Available online at
https://jmeche.uitm.edu.my/

e-ISSN: 2550-164X

Journal of Mechanical Engineering 23(2) 2026, 224 – 240.

Journal of Mechanical Engineering

Simulation of Hybrid Nanofluids in a Honeycombed PEMFC Cooling Plate

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ARTICLE INFO

Article history:
Received 16 November 2025
Revised 5 April 2026
Accepted 16 April 2026
Online first
Published 15 May 2026

Keywords:
PEMFC
Hybrid nanofluids
Thermal management
Cooling plate simulation
Pumping power

DOI:
10.24191/jmeche.v23i2.11761

ABSTRACT

Proton Exchange Membrane Fuel Cell (PEMFC) is a promising clean energy technology that generates electricity from hydrogen through an electrochemical process, which produces only water and heat as by-products. Efficient thermal management is crucial for PEMFC operation to ensure optimal performance, durability, and energy efficiency. The main challenge of current PEMFC technology is inadequate thermal management, which restricts performance, efficiency, and long-term durability. Conventional cooling methods with a simple channel design are not effective due to the lower thermal conductivity characteristics of base fluids, which restrict effective heat dissipation. Nanofluids with a superior heat transfer performance has been investigated in a honeycomb design of PEMFC cooling plate for its thermal performance improvement. In this study, a 0.5% volume concentration of Al_2 O_(3): SiO_(2)nanofluids with mixture ratio of 10:90, 50:50 and 60:40 was investigated. The simulation was conducted at laminar flow and constant heat of 8000 W/m2 to mimic the operational condition of PEMFC. At 1.6 m/s, the result shows that the highest thermal performance was obtained by the Al_2O_3: SiO_2 (10:90) hybrid nanofluids, which reduced the maximum surface temperature by 6.47% and improved the temperature uniformity by 75.7% compared to water. A 68% rise in the Nusselt number and the highest heat transfer coefficient of 1483.84 $W/m^2{\cdot}K$, with 69.7% improvement, were also observed. However, although the pumping power increases, it remains manageable relative to the overall power output of a full-scale PEMFC system in practical applications.

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https://doi.org/10.24191/jmeche.v23i2.11761

INTRODUCTION

The continued reliance on fossil fuels remains a major contributor to greenhouse gas emissions, which accelerates climate change and causes environmental and health-related issues (Wolf et al., 2025). As global energy demand continues to increase, the development of sustainable and low-emission energy technologies has become critically important. Proton Exchange Membrane Fuel Cell (PEMFC) are widely recognised as a promising clean energy technology due to their high energy conversion efficiency, low operating temperature, and environmentally friendly by-product (Tellez-Cruz et al., 2021). PEMFC also serves as an alternative solution for reducing carbon footprints in sectors such as power generation and transportation.

Since hydrogen produces almost no greenhouse gas emissions during operation, it is considered a promising energy source. Hydrogen is a clean and carbon-free energy carrier, making it a suitable alternative to fossil fuels. It also has a higher energy content per unit mass compared to conventional fossil fuels, which makes it an attractive option for energy applications (Beschkov & Ganev, 2023). Fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, allowing energy to be produced efficiently and cleanly (Thomas et al., 2020).

The working principle of PEMFC involves electrochemical reactions occurring at the anode and cathode. Hydrogen is oxidised at the anode to produce protons and electrons, while oxygen reacts with these protons and electrons at the cathode to form water (Das et al., 2017). The electrochemical process in PEMFC involves two half-reactions:

Anode reaction:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

Cathode reaction:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

Overall reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

Despite its advantages, the system inevitably produces heat as a by-product during operation, necessitating effective thermal management to maintain optimal performance and ensure long-term durability (Qasem & Abdulrahman, 2024). Inadequate thermal management is one of the critical issues in PEMFC systems. Passive cooling approaches are often constrained by the inherently low thermal conductivity of base fluids and the simplicity of channel geometries, which limit effective heat dissipation and offer minimal enhancement in fluid mixing or surface interaction. Integrating nanofluids with enhanced heat transfer properties can significantly improve thermal performance, while the incorporation of honeycomb-structured cooling channels further promotes heat transfer through increased surface area and improved flow distribution. Nevertheless, much heat continues to be produced when operating a PEMFC. Without proper heat management, it may cause degradation of membranes, a decrease in performance, and lower operational life. Consequently, optimal thermal management is a key element of developing PEMFC systems. Heat in PEMFC systems is typically managed using a cooling plate. The cooling plate helps in ensuring that the targeted operating temperature is maintained by removing the undesired heat energy in the system. In addition, the geometry of the cooling plate contributes to an efficient heat transfer and influences the pressure drop in the system (Zarizi et al., 2022).

https://doi.org/10.24191/jmeche.v23i2.11761

Previous research has established the important role of flow field geometry in determining the performance of the cooling of PEMFC and thermal uniformity. Various configurations were widely used, including serpentine and parallel flow fields due to their straightforward structure and reasonable performance at moderate operating conditions (Wang et al., 2011)(Azmin et al., 2020). Nonetheless, the conventional designs usually come with constraints such as non-uniform coolant distribution and high pressure drop at the particular structure. Alternative flow field designs have therefore been explored, with the honeycomb design gaining increasing attention due to its symmetrical arrangement and larger heat transfer surface area. Recent findings suggest that the configuration of flow fields of multi-spiral and honeycomb has the potential to improve the temperature uniformity in the fuel cell (Song et al., 2022). This was supported by the fact that there is a better distribution of the coolant flow across the active area by improving the elimination of localised hot spots and ensuring consistent operating temperatures. Whilst these designs might lead to increased pressure losses over the traditional channels, better thermal management potential underscores this. Therefore, there is great potential to be applied to advanced cooling of PEMFC systems.

Meanwhile, nanofluids are the dispersion of nanoparticles, usually in the range of 1-100 nm, in a base fluid. Various base fluids have been used, like engine oil (EO), ethylene glycol (EG), blood, polymer solutions, and kerosene oil (Zhang et al., 2021). Nanofluids have a great potential for enhancing heat transfer because of their high thermal conductivity (Mahboobtosi et al., 2024). Field emission scanning electron microscopy (FESEM) was then employed in analysing the morphology of nanoparticles (Saygılı et al., 2015). Nanofluids preparation are either using a single or two-step process with or without the addition of surfactants (Zakaria et al., 2018).

The use of nanoparticles, namely silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3), in nanofluids has a significant appeal as they could improve the thermal characteristics of the conventional base fluids. Metallic (Cu, Ag, Si) and non-metallic oxide (CuO, Al_2O_3) nanoparticles have emerged to possess great potential in thermophysical applications over the last few years. These nanoparticles enhance the thermal conductivity and the total heat transfer capacity (Rostami et al., 2020).

Previous computational fluid dynamics (CFD) studies have shown that hybrid nanofluids with an Al_2O_3:SiO_2 ratio of 10:90 can achieve superior heat transfer coefficients, particularly in distributor-type cooling plate configurations operating under low Reynolds number conditions (Idris et al., 2021). Despite the innovative work on nanofluids, their application in honeycomb-designed PEMFC cooling plates remains insufficiently explored, especially regarding the trade-off between enhanced thermal performance and increased flow resistance. This study addresses that gap by evaluating the thermal–hydraulic performance of hybrid nanofluids in a honeycomb PEMFC cooling plate, with particular emphasis on the influence of viscosity on pumping power requirements. Numerical simulations are conducted using ANSYS Fluent to analyze heat transfer characteristics and pressure drop under steady-state, laminar flow conditions with constant heat flux input.

METHODOLOGY

This study utilised numerical simulations of ANSYS Fluent to investigate the thermal and fluid flow behaviour of hybrid nanofluids in a honeycomb design cooling plate for PEMFC applications. In the assessment, the critical performance parameters, including model validation, maximum surface temperature, temperature uniformity index (TUI), heat transfer coefficient, Nusselt number, pressure drop, pumping power, and contours of surface temperature, were reported.

The simulation process consisted of a few steps, which included designing the honeycomb cooling plate geometry, mesh development, and reviewing the thermophysical characteristics of the hybrid nanofluids. The governing equations are used to describe fluid flow and heat transfer behaviour when

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subjected to certain conditions at the boundaries. The finite volume technique is applied to solve the equations, whereby discretization is done, and the equations are solved by calculations until the convergence criteria are reached. The validation of the model is achieved by conducting a comparison between the current numerical data and the established literature review to ascertain the accuracy and reliability of the model. There is also a grid-independence study to ensure that the results are independent of mesh size.

Geometric model

The geometric construction of the honeycomb cooling plate in the present study was designed using a computer-aided design (CAD) program. Fig. 1 represents honeycomb-like structural cooling channel designs. Table 1 lists detailed geometric values of these structures. The honeycomb channel pattern was preferred due to the large surface area and uniform distribution of coolant (Chen et al., 2025).

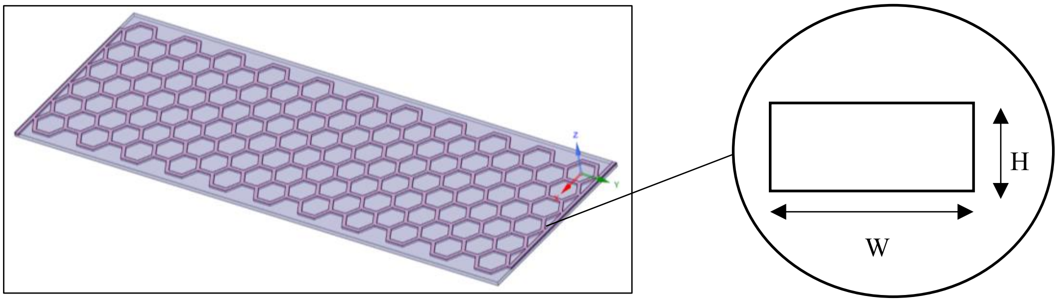

Fig. 1. 3D model of honeycomb PEMFC honeycomb cooling plate.

Table 1. Geometrical parameter and operating conditions of the honeycomb cooling plate (Chen et al., 2025)

Parameter	Value (Unit)
Cooling plate (honeycomb) length (L)	302 mm
Cooling plate (honeycomb) width (W)	108 mm
Cooling plate (honeycomb) height (H)	2 mm
Channel (honeycomb) width	2 mm
Channel (honeycomb) depth	1 mm
Hydraulic diameter (D_h)	1.33 mm
Heat flux (q)	8000 W/m^2
Inlet fluid temperature (T_{in})	313 K
Water cooling inlet flow rate	1.2 m/s

The following assumptions were applied in the simulation:

(i) The nanoparticles and base fluid were assumed as one body since the properties used were nanofluid properties

(ii) The fluid was incompressible

(iii) The flow was laminar due to a low Reynolds number calculated

(iv) Gravitational effects were neglected

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Thermophysical characteristics of the hybrid nanofluids

The thermophysical characteristics of hybrid nanofluids are critical in determining heat transfer performance. Nanoparticles exhibit a strong ability to enhance thermal transport compared to conventional particle suspensions due to their micrometer- and millimeter-sized particles (Johari et al., 2022a). The Al_2O_3 nanoparticles with a diameter of 13 nm and SiO_2 nanoparticles with a diameter of 30 nm were considered in the present simulation study (Idris et al., 2024). The properties of the nanoparticles and base fluid used in this study are shown in Table 2. The effective thermal conductivity, k, and ther dynamic viscosity, μ, of the hybrid nanofluids mixtures ratio (10:90, 50:50, and 60:40) at 80 °C were experimentally measured by Khalid et al. (2021) as shown in Fig. 2. Meanwhile, density, ρ, and specific heat capacity, Cp, of the hybrid nanofluids were calculated using the correlations given in Equations 4 and 5, and the results are depicted in Fig. 3.

The 0.5 vol.% nanoparticles are selected to balance thermal enhancement and flow performance. Higher concentrations enhance thermal conductivity but also increase viscosity, which leads to an increase in pumping power and pressure drop (Borode et al., 2023). The hybrid nanofluids at lower concentrations keep the viscosity moderate and the flow behaviour steady, yet continue to offer significant thermal conductivity improvement as compared to the base fluid (Le Ba et al., 2021). Moreover, low concentrations such as 0.5 vol.% used in this study will help to enhance stability in dispersion by decreasing particle agglomeration and sedimentation, contributing to uniform thermophysical properties over time (Le Ba et al., 2021). Therefore, 0.5 vol.% can be viewed as optimal for both thermal performance and energy efficiency.

Another important parameter to maintain thermal performance and system reliability during the operation lifetime of a PEMFC is the stability of hybrid nanofluids. Prolonged operation requires the nanofluids to maintain uniform nanoparticle dispersion and stable thermophysical properties under varying thermal and flow conditions. Various factors contribute to stability, including thermal and electrical conductivity, nanoparticle concentration, and formulation techniques (Yang et al., 2026; Coetzee et al., 2020). Furthermore, to avoid sedimentation, the coolant is circulated through forced convection in the PEMFC stack, which will minimize the sedimentation in the nanofluids. Through these strategies, it is possible to minimize aggregation behavior, as well as maintain the long-term thermophysical properties of the nanofluids.

Table 2. Solid and fluid area thermophysical properties

Parameter	Metal Plates	Water	Al_2O_3	SiO_2	Distilled water
Density, ρ (kg/m^3)	2719	992.2	4000	2220	9960
Specific heat, C_p (kg·K)	871	4179	765	745	4178
Thermal conductivity, k (W/m·K)	202.4	0.62	36	1.4	0.615
Inlet fluid velocity (T_{in})	0.8/1.0/1.2/1.4 /1.6 m/s				

$$\rho_{hnf} = (1-\emptyset)_{\rho_f} + \emptyset_{p_1}\,\rho_{p1} + \emptyset_{p_2}\,\rho_{p_2} \tag{4}$$

$$C_{p,hnf} = \emptyset_{p_1}\,\rho_{p1}C_{p1} + \emptyset_{p_2}\,\rho_{p2}C_{p2} + \left(1-(\emptyset_{p_1} + \emptyset_{p_2})\right) C_{p,f} \tag{5}$$

The subscripts f, $p1$, p_2 and hnf refer to the base fluid (distilled water), first nanoparticle (Al_2O_3), second nanoparticle (SiO_2), and hybrid nanofluid, respectively, while $\emptyset$ represents the particle volume fraction.

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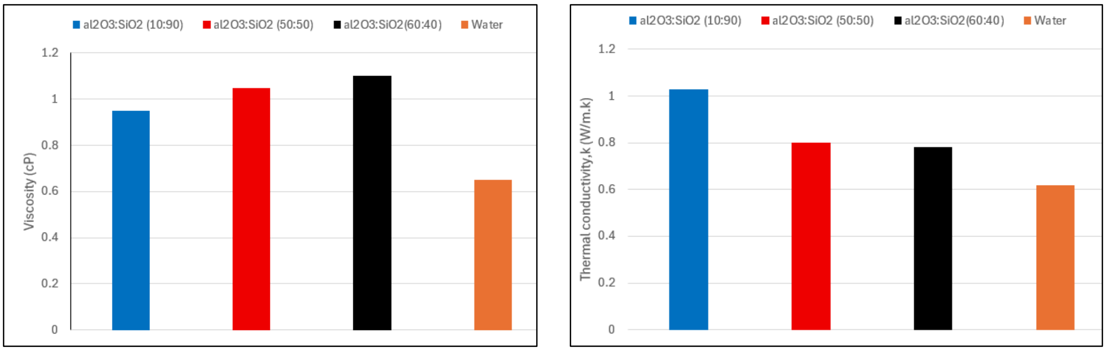
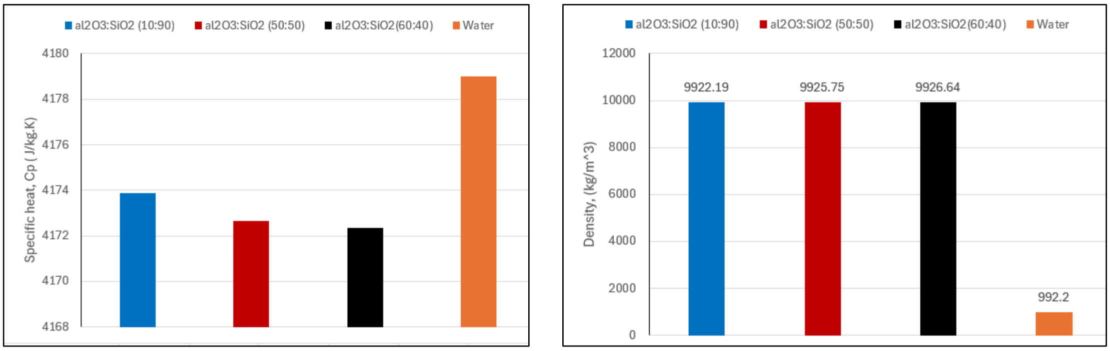


(a) (b)

Fig. 2. Thermophysical properties for working fluids: (a) viscosity for different fluids and (b) thermal conductivity for different fluids (Khalid et al., 2021).



(a) (b)

Fig. 3. Thermophysical properties for working fluids: (a) specific heat for different fluids and (b) density for different fluids.

Governing equation

The fluid flow and heat transfer behaviour in the cooling plate are described using three fundamental equations, which are the continuity, momentum, and energy equations. The continuity equation is a property that ascertains the conservation of mass in the flow domain. The momentum equation is a form of expressing fluid motion as a result of the viscous and velocity effects. The energy equation involves heat transfer in the fluid, which includes conduction and convection processes.

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (6)$$

Momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = u\frac{\partial u}{\partial x} + \frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u}{\partial_{y^2}} \qquad (7)$$

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Energy equation:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{(\rho Cp)_{nf}}\frac{\partial^2 T}{\partial_{y^2}} + Q * (T - T_\infty) + \frac{\mu_{nf}}{(\rho Cp)_{nf}}\left(\frac{\partial u}{\partial y}\right)^2 \quad (8)$$

Mathematical model used

The temperature uniformity index (TUI) is used to evaluate temperature distribution across the cooling plate:

$$TUI = \frac{T_{max} - T_{min}}{T_p} \quad (9)$$

where T_{max} and T_{min} represent the maximum and minimum surface temperatures, respectively, and T_p is the average plate temperature. The heat transfer coefficient and Nusselt number are calculated using:

$$h = \frac{q}{T_p - T_f} \quad (10)$$

$$Nu = \frac{hD_h}{k} \quad (11)$$

where h is the heat transfer coefficient, D_h is the hydraulic diameter, and k is the thermal conductivity. The pressure drop cooling channel is defined as:

$$\Delta P = P_i - P_o \quad (12)$$

where ΔP is the pressure drop difference, P_i is the inlet pressure, and P_o, is outlet pressure. The pumping power is determined using:

$$W_{pump} = \dot{Q} \times \Delta P \quad (13)$$

where $\dot{Q}$ is the volume flow rate. The flow regime within the cooling channel is characterised using the Reynolds number, *Re*, as defined in Equation 14.

$$Re = \frac{\rho u D_h}{\mu} \quad (14)$$

where ρ is fluid density, u is the average flow velocity, D_h is the hydraulic diameter, and μ is dynamic viscosity. In this study, flow is assumed to be laminar, as the Reynolds number calculated for the base fluid of water at a maximum velocity of 1.6 m/s is still 2100, which is below the critical threshold of $Re < 2300$, which is widely accepted for internal channel flows. In laminar flow, the Nusselt number depends strongly on the development of the velocity and thermal boundary layers, allowing more consistent evaluation of convective heat transfer. This regime is dominated by diffusion, making Nu–Re correlations more reliable. Therefore, the laminar flow assumption is appropriate for relating Reynolds and Nusselt numbers and for assessing the thermal–hydraulic performance of the system.

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Numerical procedure

The ANSYS Fluent and SIMPLE algorithm of pressure and velocity coupling are used to perform the simulations. The set points of under-relaxation factors are 0.7 in pressure and 0.3 in momentum, which will provide numerical stability. The convergence criterion will be determined at such a level where the residuals of all the governing equations will be less than 1×10^{-4}. The boundary conditions include a fixed inlet temperature of 313 K and an outlet pressure condition. The uniform heat flux is on the cooling plate surface. Initialisation of the solution is done with normal initialisation, and then the iterative process begins.

Grid independence validation

The accuracy and confidence of the numerical outcome at different types of mesh density were checked by conducting a grid independence test. As shown in Fig. 4, this simulation was conducted using different numbers of mesh elements that varied between 402,740 and 2,799,431. The maximum surface temperature, T_{max} was observed to stabilize at 922,051 elements. Even though 922,051 elements previously produced consistent results, a finer mesh of 1,840,249 elements was chosen to guarantee higher precision while keeping an acceptable computing cost. The simulation has been conducted using this mesh size.

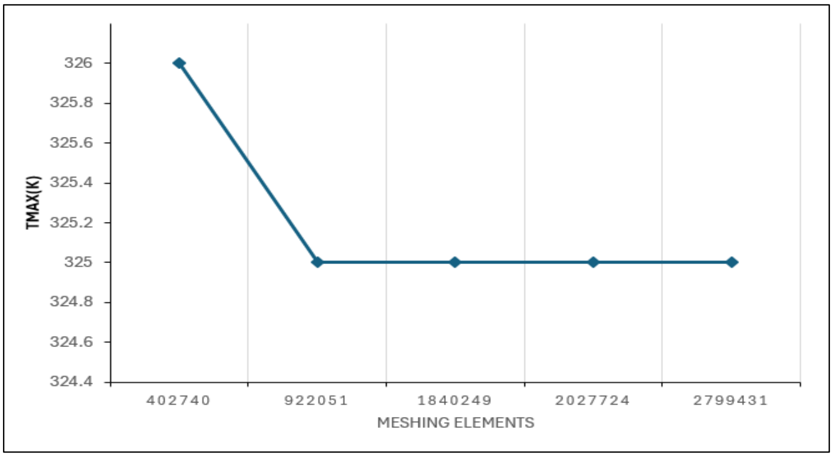

Fig. 4. Mesh independence verification.

RESULTS AND DISCUSSION

Model validation

The results of surface temperature differences were compared with the published work of Chen et al. (2025) to validate the numerical model. As illustrated in Fig. 5, a similar trend is observed across different inlet velocities. The temperature differences in the current simulation are slightly higher than the literature values, with percentage errors ranging from 3.14% to 10.01%, which is still acceptable. Therefore, the model was successfully validated and can be further used for analysis.

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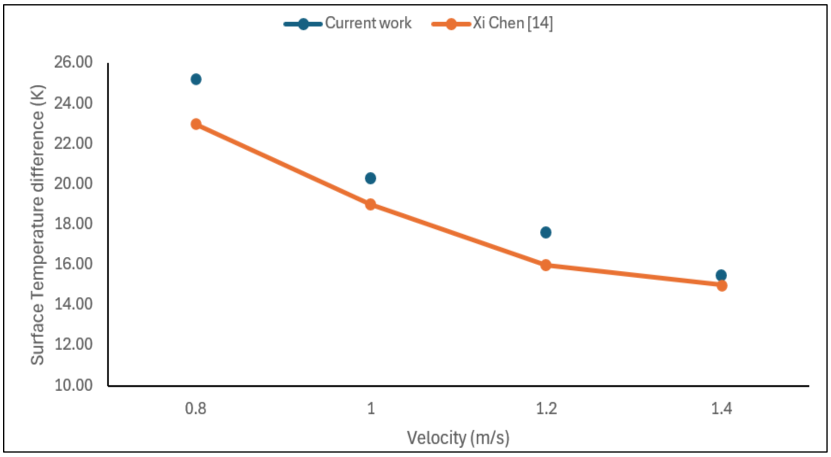
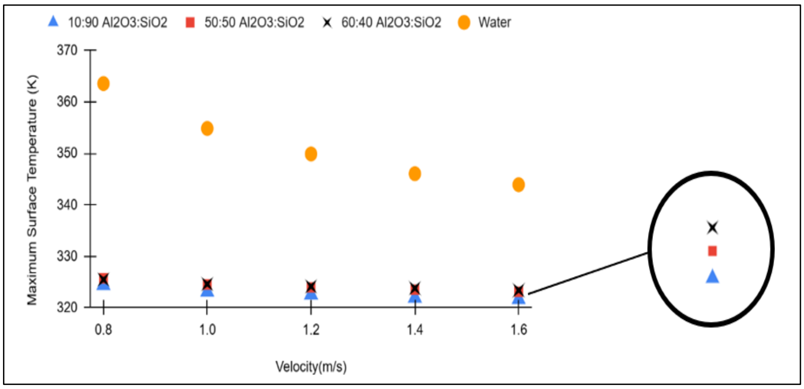


Fig. 5. Model validation.

Maximum surface temperature and Temperature Uniformity Index (TUI)

Fig. 6(a) indicates a consistent reduction in maximum surface temperature with increasing inlet velocity for all working fluids. This behaviour is associated with greater convective heat transfer achieved at higher flow rates. Among the simulated fluids, water exhibits the highest surface temperature, reflecting its lower heat removal capability. At an inlet velocity of 1.6 m/s, Al_2O_3: SiO_2 (10:90) nanofluid achieves the lowest surface temperature of 321.65 K, corresponding to a reduction of 6.47% compared to water, which is 343.92 K. The (50:50) and (60:40) mixtures also show temperature reductions of 6.06% and 5.97%, respectively.

In addition to the evaluation of the temperature distribution, the Temperature Uniformity Index (TUI) was assessed, which is expressed in Fig. 6(b). The smaller TUI values, the greater temperature distribution throughout the cooling plate. At 1.6 m/s, Al_2O_3: SiO_2 (10:90) nanofluid records the lowest TUI value of 0.0166, representing a 75.7% improvement compared to water, where 0.0683. The mixtures of 50:50 and 60:40 also show significant improvements of 74.7% and 73.8%, respectively. The improved performance of hybrid nanofluids can be linked to their high thermal conductivity and enhanced microscopic mixing, which contribute to increased heat dissipation.



(a)

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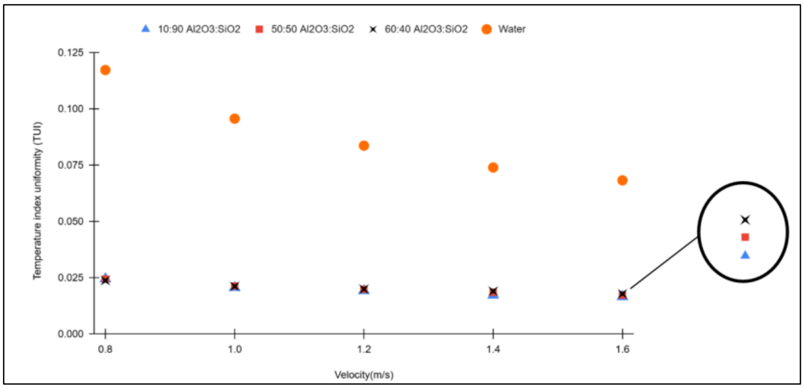
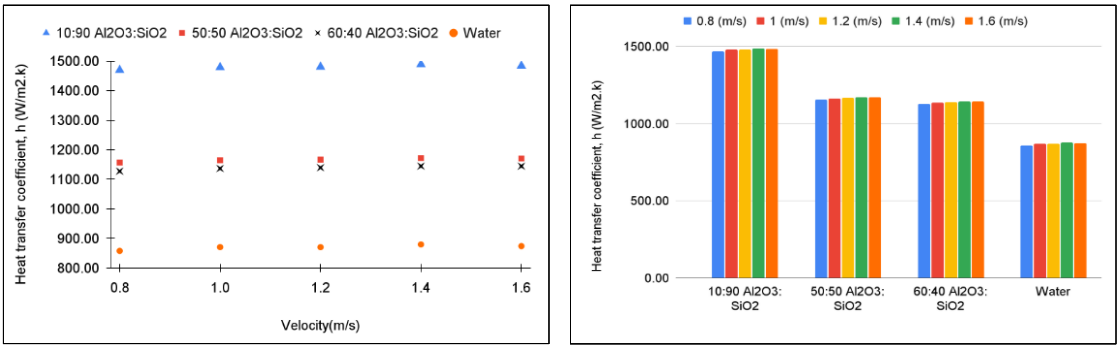


(b)

Fig. 6. (a) Maximum surface temperature at different inlet velocities and (b) temperature uniformity index at various inlet velocities.

Heat transfer coefficient

Fig. 7(a) illustrates that both water and the hybrid nanofluid's heat transfer coefficient rise with the inlet velocity. This behaviour is explained by an increase in convective heat transfer with the increase of the flow velocities to enhance the intensity of fluid mixing and decrease the thickness of the thermal boundary layer. Among all simulated cases, Al_2O_3: SiO_2 (10:90) nanofluid consistently exhibits the highest heat transfer coefficient, reaching 1483.84 W/m²·K at 1.6 m/s. This value represents an improvement of 69.7% compared to water, which records the lowest average value of 873.93 W/m²·K. Fig. 7(b) also depicts the influence of the mixture ratio of nanoparticles on the convective heat transfer coefficient. The (50:50) and (60:40) hybrid nanofluids improve by 33.9% and 31%, respectively.



(a) (b)

Fig. 7. (a) Effect of fluid velocities on heat transfer coefficient and (b) effect of mixture ratios of Al_2O_3 : SiO_2 on heat transfer coefficient.

Nusselt number

Fig. 8(a) shows the variation of Nusselt number with inlet velocity, where a significant increase can be observed as the velocity increases from 0.8 to 1.6 m/s. This behaviour is associated with improved convective heat transfer at higher flow rates, as stronger fluid motion enhances mixing and reduces the thickness of the thermal boundary layer near the heated surface. The comparison in Fig. 8(b) shows that hybrid nanofluids produce higher Nusselt numbers than water throughout the tested range. The Al_2O_3: SiO_2

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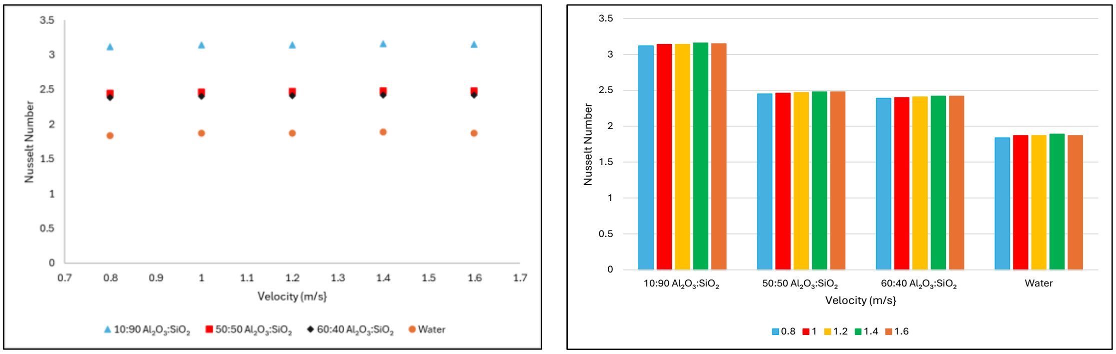
(10:90) mixture consistently records the highest values, followed by the 50:50 and 60:40 ratios. At 0.8 m/s, the Nusselt number for 10:90 nanofluid is about 3.12 compared to 2.45 and 2.39 for the 50:50 and 60:40 mixtures while water shows a lower value of 1.84. As the velocity increases to 1.6 m/s, the Nusselt number reaches approximately 3.15 compared to 1.87 for water, corresponding to an increase of around 68%. The 50:50 and 60:40 mixtures show improvements in the range 32% and 29%. The difference in performance between the mixtures suggests that the heat transfer behaviour is not governed by thermal conductivity alone. The interaction between nanoparticles and the flow field, as well as the stability of dispersion also play the role. The better performance of the 10:90 mixture indicates that this composition provides more effective heat transport within the fluid. It is also observed that the percentage enhancement remains consistent with increasing velocity. Therefore, the results confirm that hybrid Al_2O_3: SiO_2 nanofluids enhance convective heat transfer, with the level of improvement depending on the nanoparticle composition.



(a) (b)

Fig. 8. (a) Effect of fluid velocities on Nusselt number and (b) effect of mixture ratios of $Al_2O_3 : SiO_2$ on Nusselt number.

Pressure drops

Fig. 9 shows the change in the pressure drop of water and hybrid nanofluids at various inlet velocities. The decrease in pressure is more significant with the velocity of all fluids. The highest pressure drop among the simulated cases is that of Al_2O_3: SiO_2 (60:40) hybrid nanofluid, as its pressure drop is about ten times higher than that of water at 1.6 m/s. Water is shown to have the lowest pressure drop, with an average of 0.7 kPa to 3.04 kPa. Increased viscosity and density caused by nanoparticles prevail as the main reasons behind the increased pressure drop in nanofluids (Baghbadorani et al., 2025). Additionally, the honeycomb cooling plate produces a higher pressure drop because its complex structure contains many small flow passages that increase wall friction and fluid resistance. The repeated flow redirection, contraction, and expansion inside the honeycomb cells also create additional energy losses and vortices. Although this increases pumping power requirements, the enhanced surface area and mixing improve the overall heat transfer performance (Chen et al., 2025). The highest flow resistance is seen in the (60:40) mixture, which agrees with its highest dynamic viscosity values among all fluids simulated. Although nanofluids enhance heat transfer performance, the associated increase in pressure drop introduces hydraulic limitations that must be considered in system design.

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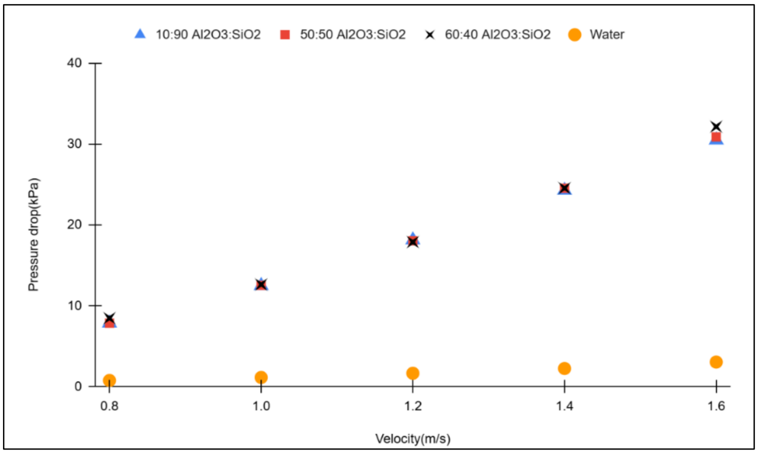

Fig. 9. Pressure drops at different inlet velocities.

Pumping power

Fig. 10 illustrates the pumping power for $Al_2O_3 : SiO_2$ hybrid nanofluids in water from 0.8 m/s to 1.6 m/s, which shows that the pumping power rises with an increase in inlet velocity. This shows that more energy is needed to pump the coolant through the cooling plate at higher flow rates. The $Al_2O_3 : SiO_2$ (60:40) hybrid nanofluids recorded the greatest pumping power of 16.178 W at the maximum velocity of 1.6 m/s. This is 10 times greater than the pumping power for water, which only needed 1.53 W. High pumping power values of 15.343 W and 15.538 W were also demonstrated by the $Al_2O_3 : SiO_2$ (10:90) and (50:50) combinations, respectively. This trend clearly shows that higher nanoparticle concentrations will make the nanofluids denser and more viscous, which will cause higher energy demand and flow resistance. Although hybrid nanofluids enhance heat transfer, the overall efficiency of the PEMFC cooling system is reduced due to parasitic losses brought on by their high pumping power needs (Johari et al., 2022b).

Although the honeycomb cooling plate increases the pumping power due to a higher pressure drop, the additional power consumption is relatively small compared to the operating wattage of a full-scale fuel cell system above 1.5 kW. The increase in pumping power is still considered acceptable in PEM fuel cell cooling systems because the additional energy required by the coolant pump is relatively small compared to the overall electrical output of the fuel cell stack. In practical PEMFC applications, maintaining stable operating temperature is more critical than minimizing a slight increase in hydraulic consumption, as excessive temperature gradients and hotspot formation can accelerate membrane degradation, reduce electrochemical efficiency, and shorten stack lifespan. Therefore, a moderate increase in pressure drop caused by nanofluids or complex cooling plate geometries is often justified when it contributes to improved heat dissipation and better temperature uniformity. This increase in pumping power is negligible if subjected to the output power of practical PEM fuel cell systems used in residential, stationary, and automotive applications, which commonly operate from several kilowatts up to more than 100 kW (Wang, Sun, & Yang, 2025).

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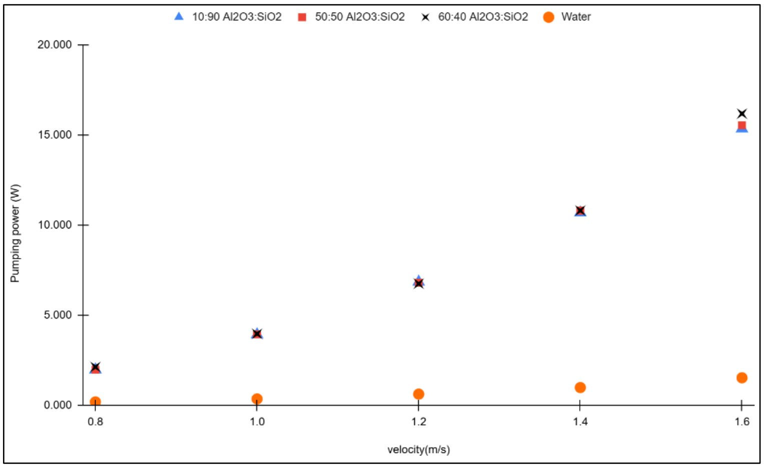

Fig. 10. Pumping power at different inlet velocities.

Contour

Fig. 11 shows the surface temperature contour for water and Al_2O_3 : SiO_2 hybrid nanofluids with different mixture ratios. All working fluids were observed at the same velocity of 1.6 m/s for the temperature contour. Water shows the highest surface temperature with red and yellow colours. This indicates that water is not very effective in removing heat. All Al_2O_3 : SiO_2 hybrid nanofluids show lower temperature contours within blue and green colours, which indicates that the hybrid nanofluids successfully distribute the heat effectively without any hotspots due to higher thermal conductivity compared to water. The addition of nanoparticles has improved the Brownian motion of the molecules in the fluid for a better heat transfer behaviour.

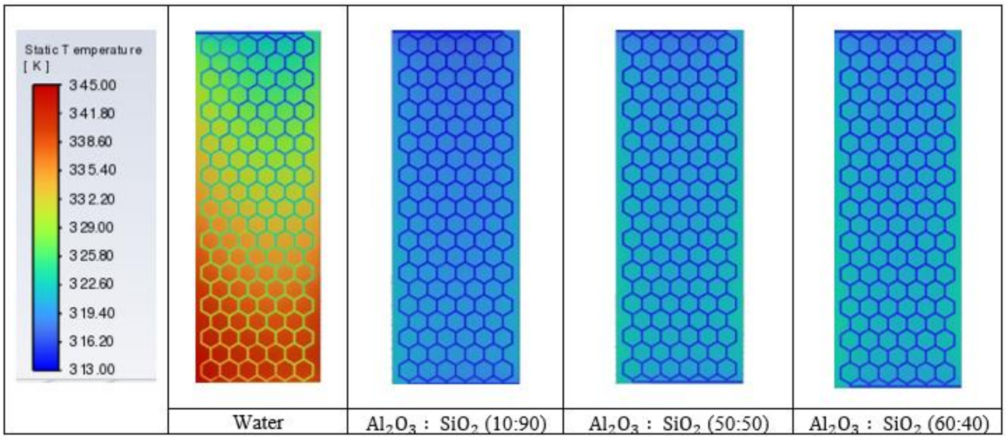

Fig. 11. Cooling plate temperature contour.

https://doi.org/10.24191/jmeche.v23i2.11761

CONCLUSIONS

The heat transfer performance of Al_2O_3:SiO_2 hybrid nanofluids with different mixture ratios in a honeycomb-designed PEMFC cooling plate under laminar flow conditions was successfully investigated using ANSYS Fluent simulations. The results demonstrated that the incorporation of hybrid nanofluids significantly enhanced the thermal performance compared to water. Among all tested mixtures, the Al_2O_3:SiO_2 (10:90) hybrid nanofluid exhibited the best overall thermal performance, achieving the highest heat transfer coefficient of 1483.84 $W/m^2 \cdot K$ at 1.6 m/s, corresponding to a 69.7% improvement over water. In addition, the nanofluid reduced the maximum surface temperature by 6.47% and improved temperature uniformity by 75.7%, indicating its strong capability in minimizing hotspot formation and maintaining a more uniform thermal distribution across the cooling plate. The Nusselt number also increased significantly, where the Al_2O_3:SiO_2 (10:90) nanofluid achieved a value of approximately 3.15 compared to 1.87 for water, representing a 68% enhancement, while the 50:50 and 60:40 mixtures showed improvements of 32% and 29%, respectively. Although the enhanced thermal performance was accompanied by higher pressure drop and pumping power due to increased viscosity and density, the additional pumping power remained relatively small compared to the output power of practical PEMFC systems used in residential, portable, and stationary applications, which is in the range of several kilowatts up to more than 100 kW. Overall, the findings confirm that the Al_2O_3:SiO_2 (10:90) hybrid nanofluid has strong potential as an effective coolant for improving heat transfer performance and temperature uniformity in PEMFC cooling systems.

ACKNOWLEDGEMENTS/ FUNDING

The authors gratefully acknowledge the Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia, for the facilities and financial support for this research.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no commercial or financial conflicts of interest associated with this research.

AUTHORS’ CONTRIBUTIONS

Amira Shahirah Malek Amir Azmin: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft.
Muhammad Harith Husaini Azmi: Methodology, Software, Validation, Formal analysis.
Khairul Imran Sainan: Investigation, Resources, Data curation.
Wan Ahmad Najmi Wan Mohamed: Visualization, Validation, Writing – review & editing.
Anwar Imar Ramadhan: Software, Formal analysis, Visualization.
Irnie Azlin Zakaria: Supervision, Conceptualization, Project administration, Funding acquisition, Writing – review & editing

https://doi.org/10.24191/jmeche.v23i2.11761

DATA AVAILABILITY/ SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA (UiTM).

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