Experimental Study on Performance of Anode Humidification System of Large Power Fuel Cell Stack

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Abstract. The heat and mass transfer characteristics of the hydrogen membrane humidification system of a 70kW atmospheric pressure proton exchange membrane fuel cell stack were experimentally studied. The shell-and-tube membrane humidifier is applied to the high-power fuel cell stack hydrogen humidification system, which has the advantages of fast humidification rate and good wettability of humidified hydrogen. The liquid hydrogen is humidified by liquid water. After the humidification in the experiment, the hydrogen can always reach the supersaturation state. When the hydrogen flow rate is constant, the temperature difference between the membrane humidifier humidification water inlet and outlet decreases with the increase of the water flow rate, and the hydrogen outlet temperature approaches the humidification water inlet temperature as the liquid water flow rate increases; increasing the humidification water flow rate can reduce the temperature difference before and after the humidification water passes through the membrane humidifier. When the temperature and flow rate of the humidified water are constant, the fuel cell stack load increases, and the relative humidity of the humidified hydrogen outlet does not change significantly.

1. Introduction
Proton exchange membrane fuel cells are characterized by environmental protection, high efficiency, fast startup speed and high power density, and are considered to be the main competitors of future ship power sources. The proton exchange membrane needs to maintain good wettability to ensure the high performance of the fuel cell. The water of the fuel cell is generated at the cathode, and the water of the anode is diffused toward the cathode by electromigration. The hydrogen of the fuel cell needs to be humidified to prevent dehydration of the proton exchange membrane, thereby improving battery performance and working life. Fuel cell stack hydrogen humidification system management is one of the key components of fuel cell system hydrothermal management.

Current fuel cell humidification technologies mainly include self-humidification, internal humidification and external humidification. The external humidification technology is easy to control, easy to install and maintain, and is often used in high power fuel cell stack humidification systems. The commonly used hydrogen humidification system uses a membrane humidification method. The proton exchange membrane fuel cell has a high hydrogen utilization rate, and the water content after the reaction is low. The hydrogen recovered is not enough to humidify the hydrogen inlet, and the liquid water is usually used to humidify the hydrogen. The current research on fuel cell humidification system mainly focuses on the humidity characteristics of fuel cell or low-power fuel cell stack and the matching of humidification technology and stack characteristics [1-5]. The thermodynamic analysis of
high-power fuel cell stack humidification system is less, directly research on the humidification performance of fuel cell stack humidifiers is still rare. In this paper, the thermodynamic experimental analysis of the atmospheric pressure fuel cell stack hydrogen humidification system using membrane humidifier is carried out, and the parameter design basis is provided for the hydrogen humidification system management.

2. Membrane humidifier structure and its humidification principle

The membrane humidifier in this paper is a shell-and-tube structure, as shown in figure 1. The tube side passes through the hydrogen, and the shell side passes through the humidifying water. The flow direction of hydrogen and humidifying water is a countercurrent mode.

Membrane humidification is a process of mass transfer and heat transfer, which is a dissolution-diffusion-evaporation model. For the atmospheric system, at the membrane/water interface side, liquid water is dissolved in the surface layer of the membrane, and the water is transferred by the concentration diffusion as the main driving force; at the membrane/gas interface side, the liquid water is evaporated into the gas. Humidification function. The mathematical model can be expressed as follows.

(1) On the membrane/water side, the water concentration on the membrane surface is

\[ c_{w/m} = \lambda_{m/w} c_s \]  

(1)

In the formula, the concentration is expressed as mol·cm\(^{-3}\), the subscript \( w \) indicates water, and \( \lambda \) the water content of the membrane, \( h_{2O}/so_{2} \) is the number of water molecules per sulfonic acid group in the membrane. The superscript \( m/w \) indicates the membrane/water side, and the subscript \( s \) indicates sulfonic acid group.

(2) The flux of water in the membrane is

\[ N = D \frac{dc}{dx} \]  

(2)

In the formula, \( N \) is the water diffusion flux, mol·cm\(^{-2}\)·s\(^{-1}\), \( D \) is the diffusion coefficient in the film, cm\(^{2}\)·s\(^{-1}\), \( x \) indicating the direction along the film thickness, cm, when \( \lambda > 4 \), there are

\[ D_w = 1.25e^{-6exp(2416(\frac{1}{303} - \frac{1}{T}))} \]  

(3)

(3) The heat obtained by humidified hydrogen is

\[ \Delta H = NAM_{H_2} \Delta h \]  

(4)

In the formula, \( H \) is enthalpy, kW, \( A \) represents the effective area of the membrane, cm\(^2\), \( M \) is the molar mass, kg·mo\(^{-1}\), and the subscript \( H_2 \) indicates hydrogen, \( h \) is rate enthalpy, w·kg\(^{-1}\).

(4) The heat released by the humidifying water is
In the formula, \( Q \) means heat, kW, \( c_p \) is constant pressure specific heat, kJ·kg⁻¹·K⁻¹, \( \dot{m} \) is mass flow rate, kg·s⁻¹, \( T \) is temperature, K.

3. Experimental system description
The experimental setup is shown in figure 2. The experimental hydrogen is from a high pressure gas cylinder, and the humidified water is deionized water. After passing through the flow controller, the hydrogen enters the humidifier. The humidified water enters the humidifier through the temperature and flow controller, and the hydrogen and humidified water pressure is controlled by the back pressure regulating valve. There are temperature and pressure sensors on the upstream and downstream of the humidification water side humidifier, and temperature, pressure and humidity sensors on the upstream and downstream of the hydrogen side humidifier. The interval between each two data points in the experiment was 5 minutes.

![Figure 2. Structure of hydrogen humidifier testing system.](image)

The membrane humidifier parameters are shown in table 1, \( \rho \) for density, \( \delta \) for thickness, subscript \( m \) for film, and \( \text{dry} \) for dry state.

| Parameter | \( \rho_{\text{m,dry}} \) | \( M_{\text{m,dry}} \) | \( A \) | \( \delta_m \) |
|-----------|-----------------|-----------------|-------|-----------|
| Value     | 1.98 kg/cm²     | 1100 g/mol      | 13945 cm² | 0.01524 cm |

4. Results and discussion
The membrane humidifier has excellent water permeability. It can obtain good humidification effect by humidifying hydrogen with liquid water. When the humidification water flow is not large, the relative humidity of the humidified hydrogen outlet can reach 100%. The temperature difference between the humidified hydrogen outlet temperature and the humidified water inlet and outlet is the main factor affecting the overall efficiency of the humidification system. When the humidified hydrogen outlet is supersaturated wet hydrogen, the higher the temperature, the less easily the water vapor condenses. When the flow rate of hydrogen is constant, the larger the flow rate of humidified water, the smaller the temperature difference between the inlet and outlet, and the higher the outlet temperature of the humidified hydrogen gas, the greater the consumption of the humidification pump. During the experiment, the hydrogen inlet temperature was 20°C, the relative humidity was less than 30%, and the humidification water inlet temperature was set to 60°C.

Figure 3 and figure 4 respectively show the relationship between the humidification water flow rate and the temperature and humidity of the humidified hydrogen outlet when the hydrogen flow rate is constant, and the relationship between the humidification water flow rate and the temperature difference between the inlet and outlet. The flow unit is slpm (in the standard state, l/min) and the temperature unit is K (Kelvin). The volume flow rate of hydrogen is 750 slpm, the flow rate of humidification water increases from 10.45 slpm to 18.68 slpm, and the difference between hydrogen
outlet temperature and humidification water inlet temperature is reduced from 2.5K to 0K; the relative humidity of humidified hydrogen outlet does not change much, always between 120%–130%, because the membrane water activity is much larger than 1 on the membrane/humidified water surface, the water content is much greater than 14, in the atmospheric system, the hydrogen working pressure is low. The evaporation of liquid water on the surface of hydrogen gas has a small evaporation resistance, so the rate of liquid water passing through the membrane to hydrogen is very fast. After passing through the membrane, some liquid water will not desorb from the membrane surface. In figure 4, the humidification water flow rate increased from 10.45 slpm to 18.68 slpm, and the humidification water inlet and outlet temperature difference decreased from 10K to 6.3K. The humidification water flow increased from 10.45 slpm to 18.68 slpm, the humidification pump power will increase significantly, and the humidification hydrogen outlet temperature and humidity conditions will not change much. After entering the fuel cell stack, there will be no significant impact on the performance of the reactor.

Figure 3. Effect of humidified water flow on hydrogen humidification performance.

Figure 4. Effect of humidified water flow on temperature difference between humidified water inlet and outlet.

Figure 5 and figure 6 respectively show the relationship between the hydrogen flow rate and the temperature and humidity of the outlet when the humidification water flow rate is 12 slpm, and the relationship between the hydrogen flow rate and the temperature difference between the inlet and outlet of the humidified water. The hydrogen flow rate is 300, 500, 750 slpm, respectively. When the hydrogen flow rate increases, the relative humidity of the hydrogen outlet does not change much, between 120% and 130%; the difference between the humidification water inlet temperature and the hydrogen outlet temperature is 0.7K, 1.2K, 2.3K respectively. In Figure 6, the hydrogen flow rate increases from 300 slpm to 750 slpm, and the temperature difference between the humidified water inlet and outlet increases from 4K to 8.4K. When the fuel cell stack load increases, the hydrogen flow rate increases, and the wet hydrogen dew point temperature entering the fuel cell stack does not change much.
According to the equation, the amount of helium gas increase and the amount of humidification water heat energy reduction are calculated separately, and the measurement error is used.

$$\delta_\vartheta = (\Delta H - Q)/[(\Delta H + Q)/2]$$

In the experiment, no more than 10%, the heat balance in the humidification process is basically reflected in the test data, and the experimental data is credible.

5. Conclusions
The experimental study on the heat and mass transfer performance of the hydrogen membrane humidification system of high-power fuel cell stack shows that the membrane humidification system which humidifies hydrogen with liquid water can obtain good hydrogen humidification effect, and the humidified hydrogen outlet is over. Saturated state; hydrogen volume flow rate is 750 slpm, when the ratio of humidified water to hydrogen mass flow is greater than 180, the temperature difference between hydrogen outlet temperature and humidification water inlet temperature is less than 2K when the temperature and flow rate of the humidified water are constant. The relative humidity of the humidified hydrogen outlet does not change significantly as the fuel cell stack load increases.

6. References
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