Comparative analysis of thermophysical properties of Al_2O_3 and SiO_2 nanofluids

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ABSTRACT

Considered, as one of the breakthrough in 21th century, Polymer Electrolyte Membrane Fuel Cell (PEMFC) is seen as one of the favourable alternative energy to internal combustion engine (ICE). However, the sensitivity of the membrane operation needs to be taken care of efficiently in order to ensure optimum performance of its power generation. The addition of nano-sized particles dispersed in water as base liquid has dramatically altered the thermo-physical property of the base coolant especially in heat transfer improvement. In this study, Al2O3 and SiO2 nanofluids with base fluid water were analysed in terms of critical thermo-physical properties for PEMFC application are experimentally studied. This covers thermal conductivity, dynamic viscosity and electrical conductivity properties. These nanofluids with low concentration of 0.1, 0.3 and 0.5 % volume is used in the study due to the limitation of low electrical conductivity limit for PEMFC in order to avoid electrical leakage to the coolant which will in effect causes a decrease the power generation. The 4.19 % and 1.42 % of improvement is shown in 0.5 % volume concentration of Al2O3 and SiO2 nanofluids in water respectively for thermal conductivity is recorded. However, the improvement also accompanied by viscosity and electrical conductivity increment in Al2O3 and SiO2 nanofluids as compared to base fluid water.

Keywords: *Aluminium Oxide; Electrical Conductivity; Silicone Oxide; Thermal Conductivity; Viscosity.*

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Introduction

The introduction of Proton Electrolyte Membrane Fuel Cell, widely known as PEMFC has accelerated the advancement of green energy technology of the world. Its application mainly in transportation has been getting a lot of attention both by the researchers and the industries. With its rapid start-up, highly efficient in energy conversion, light weight and compact, PEMFC is a leading contender for future energy converter.

Despite its huge advantages, a critical issue of PEMFC is the thermal management which is due to the device's low operating temperature. Contrary than the traditional conventional fossil-fuel engine, PEMFC works at range of 30 to 80°C. This is considered low especially for tropical country which normally has an average ambient temperature higher than 30°C. The low difference in temperature between PEMFC device and the ambient will dampen the pushing force of heat from the device, hence would cause the dissipation of heat internally. This will put a risk of overheating and breaking the components of the fuel cell. Internal components of PEMFC, especially the membrane and the catalyst are known to be prone to excessive heat and could hinder the performance of PEMFC greatly.

Heat management in PEMFC is primarily achieved through two main mechanisms. The first one which could be called as 'air cooled' mechanism is a conduction-convection process via the stacks which would then be released to the air. The second one, known as 'liquid cooled' mechanism involved the heat removal through the cooling system (radiator) [1)]. Other than these two approaches, heat could also be removed through the hydrogen and oxygen flow, and through vaporization of water product [2)].

Between these two mechanisms, 'liquid cooled' method could improve heat transfer significantly. There are a number of researches on this mechanism focusing to find the most suitable coolant for PEMFC application. Zakaria et al. has examined the thermal conductivity of Al_2O_3, as well as its electrical conductivity into PEMFC and observed enhancement of up to 12.82% and 1428% respectively [3)]. Li tested the effect of ZnO with ethylene glycol (EG) and found an enhancement of thermal conductivity by 9.13%[4)]. While Talib, shown that SiO_2 solution dispersed in Ethylene Glycol/Water base fluids shows significant improvement in physical properties compared to the the base fluid [5)].

Silicon Oxide (SiO_2) and Aluminium Oxide (Al_2O_3) are some of the metal oxide nanofluids that have been in the interest of many researchers recently due to its augmenting thermo-physical properties. However, these researches focus primarily to volume fraction 1% and above, or for a single specific property (either thermal, electrical or viscosity)

This study has been aimed to research the behavior of Al_2O_3 and SiO_2 diluted in base fluid (water) under the ambient temperature. With this knowledge, we are aiming to see the nanofluid thermal-electrical-hydaulic properties at the ambient temperature which is also the start-up temperature of PEMFC.

During the experiment, the effect of nanofluids on heat transfer and fluid flow of Al_2O_3 and SiO_2 nanofluids were investigated for volume concentration of 0.1%, 0.3% and 0.5% with pure water as base fluid under ambient temperature.

Methodology

Preparation

For this study, the method used will be the two-steps method. The advantage of this method is better stability thus minimizing agglomeration and has the effect of reducing the risk of oxidation for metal particle with high thermal conductivity 6).

The Al2O3 nanoparticles is obtained from Sigma Aldrich (M) Sdn. Bhd in powder form recorded 99.8% purity with an average particle size of 13nm. While SiO2 nanoparticles, in the form of liquid is procured from Nova Scientific Sdn. Bhd with 30nm particle size, with purity of 99.9% and weight percentage of 25wt%. To measure the required volume for mixture, the following equation is used

$$\phi = \frac{\omega \rho_{bf}}{\frac{\omega}{100}\rho_{bf} + \left(1 - \frac{\omega}{100}\right)\rho_p} \quad (1)$$

$$\Delta V = V_1\left(\frac{\phi_1}{\phi_2} - 1\right) = V_2 - V_1 \quad (2)$$

Where weight concentration of the nanofluids is denoted by ω, ρ_p and ρ_{bf} are the nanoparticle density and the water density respectively, V_1 is the volume before dilution, V_2 is the volume of nanofluid required (after dilution), $\emptyset_1$ is the volume concentration before dilution, and $\emptyset_2$ is the volume concentration that is required.

The Equation 1 is used to convert the weight percentage value into volume percentage. Table 1 listed the parameters used for Al2O3, SiO2 nanoparticles and base fluid.

Table 1: Parameters Al_2O_3, SiO_2 and water (base fluid) used for this experiment

Nanoparticle / base fluid	Density ρ, kg/m^3	Thermal Conductivity k, W/m.K	Specific Heat Capacity c, J/kg.K	Ref.
Aluminium Oxide, Al_2O_3	4000	36	765	[6], [7]
Silicon Dioxide, SiO_2	2220	1.4	745	[8][9] [10]
Distilled Water	996	0.615	4178	[11]

The stability of the prepared nanofluids is observed visually as shown in Fig 1. It is observed that after a month old, both nanofluids have minimal sedimentation showing that the solutions prepared are in stable condition.

Measurement of Thermal Conductivity

Thermal Property Analyser KD2 Pro was used for thermal conductivity measurement of the nanofluids. This instrument has been used by many researchers especially for the measurement of nanofluids [13–22)]. In room temperature of approximately 30°C, the samples thermal conductivity were measured. This device applies transient hot-wire technology which improves the accuracy of thermal conductivity reading. During the measurement, the KS-1 needle detector with a diameter of approximately 1.25mm and 60mm in length releases an impulse of heat to stabilize the temperature around the sensor. This significantly increases the reliability and reduces the error. However, some researchers found out that at high temperature, above 50°C, the reading error is quite high [23)]. Hence, the measurement in room temperature (approximately 30°C) should provide an accurate reading for the experiment. To increase the reliability of the data, multiple reading is made. The equipment used is shown in Fig 2(a).

Measurement of Electrical Conductivity

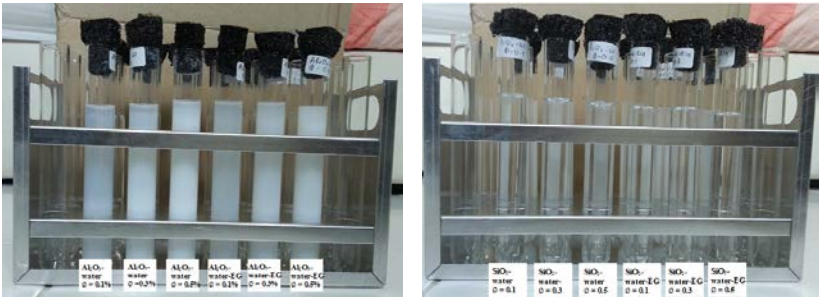
Contrary to thermal conductivity, a challenge of electrical conductivity in PEMFC is that it possesses a certain limit that restricts the highly conductive coolant to be applied through PEMFC device. The current requirement of electrical conductivity in PEMFC is lower than 5 µS at 20°C [24)]. For this study, to measure electrical conductivity of nanofluids, EUTECH Handheld Meter Kit PC450 with DJ PH probe is used. The EUTECH PC450 comes with a probe that can measure the temperature, electrical conductivity and pH value of a medium instantaneously. This device can measure a medium up to 100°C and quite easy to handle since the probe is quite small in diameter and can fit in most kind of container. A multiple measurements are made to reduce error and increase the accuracy of the reading. The equipment used is shown in Fig 2(b).

Viscosity Measurement

Viscosity for nanofluid affects the friction factor and pressure drop in PEMFC radiator. For best performance, viscosity of the nanofluid needs to be at a minimal increment or even at par with the current effort required to enable the flow. High viscosity fluid could increase the pumping power to the compressor, which will decrease its efficiency [11)]. Fluid with low viscosity could also distress the system parameters, such as temperature, noise level, torque, and running speed. Zawawi et al. also emphasize the effect it has on reducing the lifespan of the compressor [14)]. The equipment that will be used to measure viscosity is the LVDV-III (Low Viscosity Digital Viscometer) Ultra Programmable Rheometer. This equipment can measure any liquid medium up to 100°C.

Results and Discussions

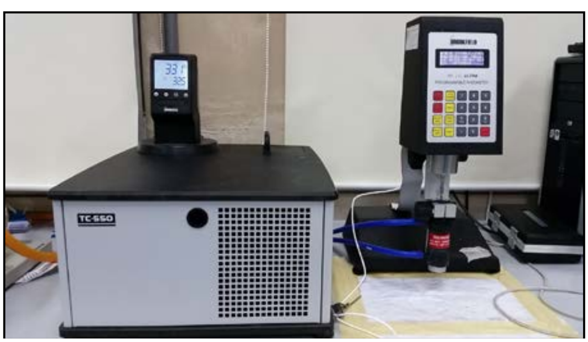
Subsequent to the measurements, the results were tabulated, and analysed. Thermal conductivity of Al_2O_3 and SiO2 is plotted and compared in Figure 3. Enhancement can be seen accelerated at higher rate for Al_2O_3 compared to SiO_2. Maximum enhancement can be observed at Al_2O_3 with 0.5% volume concentration with 4.39% enhancement. Meanwhile SiO_2 also shows thermal conductivity enhancement as the volume concentration increase with a maximum enhancement of 1.42% at 0.5% volume concentration. It is observed that, for both Al_2O_3 and SiO_2, the increase in volume concentration causes the improvement in magnitude in thermal conductivity. Hence, in PEMFC application, for an optimum heat transfer, the nanofluids of higher concentration is preferable but also subjected to the electrical conductivity limit. Between these two nanofluids, in terms of thermal conductivity, Al_2O_3 would be superior as compared to SiO_2. To confirm the validity of data, the Al_2O_3 results are compared to the data from published journal. The experimental data is compared to Zakaria [7)] and showed a minimal deviation of 0.94% to 1.68%. The reason behind the thermal conductivity enhancement in both nanofluids is due to the dispersion of Al_2O_3 and SiO_2 particles in nano-sized form which eventually increases the random movement of particles through the liquid molecules known as Brownian motion [25)].



(a) Al_2O_3 dispersed in water (b) SiO_2 dispersed in water

Fig. 1. Prepared Al_2O_3 and SiO_2 nanofluids after being prepared using two-step method after 1 month duration

(a) KD2 Pro Property Analyser with KS-1 sensor (b) EUTECH Handheld Meter Kit PC450



(c) Low Viscosity Digital Viscometer (LVDV-III) Ultra Programmable Rheometer

Fig. 2. Instruments for transport properties measurement. (a) thermal conductivity (b) electrical conductivity and (c) Viscosity measurements

Fig 4 shows the relationship of electrical conductivity to volume concentration of Al_2O_3 and SiO_2 at ambient temperature. There is a distinct variation of value when comparing the electrical conductivity between Al_2O_3 and SiO_2. It is observed that electrical conductivity readings of SiO_2 are rocketing upwards at faster rate with respect to volume concentration. Meanwhile in Al_2O_3 nanofluids, the electrical conductivity value increases at a steadier pace across increasing volume concentration. The electrical conductivity enhancement of SiO_2 from this study is 138.16 µS/cm to 531.16 µS/cm. However, a smaller enhancement range of 26.83 µS/cm to 33.4216 µS/cm is observed for Al_2O_3 nanofluids. Though both nanofluids display a huge enhancement compared to water, relatively the enhancement of electrical conductivity of Al_2O_3 are still much smaller as and feasible as alternative coolant in an active electrical application as compared to SiO_2 nanofluids.

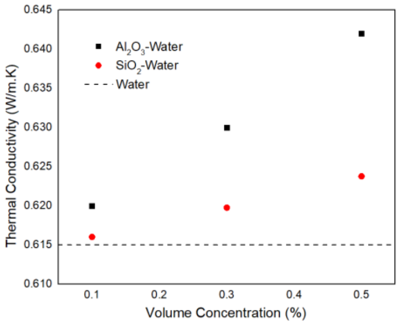


Fig. 3. Thermal conductivity against volume concentration of Al_2O_3 and SiO_2 with water as base fluid

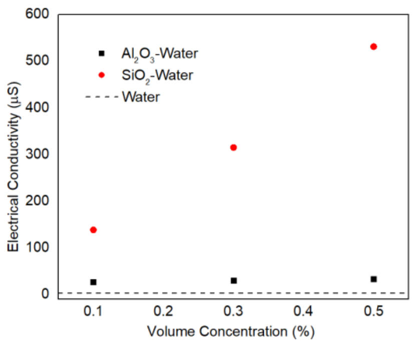


Fig. 4. Electrical conductivity against volume concentration of Al_2O_3 and SiO_2 with water as base fluid

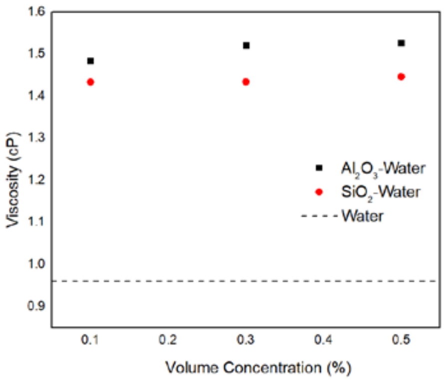


Fig. 5. Viscosity against volume concentration of Al_2O_3 and SiO_2 with water as base fluid

Even though both of Al_2O_3 and SiO_2 electrical conductivity have already exceeded the border limit of PEMFC, further work can be done to reduce the electrical conductivity value in the nanofluids. A few researchers has shown that by adding additives into base fluid could effectively reduce the electrical conductivity of the nanofluids [3,5,8]. However, doing so would result having the thermal conductivity enhancement to be compromised. Takashiba and Yagawa [26] on the other hand uses addition of anti-oxidant to coolant in order to achieve lower electrical conductivity value.

Figure 5 shows comparison between viscosity of Al_2O_3 and SiO_2 nanofluids. Both Al_2O_3 and SiO_2 nanofluids shows an enhancement in dynamic viscosity as volume concentration value rises. Nanofluids containing diffused nano-sized solid particles will act as fillers between layers of fluids, causing an increase in internal friction forces, hence causing the increase in viscosity. Bowers [27] also reported the same finding where the viscosity of Al_2O_3 and SiO_2 nanofluids increase as its nanoparticles volume concentration is increased. This is due to the adoption of nanoparticles into water has increased the internal shear stress of the fluid [28]. It can be seen that the increment of viscosity for volume concentration from 0.1% to 0.5% is about 2.83%. This suggests that at the range of 0.1% to 0.5% volume concentration, at ambient temperature, the viscosity variation of these two nanofluids are very stable.

Conclusion

For a better effect of thermal management in PEMFC, an enhanced thermal conductivity coolant is required. For this purpose, Al_2O_3 with 0.5% concentration dispersed in water shown the largest potential with 4.39%

enhancement as compared to water. In electrical conductivity aspect however, showed that both Al_2O_3 and SiO_2 nanofluids display an increment in electrical conductivity, which need to be further studied in order to fully apprehend the effect to the performance of PEMFC. Within the volume concentration studied in this experiment, the most stable parameter can be seen in viscosity.

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