Performance of Hybrid Al_2O_3:SiO_2 W:EG in PEM Fuel Cell Distributor Plate

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ABSTRACT

Efficient thermal management is essential for the optimal performance and durability of the Proton Exchange Membrane Fuel Cell (PEMFC). However, the conventional passive cooling methods require a larger heat exchanger for better heat dissipation. Alternatively, nanofluids as a coolant have gained attention recently due to their enhanced heat transfer properties. This investigation aims to evaluate the thermal performance of hybrid nanofluids in a distributor type of PEMFC cooling plate. In this investigation, 0.5% volume concentration of mono Al_2O_3, mono SiO_2 nanofluids, and hybrid Al_2O_3:SiO_2 nanofluids with a mixture ratio of 10:90, 30:70, 50:50, and 70:30 in 60:40 W:EG were investigated. The cooling plate was modelled and a fixed heat flux of 6500 w/m^2 was applied to replicate the actual working parameter of PEMFC. The study shows that the heat transfer coefficient was improved by 61% in 10:90 hybrid nanofluids of Al_2O_3:SiO_2 in W:EG in comparison to the base fluid. Meanwhile, the accompanied pressure drops in 10:90 hybrid nanofluids of Al_2O_3:SiO_2 in W:EG show a reduction up to 4.38 times lower as compared to single Al_2O_3 nanofluids at Re 1800. This is advantageous since it will reduce the parasitic loss related to the PEM fuel cell.

Keywords: *Hybrid Nanofluids; Heat Transfer Enhancement; Pressure Drop; PEMFC*

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Introduction

The urge for a reduction in dependency on fossil fuel sources has become a global direction nowadays. The depletion of fossil fuel and the carbon footprint increment has driven the direction for a renewable energy source. Hence, there is a rising trend in the adoption of alternative energy to replace current conventional internal combustion engines (ICE) with renewable energy sources as outlined by the government plan [1]. Among the potential candidates of renewable energy in the primary energy mix is hydrogen, H_2. A fuel cell is a device that generates electrical energy from the reaction of hydrogen and oxygen via an electrochemical reaction [2]. PEM fuel cells are advantageous because of their high power density, rapid startup, and dynamic load response [3]. The lower operating temperature of PEM fuel cells which is in the range of 60 °C to 80 °C has attracted researchers in various applications including automotive, small-scale stationary power generation, and portable power applications [4]. Its higher efficiency of 60% as compared to 20% to 30% in internal combustion engines has also added value to the PEM fuel cell [5].

However, despite the advantages, the PEM fuel cell comes with one critical flaw. PEM fuel cell operates at low temperature which is at 60 °C to 80 °C provides a low driving force to remove excessive heat out of the system. This in turn will cause the accumulation of heat in the system that will affect the hydration of the most critical part of the PEM fuel cell which is the membrane electrodes assembly (MEA). An efficient heat transfer is crucially needed in PEM fuel cells to maintain the optimum condition of the membrane thus ensuring its optimal performance [3].

There are various heat removal methods for PEM fuel cells such as adaptation of larger heat exchangers and improvement in MEA material. However, these methods increase the existing cost and require a bigger package for the cooling system [6]-[8]. Yong et al. [9] reviewed cooling strategies for a large-scale PEM fuel cell while Liu et al. [10] discovered phase change cooling coupled with waste heat recovery for PEM fuel cell. In addition to that, passive cooling is also explored that enhances the coolant thermal-physical properties termed nanofluids. This passive cooling is doable for adoption in a liquid-cooled PEM fuel cell with the possibility of heat exchanger size reduction [11].

Nanofluid base fluids containing a dispersion of nano-sized particles have been shown to improve cooling liquids' thermal conductivity [12]. There are several studies done by researchers on the capability of nanofluids in increasing thermal conductivity namely Islam et al. [13] who mentioned that type and concentration of nanoparticles in nanofluids is the main factor that determines the thermal conductivity of nanofluids. An experimental work by Zakaria et al. [14]-[15] reported that there is an improvement of thermal and electrical conductivity up to 12.8% and 14.3%, respectively with the adoption of Al_2O_3 nanofluids as compared to water as the base fluid. In addition to that, numerical work performed by Zakaria et al. [16] mentioned that Al_2O_3 nanofluids in her study have intensified the heat transfer up to 37% as compared to the base fluid. An experimental study by Khalid et al. [17] also reported an increase in thermal conductivity of up to 4.19% and 1.42% for Al_2O_3 and SiO_2, respectively, as compared to the water. However, the implementation of nanofluids as a coolant comes with a penalty of higher pressure drop due to its high viscosity value as compared to the base fluid which eventually required higher pumping power to force the coolant around the cooling circuit [18].

The nanofluids study has progressed from mono nanofluids to hybrid and eventually ternary nanofluids, which further improve the thermo-physical properties of the base fluid [19]. The nanofluids are prepared either from single or two-step methods where two or more nanoparticles were dispersed in a base fluid. Esfe and Afrand [20] reviewed that hybrid nanofluids enhance thermal conductivity better than mono nanofluids. However, this was further investigated by Khalid et al. [21], using Al_2O_3 and SiO_2 hybrid nanofluids in PEM fuel cells. The study reported that hybrid nanofluids increase thermal conductivity up to 51.9% but only at certain mixture ratios. In the hybrid Al_2O_3: SiO_2 water study, a lower ratio of Al_2O_3 is preferred since it enhances the heat transfer as compared to single nanofluids but not at the higher mixture ratio of Al_2O_3. Experimental work by Sahid et al. [22] on TiO_2:ZnO nanoparticles concluded that thermal conductivity increased as the volume concentration increased. A numerical study on hybrid nanofluids was also conducted by Idris et al. [23] for 10:90 and 50:50 ratios of hybrid Al_2O_3:SiO_2 nanofluid in water base fluid and concluded that the most feasible fluid is hybrid 10:90 Al_2O_3:SiO_2 nanofluids base on heat transfer and pressure drop effect.

In liquid-cooled PEM fuel cells, there are several types of cooling plates such as parallel, serpentine, and distributor type as reported by Ramos-Alvarado et al. [24]. The findings suggested that distributor type is the most recommended design for liquid-cooled because it achieved outstanding flow consistency while maintaining a remarkably low-pressure loss. In the designs of cooling plates in PEM fuel cells, mini channels were adopted as they allowed a closed-packed stack with higher heat transfer rates and lower cell temperatures. However, for the adoption of nanofluids in mini channels, there are some concerns about the additional pumping power requirement to be weighed out with the enhancement in heat transfer [25]. Apart from this, possible leakage of current produced needs to also be monitored as demonstrated by Zakaria et al. [7], [26] due to the strict limit of electrical conductivity which is 5 $\mu S/cm^2$ permissible for PEM fuel cell [27].

The effect of Al_2O_3:SiO_2 nanofluids in water has been studied previously in distributor cooling plates [28]. Al_2O_3 and SiO_2 are preferred due to the vast availability of the nanoparticles in the current market. The stability of this hybrid combination is also proven to be excellent and suitable for a closed-loop cooling circuit application [29]. However, no study has been reported on Al_2O_3:SiO_2 hybrid nanofluids in a mixture of water:Ethylene Glycol (60:40) which is commonly used in automotive as a coolant. In this work, a distributor cooling plate was modelled and heated up by a constant heat flux of 6500 W/m^2 to replicate the heat generation during the reaction in actual PEM fuel cell operation [6]. The performance of the hybrid Al_2O_3:SiO_2 nanofluids in terms of heat transfer enhancement and pressure drop against base fluid, single 0.5% Al_2O_3 nanofluids, and single 0.5% SiO_2 nanofluids in distributor cooling plate of PEMFC was observed. This study is essential as it will cover a wider range of base fluids studied for hybrid Al_2O_3:SiO_2 nanofluids. The application of cooling plates is not restricted to PEM fuel cells alone, it can be adopted in any type of cooling application such as electronics heat sinks as well.

Methodology

Thermo-physical properties

The properties of nanofluids used in this study were experimentally measured using a KD2 Pro Thermal analyser for thermal conductivity and Brookfield Rheometer for dynamic viscosity. In addition to that, the density of mono nanofluids and hybrid nanofluids was calculated using Equation (1) and Equation (2) while specific heat for mono nanofluids and hybrid nanofluids was estimated from Equation (3) and Equation (4) as listed below [30]:

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

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

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

$$C_p = \frac{(1-\emptyset)\rho_f C_f + \emptyset_{p_1}\rho_{p_1} C_{P_1} + \emptyset_{p_2}\rho_{p_2} C_{P_2}}{\rho_{hnf}} \tag{4}$$

where $\emptyset$ refers to particle volume fraction and subscripts f, p_1, p_2, n_f, and h_{nf} refer to base fluid (water:EG), first nanoparticle (Al_2O_3) second nanoparticle (SiO_2), nanofluids, and hybrid nanofluids. All properties of nanoparticles and base fluid used are listed in Table 1.

The thermal conductivity of the nanofluids was measured using the KD2 Pro thermal property analyser from Decagon Devices Inc., the United

States. Meanwhile, the dynamic viscosity measurement was performed using Brookfield LVDV-III Ultra Rheometer as shown in Figure 1.

Table 1: Properties of the base fluid and nanoparticles used in the study

Fluid name	Density ρ, (kg/m^3)	Specific heat Cp, (J/kg.K)	Thermal conductivity k, (W/m.K)	Viscosity μ, (Pa.s)	Ref.
W:EG (60:40)	1056.7	3419.8	0.4096	0.002400	[31]-[32]
Al_2O_3	1071.4	3440.9	0.412	0.003500	[23]
SiO_2	1062.5	3463.1	0.411	0.003200	[30], [33]

(a)

(b)

Figure 1: (a) KD2 Pro thermal property analyser, and (b) Brookfield LVDV-III Ultra Rheometer

Modeling and simulation of PEM fuel cell cooling plate

The geometry of the cooling plate was designed using CATIA V5R20 software where the heater pad and the fluid flow model were also attached to the PEM fuel cell cooling plate. The model is an assembly of the distributor cooling plate, attached to a heater pad as shown in Figure 2 while the channel's cross-sectional detailed dimensions are shown in Figure 3 and Table 2. The cooling plate was modelled as a carbon graphite cooling plate. The bottom surface of the plate was subjected to a fixed temperature of 343 K with a constant heat flux of 6500 w/m^2. The silicon heater pad was used to replicate the real application of the PEM fuel cell. The heat generated was conducted through the graphite cooling plate and rejected to the moving fluid that passes through the mini channel. The circulation of cooling fluid is performed through close-loop forced convection.

Several assumptions were made to simplify the simulation [28] as follows:

i. Viscous dissipation was disregarded, and fluid properties remain constant.
ii. The flow was in a steady state, laminar, and incompressible.
iii. The impact of body force was disregarded.
iv. The resulting combination can be thought of as a typical single phase, and both the fluid phase and the nanoparticles had zero relative velocities while in thermal equilibrium.
v. Laminar flow was assumed in this mini-channel analysis as being practiced by other mini-channel researchers in their studies [34]-[35].

Based on the assumptions made beforehand, the governing equations used in this study were as follows [23]:

Continuity equation:

$$\nabla.\left(\rho_{nf}.V_m\right) = 0 \tag{5}$$

Momentum equation:

$$\nabla.\left(\rho_{nf}.V_m.V_M\right) = -\nabla P + \nabla.\left(\mu_{nf}.\nabla V_m\right) \tag{6}$$

Cooling fluid's Energy equation:

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

Heat conduction through graphite cooling plate:

$$0 = \nabla.\left(k_s.\nabla T_s\right) \tag{8}$$

No slip boundary at the wall:

$$\vec{V} = 0(\text{at walls}) \tag{9}$$

The boundary condition at the inlet of the plate is assumed as;

$$\vec{V} = 0(\text{at walls}) \tag{10}$$

P = standard atmospheric pressure at outlet (11)

$$-\mathrm{k_{nf}}.\nabla\mathrm{T} = \mathrm{q}''(\text{at bottom of mini channel}) \tag{12}$$

$$-\mathrm{k_{nf}}.\nabla\mathrm{T} = 0\ (\text{at top of mini channel}) \tag{13}$$

Grid independence test

The distributor-typed cooling plate was initially meshed for the simulation work as shown in Figure 4. The grid independence test was performed to optimize the selection of meshing element requirements. The optimized meshing element selected for simulation is 2731324 as shown in Figure 5. In this figure, average plate temperature was observed as it is one of the critical data gained from the simulation. It was noticed that the average plate temperature started to get constant at 2731324 meshing elements and it continued to remain constant until the value of 3061419 meshing elements.

Therefore, the optimized meshing element of 2731324 was chosen for the complete simulation work. Lower meshing elements than this will cause inaccurate results meanwhile higher meshing elements will increase the simulation lead time but still arrive at the same result accuracy [7], [36].

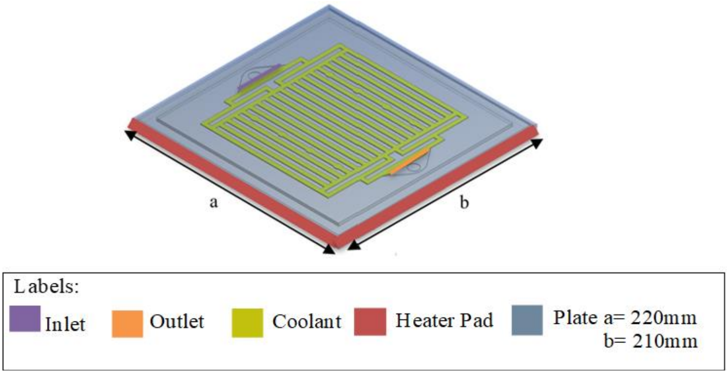

Figure 2: Distributor cooling plate of PEM fuel cell in isometric view

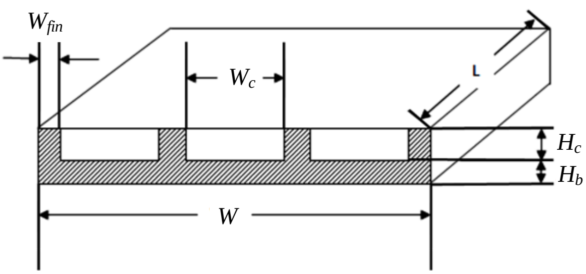

Figure 3: Cross section on the channel in the distributor cooling plate

Table 2: Detailed dimensions of the channel in the distributor cooling plate

Parameter	Diameter (mm)
W_{fin}	1
W_c	4
W	148
L	112
H_c	1
H_b	3

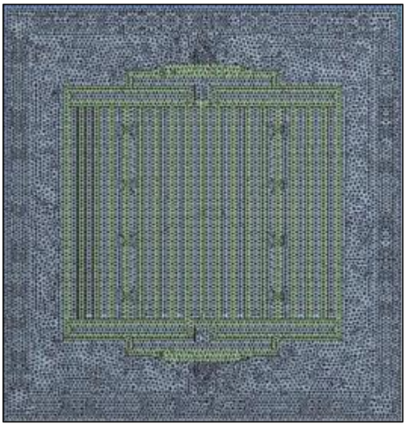

Figure 4: Meshing of distributor typed cooling plate of PEM fuel cell

Mathematical model

The heat transfer coefficient of the hybrid Al_2O_3:SiO_2 nanofluids and Nusselt number were calculated using Equation (14) and Equation (15), respectively. The average heat transfer coefficient. h_{ave} and Nu_{ave} calculation adopted the same mathematical equation as practiced by other researchers in this field [7], [37]-[38].

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

$$Nu_{ave} = \frac{hD_i}{k_{nf}} \tag{15}$$

The fluid flow parameter was calculated from the pressure drop and pumping power values. The pressure difference between the inlet and outlet flow was calculated using Equation (16) while the pumping power was calculated from Equation (17) [7].

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

$$W_{pump} = \dot{V}\Delta P \tag{17}$$

where $\dot{q}$, Pi, Po, Di, and $\dot{V}$ was referred to as heat flux, inlet pressure, outlet pressure, inlet diameter, and volume flow rate.

Results and Discussion

Thermo-physical properties

The experimentally measured critical thermos-physical properties of hybrid Al_2O_3:SiO_2 nanofluids at various mixture ratios at ambient room temperature of 30 °C are shown in Table 3. It is shown that the highest thermal conductivity of hybrid Al_2O_3:SiO_2 nanofluids is at 10:90 (Al_2O_3:SiO_2) with 0.432 W/m.K which was equivalent to 4.85% improvement as compared to its base fluid of 60:40 water:EG. This was then followed by 30:70 and 50:50 mixture ratios accordingly. It was observed that the higher value of Al_2O_3 has resulted in a lower thermal conductivity value which agrees with the findings by Khalid et al. [21].

Meanwhile, dynamic viscosity values show the highest value experienced by the 70:30 (Al_2O_3:SiO_2) ratio while the lowest viscosity value is at 10:90 of the mixture ratio at 30 °C. Other than thermal conductivity and dynamic viscosity, specific heat capacity and density were also determined prior to Ansys simulation analytically.

Table 3: Thermo-physical properties of hybrid nanofluids used in the simulation

Material: Al_2O_3:SiO_2 in 60:40 (W:EG)	Density (kg/m^3)	Specific heat capacity (J/kg.K)	Thermal conductivity (W/m.K)	Viscosity (Pa.s)
10:90	1063.422	3460.820	0.432	0.002826
30:70	1065.202	3456.368	0.428	0.002900
50:50	1066.982	3451.930	0.418	0.003039
70:30	1068.762	3447.507	0.413	0.004624

Validation of the simulation

Validation work to ensure the accuracy of the simulation data against established data published in the literature review was executed before the full simulation work. The distributor cooling plates simulation was validated against the work of Zakaria et al. [39] which used a similar base fluid of water:EG (60:40) mixture. There was a deviation range of 0.08% to 6.39% observed as compared to the established work as depicted in Figure 5. The small deviation showed that the parameters used in the simulation were accurate and fit for further analysis.

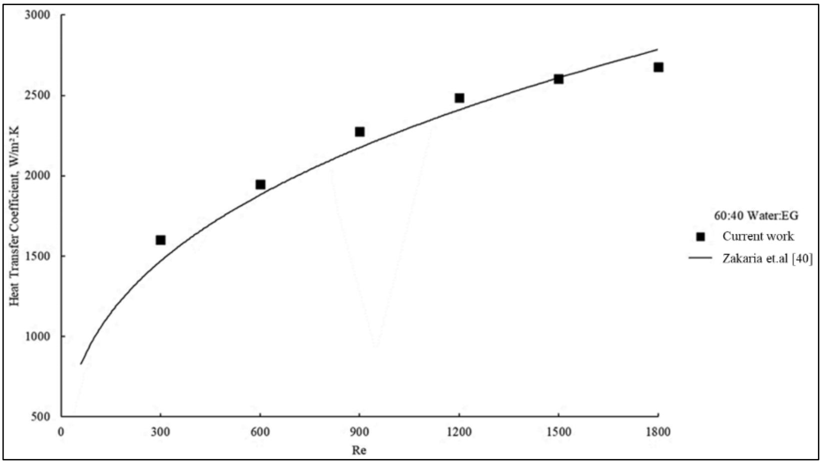

Figure 5: Validation of simulation data with published experimental work [39]

Effect on heat transfer

Average plate temperature

The initial data recorded in the effect of heat transfer is the cooling plate's temperature. Different types of cooling fluids passing through the cooling channel will result in different average temperatures as shown in Figure 6. The increment in the fluid flow rate also affected the plate temperature. As shown in Figure 6, the temperature of the plate depreciated as the *Re* number increased. This is a known relationship due to better cooling performance achieved at nanofluids' higher flow rate [8]. At *Re* 1800, 10:90 (Al_2O_3:SiO_2) hybrid nanofluids demonstrated the lowest plate temperature with a 1.5% reduction over water:EG mixture. This was subsequently followed by 30:70, 70:30, and 50:50 (Al_2O_3:SiO_2) hybrid nanofluids with 1.37%, 1.36%, and 1.20%, respectively as compared to the base fluid. Both mono nanofluids of Al_2O_3 and SiO_2 had the least reduction with 1.11% and 0.72%, respectively in comparison to the base fluid's plate temperature. The outstanding improvement in hybrid nanofluids' thermal conductivity has resulted in the improvement in the cooling plate temperature reduction in comparison to the base fluid. It was also noticed that the smaller ratio content of Al_2O_3 in a specific Al_2O_3:SiO_2 mixture of hybrid nanofluids has resulted in a better temperature of distributor cooling plate. The thermal conductivity value of the smaller fraction of Al_2O_3 ratio in Al_2O_3:SiO_2 hybrid nanofluids has shown higher values as compared to a higher fraction of Al_2O_3 as reported by Khalid et al. [22] as his novel findings.

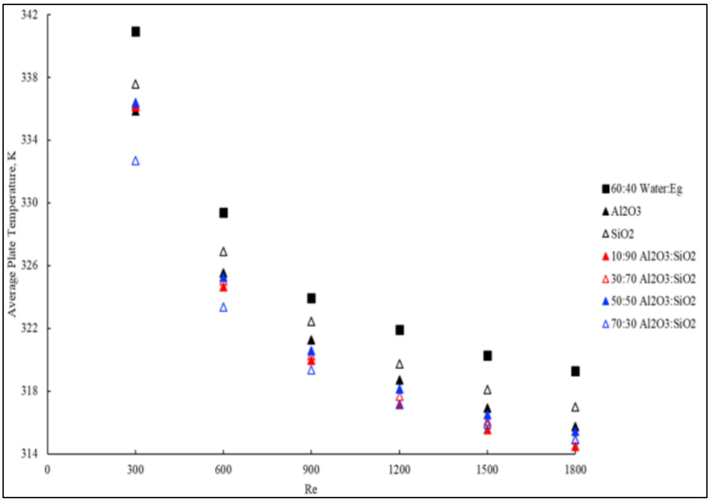

Figure 6: Effect of distributor cooling plate temperature with hybrid Al_2O_3:SiO_2 nanofluids, mono nanofluids, and base fluid of water:EG

Temperature contour

The effect of improvement in heat transfer was visualized graphically through the dispersion of plate temperature of base fluid W:EG, mono Al_2O_3 nanofluids, mono SiO_2 nanofluids, and four different ratios of hybrid Al_2O_3:SiO_2 nanofluids across the distributor typed cooling plate as depicted in Figure 7. The temperature contour was observed at the same *Re* 1800 for all working cooling fluids. It was observed that there was a reduction of hot spot area in cooling plates in single and hybrid Al_2O_3:SiO_2 nanofluids in comparison to base fluid. This might be due to lower cooling plate temperature contributed by the higher value of thermal conductivity of fluids flowing inside the plate. Higher thermal conductivity value of fluids resulting better heat transfer thus minimizing the hot spot area. The plate temperature reduction is also observed in single and hybrid Al_2O_3:SiO_2 nanofluids cooling plates.

Heat transfer coefficient

The cooling plate temperature reduction serves as a basis for further investigation on the improvement of heat transfer due to the hybrid Al_2O_3:SiO_2 nanofluids. The improvement of heat transfer coefficients for the distributor-typed cooling plate is shown in Figure 8. Overall, nanofluids' heat transfer coefficient significantly increased in hybrid nanofluids in comparison to water:EG base fluid. The linear increment of the heat transfer coefficient was also observed as the Re number was increased. The hybrid 10:90 (Al_2O_3: SiO_2) nanofluids gave the highest enhancement with 61.36% enhancement in comparison to the base fluid, recorded at *Re* 1800. The trend was subsequently followed by 30:70 (Al_2O_3:SiO_2), 50:50, and 70:30 hybrid nanofluids with 50.79%, 43.46%, and 38.58% enhancement, respectively. The lower percentage concentration of Al_2O_3 nanofluids in the hybrid nanofluids ratio showed better heat transfer performance since these ratios have better thermal conductivity value than higher ratios of Al_2O_3 nanofluids which is aligned with the highlights by Khalid et. al [21]. Meanwhile, the performance of its mono Al_2O_3 nanofluids and SiO_2 nanofluids have shown slightly smaller improvement of 6.73% and 3.61% enhancement, respectively in comparison to base fluid at *Re* 1800. A smaller increment was noticed in mono nanofluids as compared to hybrid nanofluids due to a smaller enhancement in the thermal conductivity of mono nanofluids and base fluid as compared to hybrid nanofluids studied [21], [30]. A similar effect of *Re* number increment was also noticed in the heat transfer coefficient value as well. The heat transfer coefficient increased linearly as the flowrate was increased.

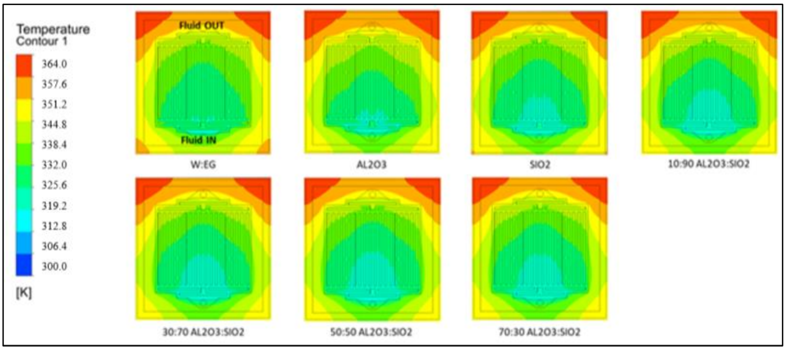

Figure 7: Distributor typed cooling plate's temperature contour

Nusselt number

The non-dimensionalized Nusselt (*Nu*) number was presented to show the heat transfer enhancement. The *Nu* number has shown a linear increment with regards to the increment in the *Re* number as expected. This was presented in Figure 9. The 10:90 (Al_2O_3:SiO_2) hybrid nanofluids showed with highest Nusselt number and subsequently followed by 30:70 (Al_2O_3:SiO_2), 50:50, and 70:30 hybrid nanofluids. There was also an increase in the *Nu* number of mono nanofluids of Al_2O_3 and SiO_2 nanofluids, but the increment was not as significant as the hybrid Al_2O_3:SiO_2 gave. The highest *Nu* number was shown by a 10:90 ratio which indicated that the 10:90 (Al_2O_3:SiO_2) has a greater convective heat transfer effect across the boundary as compared to the conductive heat transfer effect [40]. The 0.5 vol% concentration of hybrid Al_2O_3:SiO_2 in water:EG mixture enhanced the *Nu* number by up to 61.36% due to the increment in the convective heat transfer characteristic over conductive heat transfer.

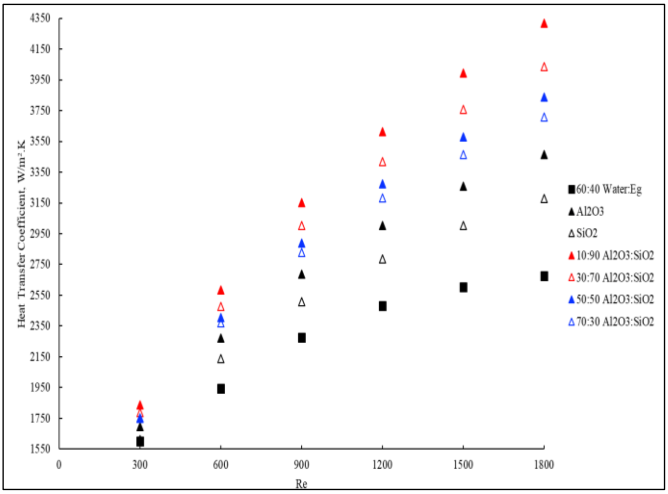

Figure 8: Performance of heat transfer coefficient in hybrid Al_2O_3:SiO_2 nanofluids, mono nanofluids, and base fluid of water:EG in distributor cooling plate

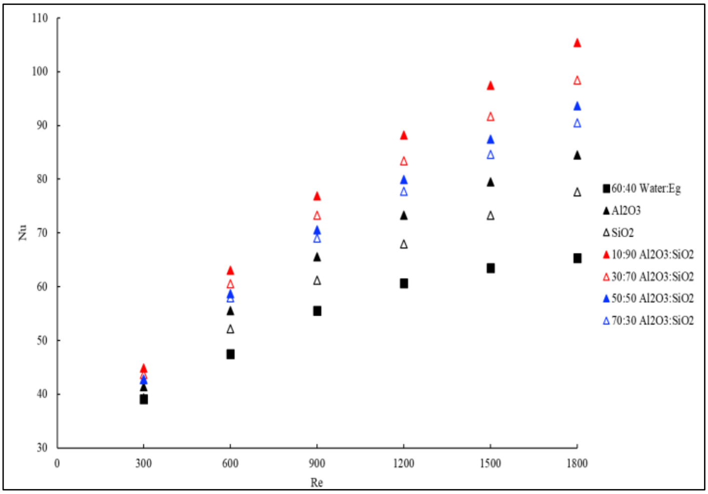

Figure 9: Distributor cooling plate Nusselt number against *Re* number

Fluid flow behaviour

As for fluid flow behaviour of hybrid Al_2O_3:SiO_2 nanofluids, mono nanofluids, and base fluid, pressure drop was recorded and translated to the pumping power effect.

Pressure drop

The pressure drop measures the difference in pressure readings between the plate's inlet and outlet. This was recorded to investigate the effect of hybrid nanofluids on the additional fluid flow required. The pressure drop readings are shown in Figure 10. Higher pressure drop was predicted as the hybrid nanofluids have higher dynamic viscosity and density in comparison to the base fluid. Moreover, the distributor plate's geometry which has sharp bends and narrow channels has made the liquid harder to circulate around the plate. The highest-pressure drop was shown by mono Al_2O_3 nanofluids which is 3 times higher followed by the mono SiO_2 nanofluids of twice higher than the base fluid respectively at *Re* 1800. The 70:30 (Al_2O_3:SiO_2) was second with 128.18% and then followed by 50:50, 30:70, and 10:90 hybrid nanofluids with 115.24 %, 91.92%, and 82.13%, respectively. The result of the 10:90 mixture ratio has shown the lowest pressure drop in comparison to other mixture ratios of hybrid nanofluids which is favourable to the application. This is an interesting finding as 10:90 (Al_2O_3:SiO_2) hybrid nanofluids showed to be the most potential candidate for PEM fuel cell cooling fluid due to its highest heat transfer enhancement but also the least impactful to the pressure drop penalty. This was due to its lower viscosity value as compared to other mixture ratios of hybrid nanofluids which has impacted such higher pressure drop [30]. This matched well with the outcomes of Khalid et al. [14] who also reported that the 10:90 ratio in water has a minimal effect on pressure drop but at a preferrable heat transfer improvement in comparison to others.

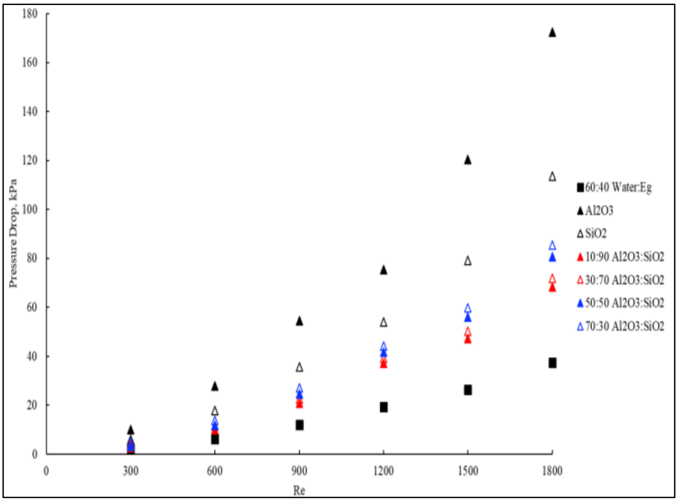

Figure 10: Comparison of pressure drop in hybrid Al_2O_3:SiO_2 nanofluids with respect to other fluids in distributor cooling plate

Pumping power

The effect of the pressure difference between the outlet and inlet of the fluid was then translated to the increase in power needed to circulate the hybrid cooling fluids around the cooling system. Figure 11 shows the increase in pumping power with the implementation of hybrid cooling fluids. As the base fluid has lower density and viscosity values, these have resulted in lower pressure drop as compared to both hybrid nanofluids and single nanofluids. To cope with the additional pressure drop penalty, additional pumping power needs to be supplied to the hybrid nanofluid system. In the PEM fuel cell distributor cooling plate, mono Al_2O_3 nanofluids, a 70:30 ratio of hybrid nanofluids and mono SiO_2 nanofluids required among the higher pumping power which was 6.73 W, 4.01 W, and 3.61 W, respectively in comparison to water:EG base fluid of 1.23 W at *Re* 1800. This was followed by hybrid 50:50, 30:70, and finally 10:90 (Al_2O_3:SiO_2) with 2.02 W, 1.55 W, and 1.34 W higher than W:EG (60:40), respectively. Nevertheless, the increase in pumping power required is considered low compared to the stack performance of at least 1 kWe.

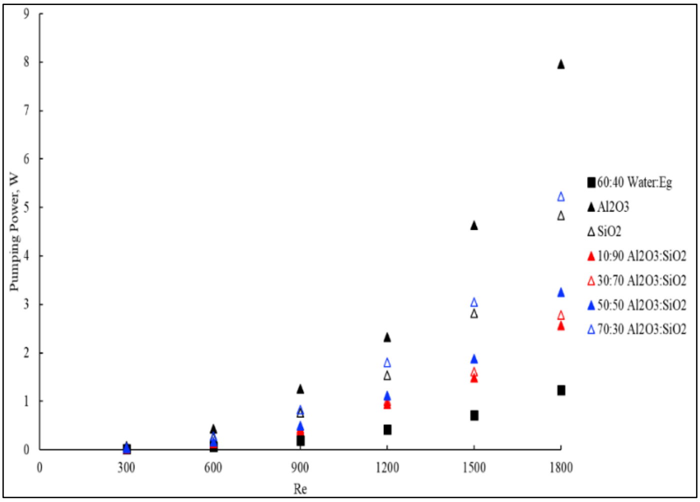

Figure 11: Effect on pumping power requirement of hybrid Al_2O_3:SiO_2 nanofluids against single nanofluids and base fluid in distributor cooling plate

Conclusions

In this simulation work, it was concluded that there was a heat transfer enhancement experienced with the adoption of hybrid Al_2O_3:SiO_2 nanofluids mixture ratios of 10:90, 30:70, 50:50, and 70:30 in water: Ethylene Glycol (60:40) as a cooling fluid in PEMFC. There highest improvement was recorded with 61% enhancement in the convective heat transfer coefficient and Nusselt number with 10:90 Al_2O_3:SiO_2 hybrid nanofluids in W:EG (60:40) as compared to its base fluid. However, the higher pressure drop analysis was also experienced with hybrid nanofluids adoption but interestingly the 10:90 Al_2O_3:SiO_2 hybrid nanofluids in W:EG (60:40) was favourable due to its capability of reducing the pressure drop effect by 4.38 times lower as compared to the single Al_2O_3 nanofluids. It was shown that 10:90 (Al_2O_3:SiO_2) hybrid nanofluids have the most advantageous adoption compared to other candidates in terms of both heat transfer and pressure drop in the distributor cooling plate of the PEM fuel cell.

Contributions of Authors

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Conflict of Interests

All authors declare that they have no conflicts of interest

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