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Review

Progress in Fuel Cell System-Level Humidification

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Abstract: Proton Exchange Membranes (PEM) exhibit high proton conductivity when hydrated, but "membrane drying" can lead to increased resistivity. This, in turn, causes higher heat generation during the operation of Proton Exchange Membrane Fuel Cells (PEMFC) and may even result in membrane tearing, significantly impacting their performance and lifespan. Therefore, the development and application of various humidification techniques have become a crucial area of research in fuel cell technology. This article provides a detailed exploration of the principles, advantages, disadvantages, and practical applications of system-level humidification methods, and proposes future research directions and key issues. System-level humidification involves altering the operating conditions or system processes to achieve membrane hydration, and is commonly used as an auxiliary method in mobile systems.

Keywords: system humidification; exhaust gas recirculation; dead end anode

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1. Introduction

Self-humidification at the cell level involves modifying the system structure (such as flow fields, membranes, catalyst layers, and gas diffusion layers) without the need for external water sources. Examples include designing new flow field structures or adding various additives to the membrane components. External humidifiers, on the other hand, involve placing humidification devices outside the fuel cell to hydrate the membrane. System-level humidification changes the operating conditions or processes of the system to achieve hydration, primarily through altering operating conditions, exhaust gas recirculation, or dead-end anode configurations. Different humidification methods have different application scenarios. For mobile power sources and new energy vehicles, self-humidification, which does not require additional equipment, can reduce weight and save space, making it more suitable for these applications. This article summarizes the humidification techniques for PEMFCs published in the last five years, providing effective guidance for humidity management in fuel cells and promoting their optimization and development in various application scenarios. Future researchers can use this article to identify key challenges that need to be addressed, guiding further innovation and optimization efforts.

2. Change System Humidification

At the system level, humidification of PEMFC can also be achieved by altering system conditions. This chapter categorizes system-level humidification methods into three approaches: changing operating conditions, exhaust gas recirculation systems and dead-ended anode operation.

2.1. Change Operating Conditions

Changing operating conditions includes modifying gas flow or altering the external working environment of the fuel cell to achieve humidification. As shown in Figure 1, Luo et al. proposed a method to improve fuel cell water management by alternating the air flow direction [1]. This approach redistributes water within the stack, leading to more uniform water distribution in the flow channels, thereby achieving humidification and enhancing PEMFC performance. Using this method, the output voltage of the fuel cell increased by 19.46% under conditions of 0.8A/cm² current density, 65°C operating temperature and non-humidified gases. This method provides a new perspective on humidification, but the alternating air flow direction causes significant voltage fluctuations in the PEMFC. Additionally, the sudden changes in pressure gradients due to alternating air flow increase membrane fatigue. Therefore, addressing these voltage fluctuations and durability issues remains a critical challenge for fuel cells.

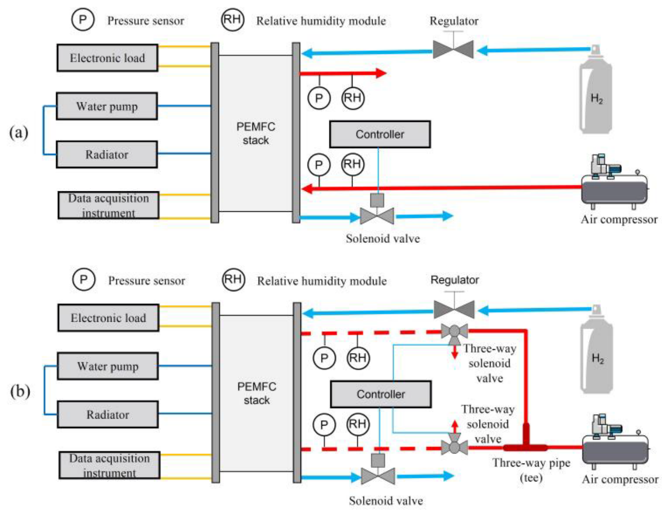

Figure 1. The original system (a) and Alternate air flow system (b) [1].

In addition to changing the gas flow direction, studies have shown that introducing a magnetic field can also enhance PEMFC performance, with higher magnetic field intensities yielding better results [2-4]. Wooyeol Lee et al. investigated the transient performance of PEMFC under low magnetic field densities by varying cell temperature, voltage, relative humidity, and pre-humidification time [5]. The magnetic field enhances oxygen mobility, leading to improved oxygen reduction reaction (ORR) performance. Membrane humidification is accelerated by the intensified ORR, resulting in an approximately 8.6% performance improvement compared to conventional PEMFC under conditions of 40% relative humidity, 80°C cell temperature, and 0.3V voltage. This study explains the reasons for the performance enhancement through reaction mechanisms and provides strategies for maximizing performance. However, practical applications of this method must consider the impact of weight and volume, and its long-term effects require extended PEMFC testing and research.

2.2. Exhaust Gas Recirculation System

Exhaust gas recirculation systems not only return moisture from the fuel cell reaction exhaust to the stack to increase humidity but also enhance gas flow velocity in the stack channels, preventing water accumulation and flooding, thereby improving gas utilization. These systems transport gas using recirculation pumps or ejectors and include both anode and cathode recirculation systems. First, research on dual-loop systems is discussed. As shown in Figure 2a, Jiang et al. designed a proton exchange membrane fuel cell system with both anode and cathode recirculation, achieving excellent self-humidification and rapid start-up capabilities [6]. Additionally, through orthogonal experimental studies [7], they found that cathode recirculation reduces cell voltage at lower current densities, while the dual recirculation system minimizes the difference in oxygen molar concentration between the inlet and outlet of the cathode gas channels. The dual recirculation system demonstrates outstanding dynamic performance and stability, achieving excellent hydration effects, with performance only 3% lower compared to systems with external humidifiers. Although the humidification capability of the dual-loop system is exceptional, detailed theoretical and experimental analysis of the individual contributions and energy consumption of anode and cathode recirculation is lacking. Addressing this issue, their further research revealed that cathode recirculation offers better humidification but consumes more power, while anode recirculation is more cost-effective [8]. Therefore, considering cost, anode recirculation is the best choice; considering performance and lifespan, cathode recirculation and dual-loop systems are preferable.

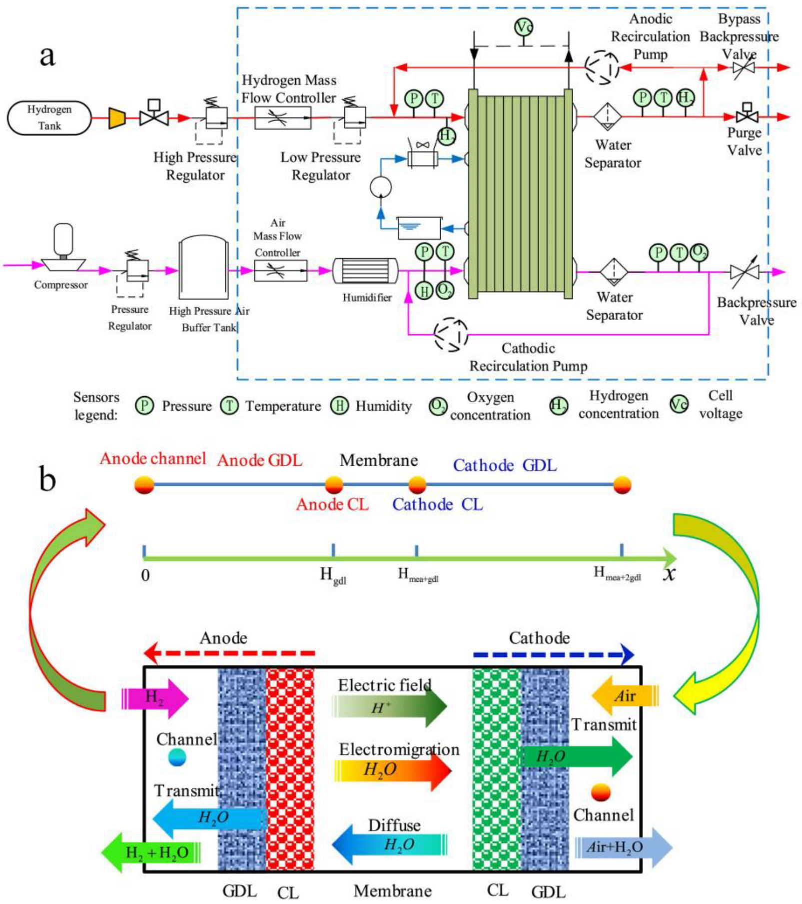

Figure 2. Schematic of PEM fuel cell dual recirculation system(a) and Schematic diagram of one-dimensional mechanism model (b) [6,9].

In addition, anode recirculation faces the issue of nitrogen crossover. Wang et al. developed a quasi-two-dimensional non-isothermal transient model to study the transient and local characteristics of a proton exchange membrane fuel cell with anode recirculation [10]. This model considers the self-humidification effect and nitrogen accumulation under low humidity conditions and compares co-flow and counter-flow structures, which were rarely considered in previous studies. In research on cathode recirculation, Zhang et al. used orthogonal experiments and AC impedance testing to investigate the impact of cathode recirculation on the high-voltage current-limiting strategy and water management characteristics of a hydrogen fuel cell system [11]. They found that cathode recirculation not only improves the relative humidity near the humidifier at the cathode inlet, enhancing output performance, but also enhances water removal capability at the stack outlet with minimal pump power consumption during high-power operation. This significantly improves the consistency of oxygen distribution along the flow channel and increases stack durability. They also designed a dynamic mechanism model for a hydrogen fuel cell system with cathode exhaust recirculation, as shown in Figure 2b and analyzed the effects of operating parameters on two-phase water migration and dynamic output performance [9]. They discovered that under passive operation of the cathode self-recirculation system, the maximum humidity of the mixed gas can reach 60%.

In exhaust gas recirculation systems, besides the commonly used recirculation pumps, ejectors can also mix the reaction gas and water produced by the fuel cell and inject them into the fuel cell inlet, achieving humidification. Ejectors offer advantages such as lighter weight, simpler and more reliable structure, and lower cost compared to recirculation pumps, and their application in industry is well-established. Research primarily focuses on internal structure and operating parameters. Pei et al. established a CFD model for an ejector, analyzing its main geometric parameters and operating conditions [12]. They found that the geometric parameters of the mixing chamber significantly influence the mixing process and energy exchange between the working fluid and the ejected fluid. Dong et al. conducted three-dimensional numerical simulations of a hydrogen ejector, showing that the entrainment ratio and critical backpressure initially increase and then decrease with the length of the mixing chamber under different Mach numbers [13]. Wang et al. designed and manufactured an ejector for an 80kW PEMFC system, achieving hydrogen consumption by adjusting the orifice of a proportional valve [14]. Experimental measurements of the temperature, pressure, and mass flow rate of the primary and secondary fluids showed that controlling the primary fluid pressure can regulate the mass flow rate of the ejector's primary fluid, with high control accuracy. However, a single ejector can only provide excellent performance within a limited operating range; beyond this range, its efficiency significantly decreases. Therefore, Xue et al. proposed a novel multi-nozzle ejector that can achieve a wide output power range by simply switching the operating mode of the nozzles without significantly changing the primary pressure [15]. This promotes the development of multi-nozzle systems for broader operating ranges. Additionally, exhaust gas recirculation systems can adopt dual ejectors, parallel recirculation pumps and ejectors, or ejectors with bypass injectors, each with its own advantages and disadvantages, as summarized in Table 1. In summary, exhaust gas recirculation systems not only improve gas utilization but also eliminate the need for additional humidification systems, streamlining the fuel cell system and showing great potential for humidification in mobile systems.

Table 1. Exhaust gas recirculation schemes and their respective advantages and disadvantages.

Scheme	Advantage	Disadvantage
Single cycle pump	Capable of actively controlling the reflux rate and achieving good cycling effect within the operating range	High noise, heavy weight, high cost, cold start icing problem, additional power consumption, etc.
Single injector	Stable structure, low quality, and low cost	Unable to meet the full range of operating conditions, cycle quantity cannot be actively controlled, and working stability cannot be guaranteed
Dual injector	Stable structure, low cost, meeting the full operating	Cycle quantity cannot be actively controlled

	range, and no parasitic power consumption	
Parallel connection of injector and hydrogen circulation pump	Satisfy the full range of operating conditions and low requirements for circulating pumps	Large size, cold start icing problem, high cost
Injector with bypass injector	Controllable circulation volume, small size, and low cost	High difficulty in matching control and easy waste of reaction gas

2.3. Dead End Anode

Recent studies have shown that passive humidification methods using a dead-ended anode are suitable for many portable devices. Guizado et al. developed a passive water content regulation system for proton exchange membrane fuel cells. The dead-ended anode mode supplies dry hydrogen, and the design allows for humidity regulation in the anode chamber [16]. They also conducted external and on-site analyses of the performance of the anode humidification system, demonstrating that this PEMFC design is capable of continuous operation. However, the system is susceptible to current density and temperature, with current dropping due to membrane drying when the cell temperature approaches 60°C. Kumar et al. also proposed a self-humidifying membrane using a dead-ended anode with intermediate water storage, designing structures such as balloon-like or localized pocket gas storage chambers [17]. They developed a dynamic numerical water balance model and validated it with experimental measurements. The results showed that power output nearly doubled compared to dry membranes, and membrane resistance decreased by 2-3 times. However, this dead-ended anode method can lead to higher electrode temperatures at high current densities, causing membrane dehydration and significant activation losses, issues that require further research and improvement. Despite these challenges, this method has potential applications in lightweight PEMFC-powered airships or drones.

3. Conclusion

It explores various humidification approaches tailored to different application scenarios. System-level humidification involves modifying the operating conditions or system processes to achieve membrane hydration and is often used as an auxiliary method in mobile systems. Among these methods, exhaust gas recirculation, primarily implemented through recirculation pumps, ejectors, or their combinations, can simplify the fuel cell system and enable the reuse of reaction gases and water. Additionally, approaches such as altering operating conditions, applying magnetic fields, or using dead-end anode configurations show promising potential in enhancing redox reactions and auxiliary humidification, particularly in specific application scenarios.

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