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Review

Fuel-Cell Thermal Management Strategies for Enhanced Performance: Review of Fuel-Cell Thermal Management in Proton-Exchange Membrane Fuel Cells (PEMFCs) and Solid-Oxide Fuel Cells (SOFCs)

Ibham Veza [1,2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Bung Karno, Jalan Kimia No. 20. Menteng, Jakarta Pusat 10320, Indonesia; ibham@vezas.org
[2] Centre for Renewable Energy System Modeling and Policy Innovation, Aras Energy Consulting, Jalan HR Rasuna Said Kav. C-5, Setia Budi, Jakarta Selatan 12920, Indonesia

Abstract

Effective thermal management is crucial for optimizing the performance, efficiency, and durability of fuel-cell technologies, including proton-exchange membrane fuel cells (PEMFCs) and solid-oxide fuel cells (SOFCs). The operation of fuel cells involves complex heat generation mechanisms, primarily driven by electrochemical reactions, which can lead to significant energy loss as heat. This review examines the specific heat generation sources and challenges associated with different fuel-cell types, highlighting the critical importance of effective thermal management strategies. Key techniques for thermal regulation, including active and passive cooling systems, are examined in detail. Active cooling methods like liquid cooling and air cooling are effective in dissipating excess heat, while passive methods leverage advanced materials and optimized designs to enhance natural heat dissipation. Furthermore, innovative heat recovery systems are explored, demonstrating their potential to enhance overall energy efficiency by capturing and repurposing waste heat. The integration of machine learning techniques has arisen as a promising avenue for advancing temperature control in fuel cells. Reinforcement learning, deep learning algorithms, and support vector machines, along with artificial neural networks, are discussed in the context of their application in managing temperature dynamics and optimizing thermal performance. The review also emphasizes the significance of real-time monitoring, as well as adaptive control strategies to respond effectively to the dynamic operating conditions of fuel cells. Understanding and applying these thermal management strategies is essential for the successful commercialization of fuel cells across various sectors, ranging from automotive to stationary power generation. With the growing demand for clean energy solutions, progress in thermal management techniques will be crucial in improving the dependability and practicality of fuel-cell systems.

Keywords: fuel-cell thermal management; proton-exchange membrane fuel cells (PEMFCs); solid-oxide fuel cells (SOFCs); integrated thermal management system; fuel-cell hybrid cooling; fuel-cell heat recovery

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1. Introduction: Fuel Cells

Fuel cells are innovative electrochemical mechanisms that change chemical energy directly into electrical energy via the reaction of H_2 with O_2, producing water as the only

byproduct [1,2]. This clean and efficient process has gathered substantial attention recently, particularly in the context of renewable and sustainable energy solutions. Various kinds of fuel cells exist; every type comes with distinctive characteristics and applications, including proton-exchange membrane fuel cells (PEMFCs) [3–6], solid-oxide fuel cells (SOFCs) [7–10], molten carbonate fuel cells (MCFCs) [11–14], and phosphoric acid fuel cells (PAFCs) [15–18]. Figure 1 shows the curve characteristics of the PEMFC.

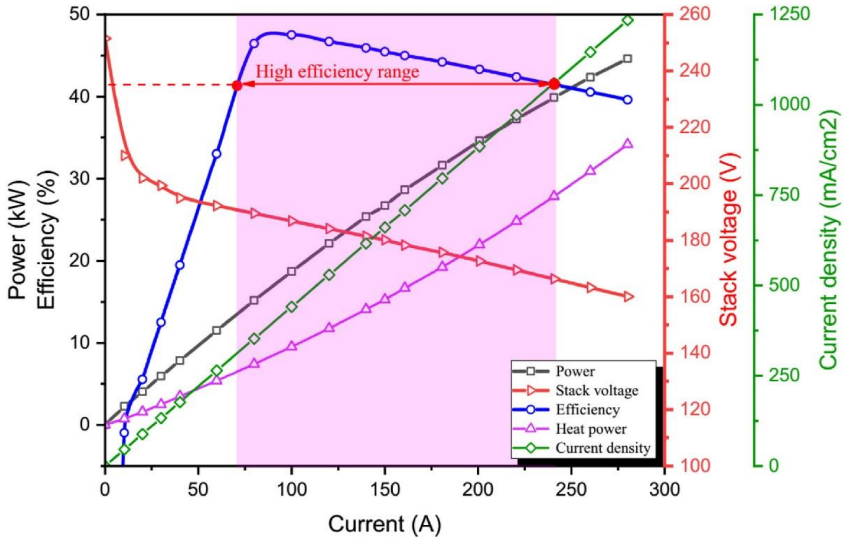


Figure 1. Curve characteristics of the PEMFC [19].

Proton-exchange membrane fuel cells (PEMFCs) are among the most extensively studied and utilized fuel cells, especially in the automotive industry [20–22]. They function at relatively low temperatures (typically 80 °C) and are characterized by their quick start-up times and high power density. Marghani [23] discusses the compatibility of PEMFCs for portable power sources because of their efficient conversion of hydrogen into electricity with minimal emissions. The simplicity of their design, combined with the availability of hydrogen as a fuel, makes PEMFCs a strong candidate for future energy systems. Despite significant progress, PEMFCs still face commercialization challenges, particularly related to durability and lifespan. Performance degradation over time results from factors such as electrode material degradation, catalyst loss, membrane mechanical damage, and fluctuating operating conditions, which ultimately affect efficiency, service life, and maintenance costs.

Solid-oxide fuel cells (SOFCs), in contrast, work at much higher temperatures (600 °C to 1000 °C) and utilize a solid-oxide or ceramic electrolyte. Wang et al. [24] highlight that SOFCs could employ various fuels, including natural gas, as well as biogas, which enhances their versatility. The high operating temperatures allow for greater efficiency in energy conversion, but they also pose challenges related to thermal management and material durability. Research into advanced materials and designs is ongoing to optimize SOFC performance while addressing these challenges.

Molten carbonate fuel cells (MCFCs) work at intermediate temperatures (around 600 °C to 700 °C) and utilize a molten carbonate electrolyte. These fuel cells are particularly effective for large-scale stationary applications, such as power plants. The possibility of using various fuels, including natural gas and hydrogen, makes MCFCs a flexible option for energy generation. Their thermal management strategies are crucial, as maintaining the appropriate operating temperature is essential for optimal performance and longevity.

Phosphoric acid fuel cells (PAFCs) are another type of fuel cell that functions at moderate temperatures (around 150 °C to 200 °C). They are famous for their robustness.

Their reliability makes them fit for stationary applications. Hossain et al. [25] note that PAFCs are used for numerous purposes, including backup power systems, as well as combined heat and power (CHP) systems, thanks to their capability to efficiently convert fuel into electricity while providing useful thermal energy.

The integration of machine learning techniques in fuel-cell technology is also gaining traction [26–32]. These techniques can enhance the control and optimization of fuel cells by analyzing data and predicting performance under various operating conditions. For instance, machine learning algorithms are used to monitor and manage temperature, pressure, and humidity within fuel cells, ensuring optimal operating conditions and improving overall efficiency [33]. Such a data-driven method enables more responsive and adaptive control strategies, which are critical for maximizing performance of fuel-cell systems in real-world applications.

In conclusion, fuel cells represent a potential technology for renewable and sustainable energy generation, with various types tailored for specific applications. The progress in fuel-cell research and development intends to enhance the efficiency, durability, and versatility of fuel cells, making them a vital element of future renewable energy systems. As machine learning and advanced materials continue to evolve, the potential for fuel cells to contribute to a low-carbon economy becomes increasingly significant.

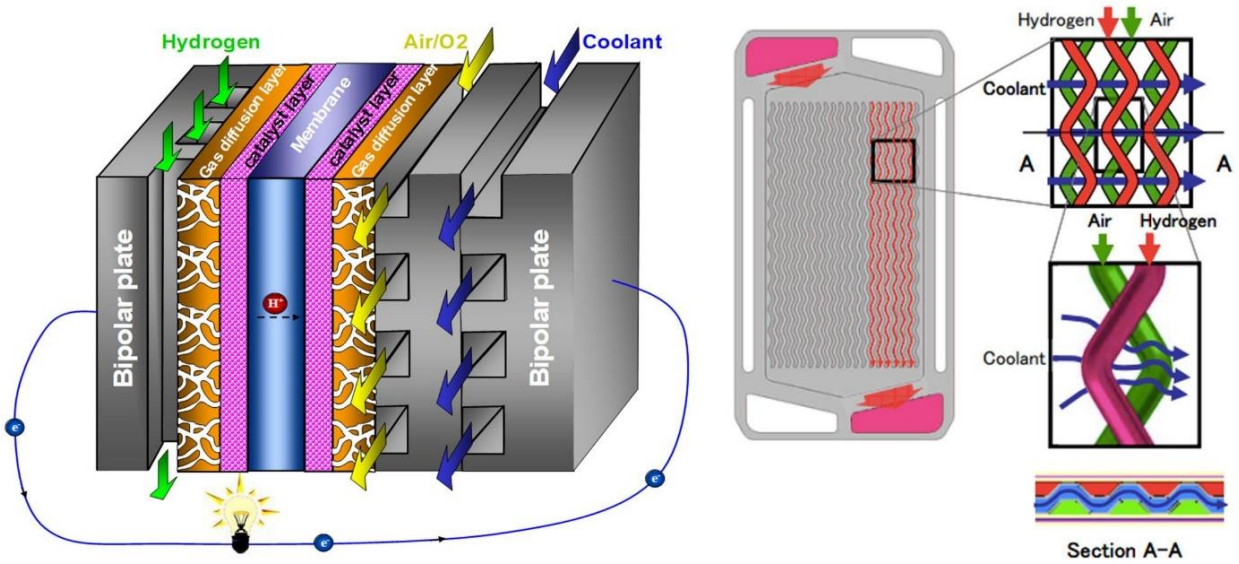
Although the main focus of this review is PEMFCs and SOFCs, brief descriptions of MCFCs and PAFCs are included in the introduction to provide a complete overview of major fuel-cell types. This broader context clarifies the distinct operating ranges and thermal management requirements across technologies, and it helps explain why PEMFCs and SOFCs—representing low- and high-temperature extremes—were selected for a detailed comparative analysis.

This review provides a novel synthesis of current advancements in fuel-cell thermal management by bridging both proton-exchange membrane fuel cells (PEMFCs) and solid-oxide fuel cells (SOFCs), highlighting the unique challenges and strategies specific to each. The inclusion of innovative cooling systems, such as hybrid active–passive approaches, coupled with machine learning-driven adaptive control, marks a forward-thinking perspective on optimizing heat dissipation. The exploration of real-time monitoring techniques, combined with the potential of heat recovery systems to boost energy efficiency, underscores the need for dynamic, data-driven approaches in advancing fuel-cell technologies for broader purposes, ranging from the automotive sector to stationary power systems.

2. Fuel-Cell Thermal Management

Fuel cells, specifically proton-exchange membrane fuel cells (PEMFCs), are more and more recognized for their potential for numerous purposes, including automotive and stationary power generation. However, effective thermal management is of importance to optimize their performance and durability. The fuel cells' thermal management involves the regulation of temperature to ensure efficient operation, as excessive heat could result in performance degradation and decreased durability.

One primary drawback in fuel-cell thermal management is the heat generation during electrochemical reactions [34–36]. This heat must be effectively dissipated to maintain optimal operating temperatures. Various cooling methods have been explored, including liquid cooling, air cooling, and phase-change cooling strategies. Chen et al. [37] provide a comprehensive review of these cooling methods, highlighting their material properties and durability implications, which are essential for PEMFCs' reliability. Figure 2 illustrates a PEMFC and its cooling channels. Additionally, Zhang et al. [38] discuss the model predictive control application for open-cathode fuel-cell thermal management systems, emphasizing the need for advanced control strategies to enhance thermal performance.



(**a**) (**b**)

Figure 2. (**a**) PEMFC with an embedded coolant channel system within the bipolar plates [39] and (**b**) coolant channels in an electric vehicle based on a fuel cell (FCEVs) [40].

Integrating waste heat recovery systems is another promising approach to improving whole-fuel-cell efficiency [41–43]. Nguyen and Shabani [42] explore the heat recovery opportunities in combined heating, cooling, and power applications, suggesting that such systems can significantly enhance energy utilization. Similarly, Sun et al. [44]. investigate the reuse of waste heat in fuel-cell vehicles, demonstrating that effective heat exchange can improve energy consumption and overall system efficiency. This aligns with the findings of Olabi et al. [45], who note that the waste heat use in fuel-cell systems has garnered considerable attention for its potential to increase energy conversion efficiency.

Moreover, the control and modeling of thermal management systems are critical for optimizing the performance of fuel-cell vehicles [35,46,47]. Xu et al. [19] present a model for vehicle-integrated thermal management systems, which allows for the better control of temperature dynamics in PEMFCs and is complemented by the work of Bai and He [48], who discuss system optimization for thermal management in a fuel-cell vehicle, emphasizing the importance of maintaining appropriate operating conditions to ensure reliability and performance.

Figure 3 illustrates the integration of fuel-cell systems at both the vehicle and energy network levels. The top schematic shows a vehicle PEMFC system where hydrogen from the storage tank and compressed air are supplied to the fuel-cell stack, producing electricity, heat, and water, with balance-of-plant components such as pumps, humidifiers, coolers, radiators, and purge valves ensuring proper thermal, water, and reactant management. The bottom schematic highlights how hydrogen can be produced via electrolysis using renewable sources such as solar and wind, stored, and later utilized in fuel cells to supply electricity back to the grid or vehicle, demonstrating hydrogen's role as an energy carrier that links intermittent renewables with end-use applications. Together, the diagrams emphasize that system scalability requires efficient balance-of-plant management, temperature control is critical to performance and durability, and techno-economic considerations remain central to achieving cost-effective deployment of large-scale hydrogen and fuel-cell systems.

In conclusion, effective thermal management is of importance for optimal fuel-cell performance. The integration of advanced cooling methods, waste heat recovery systems, and sophisticated control strategies can significantly improve PEMFCs' efficiency and

lifespans. While previous reviews have focused on aspects such as flow channel design, two-phase flow simulation, and static performance evaluation, our paper provides a broader comparative perspective by covering both PEMFC and SOFC thermal management strategies, incorporating advanced techniques such as hybrid cooling and machine learning-based optimization approaches. Additionally, we have now included references and brief discussions on flow channel optimization and dynamic coolant control strategies to enhance the comprehensiveness of our review. As research continues to evolve in this area, the development of comprehensive thermal management systems will be vital for the broader adoption of fuel-cell technologies in various applications.

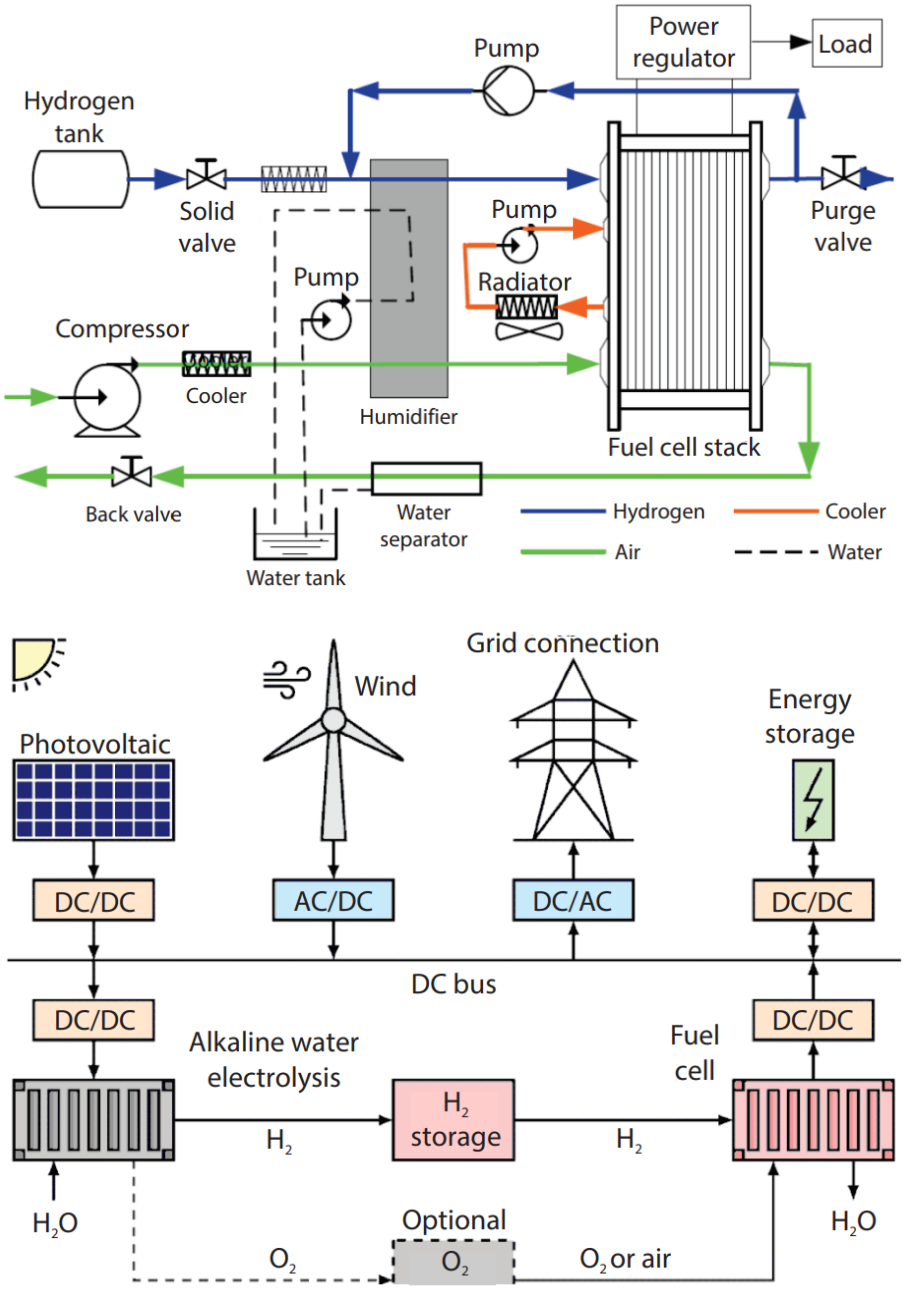


Figure 3. (**Top**) Vehicle fuel-cell system and (**bottom**) energy distribution within the stack system [48].

2.1. Heat Generation Process in Fuel Cells

2.1.1. Heat Generation Process in Proton-Exchange Membrane Fuel Cells

Heat generation in PEMFCs is a crucial element that influences fuel-cell efficiency and operational stability. The mechanisms of heat generation primarily stem from the

electrochemical reactions taking place within a fuel cell and from various physical processes associated with the transport of reactants and products. Understanding these mechanisms is essential for optimizing fuel-cell design and improving thermal management strategies.

The primary source of heat in PEMFCs is the exothermic reaction that occurs during the conversion of the electrochemicals H_2 and O_2 into water and electricity. This reaction releases a significant amount of energy, which is primarily dissipated as heat. According to Murad [49], approximately 50% or up to 60% of the energy generation from reactions of these chemicals is lost as heat, highlighting the importance of effective thermal management to enhance overall efficiency. Furthermore, heat generation is exacerbated by the resistance encountered during proton transport via a membrane and electron transport via electrodes, which contributes to Joule heating [50].

In addition to electrochemical reactions, the flow dynamics of reactants, along with products within the fuel cell, also play a critical part in heat generation. The flow fields' design, as discussed by Atasay et al. [51], can significantly affect the reactants' distribution, heat removal, and water produced during operation. Inefficient flow field designs can lead to localized overheating, which can adversely affect the fuel-cell performance and durability. Hence, optimizing the flow-field structure is vital to enhance thermal management and minimize heat generation [52].

Moreover, the working conditions of PEMFCs, for instance, temperature and pressure, influence heat generation mechanisms. High-temperature PEMFCs (HT-PEMFCs) have been shown to exhibit improved kinetics and reduced heat generation due to enhanced reaction rates and better water management capabilities [53]. However, they also require careful thermal management to prevent overheating, as the reaction rates can lead to excessive heat if not properly controlled [54]. The balance between operating temperature and heat generation is crucial for maintaining optimal performance and preventing the thermal degradation of the membrane and other components. Figure 4 shows various membranes of proton exchange used in HT-PEMFCs, with all parameters' average values derived from an analysis of ten randomly selected articles [53].

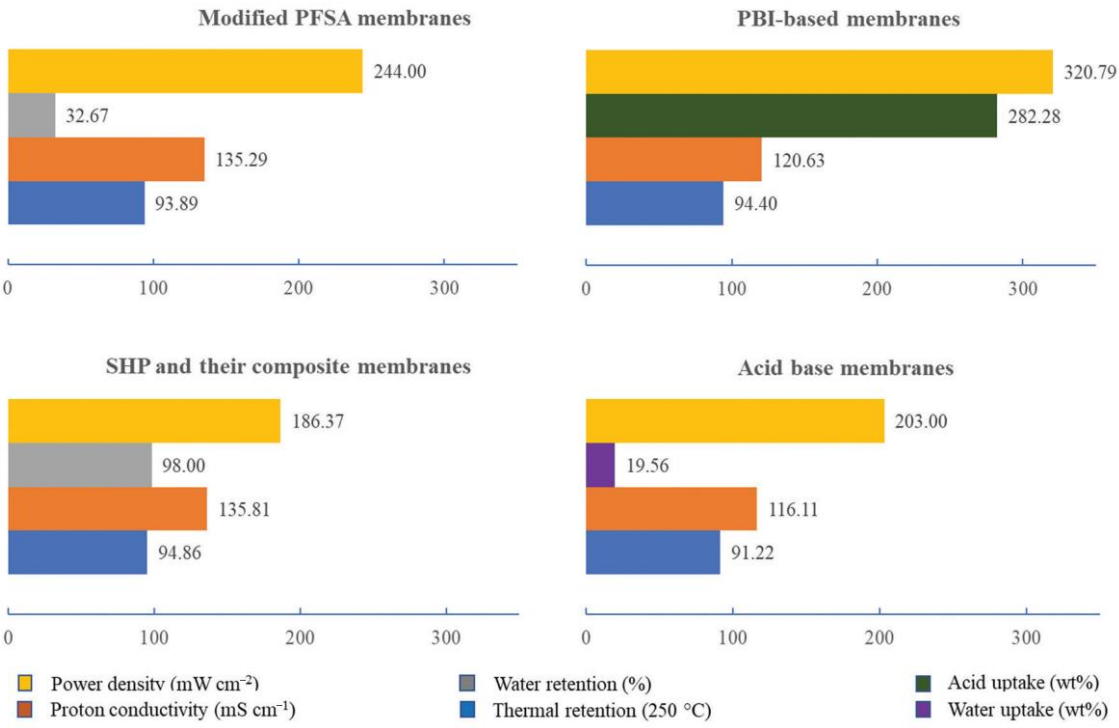


Figure 4. Various proton-exchange membranes used in HT-PEMFCs [53].

In conclusion, heat generation in PEMFCs arises from both electrochemical reactions and physical processes pertains to reactant transport. Effective thermal management strategies, including optimized flow field designs and the careful control of operating conditions, are essential to mitigate heat generation and improve PEMFCs' efficiency and durability. As research continues to advance in this field, a deeper understanding of these mechanisms will be vital for the development of next-generation fuel cells.

2.1.2. Heat Generation Process in Solid-Oxide Fuel Cells

Heat generation mechanisms in SOFCs are crucial for understanding their efficiency and operational stability [10,55]. SOFCs work at relatively high temperatures, normally between 600 °C and 1000 °C, which facilitates ionic conductivity of solid-oxide electrolyte. This enables efficient electrochemical reactions. The heat generated in SOFCs primarily arises from the exothermic reactions during the electrochemical conversion of fuel, as well as from various physical processes associated with reactant transport and resistance within the cell.

SOFCs are connected in series via interconnects to form a stack of fuel cells, allowing for higher efficiency at elevated voltages [56]. These interconnects, acting as bipolar plates, link individual cells while shielding the electrodes from environmental factors. Figure 5 displays the interconnected configuration within the stack of fuel cells, alongside the formation of native oxide scales at the interface.

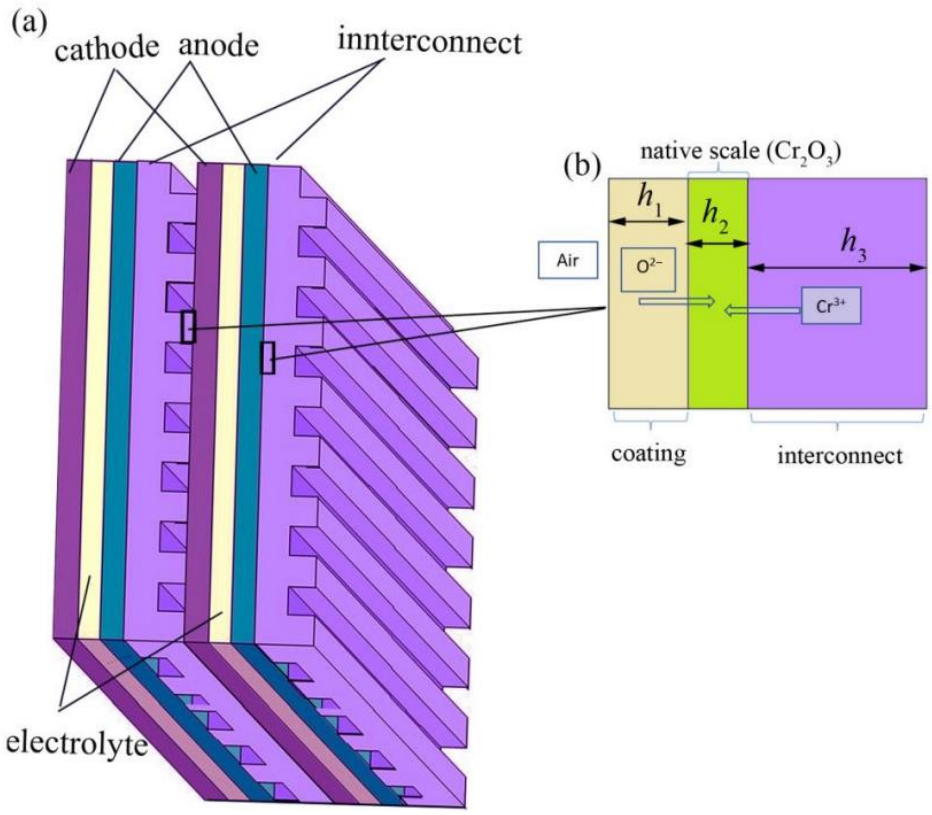


Figure 5. (**a**) Arrangement of interconnects in SOFCs. (**b**) Enlarged picture of the interconnect interface. The thicknesses are labeled as h_1 for the coating, h_2 for the native oxide scale, and h_3 for the interconnect [56].

The primary source of heat generation in SOFCs is the electrochemical oxidation of fuels, like H_2 or hydrocarbons, at the anode. This reaction releases energy, part of which is transformed into electrical energy, while the remainder is dispersed as heat. According to Xu et al. [57], the high operating temperatures not only enhance the reaction kinetics but

also contribute to significant thermal energy generation due to the inherent inefficiencies in the electrochemical processes. The heat produced can be substantial, with estimates indicating that a considerable amount of energy from fuel vanishes as heat, rather than being converted into useful work [58].

In addition to the electrochemical reactions, thermal stresses and resistive heating also contribute to heat generation in SOFCs. As noted by Sai et al. [56], the structural integrity of the cell components, particularly the metallic interconnects, can be compromised because of thermal stresses due to the high operating temperatures. These stresses can lead to mechanical degradation, which not only influences the fuel-cell performance but also generates additional heat through friction and deformation. Furthermore, the resistance to ion and electron flow within the cell generates Joule heating, which adds to the overall thermal load [59].

The design and configuration of the SOFC also play a significant role in heat generation. For instance, the use of porous electrodes allows for better reactant distribution and heat dissipation, but an improper design can lead to localized overheating. Moreover, the interaction between the anode and the electrolyte can result in additional heat generation due to concentration gradients and reaction kinetics, as highlighted by Pirkandi et al. [60]. Therefore, optimizing the fuel-cell components' design is essential for managing heat generation effectively.

In conclusion, the generation of heat in solid-oxide fuel cells is a multifaceted process driven by electrochemical reactions, thermal stresses, and resistive heating. Understanding these mechanisms is vital for improving the efficiency and durability of SOFCs. As research progresses, advancements in materials and designs will be crucial for enhancing thermal management strategies, ultimately leading to higher efficiency and reliability of fuel cells. Table 1 summarizes the key points on thermal management of PEMFCs and SOFCs.

Table 1. Overview of the heat generation mechanisms, challenges, and thermal management strategies for PEMFCs and SOFCs.

Aspect	PEMFCs	SOFCs
Heat Generation Sources	• Electrochemical reactions converting hydrogen and oxygen into water. • Proton transport and electron flow create Joule heating.	• Electrochemical oxidation of fuels (e.g., hydrogen or hydrocarbons) at the anode. • High temperatures (600–1000 °C) enhance reaction kinetics but generate heat.
Energy Lost as Heat	• Fifty to sixty percent of energy generated is lost as heat.	• Significant thermal energy is produced due to inefficiencies in electrochemical processes.
Key Challenges	• Poor flow field design leads to localized overheating.	• Thermal stresses at high temperatures affect cell components (e.g., metallic interconnects) and generate heat.
Design Considerations	• Flow field design impacts the distribution of reactants and removal of heat.	• Porous electrode designs aid heat dissipation, but improper design can cause localized overheating.
Thermal Management Strategies	• Liquid cooling, air cooling, and phase-change cooling strategies.	• Managing concentration gradients and reaction kinetics through optimal anode-electrolyte interactions is essential.
Control Strategies	• Advanced control strategies like model predictive control for optimizing open-cathode fuel-cell systems.	• Efficient design of components (e.g., electrodes, interconnects) is critical to minimize resistive heating and stress.
Waste Heat Recovery	• Heat recovery systems can enhance energy utilization in combined heating, cooling, and power systems.	• Utilizing waste heat through system optimization can enhance overall system efficiency.

2.2. Significance of Thermal Management of Fuel Cells

2.2.1. Significance of Thermal Management of Proton-Exchange Membrane Fuel Cells

Proton-exchange membrane fuel cells' (PEMFCs') thermal management is of paramount importance because of its direct effect on the performance, efficiency, and longevity of these energy conversion devices. Effective thermal management ensures that the working temperature is maintained in the range of an optimal interval, which is crucial for maximizing electrochemical reactions while preventing the thermal degradation of the membrane and other components.

One of the primary reasons for the significance of thermal management in PEMFCs is the exothermic nature of the electrochemical reactions occurring within the cell. As highlighted by Wang et al. [54], the heat generated during these reactions can lead to increased temperatures that may exceed the fuel-cell material limits' components, particularly the proton-exchange membrane (PEM). High temperatures can cause membrane dehydration, which adversely affects proton conductivity and overall cell performance. Therefore, maintaining an appropriate thermal environment is essential to ensure that the membrane remains hydrated and functions efficiently.

Moreover, the operational efficiency of PEMFCs is closely linked to their thermal management strategies. Ji [61] emphasizes that high-temperature PEMFCs (HT-PEMFCs) exhibit enhanced reaction kinetics and improved tolerance to impurities, which can be attributed to effective thermal management. By optimizing the thermal conditions, the fuel-cell performance could be significantly enhanced, leading to higher energy conversion efficiencies. This is mostly relevant in usages in which rapid response times, as well as high power densities, are required, such as in automotive and portable power applications.

In addition to enhancing performance, effective thermal management also plays an essential part in prolonging the PEMFCs' lifespan. As noted by Hao et al. [62], the ability to manage heat effectively can mitigate thermal stresses that arise from temperature fluctuations during operation. These stresses could result in mechanical failures and cell components' degradation over time. By implementing robust thermal management systems, such as advanced cooling techniques or heat recovery systems, the durability of PEMFCs can be significantly enhanced, thereby reducing maintenance costs and improving reliability.

Furthermore, the integration of thermal management systems can facilitate better water management within the fuel cell. Feng et al. [63] discuss how effective thermal management can help control the water balance in PEMFCs, which is critical to maintain optimal hydration levels in a membrane. Proper water management not only supports proton conduction but also prevents issues such as flooding or drying out, which can severely impact performance. In line with the discussion on proper water management in PEMFC membranes, Figure 6a shows that water uptake decreases with increasing filler content at both 30 °C and 80 °C, while Figure 6b demonstrates a similar decreasing trend in swelling ratio, indicating that filler incorporation helps control hydration and dimensional stability of the membrane.

In conclusion, the significance of PEMFCs' thermal management cannot be overstated. It is essential for optimizing performance, enhancing efficiency, prolonging lifespans, and ensuring effective water management. At high current densities—necessary for large-scale commercialization—excessive liquid water accumulation can cause flooding, block gas diffusion, and accelerate performance degradation. Effective thermal management supports proper water removal and distribution, ensuring stable operation and sustained high-performance output of PEMFCs. As research continues to advance in this field, the development of innovative thermal management strategies will be critical for the successful commercialization and deployment of PEMFC technologies in various applications.

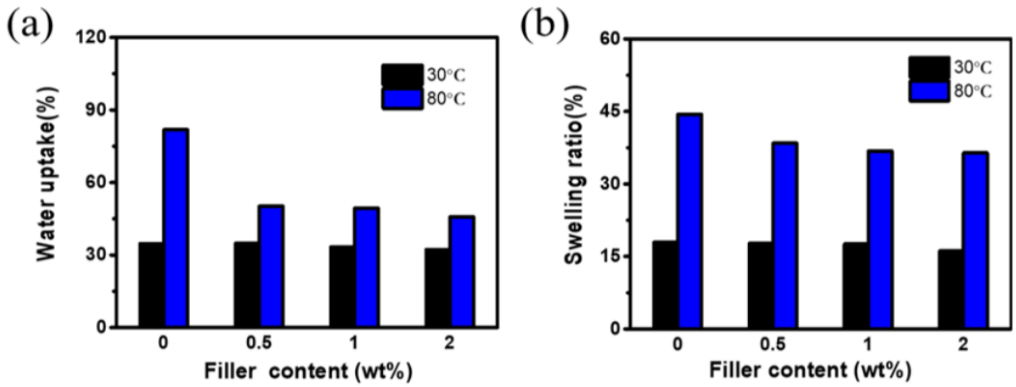


Figure 6. Sulfonated poly(arylene ether nitrile (SPEN) and SPEN/GO-Ca^{2+}-MWCNT [63].

2.2.2. Significance of Thermal Management of Solid-Oxide Fuel Cells

The importance of solid-oxide fuel cells' (SOFCs') thermal management is critical to ensure the optimal performance, efficiency, and longevity of these advanced energy conversion systems. SOFCs function at relatively high temperatures, normally from 600 °C to 1000 °C, which presents unique challenges and opportunities for thermal management strategies.

SOFCs consist of a solid ceramic electrolyte positioned between porous anode and cathode layers. Based on the type of species transported through the electrolyte, SOFCs can be classified into three categories: proton-conductive, O_2-ion-conductive, and mixed-ion-conductive. In O_2-ion-conductive SOFCs (Figure 7a), O_2 anions transport from the cathode to the anode, producing steam or CO_2 at the anode, which helps resist carbon deposition by promoting reforming reactions when fueled by hydrocarbons. Conversely, in proton-conductive SOFCs, only protons are transferred to the cathode for oxidation through oxygen (Figure 7b), increasing the risk of coking because of higher CO levels in the anode [64].

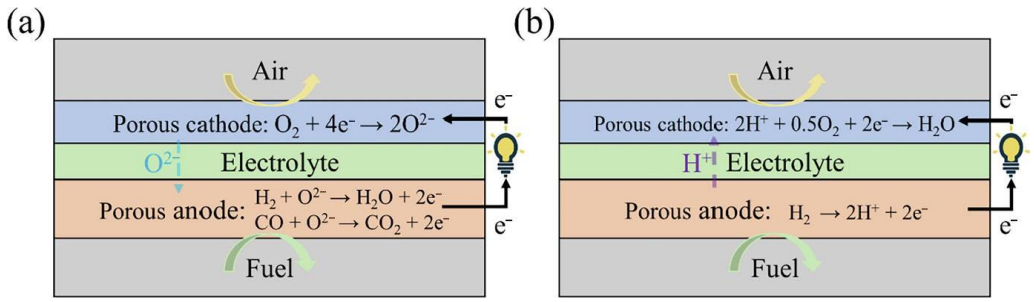


Figure 7. (**a**) O_2-ion-conductive SOFC and (**b**) proton-conductive SOFC [64].

One of the primary reasons why thermal management is crucial in SOFCs is the need to maintain the working temperature in a specific range to optimize electrochemical reactions. High operating temperatures enhance the solid electrolyte ionic conductivity, thereby improving a fuel cell's overall efficiency [64]. Nonetheless, excessive heat can lead to thermal stresses that may damage the cell components, including the cracking and delamination of the electrolyte and electrodes [65]; effective thermal management systems are essential to mitigate these risks and ensure stable operation.

Moreover, thermal management directly influences the efficiency of energy conversion in SOFCs. Maintaining optimal thermal conditions can significantly enhance the thermodynamic efficiency of the electrochemical reactions, allowing for better energy utilization. This is particularly important in applications where SOFCs are integrated into hybrid systems or combined heat and power (CHP) configurations since effective heat recovery can improve overall system efficiency [66]. By managing heat effectively, SOFCs can convert a

larger portion of chemical energy in fuels into usable electrical energy, thus maximizing their performance.

In addition to performance and efficiency, thermal management is vital for the durability and reliability of SOFCs. Prolonged exposure to thermal cycling can result in the degradation of material and fuel-cell components' reduced lifespans [10]. Implementing robust thermal management strategies can help minimize the effects of thermal fatigue, thereby extending the operational life of SOFC systems. This is particularly important in commercial applications where reliability and maintenance costs are critical factors.

Furthermore, effective thermal management facilitates better water and fuel management within the SOFC. Temperature control can influence the fuel-cell water vapor content, which is vital for preserving optimal electrolyte hydration levels. Proper hydration is crucial for ensuring high ionic conductivity and preventing issues such as flooding or drying out, which can severely impact performance [67].

In conclusion, the significance of SOFCs' thermal management is multifaceted, encompassing aspects of performance optimization, efficiency enhancement, durability, and effective resource management. As research continues to advance, innovative thermal management solutions will be important for successful SOFC use in various applications, including distributed generation and renewable energy integration. Table 2 summarizes the importance of PEMFCs' and SOFCs' thermal management.

Table 2. Critical role of thermal management in ensuring the efficiency, performance, and longevity of both PEMFCs and SOFCs.

Aspect	PEMFCs	SOFCs
Key Importance	• Ensures optimal operating temperature for electrochemical reactions and membrane hydration.	• Maintains high operating temperatures (600–1000 °C) for ionic conductivity and efficient reactions.
Impact on Performance	• Prevents thermal degradation of PEM. • Improves overall cell performance by optimizing reaction kinetics.	• Enhances electrochemical reaction efficiency by maintaining high temperatures. • Increases thermodynamic efficiency in energy conversion, especially in CHP systems.
Effect on Efficiency	• Effective heat management enhances energy conversion efficiency, particularly in high-power applications.	• Efficient heat management allows for better fuel-to-energy conversion, maximizing usable electrical energy.
Longevity and Durability	• Mitigates thermal stresses, reducing mechanical failures and component degradation.	• Reduces thermal cycling effects that can cause material degradation, extending system lifespan.
Water Management	• Facilitates better water management, ensuring membrane hydration and preventing flooding or drying out.	• Helps control water vapor content, ensuring proper hydration of the electrolyte and avoiding performance issues.
Advanced Strategies	• Integrates advanced cooling techniques, such as heat recovery systems, to enhance reliability and reduce maintenance costs.	• Implements robust thermal management systems to prevent damage to components like the electrolyte and electrodes.
Commercial Relevance	• Critical for high-performance, long-lifespan applications like automotive and portable power systems.	• Vital for reliable and efficient operation in hybrid systems, distributed generation, and renewable energy integration.

2.3. Methods for Thermal Management of Fuel Cells

Thermal management is a critical aspect of fuel-cell technology, especially for PEMFCs and SOFCs. Effective thermal management techniques are essential for maintaining optimal operating temperatures, enhancing efficiency, and prolonging fuel-cell lifespans. Various strategies are being developed to address the drawbacks related to heat generation and dissipation in these systems.

One prominent technique for thermal management in PEMFCs is the use of passive thermal management systems. According to Idi [68], these systems rely on the natural convection of air and the thermal properties of materials to dissipate heat without the need for mechanical components Idi (2023). This approach can be particularly beneficial in reducing complexity and improving reliability. Furthermore, phase-change materials (PCMs) have gained attention for their capability to absorb and release heat in phase transitions, thus offering a stable thermal environment for the fuel cell [69]. The integration of PCMs can help mitigate temperature fluctuations and improve overall thermal stability.

Active thermal management techniques are also widely employed in fuel cells. These include the use of liquid cooling systems, in which a coolant circulates through the fuel-cell stack to absorb excess heat. This method is effective in maintaining the desired operating temperature and preventing overheating, as highlighted by Kim and Yoo [70], who emphasize the importance of maintaining optimal temperature ranges for improved performance and longevity. Furthermore, advanced control strategies, such as adaptive control systems, have been developed to dynamically adjust the cooling rates based on real-time temperature measurements, ensuring efficient thermal management under varying load conditions [71].

Another innovative approach involves flow channel designs' optimization within the fuel cell. Research by Novotný et al. indicates that the shape, along with the distribution of flow channels, influences heat and mass transport within the cell [72]. By optimizing these designs, it is possible to enhance the dissipation of heat and improve the fuel-cell overall thermal management. Additionally, the use of serpentine flow patterns has been shown to facilitate better thermal and water management, addressing common issues such as flooding and dehydration [73].

In SOFCs, thermal management techniques often focus on the integration of heat exchangers and afterburners to recover waste heat and improve overall system efficiency. As discussed by Li [74], the design of these thermal management subsystems is crucial for maximizing energy utilization and ensuring stable operation. The implementation of heat recovery systems can significantly enhance the SOFCs' overall efficiency, making such fuel cells more viable for commercial purposes.

All in all, various techniques are used for fuel-cell thermal management, such as passive and active systems, flow channel optimization, and the integration of heat recovery technologies. These strategies are essential for maintaining optimal operating conditions, enhancing efficiency, and prolonging fuel-cell durability. As studies continue to advance, the development of innovative thermal management solutions will be vital, aiming at successful fuel-cell commercialization technologies in diverse applications.

2.3.1. Thermal Management of Proton-Exchange Membrane Fuel Cells (PEMFCs)

The thermal management of PEMFCs is critical for optimizing their performance, efficiency, and lifespan. The effective control of temperature within these systems ensures that electrochemical reactions take place at optimal rates while preventing damage to the components caused by excessive heat. Various techniques are being developed to address the thermal management drawbacks pertaining to PEMFCs.

One of the primary methods for thermal management in PEMFCs is the use of active cooling systems. These systems typically involve circulating a coolant, such as water or a specialized thermal fluid, through channels adjacent to the stack of fuel cells. This method helps dissipate excess heat generated during operation. According to Louis [75], maintaining the stack temperature within an optimal range is essential, as excessive temperatures can lead to catalyst deactivation and irreversible damage to the membrane. Active cool-

ing systems can be designed to respond dynamically to load changes and temperature, ensuring that the fuel cell operates efficiently under varying conditions. Figure 8 shows the optimized controller exhibiting a smaller overshoot compared to the traditional controller, with a smoother and less volatile change curve. This contributes to more stable fuel-cell operation at the step load current. Specifically, Figure 8a illustrates the stack temperature response, where the optimized controller reaches the target temperature with less fluctuation and reduced oscillations compared to the conventional controller. Figure 8b presents the coolant outlet temperature response, demonstrating that the optimized controller maintains tighter regulation with smaller deviations, ensuring better thermal management and improved overall system stability.

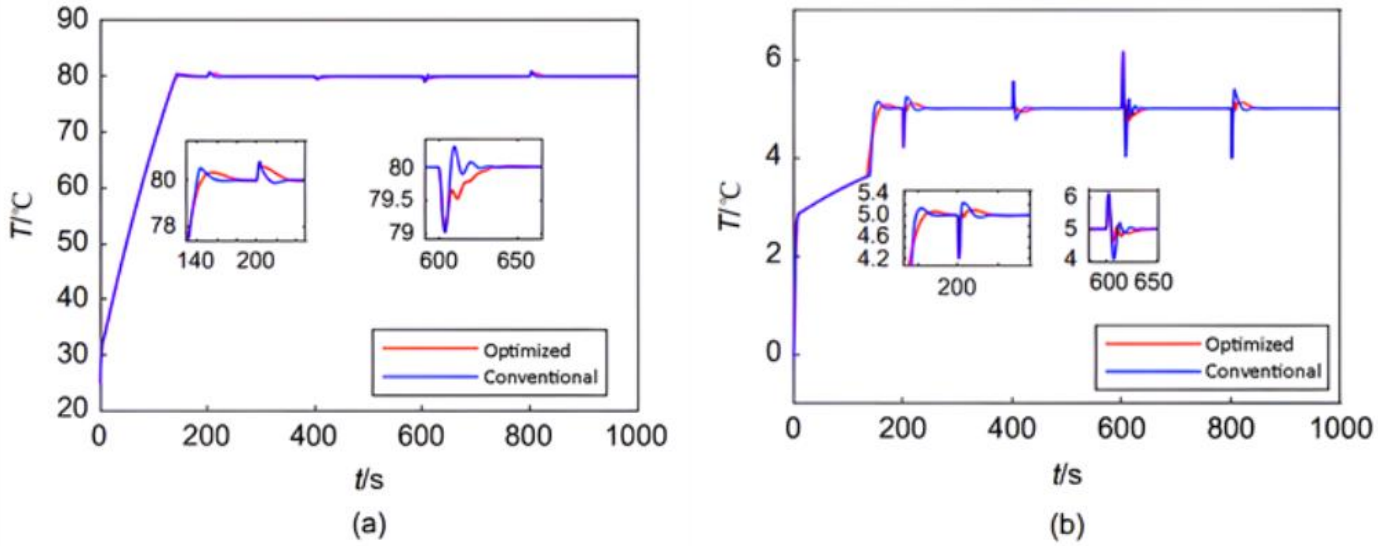


Figure 8. Temperature difference between stack and coolant at step load current [75].

Other than active cooling, passive thermal management techniques are also employed. These methods rely on the natural heat dissipation properties of materials and the fuel-cell design components. For instance, the use of materials with high thermal conductivity can facilitate heat transfer away from critical cell areas, thereby maintaining a more uniform distribution of temperature [76]. Moreover, the design of flow channels within the fuel cell can significantly impact thermal management. Research by Deng et al. [77] highlights that optimizing the design of a flow field could improve heat and mass transfer. This is important for maintaining the fuel-cell performance.

Water management is another critical aspect of thermal management in PEMFCs. The membrane of proton exchange requires a certain level of hydration to preserve its conductivity, as well as performance. However, excessive water accumulation can lead to flooding, which impairs gas transport and overall efficiency [78]. Techniques such as bypass configurations for membrane humidifiers have been developed to enhance water management and, consequently, thermal stability [76]. Effective water management not only supports the thermal balance but also enhances the fuel-cell electrochemical performance.

Furthermore, advancements in membrane materials have contributed to improved thermal management in PEMFCs. High-temperature PEMs (HT-PEMs) have gained interest because of their capability to function at elevated temperatures while maintaining performance [61]. These membranes facilitate better thermal and water management, allowing for more efficient operation and integration with fuel processing units. The development of new materials, such as phosphoric acid-doped polybenzimidazole membranes, has shown promise in enhancing both thermal stability and proton conductivity [79].

In conclusion, PEMFCs' thermal management is essential to optimize performance, ensuring longevity and facilitating effective water management. A mix of active and passive cooling methods, optimized flow channel designs, and advanced membrane materials plays an important part in keeping the operational PEMFCs' efficiency. As research continues to advance in this field, the development of novel thermal management approaches will be vital for the successful commercialization of fuel-cell technologies in various applications.

Active Cooling Methods

Thermal management is a critical aspect of proton-exchange membrane fuel cells (PEMFCs), particularly concerning the implementation of active cooling methods. Efficient thermal regulation guarantees that the fuel cell's temperature stays within the ideal range, which is vital for enhancing performance, efficiency, and durability. A variety of active cooling strategies have been introduced to tackle the issues linked to heat production in PEMFCs.

One of the most common active cooling methods is liquid cooling, in which a coolant, typically water or a water–glycol mixture, circulates via channels adjacent to the stack of fuel cells. This method effectively removes surplus heat that is generated during operation. According to Louis [75], maintaining the stack temperature within an optimal range is crucial, as excessive temperatures can lead to catalyst deactivation and irreversible damage to the membrane. Liquid cooling systems can be designed to dynamically adjust the flow rate of the coolant based on real-time temperature measurements, ensuring efficient thermal management under varying load conditions.

In addition to liquid cooling, air-cooling systems are also utilized in PEMFCs. These systems rely on forced air circulation to dissipate heat from the fuel-cell stack. Gan et al. [80] highlight that air-cooled systems are compact and require low energy consumption, thus suitable for usages in which weight and space are critical factors. The efficiency of air cooling can be enhanced by optimizing the design of the airflow paths and incorporating features such as heat exchangers to improve heat transfer rates.

Another innovative approach to active thermal management is the utilization of phase-change materials (PCMs). PCMs can absorb and release heat all through phase transitions, offering a stable thermal environment. Yan et al. [69] discuss the potential advantages of integrating PCMs into PEMFC systems, noting that they can help regulate temperature fluctuations and improve overall thermal stability. This method is particularly beneficial in applications with varying power demands, as it allows for the absorption of excess heat during peak loads and the release of stored heat during lower demand periods. It is important to note that PCMs can be deployed in both active and passive configurations. When integrated with forced fluid circulation or other auxiliary systems, PCMs form part of an active cooling approach, rapidly absorbing and redistributing heat. In contrast, when used without mechanical assistance, PCMs act as a passive system, relying solely on natural heat absorption and release during phase transitions. The inclusion of PCMs in both active and passive sections reflects these distinct operational contexts.

Moreover, advanced control strategies play a significant part in PEMFCs' thermal management. For instance, the implementation of multivariable control systems can optimize the cell cooling circuit, ensuring that temperature is maintained at an optimal level while minimizing energy consumption [81]. These control systems could adjust to variations in operational conditions, enhancing the reliability and efficiency of the thermal management process. Figure 9 depicts the illustration of a PEMFC stack-cooling system.

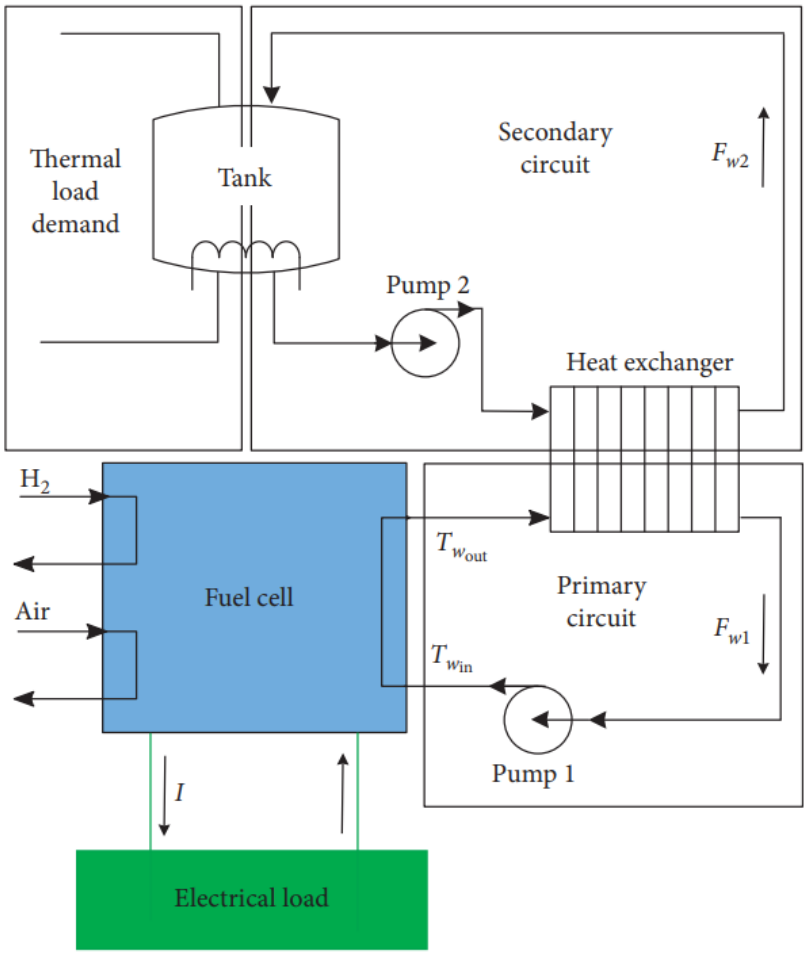


Figure 9. PEMFC stack cooling system for the PEMFC stack [81].

Furthermore, hybrid energy storage systems integrating supercapacitors with lithium-ion batteries have shown strong potential for improving power quality and mitigating the thermal load in renewable-integrated fuel-cell systems. Supercapacitors offer high power density and rapid charge/discharge capabilities, complementing the higher energy density but slower response of batteries. Experimental findings [82] demonstrate that such hybrid configurations can smooth renewable power fluctuations, maintain stable state-of-charge (SOC) profiles, and minimize peak thermal stress on fuel-cell stacks.

For example, in hybrid battery–supercapacitor systems, supercapacitors can achieve response times in the order of milliseconds and cycle lives exceeding one million cycles, while lithium-ion batteries typically provide 2000–5000 deep cycles with a higher energy capacity. Maintaining SOC in the optimal range (40–80%) through coordinated control reduces both battery degradation and fuel-cell thermal excursions.

In conclusion, active cooling methods are essential for effective PEMFCs' thermal management. Techniques like liquid cooling, air cooling, and the use of phase-change materials, along with advanced control strategies, contribute to maintaining optimal operating temperatures, thereby enhancing performance and prolonging the lifespan of PEMFCs. As research continues to advance in this area, the development of innovative thermal management solutions will be vital for the successful commercialization of fuel-cell technologies in various applications.

Passive Cooling Methods

PEMFCs' thermal management is important for maintaining optimal operating conditions, enhancing performance, and prolonging the fuel cells' lifespan. Among the various

thermal management strategies, passive cooling methods have gained attention due to their simplicity, reliability, and energy efficiency. These methods utilize natural processes to dissipate heat without the need for external power sources, leading them to be desirable for usages in which energy conservation is critical.

One of the primary passive cooling techniques employed in PEMFCs is the utilization of phase-change materials (PCMs). PCMs can absorb and then release thermal energy at phase transitions, which assists in stabilizing the fuel-cell temperature. According to Wang et al. [83], integrating PCMs into the cooling channels of PEMFCs can significantly enhance thermal management by providing a buffer against temperature fluctuations. This method is particularly beneficial during periods of high thermal load, as the PCM can absorb excess heat and release it when the temperature drops, thereby maintaining a more uniform distribution of temperature in the fuel cell.

Another effective passive cooling strategy involves the use of enhanced thermal conductivity materials, such as nanofluids. Zakaria [84] discusses how incorporating nanofluids into the coolant can improve the thermal physical properties, thereby enhancing heat transfer efficiency in liquid-cooled PEMFCs. This approach allows for a reduction in the size of heat exchangers while maintaining effective cooling performance. The ability to utilize nanofluids not only improves thermal management but also contributes to the overall cell compactness.

Additionally, the fuel-cell components design plays an important part in passive cooling. The incorporation of heat sinks, as well as optimized flow channel geometries, can facilitate better heat dissipation. For instance, the arrangement of flow channels can be designed to maximize surface area exposure to the coolant, enhancing convective heat transfer [51]. This design consideration is vital for ensuring that heat is effectively removed from critical areas of the fuel cell, thus preventing overheating and maintaining optimal performance.

Moreover, natural convection can be harnessed as a passive cooling mechanism. In configurations where the fuel cell is oriented to allow for natural airflow, heat can be dissipated through convection without the need for mechanical fans or pumps. This method is particularly advantageous in applications where energy efficiency is paramount, as it reduces the whole system of energy consumption [85].

All in all, passive cooling methods are integral to the PEMFCs' thermal management. Techniques such as phase-change materials, enhanced thermal conductivity materials, optimized flow channel designs, and natural convection contribute to maintaining optimal operating temperatures, improving efficiency, and prolonging the lifespan of PEMFCs. As research continues to advance in this area, the development of innovative passive cooling strategies will be essential for successful fuel cell commercialization technologies in various applications.

Bipolar Plates for Proton-Exchange Membrane Fuel Cells

The thermal management of PEMFCs is important for optimizing fuel cell performance, as well as ensuring its longevity. Among the various elements involved in thermal management, bipolar plates play a significant role. These plates not only serve as current collectors but also facilitate heat dissipation and manage the flow of reactants and coolant within the fuel cell stack. The design and material selection of bipolar plates are therefore critical for effective thermal management.

Bipolar plates are typically made from materials that possess good electrical conductivity and thermal conductivity. Common materials include graphite and metal composites, which can efficiently conduct electricity while also allowing for effective heat transfer. The structural design of bipolar plates can significantly influence the thermal management

capabilities of PEMFCs. Innovations such as tree-shaped fractal designs and tapered dual serpentine channels have been shown to enhance heat dissipation and promote uniform distribution of temperature across the membrane electrode assembly (MEA). This uniformity is essential for maintaining optimal operating conditions and preventing localized overheating, which can lead to performance degradation.

Moreover, the integration of cooling channels within the bipolar plates is a key aspect of thermal management. These channels allow for the circulation of coolant, which absorbs excess heat generated during the electrochemical reactions. Optimizing the flow paths within the bipolar plates can enhance heat transfer efficiency. By designing the cooling channels to maximize surface area and minimize flow resistance, the overall fuel-cell thermal management could be considerably enhanced.

In addition to their thermal management functions, bipolar plates also provide stack mechanical stability in the fuel cell. The ability of bipolar plates to withstand operational stresses while maintaining structural integrity is vital for the PEMFCs' durability. The materials' mechanical properties used in bipolar plates must be carefully considered to ensure that they can endure the thermal cycling and pressure variations that occur during operation. This durability is important for maintaining the fuel cell performance and reliability over time.

Furthermore, the surface treatment of bipolar plates can enhance their thermal management capabilities. Techniques such as coating the plates with materials that improve thermal conductivity or applying hydrophilic treatments can facilitate better heat transfer and water management within the fuel cell. Effective water management is critical in PEMFCs, as such a strategy helps uphold the membrane hydration while preventing flooding, which can adversely affect performance.

In conclusion, bipolar plates are integral to PEMFCs' thermal management. Their design, material selection, and cooling channel integration play a crucial part in optimizing heat dissipation and maintaining a uniform distribution of temperatures in a fuel-cell stack. As research continues to advance in this area, innovative designs and materials for bipolar plates will be important to improve the performance and durability of PEMFC technologies.

Heat Recovery Opportunities for Proton-Exchange Membrane Fuel Cells

Thermal management in PEMFCs is important to optimize the performance and ensure the longevity of the fuel cell system. One promising approach to enhancing thermal management is through heat recovery options, which allow for the efficient utilization of waste heat produced during electrochemical reactions. This not only improves the overall cell efficiency but also contributes to energy sustainability.

One primary method for PEMFCs' heat recovery involves the integration of heat exchangers. These devices can capture waste heat produced from the cell and then transfer it to other systems, such as water heating or space heating applications. According to Wang [86], the integration of heat exchangers could significantly enhance the overall system energy efficiency by utilizing the thermal energy that would otherwise be lost. This strategy is predominantly useful in applications in which both electricity and thermal energy are required, such as in CHP systems.

Another effective heat recovery strategy is using thermoelectric generators (TEGs). These devices transform temperature differences into electrical energy, allowing for waste heat recovery from PEMFC. As noted by Pourrahmani et al. [87], TEGs could be attached to a fuel cell to harness low-grade waste heat, thereby increasing the overall energy output. This method not only improves fuel-cell efficiency but also offers an additional source of power, which can be particularly advantageous in remote or off-grid applications.

Quantitatively, thermoelectric generators (TEGs) typically achieve thermal-to-electrical conversion efficiencies of 5–8% for low-grade waste heat (<200 °C) available from PEMFCs, and 12–15% for higher-grade heat (>500 °C) from SOFC exhaust streams. For example, in a PEMFC operating at ~70 °C with a 40–50 °C temperature gradient across the TEG module, each module can generate approximately 5–20 W of electrical power, depending on module design, thermal interface quality, and heat flux. These values underscore that, while TEGs cannot recover all waste heat, their ability to convert a fraction into useful electricity can improve system-level energy efficiency in both stationary and portable applications.

Furthermore, the design of the fuel-cell stack itself can facilitate heat recovery. For instance, optimizing the flow field configuration can enhance fuel cell heat transfer qualities. Research by Tolj et al. [88] indicates that specific flow field designs can improve heat distribution and reactants, thereby maximizing thermal energy utilization. This optimization could result in better thermal management and enhance the whole PEMFC performance. Four distinct geometries were created in Design Modeler, as shown in Figure 10. Model 1 serves as the baseline, calibrated to match an experimental PEM fuel cell, while Models 2, 3, and 4 represent various optimized configurations.

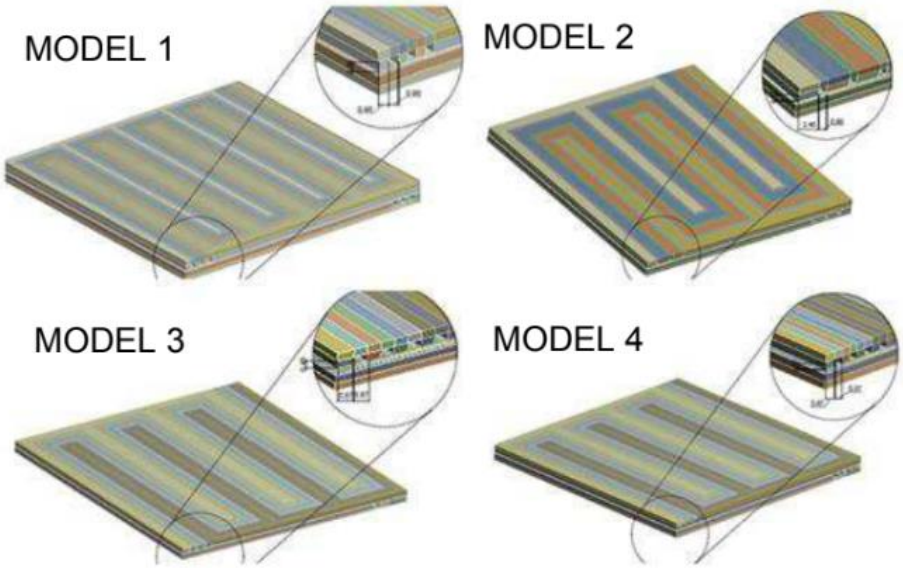


Figure 10. The computational domains for each of the models [89].

Additionally, the utilization of phase-change materials (PCMs) in conjunction with PEMFCs presents another avenue for heat recovery. PCMs can absorb excess heat during operation and release it when the temperature drops, helping maintain a stable thermal environment. Yan et al. [69] highlight the potential of PCMs to enhance thermal stability and improve the efficiency of PEMFCs by effectively managing the heat generated during electrochemical reactions. This approach can be particularly useful in applications with fluctuating power demands, as it allows for better temperature regulation.

In conclusion, the options of heat recovery for PEMFCs play a vital role in enhancing thermal management and improving overall system efficiency. The integration of heat exchangers, thermoelectric generators, optimized flow field designs, and phase-change materials can significantly contribute to the effective utilization of waste heat. As research continues to advance in this area, the development of innovative heat recovery strategies will be essential for the successful commercialization of PEMFC technologies in various applications. Table 3 summarizes the thermal management techniques in PEMFCs.

Table 3. Key techniques and strategies in PEMFCs thermal management.

Focus	Technique	Type	Description	Advantages
Thermal Management of PEMFCs	Active Cooling Systems	Active	Circulating coolant through channels to dissipate excess heat.	Prevents overheating, catalyst deactivation.
	Passive Cooling Systems	Passive	Using materials with high thermal conductivity and optimized designs to enhance natural heat dissipation.	Energy-efficient, improves reliability.
	Water Management Systems	Active	Humidifier bypass configurations to improve hydration and water distribution.	Enhances electrochemical performance and thermal balance.
	High-Temperature Proton Membranes	Advanced Materials	HT-PEMs maintain performance at elevated temperatures, improving thermal management.	Enhances thermal and water management, durable.
Active Cooling Methods	Liquid Cooling	Active	Water/glycol coolant circulates through stack channels.	Efficient heat removal, adaptable to load.
	Air Cooling	Active	Forced air dissipates heat from the fuel cell stack.	Compact, low energy consumption.
	PCMs	Active	Absorb/release heat during phase transitions to regulate temperature.	Stabilizes temperature during fluctuating loads.
Passive Cooling Methods	Phase-Change Materials (PCMs)	Passive	Stabilizes fuel-cell temperature by absorbing and releasing heat.	Reduces temperature fluctuations, improves stability.
	Nanofluids	Passive	Improves thermal conductivity in coolants, enhancing heat transfer.	Increases heat transfer efficiency, compact system.
	Natural Convection	Passive	Heat dissipation through natural airflow without mechanical assistance.	Energy-efficient, reduces power consumption.
Bipolar Plates	Bipolar Plate Design	Design Innovation	Tree-shaped fractal designs and serpentine channels for better heat dissipation and reactant flow.	Ensures uniform temperature, prevents overheating.
	Material Selection	Advanced Materials	Graphite and metal composites improve heat and electrical conductivity.	Enhances durability and performance.
	Surface Treatments	Design Innovation	Hydrophilic coatings enhance heat transfer and water management.	Improves thermal and water management.
Heat Recovery Options	Heat Exchangers	Heat Recovery	Transfers waste heat to other systems, such as space or water heating.	Improves overall energy efficiency in CHP systems.
	Thermoelectric Generators (TEGs)	Heat Recovery	Converts waste heat into electrical energy, enhancing energy output.	Harnesses low-grade waste heat, increases efficiency.
	Optimized Flow Field Designs	Design Innovation	Improves heat transfer by optimizing the flow of reactants and heat in the fuel cell stack.	Maximizes heat utilization, improves performance.
	PCMs for Heat Recovery	Heat Recovery	Absorbs excess heat and releases it during low-demand periods to maintain thermal balance.	Enhances efficiency and thermal stability.

2.3.2. Thermal Management of Solid-Oxide Fuel Cells (SOFCs)

Thermal management in SOFCs is a critical factor influencing their efficiency, performance, and longevity. SOFCs work at high temperatures, normally between 600 °C and 1000 °C, which allows for efficient electrochemical reactions but also presents challenges related to heat dissipation and thermal stress management. Effective thermal management strategies are essential to ensure optimal operating conditions and to avoid damage to the components of a fuel cell.

One of the primary methods for managing heat in SOFCs is through the design and integration of cooling systems. These systems can include active cooling methods, such as liquid cooling, where a coolant flows via channels next to the fuel cell stack to absorb surplus heat. According to Xu et al. [64], optimizing the cooling system design is crucial to maintain the temperature within an acceptable range, thus improving overall fuel-cell

efficiency. The cooling channels should be cautiously designed to guarantee uniform heat distribution and prevent localized overheating, which can lead to material degradation.

In addition to active cooling, passive thermal management techniques are also employed in SOFCs. These methods leverage the natural heat dissipation properties of materials and the fuel cell design components. For instance, the use of materials with high thermal conductivity can facilitate heat transfer away from cell-critical areas, helping keep a stable operating temperature. The fuel cell structural design, including electrodes and electrolyte arrangement, can significantly impact thermal management. Sai et al. [56] emphasize that the geometry of the interconnects and electrodes plays an important part in managing thermal stresses and providing efficient heat dissipation.

Heat recovery systems are another important aspect of thermal management in SOFCs. By capturing waste heat generated during operation, these systems can improve overall energy efficiency. For example, integrating heat exchangers can allow for the recovery of thermal energy for use in other processes, such as heating water or providing space heating. This not only improves the overall SOFC efficiency but also promotes energy conservation, as well as sustainability.

Furthermore, the use of advanced materials in the construction of SOFC components can enhance thermal management. Research into new materials, such as advanced ceramics and metal alloys, is ongoing to improve thermal stability and reduce thermal expansion mismatches between different components. These advancements can help mitigate thermal stresses and improve fuel-cell durability, ensuring reliable and durable operation [89].

In conclusion, effective SOFC thermal management is important for optimizing performance, enhancing efficiency, and prolonging the lifespan of the system. The integration of active and passive cooling methods, the careful design of fuel cell components, and the implementation of heat recovery systems are all critical strategies in managing heat within SOFCs. As research continues to advance in this field, the development of innovative thermal management solutions will be vital for the successful commercialization of SOFC technologies in various applications.

Heat Recovery Opportunities for Solid-Oxide Fuel Cells

SOFCs' heat recovery is essential for improving the overall efficiency of these systems, particularly in applications where both electricity and thermal energy are required. SOFCs operate at high temperatures, normally between 600 °C and 1000 °C, which allows for significant amounts of waste heat to be generated during operation. Effectively capturing and utilizing this waste heat can lead to improved system performance and reduced energy costs.

One of the most common methods for heat recovery in SOFCs is the integration of combined heat and power (CHP) systems [90–93]. In a CHP configuration, waste heat produced by the SOFC is recovered and utilized for the purpose of heating applications, including water heating or space heating. Wang et al. [24] highlight that this integration could considerably enhance the system efficiency, achieving total efficiencies of up to 90% when both electrical and thermal outputs are considered. Electrolyzer efficiency is highly temperature-dependent; for example, PEM electrolyzers show improved kinetics at moderate temperatures (50–80 °C) but may suffer from membrane dehydration or catalyst degradation above this range. When coupled with fuel cells in renewable-powered systems, thermal management must balance the heat recovery benefits for electrolyzer preheating with the risk of overheating, ensuring stable hydrogen production rates and system longevity. The high-quality heat produced by SOFCs is particularly suitable for such applications, making CHP systems a viable option for maximizing energy utilization.

Another effective heat recovery strategy involves the use of heat exchangers. These devices can capture waste heat coming from SOFC exhaust and then transfer it to other processes, such as preheating feedwater or supplying heat to absorption chillers for cooling applications. However, Müller et al. [94] do not directly address the implementation of heat exchangers in SOFC systems, focusing instead on waste heat recovery for dehydrogenation processes.

Additionally, the design of the SOFC system can be optimized to facilitate heat recovery. For instance, Duong et al. [95] discuss the potential of integrating thermal storage systems with SOFCs to capture surplus heat during low-demand periods and release such excess heat during peak demand. This integration allows for better management of thermal energy and can help balance the supply and demand for heat in various applications. By utilizing thermal storage, SOFC systems can operate more flexibly and efficiently, adapting to varying energy needs.

Moreover, the use of advanced materials in the construction of SOFC components can enhance heat recovery capabilities. For example, the development of materials with improved thermal conductivity can facilitate better heat transfer within the system, allowing for more effective capture and utilization of waste heat. In conclusion, SOFCs' heat recovery is vital for enhancing overall system efficiency and sustainability. The integration of CHP systems and optimization of system design contribute to effective heat recovery strategies. As R&D in this field are continuing to progress, the implementation of innovative heat recovery solutions will be vital for the successful commercialization of SOFCs in various applications.

Possibilities to Decrease the Operating Temperature of Solid-Oxide Fuel Cells

The reduction in SOFCs' working temperatures is a significant area of research aimed at improving efficiency, reducing costs, and enhancing the longevity of these systems. Traditional SOFCs work at high temperatures, normally between 600 °C and 1000 °C, which can result in the degradation of material and increased thermal stresses. Therefore, various strategies have been and are being developed to reduce the working temperature, primarily focusing on advanced materials and innovative designs.

One promising approach to lowering the working temperature of SOFCs is the development of Intermediate Temperature SOFCs (IT-SOFCs). These cells typically work at temperatures ranging from 400 °C to 800 °C, significantly lower than conventional SOFCs. According to Mazlan et al. [96], the use of doped barium cerate ($BaCeO_3$) and barium zirconate ($BaZrO_3$) as electrolytes in IT-SOFCs has shown high proton conductivity and chemical stability, causing them to be suitable candidates for lower-temperature applications. This shift not only reduces the thermal stresses experienced by the cell components but also allows for the use of less expensive materials that can withstand lower operating temperatures.

From a thermal management perspective, reducing the operating temperature from the conventional ~1000 °C to intermediate (600–800 °C) or low-temperature regimes (<600 °C) decreases the overall heat rejection requirement, thereby lowering the size and complexity of heat exchangers and auxiliary cooling systems. The smaller thermal gradients between the active layers and the balance-of-plant components also reduce thermal stresses, which mitigates the risk of mechanical failure during start-up and shut-down cycles. Furthermore, lower peak temperatures improve insulation efficiency and allow more compact system designs, enhancing overall reliability and operational stability in both stationary and mobile applications.

Another effective strategy involves the optimization of electrode materials and structures. Zamudio-García et al. [97] discuss the use of tunable electrode architectures, which

can enhance the electrochemical performance at lower temperatures. By adjusting the composition and microstructure of the electrodes, researchers can improve the reaction kinetics, thereby enabling efficient operation at reduced temperatures. This approach helps mitigate the sluggish electrochemical activity that often limits performance in traditional SOFCs.

Nanotechnology plays a critical part in decreasing the working temperatures of SOFCs. Lee et al. [98] highlight that the application of nanostructured materials can significantly enhance the performance of SOFCs while allowing for thinner electrolytes and smaller electrode particles. These advancements not only improve ionic conductivity but also reduce the thermal mass of the cell, facilitating quicker thermal responses and enabling operation at lower temperatures without sacrificing efficiency. Figure 11 depicts a thin-film SOFC, where the gas-tight electrolyte diameter columns increase with thickness. The white arrow designates the column diameter, which expands as the thickness gets bigger, resulting in residual compressive stress within the film.

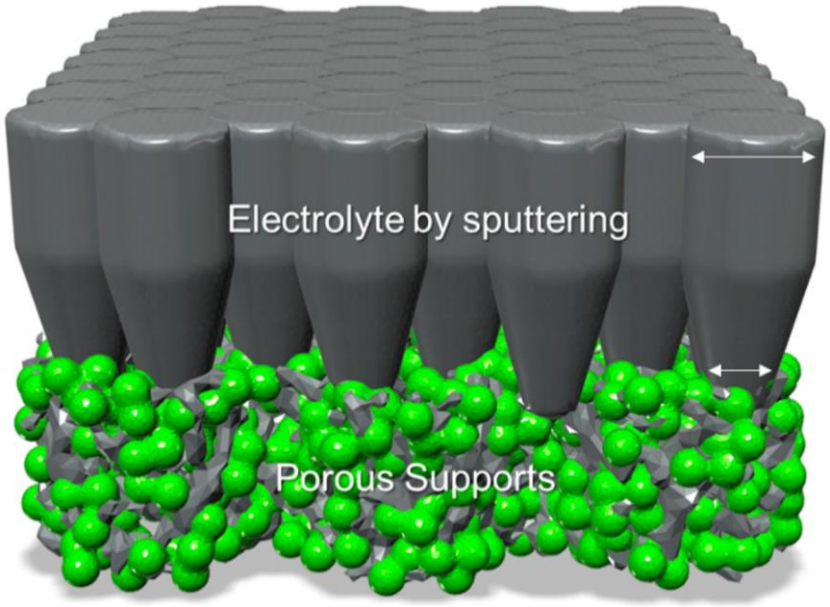


Figure 11. A thin-film SOFC where the gas-tight electrolyte diameter columns increase in thickness [98].

Furthermore, the integration of metal-supported SOFCs (MS-SOFCs) offers another pathway for reducing operating temperatures. These cells utilize a metal substrate that provides excellent thermal conductivity and mechanical strength, allowing for rapid thermal cycling and improved thermal management. Du et al. [99] note that the use of metal supports can enhance SOFCs' thermal shock resistance, allowing them to operate effectively under lower temperatures while maintaining performance. This innovation opens up new possibilities for applications in mobile and portable power applications.

Besides material advancements, the fuel cell design itself can be optimized to facilitate lower operating temperatures. For instance, the implementation of advanced thermal management strategies, such as improved heat recovery systems, can help maintain optimal thermal conditions within the fuel cell. By effectively capturing and utilizing waste heat, it is possible to lower the operational temperature while enhancing overall system efficiency.

In conclusion, lowering the SOFCs' working temperature is a multifaceted challenge that could be tackled through advanced materials' development, innovative electrode designs, and optimized system configurations. The transition to IT-SOFC, the application of nanotechnology, and the use of metal supports are all promising strategies that could

improve the performance and longevity of SOFCs while enabling their broader application in various energy systems. Table 4 summarizes SOFCs' thermal management.

Table 4. Main strategies and considerations for thermal management, heat recovery, and temperature reduction in SOFCs.

Focus	Key Points
SOFCs Thermal Management	• SOFCs work at high temperatures (600 °C to 1000 °C), requiring effective thermal management. • Active cooling systems (e.g., liquid cooling) help manage heat and prevent localized overheating. • Passive methods include using materials with high thermal conductivity and optimizing component design. • Heat recovery systems capture waste heat for increased efficiency.
Heat Recovery Options for SOFCs	• CHP systems recover waste heat for heating applications, improving overall efficiency. • Heat exchangers capture and transfer waste heat to other processes. • Thermal storage systems balance heat supply and demand. • Advanced materials with improved thermal conductivity enhance heat recovery capabilities.
Opportunities to Decrease the Operating Temperature of SOFCs	• Intermediate Temperature SOFC (IT-SOFCs) function at 400 °C to 800 °C, reducing thermal stresses. • Optimization of electrode materials and structures improves performance at lower temperatures. • Nanotechnology enhances ionic conductivity and reduces thermal mass. • Metal-supported SOFCs offer improved thermal management and shock resistance. • System design improvements, such as advanced thermal management and heat recovery, contribute to lower operational temperatures.

2.3.3. Machine Learning to Regulate Fuel Cells

Machine learning has emerged as a powerful tool for controlling the fuel-cell temperature, especially in PEMFCs and SOFCs. The capability to accurately monitor and manage temperature is critical for optimizing fuel cell performance, enhancing efficiency, and prolonging fuel-cell lifespans. Numerous machine learning approaches are being explored to develop advanced control strategies that can adapt to the dynamic operating conditions of fuel cells.

One prominent technique is the application of reinforcement learning (RL) for temperature control in fuel cells. He et al. [100] discuss how RL can be utilized to develop adaptive control strategies that respond to the fuel cell's nonlinear and time-varying behaviors. Unlike traditional control methods, which may struggle to meet the dynamic optimization requirements, RL algorithms can learn from real-time data and adjust control actions accordingly. This adaptability allows for more effective temperature regulation, ensuring that the fuel cell operates within optimal thermal limits.

Another significant application of machine learning in temperature control is through the use of deep learning algorithms. Ma [101] explores the implementation of model-free, multiple-input, multiple-output control (MFMIMOC) centered upon deep reinforcement learning (DRL) for managing the temperature of electrolysis cells from a proton-exchange membrane. By leveraging the capabilities of DRL, the system can accurately simulate complex features and dynamics, leading to improved temperature control in hybrid fuel cell vehicles. This approach highlights the potential of machine learning to enhance the precision of temperature management systems.

Moreover, support vector machines (SVMs), along with artificial neural networks (ANNs), have been utilized to predict and control temperature dynamics in fuel cells. Chatterjee presents an SVM for hybrid electric vehicles powered with fuel cells, emphasizing the effectiveness of data-driven control systems in optimizing temperature management [102]. These machine learning models could examine historical data and recognize patterns, allowing proactive adjustments to maintain optimal operating temperatures.

Additionally, the integration of machine learning with traditional control methods can further enhance temperature management. Louis [75] discusses the use of linear active disturbance rejection control in conjunction with machine learning techniques for enhancing the PEMFCs temperature control. By combining the strengths of both approaches, it is possible to achieve more robust and reliable temperature regulation, which is essential for maintaining the performance and durability of fuel cells.

In conclusion, machine learning techniques offer innovative solutions for controlling the temperature of fuel cells. The application of reinforcement learning, deep learning algorithms, and hybrid control strategies could enhance the reliability and efficiency of temperature management systems in PEMFCs and SOFCs. As research continues to advance in this field, the integration of machine learning into fuel-cell technology has an essential part to play in optimizing performance and ensuring the successful deployment of fuel cells in various applications.

2.3.4. Thermal Management of Other Types of Fuel Cells

Thermal management is a fuel-cell-crucial element, affecting the efficiency, performance, and longevity of numerous fuel cells. While PEMFCs and SOFCs are commonly discussed, other fuel-cell types, such as molten carbonate fuel cells (MCFCs) and phosphoric acid fuel cells (PAFCs), also require effective thermal management strategies to optimize their operation.

Molten carbonate fuel cells (MCFCs) work at elevated temperatures, normally between 600 °C and 700 °C. Such high operating temperatures enable the use of carbonate electrolytes, which can facilitate electrochemical reactions. However, managing the thermal environment is essential to prevent overheating and ensure consistent performance. According to Muck [103], maintaining a uniform distribution of temperature in the MCFC is important, as temperature gradients could result in thermal stresses and the degradation of fuel cell components. Effective thermal management systems, such as heat exchangers and thermal storage solutions, can help regulate the temperature and improve overall efficiency.

Phosphoric acid fuel cells (PAFCs) also work at elevated temperatures, generally around 150 °C to 200 °C. The thermal management of PAFCs is vital for maintaining the optimal operating temperature, as insufficient heat can lead to reduced reaction rates and overall efficiency. Muck [103] emphasizes the importance of integrating advanced thermal management techniques, such as fiber sensing for spatially resolved temperature measurement, to monitor and control the temperature within PAFC systems. This real-time monitoring allows for proactive adjustments to the cooling systems, ensuring that the fuel cells work in the range of their optimal thermal interval.

Protonic ceramic fuel cells (PCFCs) are also gaining attention for their potential to operate at intermediate temperatures (400 °C to 800 °C). Shimada et al. [104] discuss the development of bi-layered structures in PCFCs, which can enhance thermal stability and performance. The ability to operate at lower temperatures compared to SOFCs while maintaining high efficiency is a significant advantage, and effective thermal management strategies are essential to optimize their performance.

Hybrid fuel cell systems, which combine different types of fuel cells, also present unique thermal management challenges. For example, integrating PEMFCs with SOFCs or

other energy systems requires careful consideration of the thermal interactions between the components. Anselma et al. [71] propose a dynamic programming approach for optimizing hybrid fuel-cell thermal management, making sure that each component operates within its optimal temperature range. This integrated method could enhance the overall fuel cell efficiency as well as its reliability.

In conclusion, effective thermal management is critical for the performance and durability of various types of fuel cells, such as MCFCs, PAFCs, and PCFCs. The implementation of advanced thermal management methods, such as real-time monitoring, heat exchangers, and hybrid system optimization, can considerably improve the efficiency and reliability of such systems. As research continues to advance in this field, innovative thermal management solutions will be essential for the successful commercialization of diverse fuel-cell technologies. Table 5 summarizes the key points from Sections 2.3.3 and 2.3.4 regarding machine learning techniques for temperature control of fuel cells, along with the thermal management of various fuel-cell types:

Table 5. Main strategies, considerations, and research directions in using machine learning for temperature control and in the thermal management of various fuel-cell types.

Focus	Key Points
Machine Learning Methods to Regulate Fuel Cells Temperature	• Machine learning enhances temperature control in PEMFCs and SOFCs. • Reinforcement learning (RL) adapts to dynamic conditions for better temperature regulation. • Deep learning algorithms improve control accuracy in hybrid fuel cell vehicles. • SVM and ANN predict and manage temperature dynamics. • Integrating machine learning with traditional methods enhances robustness in temperature regulation.
Other Types of Fuel Cells: Thermal Management of	• Effective thermal management is crucial for various fuel-cell types: MCFCs, PAFCs, and PCFCs. • **MCFCs:** Function at 600 °C to 700 °C; uniform temperature distribution prevents thermal stresses. • **PAFCs:** Work at 150 °C to 200 °C; advanced techniques like fiber sensing enable real-time temperature control. • **PCFCs:** Work at 400 °C to 800 °C; bi-layered structures improve thermal stability. • **Hybrid Fuel Cell Systems:** Combining different types requires optimized thermal management to enhance efficiency.

3. Conclusions: Fuel-Cell Thermal Management

In conclusion, effective thermal management is an important component of ensuring optimal fuel cell performance, reliability, and the lifespan of various fuel-cell technologies, specifically PEMFCs and SOFCs. The complexity of heat generation within fuel cells, driven primarily by electrochemical reactions, necessitates a comprehensive approach to thermal management that addresses both heat generation and dissipation.

For PEMFCs, effective thermal strategies are critical in preventing overheating, which could result in proton-exchange membrane degradation. This degradation not only reduces fuel cell efficiency but also impacts its whole lifespan. In PEMFC systems, design and flow field optimization play important roles in distributing reactants and removing excess heat. The implementation of active cooling techniques, like liquid cooling and phase-change materials, has been shown to be effective in regulating temperature and enhancing fuel cell operation reliability. Moreover, the use of advanced materials that enhance

thermal conductivity is crucial for improving heat dissipation, thereby maintaining optimal operating conditions.

Conversely, SOFCs, which work at significantly higher temperatures (600 °C to 1000 °C), face unique thermal management challenges. The high operating temperatures enhance ionic conductivity, which is essential for efficient electrochemical reactions; however, they also introduce the risk of thermal stresses that can lead to material degradation. To address these challenges, effective thermal management strategies must be implemented to maintain uniform temperature distribution within the cells. Advanced cooling techniques, such as liquid cooling systems and heat exchangers, can capture and manage waste heat effectively, thereby enhancing overall system efficiency.

Furthermore, the heat recovery systems' integration in both PEMFCs and SOFCs has the potential to significantly improve energy utilization by capturing waste heat to be used in other applications, for example, space heating or power generation. This not only improves the overall efficiency of fuel cell systems but also promotes the sustainability of energy use in various applications.

In addition to traditional thermal management techniques, the incorporation of machine learning approaches presents new opportunities for improving temperature control and thermal management in fuel cells. Algorithms of machine learning, including reinforcement learning and deep learning, can adapt to changing operating conditions, providing real-time adjustments to temperature management strategies. These advancements offer the potential for more robust and reliable fuel cell operation, ultimately improving performance and extending the lifespan of the systems.

Despite the promising advancements in thermal management strategies for fuel cells, several challenges remain that warrant further attention. The integration of advanced cooling methods and hybrid systems often increases system complexity, which can lead to higher installation and maintenance costs. Moreover, the scalability of these approaches from laboratory prototypes to large-scale commercial applications is not straightforward, as performance benefits observed at small scales may diminish under real-world conditions. Economic feasibility remains a critical hurdle, especially for systems incorporating novel materials or complex hybrid configurations.

Using estimation derived from reported cost ranges for hybrid supercapacitor–battery systems and advanced cooling technologies in comparable renewable–integrated fuel cell applications, incorporating these components can increase capital expenditure by approximately 8–15%. This estimate reflects the additional costs of power electronics, control integration, and specialized cooling hardware. However, these investments can yield lifecycle benefits—such as extended component life, reduced maintenance frequency, and improved operational efficiency—that offset the initial cost within a 10–15-year operational period. Furthermore, the integration of heat recovery in combined heat and power (CHP) configurations can enhance return on investment by monetizing thermal output in addition to electricity generation.

Scalability considerations include thermal uniformity in large fuel cell arrays, the modularity of hybrid storage units, and integration with grid or microgrid control systems. Ensuring efficient thermal management at scale may require distributed cooling loops, advanced heat exchangers, and control algorithms capable of coordinating multiple hybrid storage modules. Economic scaling can be supported with modular designs that share common components and standardized interfaces. Addressing these limitations through cost-effective designs, simplified control strategies, and scalable solutions will be crucial for the broader adoption and commercialization of fuel-cell technologies.

Recent reviews collectively show that effective fuel-cell commercialization depends on advances in thermal management, environmental adaptability, and integrated control

strategies across both PEMFCs and SOFCs [105–109]. The ongoing research and development in fuel-cell thermal management will be critical for tackling challenges pertaining to heat generation and dissipation. By continuously optimizing thermal management strategies, the performance, efficiency, and lifespan of fuel-cell technologies can be enhanced, paving the way for their extensive adoption in numerous applications, from automotive to stationary power applications. As the energy landscape evolves toward cleaner and more sustainable solutions, the significance of effective fuel-cell thermal management will only grow, making it a key area of focus for future research and development efforts.

4. Future Research Direction: Fuel-Cell Thermal Management

The future of thermal management in fuel cells, particularly for PEMFCs and SOFCs, is ready to evolve significantly, driven by advancements in technology, materials, and computational techniques. As fuel-cell technologies become increasingly integral to the transition to clean energy systems, a concerted effort is needed to explore and refine thermal management strategies. Several key research directions can be identified to improve fuel-cell performance and reliability. Figure 12 shows the summary illustration of future research directions in fuel-cell thermal management.

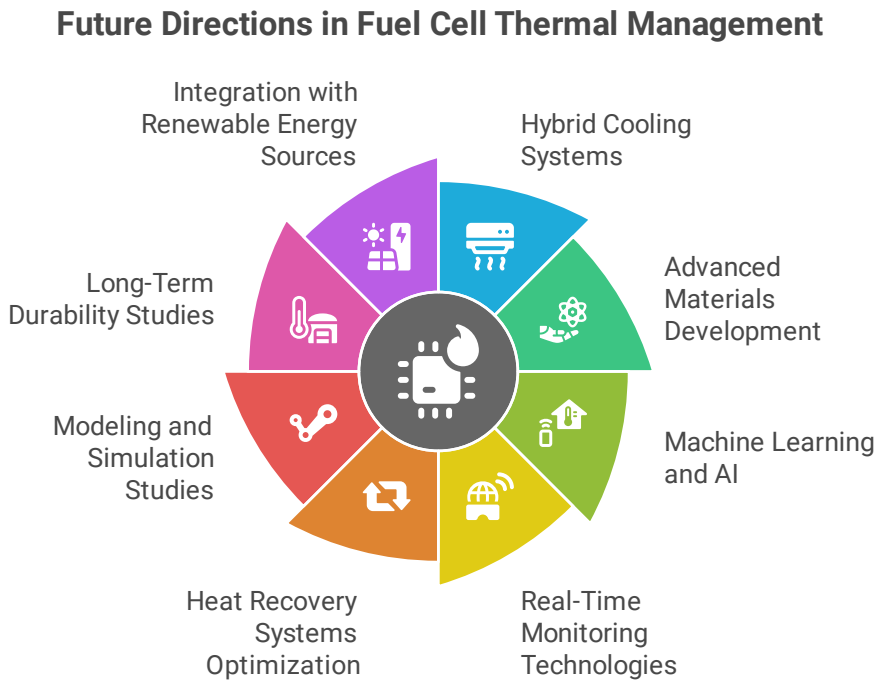


Figure 12. Future research direction in fuel-cell thermal management.

1. **Hybrid Cooling Systems**

One promising avenue for future research is the development of hybrid cooling systems that integrate both active and passive thermal management methods. Active cooling systems, such as liquid cooling, provide immediate temperature regulation, while passive systems leverage materials with high thermal conductivity and optimized designs to enhance natural heat dissipation. The synergistic combination of these approaches could lead to more efficient and reliable thermal management solutions. Research should focus on optimizing the design and control of these hybrid systems to improve their performance under varying operational conditions.

2. **Advanced Materials' Development**

The search for advanced materials that enhance thermal conductivity and stability is another critical area for research. The use of nanomaterials, composites, and innovative coatings can significantly improve heat transfer efficiency and reduce thermal stresses in fuel cells. Investigating the properties and applications of such materials in the context of fuel-cell thermal management will be essential for developing more effective systems. This includes exploring materials that can withstand the extreme conditions of SOFCs while maintaining high ionic conductivity.

3. **Machine Learning and Artificial Intelligence**

The integration of machine learning and artificial intelligence in thermal management represents a transformative opportunity. Future research should aim to leverage these technologies for the real-time monitoring and adaptive control of temperature in fuel cell systems. Machine learning algorithms can analyze vast amounts of data from fuel cell operations, identifying patterns and predicting performance under various conditions. By implementing adaptive control strategies based on this analysis, researchers can optimize thermal management systems to respond dynamically to changes in operating conditions, thus enhancing overall efficiency and reliability.

4. **Real-Time Monitoring Technologies**

The development of advanced sensing and monitoring technologies will play a vital role in improving thermal management. Integrating fiber-optic sensors, thermocouples, and infrared imaging techniques can facilitate real-time temperature measurement and distribution analysis within fuel cell systems. This data will be crucial to understanding thermal behaviors, identifying hotspots, and optimizing cooling strategies. Research should focus on developing compact and reliable sensing solutions that can be easily integrated into existing fuel cell designs.

5. **Heat Recovery Systems Optimization**

Enhancing heat recovery systems is essential for improving the overall efficiency of fuel-cell technologies. Future research should investigate innovative approaches to capture and utilize waste heat more effectively. This includes exploring advanced heat exchangers, thermal storage solutions, and integration with other energy systems. By optimizing the design and operation of heat recovery systems, researchers can significantly increase the overall energy conversion efficiency of fuel cells, making them more competitive with traditional energy sources.

6. **Modeling and Simulation Studies**

Advanced modeling and simulation studies will be critical for understanding the complex interactions within fuel cell systems. Future research should focus on developing comprehensive computational models that can accurately predict thermal behavior, efficiency, and performance under various conditions. These models will not only aid in the design of more effective thermal management strategies but also facilitate the optimization of fuel-cell systems as a whole. Collaborative efforts between researchers in computational fluid dynamics, materials science, and fuel-cell technology will be essential to achieve these goals.

7. **Long-Term Durability Studies**

Investigating the long-term durability of thermal management systems in fuel cells is crucial for ensuring reliable operation. Research should focus on understanding the effects of thermal cycling, material degradation, and operational stresses on fuel-cell performance over extended periods. This knowledge will inform the design of more robust thermal management solutions that can withstand the rigors of real-world applications. Long-term

testing and evaluation will be necessary to assess the effectiveness of newly developed strategies and materials.

8. Integration with Renewable Energy Sources

As fuel cells are increasingly utilized in renewable energy applications, research should explore the integration of thermal management systems with renewable energy sources such as solar and wind. Understanding how these systems interact and the potential for synergistic benefits will be essential for developing efficient and sustainable energy solutions. This includes exploring the use of fuel cells in hybrid systems that combine multiple energy sources and storage solutions.

All in all, the future of thermal management in fuel cells presents numerous research opportunities that can considerably improve the performance, efficiency, and durability of fuel-cell systems. By exploring hybrid cooling systems, advanced materials, machine learning applications, real-time monitoring technologies, heat recovery optimization, modeling studies, durability assessments, renewable energy integration, and standardization efforts, researchers can pave the way for the successful commercialization of fuel-cell technologies. As the requirement for renewable and sustainable energy solutions is continuing to grow, these research directions will play a crucial part in advancing fuel-cell technology, as well as its applications in various sectors.

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