World Journal of Engineering Research
ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3016

THE FLOW AND COMPONENT VARIATION CHARACTERISTICS OF THE HYDROGEN SUPPLY SYSTEM IN FUEL CELLS

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Abstract: Nitrogen gas on the cathode side of the fuel cell permeates to the anode and accumulates due to the concentration gradient, reducing the hydrogen concentration and leading to localized fuel starvation at the anode. The hydrogen, nitrogen, and water vapor concentrations, as well as the flow rate in the hydrogen circulation loop, can be monitored online using ultrasonic sensors. This study investigates the component variation in the anode circulation loop of the fuel cell system through experimental methods and analyzes its impact on output performance. The results show that as the current density increases, the water vapor concentration gradually increases. The hydrogen concentration at the anode remains between 70% and 75% across different current densities, while the nitrogen concentration remains around 20% to 25%. With the increase in current density, the time interval for opening the drainage valve gradually shortens, which is attributed to the increasing water production in the cell.
Keywords: Fuel cell; Anode circulation components; Nitrogen concentration; Ultrasonic flow meter

1 INTRODUCTION

Proton Exchange Membrane Fuel Cells (PEMFCs) convert the chemical energy of hydrogen fuel into electrical energy through electrochemical reactions, offering an ideal method for hydrogen utilization. They have garnered significant attention due to their low operating pressure and temperature, high power density, high efficiency, and low emissions, making them more favorable than other types of fuel cells [1-3]. The anode hydrogen supply system is one of the subsystems of PEMFCs, primarily involving hydrogen supply and consumption, mixed gas recirculation, and discharge [4]. The hydrogen supply system provides the required flow and pressure for the fuel cell stack reactions. The hydrogen flow rate and pressure directly impact the output performance of the fuel cell system. Insufficient hydrogen flow can cause localized fuel starvation within the stack, reducing its performance, while excessive hydrogen supply can lead to fuel wastage. Therefore, a well-designed hydrogen supply system is crucial to meet the required hydrogen flow and pressure demands of the fuel cell system.

In addition, nitrogen gas on the cathode side permeates to the anode under the influence of the concentration gradient [5]. Water also diffuses from the cathode to the anode and accumulates there, covering the gas diffusion layer and catalyst layer. This impairs hydrogen transport, hinders the reaction between hydrogen and the catalyst layer, leading to localized fuel starvation at the anode, causing carbon corrosion in the catalyst layer, and promoting catalyst degradation, which ultimately results in fuel cell performance degradation. Therefore, it is necessary to install an exhaust electromagnetic valve at the anode outlet.

Based on the hydrogen flow modes, the hydrogen supply system is primarily classified into three types: hydrogen direct discharge mode, dead-end mode, and recirculation mode [6-8]. Currently, the recirculation mode is the most widely used hydrogen flow mode in fuel cell systems. During recirculation the accumulation of nitrogen on the anode side gradually reduces the hydrogen concentration, thereby lowering the fuel cell's output performance. Therefore, this study investigates the component variations in the anode circulation loop of the fuel cell system through experimental methods and analyzes their impact on output performance.

2 SYSTEM DESIGN

2.1 System Schematic Design

Figure 1 shows the structural diagram of the hydrogen supply system, including a medium-pressure solenoid valve, a proportional valve, a hydrogen recirculation pump, a water separator, a drainage valve, and an ultrasonic flow sensor. The medium-pressure solenoid valve controls the on/off operation of the hydrogen supply system; the proportional valve regulates the pressure of hydrogen entering the fuel cell stack; the water separator separates the mixed water vapor from the anode exhaust of the fuel cell stack. The separated mixture (hydrogen, nitrogen, and water vapor) is recirculated into the anode inlet of the stack via an injector or hydrogen recirculation pump, allowing unreacted hydrogen to re-enter the reaction, thus improving hydrogen utilization. The drainage valve, located at the bottom of the water separator, periodically opens and closes to discharge the accumulated liquid water and nitrogen from the anode side of the fuel cell stack.

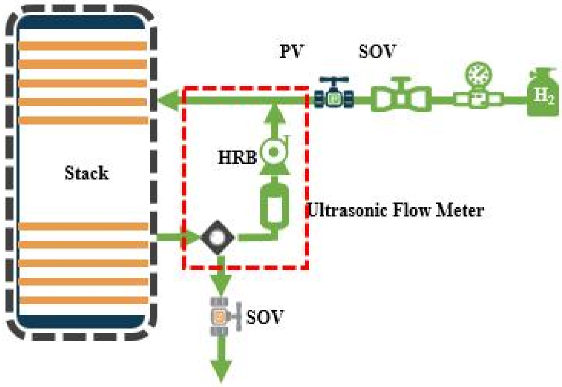

Figure 1 Schematic Diagram of the Fuel Cell Hydrogen Supply System

2.2 Ultrasonic Flow Sensor

The ultrasonic flow sensor can simultaneously measure the flow rate and concentration of hydrogen gas in real-time under high humidity conditions. Additionally, the sensor is capable of collecting temperature, pressure, and humidity data, making it suitable for testing the hydrogen circulation loop in fuel cell systems. Figure 2 shows the physical image of the ultrasonic sensor.

Figure 2 The Physical Image of the Ultrasonic Sensor

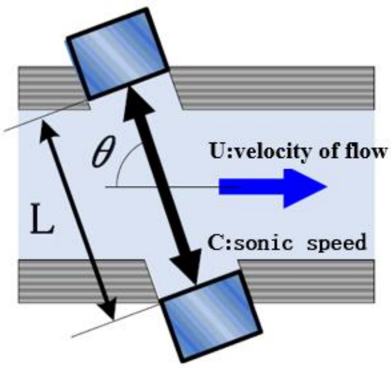

Figure 3 The Working Principle of the Ultrasonic Hydrogen Concentration Sensor

Figure 3 is a schematic diagram of the internal structure of the sensor. The measurement principle is based on detecting the sound velocity and flow velocity of the gas passing through the sensor to calculate the flow rate and concentration of the mixed gas. The calculation formulas are shown in equations (1-3):

$$U = \frac{L}{2cos\theta}\left(\frac{1}{t1} - \frac{1}{t2}\right) \tag{1}$$

$$Q = U \times S \tag{2}$$

$$M = \frac{\gamma \times R \times T}{C^2} \tag{3}$$

Where U is the gas flow velocity, L is the distance between the two ultrasonic probes, θ is the tilt angle of the ultrasonic probes, t1 and t2 are the incident and reflection times of the ultrasonic wave, S is the gas flow cross-sectional area, Q is the gas flow rate, M is the gas concentration, R is the universal gas constant, T is the gas temperature, C is the gas sound speed, and γ is the correction factor.

To prevent liquid water from adhering to the ultrasonic sensor probes and affecting measurement accuracy, the ultrasonic sensor is vertically installed and wrapped in thermal insulation cotton. As shown in Figure 4, the ultrasonic hydrogen concentration sensor is installed between the water separator outlet and the hydrogen recirculation pump inlet pipeline.

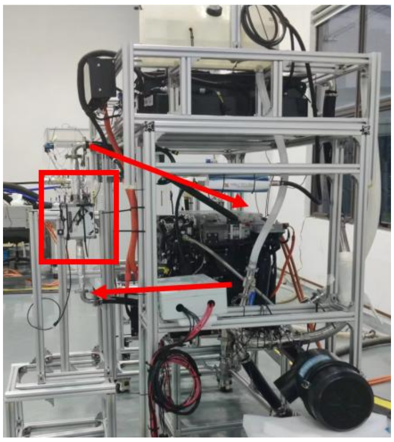

Figure 4 Schematic Diagram Showing the Installation Position of the Ultrasonic Hydrogen Concentration Sensor

3 DATA ANALYSIS

3.1 Sensor Accuracy Verification

Before conducting the fuel cell system experiments, the measurement accuracy of the ultrasonic sensor was verified. The ultrasonic flow sensor was serially connected with a calibrated Ellicott flow meter on the same pipeline, and tests were performed using hydrogen and nitrogen as media, measuring the values of both sensors at different inlet flow rates. The measurement results are shown in Figures 5 and 6. It can be observed that the measurement error between the ultrasonic flow sensor and the Ellicott flow meter does not exceed 1%, which is within the acceptable error range and meets the experimental requirements.

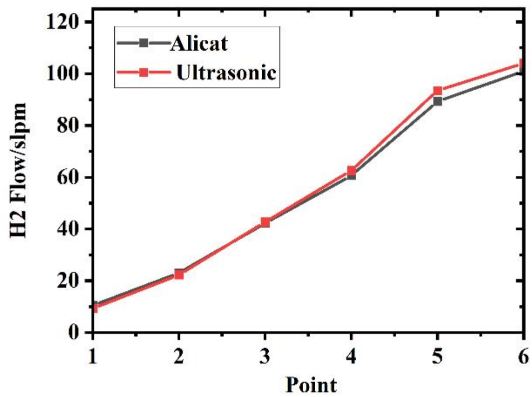

Figure 5 The Hydrogen Flow Rates Measured by Different Sensors

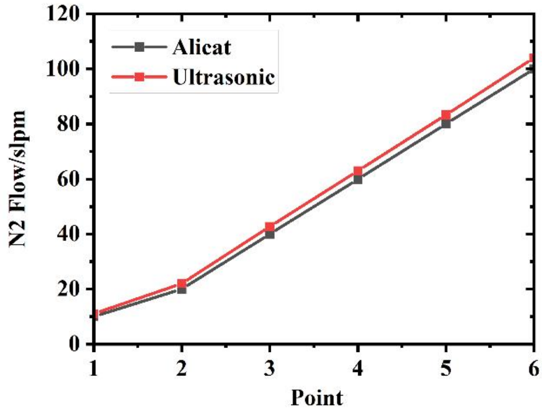

Figure 6 The Nitrogen Flow Rates Measured by Different Sensors

4 RESULTS AND DISCUSSION

4.1 Output Characteristics of the Fuel Cell

The fuel cell system used in the experiment has a rated power of 130 kW, with 418 fuel cell stacks and a single stack area of 330 cm². The experimental plan involves running each current density point stably for 5 minutes. The experimental results are shown in Figure 7. As can be seen from the figure, as the load current gradually increases, the stack output voltage decreases from 357 V to 267 V. The voltage data taken after 3 minutes of stable operation at each operating point is averaged to obtain the fuel cell's output polarization curve, as shown in Figure 8. It can be observed that as the current density increases from 0.1 A cm^{-2} to 1.6 A cm^{-2}, the cell voltage decreases from 0.83 V to 0.64 V.

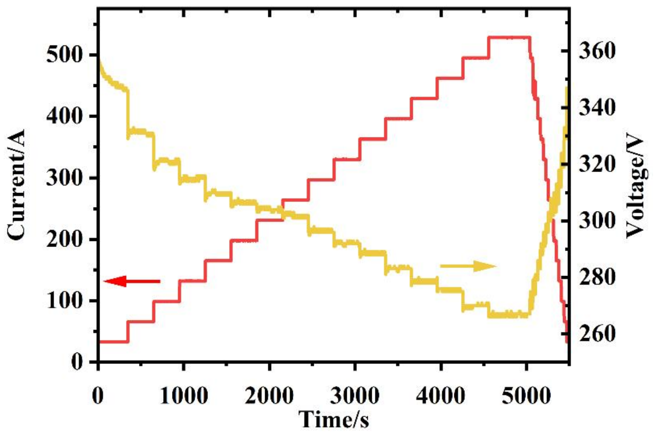

Figure 7 The Variation of the Fuel Cell Load Current and Output Voltage With Time

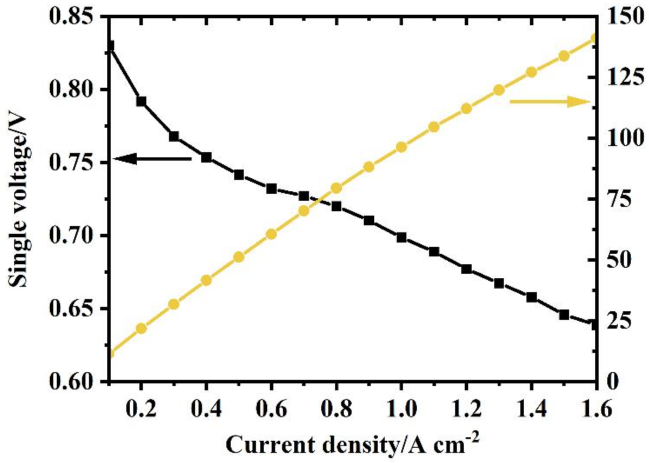

Figure 8 The Polarization Curve and Power Output of The Fuel Cell

3.2 Variation of Anode Component Concentrations

Three different current density points, 0.4, 0.8, and 1.2 A cm^{-2}, were selected for detailed analysis. The experimental results are shown in Figures 9, 10, and 11. It can be observed that when the drainage valve is opened, the nitrogen in the anode chamber is expelled, while the hydrogen concentration gradually increases and the nitrogen concentration decreases, displaying a sawtooth pattern. However, the anode water vapor concentration remains relatively constant at the same current density. As the current density increases, the water vapor concentration gradually increases. The hydrogen concentration in the anode remains between 70% and 75% at different current densities, and the nitrogen concentration stays around 20% to 25%. As the current density increases, the interval between drainage valve openings becomes shorter due to the increasing water production in the cell.

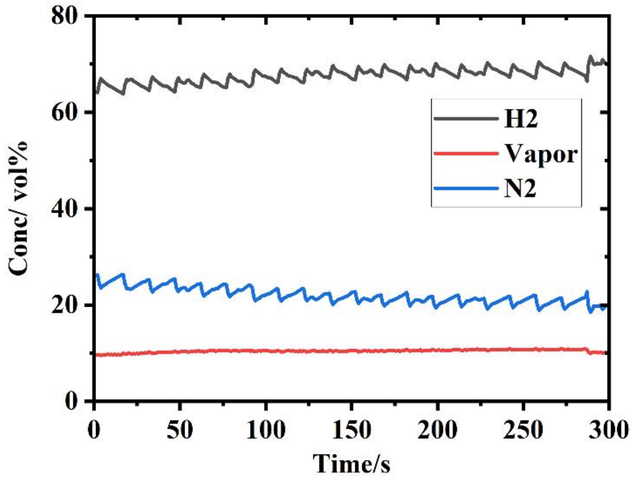

Figure 9 The Variation of Anode Gas Components at a Current Density of 0.4 A cm⁻²

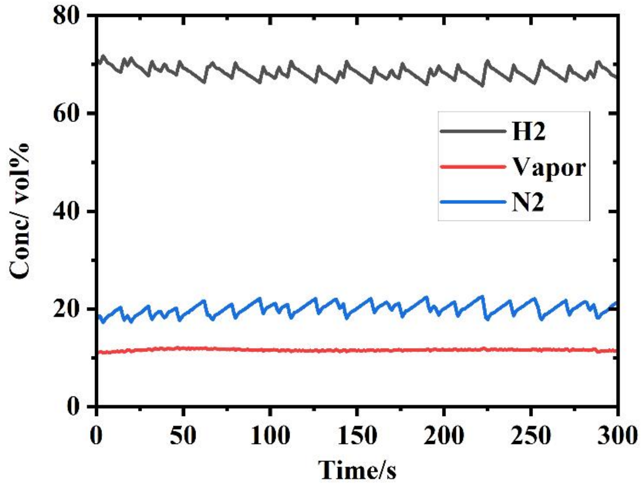

Figure 10 The Variation of Anode Gas Components at a Current Density of 0.8 A cm^{-2}

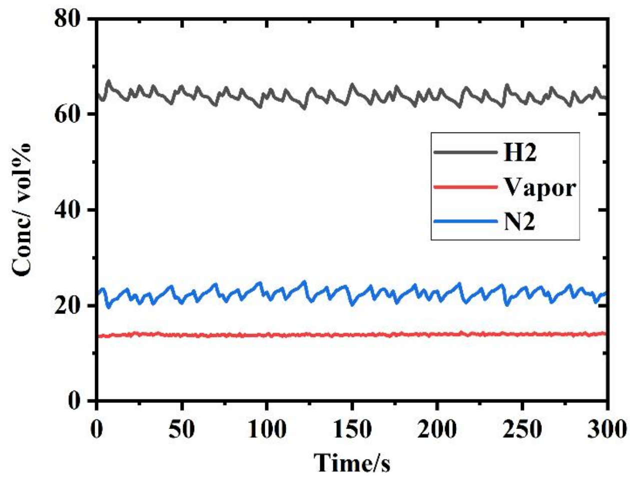

Figure 11 The Variation of Anode Gas Components at a Current Density of 1.2 A cm^{-2}.

5 CONCLUSION

Through experimental methods, the variation of components in the anode circulation loop of the fuel cell system was studied, and its impact on output performance was analyzed. The conclusions are as follows:
(1) The ultrasonic sensor can monitor the hydrogen, nitrogen, water vapor concentration, and flow rate in the hydrogen recirculation loop online. The measurement error does not exceed 1%, which is within the acceptable error range.
(2) In the 130 kW fuel cell system, as the load current gradually increases, the stack output voltage decreases from 357 V to 267 V. As the current density increases from 0.1 A cm^{-2} to 1.6 A cm^{-2}, the cell voltage decreases from 0.83 V to 0.64 V.

(3) As the current density increases, the water vapor concentration gradually increases. The hydrogen concentration in the anode remains between 70% and 75% at different current densities, while the nitrogen concentration remains between 20% and 25%.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

FUNDING

This work was supported by China National Railway Group Co., Ltd. Unveiled Its Flagship Project (grant number: N2022J016-A) and Changzhou City's "Unveiling the List and Leading the Way" Science and Technology Research Project (grant number: 2023-Z-GKB-JS-0009).

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