (7)$$

The thermal energy with constant heat flux was generated from the fuel cell. In the simulation, the energy was applied uniformly at the bottom of cooling plate. Heat was transferred from the wall surface to the fluid via conduction and dispersed through the fluid by forced convection mechanism.

$$-k_{nf}.\nabla T = q \text{ (at bottom of plate or channel)} \quad (8)$$

$$-k_{nf}.\nabla T = 0 \text{ (at top of plate or channel)} \quad (9)$$

2.3 Mathematical Model

In boundary condition, heat flux and heat generation need to be calculated by using Eq. (10) and (11). Where, W = Thermal Energy, W

Heat Flux:

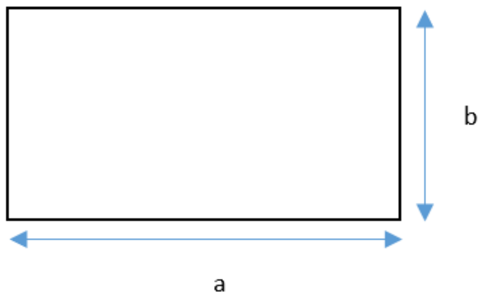
$$\frac{W}{m^2} = \frac{300}{0.0462} = 6493.5065\ W/m^2 \quad (10)$$

Heat Generation Rate:

$$\frac{W}{m^3} = \frac{300}{0.000184} = 1630434.783\ W/m^3 \quad (11)$$

The coolant temperature differences were determined by calculating the differences between the inlet and outlet temperature of the coolant channel.

Hydraulic diameter, D_h need to be calculated before calculating the inlet velocity. Eq. (12) was an equation that used to calculate hydraulic diameter.



$$D_h = \frac{2ab}{a+b} = \frac{(2)(0.0488)(0.001)}{0.0488+0.001} = 0.00196 \text{ m} \tag{12}$$

The value of inlet velocity was calculated by using Eq. (13).

$$\mathrm{V} = \frac{\mathrm{R_e \mu}}{\mathrm{\rho D}} \tag{13}$$

where,
V = Inlet velocity, m/s
R_e = Reynolds Number
μ = Viscosity, Kg/m.s
ρ = Density, kg/m^3
D = Diameter for a rectangle, m

Heat transfer was analyzed based on heat transfer coefficient and Nusselt Number. Heat transfer coefficient and Nusselt Number were calculated using Eq. (14) and (15).

$$\mathrm{h} = \frac{\dot{\mathrm{q}}}{(\mathrm{T_{avgplate}} - \mathrm{T_{avgfluid}})} \tag{14}$$

where,
h = Heat transfer coefficient, W/m^2.K
$\dot{q}$ = Heat Flux, W/m^2
$T_{avgplate}$ = Average Plate Temperature, K
$T_{avgfluid}$ = Average Fluid Temperature, K

$$\mathrm{Nu} = \frac{\mathrm{hD_h}}{\mathrm{k_{nf}}} \tag{15}$$

where,
Nu = Nusselt Number
D_h = Hydraulic Diameter
k_{nf} = Thermal Conductivity Nanofluids, W/m.K

Meanwhile, fluid flow was analysed based on pressure drop between IN and OUT flow. The pressure drops then used to calculate pumping power. Eq. (16) used to calculate pumping power.

$$\mathrm{W_{pump}} = \dot{\mathrm{V}} \times \triangle \mathrm{P} \tag{16}$$

where,
W_{pump} = Pumping Power
$\dot{V}$ = inlet velocity × inlet area
$\triangle P$ = Pressure drop

2.4 Grid Independent Test

One of the important steps in the Computational Fluid Dynamics (CFD) simulation process is meshing. The meshing process breaks the geometry or domain in small elements that develop mesh [20]. In this study, the grid independent test was conducted to ensure that the meshing element used was optimized. The process of mesh was repeated and refined until the solution was converge. Once it is converged, the elements and nodes are stable to run the simulation. It is shown that element of 335995 is the optimum meshing size for the study as shown in Figure 1 below. Figure 2 shows the meshing performed for the geometry studied.

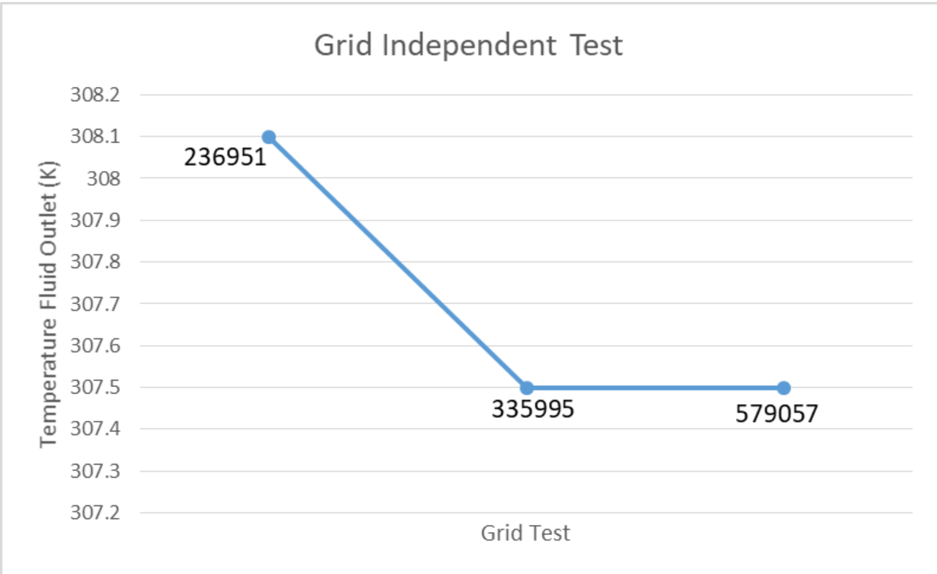


Fig. 1. Graph of grid independent test

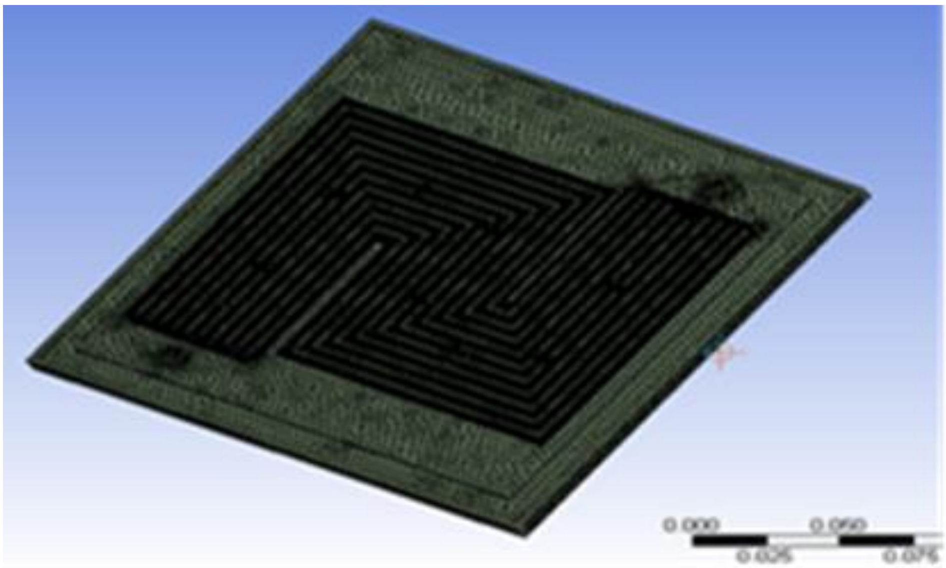


Fig. 2. Geometry of the mesh for serpentine cooling plate

3. Results and Discussion

3.1 Average Plate Temperature

Figure 3 shows the average plate temperature for base fluid, Al_2O_3 and SiO_2 nanofluids. Based on the graph, the highest average plate temperature is shown by base fluid of water Re 300. The temperature of the plate is reduced as the Re number is increased. At Re 1500, the lowest average plate temperature is shown by Al_2O_3 nanofluids, followed by SiO_2 nanofluids and lastly base fluid. It was observed that cooling plate with Al_2O_3 nanofluids has a lower average plate temperature as compared to SiO_2 nanofluids due to the higher thermal conductivity property of Al_2O_3 nanofluids over SiO_2 nanofluids. The average plate temperature for Al_2O_3 and SiO_2 nanofluids is improved by 0.92 % and 0.54 % respectively at 0.5% volume concentration as compared to base fluid. When the volume concentration and Reynolds number are increased, the value of average plate temperature is decreased. This is due to improved thermal conductivity property at higher concentration of nanofluids. The findings in good agreement with findings by Zakaria *et al.,* [21].

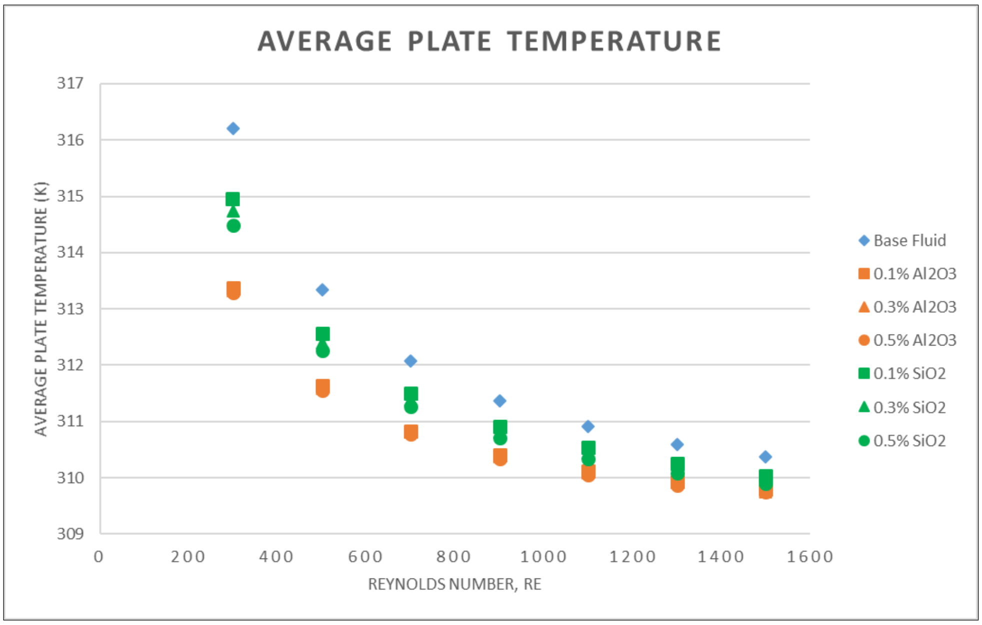


Fig. 3. Graph of average plate temperature vs Reynolds number

3.2 Heat Transfer Coefficient

The plate temperature was then further analysed to heat transfer coefficient value. Figure 4 shows the heat transfer coefficient for all fluids studied. It is shown that the heat transfer coefficient of Al_2O_3 at 0.5 % volume concentration in Re 1500 has the highest heat transfer coefficient value as compared to all other fluids. Nanoparticles addition have improved the heat transfer characteristic due to the improved Brownian motion. The highest increment for Al_2O_3 and SiO_2 at 0.5 % volume concentration with 2.14 % and 1.15 % enhancement as compared to base fluid at Re 1500. It was also observed that as the Re and volume concentration was increased, the heat transfer coefficient was also increased. The finding agreed based on graph pattern by Zakaria *et al.,* [21].

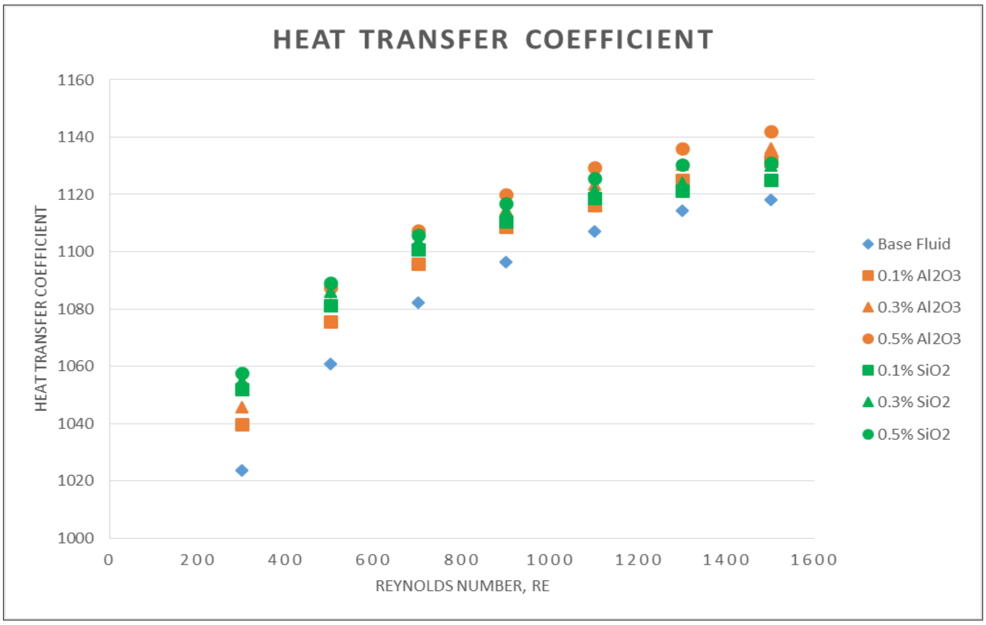


Fig. 4. Graph of heat transfer coefficient

3.3 Nusselt Number

Figure 5 shows that Nusselt number increased as the Reynolds Number was increased due to the higher convective heat transfer enhancement effect as compared to conductive heat transfer. The highest increment of Nusselt number was observed at Al_2O_3 at 0.5 % volume concentration with an improvement of 0.62 % while SiO_2 was at 0.28 % as compared to the base fluid recorded at Re 1500. It is also shown that the Nusselt number increased as both the Reynolds number and volume concentration were increased.

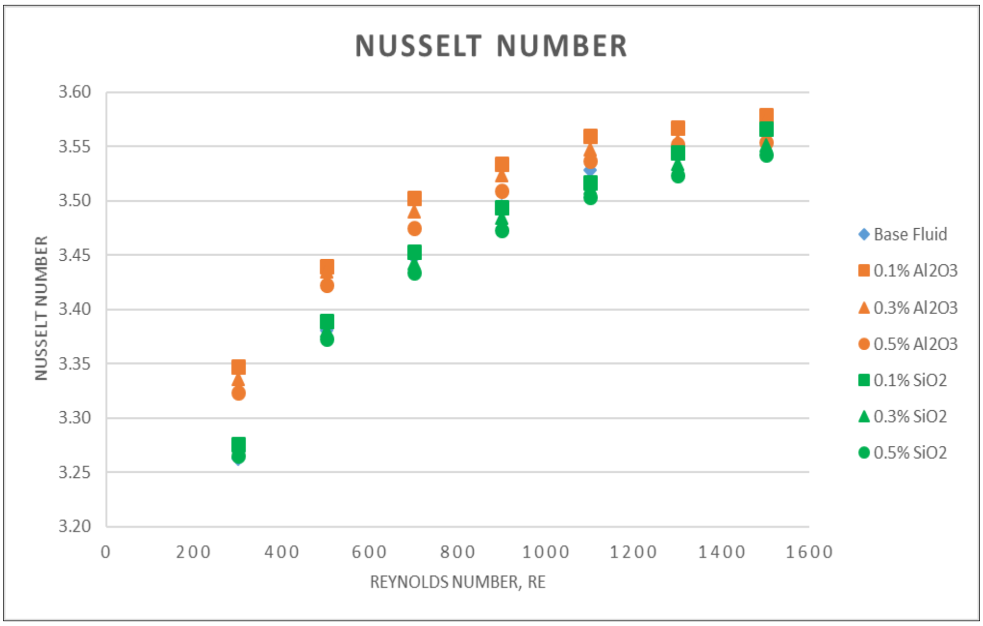


Fig. 5. Graph of Nusselt number

3.4 Pressure Drop

The fluid flow of nanofluids in cooling plate was evaluated by its pressure difference between inlet and outlet fluid as shown in Figure 6. The highest-pressure drop is shown at Reynolds number 1500 for 0.5 % volume concentration of SiO_2 followed by Al_2O_3 at 0.5 % volume concentration with 189 % and 68 % enhancement respectively as compared to base fluid. The lowest pressure drop was shown by base fluid of water. The higher-pressure drop was experienced by nanofluids due to the increase in viscosity property as compared to base fluid. The pressure drop increment was further exaggerated since the coolant has been forced to go through a narrow channel of cooling plate PEM fuel cell [22].

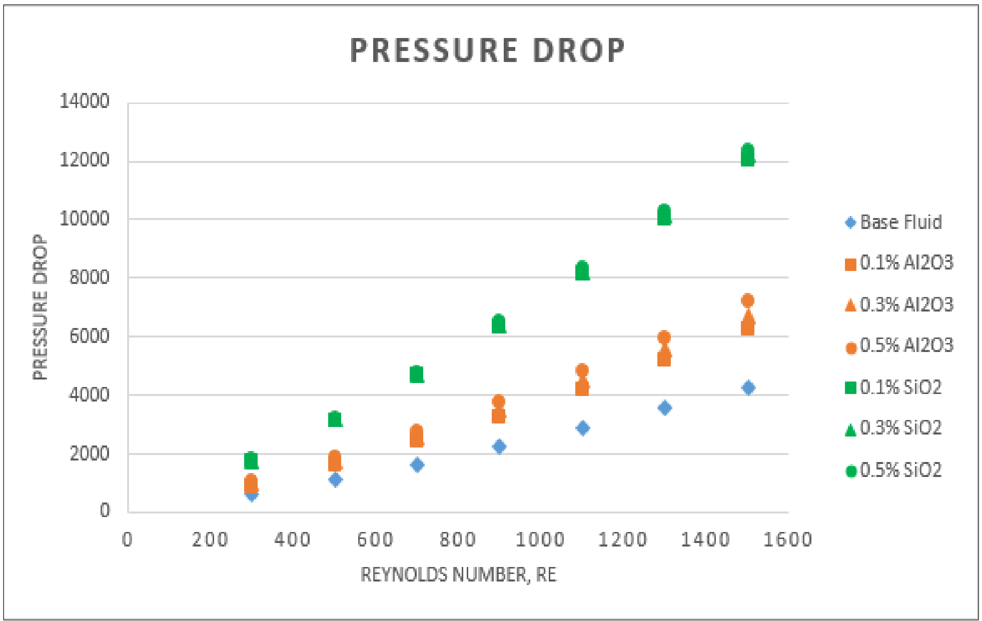


Fig. 6. Graph of pressure drop

3.5 Pumping Power

The pressure drop values were then translated to pumping power information to know the effect of nanofluids to the pumping requirement of a system. Figure 7 shows the pumping power information for all fluids studied. The highest pumping power was shown by 0.5 % volume concentration of SiO_2 nanofluids with 390 % increment as compared to water. This was then followed by 0.5 % volume concentration of Al_2O_3 nanofluids with 116 % increment as compared to base fluid. The lowest region of pumping power recorded was for base fluid water. It was also observed that the pumping power value increases when both the volume concentration and Reynolds number were increased. The increment was expected in order to circulate more viscous nanofluids through the cooling system. Higher pumping power is less desirable as it is a parasitic loss.

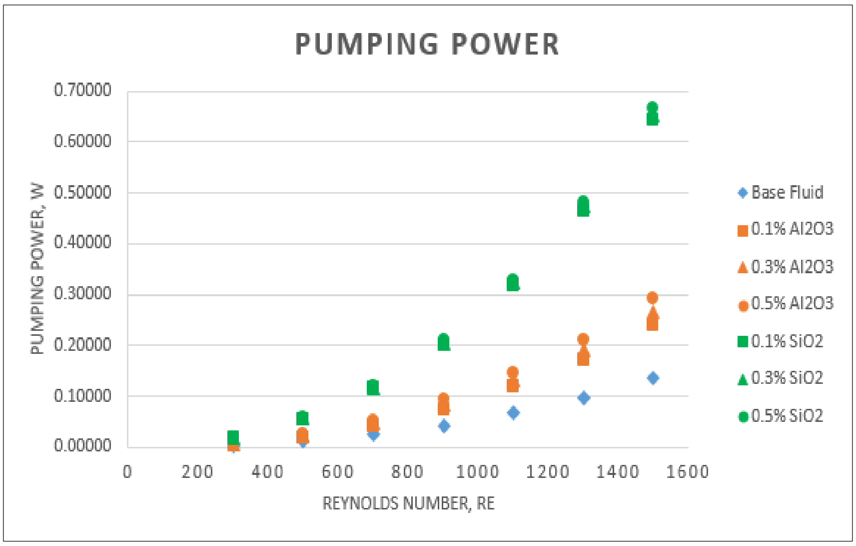


Fig. 7. Graph of pumping power

3.6 Coolant Contour Analysis

The Serpentine Cooling Plate was used in the analysis. The heat distribution on coolant flow for base fluid comparatively to all volume concentrations of both Al_2O_3 and SiO_2 nanofluids can be observed in Figure 8 and Figure 9, respectively.

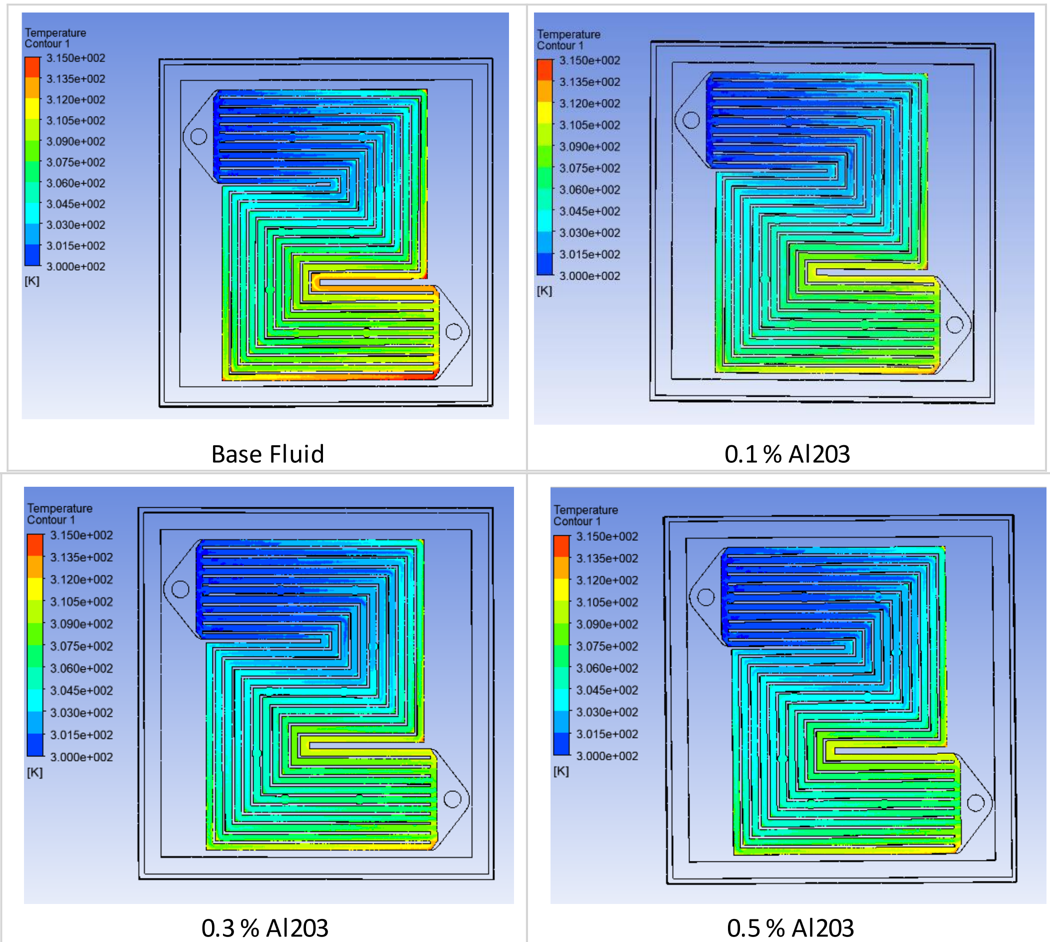


Fig. 8. Coolant temperature contour at Re 300 for Al_2O_3 nanofluids and base fluid

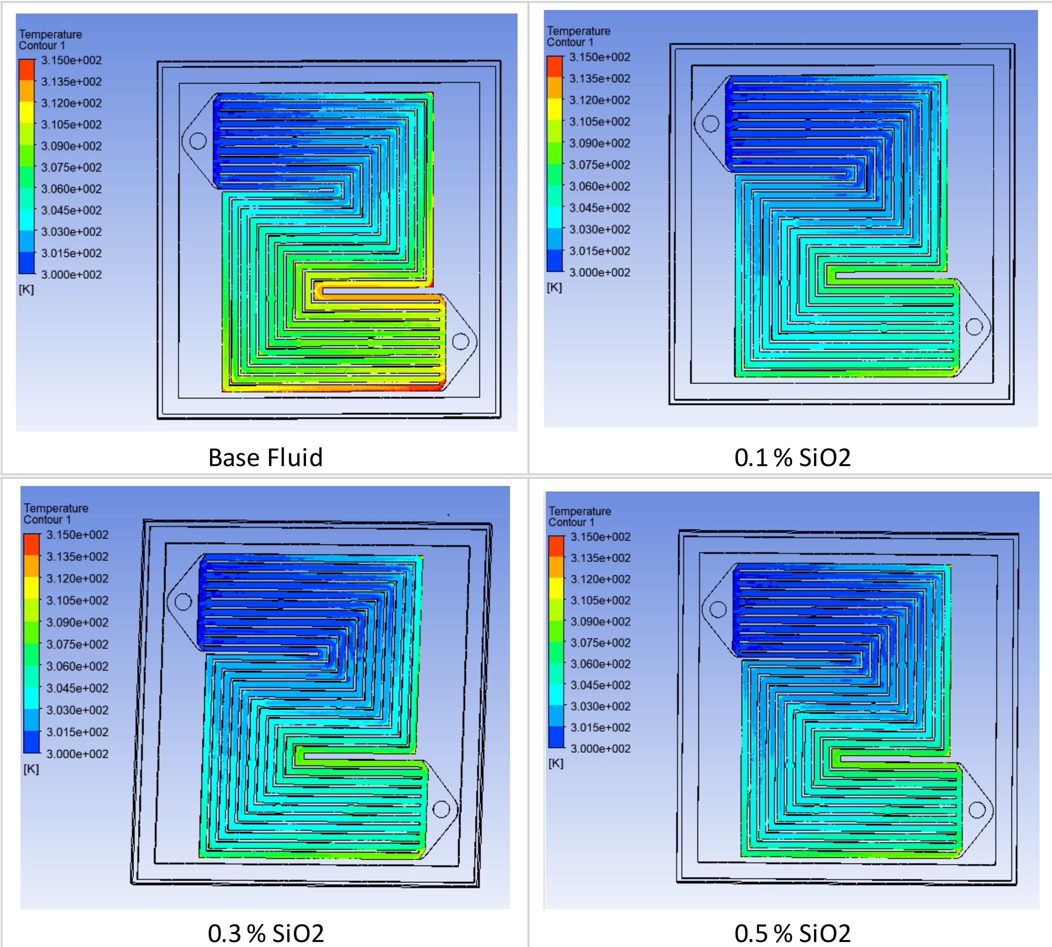


Fig. 9. Coolant temperature contour at Re 300 for SiO_2 nanofluids and base fluid

It was observed that at same Re 300, the highest fluid temperature was shown in base fluid. The coolant temperature slowly reduced their temperature as the nanofluids were used. The higher volume concentration of nanofluids resulted in lower coolant temperature value.

4. Conclusions

As a conclusion, heat transfer enhancement and fluid flow effect of nanofluid were studied in this simulation work. Based on the result obtained, it can be concluded that there is an enhancement in heat transfer performance of both Al_2O_3 and SiO_2 nanofluids as compared to the base fluid. The enhancement is due to the superior thermal conductivity of both Al_2O_3 and SiO_2 nanofluids as compared to the base fluid of water. It was also observed that Al_2O_3 nanofluids performed better than SiO_2 due to its higher thermal conductivity value. However, the pressure drop and pumping power were also observed to increase as well but at a tolerable increment considering a full stack power generation. Further study needs to be done in order to study the feasibility of the nanofluids adoption in serpentine cooling plate of PEMFC.

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