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Thermophysical Properties of Silicon Dioxide (SiO_2) in Ethylene Glycol/Water Mixture for Proton Exchange Membrane Fuel Cell Cooling Application

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Abstract

Polymer Electrolyte Membrane Fuel Cells (PEMFC) operation is sensitive to micro electrochemical changes and can only tolerate a small temperature variation for optimal power generation. An effective cooling system is needed to comply with this condition. Nanofluids are perceived as a potential coolant for thermal management in PEMFC application that allows for more compact design. The dispersion of nanofluid in water-ethylene glycol base fluid enhances the thermal conductivity for improved heat transfer. The thermal conductivity, viscosity and electrical conductivity of different Silicon Dioxide (SiO_2) concentrations diluted in Ethylene Glycol/Water (EG/W) mixtures of 40EG, 50EG and 60EG are reported. However, the electrical conductivity would contribute to electrical leakage and is a limiting factor for fuel cell operation. Highest value of thermal conductivity recorded is the dispersion of nanofluid in 40EG whereas the viscosity of SiO_2 is the highest in 60EG dilution. Electrical conductivity is recorded the highest in EG/W 40:60% with 0.5% of SiO_2. However, the electrical conductivity would contribute to electrical leakage and is a limiting factor for fuel cell operation.

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Keywords: nanofluids, thermal conductivity, electrical conductivity, viscosity, PEMFC

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1. Introduction

Fuel cell is an applications that uses hydrogen as fuel to generate electricity through electrochemical reaction with oxygen. Fuel cell is aforethought as potential energy generation device. Hydrogen is fed into the anode side and is catalytically split into positive and negative ions. The positive ions are transported through a hydrated membrane while the negative charges travels through an external circuit, generating electricity. At the cathode side, the positive and negative ions react with oxygen to produce water. The exothermic formation of water releases heat as a by-product of the overall process. PEMFC are widely applied for low power application (less than 100 kW) as it can operate at low temperatures (30˚C to 100˚C) with high power densities. Thermal management is critical to avoid the membrane of fuel cell dry thus reduce charge transport resistance. Thermal management in PEMFC is focused towards achieving an optimum cell temperature for the electrochemical reactions with limitations in maintaining the required membrane hydration levels [1]. Proton transport through the membrane is by electro-osmotic drag [2]; thus, membrane drying would significantly reduce the internal moisture content and increases charge transport resistance [1]. Temperature uniformity is also highly desirable in a PEMFC operation as it avoids internal thermal stresses and contributes to localized reaction rates. The choice of coolants for a PEMFC has been largely limited to air and water. In the closed-cathode PEMFC design, the cooling effect is achieved using separate fluid streams from the reactant streams. Water has been applied extensively while air-cooled closed cathode stacks are newly explored for improving stack size and weight [3].

To obtain more compact stack designs, the cooling system performance needs to be improved. Coolants with better thermal characteristics than water needs to be applied for a more compact cooling plate design; ie. obtaining similar cooling effects with reduced flow rates. Nanofluid is a potential coolant for heat transfer application such as fuel cell thermal management and electronic device cooling [4]. The enhanced thermophysical characteristics of suspended nanometer sized particles into base fluids have been considered in many research and application. However, it is a new integrated approach in fuel cell technology towards higher power density stack designs.

The presence of nanoparticles in the base fluid increase the thermal conductivity; an important property in heat transfer. However, nanofluid also exhibit higher viscosity and electrical conductivity (EC) as the particle concentration is increased across temperature. High viscosity correlated to the pressure drop and pumping power. A low electrical conductivity of coolant is essential in fuel cell application. Excessive electrical conductivity will lead to shunt current and coolant electrolysis on the device. Therefore, nanofluids need to be characterized in detail to meet the fuel cell operating parameter. This paper present the thermophysical properties of Silicon Dioxide (SiO2) nanofluid includes the viscosity, thermal and electrical conductivity for PEMFC application.

2. Methodology

The nanofluids are prepared using dilution method. The solution of silicon dioxide (SiO_2) with volume concentration of 13.45% is diluted in base fluid of water-ethylene glycol (WEG) mixture. The concentration of EG used are 40%, 50% and 60%. The volume concentration of SiO_2 prepared are 0.1%, 0.3% and 0.5%.

2.1. Properties of nanoparticle and base fluid used in the experiment

Table 1: Properties of nanoparticles and base fluids

Nanoparticle/base fluid	Thermal conductivity k, W/m.K	Electrical conductivity σ, μS/cm	Dielectric constant, ε	Density ρ, kg/m3	Reference
SiO_2	1.38	10^{-21}	3.9	2220	[5]
Distilled water	0.615	6	80	999	[6]
Ethylene glycol	0.252	1.07	38	1110	

The thermal conductivity, electrical conductivity and viscosity are measured at 30˚C. The thermal conductivity, viscosity and electrical conductivity are measured using KD2Pro Thermal Analyzer, Brookfield DVIII Ultra Programmable Rheometer and Cyberscan PC-10 respectively.

2.2. Mathematical Models

Hamilton & Crosser [7] extend the Maxwell model to effective thermal conductivity considering the heterogeneous two components mixture. The conductivity is defined as Eq (1) where *(n)* is the empirical shape factor given by *3/λ* and *(λ)* is the particle sphericity (λ=3), defined as surface area of sphere (with the same volume of the given particle) to the surface area of the particle.

$$\frac{k_{nf}}{k_{bf}} = \left[\frac{k_p + (n-1)k_{bf} - (n-1)\varphi(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \varphi(k_{bf} - k_p)} \right] \tag{1}$$

Maxwell [8] established the effective electrical conductivity in heterogeneous medium of a random dispersion of spherical particles in base fluid. The model predicts the effective electrical conductivity of a random suspension (σ_{eff}) as the function of the particles (σ_p), base fluid (σ_{bf}) conductivity and the volume fraction of the particles (φ) as presented in Eq (2).

$$\frac{\sigma_{nf}}{\sigma_{bf}} = \left[1 + \frac{3(\alpha-1)\varphi}{(\alpha+2)-(\alpha-1)\varphi} \right] \tag{2}$$

In the equation, $\alpha = \lambda_p/\lambda_{bf}$ represent the conductivity ratio of the two phase. Generalization of Maxwell model by Cruz et. al [9] leads to the following cases depending on the conducting nature of the particles and the base fluids:

$$a)\ \frac{\sigma_{nf}}{\sigma_{bf}} = 1 - \frac{3}{2}\varphi, \text{for } \sigma_p << \sigma_{bf} \text{ (insulating particles)}$$

$$b)\ \frac{\sigma_{nf}}{\sigma_{bf}} = 1, \text{for } \sigma_p = \sigma_{bf} \text{ (equal conductivity)}$$

$$b)\ \frac{\sigma_{nf}}{\sigma_{bf}} = 1 + 3\varphi, \text{for } \sigma_p >> \sigma_{bf} \text{ (highly conducting materials)}$$

Viscosity is defined as the resistance between two layers of the fluid. The dispersion of nanoparticles in base fluid will enhance the resistance between the two layers of the fluid if the fluid is subjected to shear. Einstein [10] introduced model that applicable to very low nanoparticle concentration ($\phi \leqslant$ 0.02%) to predict the nanofluid viscosity and it is described in Eq (3).

$$\frac{\mu_{nf}}{\mu_{bf}} = [1 + 2.5\varphi] \tag{3}$$

Brinkman [11] has extended the formula and established relative viscosity valid for volume concentration up to 4% where the equation is given as

$$\frac{\mu_{nf}}{\mu_{bf}} = \left[\frac{1}{(1-\varphi)^{2.5}}\right] \tag{4}$$

As *(bf), (nf), (μ) and (φ)* represents the base fluid, nanofluid, viscosity and volume fraction, respectively.

3. Results and Discussion

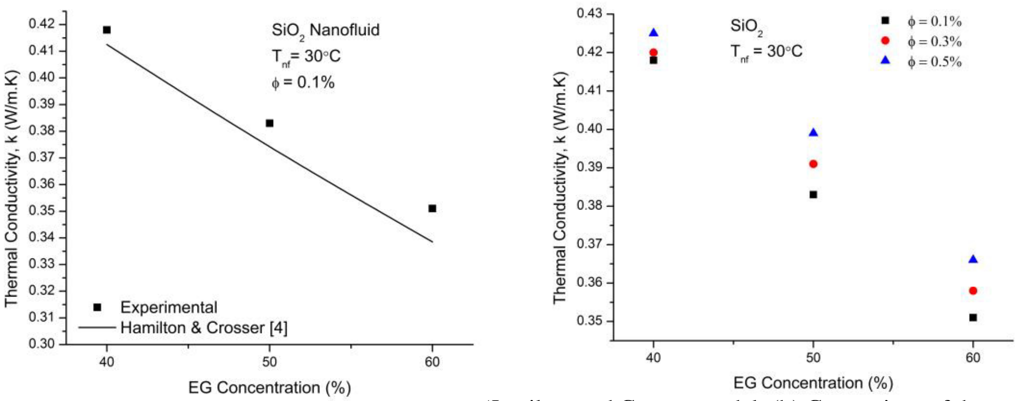

Fig. 1 (a) Comparison of thermal conductivity with Hamilton and Crosser model; (b) Comparison of thermal conductivity in different EG concentration

Figure 1 shows the thermal conductivity of SiO2 nanofluids. The thermal conductivity of .1% SiO2 nano particles dispersed in various EG concentrations to water is plotted. The increment of EG concentration in base fluid exhibits lower thermal conductivity of SiO2 nanofluid. Fig. 1 (a) demonstrates the comparison of experimental value with Hamilton and Crosser model. The model fairly predict the actual thermal conductivity of SiO2. From Fig 1 (b), it can be deduced that the thermal conductivity of the solution is sensitive to the EG concentration and the dispersion volume of the nanoparticles. Higher volume dispersion yields higher thermal conductivity while greater EG concentrations reduces the thermal conductivity. An average reduction of 10% to 15% were registered as the EG concentration increases from 40% to 60%. Zakaria et. al [12] also observed similar pattern of thermal conductivity of 0.1% Al2O3 dispersed in base fluids.

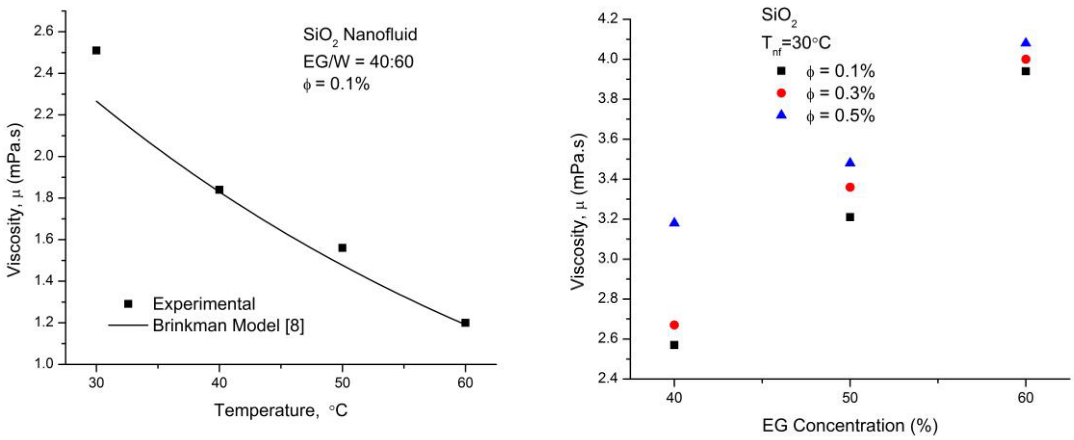

Fig. 2(a) Comparison of experimental viscosity with Brinkman model across the temperature; (b) The Viscosity of SiO_2 nanofluids with volume concentration of 0.1%, 0.3% and 0.5% at different EG concentration

The experimental viscosity of SiO_2 nanofluids agrees with the Brinkman model as shown in Fig 2(a). Fluid temperature increase leads to reduced internal friction which leads to the fluid becoming less viscous. However, nanofluid coolants that contains dispersed solid particles registers higher viscosities than its base fluids as the particles fills the gap between the fluid layers. Greater EG concentrations leads to higher viscosity as EG is more viscous than water. The ASHRAE handbook presented that 60:40% EG/W is more viscous than other 40:60% and 50:50% EG/W base fluids [6]. Sundar [13] and Kulkarni et. al [14] also observed the same pattern of viscosity of Aluminum Oxide (Al_2O_3) and SiO_2 consecutively dispersed in EG/W base fluids across varying temperature.

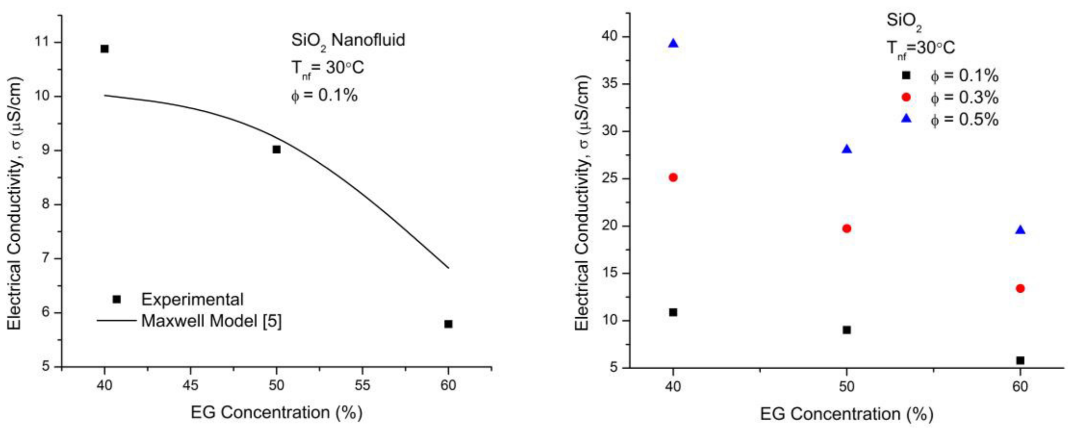

Fig. 3 (a) Comparison of experimental electrical conductivity and Maxwell model; (b) The electrical conductivity of SiO2 nanofluids with volume concentration of 0.1%, 0.3% and 0.5% at different EG concentration

The actual profile of electrical conductivity is marginally linear while the Maxwell model predicts an exponential profile.[8]. The maximum difference obtained is 15% whilst the minimum difference is 6%. High concentration of nanoparticles exhibit higher electrical conductivity. As the EG concentration increased, the electrical conductivity decreased due to lower electrical conductivity of EG. The base fluids of EG/W 60:40% has lower electrical conductivity. It is established through the study that the desired thermal conductivity enhancement was achieved using SiO2 in EG/W with the accompanying effect of viscosity and electrical conductivity increases. The effect of the properties to the actual operation of a PEMFC must be modelled separately. Analytical tools such as the Thermo-Electrical Ratio (TEC) by Zakaria et al. [12] can be applied to evaluate the performance of the nanofluid coolants in a fuel cell environment.

2. Conclusion

Compact PEMFC designs require coolants with improved thermal characteristics for greater cooling effect. Enhanced thermal conductivity can be obtained by dispersing high concentrations of nanoparticles. However, the electrical conductivity increases as well which is undesirable in an active electrical environment. To limit the EC increase, EG was mixed with the water base fluid but the viscosity of the nanofluid increases with EG concentration. In operation, this would lead to higher pumping power requirement. This paper has established the corresponding electro-thermal relationships between EG/W concentrations to the volume of SiO2 dispersion. The identified properties can be applied in the design and operation analysis of PEMFC stacks with nanofluid coolants.

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References

[1] F. Barbir, *PEM Fuel Cells: Theory and Practice*: Elsevier Science, 2005.
[2] Z. Luo, Z. Chang, Y. Zhang, Z. Liu, and J. Li, "Electro-osmotic drag coefficient and proton conductivity in Nafion® membrane for PEMFC," *International Journal of Hydrogen Energy,* vol. 35, pp. 3120-3124, 4// 2010.
[3] W. A. N. W. Mohamed and R. Atan, "Experimental Cooling Mode Variation of an Air-cooled PEM Fuel Cell using Second-order Thermal Analysis," *Journal of Mechanical Engineering* vol. 10, pp. 55-78, 2013.
[4] A. Ijam and R. Saidur, "Nanofluid as a coolant for electronic devices (cooling of electronic devices)," *Applied Thermal Engineering,* vol. 32, pp. 76-82, 2012.
[5] S. Zhang and N. Ali, "Nanocomposite Thin Films and Coatings - Processing, Properties and Performance," ed: World Scientific.
[6] "2012 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Systems and Equipment (SI Edition)," in *Combined Heat and Power System*, ed: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2012.
[7] R. L. Hamilton and O. K. Crosser, "Thermal Conductivity of Heterogeneous Two-Component Systems," *Industrial & Engineering Chemistry Fundamentals,* vol. 1, pp. 187-191, 1962/08/01 1962.
[8] J. C. Maxwell, *A Treatise on Electricity and Magnetism*: OUP Oxford, 1998.
[9] R. C. D. Cruz, J. Reinshagen, R. Oberacker, A. M. Segadães, and M. J. Hoffmann, "Electrical conductivity and stability of concentrated aqueous alumina suspensions," *Journal of Colloid and Interface Science,* vol. 286, pp. 579-588, 6/15/ 2005.
[10] A. Einstein, "Eine neue Bestimmung der Moleküldimensionen," *Annalen der Physik,* vol. 324, pp. 289-306, 1906.
[11] H. C. Brinkman, "The Viscosity of Concentrated Suspensions and Solutions," *The Journal of Chemical Physics,* vol. 20, pp. 571-571, 1952.
[12] I. Zakaria, W. H. Azmi, W. A. N. W. Mohamed, R. Mamat, and G. Najafi, "Experimental Investigation of Thermal Conductivity and Electrical Conductivity of Al2O3 Nanofluid in Water - Ethylene Glycol Mixture for Proton Exchange Membrane Fuel Cell Application," *International Communications in Heat and Mass Transfer,* vol. 61, pp. 61-68, 2015.
[13] L. Syam Sundar, E. Venkata Ramana, M. K. Singh, and A. C. M. Sousa, "Thermal conductivity and viscosity of stabilized ethylene glycol and water mixture Al2O3 nanofluids for heat transfer applications: An experimental study," *International Communications in Heat and Mass Transfer,* vol. 56, pp. 86-95, 2014.
[14] D. P. Kulkarni, D. K. Das, and R. S. Vajjha, "Application of nanofluids in heating buildings and reducing pollution," *Applied Energy,* vol. 86, pp. 2566-2573, 12// 2009.