



Evaluation on Thermo-Electrical Characteristics of SiO₂ Nanofluids for Fuel Cell Cooling Application in Automobiles

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Abstract

Effective thermal management is critical requirement in fuel cell technologies to avoid the performance degradation during operation. Nanofluids offer the potential to address this cooling challenge in fuel cells better than pure fluids. However, due to the electrochemical changes associated with the proton exchange membrane system, a strict limit on thermal and electrical properties of coolant needs to comply. In this study, the thermal and electrical conductivities of silicon dioxide (SiO₂) dispersion of ethylene glycol (EG), glycerol (G), and 40:60 by mass ethylene glycol-glycerol (EG/G) was investigated experimentally. Measurements were carried for particle volume concentrations of 0.25–2.0% at a temperature of 30 °C. The thermal and electrical conductivity of the nanofluids significantly increases with SiO₂ loading. Maximum enhancements of ~4.0% and ~198% at a volume concentration of 2.0% were obtained with SiO₂-EG/G, respectively. Further, analysis of the results reveals that SiO₂/G exhibited the greatest thermo-electrical performance, followed by SiO₂-EG/G and EG. Therefore, SiO₂-EG/G nanofluid is best-suited coolant for PEM fuel cell thermal applications.

Keywords: SiO₂; nanofluid; electrical conductivity; thermal conductivity, PEM fuel cell

1. Introduction

Enhancing the thermophysical properties of single-phase fluids offers a smarter and sustainable means to achieve improved thermal transport efficiency, save energy consumption, and cost with less environmental impacts. A proton exchange membrane fuel cell (PEMFC) is a power source like batteries which combines hydrogen and oxygen into usable electric power through an electrochemical reaction. A typical operation of the device for low power application occurs at high power densities with temperatures ranging from 30 °C to 100 °C. Due to exothermic nature of the electrochemical process, heat generated needs to be managed effectively to keep the fuel cell operating efficiently. Water is typically used as a medium for cooling closed-cathode fuel cell technologies. For a highly compact stack design fuel cells, a new improved cooling system is required. Thus, nanofluids have been proposed as alternative cooling fluid to water [1]

Nanofluid is a new heat transfer fluid engineered by dispersing solid particles of less than 100 nm dispersed in conventional fluids such as water, ethylene glycol, and glycerol [2]. Nanofluids are proven for enhanced thermal conductivity, electrical conductivity, and heat transfer performance [3]. It has been proposed as next-generation cooling fluids for electronics devices, automotive engine, fuel cells exchange membrane, etc.

The electrical conductivity is an important property of a suspension involving electric-active fluid flow applications. It depends upon the nature of suspended particles, base fluid, volume fraction, particle size and surface charge. Nanofluids utilizing metallic oxides dispersion would exhibit high electric conductivity than pure base liquids. This is because of very well structured and larg-

er electrical double layer (EDL) of high ionic conductivity, resulting from strong interactions between the ions/molecules in solution and charges on the surface of nanoparticles [4]. So far, efforts to measure the electrical conductivity of nanofluids have been relatively few.

Angayarkanni and Philip [5] reported the electrical conductivity Al₂O₃ (~15 nm)/water nanofluids for volume concentration up to 4.0% at room temperature of (25 °C). Adio et al. [6] have examined the electrical conductivity of glycerol-based γ -Al₂O₃ (17 nm) at 0.1–2.0% volume and temperatures between 20 and 70 °C. Sharifpur et al. [7] investigated the electrical behavior of SiO₂ (13.4 nm)/ethylene glycol nanofluids. Recently, Zyla and Jacek [8] studied ethylene glycol-based nanofluid of SiO₂ (7–14 nm) nanoparticles at a temperature of 25 °C and volume concentrations of 0.5–2.6%.

In light of the above discussion, therefore, present work aimed to investigate the electrical and thermal conductivity properties of SiO₂ nanofluids for potential cooling applications in Proton Exchange Membrane (PEM) fuel cells systems. Different SiO₂ dispersions in ethylene glycol, glycerol, and ethylene glycol-glycerol for particle volume concentrations of 0.25–2.0% and at temperatures of 30 °C were considered for the present study.

2. Theory

Maxwell [9] firstly introduced a model for the electrical conductivity of suspensions of ceramic particles which holds for the homogeneous medium of low volume fraction liquid-solid system with uniformly sized, randomly dispersed, and non-interacting spherical particles given as:

$$\frac{\sigma_{nf}}{\sigma_{bf}} = \frac{3(\alpha-1)\phi}{3(\alpha-2)-3(\alpha-1)\phi} \quad (1)$$

The Maxwell's model (1) was later generalized by Cruz et al. [10] which resulted in the following conditions:

$$\frac{\sigma_p}{\sigma_{bf}} = 1 - 3\phi, \text{ for } \sigma_p \ll \sigma_{bf} \text{ (insulating particles)} \quad (i)$$

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

$$\frac{\sigma_p}{\sigma_{bf}} = 1 + 3\phi, \text{ for } \sigma_p \gg \sigma_{bf} \text{ (conducting particles)} \quad (iii)$$

Where, ϕ is the particle concentration, σ_{nf} , σ_{bf} , and σ_p are the electrical conductivities of the nanofluid base liquid and nanoparticle, α is the conductivity ratio of the two phases given by σ_p/σ_{bf} and obtained from Maxwellian approximation.

2.1. Thermo-Electrical Ratio

Thermo-electric (TEC) ratio is a figure of merit defined as the ratio of thermal to electrical conductivity. It is used as a benchmark for assessing the suitability of the nanofluids in proton exchange membrane fuel cell (PEMFC) cooling as represented in Eq. (2):

$$TEC = \frac{5k_{nf}}{\sigma_{nf}k_{bf}} \quad (2)$$

The variables k_{nf} and k_{bf} describe thermal conductivity of nanofluid and base liquid, respectively. Higher values of TEC indicate better cooling capacity of the fluid medium.

3. Experiments

Materials and Methods: Silicon oxide nanopowder (SiO_2 , 15-20 nm, S-type, spherical, non-porous and amorphous) was procured from US Research Nanomaterials, Inc. while analytical grades of ethylene glycol (EG) and glycerol (G) were obtained from R&M Chemicals.

Nanofluids were prepared in two steps by dispersing the procured SiO_2 powder in the three base fluids namely, ethylene glycol, glycerol, and ethylene glycol glycerol mixture (40:60) at 0.25, 0.5, 0.75, 1.0 and 2.0% volume concentrations, respectively. About 100 ml of nanofluid solution was ultrasonicated for 2 hours to break down the agglomerates.

The structure and size of the as-received powder were examined by field emission gun assisted scanning electron microscopy analysis (FE-SEM) on LEO 1525, GEMINI).

The electrical conductivity was measured using a portable dual-channel conductivity/pH meter (SG23-SevenGo, Mettler Toledo) with an accuracy of $\pm 0.01 \mu\text{S}/\text{cm}$. The thermal conductivity was measured using KD2 Pro device within $\pm 5\%$ uncertainty. All data were recorded at steady-state temperature of 30°C .

4. Results and Discussion

The SEM image of the silica powder is shown in Figure 1. From this image, the SiO_2 particles appear to be nearly uniform in size and are closely packed spheres. The average size of the nanoparticles was estimated as 21 nm.

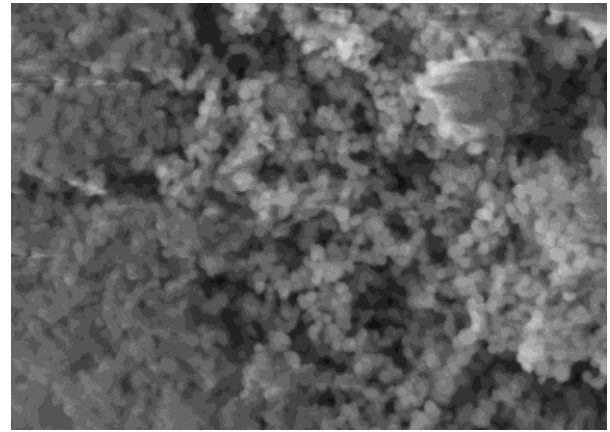


Fig. 1: SEM image of silicon dioxide nanoparticles.

The measured data for electrical conductivity of base liquids; EG, G and EG/G base liquids is presented in Table 1. The obtained values for EG and G were compared with reference values [11,12]. It must be mentioned that comparison data were unavailable for EG/G. As can be observed from this table, the electrical conductivity values strongly deviated from reference values. The reason for these discrepancies are unclear but the differences in purity levels or ionic species could be a probable cause [13].

Table 1: Font Specifications for A4 Papers

| T(°C) | Exp (EG), $\mu\text{S}\cdot\text{cm}^{-1}$ | Theo. (EG), $\mu\text{S}\cdot\text{cm}^{-1}$ |
|-------|--|--|
| 20 | 0.18 | 1.07 [11] |
| 20 | 0.26 | - |
| T(°C) | Exp (G), $\mu\text{S}\cdot\text{cm}^{-1}$ | Theo. (G), $\mu\text{S}\cdot\text{cm}^{-1}$ |
| 25 | 0.0 | - |
| 25 | 0.0 | 0.064 [12] |
| T(°C) | Exp (G), $\mu\text{S}\cdot\text{cm}^{-1}$ | Theo. (G), $\mu\text{S}\cdot\text{cm}^{-1}$ |
| 20 | 0.0 | NA |
| 25 | 0.08 | NA |

*NA – not available

The variation in electrical conductivity with loadings of SiO_2 nanoparticles in EG, G, and EG/G, respectively at 30°C are presented in Figure 2. As can be seen, the electrical conductivity of the nanofluid increase linearly with increase in particle volume

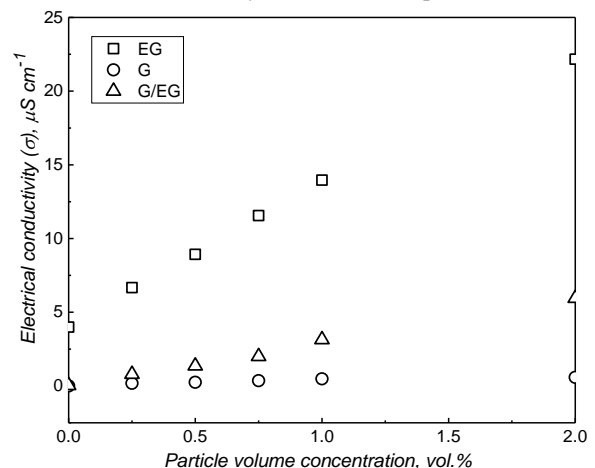


Fig. 2: SEM image of silicon dioxide nanoparticles versus particle volume fraction.

concentration. The EG based SiO_2 nanofluids exhibits higher electrical conductivity increase than SiO_2 dispersions in G and EG/G. The maximum values observed for EG, G, and EG/G at 2.0% volume fraction were $22.2 \mu\text{S}\cdot\text{cm}^{-1}$, $0.58 \mu\text{S}\cdot\text{cm}^{-1}$, and $5.94 \mu\text{S}\cdot\text{cm}^{-1}$, respectively. The main cause for electrical conductivity increase can be attributed to the net charge effect of the suspended particle and the consequent EDL interactions in the nanofluid [14]. Figure 3 compares electrical conductivity ratio of SiO_2 -EG and SiO_2 -EG/G nanofluids at different volume fractions. The data of

SiO₂ G-nanofluids is not presented since glycerol (G) had a very negligible electrical conductivity value at 30 °C. From the plot, higher electrical conductivity enhancement values are found at 2.0% volume concentrations of nanofluids. The conductivity enhancement ratio was up to 63% for SiO₂/EG and 198% for SiO₂-EG/G as compared to their respective base liquids EG and EG/G. This enhancement may be caused by polarization effects due to surface charges around nanoparticles in a polar medium [15]. The comparison between the electrical conductivity enhancements of SiO₂ nanofluids and theory is depicted in Figure 4. It is apparent that the Maxwell model (case 1) failed to predict the electrical conductivity values. According to Maxwell theory SiO₂ nanoparticles will decrease the electrical conductivity of the base fluids due to their insulating characteristics. This is consistent with the results of Khedher et al. [4].

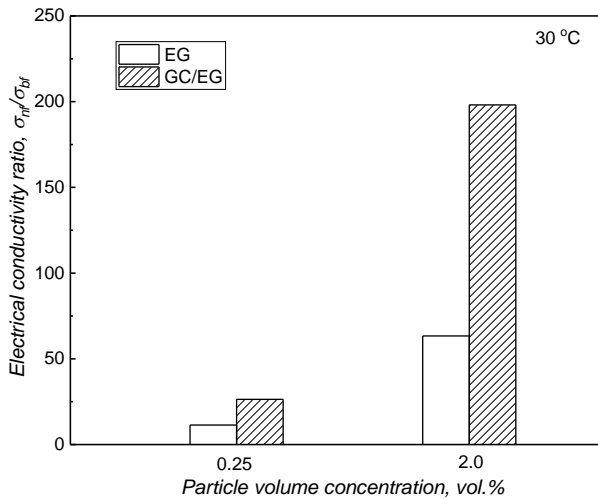


Fig. 3: Electrical conductivity ratio of SiO₂ nanofluids versus particle volume fraction.

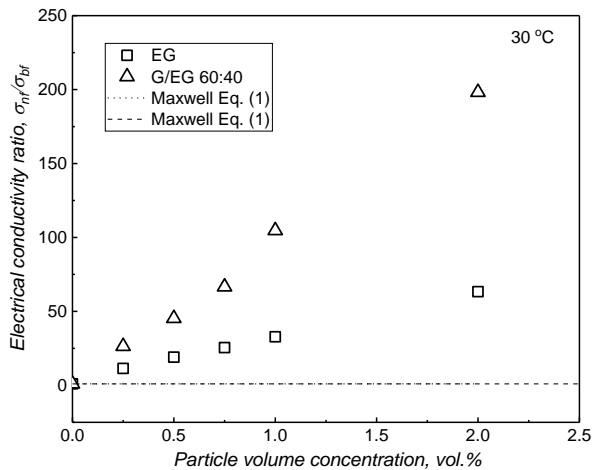


Fig. 4: Comparisons of electrical conductivity ratio of SiO₂ nanofluids with theory.

Figure 5 shows the variation of electrical conductivity with loadings of SiO₂ nanoparticles in EG, G, and EG/G, respectively at 30 °C. The thermal conductivity of nanofluid increased with increasing particle concentration. The enhancement is the highest for EG based SiO₂ nanofluids compared to G and EG/G nanofluids. Maximum enhancements for EG, G, and EG/G nanofluids, respectively were 9.4%, 1.3%, and 3.2% at 2.0% volume concentration compared to base liquids. The reason for this phenomenon may be explained by nature of layering of the base fluid molecules on the surface of the SiO₂ nanoparticles [4].

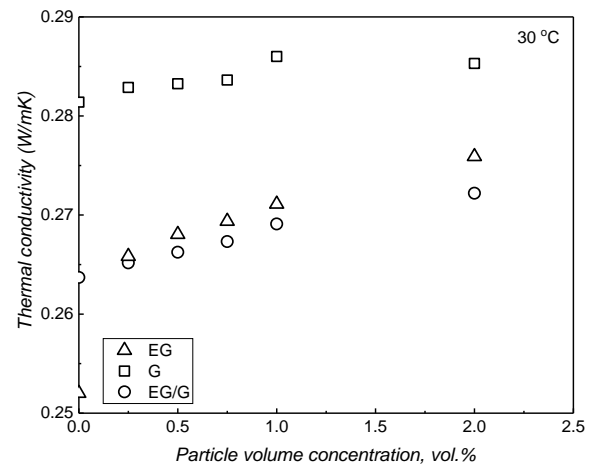


Fig. 5: Thermal conductivity of SiO₂ nanofluids versus particle volume fraction.

Figure 6 shows the thermo-electrical conductivity of SiO₂ nanofluids at 30 °C. As can be observed, as the particle volume concentration increases, the TEC ratio decreases. The SiO₂/G nanofluids exhibited the highest values compared to SiO₂-EG and SiO₂-EG/G. The maximum values for the nanofluids are 28.6, 1.26 and 6.3, respectively at 0.25% volume concentration. Therefore, the SiO₂-EG nanofluid in the present study had better TEC ratios for PEM fuel cell thermal applications that prioritized higher thermal conductivity enhancements than electrical conductivity.

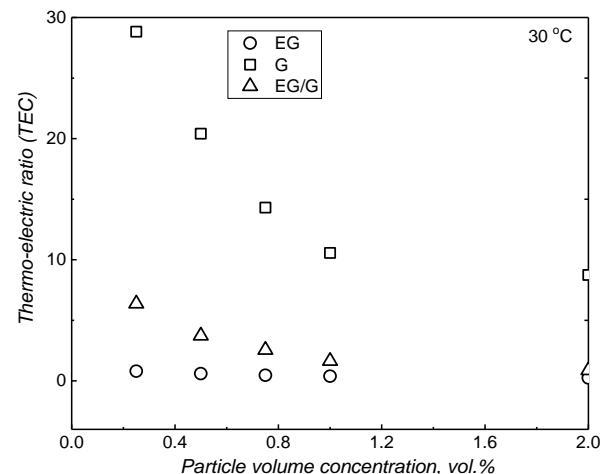


Fig. 6: Comparison of thermos-electric conductivity (TEC) of SiO₂ nanofluids.

5. Conclusions

In this work, the electrical and thermal conductivity of silica nanoparticles in different base liquids viz., ethylene glycol, glycerol and ethylene glycol-glycerol mixture (40:60) ratio by weight is investigated in the range of 0.25–2.0% vol. and at temperature of 30 °C. The following conclusions can be drawn from the experimental work:

- (1) The effective electrical and thermal conductivities increased with concentration and SiO₂ exhibit larger increment values in EG compared to G and EG/G as base liquids.
- (2) The EG/G based SiO₂ nanofluids had superior electrical conductivity ratio (198%) than EG nanofluid (63.3%). Comparison was not possible for SiO₂/G due to zero values of electrical conductivity of G as base liquid. On the other hand, SiO₂-EG exhibited highest thermal conductivity enhancements of 9.4% followed by EG/G (3.2) and G nanofluid with 1.3% at 2.0% volume concentration.

(3) The classical Maxwell's model for electrical conductivity is not applicable to SiO₂ nanofluids.

(4) The highest TEC ratio was observed with SiO₂-G showing a maximum value of 28.6%, whereas SiO₂-EG/G and SiO₂-EG had lower values of 6.3% and 1.26%, respectively at a particle volume concentration of 0.25%. Hence, SiO₂-G nanofluid is more favourable for PEM fuel cell cooling benefit.

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