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The Characteristics of Hybrid Al_2O_3:SiO_2 Nanofluids in Cooling Plate of PEMFC

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ABSTRACT

A Proton Electrolyte Membrane fuel cells (PEMFC) is considered to be a viable alternatives to Internal Combustion Engines (ICEs) in automotive applications due to the key advantages in thermal management system. The main duty of thermal management system is to maintain the desirable temperature, with a uniform temperature distribution across the stack and its individual membranes. In this paper, the thermal enhancement of a PEMFC cooling plate was analysed and presented. The hybrid Al_2O_3:SiO_2 was used as coolant in distributor cooling plate. The study focuses on water based 0.5% volume concentration of single Al_2O_3 , single SiO_2 nanofluids, hybrid Al_2O_3:SiO nanofluids with mixture ratio of 10:90, 20:80, 50:50, 60:40 and 90:10. The effect of different ratios of nanofluids to heat transfer enhancement and fluid flow in Reynold number range of 400 to 2000 was observed. A 3D computational fluid dynamic (CFD) was developed based on distributor cooling plates using Ansys 16.0. Positive heat transfer enhancement was obtained where the 10:90 Al_2O_3:SiO_2 nanofluids has the highest heat transfer coefficient as compared to other nanofluids used. However, all nanofluids experienced higher pressure drop. Therefore, the advantage ratio was used to analyze the effect of both heat transfer enhancements and pressure drop demerits for nanofluids adoption. The results concluded that 10:90 Al_2O_3:SiO_2 hybrid nanofluid is the most feasible candidate up to fluid flow of Re1000. The positive results implied that hybrid Al_2O_3:SiO_2 nanofluids do improve the single nanofluids behaviour and has a better potential for future applications in PEMFC thermal management.

1. Introduction

Nowadays, there are an increasing trend of the emergence of an alternative energy to replace internal combustion engine (ICE) in automotive industry. Among the highly potential alternative is proton electrolyte membrane fuel cell (PEMFC). The PEMFC is an electro-chemical device, which generates electricity by converting chemical energy [1] of hydrogen that acts as a fuel with pure oxygen or oxygen from surrounding air [2]. The PEMFC is a forethought as potential energy

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generation device due to its high energy conversion efficiency of 60 % as compared to 20 % to 30 % in ICE [3]. The PEMFC offers better promising clean energy technology without any form of combustion due to its by-products which are merely water and heat. The key constituent of the PEMFC is the Membrane-Electrode Assembly (MEA), which acts as the component where the proton migrates from anode to cathode [4]. The proton is produced by catalytically oxidized the hydrogen at the anode, and then it will migrate to the cathode to react with oxygen and produces water and heat [5]. The electro-chemical reactions will require an excellent maintenance in its membrane hydration level [1]. It is very essential as to ensure that the operating condition of a fuel cell are balanced in terms of temperature, humidity, and reactant flow rates to achieve optimum fuel cell performance [2]. Heat constituents in PEMFC are comparable with power output with percentages of 55% to entropic heat, 35% to irreversible reaction heat and remaining 10% to ohmic heating respectively [5]. The by-product of this electro-chemical reactions is the main contributor of heat generation where the elimination of heat is not efficiently executed as the temperature difference between the ambient temperature and the operating temperature of PEMFC (60˚C- 80˚C) is quite small [6].

The heat generated from PEMFC can be removed through various ways namely through cathode air cooling, liquid cooling, phase change cooling and heat spreader cooling [7]. However, there are many challenges for the heat to be eliminated efficiently. Among the initiatives studied by other researchers are by increasing the heat transfer area, improving the flow of the coolant in order to eliminate the hot spots and to improve the heat transfer property of the PEMFC cooling medium itself. The thermal properties of the conventional coolant used in PEMFC which is distilled water can be further improved in order to increase the heat dissipation from the system without sacrificing the compactness of the size[8]. Therefore, nanofluids as an alternative coolant to PEMFC is believed to offer a promising solution to the thermal management system of PEMFC.

Nanofluids are engineered colloids made of a base fluid and nanoparticles of 1 to 100nm in size. Nanofluids intensifies the heat transfer due to the superior thermo-physical properties mainly in term of thermal conductivity. Addition of metallic and non-metallic nano particles to the base fluids have increased the total surface area of the particles which eventually improved the heat transfer rate as compared to the base fluids. There are various of heat transfer studies on adoption of nanofluids [8-10]. Zakaria et al. [11] has concluded that both thermal conductivity and electrical conductivity of Al_2O_3 nanofluids have improved up to 12.8 % and 14.3 % respectively as compared to the base fluid. Another experimental analysis conducted by Zakaria et al. [12] using water based SiO_2 nanofluids proved that it reduced average plate temperatures by 15% to 20% as compared to conventional coolant. In terms of heat transfer coefficient enhancement by nanofluids, SiO_2 nanofluids has shown improvement of 3.5% as compared to base fluid of water through numerical analysis by Zakaria et al. [13]. Azmi et al. [14] has also experimented Al_2O_3 nanofluids and reported that its thermal conductivity has improved from 2.6% to 12.8% as compared to base fluid of water:ethylene glycol. Murshed and Estelle have reported that Al_2O_3 nanofluids is considered as one of the most commonly used nanoparticles by researchers, while SiO_2 is the least used non-metallic nanofluids [15]. . However, adoption of nanofluids as coolant has a penalty of additional pressure drop, resulting higher pumping power required [16]. This is due to the higher viscosity value of nanofluids as compared to the base fluids.

The single nanofluids are then further enhanced in order to improve the thermo-physical properties through combination of more than a single nano particle to form hybrid nanofluids or even tri-hybrid nanofluids. Abdul et al. [17] has performed an experimental investigation on water-based hybrid TiO_2:SiO_2 nanofluids. The study reported that the thermal conductivity enhancement exceeded up to 16 % higher than the base fluid. Meanwhile, Nabil et al. [18] conducted an experiment on water:EG based hybrid TiO_2:SiO_2 nanofluids and reported that the thermal conductivity has tremendously improved up to 22.8 % as compared to base fluid. However, not all hybrid nanofluids are a success story. There are failed hybrid nanoparticles reported which are due to the inhibition of natural convection because of agglomeration of two types of nanoparticles, causing the thermal conductivity of the nanofluids to decrease. The stability of hybrid nanoparticles also highly influenced the thermal conductivity of the nanofluid. Thus, the interaction between the two nanoparticles also important in contribution to the enhancement of thermal conductivity [13].

Nanofluids have a potential to be adopted in PEMFC as an alternative coolant. Nanofluids for PEMFC was initially developed by Dynalene Incorporation, USA who claimed to capable of maintaining its low electrical conductivity of the coolant which is less than 5 µS/cm for a minimum of 5000 h [6]. The low electrical conductivity property is strictly needed in PEMFC application as to avoid shunt current due to leakage of the electricity generated to the conductive coolant. This leakage will eventually reduce the performance of a PEMFC [19]. Studies have been performed by researchers namely Zakaria et al. [12] in both fundamental and stack level of PEMFC. The study shows that the heat transfer is improved by 13.8 % with the adoption of Al_2O_3 nanofluids in 50:50 (w:EG) as coolant in an experimental work of a single PEMFC cooling plate [20]. This is also in good agreement by findings of Islam et al. [21] who concluded that the radiator size can be further reduced up to 29 % with the adoption of ZnO in 50:50 (w:EG) as coolant in PEMFC. Zakaria et al. [11] later investigated the Al_2O_3 nanofluids in a 2.4 kWe fuel cell stack and observed that there is a slight reduction in the electrical power produced by the stack but still tolerable with the significant improvement in heat transfer rate. The suggested ratio was 0.1 vol % of Al_2O_3 nanofluids in water based on the TER (Thermo-electric ratio) established.

This study explored the improvement of hybridizing both Al_2O_3: SiO_2 nanoparticles in term of heat transfer and pressure drop in a PEMFC single plate. The hybrid nanofluids were varied in mixture ratios and Re number. It is expected that the hybrid nanofluids will perform better than the single nanofluids. At the end of the study, the most feasible Al_2O_3: SiO_2 hybrid nanofluids as an alternative cooling medium for PEMFC is established.

2. Methodology

2.1 Thermophysical Properties Measurement

Thermo-physical properties such as thermal conductivity and viscosity of nanofluids used in this study were measured experimentally at temperature of 27 °C.

The density of nanofluid was calculated using equation

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{1}$$

The density of hybrid nanofluid was calculated using equation

$$\rho_{hnf} = (1-\phi)\rho_f + \phi_{p_1}\rho_{p_1} + \phi_{p_2}\rho_{p_2} \tag{2}$$

The specific heat of nanofluid was calculated using equation

$$\frac{(1-\phi)\rho_f C_f + \phi\rho_p C_p}{\rho_{nf}} \tag{3}$$

The specific heat of hybrid nanofluid was calculated using equation

$$\frac{(1-\phi)\rho_f C_f+\phi_{p_1}\rho_{p_1}C_{p_1}+\phi_{p_2}\rho_{p_2}C_{p_2}}{\rho_{hnf}} \tag{4}$$

Where ϕ was referred.as particle volume fraction and subscripts *f*, *p1*, *p2*, *nf* and *hnf* are referred to base fluid (water), first nanoparticle (Al_2O_3), second nanoparticle (SiO_2), nanofluid and hybrid nanofluid. All required properties were tabulated in Table 1.

Table 1
Thermophysical Properties of Nanoparticles

Nanofluids	Thermal Conductivity, k (W/mK)	Specific Heat, Cp (J/kg.K)	Viscosity, μ (Pa.s)	Density, ρ (kg/m³)	Reference
SiO_2 0.5% conc.	1.38	740	-	2220	[13,22]
Al_2O_3 0.5% conc.	36	765	-	4000	[20,23]
Water	0.615	4180	0.000854	999	[13,20,24,25]

2.2 Mathematical Model of Mini Channel PEMFC Cooling Plates

A 3D computational fluid dynamic (CFD) was developed based on the distributor cooling plates dimensions. The material used for the mini channel was carbon graphite to mimic the conventional material used in cooling plate of PEMFC. The cooling plate was assembled with heater pad and coolant body using CATIA V5 software. The heater pad was placed at the bottom. of the cooling plate. The overall dimension for the distributor plates is shown in Figure 1. The Figure 2 explains the detailed dimension of the mini channel.

The heating pad was selected as a source term with only one energy source that bear the value of 1,298,701 w/m³ and assumed as constant. As for boundary conditions, the inlet velocity was varied in a range of Reynold Number between 400 to 2000 while the outlet is subjected to zero pressure. The fluid flow was assumed to be incompressible, laminar, and in steady state.

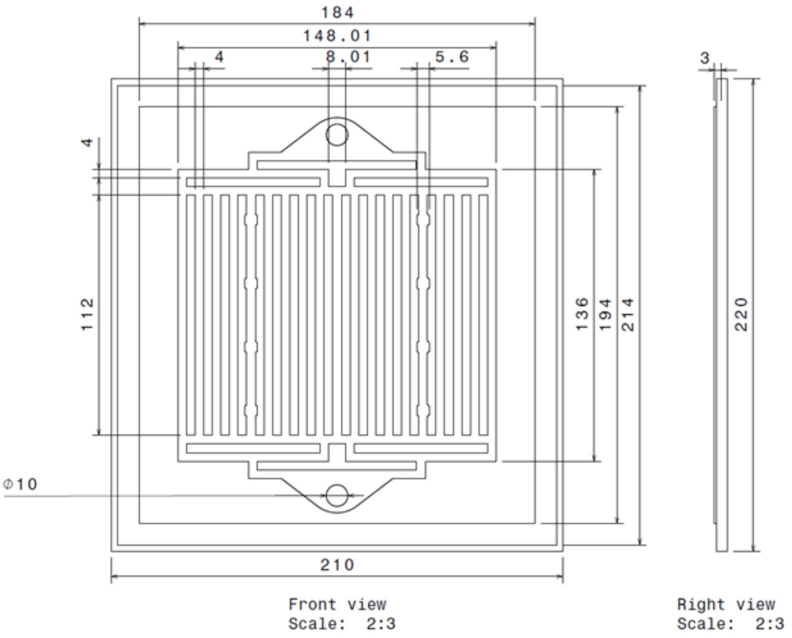
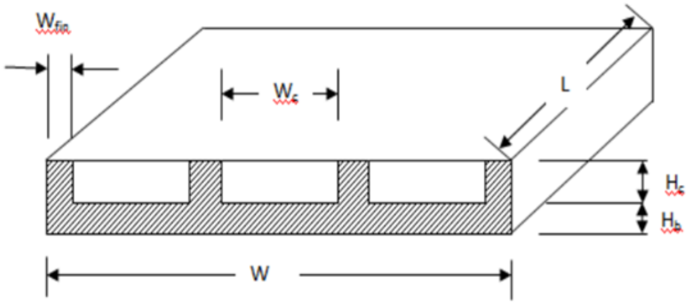


Fig. 1. Dimensions of distributor cooling plate



Parameter	Dimension, mm
Wfin	4
Wc	4
W	28
L	112
Hc	1
Hb	8

Fig. 2. Cross section of cooling plate mini channel

The simple algorithm (semi-implicit method for pressure linked equations) was selected as scheme to couple the pressure and velocity. The solution was executed using the hybrid initialization with iterations value of 30. The grid independence test conducted was presented in Figure 3. The result shows that the number of elements required was 2,731,324 for distributor cooling plate as the plate temperature remained stable from that point onwards.

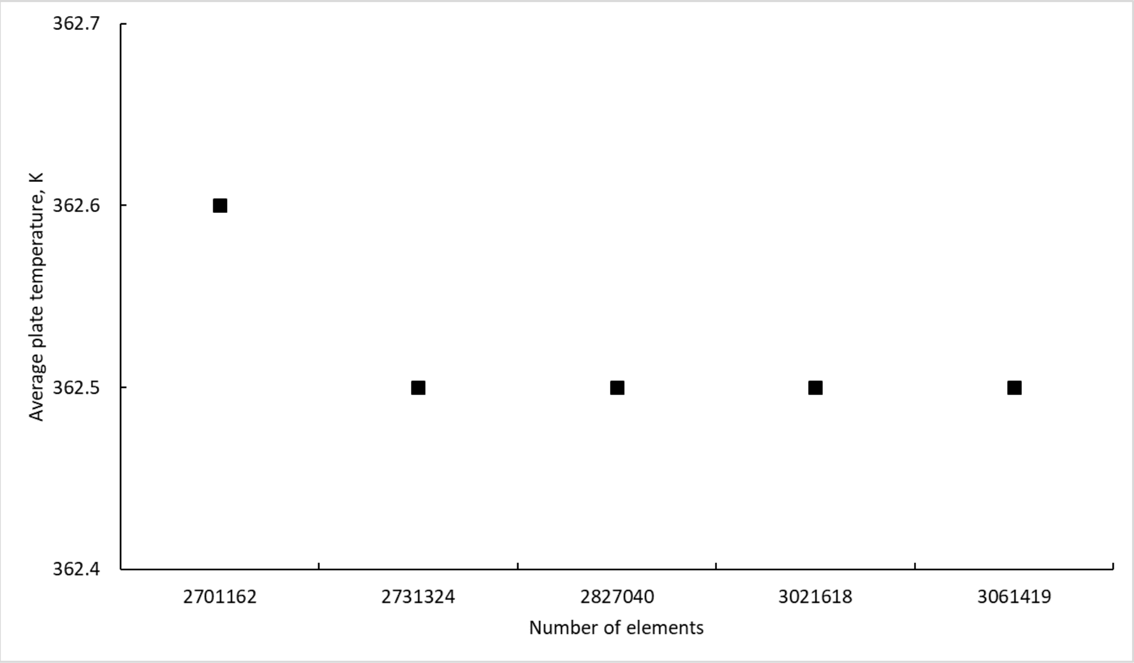


Fig. 3. Grid independence test on distributor cooling plate

The simulation done in Ansys 16.0 Fluent is governed by the following Eq. **Error! Reference source not found.**to**Error! Reference source not found.** [26]

Continuity equation

$$\nabla \cdot (\rho_{nf} \cdot V_m) = 0 \tag{5}$$

Momentum equation

$$\nabla\cdot\rho nf\cdot Vm\cdot VM=-\nabla P+\nabla\cdot(\mu nf\cdot\nabla Vm) \tag{6}$$

Energy equation for fluid

$$\nabla \cdot (\rho_{nf} \cdot C \cdot V_m \cdot T) = \nabla \cdot (k_{nf} \cdot \nabla T) \tag{7}$$

Heat conduction through solid wall

$$0 = \nabla \cdot (k_s \cdot \nabla T_s) \tag{8}$$

No slip boundary at the wall

$$\vec{V} = 0(@\text{Walls}) \tag{9}$$

Boundary conditions at inlet were assumed as

$$\vec{V} = V_m(@\text{inlet}) \tag{10}$$

$$P = \text{atmospheric pressure } (@\text{outlet}) \tag{11}$$

The heat is conducted through the solid and dissipated away via forced convection of fluid that flow through the distributor cooling plate. Bottom surface is uniformly heated with constant heat flux.

$$-k_{nf} \cdot \nabla T = q''(@\text{bottom of distributor cooling plate}) \tag{12}$$

$$-k_{nf} \cdot \nabla T = 0(@\text{top of distributor cooling plate}) \tag{13}$$

2.3 Heat Transfer and Fluid Flow Analysis

Heat transfer was then calculated using equation

$$h = \frac{q}{T_p - (\frac{T_i + T_o}{2})} \tag{14}$$

Nusselt number was calculated using equation

$$Nu = \frac{hD_i}{k} \tag{15}$$

Pressure drop was determined using equation

$$\Delta P = P_i - P_o \tag{16}$$

Pumping power was estimated using equation

$$W_p = \dot{Q} \times \Delta P \tag{17}$$

Advantage ratio was calculated using equation

$$\mathrm{AR} = \frac{\mathrm{h}}{\Delta \mathrm{P}} \quad (18)$$

where,
q = Heat flux
T_p = Average plate temperature
T_i = Inlet temperature
T_o = Outlet temperature
D_i = Inlet diameter
P_i = Input pressure
P_o = Output pressure
$\dot{Q}$ = Volume flow rate

3. Results and Discussion

Prior to analysing the heat transfer and pressure drop effect of hybrid nanofluids, the simulation was first validated to ensure its accuracy against published data [9]. The graph showed that the simulation conducted was in the range of 0.9 % to 9 % deviation from the published work as shown in Figure 4. The small deviation showed that the simulation was reliable and further analysis then was carried out.

In this study, plate temperature was the first data analysed for heat transfer effect of hybrid nanofluids on distributor cooling plate of PEMFC. The average plate temperature effect on different types of coolant across a range of Re was recorded in Figure 5. The lowest plate temperature was shown by 10:90 (Al_2O_3:SiO_2) hybrid nanofluids with 2.19 % reduction as compared to base fluid water at Re 2000. This was then followed by 20:80 (Al_2O_3:SiO_2) with 1.83 % reduction as compared to base fluid. The 50:50 and 60:40 (Al_2O_3:SiO_2) hybrid nanofluids on the other hand showed a slightly improved plate temperature as compared to single nanofluids of Al_2O_3 and SiO_2. The 90:10 (Al_2O_3:SiO_2) hybrid nanofluids were moreless at similar performance of single Al_2O_3 and SiO_2 nanofluids which were both at 1.64 % and 1.04 % reduced from water plate temperature consecutively. This improvement was due to the excellent thermal conductivity property of hybrid nanofluids as compared to single nanofluids and base fluid. The lower the ratio of Al_2O_3 in Al_2O_3:SiO_2 hybrid nanofluids proved to be more beneficial in reducing the plate temperature. This was in good agreement with the thermo-physical property measurement made by Khalid et al. [27]. Mixture of 30 nm SiO_2 and 13 nm of Al_2O_3 has improved the Brownian motion among the nanoparticles in the fluids.

The heat transfer enhancement was dictated by the cooling plate temperature reduction. The lower the plate temperature, the higher the convective heat transfer enhancement. The heat transfer coefficients for a distributor cooling plate were shown in Fig. 6. The figure showed that heat transfer coefficient was increased linearly as the Re number is increased. The highest enhancement was given by the hybrid 10:90 (Al_2O_3: SiO_2) nanofluids with 5.52 % enhancement as compared to the base fluid followed by hybrid 20:80, 50:50, 60:40 and 90:10 (Al_2O_3: SiO_2) with 4.61 %, 3.98 %, 3.77 % and 2.89 % enhancement respectively. Meanwhile, single Al_2O_3 nanofluids and single SiO_2 nanofluids showed 3.33 % and 2.33 % enhancement respectively as compared to base fluid at Re 2000. This showed that hybridization has greatly improved the heat transfer coefficient of the cooling fluid. The higher mixture ratio of SiO_2 provides a better heat transfer capability as compared to Al_2O_3 as concluded by Khalid et al. [27].

The Nusselt number (Nu), then calculated to represent the non-dimensionalize heat transfer enhancement. The Nusselt number analysis was shown as in Figure 7. Similar to heat transfer coefficient, Nusselt number was also observed to increase linearly as the Re is increased. The highest Nusselt number was shown by hybrid nanofluids which were at 10:90, 20:80, 50:50 and 60:40 (Al_2O_3: SiO_2) ratios. The 90:10 (Al_2O_3: SiO_2) hybrid nanofluids and both single Al_2O_3 and single SiO_2 nanofluids were at a lower region of Nusselt number and finally the lowest one was the base fluid of water. As the Nusselt number definition itself, it was concluded that hybrid nanofluids have higher convective heat transfer effect to conductive heat transfer across the boundary layer.

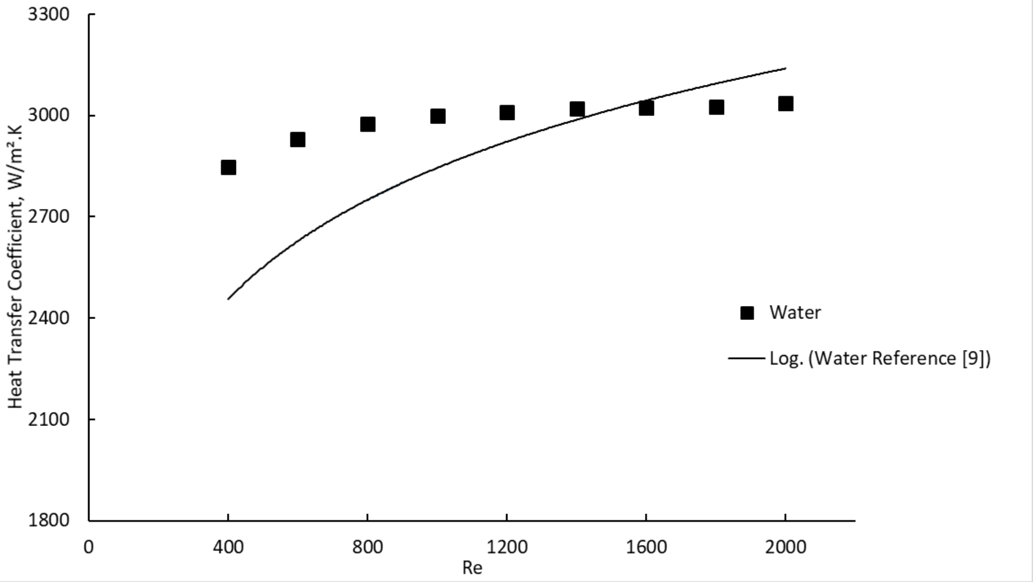


Fig. 4. Validation of this numerical study with reference in distributor cooling plate [12]

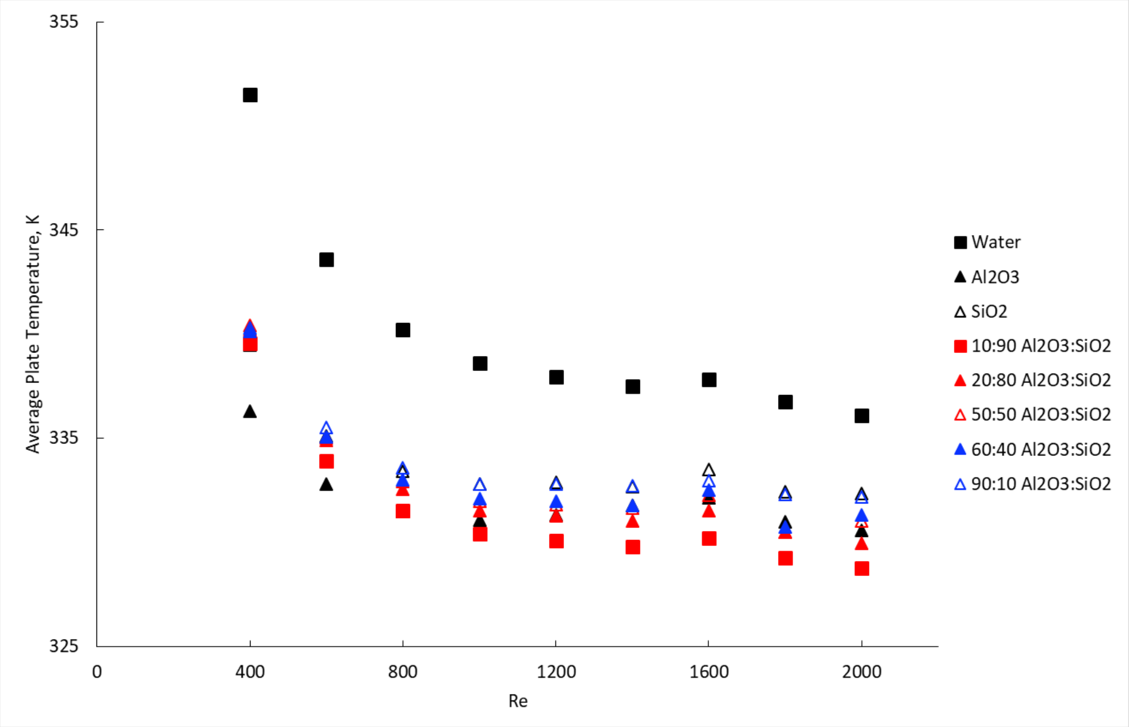


Fig. 5. Plate temperature comparison between hybrid nanofluids in distributor cooling plate

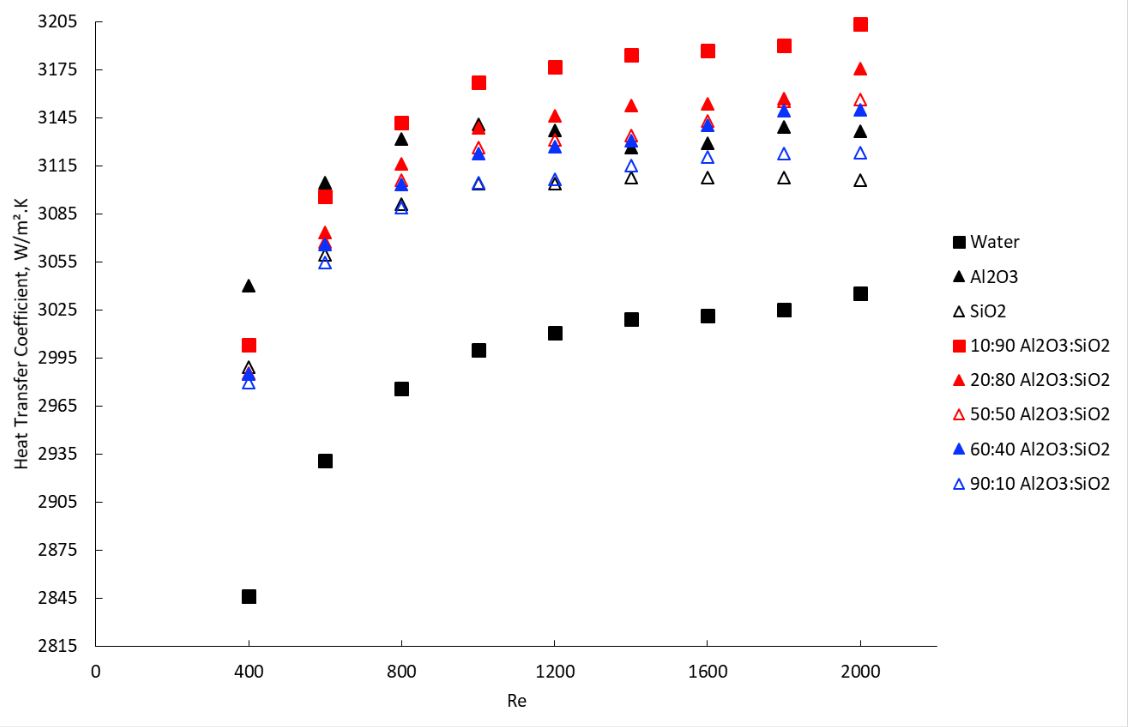


Fig. 6. Heat transfer coefficient comparison of hybrid Al_2O_3:SiO_2 , single nanofluids and base fluid in distributor cooling plate

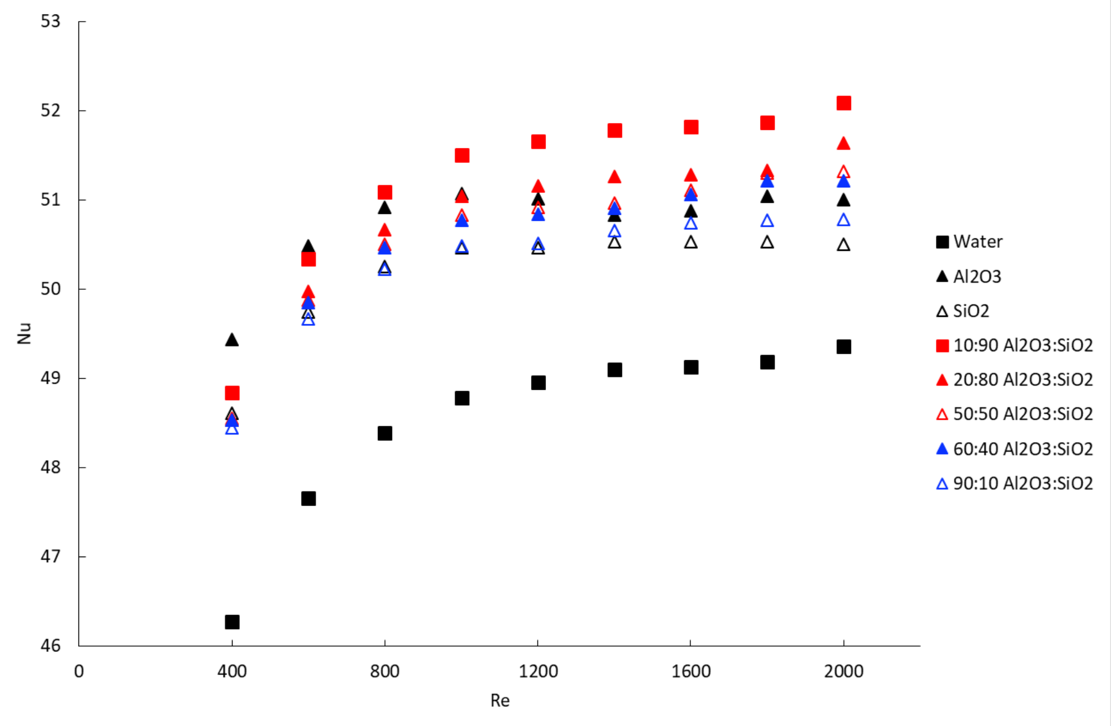


Fig. 7. Nusselt number comparison among hybrid nanofluids in distributor cooling plate

As to assess the fluid flow capability of hybrid nanofluids, pressure drop across the inlet and outlet was measured. The Figure 8 showed the pressure drop information between inlet and outlet for coolant flowing through the distributor plate. As the coolant was forced to pass through the narrow channels of the cooling plate, a high-pressure drop was expected. As shown in the graph, single nanofluids of Al_2O_3 nanofluids and SiO_2 nanofluids experienced were among the highest pressure drop fluids of 368 % and 210 % as compared to the base fluids. This was then followed by 90:10, 60:40, 50:50, 20:80 and 10:90 (Al_2O_3: SiO_2) with 161.4 %, 132.35 %, 123 %, 95.6 % and 88 % respectively as compared to base fluid. The hybrid nanofluids were found to be advantageous in reducing the pressure drop penalty as compared to single nanofluids adoption in cooling plate of PEMFC. Higher viscosity value of single Al_2O_3 nanofluids and SiO_2 nanofluids as compared to hybrid nanofluids studied has resulted a much higher pressure drop. This was well aligned with findings by Khalid et al. [27]. The design of the cooling plate itself also added to the higher pressure drop value as the flow was forced to go through a lot of 90 ° bends from inlet to outlet of the cooling plate. However, this was an advantage of hybrid nanofluids especially to the 10:90 (Al_2O_3: SiO_2) hybrid nanofluids as this fluid has a relatively lower pressure drop as compared to other but at the same time having a significantly high heat transfer enhancement. The pressure drop was also observed to increased linearly as the Re is increased.

The pressure drop information was then translated to pumping power requirement as to assess the additional pumping power requirement with the adoption of hybrid nanofluids in PEMFC cooling system. The pumping power requirement was shown in Figure 9. As both the hybrid and single nanofluids possessed higher density and viscosity values as compared to the base fluid, it has resulted in a higher pressure drop effect. To overcome such losses, additional pumping power was required. In distributor cooling plate, the highest pumping power required was required by single Al_2O_3 nanofluids and SiO_2 nanofluids with respectively 0.65 W and 0.32 W as compared to water of 0.07 W. This was then followed by hybrid 90:10, 60:40, 50:50, 20:80 and finally 10:90 (Al_2O_3: SiO_2) with 0.23 W, 0.18 W, 0.17 W, 0.12 W and 0.11 W respectively.

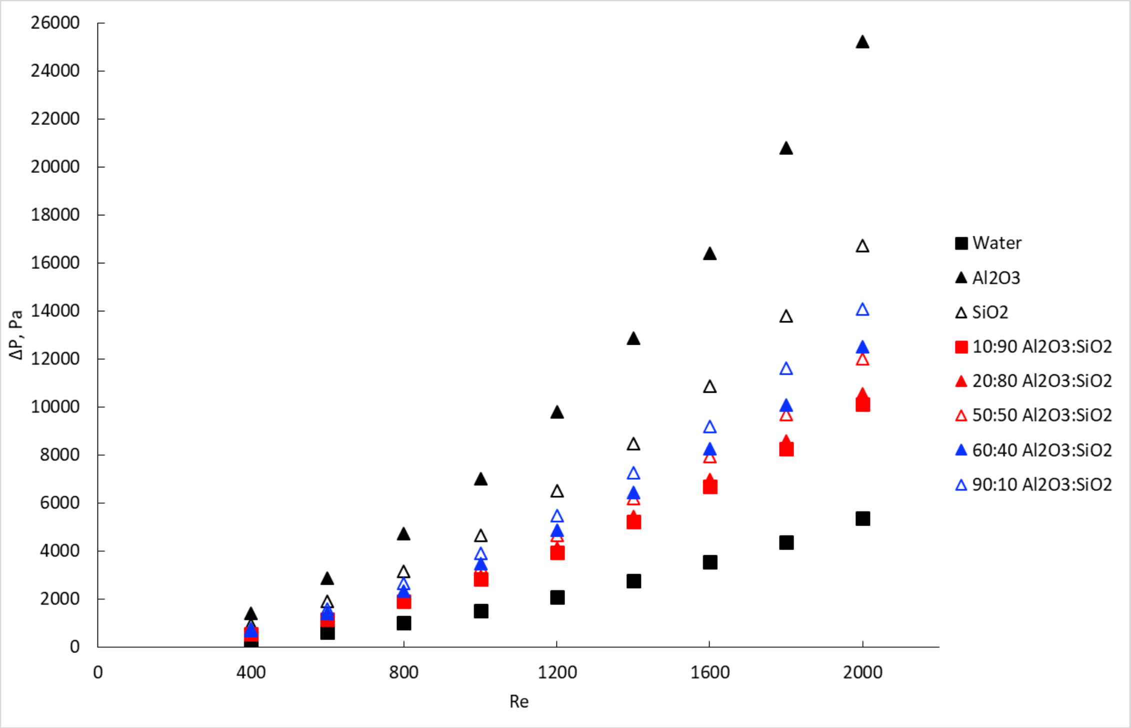


Fig. 8. Pressure drop comparison between hybrid nanofluids, single nanofluids and base fluid

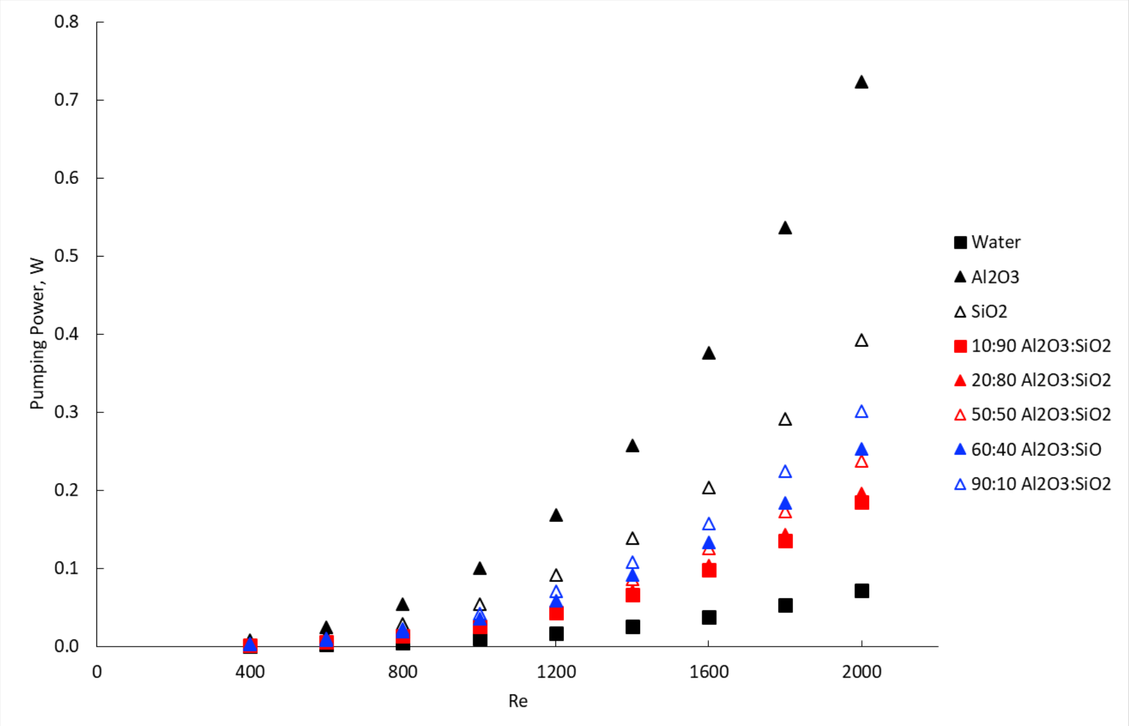


Fig. 9. Pumping power comparison between hybrid nanofluids, single nanofluids and base fluid in distributor cooling plate

The feasibility of the adoption of hybrid nanofluids in PEMFC cooling plate was analysed from the advantage ratio. The advantage ratio considers both effects of heat transfer enhancement over the penalty of the additional pressure drop experienced by the nanofluids. Advantage ratio of applied nanofluids was shown in Figure 10. The specification of AR 1 was used in analysing the feasibility of the adoption of hybrid nanofluids. Advantage ratio bigger than 1 should be feasible for applications considering both heat transfer enhancement and pressure drop factors [28]. The higher the advantage ratio showed that the more feasible the adoption is. As shown in the graph, the most feasible coolant for PEMFC was the hybrid 10:90 (Al_2O_3: SiO_2) nanofluids, followed by 20:80, 50:50, 60:40 and 90:10 (Al_2O_3: SiO_2) hybrid nanofluids. The single nanofluids were observed to be least feasible for the adoption considering the higher pumping power required as compared to the benefit of the heat transfer enhancement. However, it was also observed that the adoption was only feasible at Re lower than 1000. This was due to the exponential increment in additional pumping power requirement at higher Re.

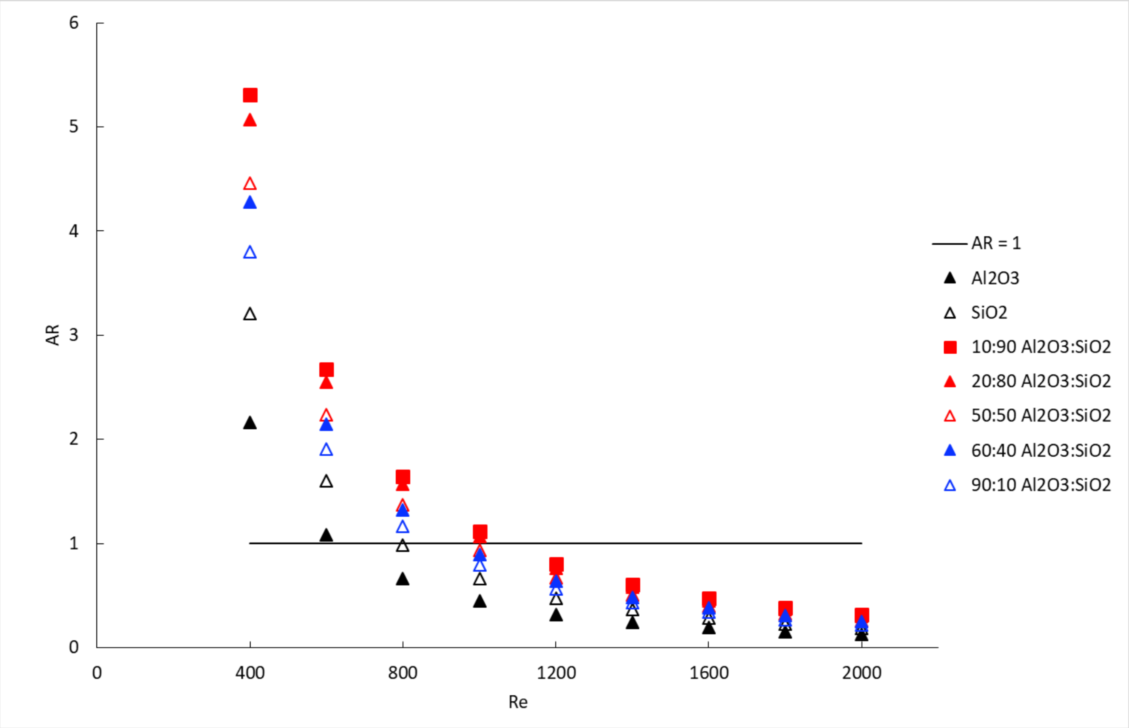


Fig. 10. Advantage ratio comparison between hybrid nanofluids, single nanofluids and base fluid in distributor cooling plate

4. Conclusions

In this numerical study, the heat transfer enhancement and pressure drop of 10:90, 20:80, 50:50, 60:40 and 90:10 (Al_2O_3: SiO_2) hybrid nanofluids in water based fluid on a distributor cooling plate of PEMFC were presented The improvement in the convective heat transfer coefficient and Nusselt number were compared against both single Al_2O_3 nanofluids, single SiO_2 nanofluids and base fluid of water. It was shown that the hybrid nanofluids were advantageous in term of heat transfer enhancement as compared to single nanofluids and base fluid. The pressure drop analysis was also favourable to hybrid nanofluids as all hybrid nanofluids candidates showed lower pressure drop than single nanofluids. The lower pressure drops then translated to minimum pumping power requirement. The feasibility of adoption of hybrid nanofluids as a coolant was justified by combining parameters of heat transfer enhancement over the penalty of pressure drop. The advantage ratio showed that 10:90 (Al_2O_3: SiO_2) hybrid nanofluids was an advantageous adoption in PEMFC at Re 1000 or lower. However, the findings needs to be verified by actual experiment to establish a stronger conclusions on this.

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