Establishment and Experimental Analysis of Runtime Humidity Soft Sensing Model of PEMFC Based on Internal Resistance

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Abstract. The internal humidity is very important in Proton Exchange Membrane Fuel Cell, but it cannot be measured directly because of the closed structure of the cell. It has been proofed that humidity has strongly contract with some internal parameters such as resistance, temperature and gas pressure. After studying and analysis on classical humidity mechanism models, this paper operated some experiments on PEMFC runtime humidity based on soft sensing technology, then established and test humidity soft sensing model based on runtime internal resistance. The experiment results shown that the output value of soft sensing model matched well with the theoretical calculation data. And the errors were almost within 1%. It verified the effectiveness of soft sensing model based on internal resistance.

1. Introduction
The internal humidity of fuel cell is a very important operating parameter [1]. The operating environment and working load of fuel cells for electric vehicles often change greatly [2-4]. Therefore, how to accurately and quickly measure and control internal humidity state parameters, and maintain its operation within the optimal range, that is a key issue of research in fuel cell measurement and control. At present, many studies have been carried out on the parameters of fuel cell such as temperature, inlet gas humidity and the influence on the running state. However, there are few studies on humidity measurement and fuel cell health monitoring, and most of them are at the level of qualitative analysis. The corresponding quantitative analysis is not sufficient, and the problem research is not perfect and needs to be further studied.

Figure 1 shows the structure of the PEMFC. Due to structural and system problems, the fuel cell humidity cannot be tested directly. At the same time, the internal humidity problem will directly affect the working performance of the battery system, leading to fatal failure of the fuel cell system, and finally leading to the durability failure of the battery. Therefore, it is urgent to adopt a new method of indirect detection to accurately measure and monitor the operating humidity parameters. Therefore, it
is very necessary and urgent to develop the study of systematic humidity soft sensing with fuel cell as the object [5].

Figure 1. Single cell working principle of PEMFC.

Figure 2. Humidity soft sensing model based on internal resistance and operating temperature.

Table 1. Classical humidity mechanism models and their comparison.

| No. | Model name                  | Representative personage | Assumptions                                                                 | The main idea                                                                 | Disadvantages                                                                                                                                 |
|-----|-----------------------------|---------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Convection and transfer model | Eikerling                 | The main structure of proton exchange membrane is porous medium. The structure of membrane hole will affect water transfer. | The concepts of limiting current and ohmic control area are explained. The characteristics of membrane structure and polarization curve were analyzed. | Without considering the limit of gas transfer in the electrode, it is assumed that capillarity affects the water balance in the electrolyte membrane only. |
| 2   | Dust flow model              | ThamPan                   | Water transport in the membrane includes convection and diffusion. The dissociated H+ of water molecules and sulfonic groups in the membrane forms as H3O+. | Under variable operating conditions, the conductivity of the membrane can be calculated. | It is assumed that there's only liquid water. |
| 3   | Statistical mechanics model  | Paddison                  | The pore of the membrane is filled with a cylinder of N water molecules, each of which has μ dipole momentums. | The proton diffusion coefficient is derived. | The study on the transport process of protons and water molecules inside the membrane is isolated. |
| 4   | Diffusion model              | Springer and Berbardi     | Water equilibrium in gas phase and membrane phase; The film is uniformly moist and completely saturated with water. The water dissolved in the membrane is mainly generated by the electroinduced drag migration and electrochemical reactions at the cathode. | According to the water activity on the surface of the membrane, The relationship between diffusion coefficient and membrane water content was summarized. Proton exchange membrane fuel cells do not need external humidification in a large current density range | It is only effective for water saturated electrolyte film, and it is suitable for thin film, and ignoring the water flooding of diffusion layer and cathode in the calculation. |
2. Humidity Model Study

Currently, there are many researches on water management models of proton exchange membrane, but most of them are realized around convection and transfer model, dust flow model, statistical mechanics model and diffusion model [6]. Classical humidity mechanism models and their comparison are shown as table 1.

The results show that the diffusion model assumes that water is in equilibrium in the gas phase and the membrane phase, the membrane is uniformly wet and completely saturated with water, and the water dissolved in the membrane is mainly generated in the cathode by the electroinduced drag migration and electrochemical reaction. It is consistent with the actual situation of proton exchange membrane fuel cell operating state [7]. Therefore, the research object in this paper is more suitable for applying the diffusion model.

3. Establishment and Experiment of Humidity Soft Sensing Model

3.1. Humidity Soft Sensing Model Establishment

From the water balance process of proton exchange membrane fuel cell, and according to the electroinduced drag migration, concentration difference reverse diffusion and pressure migration, there are:

\[ W_{in}^{a} - W_{out}^{a} = -W_{drag}^{a} + W_{diff}^{a} + W_{pres}^{a} \]  

(1)

Where, \( W_{in}^{a} \) is anode humidifying water; \( W_{out}^{a} \) is the water which expelled from the anode in gaseous form; \( W_{drag}^{a} \) is the water of the electroinduced drag migration; \( W_{diff}^{a} \) is concentration difference reverse diffusion water; \( W_{pres}^{a} \) is the water coursed by pressure migration.

Set \( D_{w} \) is the diffusion coefficient, set \( \alpha_{w} \) is the activity of water, and set \( \lambda \) as the water content of proton exchange membrane, then the water content of proton exchange membrane can be expressed as formula 2:

\[ \lambda = 0.043 + 17.81\alpha_{w} - 39.85\alpha_{w}^{2} + 36.0\alpha_{w}^{3} \]  

(2)

| T | R   | H   | T   | R   | H   | T   | R   | H   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
| 23.8 | 28.02 | 0.158 | 28.8 | 12.50 | 0.329 | 38.5 | 8.03 | 0.449 |
| 24.1 | 19.59 | 0.224 | 29.4 | 10.39 | 0.393 | 39.3 | 8.05 | 0.443 |
| 24.5 | 19.58 | 0.223 | 30.1 | 10.38 | 0.389 | 40.8 | 7.16 | 0.489 |
| 25.0 | 19.58 | 0.222 | 30.8 | 10.42 | 0.384 | 41.7 | 7.17 | 0.483 |
| 25.3 | 19.67 | 0.220 | 31.8 | 9.19  | 0.430 | 42.6 | 7.17 | 0.478 |
| 25.6 | 14.88 | 0.289 | 32.4 | 9.16  | 0.428 | 43.5 | 7.17 | 0.473 |
| 26.1 | 14.92 | 0.287 | 33.8 | 9.17  | 0.434 | 44.3 | 7.18 | 0.467 |
| 26.7 | 14.92 | 0.284 | 34.8 | 8.04  | 0.471 | 45.1 | 6.55 | 0.507 |
| 27.1 | 14.92 | 0.283 | 35.7 | 8.05  | 0.465 | 46.1 | 6.54 | 0.501 |
| 27.6 | 12.55 | 0.333 | 37.0 | 8.04  | 0.458 | 47.1 | 6.52 | 0.496 |
| 28.2 | 12.51 | 0.332 | 37.6 | 8.04  | 0.454 | 48.1 | 6.54 | 0.488 |

According to the requirements of the diffusion model, internal resistance and operating temperature, which have significant impacts on the internal humidity of the proton exchange membrane [8-10], are taken as the main factors and as the input of the fuel cell soft sensing model. And the water content (humidity) value is taken as the output of the soft sensing model [11,12]. The model of internal humidity (i.e. membrane water content) based on internal resistance of fuel cell is shown in figure 2.
3.2. Experiment Results
Table 2 shows the partial data of internal resistance and temperature measured in the test. T is temperature, R is internal resistance, H is humidity. Where, the unit of temperature is °C and the unit of internal resistance is \(m\Omega\).

**Table 3.** Comparison between output value of soft sensing model and theoretical calculation data.

| theoretical data | output value | theoretical data | output value | theoretical data | output value |
|------------------|--------------|------------------|--------------|------------------|--------------|
| 0.149            | 0.158        | 0.336            | 0.329        | 0.455            | 0.449        |
| 0.212            | 0.224        | 0.388            | 0.393        | 0.452            | 0.443        |
| 0.222            | 0.223        | 0.388            | 0.389        | 0.480            | 0.489        |
| 0.224            | 0.222        | 0.386            | 0.384        | 0.481            | 0.483        |
| 0.229            | 0.220        | 0.427            | 0.430        | 0.481            | 0.478        |
| 0.281            | 0.289        | 0.429            | 0.428        | 0.475            | 0.473        |
| 0.284            | 0.287        | 0.436            | 0.434        | 0.470            | 0.467        |
| 0.286            | 0.284        | 0.468            | 0.471        | 0.517            | 0.507        |
| 0.289            | 0.283        | 0.466            | 0.465        | 0.506            | 0.501        |
| 0.330            | 0.333        | 0.460            | 0.458        | 0.503            | 0.496        |
| 0.331            | 0.332        | 0.460            | 0.454        | 0.491            | 0.488        |

According to the soft sensing model, the output value of water content (humidity) is obtained. And the value of the maximum water content is formed as scalar 1. The comparison results between the soft sensing model output value and the theoretical calculation data is shown in table 3 and figure 3.

![Figure 3](image)

**Figure 3.** The comparison results between the soft sensing model output value and the theoretical calculation data.

The error curve is shown in figure 4. It can be seen from figure 4 that all data errors are almost within 1%, except for a few points. Which show that the output value of soft sensing model based on internal resistance coincide well with the theoretical calculation data.

![Figure 4](image)

**Figure 4.** The error curve.
4. Conclusion

The internal humidity is very important in Proton Exchange Membrane Fuel Cell, but it cannot be measured directly. To solve this problem, we studied and analyzed the classical mechanism models of PEMFC and carried out relevant experiments based on soft sensing technology. The main conclusions are as follows:

1) Due to the special structure of PEMFC, sensors or detection devices cannot be directly placed, so this paper adopts soft sensing method.
2) Although many assumptions are made in the diffusion model, it is quite consistent with the actual operation of PEMFC. Therefore, this paper uses the diffusion model to complete the relevant experiments and modelling analysis process.
3) Based on the mechanism relationship between humidity and internal resistance, temperature and pressure, etc., we adopted runtime internal resistance, runtime battery temperature, reaction gas pressure and other parameters as the input of the model in the experiment, and completed the experiment and modelling of the humidity soft sensing model according to the diffusion model.
4) The experiment results shown that the output value of soft sensing model matched well with the theoretical calculation data. And the errors were almost within 1%. And the results verify the effectiveness of soft sensing model based on internal resistance.

The study in this paper is based on many assumptions of PEMFC diffusion model. However, the actual operation of PEMFC is more complex, and it is more difficult to estimate the humidity of PEMFC during operation, which requires further study and exploration.

Acknowledgement

The relevant research work of this paper was supported by the national natural science foundation of China (51977061), and the PHD start fund in Hubei University of Technology (BSQD2014063).

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