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Numerical Investigation of Al2O3 Nanofluids with various Hydraulic Diameter for A Single Channel Serpentine Cooling Plate

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Abstract

Thermal management analysis has always been a major concern in the energy-based sector. Proton Exchange Membrane Fuel Cell (PEMFC), as one of the leading green energy converters for electric vehicles (EVs) is known to produce a cleaner energy with higher efficiency. The low operating temperature of PEMFC has been known to reduce the rate of heat transfer which contributes to large volume space consumption for the cooling mechanism. This study aims to investigate the effect of Al2O3 nanofluids in PEMFC by simulating the fluid flow in a single channel serpentine-type plate. The study is conducted in 10 different geometrical dimensions to examine the synergistic effect that it possesses to heat transfer in nanofluids. The numerical study shows that Al2O3 nanofluids performance far exceeds the performance shown by water in heat transfer. Examination on the effect of geometrical dimension showed that the relationship between hydraulic diameter and heat transfer is not direct, where the enhancement on heat transfer can be significantly observed at lower range. While at higher range, the enhancement of heat transfer was observed to be stagnant.

1. Introduction

In recent decades, the urge to develop an alternative to the traditional, fossil-based vehicular system has been getting a lot of attention due to a growing concern in the environment. Electric vehicles (EVs) are getting more commercially attractive due to numerous benefits it offers mainly due to its eco-friendly features which reduce the emission of CO_2 of up to 50% compared to conventional Internal Combustion Engine Vehicles (ICEVs), and its high efficiency up to 60 % (Church, 2016). These benefits shown in EV are mainly due to the

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revolutionized engine system known as fuel cell. First discovered by Humphry Davy (Sharaf & Orhan, 2014) , the system which utilizes the electrochemical reaction of hydrogen and oxygen in water was continuously developed and several different types of fuel cell has been produced, such as Solid Oxide Fuel Cell (SOFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), and Proton Exchange Membrane Fuel Cell (PEMFC) (Ho et al., 2014).

Proton Exchange Membrane Fuel Cell or also known as Polymer Electrolyte Membrane Fuel Cell (PEMFC), is currently one of the most commonly used fuel cells for Electric Vehicles. Other than the benefit it has towards the environment, PEMFC has so many advantages compared to other traditional choices of fuel cells and conventional engines. PEMFC is known to have a high volumetric power density as compared to other types of fuel cells. Low Temperature PEMFC (LT-PEMFC) is known to produce a power density up to 680 $mWcm^{-2}$ (Millington et al., 2011), while a High Temperature PEMFC (HT-PEMFC) can produce a power density up to 100 $mWcm^{-2}$ (Taccani & Zuliani, 2011). Another important characteristic of PEMFC is its rapid start-up and dynamic load response (Garland et al., 2012). Additionally, PEMFC is also known to have a significantly high efficiency of 50-60 % as compared to 20-30 % in conventional combustion engines (Fayaz et al., 2012).

Despite these advantages, PEMFC comes with one critical flaw. It might not be critical enough to cause retardation of the system as a whole, but if it is left unaddressed, it will cause a huge upset in fuel cell development in the future. The low operating temperature of PEMFC which is approximately 60 °C will provide a low driving force to remove excessive heat out of the system. This, in turn, will cause the accumulation of heat in the system (Yan et al., 2020), thus could cause a spike increase in temperature in the central part. As a result, some sensitive parts which has lower resistance towards heat such as the cathode electrode and catalyst layer could experience physical degradation. The issue with thermal management in PEMFC has been discussed and debated greatly with many solutions suggested.

Among them, the most critical problem is the build-up of water in the cathode area (Al-Zeyoudi et al., 2015). The formation of water in the cathode area due to the reaction between hydrogen ions and oxygen is expected to be released externally through a specific chamber for the water outlet. However, water overloading could follow when the fuel cell is run at a high current density and with moistened reactants (Kandlikar & Lu, 2009). The excess of water could block the pores in the gas diffusion layer or the electrodes hence slowing down

its performance (Faghri & Guo, 2005). In addition, non-uniformity of heat distribution around the membrane will cause hydrophilicity deterioration, where in time will contribute towards thermal conductivity reduction and reduce the stack performance (Schmittinger & Vahidi, 2008).

Another critical factor in PEMFC due to thermal management is the dryness in the membrane- electrolyte area (Zhang et al., 2006). For a fully functional PEMFC membrane, the area must be hydrated sufficiently to allow high performance of the fuel cell. Low hydration in the membrane area will cause an increase in ohmic loss, which will cause the increase in electrical resistance (Kang et al., 2009). Insufficient air supply, high volumetric airflow and continuous evaporation process around the membrane area are known as the main reason for the shortage of water supply in the membrane area (Islam et al., 2016). Additionally, the proton transfer process from anode to cathode which passes through the membrane area also contributes to this event through the occurrence known as electro-osmotic drag. The movement of hydrogen ions through the membrane influences the surrounding water or solvent to cause a bulk fluid motion due to momentum transfer (Ise et al., 1999). This process also increases the amount of water in the cathode area and increases the chances of flooding.

Therefore, it is imperative that the thermal management issue in PEMFC is being addressed to improve its performance and to increase its life expectancy. Application of nanofluids material as an advanced coolant to replace the conventional cooling agent for fuel cells has recently gained attention. Nanofluids are nano-sized particles at approximately 100 nm in diameter (Dhinesh Kumar & Valan Arasu, 2018) which are suspended in a base fluid to form colloidal suspension medium. A lot of research has been done to study the effect of nanoparticles to enhance the thermal conductivity of nanofluids. Among the nanofluid that has been used are Al_2O_3 (Usri et al., 2015; Zakaria et al., 2016, 2018), SiO_2 (Akilu et al., 2017; Nawi et al., 2018; Talib et al., 2015), TiO_2 (Islam et al., 2017), CuO (Agarwal et al., 2016) and Carbon nanoparticles(Singh et al., 2016; Xing et al., 2015). Most of these studies have shown a significant improvement in heat transfer and fluid flow (Bowers et al., 2018; Li et al., 2016; Zakaria et al., 2015). Among all these candidates, aluminum oxide (Al_2O_3) is known as one of the highest thermal conductivities and the lowest electrical conductivity nanofluids known. Hence, it is currently known as the best contender for coolant in fuel cell applications (Khalid et al., 2019).

Thus, this study aims to investigate the synergistic effect of Al_2O_3 nanofluids and geometrical impact of fuel cell channels for the enhancement of heat transfer in serpentine-type fuel cell. Al_2O_3 nanoparticles were suspended in water as base fluid to form nanofluids with 0.5% concentration. The thermophysical properties of Al_2O_3 nanofluids are used in this study to simulate the effect of heat transfer in a serpentine-type fuel cell with varying geometry.

2. Methodology

2.1 Properties of Al_2O_3 nanofluids and water

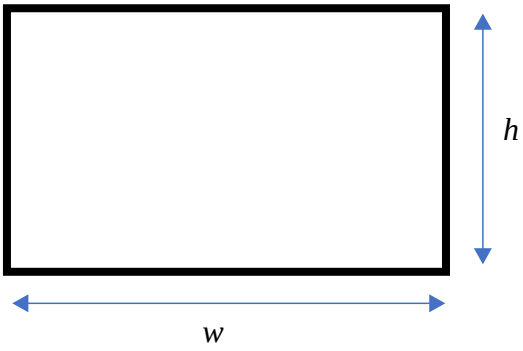
The enactment of simulation used for this study is based on a released study by Khalid et al. (Khalid et al., 2019) which verified the thermal properties of Al_2O_3 and SiO_2 nanofluids at 0.1%, 0.3% and 0.5% concentration. For this study, 0.5% concentration of Al_2O_3 nanofluids is used due to its high thermal conductivity value. Table 1 shows the thermophysical properties of nanofluids referred for this study.

***Table 2.1**: Thermophysical properties of 0.5% Al2O3 nanofluids and water*

Fluid Name	Thermal Conductivity, K (W.m/K)	Specific Heat, Cp (J/kg.k)	Viscosity, μ (Pa.s)	Density, ρ (Kg/m^3)
Al_2O_3 (0.5%)	0.642	4118	0.00130	998
Water	0.615	4185	0.0004658	983

2.2 Mathematical Formula and Governing Equations

Hydraulic diameter D_h is a commonly used geometrical value to define a non-circular cross-sectional tube or channels (Ghasemi et al., 2017). In this study, where the shape of the fuel cell channel is rectangular, the hydraulic diameter, D_h of a channel is formulated as follows:



$$\text{Hydraulic Diameter, } D_h = \frac{2wh}{w+h} \tag{2.1}$$

Where w and h represent the width and height of a channel respectively.

The fluid is assumed to be incompressible while simulated under laminar flow conditions to reduce the effect of friction on the vertices. The same Reynolds value (Re) for inlet flow is used at all conditions to ensure similar fluid behavior during the simulation. Inlet velocity V_{in} is defined as follows

$$V_{in} = \frac{R_e \mu}{\rho D} \tag{2.2}$$

where μ and ρ represents the viscosity and density of the fluid respectively, while D represents the diameter of the channel.

Convective heat transfer coefficient indicates the rate of heat transfer between the cooling plate and the fluid. It is a parameter which is influenced by all variables that influence the convection process including the surface geometry, the fluid motion, and the fluid properties. The parameter is governed by the following equation

$$\text{Convective heat transfer, } h = \frac{\dot{Q}}{T_p - T_f} \tag{2.2}$$

where $\dot{Q}$ signifies the rate of heat flux, while T_p and T_f designate the temperature of the plate and temperature of the fluid respectively.

Another important parameter to be studied is the Nusselt number which represents the ratio of convective (h) to conductive heat transfer (k) between the cooling plate and the fluid. This is defined as

$$\text{Nusselt Number, } Nu = \frac{D_h h}{k} \tag{2.3}$$

1.1 Serpentine Cooling Plate Design

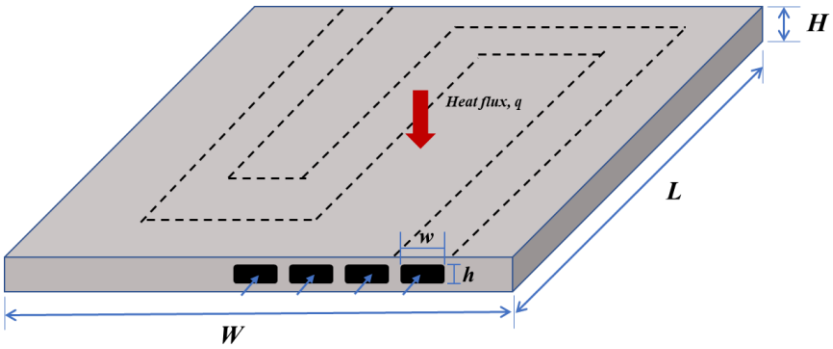


Figure 2.1: *Schematic diagram for a serpentine cooling plate*

A schematic diagram for a serpentine cooling plate is depicted in Figure 2.1. Parameters of interest in this study are focused on the width (w) and height (h) of the channels. Although the width (W), and length (L) of the plate would also affect the heat transfer, it is disregarded in this study since it would affect a much larger modification which would involve the size of casing, the fitting, and the weight of the cooling plate set.

To investigate the effect of geometrical change in a cooling plate channel, a single channel of fuel cell is designed with variation of height differences as shown in Table 2.2. The characteristics of the cooling plate is shown in Table 2.3.

Table 2.2 *Dimensions and value of hydraulic diameter, Dh for 10 models with different height*

Model	Width, w (mm)	Height, h (mm)	Hydraulic Diameter, D_h (mm)
1	5.0 mm	1.0 mm	1.67
2	5.0 mm	2.0 mm	2.86
3	5.0 mm	3.0 mm	3.75
4	5.0 mm	4.0 mm	4.44
5	5.0 mm	5.0 mm	5.00
6	5.0 mm	6.0 mm	5.45
7	5.0 mm	7.0 mm	5.83
8	5.0 mm	8.0 mm	6.15
9	5.0 mm	9.0 mm	6.43
10	5.0 mm	10.0 mm	6.67

Table 2.3*: Characteristics of serpentine cooling plate design (Zakaria et al., 2015).*

Specification	**Description**
Material	Carbon Graphite
Type	Serpentine
Dimension (length x width x height)	180 x 140 x 2.5 mm
Length of mini channel	215 mm
Thermal Conductivity	20 W/m.K

The geometrical variation in this study is purposed to examine the effects that it has on heat transfer. Additionally, this study also expects to investigate the synergistic effect of geometrical change to the fluid flow. All ten model with variation on height is applied on both Al_2O_3 nanofluids and water to see comparison of the fluid influences toward the convective heat transfer coefficient.

3. Result and Discussion

Figure 3.1 shows the simulated outlet temperature of Al_2O_3 at 0.5% concentration and water at increasing hydraulic diameter, D_h. The graph shows a distinct difference between the two sets of results with Al_2O_3 nanofluids showing lower reading of temperature as compared to water. This indicates that Al_2O_3 nanofluids have stronger convection effects to transfer heat from the heat plate surface to the fluids, causing lower temperature in the outlet as more heat is being omitted out. The lowest point is shown at 3.75 mm hydraulic diameter for both Al_2O_3 nanofluids and water with outlet temperature of 64.66 and 66.37 °C respectively.

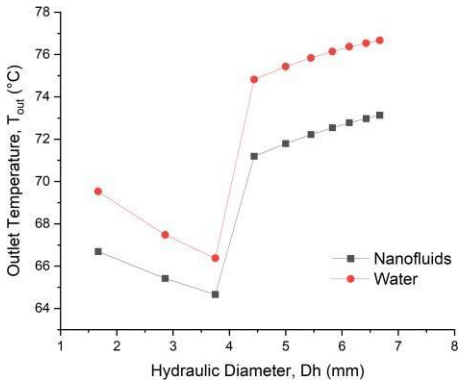
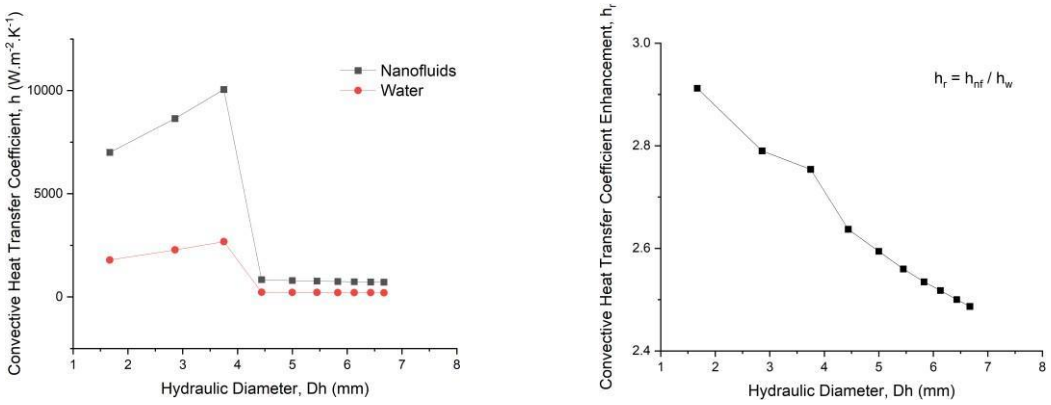


***Figure 3.1**: Outlet Temperature vs Hydraulic Diameter (m)*

Figure 3.2 shows the heat transfer coefficient, *h* of both Al_2O_3 nanofluids and water at varying hydraulic diameter. The charted value for both nanofluids and water indicates the superiority of nanofluids in terms of heat transfer coefficient as compared to water. The effect is more significant as viewed in lower hydraulic diameter between 1.67 mm and 3.75 mm, with the latter showing the maximum heat transfer coefficient of 10051.96 $Wm^{-2}K^{-1}$. The suspension of Al_2O_3 to water shows enhancement to the value of heat transfer coefficient up to 291.2 %. However, as exhibited in the figure, the enhancement is significantly reduced as the hydraulic

diameter reaches 4.44 mm. The enhancement graph also shows that its value consistently decreases as the hydraulic diameter decreases. This indicates that larger channels in fuel cells give a drawback effect where it reduces the heat transfer efficiency even though the surface area is increased.



a) Convective heat transfer coefficient b) Heat transfer enhancement

***Figure 3.2**: Heat Transfer Coefficient vs Hydraulic Diameter*

Nusselt number represents the ratio of convective to conductive heat transfer at a boundary in a fluid. In figure 3, the Nusselt number of Al_2O_3 nanofluids and water are plotted against the hydraulic diameter in a Serpentine channel. Nanofluids show dominance against water indicating that the convective effect of the fluid is higher compared to water. Since Nusselt number represents the degree of merit of convective to conductive effect in heat transfer, the presented graph shows that the effect of heat convection in Al_2O_3 nanofluids is far surpassing its conduction effect. This effect is relatively significant at the lower hydraulic diameter value where the value of Nusselt number reaches up to 58.71 at D_h = 3.75 mm. The maximum enhancement due to the suspension of Al_2O_3 to water in this study is shown at the lowest D_h value i.e., 1.67 mm with 296.63%, and the enhancement effect keeps decreasing as the D_h value increases. From a thermodynamic point of view, Al_2O_3 nanofluids increase the rate of transporting heat energy by means of convection by almost three fold if comparison is made to water. This result confirms the potential of Al_2O_3 nanofluids as a medium for heat transfer in fuel cell due to its ability as a better thermal conductivity which result to better performance in heat transfer as it used as coolant compared to water (Azmin et al., 2020)

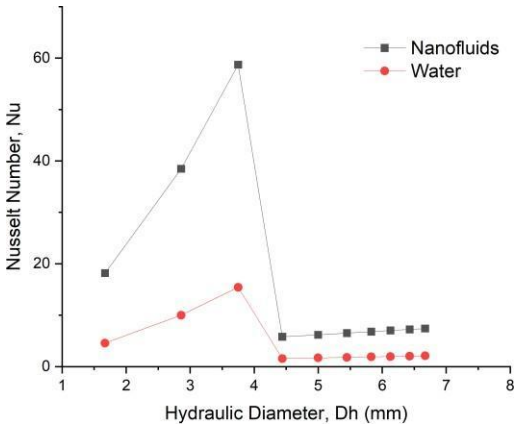


***Figure 3.3**: Nusselt Nu vs Hydraulic Diameter*

4. Conclusion

The study investigates the synergistic effect of heat transfer enhancement in Al_2O_3 nanofluids and geometrical customisation for a single channel serpentine-type cooling plate. The numerical results shown in this study confirms the superiority of Al_2O_3 nanofluids with 0.5% concentration as compared with its base fluid water. Additionally, through the examination in geometrical factor by the process of variegating the dimension of the channel, significant enhancement could be observed in the lower range of hydraulic diameter. Hence, to optimize the heat transfer effect in a Serpentine cooling plate for PEMFC application, it is recommended to limit the geometry of the channel to within the specified value.

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