Paper ID: 528

Advancements and Challenges in Sustainable Thermal Management of Proton Exchange Membrane Fuel Cells for Clean Energy Applications

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Abstract

To preserve the overall efficiency and durability of the polymer electrolyte membrane fuel cell (PEMFC) stack, an efficient heat management technique is essential. Despite being a highly effective power source, the PEMFC loses around half of the energy produced by the electrochemical reaction as heat. To keep the cell/stack at a consistent operating temperature, efficient heat evacuation from the PEMFC is crucial. The recent developments in PEMFC thermal control techniques for different stack sizes are presented in this study. Moreover, each technique's function, benefits, drawbacks, and performance on heat transfer are well explained. Additionally, the primary obstacles and future directions for PEMFC thermal management research are addressed.

Keywords: Thermal management; PEMFC; Cooling strategy; Durability; Sustainability.

1. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) are increasingly recognized as a vital advancement in the hydrogen economy, particularly as the world turns its attention to cleaner and more sustainable energy solutions. The worldwide transition to sustainable energy options has led to a growing need for effective and eco-friendly technologies. Proton exchange membrane fuel cells (PEMFCs) represent a significant and innovative advancement in energy generation, offering great potential for diverse applications, such as in transportation, residential, and commercial settings. Hydrogen is considered as a major energy carrier in the transition from petroleum and coal to renewable energy sources. Higher efficiency, lower emissions and probable opportunities to collaborate with other renewable energy sources are included in all characteristics of PEMFC, which can spontaneously convert hydrogen into much needed electricity. Yet one of the most significant obstacles to maximizing PEMFCs longevity and performance is still controlling the heat generated during operation. The maximum temperature of operation for PEMFCs fluctuates between 60-90 °C. Keeping consistent temperatures is necessary to avoid issues such as water overflow and membrane drying, both of which can significantly affect cell performance [1]. In managing the temperature of PEMFC, it is important to achieve a careful balance between efficiently removing heat and maintaining the system's cost-effectiveness and performance. Managing the internal temperature of the fuel cell system is crucial, and cooling systems play a big role in this matter. However, their complexity can make the system heavier and more expensive, especially for high-power uses. In fuel cells larger than 5 kW, for example, liquid cooling systems are frequently used when air cooling is not anymore suitable [2]. Though stability and financial considerations continue to be barriers, recent developments have brought up unique cooling techniques, such as the use of nanofluids, which provide superior thermal conductivity [3].

In order to ensure the reliability and effectiveness of fuel cells, it is important to follow appropriate thermal management and heat recovery techniques. To avoid hotspots and ensure consistent electrochemical reactions, it's essential to keep temperatures evenly distributed across the fuel cell stack.

This review's objective is to provide an in-depth review of thermal management in PEMFC systems. It highlights methods for managing heat that improve performance and dependability. By examining existing engineering approaches and research outcomes, it is anticipated to offer valuable engineering activities and insights for future research.

2. Thermal management strategies

Thermal management systems account for almost 8% of PEMFC stack costs in the majority of situations. The particular application's characteristics and related elements, including size and heat removal rate, influence the thermal management technique selection. Fig. 1 shows the typical thermal management strategies for PEMFC. The goal of PEMFC cooling is to keep the temperature uniform within the stack in addition to lowering the system temperature.

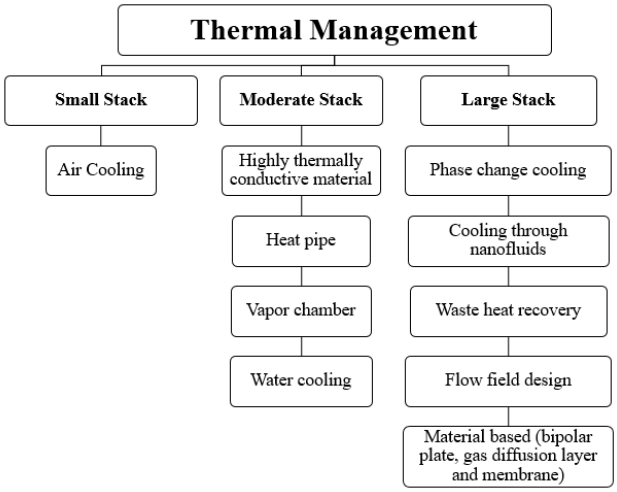


Fig. 1. Typical thermal management strategies for PEMFC.

Small stack (<5 kW)

Air cooling: Heat dissipation in this cooling method takes place by air flowing through particular cooling plates or in the cathode. Much attention has been drawn to the air-cooling technique because of its ease of use and the possibility. This system can significantly reduce the size and weight of the cooling system [4].When compared to liquid coolant, air cooling is preferable because it has a simpler design, and the cooling unit is lighter in weight. This cooling strategy is primarily designed for small-power fuel cell systems (e.g., less than 2 kW) because of its significantly limited capacity to remove heat, which is caused by the air's heat capacity. Inlet temperature, mass flow rate of air, and flow field arrangement are the primary factors influencing air-cooling performance [5].

Moderate stack (<10 kW)

Highly thermally conductive material: The heat from the center of the PEMFC stack is absorbed by the spreaders made of materials with high thermal conductivity. After that, they move this heat to the cell's periphery and eventually release it into the environment. Heat spreaders have high thermal conductivity and are employed near the flow channel plate. PEMFC, that with a heat spreader for high-temperature PEMFCs is simpler. According to the findings, thermal pyrolytic graphite, or TPG, dissipates heat more effectively than pyrolytic graphite sheet, or PGS [6]. Fig. 2 illustrates the effects of PGS and TPG thickness on the temperature difference in the MEA.

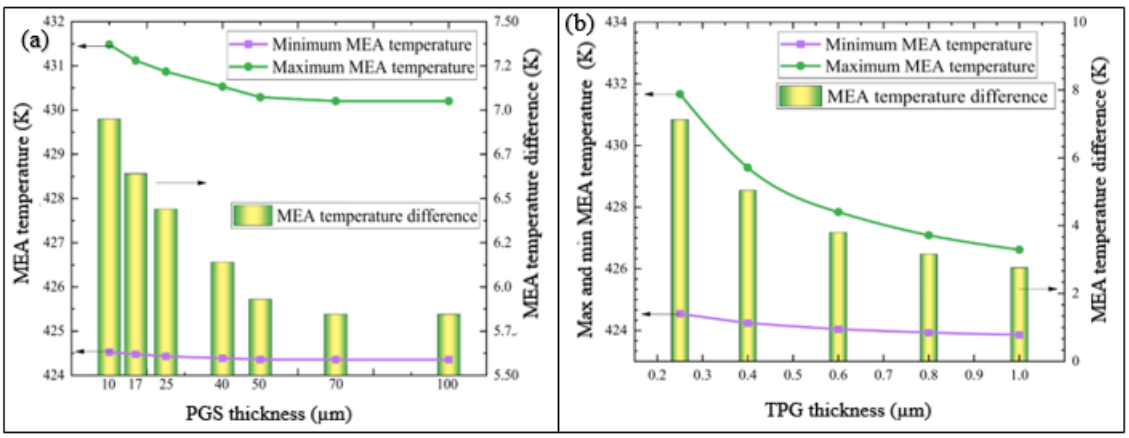


Fig. 2. TPG thickness effect on temperature difference in MEA [6].

Heat pipe: A heat pipe's passive design and high thermal conductivity (between 2100 and 50,000 W/mK) make it an excellent heat transmission device. The Conventional Heat Pipe (CHP) is essentially an evacuated tube that holds a working fluid in both vapour and liquid states, along with a wick structure designed to transport the condensed working fluid back to the evaporator section, as illustrated in Fig. 2. Numerous studies have demonstrated that several kinds of heat pipes, such as the Loop Heat Pipe (LHP), the Pulsating Heat Pipe (PHP), and the micro–Heat Pipe (mHP), are suitable for the thermal control of PEMFC. A numerical and experimental analysis was presented. The tests indicated that the proposed heat pipe could dissipate as much as 12 W, which translates to 1.8 W/cm^2 in the evaporator section, thereby ensuring effective operation of the PEMFC [7]. Overall, the heat pipe can ensure temperature distribution in a highly uniform way and current density through the structure of the fuel cells. Studies suggest that during heating, a temperature gradient of 0.214 °C per unit cell and while cooling process is done the temperature gradient of 0.054 °C per unit cell had been notified [8]. The heat distribution over the stack was maintained uniformly by the heat pipes heating technology, as shown in Fig. 3 (a-b). However, using the conventional heating method, the maximum temperatures were found on both ends of the stack in Fig. 3 (c-d). Furthermore, greater coverage was obtained using the heat pipes cooling technology [8].

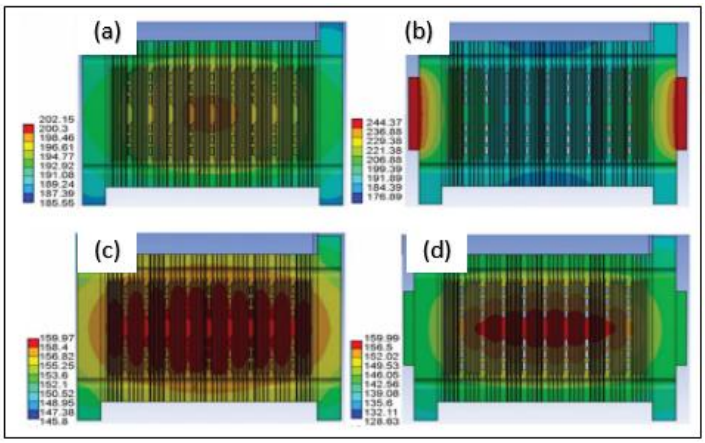


Fig. 3. (a) longitudinal cross-section view of (a-b) heating stack with heat pipes and ordinary method, (c-d) heat pipes cooling stack with heat pipes and air [8].

Vapor chamber: One passive heat transfer technique that could be applied to PEMFC production is the Vapour Chamber (VC). To ensure that a proton exchange membrane fuel cell stack is technically feasible from an industrial point of view, ultra-thin vapour chambers have been created for the purpose of temperature control. The test results revealed that ultra-thin vapour chambers can achieve a remarkably uniform temperature distribution [9]. Furthermore, a vapour chamber that has been specifically built may remove about half of the heat that is present in the stack [10].

Water cooling: Water is nearly four times more heat-efficient than air, thus utilizing it as a coolant decreases heat exchanger size and improves cooling. For high cooling demands, water cooling is preferred over air circulation, especially for large PEMFC stacks that produce more than 5 kW of power. The design of water-cooling coolant flow tubes influences heat removal, similar to air-cooling.

Large stack (>10 kW)

Phase change cooling: Phase change cooling is appealing because it takes advantage of the significant latent heat released during phase changes, simplifies system design, and removes the need for coolant pumps and fans. Unlike liquid or air cooling that relies on the sensible heat of a coolant, phase change cooling takes advantage of latent heat, which is significantly greater than sensible heat. Two common methods of phase change cooling are evaporation and boiling cooling. A validated model for an evaporatively cooled fuel cell stack shown that the evaporatively cooled system had an exceptional capacity to self-regulate temperature within a range of ±2 degrees Celsius under typical operating circumstances [11]. Two-phase cooling has better cooling performance than water-cooling [12].

Cooling through Nano-fluid: Water, as a traditional coolant for PEMFCs, has many drawbacks, notably its poor heat conductivity. Nanofluids have superior average thermal conductivities compared to their base fluids, attributable to the enhanced thermal conductivity of the suspended nanoparticles. The superior thermal conductivity of nanofluids relative to traditional coolants, such as water/EG mixtures, presents prospects for reducing the dimensions of heat exchangers used in fuel cell cooling systems. It was found that the average plate temperature decreased for both cooling plates as the Reynolds number rose. As shown in Fig. 4, when compared

to the base fluid of W:BG (60:40), the Al_2O_3:SiO_2 (30:70) hybrid nanofluids at Re 1800 experienced the greatest drop in plate temperature, with reductions of 1.23 percent in serpentine and 2.15 percent in distributor plates, respectively [13] .

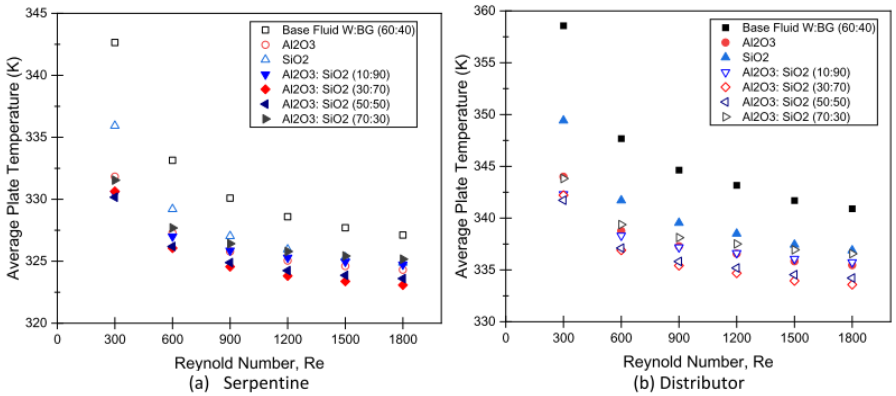


Fig. 4. Average plate temperature versus Re for cooling plates with various nanofluids [13].

Waste heat recovery: The advancement of PEMFC reactions produces significant quantities of water and heat, with over fifty percent of the energy lost to the surrounding environment as heat. Recovering waste heat while preserving the optimal temperature inside the PEMFC stack would enhance the operational efficiency of the FCEV. Recently, waste heat recovery (WHR) in proton exchange membrane fuel cells (PEMFCs) has garnered heightened scientific attention, with several studies investigating potential methods for the effective utilization of the produced heat via various conversion systems as shown in Fig. 5.

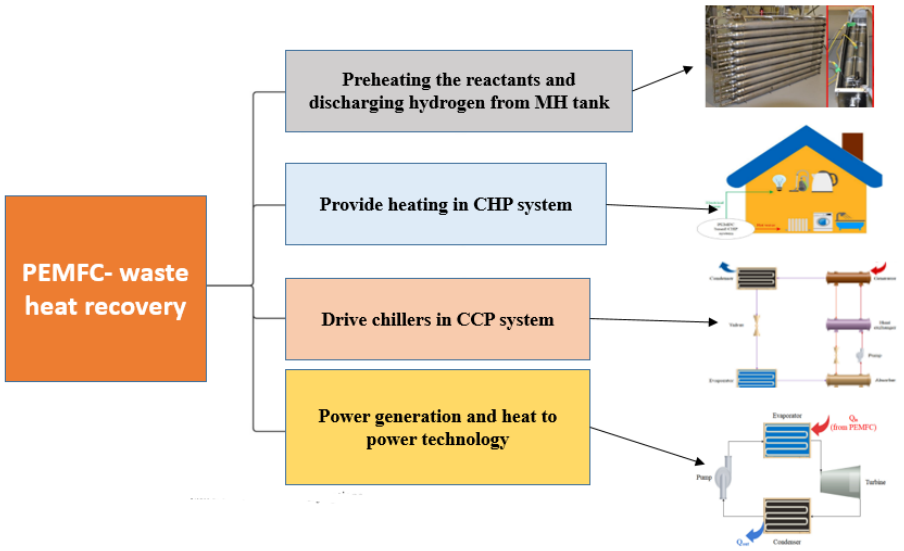


Fig. 5. Different pathways of PEMFC waste heat recovery.

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Flow field design:

From simple structures with fundamental functions to multidimensional complex structures, flow-field plate designs have undergone significant change. For instance, typical simple flow fields like meandering, integrated, serpentine and straight flow are suggested and used in the early stages. A variety of innovative flow fields, including baffle flow fields, porous-medium flow fields, bio-inspired flow fields, composite flow fields, and the so-called 3D flow fields, are proposed to improve mass transfer because the heat and mass transfer capacities of these straightforward flows are far from adequate. Another amazing design technique is the bio-inspired flow field [14]. Flow field design plays viral role in the thermal management of PEMFC. Various flow field designs, including divided serpentine, divided spiral, distributed serpentine, and distributed spiral, as depicted in Fig. 6, were taken into consideration. When compared to ordinary serpentine, it was discovered that distributed serpentine performs better due to its homogeneous temperature distribution, improving by roughly 25%. Additionally, divided spirals and serpentines perform almost as well as spirals, with the former doing marginally better [15].

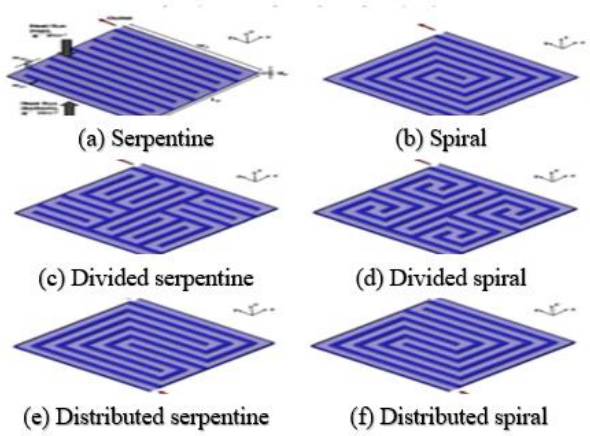


Fig. 6. Different flow field design of PEMFC with air cooling [15].

Material based

Bipolar plates: The bipolar plate creates a pathway for gas flow, ensuring that hydrogen and oxygen in the battery gas chamber do not mix with one another. The material properties significantly influence the thermal management of the PEMFC. Graphite, metal, and composite materials are the three main types of bipolar plate materials utilized in PEMFCs at the moment. Metal materials like stainless steel and titanium are preferred due to their excellent conductivity, resistance to corrosion, and relatively affordable price. The composite bipolar plate has combined the corrosion resistance of graphite bipolar plate and as well as high strength of metal bipolar plate. The composite bipolar plate has also ensured high production efficiency. The primary factor hindering its development is low conductivity.

Gas diffusion layer: The diffusion layer plays a crucial role in the membrane electrode assembly of the PEMFC by transporting reactants and products while also conducting electricity and heat. The relatively low thermal conductivity of the fuel cell microporous layer frequently leads to increased temperatures in the gas diffusion layer, where the product water might undergo a phase change.

Membrane: The proton exchange membrane is essential for the operation of the PEMFC. The membrane's thickness and the material's conductivity both influence ohmic heat. The proton exchange membranes used in PEMFCs can primarily be divided into three types: Perfluorinated PEM, partly fluorinated PEM, and non-fluorinated PEM. The perfluorinated PEM shows excellent proton conductivity, significantly influenced by its hydration level. Both the partly fluorinated and non-fluorinated PEM have enhanced their electrochemical impedance, which, in the end, has influenced the result in a longer service life for the PEMFC and, simultaneously, reduced manufacturing costs.

3. Remaining challenges and prospects

For tiny PEMFC stacks, the heat spreader is the best cooling method [16]. Due to the small size its designing importance cannot be overlooked. Moreover, small PEMFCs requires careful consideration of several important considerations, including the cooling device's size and weight in addition to its cooling capacity. To meet the design's competing goals, sophisticated multi-objective optimization techniques must be used. Using optimization approaches to improve the cooling surface's efficiency may lead to highly complicated geometric designs that are very costly to construct using conventional methods. Future studies should pay more attention to the adoption of additive manufacturing for PEMFC thermal control applications [17] [18]. The most popular coolant for the liquid cooling system was water, while other kinds of working fluid received very little attention. Future study could focus on this by examining different coolants that are appropriate for PEMFCs and their cooling capabilities. It may be necessary to combine many cooling methods in a single hybrid cooling system for higher energy efficiency. These integrated hybrid systems may solve many emerging problems and thus further research is advised. To verify the efficiency, sustainability, and financial feasibility of the suggested cooling solutions, more trustworthy experimental studies and thorough environmental analysis are still needed.

4. Conclusion

One of the most adaptable energy conversion technologies for a wide range of uses is the PEMFC. Ironically, effective thermal management is a crucial barrier to its commercialization from a systems perspective. However, the temperature affects the stack's durability even though it is an essential factor in determining PEMFC

performance. Numerous thermal management techniques, as well as the fundamental problems and possibilities for PEMFCs, have been covered in this paper. Because of its high working temperature, PEMFCs require strict design and operating condition standards. Meeting the high-temperature reaction demand while reducing sudden temperature gradients is the aim of PEMFC stack thermal management. Increased stack and system performance concerning thermal management also requires parallel computing and sophisticated stack and system-level modelling. Artificial intelligence (AI) approaches are another new technology that may offer a more viable answer for the PEMFC thermal control strategy.

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