Structural Design and Strategy Optimization of PEMFC in Thermal Management

Tao Zhou*, Ziqi Ma, Jiaxing Gao

School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, China, 212013

* Corresponding Author Email: 2838937434@qq.com

Abstract. Due to growing energy and environmental issues, clean energy technology has gained recognition around the world. Because of its great energy transfer efficiency, outstanding power density, low operational temperatures, and environmental protection, PEMFC has been employed extensively in a variety of fields. But the thermal management of PEMFC has been a great challenge limiting its commercialization. Ineffective heat management strategies can shorten the fuel cell battery's lifespan in addition to affecting its performance. Therefore, this study provides an overview of how fuel cell bipolar plate structure and thermal management techniques have improved fuel cell performance. The results show that the tree-shaped fractal fuel cell bipolar plate, novel tapered dual serpentine channel and so on can enhance the heat dissipation effect of the bipolar plate and the temperature uniformity of the MEA, and form a uniform temperature distribution and pressure. Process strategies such as the new thermal management system with a thermal peak regulator can efficiently regulate the peak temperature and the average temperature of the fuel cell system to improve its starting performance. Most importantly, this research can help to alleviate the energy tension and reduce the environmental pressure.

Keywords: PEMFC, Thermal Management, Structural Design, Strategy Optimization.

1. Introduction

Energy and environmental problems are becoming increasingly serious. Then, clean energy technology has received attention around the world, and the proton exchange membrane fuel cell (PEMFC) can be considered the ultimate choice for automobile travel due to its lower tail gas emissions, high energy conversion efficiency, and low operating temperatures..

Traditional fuel cells can be grouped into PEMFC, Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC) and so on. And PEMFC is widely studied for its advantages of fast starting speed, low operating temperature and small size. The PEMFC works on the basis of the fuel (hydrogen H2) entering the anode and dissolving into positively charged protons (H+) and negatively charged electrons (e-). While electrons go to the cathode via the load and the external circuit, protons go there via the proton exchange membrane while being influenced by the anode catalyst. In parallel, oxygen diffuses to the cathode catalyst's surface, where it undergoes an oxygen reduction process with protons, electrons, and water under the influence of the cathode catalyst.

However, the thermal management of combustion PEMFC has been a great challenge to limit its commercialization. Abnormal temperature of PEMFC can greatly reduce the normal working performance of PEMFC or even damage the related components. Heat transfer is closely related to the electrochemical reaction, gas-liquid two-phase flow, charge transfer, and mass transfer processes inside PEMFC; alterations in temperature impact each of these processes. The performance of PEMFC is significantly impacted by its temperature. Since PEMFCs typically have an efficiency of 40% to 60%, 40% to 60% of the energy produced is converted to heat. A reliable and efficient thermal management system structure and matching control technique are necessary to maintain the PEMFC's internal temperature homogeneity.

Therefore, this study explores and summarizes the ways in which structural design and process optimization can enhance PEMFC's thermal management performance. The results show that the concave-convex dual flow channel bipolar plates, tree-shaped fractal fuel cell bipolar plate and novel tapered dual serpentine channel can enhance the heat dissipation effect of the bipolar plate and the

temperature uniformity of the MEA and form a uniform temperature distribution and pressure. The new thermal management system with a thermal peak regulator, and other process strategies can effectively regulate the peak and average temperatures of the fuel cell system and improve its startup performance, durability and reliability of fuel cell related components, and alleviates energy constraints, exhaust emissions and environmental pollution.

2. Structural design

The structural design of metal bipolar plates is one of the effective ways to solve its thermal uniformity distribution, pressure drop distribution and other problems. The output power and service life of the proton exchange membrane fuel cell (PEMFC) are significantly influenced by the bipolar plate, which is its central component. Because of its low cost, easy electrical and thermal conductivity, and high material strength, metal bipolar plates have become a key mainstream in fuel cell bipolar plate design and application. Nonetheless, the output power and thermal uniformity of fuel cells are significantly impacted by the structure of metal bipolar plates.

Xianxian Yu [1] et al. designed an air-cooled PEMFC stack with a concave-convex dual channel metal (BPP) structure as shown in Fig.1(a-c). The results of examining the airflow and heat transfer mechanisms of each concave-convex double-runner construction indicate that adding a fan prior to the radiator or lengthening the BPP's two sides can both improve heat dissipation. In the other hand, it is found that the air velocity increases to 1.5 m/s at the matching current intensity in the first BPP. The concave double-runner BPP's MEA temperature uniformity can be more than 0.9. The cathode can be extended on both sides to increase the heat dissipation effect. Reducing the cathode's flow channel can result in a more consistent temperature distribution, and the temperature distribution cloud diagrams are shown in Fig.1(e-f). Yuqi Han [2] et al. designed a new heat pipe bipolar plate (HPBP) with a cooling system as shown in Fig.1(g). The reactor volume is decreased with this bipolar plate (HPBP), while the heat load capacity is kept constant. It is possible to drastically lower the maximum temperature in the central plane of the cathode catalyst layer while maintaining a more uniform temperature distribution. Its temperature distribution cloud diagram of the pole plate at an operating voltage of 0.5 V is displayed in Fig.1(h) as a result of the enhanced thermal performance. Additionally, when compared to traditional liquid cooling, the PEMFC cooling system with HPBP has a much superior weight and volumetric power density. Huawei Chang [3] et al. designed an ultra-thin metallic bipolar plate fuel cell stack with an open cathode air cooling system. The water-cooled stack's thermal distribution differed from the open cathode air-cooled stack's, according to experimental testing. The findings indicate a "parabolic" distribution for the stack's maximum and average temperatures as well as the highest temperature of each individual cell at the cathode inlet side. Increasing the airflow rate in the air-cooled stack can effectively improve the temperature inhomogeneity of the battery pack at high current densities. When the fan's maximum pulse width modulation (PWM) duty cycle is 70% and the current density is 500 mA/cm^2, there can be a 19.7 degree and an 8.4 degree temperature difference between two separate cells and inside one of them. Tabbi Wilberforce [4] et al. designed conical flow channels with three different structures. The findings showed that the flow plate geometry's design has a significant impact on the pressure, velocity, and even distribution of reactive materials inside the cell. When comparing the TDMC flow channel to the TDSC and the TPCD flow channels, the current flow density rose by 2.163% and 1.421%, respectively. Additionally, compared to TPCD and TDSC flow channels, the TDMC channel geometry's smaller pressure drop enhances the cell's pressure, pumping power, and uniform temperature distribution.

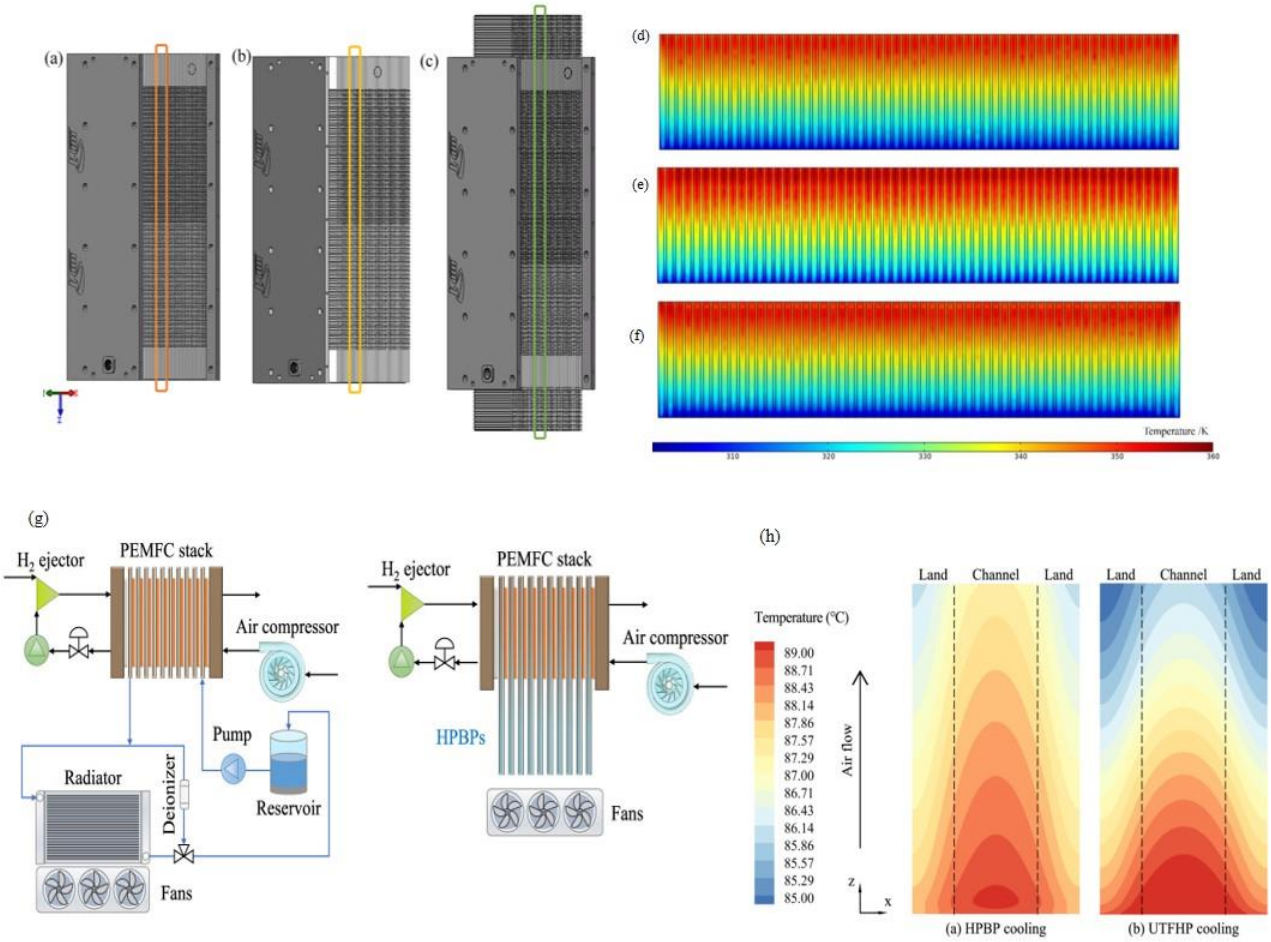


Figure 1. Structure of the three-type metallic bipolar plate air-cooled PEMFC stack. (a) BPP A; (b) BPP B; (c) BPP C; The distribution of temperatures on the surface of MEA; (d) plate A; (e) plate B; (f) plate C; (g) Schematics of PEMFC systems with liquid cooling and HPBP cooling; (h) Temperature profiles at a V_{cell} of 0.5 V in the CCL's middle plane

Yan [5] et al. designed two varieties of flow fields featuring channel geometry in three dimensions. One flow field is composed of waved channels that produce a localized oxygen convective flux from the catalyst layer to the flow channel/diffusion layer interface, hence improving the oxygen supply. Its structure is shown in Fig 2. (a). The other is a ladder flow channel Its structure is shown in Fig 2. (b). The findings showed that the channel's three-dimensional design enhances flow velocity at the channel's outlet by roughly 120% at high current densities, which contributes to better water drainage and can greatly enhance the cell's performance.

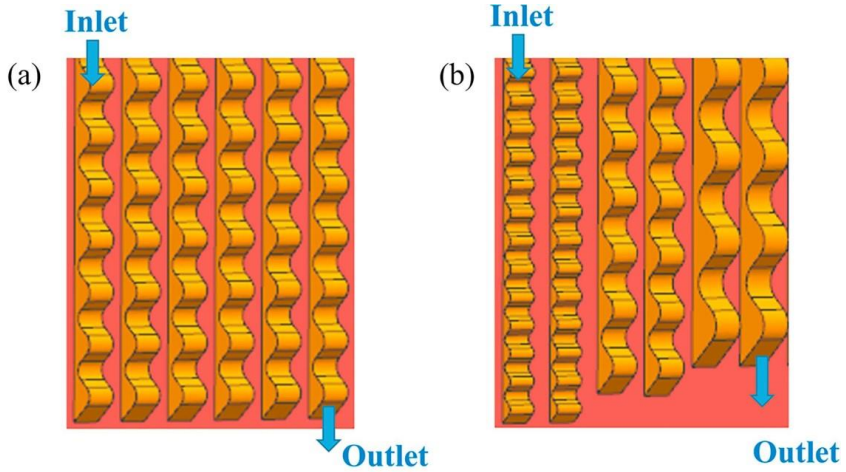


Figure 2. (a) 3D wave-shaped channel flow field; (b) 3D flow gradient with wave-shaped channels

Cho [6] et al. formed a capillary hole by laser machining at the parallel flow channel ribs. The capillary effect was utilized to draw water into the water channel by passing it through the capillary holes. It was found that the parallel flow channel with capillary holes can suck water into the water channel, which makes the gas channel not be blocked by water. Consequently, the fuel cell's performance is substantially improved. Xi Chen [7] et al. proposed a novel tree-shaped fractal fuel cell bipolar plate cooling flow field by studying the microstructure of the blade. It is demonstrated that, when fractal cooling flow fields are of varying dimensions, the tree-shaped fractal cooling flow field exhibits a more uniform temperature distribution and superior cooling impact when compared with the parallel cooling flow field. The maximum temperature and temperature difference of the flow field at different Reynolds numbers are shown in Fig 3.(a-b). There is a 1.02 decrease in the temperature uniformity index and a 2.9 K decrease in the maximum temperature.

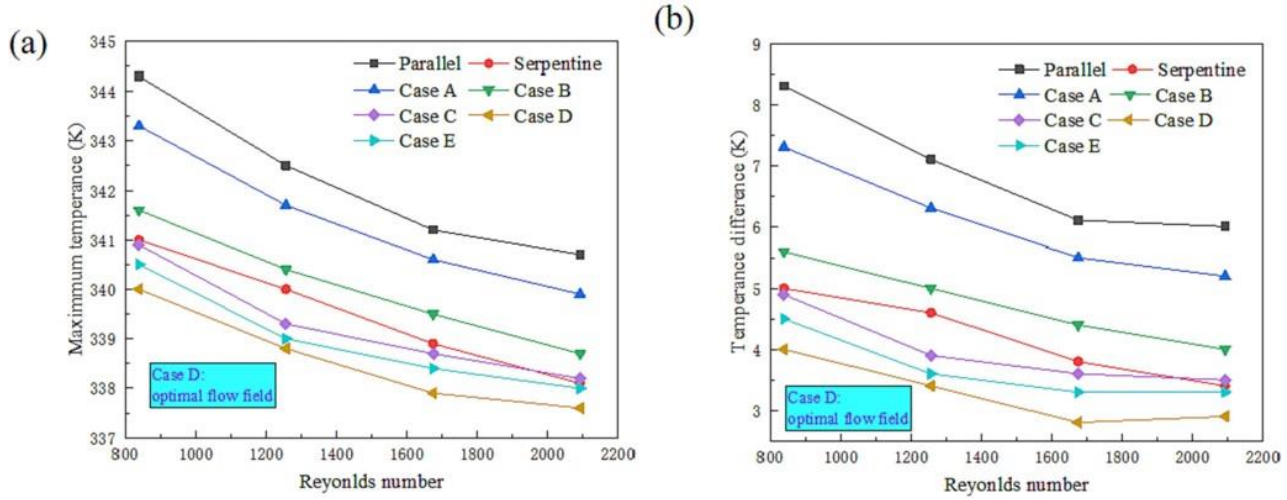


Figure 3. Features of temperature distribution with varying Reynolds numbers of the PEM's cathode side. (a) maximum temperature; (b) temperature differential

Chengyuan Gong [8] et al. designed a novel rotary L-type main flow field. Its thermal and flow characteristics were investigated. The findings demonstrate that enhancing temperature uniformity can effectively reduce localized hot patches and thermal strains. The improvement in the temperature uniformity index was at least 40%. Compared to the same-flow and staggered-flow configurations, the rotating L-shaped flow field's maximum temperature gradient (TG) is 20% smaller. Comparing the average TG to the countercurrent configuration, the difference is 32.72%. And Fig 4.(a) depicts its temperature dispersion. The TG is shown in Fig 4.(b). The rotating L-type provides the best thermal properties while having a less uniform current density distribution than the co-current field. This suggests that by maximizing the fluid's structure, the inferior thermal properties brought about by the inhomogeneous current density distribution can be resolved. Shen [9] et al. improved the performance of PEMFC by adding rectangular blockage in the gas channel. The results show that the output voltage is enhanced with the increase of rectangular blockage. This fuel cell operates at an electrical density of 2 A·cm-2, which is about 0.02 V higher than that of a fuel cell with a conventional straight-through channel. The output voltage shows essentially little improvement at low current densities. Finally, the polarization curves are almost the same under all conditions when the current density is less than 1 A·cm-2. As the current density increases, the performance improvement gets bigger and more obvious.

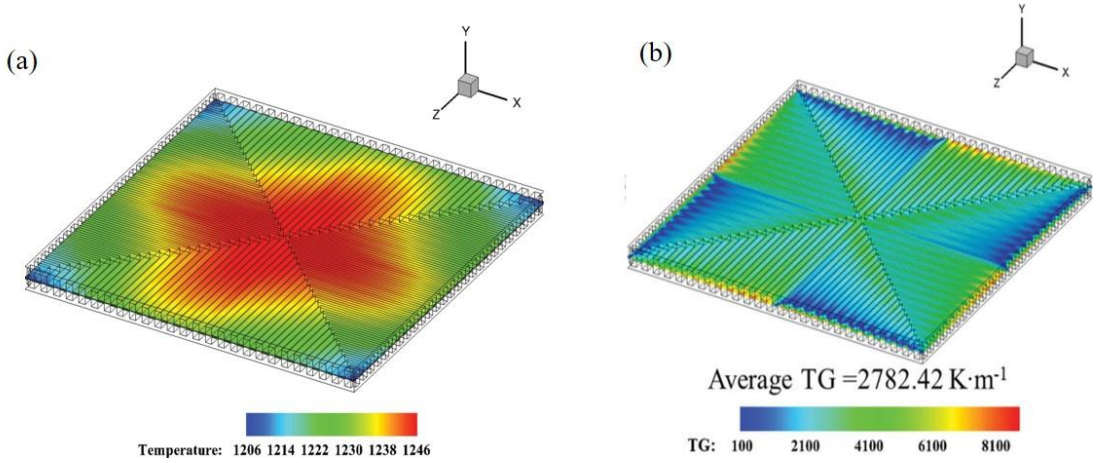


Figure 4. (a) Temperature distribution of the rotary-L type flow field; (b) Temperature gradient of the rotary-L type flow field

Therefore, the performance of the PEMFC can be enhanced to varying degrees by waveform, serpentine, and some cooling bipolar plate designs, particularly when it comes to enhancing the flow channel's uniformity of temperature distribution. For instance, Xianxian Yu et al.'s concave-convex dual flow channel structure improved the bipolar plate's MEA temperature uniformity and heat dissipation effect. The conical flow channel designed by Tabbi Wilberforce et al. improved the pumping power, uniform temperature distribution and pressure of the cell. However, high temperatures, hot spots, high pressure losses and auxiliary power generated by cooling pumps remain to be addressed.

3. Strategy optimization

The output performance, safety, dependability, and service life of the PEMFC electric pile depend on the design of an efficient thermal management system that keeps the electric pile within the proper operating temperature range, integrating and coordinating the vehicle's and the environment's heat control, and making sure that all components are in the ideal operating temperature range. Therefore, it is crucial to study and explore the possibility and feasibility of thermal management strategies for PEMFC stacks.

Jinyong Lei [10] et al. designed a multi-stack combined heat and power (CHP) system using a battery hybrid system (SBH) and SOFC. Regarding this multi-stack system, a dual-adaptive control scheme is suggested. In the end, the system's strong and quick dynamic response qualities contribute to its longer operational life. The investigation focuses on the effects of temperature on the multi-stack SBH-CHP system and its dynamic properties. The results show that the multi-stack system can stabilize in 80 seconds. Jian Guo [11] et al. proposed a novel thermal management system using a thermal peak regulator based on the developed thermal model. The system schematic is shown in Fig 5.(a). The findings demonstrate that, depending on the amount of phase change material inserted into the thermal peak regulator, this innovative thermal management system can either completely prevent or significantly reduce the fuel cell pack's thermal runaway. The global Harmonized Light Duty Test Cycle and the standardized New European Driving Cycle both have the potential to reduce the thermal runaway durations of 135 and 250 seconds to 0 and 105 seconds, respectively. The latter's maximum temperature might drop from 89 degrees to 83 degrees throughout the summer. Qiao Yang [12] et al. proposed an integrated thermal management system model, whose system schematic is shown in Fig 5.(b). Through testing, it was discovered that the critical temperatures of the subsystems could be fairly regulated and that the thermal power produced by the fuel cell was more than twice as high when the battery was charging. Furthermore, the radiator fan has little effect because the condenser and radiator are connected in series.

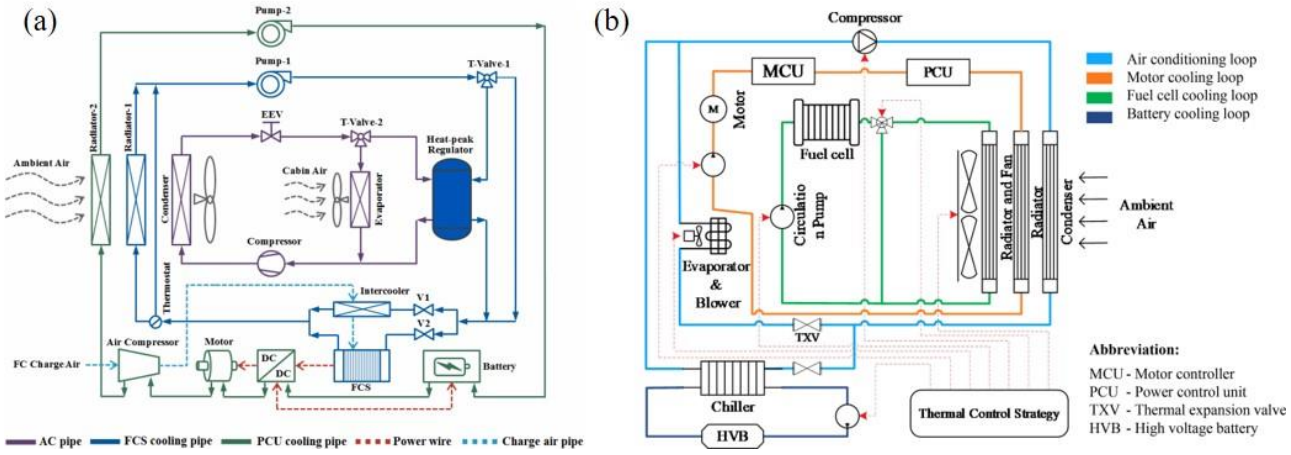


Figure 5. (a) The innovative method for integrated thermal control; (b) Thermal management system for automobiles

Montaner [13] et al. proposed two thermal management strategies for cold start of PEMFC systems, active and passive thermal management. A large number of tests on these two strategies were conducted from 0 ℃ to 30 ℃. The results show that the passive strategy is more effective for -30 ℃ cold start. Cold starts at -25 to -15 degrees Celsius are better with an active thermal management strategy. Zhiyang Liu [14] et al. proposed a model-based decoupling control method. It is possible to simultaneously regulate the PEMFC stack's cooling water temperatures at the intake and outlet. Experiments demonstrate that the suggested decoupling controller can precisely manage the cooling water's input and output temperatures online for the PEMFC stack. There is less than 0.2 °C of temperature inaccuracy even under dynamic current loading scenarios. Aida Farsi [15] et al. proposed an air-cooled cell thermal management system that removes air from the environment, preheats it by cooling the cell. The cooling air maintained the temperature of the lithium-ion cell at roughly 25 °C by removing an average of 3.5 W of heat generation per unit area of the cell.

In summary, proper temperature enhancement can increase the fuel cell's operating efficiency; however, overheating can severely worsen the membrane's and catalyst's degradation, which will cause the PEMFC to irreversibly lose performance. Along with dehydrating the membrane, it can also make it less proton-conductive. Therefore, research into the fuel cell's temperature control system is essential to improving the performance of PEMFC.

4. Conclusion

PEMFC are widely used because of its great energy transfer efficiency, outstanding power density, low operational temperatures and other advantages. However, temperature has a significant impact on PEMFC performance; therefore, efficient thermal management technologies can both increase fuel cell efficiency and prolong fuel cell life. As a result, this study provides an overview of how fuel cell bipolar plate design and process heat control techniques have improved fuel cell performance. It is shown that the concave-convex dual channel metal structure, tree-shaped fractal bipolar plate flow channel structure and conical flow channel structure can enhance the heat dissipation effect and MEA temperature uniformity of the bipolar plate, and form a uniform temperature distribution and pressure. Strategies such as multilayer SOFC cell hybrid SBH system and new thermal management system with thermal peak regulator can effectively regulate the peak and average temperatures of the fuel cell system and improve its startup performance. It is crucial for raising the bar for PEMFC application technology, reducing emissions and energy consumption, and producing low-carbon products that safeguard the environment.

References

[1] X. Yu, Z. Tu, S.H. Chan, Thermal management on an air-cooled PEMFC stack with concave-convex dual flow channel bipolar plates, International Journal of Hydrogen Energy (2023).

[2] Y. Han, W. Zhuge, J. Peng, Y. Qian, P. Ming, Y. Zhang, A novel heat pipe bipolar plate for proton exchange membrane fuel cells, Energy Conversion and Management 284 (2023).

[3] H. Chang, F. Cai, X. Yu, C. Duan, S.H. Chan, Z. Tu, Experimental study on the thermal management of an open-cathode air-cooled proton exchange membrane fuel cell stack with ultra-thin metal bipolar plates, Energy 263 (2023).

[4] T. Wilberforce, A. Amiri, Comparative study on bipolar plate geometry designs on the performance of proton exchange membrane fuel cells, Fuel 346 (2023).

[5] X. Yan, C. Guan, Y. Zhang, K. Jiang, G. Wei, X. Cheng, S. Shen, J. Zhang, Flow field design with 3D geometry for proton exchange membrane fuel cells, Applied Thermal Engineering 147 (2019) 1107-1114.

[6] J.I.S. Cho, T.P. Neville, P. Trogadas, J. Bailey, P. Shearing, D.J.L. Brett, M.O. Coppens, Capillaries for water management in polymer electrolyte membrane fuel cells, International Journal of Hydrogen Energy 43(48) (2018) 21949-21958.

[7] X. Chen, F. Chai, S. Hu, J. Tan, L. Luo, H. Xie, Z. Wan, Z. Qu, Design of PEMFC bipolar plate cooling flow field based on fractal theory, Energy Conversion and Management: X 20 (2023).

[8] C. Gong, Z. Tu, S. Hwa Chan, A novel flow field design with flow re-distribution for advanced thermal management in Solid oxide fuel cell, Applied Energy 331 (2023).

[9] J. Shen, L. Zeng, Z. Liu, W. Liu, Performance investigation of PEMFC with rectangle blockages in Gas Channel based on field synergy principle, Heat and Mass Transfer 55(3) (2018) 811-822.

[10] J. Lei, X. Huang, J. Pan, Y. Yang, F. Yu, Z. Liao, D. Ou, Y. Tang, Y. Yang, Dual-adaptive energy management strategy design for fast start-up and thermal balance control of multi-stack solid oxide fuel cell combined heat and power system, Energy Conversion and Management: X 20 (2023).

[11] J. Guo, Z. Li, L. Wei, J. Fangming, A novel thermal management system with a heat-peak regulator for fuel cell vehicles, Journal of Cleaner Production 414 (2023).

[12] Q. Yang, T. Zeng, C. Zhang, W. Zhou, L. Xu, J. Zhou, P. Jiang, S. Jiang, Modeling and simulation of vehicle integrated thermal management system for a fuel cell hybrid vehicle, Energy Conversion and Management 278 (2023).

[13] G. Montaner Ríos, J. Schirmer, C. Gentner, J. Kallo, Efficient thermal management strategies for cold starts of a proton exchange membrane fuel cell system, Applied Energy 279 (2020).

[14] Z. Liu, J. Chen, L. Kumar, L. Jin, L. Huang, Model-based decoupling control for the thermal management system of proton exchange membrane fuel cells, International Journal of Hydrogen Energy 48(50) (2023) 19196-19206.

[15] A. Farsi, M.A. Rosen, PEM fuel cell-assisted lithium ion battery electric vehicle integrated with an air-based thermal management system, International Journal of Hydrogen Energy 47(84) (2022) 35810-35824.