Quantification of Liquid Water Saturation in a Transparent Single-Serpentine Cathode Flow Channels of PEM Fuel Cell by Using Image Processing

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Abstract

The objective of this research is to quantify the amount of water on the cathode side in different PEM fuel cell operations. It can be revealed by direct visualization in an operational transparent single-serpentine PEM fuel cell. Images of water formed inside the cathode gas channels are recorded by a digital camera to present the phenomena of water flooding in PEM fuel cell. Effects of oxygen flow rate, cell temperature and time development on water flooding are discussed. The water coverage area in the cathode flow channels is estimated by image processing. The experimental results show that the excessive low or high cell temperature provides the undesirable water content in the PEM fuel cell. The increasing of oxygen flow rate can remove the liquid water out of the cathode flow channels but too high oxygen flow rate, the membrane is in the dehydrated state and the fuel cell performance decreased dramatically. The water flooding doesn’t appear in the cathode flow channels when fuel cell operated with time development.

Keywords: PEM fuel cell; water management; direct visualization; transparent single-serpentine, image processing

1. Introduction

Fuel cell is presently regarded as a promising energy conversion system for the electric vehicles and power stations. PEM fuel cell has been interested more than the other types of fuel cells because it has many advantages such as using of solid polymer electrolytes, low operating temperatures, cold start up, high energy efficiency and power density [1-2]. The polymer membrane in the PEM fuel cell should be in a hydrated state to facilitate proton transport across the membrane. If there is not enough water, the membrane becomes dry and its resistance increases sharply. However, if too much water is present, flooding may occur, which will block the transport of reactants to the reaction sites. So that the water management in PEM fuel cell is an importance key and has been stressed widely in the literature [3]. In the present, there are many techniques to study the liquid water distribution in PEM fuel cell [4]. The visualization technique offers the advantage of studying the two-phase
phenomena at different levels of fuel cell operating condition on water distribution and water flooding in PEM fuel cell. However, the visualization technique primarily provides qualitative data and there have been few reports concerning to quantify the water content through this technique [5]. The purpose of this paper is to quantify the amount of water on the cathode side in different fuel cell operating conditions. The effects of cell temperatures, cathode gas flow rates and time development on the water flooding were examined. The water images were recorded by digital camera. The image processing routine was use to quantify the water coverage area on the gas flow channels in the cathode side of PEM fuel cell.

2. Image processing

A digital image is defined as a two-dimensional function, \( f(x,y) \), where \( x \) and \( y \) are spatial coordinates, and the amplitude of \( f \) at any pair of coordinates \((x,y)\) is image the intensity or gray level (0-255) of the image at that point. A digital image is composed of a finite number of elements, each of which has a particular location and gray level value. These elements are referred to as image elements or pixels. Pixel is the term most widely used to denote the elements of a digital image. The digital image can be considered as a large array of pixels, which constitute digital image. So that, the digital image can be manipulated with matrices operation in image processing routine to evaluate any important information.

The amount of water in the cathode flow channels of PEM fuel cell can be quantified by using image processing routine. The water appearance in the cathode flow channels was represented by the water pixels in spatial domain of the digital image. The water image \( W(x,y) \) was separated from background image \( I(x,y) \) by subtracting the image of reaction state \( I_r(x,y) \) described in Eq. (1) from dry state image \( I_d(x,y) \). (Eq. (2)). The calculation of water content form the images may be written as the following equations.

\[
I_d(x,y) = I(x,y) + \eta_d(x,y), \quad (1)
\]

\[
I_r(x,y) = I(x,y) + W(x,y) + \eta_r(x,y), \quad (2)
\]

\[
W(x,y) = I_r(x,y) - I_d(x,y) + (\eta_d(x,y) - \eta_r(x,y)) \quad (3)
\]

where \( \eta_d(x,y) \) and \( \eta_r(x,y) \) are noise functions of dry state and reaction state, respectively. These may be occurred from reflection and disturbance of light source frequency (50 Hz). However, the term of noise function in Eq. (3) may be negligible because the subtraction of both noise functions is very small. So that Eq. (3) can be rewritten as Eq. (4) without the term of noise function.

\[
W(x,y) = I_r(x,y) - I_d(x,y) \quad (4)
\]

The number of water pixels in Eq. (4) can be determined by using histogram of the image \( W(x,y) \). The histogram is a graph indicating the number of times each gray level occurs in the image. The probability density of water pixels \( P_w(k) \) can be obtained by normalized histogram with dividing all water pixels \( n_k \) by the total number of pixels \( n \) in the image as showed in Eq. (5).

\[
P_w(k) = \frac{n_k}{n} \quad (5)
\]

where \( k \) is gray level of water. Therefore, the water coverage area \( A_w \) on the cathode side can be quantified from the image by multiplication of \( P_w(k) \) with active area size 25 cm\(^2\).

\[
A_w = 25 \times P_w(k) \quad (6)
\]

However, the capable water coverage area has only in the part of gas flow field channels area, it is not including of the ribs area. Therefore, from the single-serpentine flow field design of cathode side, the
maximum area is covered by water about 55 percent of the whole active area.

3. Experimental

A transparent PEM fuel cell was designed in single-serpentine flow channels (1.5 mm in channel width, 2 mm in depth and 1.5 in rib width). Fig. 1 shows the schematics drawing of the cathode side of a transparent PEM fuel cell.

The brass plate was machined as the cathode flow field and current plate, but on the anode side used conventional graphite as a flow field plate. Transparent plastic thickness of 15 mm was used as the end plate at the cathode side. Membrane electrode assembly (MEA) was made form Gore in 5612 series. There is 0.6 mg/cm² at cathode and 0.4 mg/cm² at anode. The membrane thickness is 25 µm. The size of physical active area is 25 cm². When the machined brass plate was assembled between the transparent plastic and MEA, the 3M 468MP adhesive film was used as sealing strip between the flow field channel and the transparent plastic to obstruct the gas cross over the ribs and leak out from the cathode active area. A transparent window was set up in the cathode clamping plate so that we were able to investigate the water build-up and flooding inside the PEM fuel cell as shown in Fig. 2. Two circle electrical heater pads were attached on the anode end plate and cathode flow field plate. A temperature controller and temperature sensor were used to control the cell temperatures.

Fig. 1 The schematic drawing of the cathode flow field plate

Fig. 2 A transparent single-serpentine PEM fuel cell

Fig. 3 shows the experimental set up. The experimental set-up consists of: (i) a fuel and oxidant reactant supply system; (ii) a fuel cell test system; (iii) a digital camera recording system. Pure hydrogen and oxygen were used as fuel and oxidant reactant, respectively.

Fig. 3 The diagram of experimental set-up in transparent PEM fuel cell

Both hydrogen and oxygen gas to the fuel cells was not humidified; so the water was observed in the flow channels of the transparent fuel cells was generated only from the electrochemical reaction. Gas flow rates were controlled by mass flow controllers (MKS, Type MB-100) with a precision of ± 0.1%. A nitrogen purge system made sure to clean out the fuel and oxidant reactant left in the test system pipelines.
and fuel cells. An electronic load (TDI, RBL448 Series) was applied in the external circuit of the tested fuel cell. The flow patterns and images of water distribution and water flooding in the cathode flow channels were recorded by digital camera (Cannon, GT10). During each experiment, the reaction area of the cathode side was first took a photo in dry state, and then took it again every 5 minutes after fuel cell reaction occurred with a constant current loading of 5 A. All images should be positioned on the same frame reference and same intensity of light sources. Before change the operating conditions, nitrogen gas was used to purge along the gas flow channels to recondition to the dry state again.

4. Results and discussion

The water flooding images in the transparent PEM fuel cell with the difference fuel cell operating conditions were recorded by digital camera. The image processing was used to manipulate the digital images in this experiment. Fig. 4 (a) – (b) are showed an example of image processed in this study

![Fig. 4 The images manipulated by image processing; (a) water flooding image (b) the processed image](image)

4.1 The effect of cell temperature

Fig. 5 shows the effect of cell temperature in the cathode flow channels. All images were recorded at 20 minutes after fuel cell had loaded at a constant current of 5 A. The fuel cells operated at the condition of atmosphere pressure, oxygen gas flow rate of 40 ml min⁻¹ and hydrogen flow rate of 60 ml min⁻¹. There was no external humidifier supplied to the both side of PEM fuel cell, in order to confirm the water was generated from the fuel cell reaction

![Fig. 5 Effect of cell temperature on water appearance in cathode flow channels](image)

Fig. 5 shows that the liquid water in the flow channels at low temperature was much more than at high temperature. When fuel cell operated at temperature lower than 60 °C, there was greater area of water covered in the cathode flow channels than higher temperature. By increasing of the cell temperature, the area of water coverage in the flow channels decrease according to the result of water quantified by image processing in Fig. 6 because the vapor
condensation rate at high temperature was much slower than that at low temperature. So that, at the highest temperature of 70 °C, there was only a little water in the cathode flow channels. In addition, Fig. 7 shows that when the cell temperature was increasing from 25 °C to 60 °C, the fuel cell performance would be higher. According to the water product from fuel cell reaction appeared in the cathode flow channels of 40 °C was higher than 25 °C. But, the water began to decrease a little at temperature of 60 °C, because there was more water vapor generated in cathode flow channels. Before, it was decreased rapidly in the highest temperature of 70 °C, which provided the lowest of fuel cell performance.

Fig. 7 The cell voltages in difference cell temperatures at constant current loading of 5 A

4.2 The effect of oxygen flow rates
The cathode gas flow rate can contribute to water removal. Fig. 8 shows the images of condensation of liquid water in the cathode flow channels at different oxygen flow rates. These photos were taken at current of 5 A after the fuel cell had operated for 20 minutes at the ambient pressure and cell temperature of 25 °C. The oxygen flow rates were 40 ml min⁻¹, 70 ml min⁻¹, 150 ml min⁻¹ and 280 ml min⁻¹, and according to the stoichiometric ratios were 2.18, 3.81, 8.16 and 15.24, respectively. In these cases, the oxygen gas was not humidified.

![Image of water coverage area size in cathode flow channels](image1)

**Fig. 6** The water coverage area size in cathode flow channels of difference cell temperatures

![Image of cell voltages in difference cell temperatures](image2)

**Fig. 7** The cell voltages in difference cell temperatures at constant current loading of 5 A

![Image of effect of oxygen flow rates on water appearance in cathode flow channels](image3)

**Fig. 8** Effect of oxygen flow rates on water appearance in cathode flow channels

When the oxygen flow rate was higher than 40 ml min⁻¹, the water content in cathode flow channels were decreased almost fifty percent and more decrease in flow rate higher than 150 ml min⁻¹ as presented in Fig. 9. Therefore, the water flooding in the flow channels was more
serious in flow rate condition of 40 ml min\(^{-1}\) because oxygen flow rate was too low to remove the water occurring from the electrochemical sites of the PEM fuel cell. On the other hand, if the flow rate is higher than 150 ml min\(^{-1}\), there is not enough water to keep the membrane in hydrate state according to the experimental result in flow rate of 280 ml min\(^{-1}\) which provided the lowest cell performance as shown in Fig. 10. In this case, due to the oxygen gas was not humidified before entering the fuel cell, the generated water was insignificant on fuel cell operation. So, a appropriate amount of oxygen flow rate must be supplied to remove the excess liquid water out of the cathode flow channels, but still some water remained for fuel cell operation.

![Graph](image1)

Fig. 9 The water coverage area size in cathode flow channels of difference oxygen flow rates

Fig. 10 The cell voltages in difference oxygen flow rates at constant current loading of 5 A

4.3 Effect of fuel cell operation time

The water generation is occurred continuously under fuel cell operation. It has been monitored and recorded by digital camera under an operating condition regardless of temperature and oxygen flow rate during fuel cell operation time. During this progression, a transparent PEM fuel cell was loaded at constant current of 5 A, a constant cells temperature of 50 °C with 100 % RH on both side of anode and cathode from external humidifiers at atmospheric condition. The oxygen gas flow rate of 40 ml min\(^{-1}\) and hydrogen flow rate of 60 ml min\(^{-1}\). Fig. 11 shows the processed images of liquid water in the transparent cathode flow channels on the different time of PEM fuel cell operation. All images were recorded at 10 min, 20 min, 30 min and 40 min after constant current loading.

![Images](image2)

Fig. 11 Effect of operation time on cathode water build-up in the flow field channels
It can be observed that the small water droplets condensed on the inner surface of transparent acrylic after current loading for 10 min. Between 20 min and 40 min of fuel cell operation, the water droplets increased in size and accumulated in the flow channels. The quantification of water coverage area in different fuel cell operating time can be presented in Fig. 12. It shows that the water coverage area in the cathode flow channels decreased gradually while the water droplets increased in size after 20 min of operation. Due to the flow field pattern in this research is single serpentine and also fuel cell assembled in single cell configuration. It is easy to drive the large size of water droplets in the cathode flow channels under oxygen flow rate of 40 ml/min or stoichiometric ratios of 2.18. So that, the water flooding in the transparent cathode flow channels did not observe and also the fuel cell performance curve did not show any signal of voltage drop during fuel cell operation time as shown in Fig. 13.

5. Conclusion

The present study has revealed the effect of cell temperature; oxygen flow rates and time development of water flooding in transparent cathode flow channels of PEM fuel cell. The digital images from transparent cathode flow channels were recorded to quantify the water coverage area in different operating condition by using image processing routine. The processed images provide the information of water flooding phenomena in difference fuel cell operating conditions as following:

(1) At low temperature, there was a lot of liquid water in flow channels. But at very high temperature, there was not enough water to humidify the membrane. Excessive low or high can lead to deterioration of fuel cells performance.

(2) Increasing cathode flow rate can remove water out of the cathode flow channels and lead to high cell performance, but too high flow rate, the membrane became too dry and its conductivity to proton ions reduced. Then, the fuel cell performance decreased dramatically.
The time development of water flooding did not affect on the PEM single cell performance and the water flooding did not appear in the transparent single serpentine of cathode flow channels.

However, despite its initial promise, image processing technique requires much more development and refinement for the application of PEM fuel cell. A further improvement in the resolution of image and the photography technique will increase the accuracy of this technique.

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7. References