

Numerical Study on Enhancing the Cooling Efficiency of Fuel Cell Using Nanofluids

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ABSTRACT:

This study presents a numerical investigation of the cooling performance of a proton exchange membrane fuel cell (PEMFC) using nanofluids as the coolant. A computational fluid dynamics (CFD) model was developed to analyze the thermal behavior under different Reynolds numbers and nanoparticle concentrations (0–3%). The effects of nanofluids on maximum temperature and temperature uniformity were systematically evaluated. The results show that increasing the Reynolds number significantly enhances convective heat transfer, resulting in lower maximum temperatures and a more uniform temperature distribution. The introduction of nanoparticles further improves cooling performance. Specifically, the maximum temperature decreases by approximately 0.7–2.7% when nanofluids are used instead of pure water. More notably, the maximum temperature difference is reduced by up to 15%, indicating a substantial improvement in temperature uniformity. However, increasing the nanoparticle concentration beyond 1% does not yield additional benefits in temperature uniformity and may slightly reduce performance due to increased viscosity. Overall, the findings demonstrate that nanofluids are effective in enhancing fuel cell thermal management, with an optimal concentration of around 1% providing the best balance between heat transfer enhancement and flow characteristics.

KEYWORDS: PEMFC; Nanofluids; Thermal management; Heat transfer; Temperature uniformity; CFD simulation

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I. INTRODUCTION

Fuel cells, particularly proton exchange membrane fuel cells (PEMFCs), have attracted significant attention for automotive applications due to their high efficiency, low emissions, and fast dynamic response. However, a major challenge associated with their operation is the generation of substantial waste heat. In practical systems, the heat generation rate can be comparable to the electrical power output; for instance, a 100 kW fuel cell system may require the dissipation of nearly 100 kW of thermal energy. If this heat is not effectively removed, it can lead to excessive temperature rise and non-uniform temperature distribution within the stack, especially in the membrane electrode assembly (MEA), where most of the heat is generated. Such temperature gradients can accelerate membrane degradation, reduce system efficiency, and shorten the operational lifespan. Therefore, effective thermal management is essential to ensure stable performance and durability of PEMFC systems [1].

Various cooling strategies for fuel cells have been extensively investigated, including air cooling, liquid cooling, and phase-change heat transfer techniques [2]. Air-cooling systems are attractive for their structural simplicity and ease of integration, as they eliminate the need for pumps and complex piping. However, their relatively low heat transfer capability limits their effectiveness, particularly in high-power applications. The cooling performance of air-cooled systems depends strongly on airflow rate, inlet temperature, and system configuration, leading to a non-uniform temperature distribution within the fuel cell stack [3–5].

In contrast, liquid cooling systems provide higher heat removal capacity due to the superior thermal properties of liquid coolants. In such systems, coolant flows through channels embedded within bipolar plates to remove heat from the stack. Key factors influencing performance include coolant flow rate, coolant type, and channel geometry [6]. Previous studies have shown that optimized channel designs, such as zigzag and serpentine configurations, can significantly improve temperature uniformity and reduce maximum temperature compared to conventional straight or parallel channels [7–9]. However, these designs often result in higher pressure drop, increasing the energy consumption required for coolant circulation.

Operating conditions also play an important role in thermal behavior. In particular, coolant inlet temperature strongly affects heat transfer performance. Lower inlet temperatures enhance heat removal but increase the cooling demand on auxiliary systems. In comparison, higher inlet temperatures may lead to larger temperature gradients and reduced cooling effectiveness under high load conditions [10].

Phase-change cooling methods have also been explored due to their high heat removal capability, driven by latent heat effects [11,12]. These systems can maintain a relatively uniform temperature distribution and reduce the size of thermal management components. However, under critical heat flux conditions, excessive temperature rise may still occur, potentially negatively affecting system reliability [13]. In addition, phase-change cooling has been reported to reduce the size of cooling systems compared to conventional liquid cooling approaches [14].

To further enhance cooling performance, nanofluids have emerged as a promising alternative to conventional coolants. By dispersing nanoparticles into a base fluid, nanofluids exhibit improved thermophysical properties, particularly higher thermal conductivity and enhanced convective heat transfer characteristics. However, studies on the application of nanofluids in fuel cell cooling systems remain limited [15–17].

Therefore, there is a clear need for a systematic investigation of nanofluid-based cooling strategies for PEMFCs. In particular, achieving both low maximum temperature and high temperature uniformity remains a critical challenge. This study aims to address this gap through numerical simulations, focusing on the effects of nanoparticle concentration and flow conditions on key thermal performance indicators, thereby providing useful insights for the design and optimization of advanced fuel cell cooling systems.

II. COMPUTATIONAL DOMAIN AND GOVERNING EQUATIONS

The three-dimensional model of the cooling plate in a PEMFC, developed using ANSYS Workbench, is shown in Figure 1(a). During the simulation, the heat flux is set to a constant value (1871 W/m^2) and imposed on the upper and lower boundaries. The nanoparticles used in this study were Al_2O_3 , and the properties of the nanofluid solution were calculated based on the literature [18]. Table 1 outlines the thermal and physical properties of the materials used in the study, including water, nanofluids, and the cooling channel.

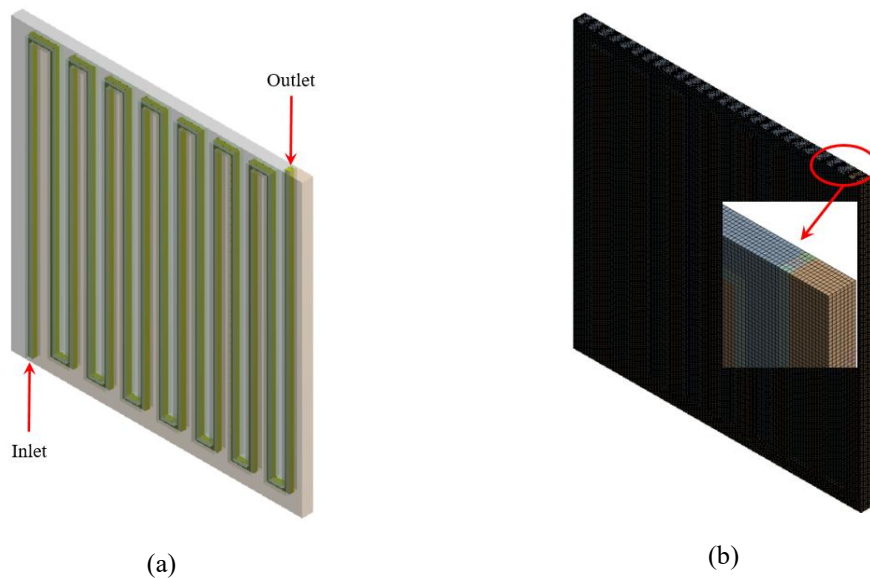


Figure 1: (a) 3D model of cooling plate (b) meshing model

The computational domain is discretized using a structured hexahedral mesh, as shown in Fig. 1 (b). To ensure that the numerical calculation results are not affected by the number of meshes, the mesh independence is verified. Three mesh sizes were tested: 150,783, 306,085, and 580,132 elements, with the mesh density nearly doubling with each refinement. Figure 3 presents the results of the grid independence study, showing the maximum temperature of the cooling plate. The second mesh size (306,085 elements) is used for the simulation.

Table 1. Thermal physical properties of materials of the coolant, cooling channel and lithium battery cell.

No.	Parameters	Materials				
		Water	1% Nano-fluid	2% Nano-fluid	3% Nano-fluid	Aluminum
1.	Density (kg/m ³), ρ	992	1021.68	1051.36	1081.04	2719
2.	Heat capacity (J/kgK), c	4174	4042.178	3917.8	3800.25	891
3.	Thermal conductivity (W/mK), k	0.633	0.65	0.67	0.69	202.4
4.	Dynamic viscosity (kg/ms), μ	0.00065	0.000705	0.000777	0.000864	-

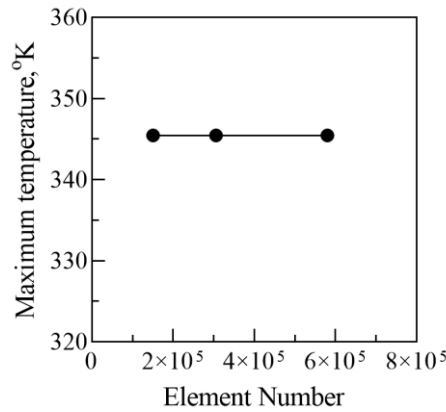


Figure 2. Grid independency test

The CFD solver solves the conservation equations for mass, momentum, and energy for Newtonian incompressible fluids. In this study, only steady-state conditions are considered, and the equations used are as follows:

The energy conservation equation of the coolant is:

$$\rho_l c_l \left(\frac{\partial T_l}{\partial t} \right) + \nabla(\rho_l c_l v T_l) = \nabla(k_l \nabla T_l) \tag{1}$$

where ρ_l, c_l, T_l, k_l, and v are the density, heat capacity, temperature, thermal conductivity and velocity of the liquid coolant, respectively.

The continuous equation and momentum conservation equation of water are given as follows:

$$\nabla v = 0 \tag{2}$$

$$\rho_l \frac{dv}{dt} = -\nabla p + \mu \nabla^2 v \tag{3}$$

III. RESULTS AND DISCUSSION

The temperature distribution on the fuel cell cooling plate as a function of coolant nanoparticle concentration is illustrated in Fig. 3. It is evident that the cooling performance varies significantly with the coolant type and concentration. When pure water is used, the maximum temperature reaches approximately 345.46 K, indicating a relatively limited heat removal capability under the given operating conditions. When nanofluids are introduced, a clear reduction in temperature can be observed. At a concentration of 1%, the maximum temperature decreases to about 344.04 K, demonstrating an initial improvement in heat transfer performance. As the nanoparticle concentration increases to 2%, the maximum temperature further drops to approximately 342.21 K, indicating enhanced thermal conductivity and more effective heat dissipation. The

lowest temperature is achieved at a concentration of 3%, where the maximum temperature reaches around 340.32 K.

In addition to the reduction in peak temperature, the temperature distribution becomes more uniform as the nanoparticle concentration increases. This suggests that nanofluids not only improve overall cooling capacity but also enhance temperature uniformity within the system, a critical factor for maintaining stable operation and preventing localized overheating in fuel cells. These results confirm that the addition of nanoparticles significantly enhances the thermophysical properties of the coolant, thereby improving convective heat transfer. Therefore, optimizing the nanoparticle concentration is an effective approach to improving the thermal management performance of fuel cell systems.

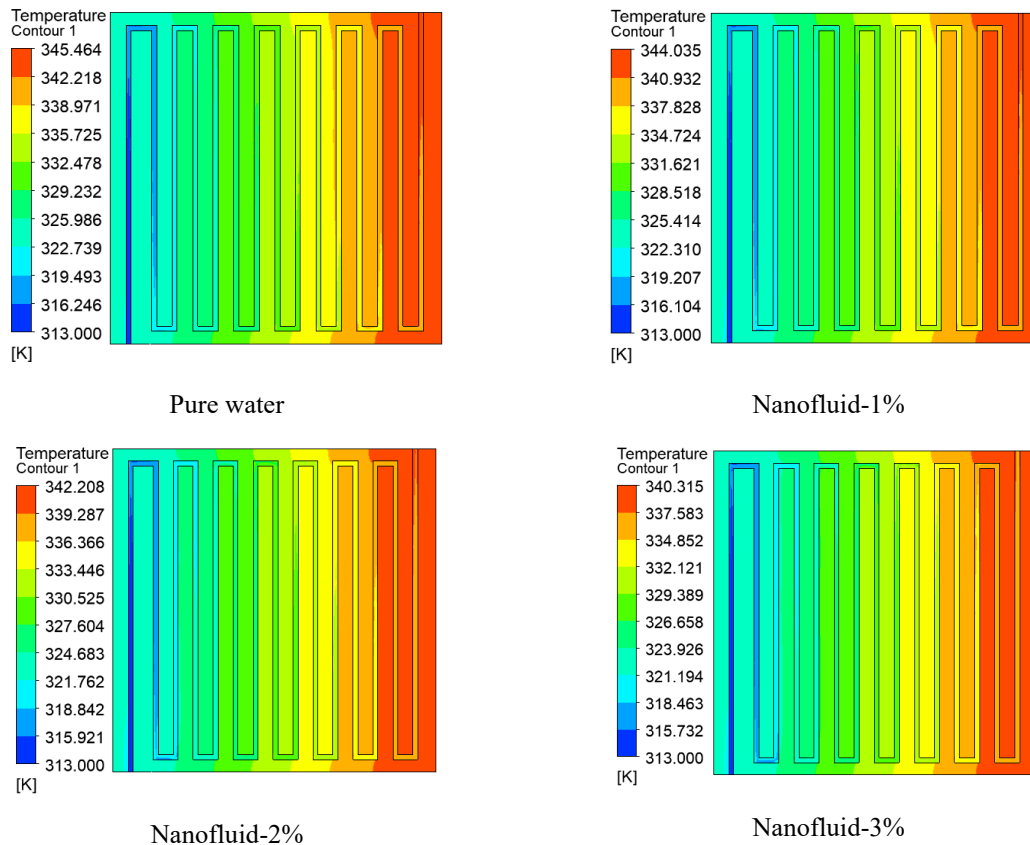
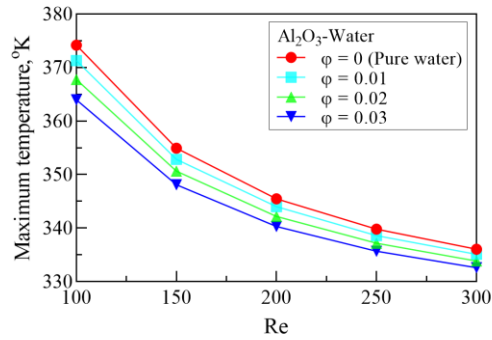


Figure 3. Comparison of temperature contours for different nanofluid concentrations

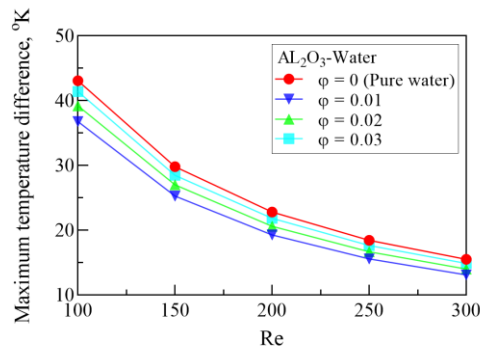
Figure 4 presents the effect of nanoparticle concentration on the maximum temperature and maximum temperature difference of the fuel cell as a function of Reynolds number. As shown in Fig. 4(a), the maximum temperature decreases consistently with increasing Reynolds number for all coolant types, indicating enhanced convective heat transfer at higher flow rates. In addition, for a given Reynolds number, increasing the nanoparticle concentration from 0% (pure water) to 3% leads to a noticeable reduction in the maximum temperature. Specifically, the coolant with $\phi = 0.03$ exhibits the lowest peak temperature across the entire Reynolds number range, whereas pure water consistently yields the highest peak temperature.

A similar trend is observed in Fig. 4(b) for the maximum temperature difference. As the Reynolds number increases, the temperature difference decreases significantly, reflecting improved temperature uniformity within the fuel cell. Moreover, higher nanoparticle concentrations further reduce the temperature difference, with $\phi = 0.03$ achieving the most uniform temperature distribution. The observed reduction in both maximum temperature and temperature difference with increasing nanoparticle concentration can be attributed

to the enhanced thermal conductivity and improved heat transfer characteristics of nanofluids. These properties facilitate more efficient heat removal from the fuel cell, thereby mitigating temperature gradients and reducing the risk of localized overheating. Overall, the results demonstrate that both increasing the Reynolds number and optimizing the nanoparticle concentration are effective strategies for improving the thermal management performance of fuel cell systems.



(a) Maximum temperature



(b) Maximum temperature difference

Figure 4. Maximum temperature difference of battery pack with different percentage of nanofluid

V. CONCLUSION

This study numerically evaluates the cooling performance of a fuel cell system using nanofluids with different nanoparticle concentrations. The results show that adding nanoparticles reduces the maximum temperature by approximately 0.7–2.7% compared to pure water, with higher concentrations leading to greater reductions. More importantly, temperature uniformity is significantly improved. The maximum temperature difference decreases by up to about 15% when using a 1% nanofluid, indicating more effective heat distribution. However, increasing the concentration beyond 1% does not further enhance uniformity and may slightly reduce performance due to increased viscosity effects. Overall, nanofluids improve thermal management, with a concentration of around 1% identified as the optimal condition for balancing heat transfer enhancement and flow characteristics in fuel cell cooling systems.

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