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Research paper

Numerical Analysis of SiO_2 Nanofluid Performance in Serpentine PEMFC Cooling Plate

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Abstract

Proton exchange membrane fuel cell (PEMFC) is among the potential substitute to current conventional internal combustion engine (ICE) in the automotive sector due to its efficient conversion efficiency and environmental friendly. However, thermal management issues in PEMFC needs to be addressed as excessive heat in PEMFC can deteriorate its performance as well as causing dehydration to the membrane. In this study, an advanced coolant of SiO_2 nanofluids was numerically studied and effect in term of the heat transfer and fluid flow behavior in a single PEMFC cooling plate is investigated. The study simulated SiO_2 nanofluids in a serpentine PEMFC cooling plate. The simulation is conducted at a low volume concentrations of 0.1, 0.3 and 0.5 % of SiO_2 in water and water: Ethylene Glycol (W:EG) of 60:40 as base fluids. In this serpentine cooling plate design of PEMFC, a constant heat flux is applied to mimic the actual application of PEMFC. Upon completion of the study, heat transfer and fluid flow shows that the heat transfer coefficient of 0.5 vol. % of SiO_2 nanofluids has improved by 3.5 % at Reynold (Re) number of 400 as compared to the base fluid of water with an acceptable pumping power increment.

Keywords: *Heat transfer; serpentine; numerical; fluid flow; PEMFC.*

1. Introduction

Hydrogen energy emerges as a promising alternative energy due to their high efficiency and minimal impact to the environment [1]. Among the highlight of hydrogen energy carrier is PEMFC which has a huge potential to ICE replacement due to its excellent conversion efficiency and environmental friendly [2]. The PEMFC is an electrochemical device that converts chemical energy (hydrogen) into electrical energy, with the conversion energy efficiency closes to two times higher than the internal combustion engine. It can convert chemical energy into electrical energy up to 60 % efficiency as compared to ICE [3]. This has attracted global automotive players to invest in their fuel cell vehicles namely Hyundai Tucson ix35, Toyota Mirai and Honda Clarity [4, 5].

In order to secure the excellent energy conversion, an effective thermal management is crucially required. This is essential as to obtain an optimum humidity of the membrane electrode assembly (MEA), which is the most vital component to the reaction process. The MEA humidity needs to be optimized as excessive heat can result in dehydration while too much humidification can cause flooding issue [6]. A small temperature difference between ambient and PEMFC working temperature of 60 to 80 °C has made the heat removal more challenging [7].Several attempts made by researchers worldwide in order to improve the thermal management of PEMFC including adoption of larger heat exchangers [8] and improving the MEA material from the traditional Nafion to phosphoric acid doped material that can withstand a higher temperature range of 120 to 200 °C [9]. However, larger heat exchanger is not preferred due to strict packaging requirement and new membrane material has added the greatly to the existing cost.

Alternatively, a passive method through adoption of nano-sized solid particles dispersed in base fluid is introduced. Nanofluids was initiated by Choi and Eastman [10] from Argonne National Laboratory in 1995. Nanofluids have significantly increased the thermal conductivity of the base fluid thus enable an enhancement in heat transfer. The first adoption of nanofluids in fuel cell application was performed by US Department of Energy (DoE) with the in 2013 [11]. Nanofluids were initially introduced to improve the coolant's durability performance since the electrical conductivity requirement in PEMFC is very stringent. The electrical conductivity requirement for PEMFC is 1.5 µS/cm at 20°C temperature as outlined by McMullen et al. in his Dynalene FC [12].

The nanofluids studies in PEMFC then continuously explored by researchers. Zakaria et al.[13] has established a TEC (thermal-electrical conductivity) ratio to evaluate the feasibility of Al_2O_3 as coolant in PEMFC. The potential and challenges of nanofluids as coolant in PEMFC has been reviewed by both Islam et al. and Zakaria et al.[14, 15]. Zakaria et.al then further evaluate the heat transfer enhancement and fluid flow effect in both numerical and experimental studies of PEMFC cooling plate. Experimental validation was performed on full stack of PEMFC and reported to be feasible for the adoption [16, 17].

This study explores the potential of SiO_2 nanofluids as an alternative cooling medium to PEMFC. Both heat transfer and fluid flow behaviours in a single serpentine PEMFC cooling plate is observed numerically.

2. Methodology

2.1. Nanofluids Preparation

In this experiment, silicon dioxide (SiO2) aqueous solution was procured from US Research Material Inc. The solution of 13.45% volume concentration of SiO_2 nanofluids was then diluted to form SiO_2 nanofluids with volume % concentration of 0.1, 0.3 and 0.5 %. The solution was diluted in base fluid of water and water:EG mixture with ratio of 60:40 (W:EG). EG used were supplied by R&M chemicals with 99.96 % purity. The basic properties of nanoparticles and base fluids used are tabulated in Table 1.

Table 1: Properties of nanoparticles and base fluids used in this experiment

Nanoparticles/ Base fluid	Thermal Conductivity, K (W/m.K)	Electrical conductivity, σ (µS/cm)	Density, ρ (kg/m^3)	Ref
SiO2	1.38	10^{-21}	2220	[18]
Distilled water	0.615	6	999	[19]
Ethylene Glycol	0.252	1.07	38	[19]

2.2. Thermo-Physical Properties of SiO2 Nanofluids

There are several thermo physical properties measured for SiO_2 nanofluids namely thermal conductivity and dynamic viscosity. The actual measurement of thermo physical properties were performed in order to produce a higher accuracy numerical analysis due to actual properties input during the simulation. Both thermal conductivity and dynamic viscosity were measured using KD2 Pro thermal property analyzer of Decagon Devices, Inc., USA and Brookfield LVDV-III Ultra rheometer respectively. The properties were measured at 40°C to replicate coolant working temperature in PEMFC. The properties then keyed in to the simulation software for analysis.

2.3. Numerical Model

The numerical investigation was performed using ANSYS FLUENT Version 15 for a single serpentine cooling plate of a PEMFC. The information on the cooling plate is shown in Fig. 1. The material used for the plate is carbon graphite which was subjected to a constant heat flux of 100 W to mimic the working operation in PEMFC [20].
The geometry was designed using CATIA V5R20 before exported to ANSYS FLUENT for mesh generation and simulation.
For simplification , several assumptions have been made [21]:-

1. The fluid properties are constant and viscous dissipation is neglected.
2. The flow is in steady state and laminar.
3. Both fluid phase and nanoparticles are in thermal equilibrium with zero relative velocity and the resultant mixture can be considered as a conventional single phase.
4. Heat transfer and fluid flow are identical in all channel in the cooling plate.

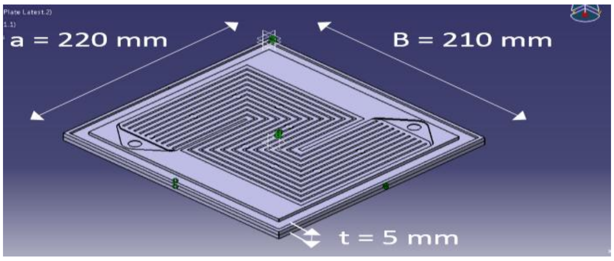

Fig. 1: Geometry of a single serpentine cooling plate with the basic dimension used in this study

The governing equations on the above assumptions are as follows.[22]
Continuity equation :

$$\nabla.\left(\rho_{nf}.V_m\right) = 0 \quad (1)$$

Momentum equation :

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

Energy equation for coolant :

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

The heat conduction through the solid wall :

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

No slip boundary at the wall :

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

Boundary conditions at channel inlet were assumed as :

$$\vec{V} = V_m\ (@inlet) \quad (6)$$

$$P = atmospheric\ pressure\ (@outlet) \quad (7)$$

The governing equations were solved at every cell for different values of Re number studied. Grid independence study was performed in order to verify that the meshing element used is an optimum option since higher number of meshing element will increase simulation time while lower meshing number or insufficient meshing will result in inaccurate result of simulation [23].
In this study, three meshing elements were used to evaluate the plate temperature and the optimized meshing element of 245362 was selected for the simulation work. The grid independent study performed is presented in Fig 2.

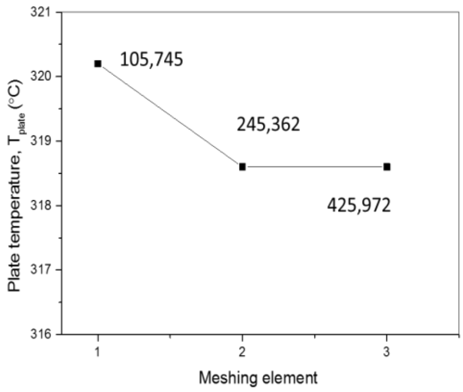

Fig. 2: Grid independent study performed in this numerical work

2.4. Mathematical Model

Heat transfer was analyzed through heat transfer coefficient and Nu number. Both heat transfer coefficient and Nu number were calculated using Eqn.(8) and Eqn.(9) respectively.

$$h = \frac{\dot{q}}{(T_{avgplate} - T_{avgfluid})} \quad (8)$$

$$Nu = \frac{hD_h}{k_{nf}} \quad (9)$$

Meanwhile, fluid flow was analyzed based on the pressure drop effect between IN flow and OUT flow. The pressure drop was then used to represent additional pumping power required in order to circulate SiO_2 nanofluids through serpentine cooling plate. Pumping power requirement is calculated using Eqn. (10) :

$$W_{pump} = \overset{*}{V} \times \Delta P \quad (10)$$

Where $\dot{V}$ is the volumetric flow rate and ΔP is the pressure drop.

3. Result and Discussion

3.1. Heat Transfer Enhancement

The initial parameter investigated was plate temperature measurement as this will indicate the enhancement gained from the SiO_2 nanofluids adoption. Plate temperature information is shown in Fig. 3. The plate temperature reduces as the Re number increased due to the higher cooling effect gained with the increase in flow rate of both SiO_2 nanofluids and base fluids. Highest plate temperature was recorded at base fluids of both water and 60:40 (W:EG). The plate temperature then started to reduce as the vol % concentration of SiO_2 nanofluids is increased. Addition of 0.5 vol % of SiO_2 nanofluids at Re 150 in water has resulted temperature drop of 0.3 % as compared to base fluid. This is due to the higher thermal conductivity property of SiO_2 nanofluids as compared to base fluid. Meanwhile, the reduction of plate temperature is lower in base fluid of 60:40 (W:EG) with 0.1 % reduction of plate temperature for 0.5 vol % of SiO_2 nanofluids as compared to the base fluid. The effect of SiO_2 nanofluids in W:EG is less significant as compared to SiO_2 nanofluids in water due to the smaller increment in thermal conductivity property of SiO_2 nanofluids in 60:40 (W:EG) as compared to SiO_2 nanofluids in water.
The temperature difference recorded was then further evaluated to observe the convective heat transfer coefficient as depicted in Fig. 4. In general, heat transfer coefficient of SiO_2 nanofluids were tremendously increased in SiO_2 nanofluids as compared to base fluid of water. The higher concentration of SiO_2 nanofluids shows better improvement as the intensity of Brownian motion induced by nanoparticle movement increased. This is consistent with findings from other studies of nanofluids in mini channel application [22, 24]. It is observed that an increment of 3.5 % is gained in 0.5 vol % concentration at re 400, while 0.3 and 0.1 vol % showed improvement of 2.6 % and 1.6 % respectively.

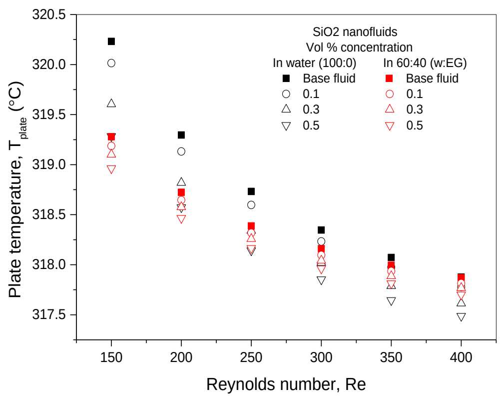

Fig. 3: Plate temperature SiO_2 readings for nanofluids and base fluids studied

SiO_2 nanofluids in base fluid water shows obvious difference as compared to SiO_2 nanofluids in 60:40 (W:EG). This significant difference is due to the higher thermal conductivity property of base fluid water as compared to 60:40 (W:EG) base fluid. However, the addition of SiO_2 nanofluids to 60:40 (W:EG) base fluid does alter the heat transfer coefficient readings as 0.5 vol % concentration of 60:40 (W:EG) has improved by 2.4 % at re 400. The 0.3 vol % and 0.1 vol % SiO_2 nanofluids in 60:40 (W:EG) have also resulted an improvement of 1.6 % and 0.9 % respectively as compared to the base fluid. The smaller increment was observed in SiO_2 nanofluids in 60:40 (W:EG) as compared to SiO_2 nanofluids in water due to the smaller improvement in thermal conductivity property between SiO_2 nanofluids and 60:40 (W:EG) base fluid. It was also observed that the heat transfer coefficient increases with the increase in Re number as an effect to the lower plate temperature experienced with the increase in volumetric flow rate of fluid.

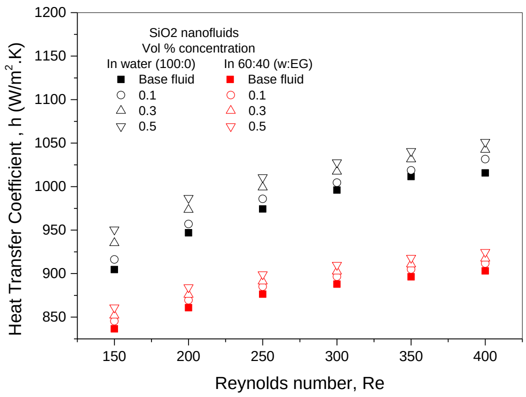

Fig. 4: Heat transfer coefficient comparison between SiO_2 nanofluids and base fluids studied.

Another parameter investigated was Nusselt number, Nu. Nu number serves as a valid comparison among other researchers' works in the same field due to its non dimensionalized characteristic. The Nu number information is shown in Figure 5. It is observed that the Nu number increases as the Re number is increased due to the increase in convective heat transfer enhancement with respect to volumetric flow rate increment.

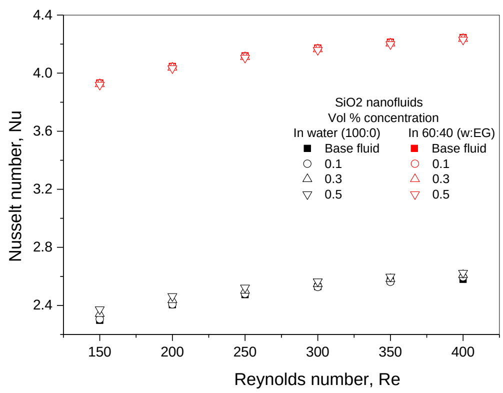

Fig. 5: Nu number comparison between SiO_2 nanofluids

The SiO_2 nanofluids in base fluid of 60:40 (W:EG) was observed to be significantly higher than SiO_2 nanofluids in base fluid of water. This indicates that SiO_2 nanofluids in base fluid of 60:40 (W:EG) possess higher convective heat transfer method as compared to conduction across the boundary layer. This was mainly contributed by the low thermal conductivity value characteristic of SiO_2 nanofluids in base fluid of 60:40 (W:EG) as compared to SiO_2 nanofluids in base fluid of water.

Addition of nano-sized SiO_2 particles have increased Nu number of base fluid for instance 0.5 vol % concentration of SiO_2 nanofluids in water has enhanced the Nu number by 1.7 % due to the increased in the convective heat transfer coefficient characteristic.

3.2. Fluid Flow Effect

Upon knowing the advantage of heat transfer advancement of SiO_2 nanofluids adoption in cooling plate of PEMFC, fluid flow analysis is also crucial to ensure that it is a feasible adoption. Higher fluid flow will result in higher pumping power which is not favourable in a PEMFC application [1].

Fluid flow was analysed through pressure drop experienced between IN and OUT of cooling plate. The pressure drop across plate then calculated to represent pumping power. Information on pumping power is presented in Figure 6.

It was observed that the pumping power increases as the volume concentration is increased. The highest pumping power was recorded by 0.5 vol % concentration of SiO_2 nanofluids in 60:40 (W:EG) with increment of 0.03 W as compared to the base fluid of 60:40 (W:EG). Meanwhile, 0.5 vol % concentration of SiO_2 nanofluids in water recorded an increase of 0.01 W as compared to base fluid water.

The increase in pumping power was expected due to the increase of viscosity and density of SiO_2 nanofluids against base fluids. The addition of nanoparticles have resulted in higher internal friction and resistance to flow which eventually increases the pumping power required [24]. However, this parasitic losses increment was observed to be at an acceptable value. This was concluded based on reviewing other researchers' work on complete PEMFC stack such as the experimental work by Zakaria et. al [16] which shows that the actual lab scale stack has a rated power up to 2.4 kW. This high rated power makes the pumping power penalty to be acceptable.

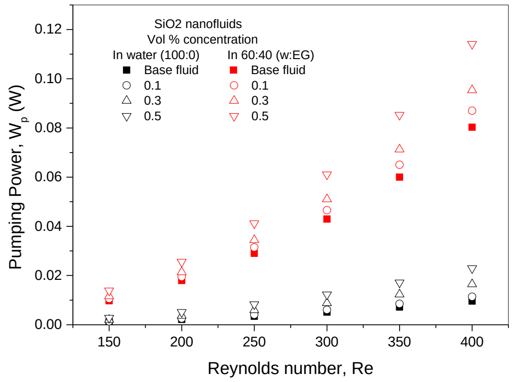

Fig. 6: Pumping power effect with the adoption of SiO_2 nanofluids

Graphically, the effect on the heat transfer enhancement was also visible through the temperature distribution of SiO_2 nanofluids temperature across the cooling plate as shown in Figure 7.

The contour was recorded at the same Re number of 200. In comparison, as the volume concentration of SiO_2 nanofluids is increased, the temperature of the fluid started to reduce. This is contributed by the reduction of plate temperature as discussed above.

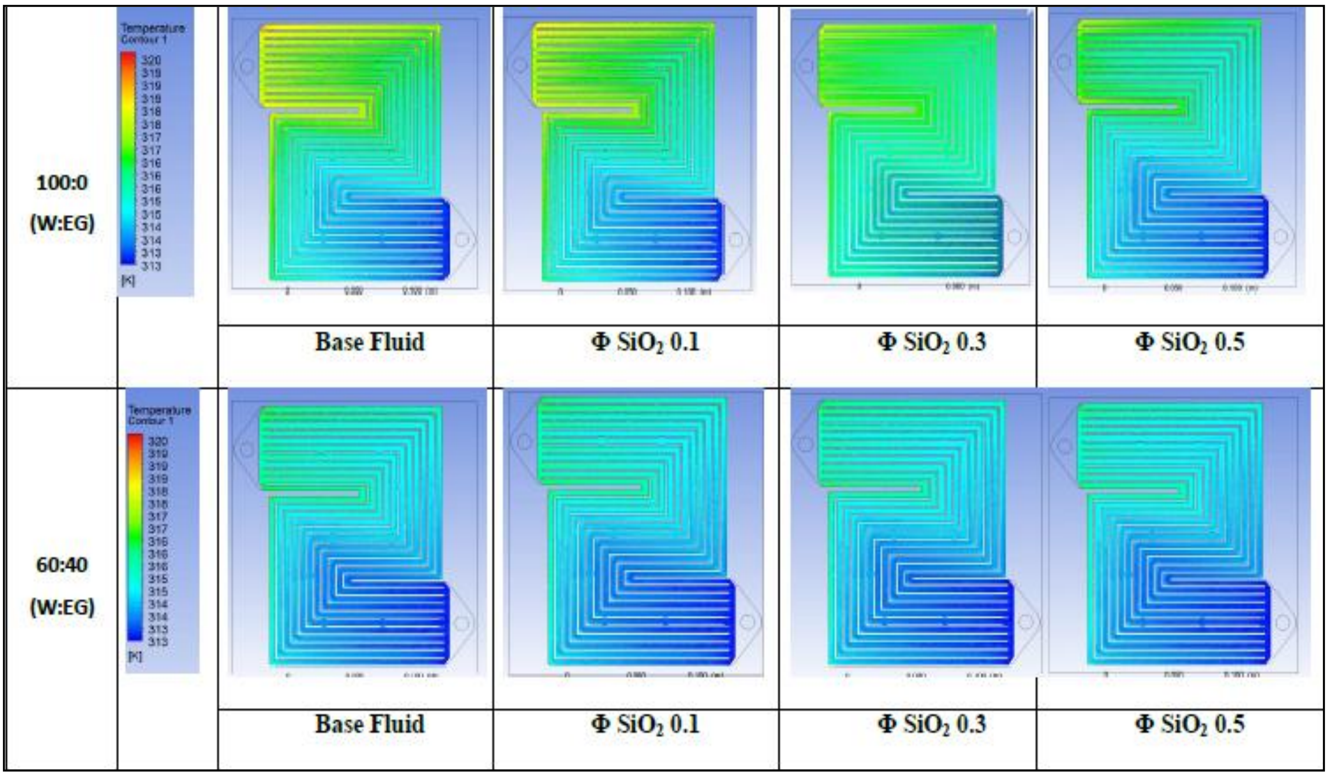

Fig. 7: Temperature distribution for SiO_2 nanofluids and base fluids at Re 200

4. Conclusion

Adoption of SiO_2 nanofluids to the heat transfer of a serpentine plate of PEMFC has resulted in an enhancement in heat transfer. This study which focuses on low volume concentrations of 0.1 to 0.5 vol % in water give a significant improvement in term of convective heat transfer improvement up to 3.5 % at Re 400. The improvement is lower for SiO_2 nanofluids in 60:40 (W:EG) due to its lower base fluids thermal conductivity property. However, there was a slight penalty in term of additional pumping power required for the adoption of SiO_2 nanofluids in PEMFC. This additional pumping is relatively small if compared to the actual electrical power produced by a full stack of PEMFC. Further experimental validation is required to justify the findings.

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