Design of humidifier test system for proton exchange membrane fuel cell

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Abstract. Humidifiers are often used in the system of fuel cells to ensure the continuous and stable working operation. In order to evaluate the performance of the same humidifier under different operating conditions, this paper proposes a test system for proton exchange membrane fuel cell humidifier (PEMFC). In this paper, the study factor is gas flow rate. During the test process, the system simulates the working condition of the humidifier in the fuel cell system, and measures the dry-and-wet bulb temperature and the pressure flow at the outlet of the dry side of the humidifier with different gas flow rate. Finally, calculated relative humidity, determines the water permeability of the humidifier membrane. And the main factors affecting the humidification effect of the humidifier was analysed. According to the test results, compared with the relative mass transfer time, heat transfer has more effect on the humidification effect.

1. Introduction

The extensive use of non-renewable fossil fuels, such as coal and petroleum, has made environmental pollution increasingly prominent. In order to reduce the influence of environmental pollution, countries have begun to study different renewable alternative energy sources with little or no harm to pollution. Among these renewable energy sources, hydrogen energy was considered as the energy sources with the highest potential. Fuel cell, as a power source using hydrogen energy to generate electricity, has also ushered in a high-speed development in the 21st century. At present, there are many kinds of fuel cells, with different classification methods. The common classification methods are mainly based on the different electrolyte and working temperature of fuel cells. According to the electrolyte types, fuel cells are divided into five types: proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), alkaline fuel cell (AFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). According to the working temperature, PEMFCs and AFCs are low-temperature fuel cells; PAFCs are medium-temperature fuel cells; MCFCs and SOFCs are high-temperature fuel cells. Among all kinds of fuel cells, PEMFCs have captured much attention of researchers due to its low working temperature, long working life and high volume power density[1].

Figure 1 roughly demonstrates the reaction process of PEMFC[1]. Hydrogen at the anode passes through the gas flow channel of the current collector plate and diffuses to the surface of the catalytic layer through the diffusion layer. Activated by the catalyst, hydrogen is decomposed into hydrogen ions and electrons. The reaction equation is as follows:

Anode reaction equation: \[ \text{H}_2 \rightarrow 2\text{H}^++2\text{e}^- \] (1)
The hydrogen ions reach the cathode through the proton exchange membrane, while the electrons reach the cathode through an external circuit. At the cathode of the cell, the air passes through the gas channel of the collector plate and diffuses to the surface of the catalytic layer through the diffusion layer. Due to the catalyst, the oxygen in the air reacts with hydrogen ions and electrons to form water. Since electrons pass through the external circuit to form the current, when the load is connected to the external circuit, power can be supplied. The reaction equation is as follows:

Cathode reaction equation: \( \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \)  
Equation for the overall development: \( H_2 + \frac{1}{2}O_2 \rightarrow H_2O \)

It can be seen from the reaction principle that proton exchange membrane (PEM), as the electrolyte for conducting hydrogen ions, is the core component of PEMFC. Water is needed as a carrier medium for PEM conducting hydrogen ions, so that the cathode oxygen can react with the hydrogen ions transferred to the cathode. Under the working condition of high current density, the moisture in the proton exchange membrane gradually decreases, which leads to the dehydration and even damage of the PEM, and then the ohmage of the PEMFC increases significantly, which eventually leads to the reduction of the working efficiency and the sharp reduction of the service life of the fuel cell. Therefore, in the application system of PEMFC, humidifier is often used in conjunction with PEMFC to maintain the high water content of proton exchange membrane, so as to ensure the normal and continuous operation of fuel cell[2].

In recent years, one of the representative humidifier with high-quality and good commercialization is the hollow fiber membrane humidifier, and the structure of the humidifier is shown in Fig. 2(a). The working principle is that dry air enters the inside of the hollow fiber tube, while water flows through the outside of the hollow fiber tube, and the concentration gradient between the two sides of the membrane drives the water to enter the inside of the membrane from the outside. The humidifier is generally used as a liquid-to-gas humidifier and has a good humidifying effect, but it has two obvious disadvantages. One is the need for external waterway circulation, which will increase the parasitic power of the fuel cell system, and the other is the difficulty of replacement after damage. The plate film humidifier, used for gas-to-gas humidification that takes the airflow at the cathode outlet of the battery as the moisture, can perfectly solve the aforementioned two problems. Its working principle is shown in Figure 2(b). Wet gas flows along one side of the film, while dry gas flows along the other side of the film. Due to the concentration difference, water is transferred from the wet side to the dry side, increasing the water content in the dry gas [3].
With the development of plate membrane humidifier in recent years, the research on its simulation model and mechanical properties has made great progress. Park and Oh[4] proposed a one-dimensional analysis model for evaluating the humidification capacity of Nafion membrane humidifiers. The results show that the thinner the Nafion membrane has higher relative humidity. It is because the thickness of the Nafion membrane determines the permeability of water. Samimi et al.[5] conducted an experimental study on the mechanical properties of polyethersulfone and polyethersulfone porous membranes, and brought into nano-particle TiO₂ mixed membranes for planar membranes. They found that membrane materials had a significant impact on the performance of planar membrane humidifier. The addition of nano-TiO₂ improves the hydrophilicity of the membrane and the wetting degree of the membrane. Yu et al.[6] developed a static model to evaluate the mass and heat exchanger model of the planar heat exchanger based humidifier. The results show that the humidity of wet air, channel length and film thickness all affect the humidification performance. In addition, the material properties of the film are another key parameter to determine the vapor transport capacity. Sabharwal et al.[7] proposed a two-dimensional steady-state model for transverse flow planar membrane-based humidifier. The flow in different channels is assumed to be a volume space of equivalent width. They found that the water transfer rate increased with increasing dry and wet channel flow rates, wet channel inlet pressure, wet channel inlet relative humidity, dry channel inlet temperature, and plate number. Afshari’s research group has done a lot of research on the three-dimensional numerical model of planar membrane-based humidifier[8-9]. The results show that the performance of humidifier with counter flow structure is better than that with parallel structure, and the performance of humidifier with metal foam as flow distributor is better than that of traditional humidifier. Although the theoretical model research is abundant, but how to quickly evaluate the humidification performance of the humidifier by experimental methods has become an urgent problem which need to be solved, so this paper proposes a performance test system of the plate membrane humidifier in order to analyze the performance of the humidifier under different working conditions.

2. Design of Humidifier Test System

2.1 Working principle of test system

The humidifier test system is mainly composed of deionized water tank, hollow fiber membrane humidifier, plate membrane humidifier and various auxiliary accessories. The structure of humidifier test system is shown in Figure 3. The test target of the whole system is the plate membrane humidifier located at the upper part, and the specific structure is shown in Figure 4. This part is mainly composed of two flow plates and a humidifier membrane. The two flow plates are installed on both sides of the humidifier membrane by a certain extrusion force and silica gel seal. The two flow plates usually have four gas paths recorded as dry side inlet, dry side outlet, wet side inlet and wet side outlet respectively. The air flow will flow in the channel of the flow plate and exit through the air hole on the plate. In the
actual application of the humidifier, the wet side inlet gas is usually the fuel cell cathode outlet gas, and the humidified dry side outlet gas is connected to the fuel cell cathode inlet. In order to simulate the actual operation of the humidifier, the system will provide saturated steam with 100% relative humidity (RH) to the wet side inlet and dry gas with 0% RH to the dry side inlet. In order to determine how much moisture is actually absorbed from the wet side by the dry side gas through the membrane under different working conditions, the dry-and-wet bulb temperature and the pressure of the gas flow at the outlet of the dry side under different working conditions are measured to calculate the water content and relative humidity of the gas flow.

Deionized water tank is the main component of external water circulation system, which is mainly used to provide constant temperature circulating water for hollow fiber membrane humidifier to produce 100% RH wet gas. The humidified gas will enter the membrane humidifier and diffuse water molecules to the dry gas on the other side of the membrane. Finally, the dry-and-wet bulb temperatures of the air stream at the dry side outlet of the membrane humidifier will be measured by a set of dry-and-wet bulb temperature sensors, while the pressure will be measured by a pressure sensor.

Figure 3 Structure of Humidifier Test System

Figure 4 Three-Dimensional Structure of Membrane Humidifier

2.2 Test System Operation process
The operating process of the system is as follows: First, the water in the deionized water tank is heated by the heating element, and the temperature of the water is controlled to be constant according to the test requirements. With the circulating pump, the deionized water tank is continuously transferring to the hollow fiber membrane humidifier with thermostatic water, which continues to flow the outside of the hollow fiber membrane. Air injected from the outside will also enter the hollow fiber membrane humidifier and flow through the inner side of it. Activated by the concentration gradient, water molecules diffuse to the inner side of the hollow fiber membrane to complete air humidification. When air passes through the hollow fiber membrane humidifier, the thermostatic water also transfers its heat
to the air inside the membrane, so the gas temperature is directly affected by the temperature of the water. The humidified gas with 100%RH is discharged from the air outlet of the hollow fiber membrane humidifier and enters the humidifier along the gas pipeline. At the same time, the filtered dry gas is also delivered to the membrane humidifier by the gas pipeline. It is worth noting that the temperature of the dry gas is controlled by the air heater, while the flow rates of the dry gas and the wet gas are controlled by the pressure control valve and displayed by the flow meter. Under the condition of different flow rates, the water from the wet side of the membrane humidifier is transferred to the dry side by concentration gradient with different speeds. At last, the dry and wet bulb temperature sensor and the pressure sensor are set at the dry gas outlet of the membrane humidifier to measure the dry and wet bulb temperature and the pressure of the air flow at the dry air outlet under different flow rates. To ensure the accuracy of the measurement results, the dry-and-wet bulb temperature sensor and the pressure sensor need to be calibrated before testing.

3. Testing Process

3.1 Calculation of Relative Humidity

In this paper, the study factor of humidifier is the flow rate of gas. In order to determine the water permeability of the humidifying membrane under different gas flow rates, a Nafion proton exchange membrane is selected for testing. When the dry bulb temperature \( T_{db} \), the wet bulb temperature \( T_{wb} \) and the pressure \( p \) of the air flow at the outlet of the dry side are measured, the actual humidity ratio \( w \) and the saturated humidity ratio \( w_S \) are obtained by using the equations (4) to (8) [10], and finally the relative humidity \( RH \) is obtained by using the equation (9). The water permeability of the humidifier film is measured by the relative humidity, and then the main factors affecting the humidification performance are discussed. In these equations, \( w \) represents the mass of gaseous water carried per kilogram of air and \( w_s \) represents the maximum mass of gaseous water that can be carried per kilogram of air at the corresponding temperature.

\[
C_{pw} = 1.0044 - 2.18264 \times 10^4 T_{db} + 6.19428 \times 10^2 T_{db}^2
\]  
\[
C_{pv} = 1.845 - 5.80838 \times 10^{-2} T_{db} + 3.47902 \times 10^{-5} T_{db}^2 - 1.66303 \times 10^{-7} T_{db}^3 + 6.61315 \times 10^{-10} T_{db}^4
\]  
\[
C_{pw} = 4.21754 - 1.54336 \times 10^{-3} T_{db} + 1.48244 \times 10^{-5} T_{db}^2
\]

\[
w_s = \frac{M_w p_{ws}(T_{db})}{M_a p - p_{ws}(T_{db})}
\]

\[
w = \frac{h_o - (C_{pw} - C_{pv}) T_{wb} w_s - C_{pw}(T_{db} - T_{wb})}{h_o + C_{pv} T_{db} - C_{pw} T_{wb}}
\]

\[
RH = \frac{w}{w_s}
\]

Among them, \( C_{pw}, C_{pv} \) and \( C_{pw} \) are the specific heat capacities of air, gaseous water and liquid water respectively, and the latent heat of vaporization \( h_o \) is 2500.8J·g⁻¹. In the equation (7), the molar masses of liquid water and air are \( M_w \) and \( M_a \) respectively, and \( p_{ws} \) is the pressure of gaseous water. According to the display of the pressure sensor, the outlet gas pressure \( p \) at the dry side is basically consistent with the atmospheric pressure, so they are all taken as 0.1MPa.

3.2 Analysis of Test Results

In the same test system, the flow rates of dry gas and wet gas entering the membrane humidifier are controlled by the pressure control valve, so that the flow rates of the dry gas and the wet gas are changed according to the rules of 8lpm, 6lpm and 4lpm. Under the conditions of different flow rates, the dry bulb temperature and the wet bulb temperature of the air flow at the outlet of the dry side are measured, and the measurement results are substituted into the equations (4) to (9) for calculation. The calculation results are shown in Table 1. The test results are plotted as shown in Figure 5. The temperature conditions
for this test were as follows: gas at 25 °C was injected on the dry side and gas at 65 °C on the wet side.

As can be seen from Table 1 and Figure 5, with the decrease of the flow rate, $T_{db}$ decreases continuously, $T_{wb}$ increases continuously, $w$ and $w_s$ decrease accordingly, and finally $RH$ increases accordingly. The water permeability represents the mass of water absorbed by dry gas from humid gas per minute.

According to equation (9), when $w$ and $w_s$ decrease respectively, $RH$ will decrease or increase in theory. However, the final test results (Figure 5) show that $RH$ increases under the combined effect of $w$ and $w_s$, so the influence of $w_s$ on $RH$ exceeds that of $w$. On the one hand, it can be seen from equation (7) that $T_{db}$ mainly affects $w$. And in the test system, the heat exchange effect of the membrane humidifier affects the value of $T_{db}$, thus affecting $w$. On the other hand, it can be seen from the test results that $w$ varies with the change of flow rate, and the flow rate directly affects the relative mass transfer time of membrane humidifier, so the relative mass transfer time has a direct impact on $w$. To sum up, between the two influencing factors (the heat exchange effect and the relative mass transfer time), for the membrane humidifier, the former has a greater impact on the humidification effect.

**Table 1 Test Results at Different Flow Rates**

| Flow rate (lpm) | $T_{db}$ (°C) | $T_{wb}$ (°C) | $w$ (kg/kg) | $w_s$ (kg/kg) | Water permeability (kg/min) | $RH$ (%) |
|----------------|---------------|---------------|-------------|---------------|---------------------------|----------|
| 8              | 48.9          | 40.8          | 0.080       | 0.085         | 0.6054                    | 96.0     |
| 6              | 48.4          | 42.1          | 0.079       | 0.081         | 0.4484                    | 96.8     |
| 4              | 47.5          | 43.1          | 0.075       | 0.077         | 0.2838                    | 97.6     |

**Figure 5** Test and calculation results (a) wet and dry bulb temperature test results. (b) relative humidity calculations.

Note: Under different flow rates, the wet side is fed with 100%RH wet gas at 65°C, and the dry side is fed with 0%RH dry gas at 25°C.

### 4. Conclusion

As humidifier plays an increasingly important role in fuel cell water management, how to evaluate the performance of humidifier has become an important issue in fuel cell system design. This paper presents a system for testing the performance of a PEMFC humidifier. The simulation of the real working condition of the PEMFC plate humidifier is realized, when the corresponding test system is built. After measuring the dry and wet bulb temperature and pressure of the air flow at the outlet of the dry side of the membrane humidifier by using the dry-and-wet bulb temperature sensor and the pressure sensor, the relative humidity of the air flow at the outlet of the dry side is calculated to measure the water permeability of the humidifier membrane. Finally, the performance of the same Nafion-based humidifier at different flow rates was tested successfully. According to the test results of the test object, it is concluded that the humidification effect of the membrane humidifier is greatly affected by the heat transfer effect, but is less affected by the relative mass transfer time. Since the study factor in this paper is gas flow rate, the performance of the humidifier is also affected by temperature, pressure and the flow
channel of the splint, so this study will focus on the influence of the above three factors on the humidifier's working performance in the future.

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