Numerical Analysis Of Al_2O_3 Nanofluids In Serpentine Cooling Plate Of PEM Fuel Cell

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ABSTRACT

PEM fuel cell converts the energy potential of a hydrogen based fuel into electricity with water and heat as the major by-products. In order to optimize the performance of a PEM fuel cell, the cooling system is responsible to manage the accompanying heat. In this study, heat transfer and fluid flow performance of Aluminium oxide, Al_2O_3 nanofluids in a serpentine cooling plate is investigated numerically. The Al_2O_3 nanofluids concentration of 0.1%, 0.3% and 0.5% was dispersed in both water and 60:40 and 50:50 water:ethylene glycol (w:EG) mixture of base fluids. The thermo-physical properties of the prepared nanofluids namely thermal conductivity and viscosity were measured and then fed to the simulation to enable maximum accuracy to the real experimentation result. A steady and incompressible flow with constant heat flux is assumed in the carbon graphite channel of 210mm x 220mm. All characteristics studied is at Re number range of 150 to 400. A serpentine cooling plate is used to mimic a single cooling plate in a complete stack of PEM fuel cell. The simulation used was ANSYS Fluent in laminar flow condition. The result shows that the heat transfer coefficient of 0.5 % volume concentration of Al_2O_3 in 100:0(w:EG) has increased up to 37 % as compared to base fluid. The increase in pumping power is experienced but at a much lower value as compared to the thermal management advantage.

Keywords: *PEM fuel cell, serpentine, nanofluids, thermal,numerical.*

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Introduction

Hydrogen fuel cell is recently favourable as an alternative solution of energy diversification over internal combustion engine since it is environmental friendly that produces only water and heat as by products. It is predicted to has a large scale production tailored for fuel cell by 2020 [1]. Hydrogen fuel cell offers a completely greener solution to conventional power conversion system as only water and heat are produced as byproducts [2]. PEM fuel cell is favourable in many applications due to its high power density, quick start up and dynamic load response [3]. PEM fuel cell operates at low temperature of 60 to 80 °C thus making it a favourite candidate for automotive application, small scale distributed stationary power generation and for portable power applications [4]. PEM fuel cell offers higher power density as compared to internal combustion engine (ICE), thus making it more compact to package. PEM fuel cell can reach its efficiency as high as 60 % as compared to 20 to 30 % in internal combustion engine [5]. The accompanying heat of a PEM fuel cell would then requires an excellent thermal management in order to ensure an optimum condition of operation in term of temperature, reactants flow rates and also humidity. Membrane humidity is extremely important as it proton conductivity sensitivity is very much dependant on the hydration level.

Maxwell (1873) has originated the novel findings of nanofluids which is dispersant of metallic particles to enhance the thermal conductivity of a basefluid. Choi and Eastman [6] then initiated the study on copper (Cu), which has 700 times greater than water and 3000 times greater than oil at room temperature to form nanofluids. The Cu nanofluids showed dramatic increment in thermal conductivity by factor of three without any significant increase in pumping power requirement in heat exchanger.

As coolant in PEM fuel cell is circulated through mini channels in cooling plate, a fundamental understanding on the heat transfer enhancement and fluid flow characteristics of nanofluids in mini cooling channel is needed. Nanofluids in mini channels were investigated mostly for electronic heat sink and automotive heat exchangers including Sohel et al. [7], Khaleduzzaman et al. [8], Naphon and Nakharintr [9], Moraveji and Ardhehali [10], and Ho and Chen [11]. The mini channel materials are normally made of highly conductive material such as copper and aluminium. Very limited studies found on heat transfer and fluid flow conducted on conventional carbon graphite material. Mini channels in PEM fuel cell cooling plate designs is beneficial as it allows a more compact stack size with improved heat transfer rates that leads to lower maximum cell temperature [12-14].

Mini channel performance with respect to volume % concentration has been the most widely studied factor by researchers [7, 15-19]. Effect of volume fractions towards thermal performance of Al_2O_3 nanofluids in water has been investigated by Sohel et al [7]. He observed increment of 18 % of heat transfer coefficient for 0.25 vol % of Al_2O_3 at Re 1000 as compared to base fluid. However, a higher pumping power is experienced with nanofluids since the density and viscosity of nanofluids are higher than the base fluid but at a tolerable scale.

Ramos-Alvarado et al.[12] has reviewed few options for cooling plate design including serpentine, parallel and distributor type. In this study, parallel is reported to have the lowest pressure drop and pumping power, which is favourable for practical application. Uniformity of flow distribution was also reported to be in average region and does not change very much with the increase in Reynolds number.

In this study, heat transfer enhancement and fluid flow effect upon adoption of Al_2O_3 in a serpentine mini channel of a PEM fuel cell is investigated.

Methodology

Nanofluids preparation

Nanoparticles used are Al_2O_3 was procured from Sigma Aldrich (M) Sdn Bhd. It is in powder form with purity of 99.8% and it is in 13 nm size. The based fluid used in this study is distilled water alone and the mixture of distilled water and ethylene glycol, (EG). EG used were purchased from R&M chemicals with 99.96 % purity. The basic properties of nanoparticles and base fluids used are tabulated in Table **1**.

Thermo-physical properties of nanofluids

Thermo physical properties of thermal conductivity and viscosity of Al_2O_3 nanofluids used in this study were measured at temperature of 40°C to mimic the working conditionin PEM fuel cell. Thermal conductivity of nanofluid is measured using KD2 Pro thermal property analyzer of Decagon Devices, Inc., USA while viscosity was measured using Brookfield LVDV-III Ultra rheometer as illustrated in Figure 1 .

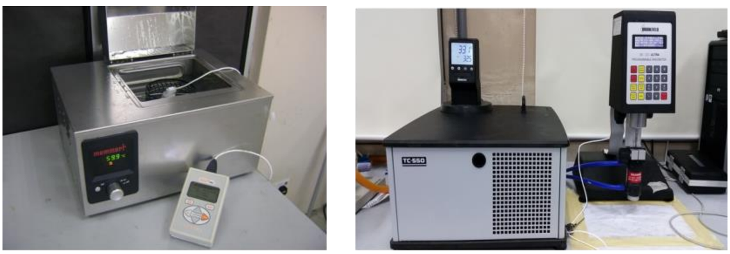
Table 1: Properties of nanoparticles and base fluid used in the experiment

Nano particle / Base fluid	Thermal conductivity κ,W/m.K	Electrical conductivity σ, μS/cm	Density ρ, kg/m^3	Ref
Al_2O_3	36	10^{-8}	4000	[20-23]
Distilled water	0.615	6	999	[20, 21, 24]
Ethylene glycol	0.252	1.07	1110	

Specific heat and density are calculated using model from Xuan and Roetzel [25] and Pak and Cho [22] respectively through Eqns (1) and (2).

$$C_{nf} = \frac{(1-\varphi)(\rho C)_{bf} + \varphi(\rho C)_{p}}{(1-\varphi)\rho_{bf} + \varphi\rho_{p}} \tag{1}$$

$$\rho_{nf} = (1-\varphi)\rho_{nf} + \varphi\rho_{p} \tag{2}$$



(a) (b)

Figure 1 : (a)Thermal conductivity and (b) viscosity measurement instruments

Serpentine cooling plate

The material used for the cooling plate and heater pad is carbon graphite and silicon respectively. An artificial heat of 100 W was subjected to the cooling plate to mimic the thermal power generated by the bipolar plates of PEM fuel cell. The assembly of cooling plate and heater pad is shown in the Figure 2.

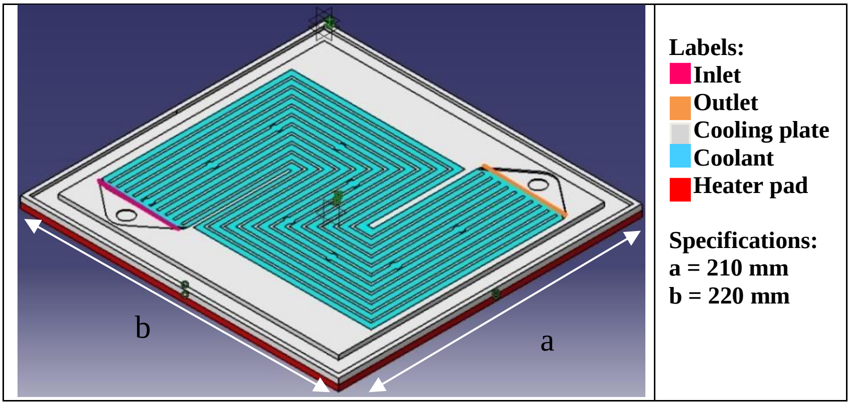


Figure 2: Isometric view of Serpentine Channel Cooling Plate

In order to simplify the analysis, few assumptions have been made [26]:-

1. The flow is in steady state and laminar.
2. The effect of body force is neglected
3. The fluid properties are constant and viscous dissipation is neglected.
4. The fluid phase and nanoparticles are in thermal equilibrium with zero relative velocity and the resultant mixture can be considered as a conventional single phase.
5. All mini channels are identical in heat transfer and fluid flow characteristic thus only one channel is simulated for computation.

The governing equations on the above assumptions are as follows.[27]
Continuity equation :

$$\nabla.\left(\rho_{nf}\,.V_m\right) = 0 \quad (3)$$

Momentum equation :

$$\nabla.\left(\rho_{nf}\,.V_m.V_M\right) = -\nabla P + \nabla.\left(\mu_{nf}\,.\nabla V_m\right) \quad (4)$$

Energy equation for coolant :

$$\nabla.\left(\rho_{nf}\,.C.V_m.T\right) = \nabla.\left(k_{nf}\,.\nabla T\right) \quad (5)$$

The heat conduction through the solid wall :

$$0 = \nabla.(k_s\,.\nabla T_s\,) \quad (6)$$

No slip boundary at the wall :

$$\vec{V} = 0\ (@Walls) \quad (7)$$

Boundary conditions at channel inlet were assumed as :

$$\vec{V} =\ V_m\ (@inlet) \quad (8)$$

$$P = atmospheric\ pressure\ (@outlet) \quad (9)$$

Heat is conducted through the solid and dissipated away via forced convection of cooling liquid that passes through the mini channel. Bottom surface is uniformly heated with constant heat flux.

$$-k_{nf}.\nabla T = q''(@Bottom\ of\ cooling\ plate) \quad (10)$$

$$-k_{nf}.\nabla T = 0(@Top\ of\ cooling\ plate) \quad (11)$$

Heat transfer and fluid flow analysis

Heat transfer coefficient is calculated by using Eqn.(12). While Nusselt number is obtained from Eqn.(13)

$$h = \frac{\dot{q}}{(T_{avgplate} - T_{avgfluid})} \quad (12)$$

$$Nu = \frac{hD_h}{k_{nf}} \quad (13)$$

The pumping power is calculated using Eqn. (14) to analyze the fluid flow of the coolant based on the mixture.

$$W_{pump} = \overset{*}{V} \times \Delta P \quad (14)$$

Results and Discussion

In single cooling plate thermal analysis, temperature reduction was initially evaluated as depicted in Figure 3. The average channel temperature was observed to reduce as the Reynolds number increased. This positive cooling effect shows that base fluid of water has the highest average plate temperature as compared to other fluids. As the Reynolds number increases to 350 and 400, 0.1, 0.3 and 0.5 % Al_2O_3 in 100:0 (W:EG) have shown a lower plate temperature than the rest. Addition of nanoparticles to the fluid has enable the plate temperature to be lowered by 0.2 % in 0.5 volume % concentration of Al_2O_3 in 100:0 (W:EG) at Reynolds number of 400 as compared to base fluid. The effect of Al_2O_3 nanofluids to cooling plate temperature contours is shown in Figure 7. In this comparative contour taken at Re 300, the plate temperature is observed to be lower as the nanofluids concentration is increased. The pattern is true to all base fluids and nanofluids studied. The Al_2O_3 in 100:0 (W:EG) nanofluids shows obvious improvement as compared to other basefluids.

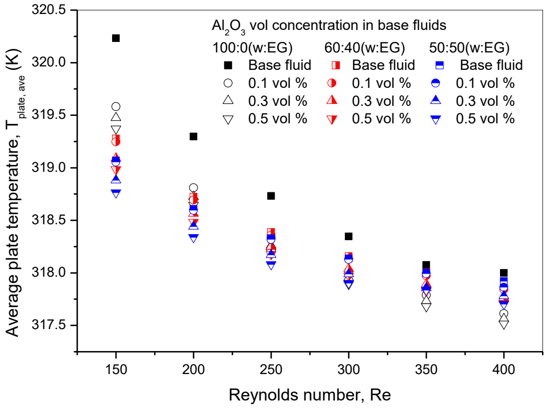


Figure 3 : Effect of Al_2O_3 nanofluids to average plate temperature

The average plate temperature was then further analysed to convective heat transfer coefficient. The effect of volume concentration and Reynolds number to the heat transfer coefficient is shown as in Figure 4. The 0.5 volume % concentration of Al_2O_3 gives the highest heat transfer coefficient value among all with 34.7 % higher as compared to base fluid of water at Re 400. This was then followed by 0.3 and 0.1 volume % concentration in 100:0 (W:EG). Both nanofluids and base fluids of 60:40 and 50:50 (W:EG) are at the lower region as compared to water base. It was also observed that the heat transfer coefficient increased as both the volume % concentration and Reynolds number increased. This is due to the higher thermal conductivity value of Al_2O_3 in 100:0 (W:EG) as compared to Al_2O_3 in 60:40 and 50:50 (W:EG) mixture.

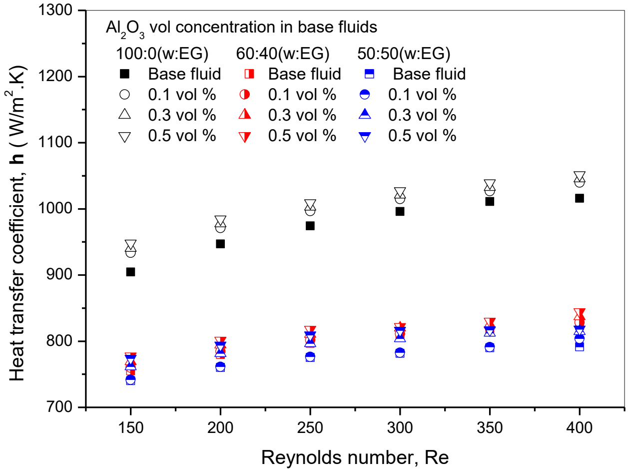


Figure 4: Heat transfer coefficient for all fluids simulated in serpentine cooling plate

The calculated convective heat transfer coefficient then analysed to determine the non-dimensionalized Nusselt number. In general, Nusselt number is observed to linearly increase as the Reynolds number is increased. There is a clear trend of higher Nusselt number in all Al_2O_3 nanofluids in 50:50 and 60:40 (W:EG) as compared to Al_2O_3 nanofluids in 100:0 (W:EG). This is associated with higher convective to conduction heat transfer ratio across the boundary in Al_2O_3 nanofluids of 50:50 and 60:40 (W:EG) as compared 100:0 (W:EG) nanofluids due to the smaller thermal conductivity value. Highest Nusselt number was recorded for Al_2O_3 nanofluids in 50:50, followed by 60:40 (W:EG) and lastly Al_2O_3 nanofluids in 100:0 (W:EG). Nusselt number trend was illustrated as in Figure 5.

The increase in pressure drop leads to higher pumping power requirement in order to circulate more viscous Al_2O_3 nanofluids throughout the cooling circuit. However, the increase is comparatively small due to the incompressible nature of the liquid-solid mixtures. Pumping power associated with Al_2O_3 adoption in single cooling plate PEM fuel cell is shown as in Figure 6. The 0.5 % volume concentration of Al_2O_3 in 50:50 (W:EG) at Re 400 has resulted pumping power of 0.2 W as compared to 0.16 W in the base fluid. The additional pumping power requirement is not favourable to fuel cell performance as this will add to parasitic losses associated with cooling system requirement [4]. However, the additional pumping power required is relatively small in a full scale PEM fuel cell due to the electrical power produced is in magnitudes of order higher.

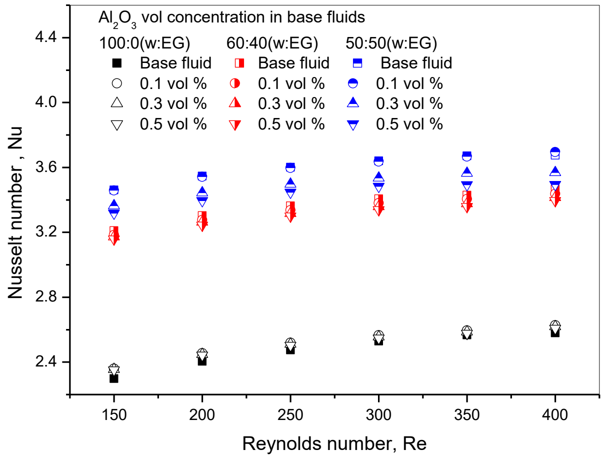


Figure 5: Nusselt number for base fluids and nanofluids simulated

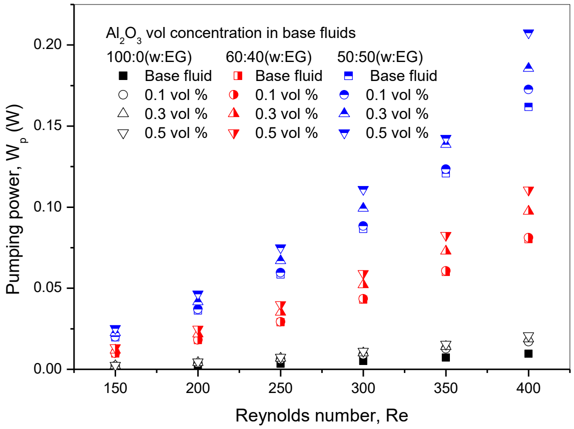


Figure 6: Pumping power effect with the adoption of base fluids and nanofluids in serpentine cooling plate

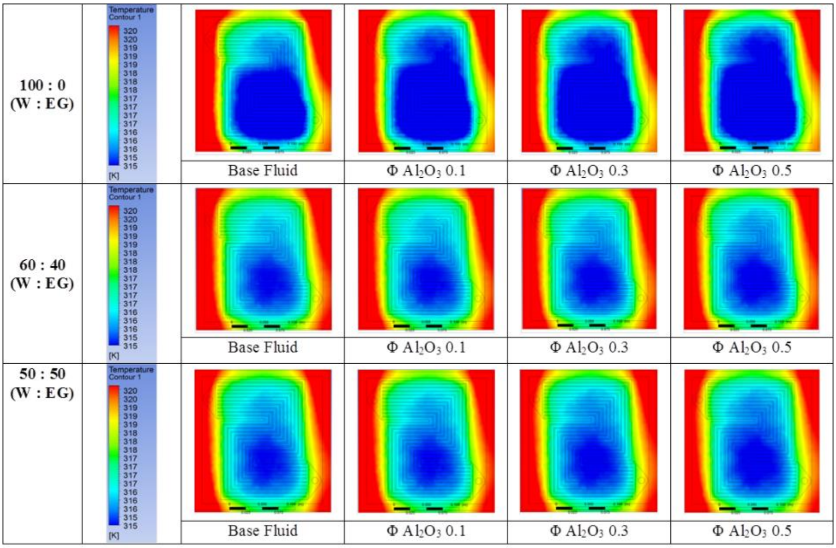


Figure 7: Effect of nanofluids to cooling plate temperature contour for all base fluids and Al_2O_3 nanofluids at Re 300

Conclusion

Upon the completion of the study, it is concluded that adoption of Al_2O_3 nanofluids does give significant advantage to the thermal management of a serpentine cooling plate of PEM fuel cell. Penalty of increased in pumping power is experienced but at a smaller scale as compared to the heat transfer improvement. The increased in pumping power is also considered insignificant if viewed from the complete PEM fuel cell stack output.

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References

[1] W. A. N. W. Mohamed and R. Atan, "Experimental thermal analysis on air cooling for closed-cathode Polymer Electrolyte Membrane fuel cells," *International Journal of Hydrogen Energy*, vol. 40, pp. 10605-10626, 2015.

[2] R. K. Ahluwalia and X. Wang, "Fuel cell systems for transportation: Status and trends," *Journal of Power Sources*, vol. 177, pp. 167-176, 2008.

[3] N. L. Garland, D. C. Papageorgopoulos, and J. M. Stanford, "Hydrogen and Fuel Cell Technology: Progress, Challenges, and Future Directions," *Energy Procedia*, vol. 28, pp. 2-11, 2012.

[4] F. Barbir, *PEM Fuel Cells : Theory and Practice*, 2005.

[5] S. H. Yua, S. Sohna, J. H. Namb, and C.-J. Kima, "Numerical study to examine the performance of multi-pass serpentine flow-fields for cooling plates in polymer electrolyte membrane fuel cells," *Journal of Power Sources* vol. 194, pp. 697-703, 2009.

[6] S. U. S. Choi, J. A. Eastman, and "Enhancing Thermal Conductivity of fluids with Nanoparticles," presented at the ASME International Mechanical Engineering Congress & Exposition, San Francisco, CA, 1995.

[7] M. R. Sohel, S. S. Khaleduzzaman, R. Saidur, A. Hepbasli, M. F. M. Sabri, and I. M. Mahbubul, "An experimental investigation of heat transfer enhancement of a minichannel heat sink using Al2O3–H2O nanofluid," *International Journal of Heat and Mass Transfer*, vol. 74, pp. 164-172, 2014.

[8] S. S. Khaleduzzaman, R. Saidur, J. Selvaraj, I. M. Mahbubul, M. R. Sohel, and I. M. Shahrul, "Nanofluids for Thermal Performance Improvement in Cooling of Electronic Device " *Advanced Material Research*, vol. 832, pp. 218-223, 2014.

[9] P. Naphon and L. Nakharintr, "Heat transfer of nanofluids in the mini-rectangular fin heat sinks," *International Communications in Heat and Mass Transfer*, vol. 40, pp. 25-31, 2013.

[10] M. K. Moraveji and R. M. Ardehali, "CFD modeling (comparing single and two-phase approaches) on thermal performance of Al2o3/water nanofluid in mini-channel heat sink," *International Communications in Heat and Mass Transfer*, vol. 44, pp. 157-164, 2013.

[11] C. J. Ho and W. C. Chen, "An experimental study on thermal performance of Al2O3/water nanofluid in a minichannel heat sink," *Applied Thermal Engineering*, vol. 50, pp. 516-522, 2013.

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[12] B. Ramos-Alvarado, P. Li, H. Liu, and A. Hernandez-Guerrero, "CFD study of liquid-cooled heat sinks with microchannel flow field configurations for electronics, fuel cells, and concentrated solar cells," *Applied Thermal Engineering,* vol. 31, pp. 2494-2507, 2011.

[13] S. Pandiyan, K. Jayakumar, N. Rajalakshmi, and K. S. Dhathathreyan, "Thermal and electrical energy management in a PEMFC stack – An analytical approach," *International Journal of Heat and Mass Transfer,* vol. 51, pp. 469-473, 2008.

[14] S. G. Kandlikar and Z. Lu, "Thermal management issues in a PEMFC stack – A brief review of current status," *Applied Thermal Engineering,* vol. 29, pp. 1276-1280, 2009.

[15] B. A. Bhanvase, M. R. Sarode, L. A. Putterwar, A. K.A, M. P. Deosarkar, and S. H. Sonawane, "Intensification of convective heat transfer in water/ethylene glycol based nanofluids containing TiO2 nanoparticles," *Chemical Engineering and Processing: Process Intensification,* vol. 82, pp. 123-131, 2014.

[16] P. Selvakumar and S. Suresh, "Convective performance of CuO/water nanofluid in an electronic heat sink," *Experimental Thermal and Fluid Science,* vol. 40, pp. 57-63, 2012.

[17] B. H. Salman, H. A. Mohammed, and A. S. Kherbeet, "Heat transfer enhancement of nanofluids flow in microtube with constant heat flux," *International Communications in Heat and Mass Transfer,* vol. 39, pp. 1195-1204, 2012.

[18] C. T. Nguyen, G. Roy, C. Gauthier, and N. Galanis, "Heat transfer enhancement using Al2O3–water nanofluid for an electronic liquid cooling system," *Applied Thermal Engineering,* vol. 27, pp. 1501-1506, 2007.

[19] N. A. Roberts and D. G. Walker, "Convective Performance of Nanofluids in Commercial Electronics Cooling Systems," *Applied Thermal Engineering,* vol. 30, pp. 2499-2504, 2010.

[20] A. A. Minea and R. S. Luciu, "Investigations on electrical conductivity of stabilized water based Al2O3 nanofluids," *Microfluidics and Nanofluidics,* vol. 13, pp. 977-985, 2012.

[21] K. G. K. Sarojini, S. V. Manoj, P. K. Singh, T. Pradeep, and S. K. Das, "Electrical conductivity of ceramic and metallic nanofluids," *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* vol. 417, pp. 39-46, 2013.

[22] B. C. Pak and Y. I. Cho, "Hydrodynamic and Heat transfer study of dispersed fluids with submicron metallic oxide particles," *Experimental Heat Transfer,* vol. 11, pp. 151-170, 1998/04/01 1998.

[23] S. Aldrich, "Safety Data Sheet," in *Aluminium Oxide*, ed, 2013.

[24] ASHRAE, "2009 ASHRAE® Handbook Fundamentals," in *Physical Properties of Secondary Coolants (Brines)*, ed, 2009.

[25] Y. Xuan and W. Roetzel, "Conceptions for heat transfer correlation of nanofluids," *International Journal of Heat and Mass Transfer,* vol. 43, pp. 3701-3707, 2000.

[26] X. L. Xie, Z. J. Liu, Y. L. He, and W. Q. Tao, "Numerical study of laminar heat transfer and pressure drop characteristics in a water-cooled minichannel heat sink," *Applied Thermal Engineering,* vol. 29, pp. 64-74, 2009.

[27] I. Zakaria, W. A. N. W. Mohamed, A. M. I. B. Mamat, R. Saidur, W. H. Azmi, R. Mamat, K. I. Sainan, and H. Ismail, "Thermal Analysis of Heat Transfer Enhancement and Fluid Flow for Low Concentration of Al2O3 Water - Ethylene Glycol Mixture Nanofluid in a Single PEMFC Cooling Plate," *Energy Procedia,* vol. 79, pp. 259-264, 2015.