Thermal-electrical-hydraulic Behaviour of Al_2O_3:SiO_2 in Charged Cooling Channel

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Abstract: *Proton Exchange Membrane Fuel Cell (PEMFC) emerges as an alternative greener energy carrier that offers higher efficiency, emissions reduction, and dynamic response as compared to an internal combustion engine. PEMFC thermal management presents a challenge due to the minimal temperature gradient between its operating conditions and the surrounding environment. Thus, nanofluids as a passive heat transfer solution seem promising for PEMFC. Nanofluids offer better heat transfer performance due to their significant thermal conductivity improvement. This paper presents the thermal-electrical-hydraulic behaviour of single Al_2O_3, single SiO_2, and hybrid ratios (10:90, 30:70, 50:50, 60:40) of hybrid Al_2O_3:SiO_2 nanofluids through circulation in a charged, heated channel. In comparison to the base fluid, the heat transfer coefficient is significantly enhanced as the thermal-electrical-hydraulic behaviour of hybrid Al_2O_3:SiO_2 nanofluids showed that a hybrid ratio of 10:90 demonstrates the most feasible application, with the improvement of 4 times higher and minimal pressure drop effect.*

Keywords: Heat transfer; Pressure drop; Current drop; Hybrid nanofluids

1. INTRODUCTION

A PEMFC is a device that transforms chemical energy into electrical energy through an electrochemical reaction, owing to the electrochemical reaction of hydrogen and oxygen [1]. PEMFC is more efficient than internal combustion engines as it converts up to 60% of the fuel's energy into electricity, compared to 20-30% for internal combustion engines [2]. PEM fuel cells offer several advantages, including high power density, rapid start-up, low operating temperature, efficient electrical energy conversion, compact design, lightweight construction, and adaptability to dynamic driving conditions [3, 4].

The heat produced by a PEMFC mainly comes from several sources: the entropic heat of chemical reactions, the irreversible heat generated by electrochemical processes, the heat arising from ohmic resistance, and the thermal energy released during the condensation of water vapor [5]. The heat transfer in a PEM fuel cell is limited because the temperature difference between the fuel cell and the surrounding environment is relatively small, reducing the overall driving force for thermal exchange. The challenge is even greater in hot regions like deserts, where the high ambient temperature further reduces the effectiveness of heat dissipation [6].

In a PEMFC, thermal management plays a crucial role in removing waste heat, as the heat dissipation through reactant and product streams is minimal. For higher power output fuel cells, active cooling becomes necessary since passive cooling and the effects of gas streams provide only limited heat removal [7]. This poses a challenge for the cooling system, as it requires a radiator with a large heat transfer area, which is difficult to accommodate within the constraints of a compact design. An alternative approach is to raise the stack temperature to around 90–95°C, which helps minimize the need for a large and bulky heat exchanger [8]. However, current membrane technology struggles to effectively accommodate the high temperature requirements.

Effective thermal management in a PEMFC is crucial in order to maintain the membrane's proton conductivity, as its performance is highly dependent on adequate hydration levels. Since water is a byproduct of PEM fuel cell operation, its condensation at temperatures below 80°C can lead to water flooding in the electrode regions, posing a challenge for efficient performance. Water flooding in a PEM fuel cell weakens the delivery of reactants to the membrane, ultimately diminishing its overall performance [9]. Elevated temperatures enhance both electrochemical reaction kinetics and membrane conductivity, making high-temperature operation preferable for optimal fuel cell performance. However, excessively high temperatures can lead to a loss of moisture in the membrane, increasing the risk of dehydration and compromising its performance. For optimal performance, the membrane should be maintained at full relative humidity, ideally at 100%.

Researchers have explored various advancements in liquid-cooled PEM fuel cells to enhance thermal management. Most studies focus on optimizing flow field configurations, refining channel designs, and improving cooling system components. Enhancing the coolant flow field by incorporating a multi-pass serpentine design and a hybrid parallel-serpentine-oblique configuration has been shown to improve both peak temperature management and temperature uniformity [10]. Lasbet et al. [11] explored the optimization of coolant channel design using a 3D chaotic advection flow, while Morikawa et al. [12] developed a V-flow system for the Honda FCX, leveraging gravity for efficient water drainage.

Nanofluids represent a novel class of engineered solutions, first introduced by Choi and Tran [13], involving the dispersion of micron-sized solid particles within a water-based fluid, commonly referred to as

microfluidics. Incorporating metal particles with significantly higher thermal conductivity than the base fluid has led to a substantial enhancement in the heat transfer coefficient. However, incorporating micron-sized particles has led to challenges such as agglomeration and pipeline erosion, ultimately increasing the demand for higher pumping power.
Choi and Eastman [14] from Argonne National Laboratory later discovered ultra-fine nanometer-sized particles dispersed in a base fluid, leading to the development of 'Nanofluids.' These fluids consist of a base liquid with suspended nanoparticles smaller than 100 nm. Base fluids for nanofluids can include water, ethylene glycol mixtures, propylene glycol mixtures, or engine oil. The engineered nanofluids significantly modify their thermal properties, leading to enhanced heat transfer performance. Researchers have examined various types of nanofluids, including metal-based and oxide-based formulations such as SiO_2 (silicon dioxide), Fe_3O_4 (iron oxide), ZrO_2 (zirconium oxide), ZnO (zinc oxide), and Cu (pure copper). Scholarly literature, both experimental and theoretical, predominantly focuses on metallic oxide nanofluids for studying transport properties and heat transfer enhancement. Nanoparticles are dispersed at different concentration levels using a range of base fluid options.

Islam et al. [15] analyzed the feasibility of using nanofluids in fuel cell cooling systems, considering both their benefits and drawbacks. The author noted that, so far, experimental and theoretical investigations on fuel cell cooling with nanofluids remain scarce and limited.
Zakaria et al. [16] explored the feasibility of using nanofluids as a potential coolant for PEM fuel cells, conducting both experimental and simulation-based studies.

The study examines Al_2O_3 nanofluids as a potential alternative coolant for PEMFC, given that Al_2O_3 possesses one of the highest thermal conductivities among oxide-based nanofluids, after CuO [17]. Sarojini et al. [18] reported that Al_2O_3 has a lower electrical conductivity than CuO, which is advantageous for PEM fuel cell applications. Agglomeration is a key consideration in selecting Al_2O_3 over other nanoparticles, as it has been found to exhibit less agglomeration compared to other oxide-based nanofluids [19].

Research on the electrical conductivity of nanofluids remains limited, with available literature being scarce. This may be due to the relatively few applications of nanofluids in electrically active thermal systems such as PEM fuel cells. Research on the electrical conductivity of different nanofluids has been relatively limited, with studies by Dolati et al. [20] and Rudyak et al. [21] primarily focusing on macroscopically stationary conditions rather than any specific practical applications.

This paper considers all aspects, including heat transfer, measurement of electrical conductivity property of hybrid nanofluids, current drop, and additional pressure drop associated with the adoption of nanofluids in PEMFC. This experimental study models a PEM fuel cell application by utilizing a charged channel exposed to a constant heat flux, replicating its operational conditions.
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2. METHODOLOGY

The Al_2O_3 nanoparticles, which were 13 nm in size and 99.8% pure, were used in this experiment. In the meantime, SiO_2 was in a liquid form of 30 nm in size with weight percentage of 25%. In this experiment, the two-step method was employed [22]. This approach was simpler and more convenient. Upon preparation, the nanofluids were then sonicated using both a mechanical stirrer and a DAIHAN scientific ultrasonic sonicator to ensure the homogeneity and stability of the nanofluids prepared. The sonication was performed for two hours as practiced by other researchers [23]. The studies were conducted at four different Al_2O_3- SiO_2 mixture ratios, which were 10:90, 30:70, 50:50, and 60:40. The mathematical equation used for sample preparation is as shown in Equation (1), which was used to convert mass concentration to volume concentration, whereas Equation (2) was utilised to dilute nanofluids. Distilled water was used as the base fluid for the nanofluid preparation.

$$\phi = \frac{(\frac{m_p}{\rho_p})}{(\frac{m_p}{\rho_p} + \frac{m_{bf}}{\rho_{bf}})} \, x \, 100 \quad (1)$$

Where ϕ represents volume concentration, m represents mass concentration, and ρ represents density. The subscripts p and bf stand for nanoparticles and base fluid.

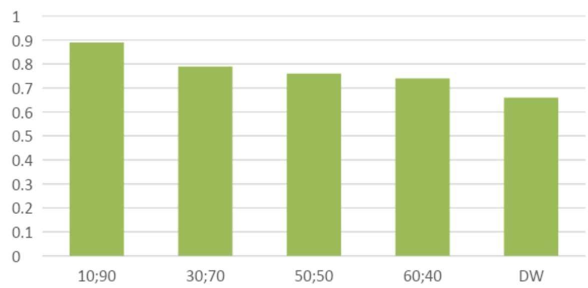
$$\Delta v = (v_2 - v_1) = v_1 \left(\frac{\emptyset_1}{\emptyset_2} - 1 \right) \quad (2)$$

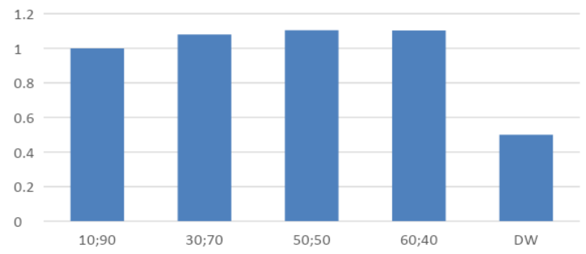
The Δv represents the base fluid's volume that must be added to the current volume of the base fluid, v_1, which is in a concentration of $\emptyset_1$to achieve the required nanofluid volume, v_2, with volume concentration $\emptyset_2$. Each of the nanoparticles was made separately. Properties of nanoparticles (Al_2O_3 and SiO_2), distilled water used, and their physical properties of nanofluids used in this experiment are shown as follows (see Table 1)and (see Fig 1).

Table 1. Properties of nanoparticles (Al_2O_3 and SiO_2) and distilled water.

Property	Al_2O_3	SiO_2	Distilled Water
Average particle diameter, nm	13	30	-
Density, kg/m³	4000	2200	996
Thermal conductivity, W/ m.K	36	1.4	0.615
Specific heat capacity, J/kg.K	765	745	4178
References	[24]	[25]	[26]

(a)

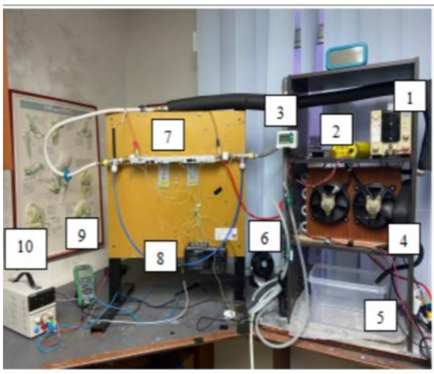




(b)
Fig. 1. Thermal conductivity (a) and dynamic viscosity (b) properties of nanofluids used [27].

The measurement of electrical conductivity of the nanofluids was taken in this study with a Cyberscan PC-10 equipped with the ATC (automatic temperature correction) capability.

To imitate the PEMFC's ideal working temperature, the cooling channel in the test section was heated to 70°C with 3 Amps of current and 0.8V of voltage applied to charge the channel. A heating pad was positioned right underneath the cooling channel. An Ethylene Propylene Diene Monomer (EPDM) foam was used to insulate the cooling channel and pipes to reduce heat loss to the environment. Nanofluids were circulated throughout the system via a pump. The nanofluids are cooled before returning to the reservoir by passing through a radiator. The flow rate was adjusted to achieve a targeted Reynolds number ranging from 100 to 400. The cooling channel was equipped with 5 positions of K-type thermocouples for surface and fluid temperature measurement. The pressure drop and current drop were also recorded during the experiment. The test bench is shown as follows (see Fig. 2)



Test bench components	
1	Power supply
2	Thermostat
3	Flowrate meter
4	Radiator
5	Reservoir tank
6	Pump
7	Cooling channel
8	Data logger
9	Digital ammeter
10	Voltage regulator

Fig. 2. Experimental setup

3. RESULT AND DISCUSSION

3.1 Stability of nanofluids

The sedimentation of Al_2O_3- SiO_2 hybrid nanofluids was monitored starting from after preparation up to 30-day-old samples (see Fig. 3). There was barely sedimentation or coagulation seen in any of the samples. There was a slight sedimentation seen in the 60:40 ratio since this ratio has the highest content of Al_2O_3, which is whitish in colour. However, the application of forced circulation will minimize the effect of sedimentation of the nanofluids. This observation demonstrated that the generated nanofluids were stable and adequate for further research work.

3.2 Thermal : Heat Transfer Enhancement

The temperature of the channel and cooling fluids were measured in this experiment. The data on the temperature was then processed to the convective heat transfer coefficient (see Fig. 4). The convective heat transfer coefficient represents the ability to transmit heat from the heated channel to the cooling fluid flowing through the channel [28]. The convective heat transfer coefficient increased linearly as the Reynolds number was increased. The hybrid 10:90 (Al_2O_3: SiO_2) ratio at Re 400 has a maximum heat transfer coefficient of 265.1% higher than the base fluid, followed by the ratio of 30:70 with 234% enhancement. The lowest heat transfer coefficient is shown by the base fluid of water, as the thermal conductivity of the base fluid is the lowest compared to nanofluids. The findings correlate well with the thermal conductivity properties of the nanofluids (see Fig. 1). The enhancement in convective heat transfer coefficient was mainly contributed from the improved Brownian motion, thus increasing the micro-scale energy transport. This was due to the increase in the random movement of nanoparticles in the base fluid.

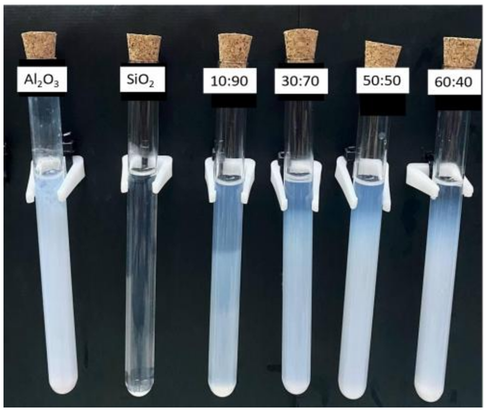


Fig. 3. Samples of prepared nanofluids after 30 days of preparation

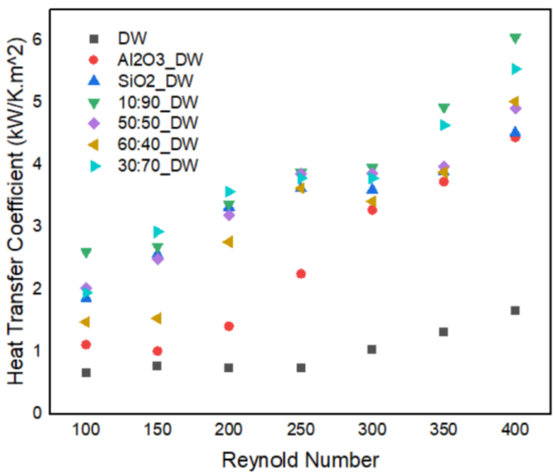


Fig. 4. Heat transfer coefficient improvement with hybrid nanofluids.

3.3 Electrical: Effect on current drop

In this experiment, the electrical conductivity value of the nanofluids was measured before and after the experiment. The electrical conductivity values before and after the experiment were recorded (see Fig. 5). The figure shows that the highest electrical conductivity value of nanofluids was given by the ratio of 10:90, followed by single SiO_2 nanofluids, and then the ratio of 30:70. The post experimental readings also shows that there was additional electrical conductivity picked up by the coolant during the experiment. This has resulted in the current drop phenomenon in nanofluids in the charged channel (see Fig. 6). The current drop was highest in the ratio of 10:90, which is in good agreement with its highest electrical conductivity value of that ratio. The 0.5% volume concentration of the hybrid 10:90 ratio, representing a threefold increase compared to the base fluid, water. This was then followed by single SiO_2 nanofluids and the ratio of 30:70 nanofluids. The current drop was purely driven by the hierarchy of electrical conductivity associated with the fluids.

In terms of flow rate, increasing the Reynolds number has a minimal effect on the current drop. The current drop issue needs to be tackled properly before application in a full-size PEMFC stack, as this will represent shunt current, which is harmful to the operator and also reduces the PEMFC performance [29].

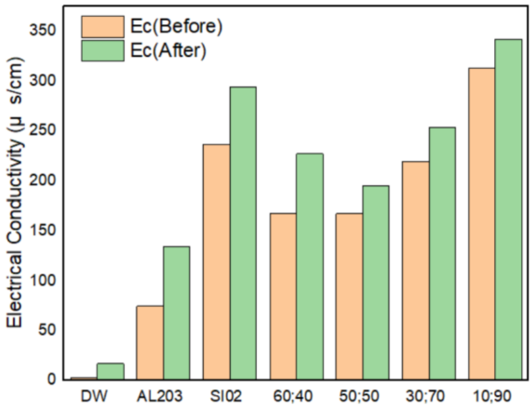


Fig. 5. Electrical conductivity values of nanofluids.

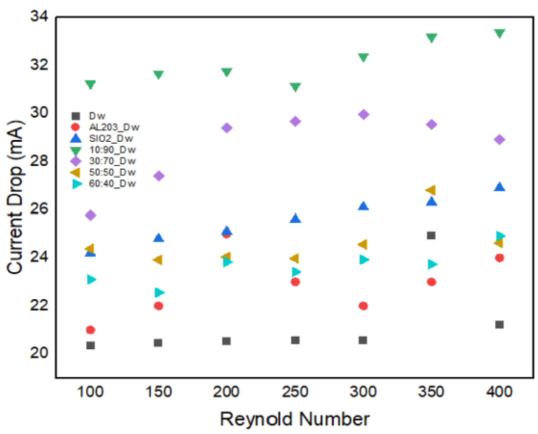


Fig. 6. Current drop in the charged channel

3.4 Hydraulic: Effect on Pressure Drop

The pressure drop effect against the Reynolds number shows that hybrid nanofluids have higher pressure drop as compared to the base fluid of water (see Fig. 7). The highest increment was shown by 60:40 ratio, with value of 207.31 Pa or equivalent to 3 times higher than the base fluid of water, followed by 50:50 and 30:70 mixture ratios. The mixture ratio of 10:90 was in the average region of the pressure drop, which signifies a moderate effect on the pressure drop penalty. It has the lowest pressure drop effect in comparison to other hybrid Al_2O_3: SiO_2 mixture ratios. The trend of pressure drop resembles the effect of their dynamic viscosity properties (see Fig. 1(b)). As the dynamic viscosity values increase, the pressure drop will become larger. Adding nanoparticles to a base fluid increases viscosity due to enhanced particle-fluid interactions, agglomeration, and greater surface area, all of which create more internal resistance to flow. This thickened fluid requires higher pumping power to maintain circulation, leading to a greater pressure drop across the system.

The increased viscosity and pressure drop can be a challenge in applications like PEMFC cooling, where maintaining efficient heat transfer without excessive energy demands is critical. However, further investigation needs to be conducted in the actual fuel cell stack since the power output is relatively high, namely 1.5 kW, so the additional pressure drop with the adoption of hybrid nanofluids might be negligible in real application.

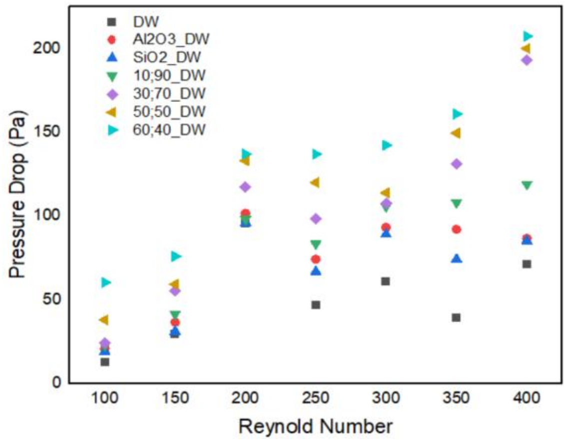


Fig. 7. Pressure drop effect of the hybrid nanofluids

4. CONCLUSION

The behavior of Al_2O_3: SiO_2 hybrid nanofluids in water as the potential cooling medium for PEMFC was investigated comprehensively. The effect of heat transfer coefficient performance, current drop, and pressure drop was reported as thermal-electrical-hydraulic behaviour of the hybrid Al_2O_3: SiO_2 in water subjected to a charged, heated channel was reported in this study. In conclusion, hybrid Al_2O_3: SiO_2 in water has significantly increased the heat transfer performance in the channel. The mixture ratio of 10:90 was able to lower the channel temperature, thus resulting in the highest enhancement of convective heat transfer coefficient, with an enhancement of 265%. This is contributed by the superior thermal conductivity property of the hybrid nanofluids as compared to the base fluid. In terms of the electrical conductivity property, hybrid Al_2O_3: SiO_2 10:90 has also exhibited the highest value, which has eventually resulted in the highest current leakage as compared to the base fluid. This was then supported by the electrical conductivity measurement performed on the electrical conductivity value of the fluids after experimentation. It indicates that the conductive coolant employed in the charged channel might be the cause of the current leakage from the channel. Meanwhile, the mixture ratio of 10:90 is favorable in the pressure drop effect as the ratio has resulted in the lowest pressure drop effect among all hybrid nanofluids studied. It can be concluded that hybrid nanofluids of Al_2O_3: SiO_2 10:90 have the potential to be further explored as an alternative coolant to PEMFC, provided the current leakage is taken care of. However, further experimental study is recommended in an actual PEMFC full stack for a more comprehensive analysis on the effect of hybrid Al_2O_3: SiO_2 as coolant in PEMFC

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