International Journal of Energy
ISSN: 2957-9473 | Vol. 10, No. 3, 2026

Review of the Current Research Status of Thermal Management Systems for Proton Exchange Membrane Fuel Cells

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Abstract: Proton Exchange Membrane Fuel Cell (PEMFCs) is a key technology for the efficient conversion of clean energy, and the thermal management system is a critical auxiliary system for PEMFCs. This paper reviews the multi-field applications of PEMFCs thermal management in areas such as combined heat and power (CHP) and waste heat power generation. It focuses on three major technical aspects: cell system cooling technology, ultra-low temperature vehicle cold-start, and stack waste heat recovery. The advantages and disadvantages of various research methods are compared and analyzed, and the current research status and future trends are summarized.

Keywords: Proton Exchange Membrane Fuel Cell; Thermal Management; Cooling Technology; Cold Start; Waste Heat Recovery.

1. Introduction

With the advancement of global green and energy-saving policies and the implementation of the 'dual carbon' targets, strategic planning for the hydrogen energy sector is accelerating, and proton exchange membrane fuel cells (PEMFCs) have become a hot topic of research across multiple fields. The European Union, Japan and China have successively introduced hydrogen energy development plans to drive technological innovation and the development of the entire industrial chain; consequently, research, innovation and commercialisation of low-noise, high-efficiency PEMFCs fuelled by renewable hydrogen are becoming increasingly urgent.

PEMFCs are categorised into low-temperature and high-temperature types. As a green, efficient and portable fuel cell, they have been widely applied in new energy vehicles, combined heat and power generation, unmanned aerial vehicles (UAVs), seawater desalination and energy storage and power generation. However, nearly half of the energy generated by PEMFCs is lost as heat; improper thermal management can lead to issues such as membrane drying, water flooding and degradation, severely affecting cell performance. It is therefore crucial to maintain a uniform and appropriate cell temperature through a thermal management system.

Existing literature largely focuses on cooling technologies and cold start research, with few systematic reviews covering the multi-domain applications of PEMFCs and the utilisation of waste heat. Whilst some studies have categorised heat pipe cooling technologies or compared air-cooling and liquid-cooling solutions, there remains a lack of standardised thermal performance evaluation metrics, such as temperature uniformity, and research into the integrated cooling of active and passive systems is insufficient.

This paper provides a systematic review of the latest advances in PEMFCs thermal management from 2022 to 2026. It not only elaborates on and compares new findings regarding cooling technologies and cold start-up but also summarises recent developments in the multi-domain applications of PEMFCs and the utilisation of waste heat. Addressing the engineering challenges of doubled thermal loads and wide-temperature-range operation, the paper focuses on three key technical areas: stack cooling (air-cooling/liquid-cooling/ phase change/heat pipes), ultra-low-temperature cold start preheating and waste heat recovery. A technology maturity assessment has been established to reveal the synergistic optimisation mechanisms between cooling, cold start and waste heat recovery, and to identify gaps in evaluation standards for adaptability to extreme environments, thereby providing theoretical guidance and a basis for technical decision-making regarding future PEMFCs research directions.

2. NEV PEMFCs Thermal Management Systems

International research focuses on mass-produced hydrogen fuel cell vehicles in East Asia, Europe, and America. Passenger vehicles include the 2023 Hyundai second-generation NEXO, which utilizes an integrated four-circuit coupled heat exchanger for the stack, battery, motor, and air conditioning. Since both propulsion and heating in the Hyundai Nexo rely on the same energy source, the development of a high-efficiency HVAC (Heating, Ventilation, and Air Conditioning) system has become essential for achieving extended driving range, particularly through the recovery of stack waste heat to support winter operation. The Nexo's advanced thermal management system incorporates a two-way valve and a four-way valve, which significantly enhances the response speed of the coolant temperature control. This architecture improves the Nexo's cold-start performance, enabling reliable operation even at extreme ambient temperatures as low as -30°C (-22°F) [1].

For heavy-duty trucks, Mercedes-Benz's NextGenH2 employs a "five-in-one" thermal management system to achieve deep coupling between liquid hydrogen, the stack, the motor, the air-conditioning and PTC heater preheating. Toyota's third-generation fuel cell (FC) system marks a

significant technical evolution by eliminating the hydrogen recirculation pump and integrating advanced self-humidification technology, with a primary strategic focus on heavy-duty trucks and public buses. Furthermore, at the 2026 Tokyo Motor Show, Toyota debuted the FCV Plus concept, which functions as a mobile distributed power generation system. This architecture features a fuel cell stack positioned between the front axles and hydrogen storage tanks situated beneath the rear seats, supporting external power supply capabilities. While research into fuel cell vehicles (FCVs) in China commenced later than in other regions, the country has achieved significant milestones in the independent production of core battery components and the domestic manufacturing of complete vehicles. A notable example is the Changan Deepal SL03 Hydrogen Edition, China's first mass-produced hydrogen fuel cell sedan, which utilizes a stack with water and gas manifolds and a fully variable decoupled thermal management system to ensure superior thermal and flame retardation.

2.1. Applications in Other Fields

PEMFCs are not only highly compatible with the new energy vehicle but also with small-scale mobile platforms, including Unmanned Aerial Vehicles (UAVs) and electric bicycles, as well as on-grid and off-grid energy storage and multi-generation systems. Given the environmental and economic limitations associated with traditional lithium-ion batteries, PEMFCs have emerged as a significant research hotspot in energy storage due to their superior eco-friendliness. For instance, integrated systems can utilize photovoltaic (PV) power for hydrogen production during the summer, subsequently utilizing PEMFCs to convert stored hydrogen back into electricity during the winter months.

PEMFC-based multi-generation systems primarily encompass Combined Heat and Power (CHP), Combined Cooling and Power (CCP), and Combined Cooling, Heating, and Power (CCHP) configurations. Within CHP systems, PEMFCs offer distinct advantages, including high efficiency, operational stability, environmental friendliness, and low noise levels, making them particularly well-suited for applications in the building sector.

Compared with low-temperature types, high-temperature proton exchange membrane fuel cells (HT-PEMFCs) offer more convenient water management and higher carbon. PEMFC-based multi-generation systems primarily encompass Combined Heat and Power (CHP), Combined Cooling and Power (CCP), and Combined Cooling, Heating, and Power (CCHP) configurations. Within CHP systems, PEMFCs offer distinct advantages, including high efficiency, operational stability, environmental friendliness, and low noise levels, making them particularly well-suited for applications in the building sector.

Oxidation tolerance, making them more suitable for CHP systems; their efficiency is 5.44 per cent higher than that of conventional systems [2]. Current optimisation of PEMFCs-CHP systems focuses on system structure and energy management strategies. In terms of structural optimisation, integrating PEMFCs with the Organic Rankine Cycle (ORC) can enhance overall efficiency; the Kalina cycle has attracted attention due to the easy availability of ammonia water, its environmental friendliness and its compatibility with mature steam turbine designs. Research has utilised waste heat from HT-PEMFCs to drive the Kalina cycle, whilst reducing turbine back pressure through semi-absorption refrigeration to improve performance [3]. Furthermore, integrating heat pumps or energy storage devices into distributed energy systems can help balance output. In response to the seasonal energy demands of Chinese households, a parallel air-source heat pump integration architecture offers greater advantages in terms of overall system efficiency.

In addition to CHP, waste heat from PEMFCs can also drive refrigeration cycles in CCP or CCHP systems. With regard to CCP, the efficiency of silica gel-water absorption-type refrigeration CCP systems has increased by between 15.98per cent and 23.23per cent compared with conventional systems [4], as shown in Figure 1. With regard to CCHP, research has been conducted to develop systems that balance thermal comfort with high efficiency and environmental sustainability, but this needs to be extended to a wider range of scenarios.

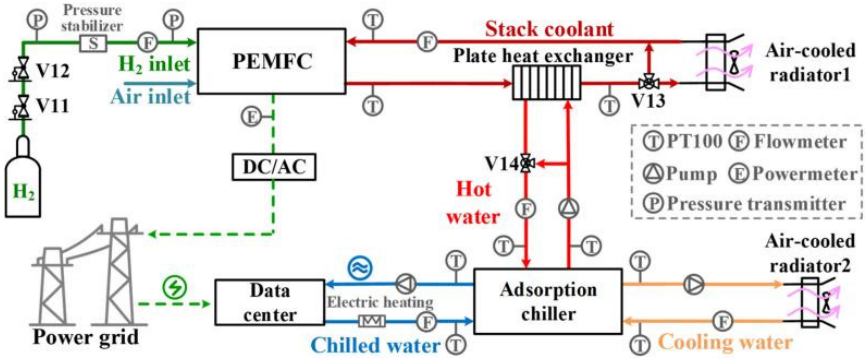


Figure 1. Schematic diagram of the CCP system

In addressing environmental issues, some studies have combined HT-PEMFCs with high-temperature hydrophilic modified distiller tubes (HMTDs) to utilise waste heat for seawater desalination. Other studies have proposed an integrated system combining methanol reforming HT-PEMFCs with liquefied CO_2, which enables the recycling of methanol and CO_2 through an absorption-driven refrigeration cycle, thereby establishing a zero-carbon industrial chain. In the aforementioned studies, integrated heat exchangers play a key role.

3. Research Status of PEMFCs Thermal Management Technologies

3.1. Cooling Technology

Cooling methods are selected based on stack power. Air cooling is suitable for small PEMFCs, while liquid and phase-change cooling are used for large-scale applications.

3.1.1. Air Cooling

Excessive air cooling may lead to membrane drying, and the compact bipolar plate structure also increases flow resistance. Consequently, optimising the cathode flow field (CFF) remains a key area of research. The aim is to enhance cooling performance, facilitate waste heat removal and maintain water retention capacity.

Air-cooling include cathode-open-cell air-cooling(OC-ACFC) and independent air-cooling channel configurations. In OC-ACFC systems, air is drawn directly into the cathode channel, serving as both a reactant and a coolant, which simplifies the system and reduces weight, volume and cost. However, these systems have lower heat dissipation efficiency and poor temperature uniformity, and are primarily used in applications such as drones, emergency power supplies and hydrogen-powered bicycles. Separate air cooling channels supply reactant and cooling air respectively; when the cell power exceeds 2 kW, additional independent air ducts are required [5]. The multi-point control model developed by Yuan et al. can maintain the temperature gradient within 0.5 °C [6]. Zhang et al. found that increasing the air flow rate reduces cell temperature and promotes uniform distribution of gas [7]. But their study neglected the distribution of hydrogen in the cell. They did not specify an upper limit for the air flow rate to prevent membrane drying. They also constructed a three-dimensional, full-scale and kilowatt-class air-cooled cell model. The model has high geometric accuracy. And they compared forced-air and induced-air modes [8]. The forced-air mode was demonstrated superior cooling capacity. But the induced-air mode offered advantages in electrochemical performance and voltage uniformity.

In areas of flow field optimisation, the bean-shaped flow field is 9.4per cent lighter and 6.9per cent more compact than the parallel flow field [9]. The uniformity of airflow velocity and temperature distribution in the annular structure was improved by approximately three times. That made fuel cell performance increased by 15per cent. Researchers explored the heat transport mechanisms and distribution characteristics of liquid water and reactants in bamboo-shaped flow field. The flow field demonstrating excellent cooling efficiency and the ability to mitigate hotspots. In regard to water retention capacity, inserting a porous medium at the air duct outlet made an 18.2per cent increase in current density [10]. Metal foam can suppress excessive water loss. But its pressure drop is approximately three times that of a conventional parallel flow field. This implies a trade-off between water management and the power consumption of auxiliary fans in air-cooled fuel cells. Lim et al. designed and compared nine flow fields, The blocked flow field with a nozzle cross-section proved most effective. A cathode flow field with secondary cooling increased the oxygen fraction on the surface of the cathode catalyst layer by 5.42 per cent [11], raised the membrane water content by 12.03 per cent, and improved cell output performance by 5.40 per cent. A staggered water reservoir structure in the cathode storage layer also enhanced water retention capacity and improved thermal and fluid management.

3.1.2. Liquid Cooling

Liquid cooling is favoured for its high heat transfer efficiency and uniform temperature distribution. It features a dedicated cooling channel. Heat is transferred to the coolant via bipolar plates, before being dissipated by a heat exchanger. High-power PEMFCs for automotive applications typically employ liquid cooling. And they are equipped with auxiliary components such as circulation pumps, radiator assemblies and three-way thermostatic valves.

Flow channel design is crucial for liquid cooling. Heat accumulation and the formation of hotspots are key factors affecting battery performance and lifespan. An appropriate cooling flow field can effectively extend the battery's lifespan. New types of channels include zigzag, serpentine, parallel straight channels with enhanced heat transfer fins, and wavy channels. Research has subdivided serpentine flow channels into left and right channels. They have improvements in temperature distribution uniformity of 55.45 per cent and 24.39 per cent, respectively [12]. Inspired by spiderwebs, researchers had proposed a novel biomimetic spiderweb cooling flow channel [13]. Compared with traditional serpentine flow channels, this design improved the temperature uniformity at the cathode catalyst–membrane interface by 38 per cent.The current density of PEMFCs was increased by up to 1.1 per cent.And the average membrane water activity raised to a maximum of 12.1 per cent.

The CFC transition zone in the thermal management of large-scale PEM fuel cells plays an important role in regulating the cooling flow rate. The CFC transition zone in thermal management systems for large-scale PEM fuel cells is primarily used in vehicles such as FCEVs.But this aspect has received little attention in existing research. Adding a perforated horizontal grid to the conventional transition zone improves coolant flow and temperature uniformity.It also reduces the average temperature of the fuel cell. With regard to coolant flow rate control, U-shaped channels exhibit higher heat transfer efficiency than I-shaped channels at low flow rates.But the heat transfer rates of the two are similar at high flow rates.

The CFC transition zone plays a crucial role in the thermal management of large-scale PEM systems and in regulating the cooling flow rate. The CFC transition zone in thermal management systems for large-scale PEM fuel cells is primarily used in vehicles such as FCEVs; however, this aspect has received little attention in existing research. The addition of a perforated horizontal grid to the traditional transition zone improves coolant flow and temperature uniformity, thereby reducing the average temperature of the fuel cell. With regard to coolant flow rate control, U-shaped channels exhibit higher heat transfer efficiency than I-shaped channels at low flow rates, whilst at high flow rates, the heat transfer rates of the two are similar.

3.1.3. Phase Change Cooling

Phase-change cooling includes evaporative cooling and boiling cooling.

Evaporative cooling requires the coolant's boiling point to be higher than the stack's operating temperature. Existing evaporative cooling models have revealed water transport pathways.But the models have not taken into account the anisotropy of the gas diffusion layer (GDL). In recent years, bubble columns (BCs) have been innovatively applied to heavy-duty truck PEMFCs.Utilising the latent heat of water to enhance cooling capacity provides an additional 153 kW of heat dissipation. However, moisture management of the fuel cell remains a challenge.

Boiling cooling requires the boiling point of the coolant to be lower than the operating temperature of the fuel cell. Researchers have established a one-dimensional model of flow-induced boiling cooling.They investigate internal temperature distributions under different operating conditions. And they found that the two-phase cooling method exhibits

less temperature dependence on system load variations. Boiling cooling delivers reliable cooling performance. Systematic studies have shown that boiling cooling significantly improves temperature uniformity. Boiling cooling increases fuel cell output power by 9.04 per cent [14]. Optimising relevant parameters can enhance reaction efficiency. It can also mitigate membrane dehydration and water flooding issues.

3.1.4. Passive Cooling

Passive cooling involves the use of heat sinks, which require materials with high thermal conductivity,such as copper, aluminium, graphite or graphene carbon nanotubes,to reduce thermal resistance. Researchers have proposed a heat sink composed of pyrolytic graphite (TPG) and copper [15], as shown in Figure 2, which outperforms oil cooling in the thermal management of HT-PEMFCs. A double-sided TPG configuration provides better cooling performance than a single-sided one, and the temperature difference across the PEMFC membrane electrode assembly (MEA) cooled by TPG is less than 5 K.

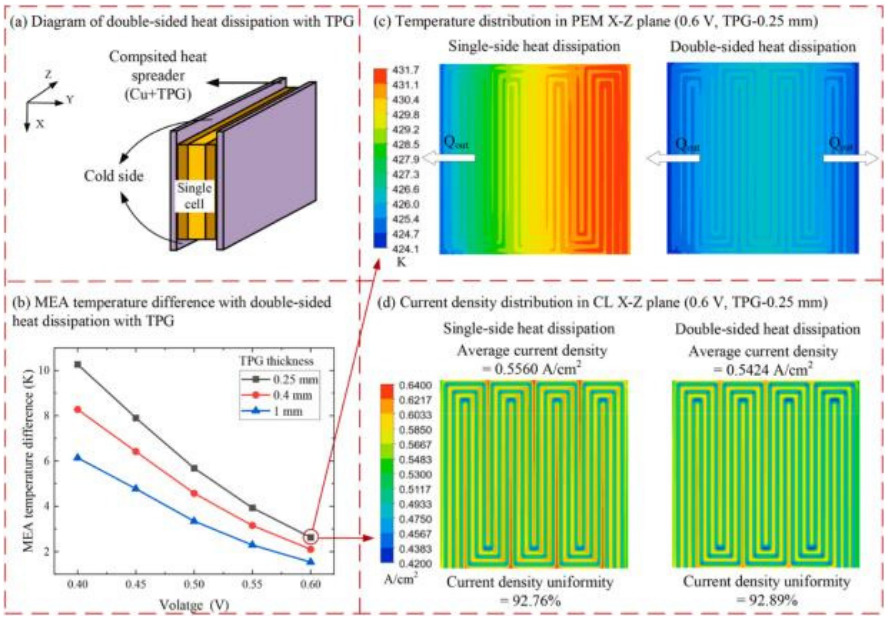


Figure 2. The Effect of Bilateral TPG Heat Dissipation on HT-PEMFCs Performance

Due to their exceptional thermal conductivity, heat pipes are suitable for a variety of applications, including temperature control and heat flux conversion. Since the proposal in 2005 to embed heat pipes within graphite bipolar plates, heat pipe cooling has become a key area of research in PEMFCs cooling technology.

The internal structures of heat pipes primarily include layered, spaced and composite configurations. Spaced structures offer strong heat transfer capabilities but are prone to hot spots. Composite structures, on the other hand, combine the advantages of both; researchers have proposed a novel, high-porosity composite internal structure heat pipe suitable for mass production, with maximum heat transfer capacity and thermal conductivity superior to those of traditional ultra-thin layered heat pipes. Modelling has shown that heat pipes with composite structures can reduce the thermal resistance of the PEMFCs system and enable a wider operating temperature range.

In recent years, phase-change materials (PCMs) such as paraffin and fatty acids have attracted considerable attention. Battery thermal management systems (BTMS) combining PCMs with heat pipes are considered the optimal solution, as they can maintain a uniform battery temperature distribution at high discharge rates without the need for an external power source; however, this requires the appropriate selection of materials and the optimisation of the number, arrangement and configuration of the heat pipes.

3.2. Ultra-low Temperature Cold Start

The key to a successful cold start of a fuel cell lies in raising the overall temperature of the cell before the electrochemical reaction ceases, preventing condensation within the cell and blocking air intake gaps, amongst other factors. Cold start performance is analysed based on the minimum start-up temperature and start-up time. Ice initially forms within the catalyst and the liquid diffusion layer, adhering to solid surfaces and blocking the pathways for reaction gases, thereby reducing reaction rates and cold start efficiency. Delamination may also occur between the PEM and the GDL, leading to unnecessary energy losses. To accurately predict the ice-melting process, Fang W.Z. and colleagues developed a porosity model that precisely predicts ice melting within the GDL using a microscopic, high-thermal-conductivity mean-field model. Researchers have captured the multi-physical aspects of the cold start phenomenon, enabling the prediction of catalyst degradation during the cold start process via computer simulations.

In terms of enhancing cold-start performance, effective temperature control, cell clamping force, current density and optimised thermal management are crucial. Solutions are primarily categorised into active and passive strategies. Active strategies rely on external auxiliary equipment, such as preheaters, thermal insulation using phase-change or insulating materials, and advanced control algorithms; whilst these enable rapid cold starts, they increase energy consumption, hardware complexity and integration costs. A common method involves using heating devices to preheat the cathode plate in order to warm the cell. Researchers employed a staged preheating method from battery start-up to steady-state operation; however, this incurs energy consumption and increases the cost of additional equipment. Cost control for auxiliary equipment is also a priority and requires separate

consideration.

Passive strategies rely on the fuel cell itself, thereby avoiding energy consumption from auxiliary equipment; however, thermal non-uniformity within the cell persists, with the central region heating up faster than the ends during cold start-up. To reduce this thermal non-uniformity, the optimisation of passive strategies has become a research focus in recent years. Self-start-up methods typically focus on controlling the initial load current or cell voltage to maximise internal heat generation whilst avoiding cell damage. With regard to stack clamping force, Xie,X. et al. found that vertical vibration plays a positive role in improving cold start performance. In terms of current density, Researchers proposed a novel cold start mode based on the design of key parameters during the cold start period, which reduced the maximum ice volume fraction and start-up time, whilst lowering hydrogen consumption. It was confirmed that combining this cold start mode with multi-objective optimisation strategies is an effective method for enhancing cold start performance. Liu,G.Q. et al. proposed a stepped current load optimisation strategy suitable for serpentine flow fields, systematically revealing the dynamic coupling mechanisms of ice–thermal–electrochemical interactions in single-channel serpentine flow fields and elucidating the control mechanisms under initial parameters.

In terms of optimised thermal management, for short-term shutdowns, the phase-change material, metal foam ,can increase thermal diffusivity and diffusion rate, thereby enhancing battery performance, and can also serve as a thermal storage medium to improve cold-start performance. Agus et al. proposed a passive thermal management optimisation strategy utilising PCM to maintain the battery temperature above freezing point. Furthermore, addressing the issue of thermal imbalance during the preheating phase, El Ahmadi Mortada et al. experimentally evaluated a novel passive heating strategy utilising alternating coolant flow to improve thermal management. This approach achieved heat retention and redistribution, thereby controlling the temperature difference within the battery. Whilst promoting the homogenisation of horizontal temperature differences, it ensured the coolant's heating capacity, reduced vertical temperature gradients, and provided a safe cold-start strategy based on dynamic flow direction switching triggered by internal thermal sensing.

3.3. Waste Heat Recovery (WHR)

Industrial energy consumption accounts for 33 per cent of greenhouse gas emissions, and approximately 70 per cent of the energy consumed by the industrial sector is used for thermal energy. Heating processes generate significant amounts of waste heat; researchers believe that waste heat recovery (WHR) offers considerable potential for utilisation, and it has therefore become a key area of research in thermal management. WHR methods for PEMFCs are primarily used for preheating the reaction zone, releasing hydrogen from metal hydride (MH) storage materials, providing heating in combined heat and power (CHP) systems, driving combined cooling and power (CCP) systems, generating electricity via thermal cycles, and addressing environmental issues.

MH releases hydrogen through an endothermic dehydrogenation reaction and is a promising hydrogen storage medium, attracting particular attention in small-scale and portable applications. Its advantages include high hydrogen density, safe low-pressure operation and good cyclic reversibility; however, it faces challenges such as desorption instability, non-uniform temperature and pressure distribution within the tank, and localised overheating. Miao,S. proposed a compact hydrogen supply system integrating MH and PEMFCs. The MH was designed as a honeycomb tank, which significantly improved the system's thermal utilisation rate; the thermal utilisation efficiency of the double-layer MH tank reached 39.90per cent [16]. Taking a region in Shandong Province, China, as an example, Wang,Y.H. et al. developed a PEMFCs-MH distributed energy system equipped with electrical and thermal energy storage devices. By comparing the energy efficiency and payback periods of different configuration schemes, they provided recommendations for resource allocation strategies, which are crucial for enhancing the reliability and sustainability of renewable energy systems.

Heat pipe heat exchangers (HPHEs) are effective tools for recovering waste heat. PEMFCs thermal management systems utilise the waste heat from HPHEs in applications such as seawater desalination, the realisation of zero-carbon industrial chains, and hydrogen desorption from MH tanks in PEMFCs systems. M.Dolatyar et al. connected the PEMFCs and MH tank via a heat pump, effectively utilising waste heat to facilitate hydrogen desorption and accelerate its regeneration. This reduced the thermal load of the air-cooling system by 21 per cent, increased MH utilisation time by 58 per cent, and achieved integrated thermal management of the fuel cell and hydrogen storage alloy materials [17].

With regard to thermal management systems utilising waste heat recovery from heat pumps, Zeng et al. proposed a vehicle thermal management system utilising a heat pump. After comparing the economic viability of various heating methods in vehicles, they demonstrated that economic benefits increased by 25.5per cent when using a heat pump system for heating in conjunction with fuel cell waste heat recovery [18]. Zhu, Z.W. et al. proposed a novel integrated thermal management topology incorporating a heat pump system, which utilises the waste heat generated by the PEMFCs and electrodes through the mutual coupling of various components, thereby significantly improving the thermal efficiency of fuel cell vehicles. Zhao,J.J. et al. proposed a novel combined heating, power and cooling (HPC) system with dehumidification functionality, in which the waste heat from the PEMFCs is used as the heat source for the adsorption chiller and dehumidification system.

In the field of thermal cycle power generation, researchers have proposed a novel, highly efficient heat transfer system that utilises an organic working fluid to directly cool the PEMFCs and recovers waste heat through integration with an organic Rankine cycle (ORC). H. Montazerinejad et al. conducted a detailed analysis of a power generation system comprising a PEMFCs and an ORC. The ORC system, used to recover waste heat from the PEMFCs, comprises a turbine, a condenser and a pump. The working fluid absorbs the waste heat to vapourise, driving the turbine to generate electricity; it is then cooled via the condenser and pumped to the high-pressure side to complete the cycle. In addition to the ORC, the Kalina cycle can be used to recover low-grade waste heat in the range of 80 to 400 °C. It is suitable for both LT-PEMFCs and HT-PEMFCs and, compared to the ORC, is more appropriate when the waste heat flux is consistent across different temperature ranges and when the low-temperature heat flux exceeds the high-temperature heat flux [19]. Some researchers have also applied PEMFCs waste heat to drive the

Kalina cycle for power generation.

4. Conclusion

Research into PEMFC thermal management primarily covers three key areas, cooling technologies, ultra-low-temperature cold start-up, and waste heat recovery. In regard to cooling technologies, both forced and natural convection methods face the challenge of optimising flow field structures and struggling to reconcile energy consumption and cost. A balance must be struck between thermal control performance, operational energy efficiency and economic viability. Currently, the development of multi-field coupled models based on artificial intelligence and machine learning represents a cutting-edge approach to optimising cooling structures. But the investigation about the performance of novel, environmentally friendly, high-thermal-conductivity heat exchange materials and multi-component cooling fluids remains a research challenge. Existing hybrid active-passive cooling schemes generally lack quantitative validation of their practicality and economic viability.

During ultra-low-temperature cold starts, water generated by the battery's self-heating at low temperatures is prone to freezing, hydrothermal imbalance, temperature fluctuations and voltage variations. Current research focuses on establishing precise dynamic thermo-electro-hydraulic coupled models to monitor parameters such as internal battery temperature and ice volume. Utilising reciprocating coolant flow technology to mitigate temperature inhomogeneities and ensuring start-up stability by regulating the start-up current density are also the key areas of current research. In the field of waste heat recovery, existing research has largely focused on thermodynamic analysis. But the research neglecting practical applications and economic benefits. The Kalina cycle is better suited to low-temperature waste heat recovery. And the coupling of waste heat with seawater desalination represents an emerging direction. In the future, it will be necessary to move beyond traditional cogeneration models and develop multi-cogeneration systems. By integrating cooling technologies, the battery's adaptability to extreme cold can be enhanced And the overall efficiency of the system will be improved.

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