

Electro-Thermal Characteristics of Hybrid Tioz-Sioz Nanofluid Coolants in An Electrically-Active System

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ABSTRACT

Thermal management in an electrically-active system is a challenging engineering branch due to the critical requirement for rapid cooling rates with inhibition of electrical discharge. A Polymer Electrolyte Membrane Fuel Cell (PEMFC) is an example of a system that needs both conditions to be critically fulfilled. The use of conventional deionised water with low electrical conductivity as the cooling fluid ensures insignificant electrical potential losses but large thermal capacities can only be achieved with a significant penalty to the PEMFC system size. Formulation of nanofluid coolants has been highly successful for systems working under normal environments, but research towards new nanofluid coolants for active electrical systems are relatively new. This paper reports a fundamental investigation on the electrical and thermal behaviours of a hybrid 1%v TiO₂-SiO₂(at 50:50 ratio) nanofluid dispersed in 60:40 water/ethylene glycol solution. A test bench consisting of a heated rectangular channel combined with continuous electrical supply at 0.7 V and 3 A nominal current was developed to simulate the operating conditions of a PEMFC stack cooling. The test variables are the heater temperature and Reynolds number (300 to 700) of the coolants. The cooling profiles and changes in electrical properties of the system and coolants were analysed. Significant increase in cooling rates were achieved by the hybrid nanofluids (200% to 250%) compared to water and water/ethylene glycol coolants. The electrical



analysis indicates that the power drop is low for water and water/ethylene glycol but drops rapidly in an exponential profile (between 15% to 45%) which also leads to a visible increase in the electrical conductivity of the nanofluids coolants. As such, further research is needed to reduce the apparent electrical discharge problem before a suitable nanofluid coolant can be developed for electrically-active systems.

Keywords: *hybrid nanofluid, electro-thermal analysis, fuel cell, thermal conductivity, electrical conductivity*

INTRODUCTION

Nanofluids is a class of engineered fluids to modify the properties of the base fluid using colloidal suspensions of nanoparticles (1 to 100 nm in size) to meet specific applied engineering objectives. Extensive research has been conducted to develop nanofluids coolants for different thermal systems, mainly motivated by the engineering advantage of greater achievable cooling rates that would lead to the reduction of the thermal system size. A more compact thermal management system enhances the cost-effectiveness of the overall system and allows a more diverse system architecture for application in constrained spaces with great potential for advanced cooling system designs for microelectronics, internal combustion engines and heat exchangers [1].

Nanofluid coolants research is highly progressive with new types being developed for different thermal systems. The main criteria for nanofluids coolants is to obtain a significant increase in thermal conductivity compared to its base fluids. Common nanoparticles used for this purpose are aluminum oxide (AL₂O₃), titanium oxide (TiO₂), silicon oxide (SiO₂), carbon nanotubes (CNT) and zinc oxide (ZnO) [2]. However, the addition of nanoparticles into a fluid also causes the viscosity and density of the nanofluids to increase while reducing its specific heat values. Common base fluids used for nanofluids coolants are water, ethylene glycol and propylene glycol as anti-freezing agents [3] with new emerging trends in the use of bio glycols as a greener alternative [4]. The nanoparticles capable of increasing the thermal conductivity are typically made of metals, oxides, carbides or carbon nanotubes. The identified factors influencing the thermal conductivity of

nanofluids are nanoparticle type, size, shape and concentration, as well as the type of base fluids and its operating temperature [5].

A hybrid nanofluid is a stable homogeneous mixture of two or more different nanoparticles suspended in a base fluid to obtain property enhancements that is not possible by merely using a single nanoparticle. As an example, Moldoveanu et al. [6] conducted studies using Al₂O₃-TiO₂ hybrid nanofluids and proved that the hybrid mixture has greater thermal conductivities than its relative mono nanofluids. Hamid *et al.* [2] formulated a TiO₂-SiO₂ hybrid nanofluids in water/ethylene glycol mixture at different ratios and found that small volumetric changes to the SiO₂ produces significant increases in thermal conductivity. Recent directions in hybrid nanofluids uses green plant-derived base fluids known as bio-glycols. Khedher *et al.* [7] reported positive changes were obtained where the thermal conductivity increases by 17% for Al₂O₃ water/bio-glycol nanofluids compared to Al₂O₃ in water/propylene glycol nanofluids.

A new branch in the formulation of nanofluid coolants focuses on the critical thermal management needs of PEMFC stacks. The PEMFC is an important and widely used type of fuel cell technology that uses oxygen and hydrogen to produce electricity with water and heat as a by-product. This means a PEMFC stack is an electrically-active system with free electrons moving throughout the stack. Small stacks (less than 2 kW power output) only require cooling by air, but larger modular stacks with capacities of hundred kW power would require a cooling system with greater cooling capacity. Deionised water has been the conventional liquid coolant for large PEMFC stacks. Its thermal conductivity at ambient is 0.61 W/m.K which has been proven to be adequate for cooling large PEMFC stacks. However, the major disadvantages are the requirement for large heat exchanger frontal areas to effectively dissipate the waste heat to the surrounding, and highly non-homogeneous stack temperatures are usually obtained [8].

The size of the PEMFC system would be a significant factor for its commercial acceptance. One viable approach to reduce the stack size and system components is through the thermal engineering aspect. Fuel cells need rapid and effective cooling to remove the continuously generated heat due to the exothermic reactions at the cathode as well as the irreversibility in the system. Cooling failure would critically reduce the capacity of the

temperature-sensitive membrane within the stack to effectively transport ionic charges at the electrodes, leading to significant electrical potential losses [9].

The research in nanofluid coolants specifically for PEMFC were initiated by Zakaria *et al.* [10] using alumina nanoparticles in water and water/ethylene glycol and supported by Talib *et al.* [11] using SiO₂ in water and water/ethylene glycol base fluids. Tests have been conducted using 2 kW PEMFC stacks [12] as well as at cooling plate scale [13-14]. The combined works have successfully proved that nanofluid coolants significantly increases the cooling rates and may lead to a reduction of 30% from the conventional cooling system size. However, stack power losses have also been detected especially for nanofluids with high volume concentration of oxide particles [12].

Currently, it has been identified that the electrical conductivity of nanofluids increases with the increase of thermal conductivity value, deionised water has low electrical conductivity of 6 $\mu\text{S}/\text{cm}$ at 20°C while 0.1%v Al₂O₃ and 0.1%v SiO₂ nanofluids in water has an electrical conductivity of 22 $\mu\text{S}/\text{cm}$ [10] and 11 $\mu\text{S}/\text{cm}$ [11] respectively. At these levels of electrical conductivities, the electrical charges that are generated within the system partly flow into the coolant and leading to losses in net electric output. As a result, the practical application of nanofluid coolants for PEMFC stack still requires extensive fundamental research work to overcome this major challenge.

As part of the research work in practical application of nanofluid coolants in an electrically-active system such as a PEMFC stack, fundamental studies on the electro-thermal of nanofluids are needed. The analysis of simultaneous thermal and electrical responses of the coolant would be useful to relate to actual conditions encountered in a full-scale operation. A test bench was developed to analyse the characteristics of convection mechanics, electrical discharge and changes in the electrical conductivity of the nanofluids. The test bench is configured with a channel that can be externally heated at variable load to allow the cooling fluid to absorb heat from the channel surfaces at high temperature, while electrical current at a specific voltage is regulated within the channel. Using a nanofluid solution consisting of hybrid TiO₂-SiO₂ (50:50) at 1%v concentrations in a 60:40 ratio

of water/ethylene glycol base fluid, the main objective of this research is to obtain preliminary information on the changes to the thermal capacity and electrical effects of the nanofluids at a fundamental level. This information would then serve as reference for future development and performance characterisation of new highly-effective nanofluids for electrically-active systems.

METHODOLOGY

A test bench was developed specifically for the characterisation of nanofluid coolants under simultaneous thermal and electrically-active operation. The main section is the test panel where it consists of an insulated, square stainless steel cooling channel with an electrical heater pad and electrical input/output terminals at both ends of the channel. The system also consists of a coolant reservoir tank and pump, a heat exchanger to dissipate the collected heat to the surrounding, an electrical power loader to regulate the supplied current and voltage to the channel, and a data logger attached to thermocouples and flow meter for real-time data recording. Table 1 lists the specifications of the system and major components while Figure 1 shows the schematic diagram of the dedicated test bench.

There were three cooling fluids used in the experiment to provide a preliminary basis for comparative performance; deionised water, a fluid mixture of water/ethylene glycol at 60:40 ratio, and a hybrid nanofluid coolant of 1%v TiO₂-SiO₂ (50:50) dispersed in 60:40 mixture of water/ethylene glycol. Table 2 provides the properties of the coolants used in this study. The experiments were planned with two operating variables for all the cooling fluids as listed in Table 3 - the Reynolds number (Re) and heater temperature (T_H). The corresponding flow rate for each Reynolds number differs for each fluid due to variations in density and viscosity. The experiment Reynolds number from 300 to 700 were chosen according to normally applied fuel cell coolant flow conditions within a stack [12]. Therefore, preliminary calculations were made to determine the correct flow rates for each coolant. The coolants are stored in the tank and the flow is controlled by a power regulator that controls the voltage of the pump.

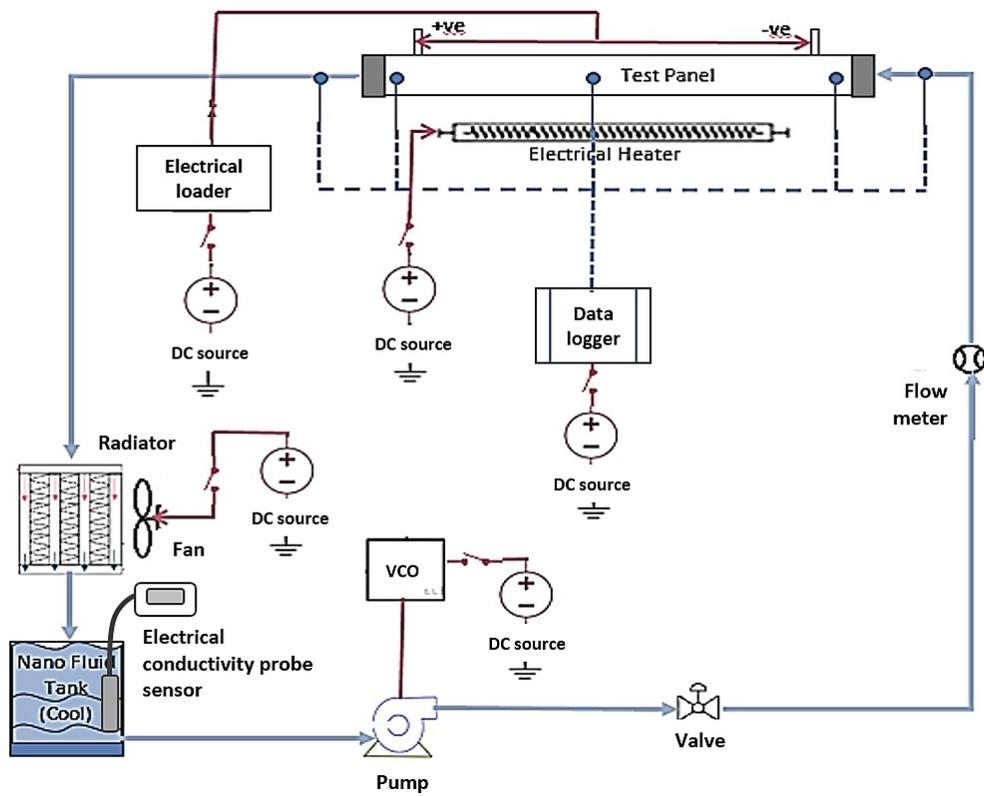


Figure 1: Schematic Diagram of the Electro-Thermal Test Bench System

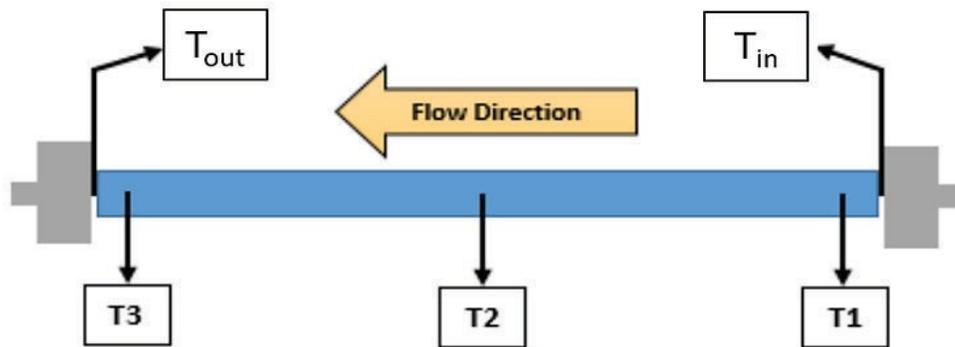


Figure 2: The Positions of the Thermocouple Wires for Temperature Measurement

Table 1: System Component Specifications

Components	Specifications
Cooling channel	Dimensions: 20mm x 10mm x 380mm (WxHxL) Material: Stainless steel 304 Heating area: 0.0076 m ²
Heater pad	Custom AC240V with thermostat Temperature range: 30°C to 120°C
Pump	Type: 12V Micro diaphragm pump Max. pressure: 0.8 MPa Max. flow rate: 6 L/min
Data logger	Model: GL220 Graphtec 10 channels
Electrical conductivity sensor	Model: TDS OEM Range: 0 to 9999 μ S/cm

An electrical heater pad supplies heat to the cooling channel bottom surface. The experimental heater temperatures of 60°C and 70°C were selected because these temperatures represent the normal operating temperatures of a PEMFC stack. When the designated heater temperatures have been reached, the coolant is allowed to flow into the channel. As illustrated in Figure 3, three thermocouple wires were fixed on the cooling channel surfaces (T_1 , T_2 , T_s) while two thermocouple wires were inserted into the fluid line to measure the inlet and exit temperatures at the cooling channel (T_{inlet} , T_{outlet}). Another thermocouple wire was used to measure the fluid temperature at the radiator exit (T_R).

At steady-state, the electrical power loader supplies current into the channel at a fixed voltage of 0.7 V, which is the typical voltage of a single PEMFC cell. The nominal current was set at 3 A and the changes in current as the coolant flows within the channel are monitored in real-time. Theoretically, fluids with high electrical conductivity would easily allow some of the free electrons to be discharged from the channel circuit into the fluid, and the electron losses can be detected by a drop in supplied current at the electronic loader display panel. During the experiment, the electrical conductivity of the coolants was measured to analyse changes caused by the dynamics changes in the electrical field within the cooling channel domain. A probe sensor was used at the tank to monitor the electrical conductivity values of the coolants after steady-state condition has been reached.

Table 2: Properties of Nanoparticles and Base Fluid [12]

Type of fluids	Thermal conductivity k, (W/m K)	Specific heat C_p , (J/kg K)	Viscosity μ , (kg/m.s)	Density ρ , (kg/m ³)	Electrical conductivity σ , (μ S/cm)
Distilled water	0.615	4180.0	0.000854	997	6
W: EG (60:40)	0.4096	3491.8	0.002446	1056.716	4
1%v TiO ₂ -SiO ₂ (50:50) in W:EG (60:40)	0.4350	3470.5	0.003000	1109.336	25 (measured)

The analysis in the results section starts with the mapping of all the temperature profiles at steady-state. Then, a representative mean surface temperature was calculated from the summation of T_1 , T_2 and T_s . The inlet and outlet fluid temperatures were applied to calculate the rate of heat change within the fluid, Q_c . Then the value of Q_c was used to calculate the surface heat flux, q_H , where it represents the cooling rate of the heated channel surface per unit area.

Initially, the flow rate of the coolants, u , was calculated from its Reynolds number, hydraulic diameter of the channel, D_h , and the physical properties of the fluids;

$$\text{Mass feed rate, } n = q \cdot V \cdot A_c = \frac{\text{Re} \cdot \mu}{D_h} A_c \quad (\text{kg/s}) \quad \text{Eq. 1}$$

where $D_h = 0.0133 \text{ m}$.

$$\text{The rate of heat change within the fluid, } Q_c = n \cdot C_p \cdot \Delta T \quad (\text{Watts}) \quad \text{Eq. 2}$$

where the fluid temperature difference, $\Delta T = T_{\text{out}} - T_{\text{in}} \quad (\text{K})$

$$\text{Then, the surface heat flux, } q_K = \frac{Q_c}{A_s} \quad (\text{W/m}^2) \quad \text{Eq. 3}$$

where A_s is the area of the heating surface, $A_s = 7.6 \times 10^{-3} \text{ m}^2$

Table 3: Experimental Matrix for Each Fluid at Different Reynolds Number

Fluid type	Heater temperature, T_H (°C)	Reynolds Number, Re	Flow rate, V_c (L/min)	Mass feed rate, n (kg/s) $\times 10^{-3}$
Distilled water	60	300	0.231	3.84
		400	0.308	5.12
	70	500	0.385	6.40
		600	0.462	7.70
		700	0.539	8.97
W: EG (60:40)	60	300	0.625	11.01
		400	0.833	14.71
	70	500	1.041	18.34
		600	1.250	22.02
		700	1.458	25.70
1%v TiO ₂ -SiO ₂ (50:50) in W:EG (60:40)	60	300	0.729	13.49
		400	0.972	17.99
	70	500	1.215	22.48
		600	1.459	26.98
		700	1.704	31.46

RESULTS AND DISCUSSION

The analysis is divided into three sections:

- i. Discussion on the temperature profiles for a selected coolant and operation setting,
- ii. Evaluation on the thermal performance of the coolants, and
- iii. Analysis of changes in electrical characteristics of the system and the cooling fluids.

Steady-State Temperature Profiles

There are a total of ten sets of temperature profiles for each coolant due to the parametric changes in surface temperatures and Reynolds number. In Figure 3, an example of the temperature profiles at $T_H = 60^\circ\text{C}$ and $Re = 700$ are shown for general discussion. These temperature profiles are important results as it is needed to calculate the surface heat flux, q_s . The main analysis is on the temperature difference between the inlet (T_{in}) and outlet (T_{out}) temperatures of the coolant. For all fluids, there is significant change in the

coolant temperature as it flows through the heated channel. The magnitude of temperature difference varies for each fluid. The nanofluid coolant has a temperature difference of 4°C while water and water/ethylene glycol only registers a 3°C difference. This directly indicates the fluid with better thermal performance. The nanofluids have superior thermal conductivity that led to better convection efficiency at the channel surface and rapid thermal diffusivity through the fluid-solid particles. Similar temperature profiles were also obtained for all fluids at both heater temperatures and Reynolds number.

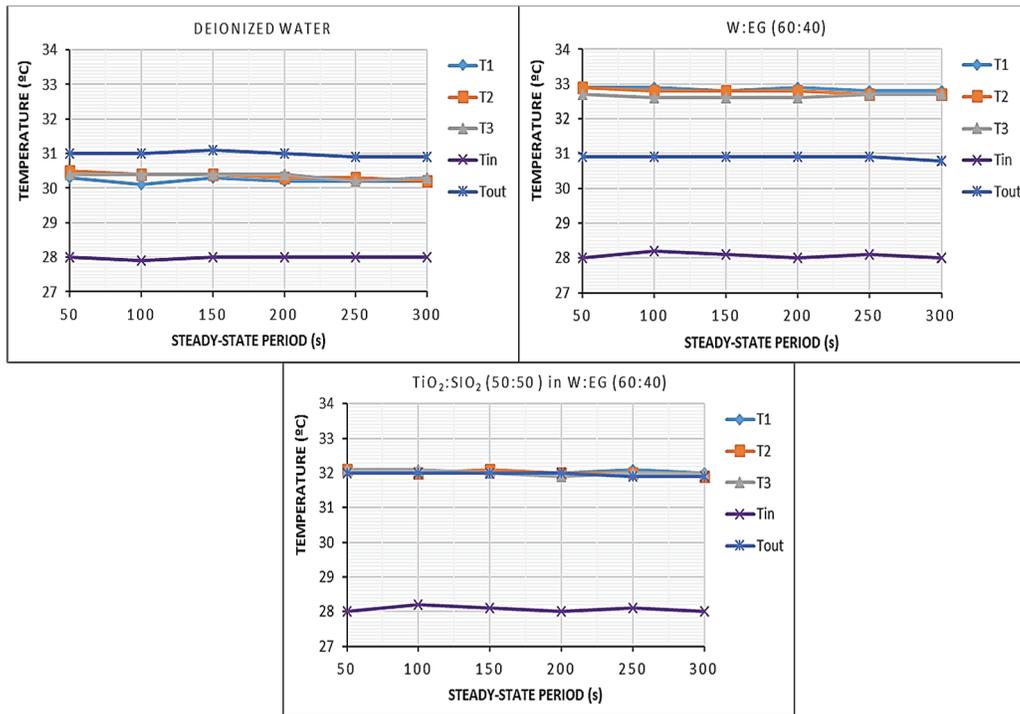


Figure 3: An Example of Steady-State Temperature Profiles for the Coolants at Heater Temperature, $T_H=60^\circ\text{C}$ and Reynolds Number, $Re=700$

Thermal Performance Evaluation

The determination and profiling of surface heat fluxes (q_H) in Figure 4 provides better evaluation on the thermal performance of each coolant compared to the temperature profiles alone as each fluid differs in thermal conductivity, specific heat capacity and density. The surface heat flux was calculated from Eq. 2 and 3. In general, the heat flux is evidently two times higher when the heater temperature increases from 60°C to 70°C. This is an expected phenomenon as surface convection mechanics are

largely affected by the generated temperature gradient along and above the channel surfaces. Larger nominal temperature difference between the fluid and surface generates a larger thermal gradient that enhances conduction mechanics within the active convection region.

Across each heater temperature and Reynolds number, the nanofluid coolant was able to absorb greater thermal power than water and water/ethylene glycol coolants. The surface heat flux for each fluid has a linear profile between the applied Reynolds number due to its laminar flow nature. The nanofluid is expected to perform better at higher surface temperatures and Reynolds number as shown by the slope of the graphs. By comparing the heat fluxes for both heater temperatures, it was calculated that the nanofluids thermal performance at $T_H = 70^\circ\text{C}$ increases by 200% at low Reynolds number and rises to 250% increase at higher Reynolds number. The thermal performance for the other fluids only increases by approximately 10% for every Reynolds number increase of 100. The surface heat flux analysis successfully proves that the 1%v TiO₂-SiO₂ (50:50) in 60:40 water/ethylene glycol nanofluids mixture enhances the coolant thermal performance significantly over its base fluid. Across both heater temperatures, it has a thermal performance 250% to 500% better than water and 20% to 60% better than its base fluid.

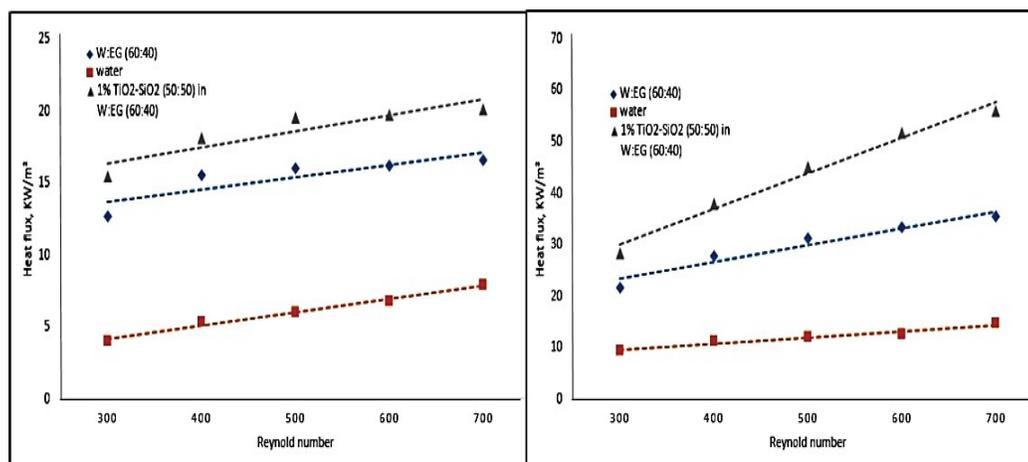


Figure 4: Surface Heat Flux Profiles as the Reynolds Number, Re , Changes at Heater Temperatures, $T_H = 60^\circ\text{C}$ (left) and 70°C (Right) Surface Temperatures

Electrical Characteristics

Figure 5 shows that the electrical current decreases from its nominal value of 3 A when the Reynolds number increases. The experimental procedure has successfully shown that free electrons travelling across the terminals are attracted to the coolants with greater electrical conductivity values. The electrical current decreases in a linear profile for water and water/ethylene glycol fluids but shows a rapid exponential decrease for the hybrid nanofluid. The results can be related to the value of electrical conductivity of each fluid, as shown in Table 2. However, the exponential current decrease rate with Reynolds number for the hybrid nanofluid is a new finding. This profile might be related to the random Brownian motion of the nanoparticles that fills in the spaces between the fluid molecules. As a result, free electrons are diffused or transported better across the fluid layers due to greater contact rates of the nanoparticles at higher Reynolds number.

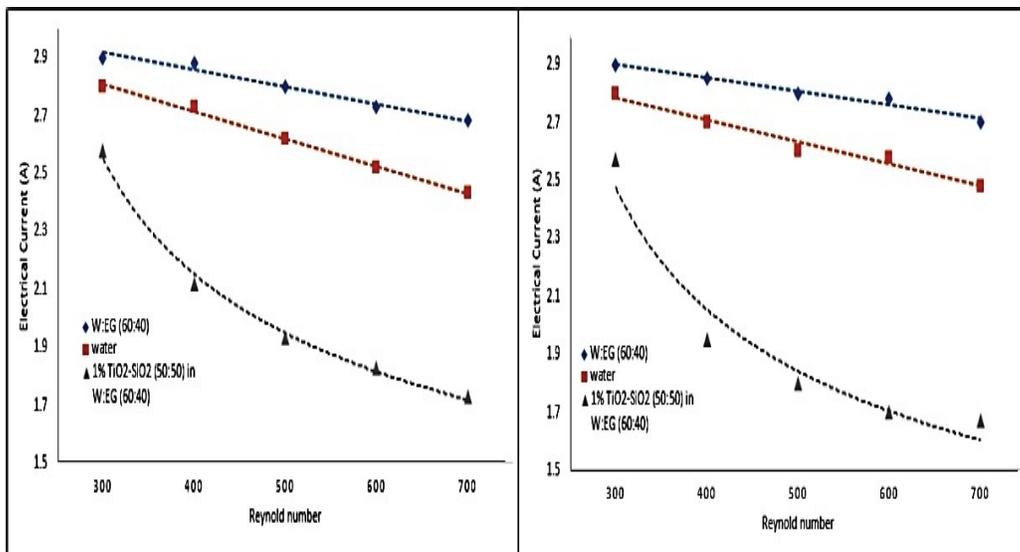


Figure 5: Profile of the Actual Electrical Current Through the Channel Circuit as the Reynolds Number, Re Changes at $T = 60^{\circ}\text{C}$ (left) and 70°C (Right) Surface Temperatures^H

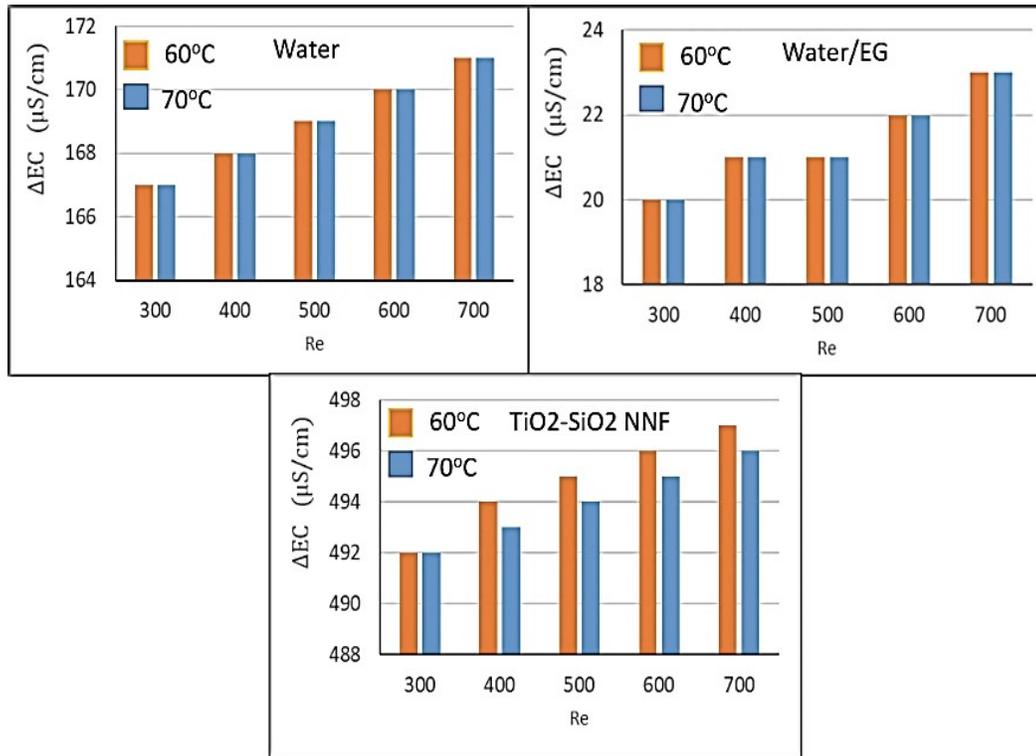


Figure 6: Changes in Electrical Conductivity of the Coolants at Various Heater Temperatures and Reynolds Number

Between the Reynolds number of 300 to 700, the 60:40 water/ethylene glycol solution promotes the lowest electrical current drop (3% to 10%) from the nominal 3 A supplied current. For water, the drop is between 6% to 20% while for the hybrid nanofluid, it is between 15% to 45%. The electrical current profiles for 0.1%v TiO₂-SiO₂ (50:50) in 60:40 water/ethylene glycol are quite similar for both heater temperatures and can be expressed with these empirical correlations with a 10% standard deviation;

$$I = 34.57.Re^{-0.46} \quad \text{for } T_H=60 \text{ }^\circ\text{C} \quad \text{Eq. 4}$$

$$I = 40.93.Re^{-0.496} \quad \text{for } T_H=70 \text{ }^\circ\text{C} \quad \text{Eq. 5}$$

It is also worthy to note that the heater temperatures (channel surface temperature) between 60°C and 70 °C did not have an evident influence on the rate of current discharge into the coolants. However, this trend might change at elevated temperatures.

The increase in electrical conductivity of all the fluids were obtained as in Figure 6 by comparing the electrical conductivity value of each operation with its initial values as listed in Table 2. In general, the changes are not influenced by the surface temperature, as was also registered for the electrical current profiles. Very high increase is seen for the hybrid nanofluids due to the greater diffusion of electrical energy from the channel surfaces. However, the increase trend is linear and does not follow the exponential electrical current drop profile. The changes for water is also high relative to its initial value of $6 \mu\text{S}/\text{cm}$. Further study on this internal property changes are needed before a conclusive scientific statement can be produced. For this study, it is sufficient to physically show that a greater rate of electron discharge into the fluid would lead to increases in the electrical conductivity values.

CONCLUSION

A dedicated test bench was successfully developed to characterize the fundamental electrical and thermal profiles of advanced coolants especially for electrically-active systems such as a PEM fuel cell. Preliminary tests using water, water/ethylene glycol and 1%v $\text{TiO}_2\text{-SiO}_2$ (50:50) in 60:40 water/ethylene glycol base fluid were conducted under varying Reynolds number (300 to 700) and at 60°C and 70°C heater temperatures. The hybrid nanofluids showed a significant enhancement in surface heat flux compared to its base fluids due to the increase in thermal conductivity. However, it was also proved that the hybrid nanofluids causes a severe electrical energy discharge from the electrical circuit due to its high values of electrical conductivity. The suitability of this hybrid nanofluid for practical application in electrically-active systems is not recommended as it would lead to a 50% electrical energy loss from the system. These results have fundamentally shown that the development of a suitable nanofluid coolant type for electrically-active systems is a very challenging task and electro-thermal evaluation, as presented here, is a very necessary assessment procedure.

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