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Evaluation of current intensity distribution of PEMFC based on 4-points magnetic field measurement

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ABSTRACT

The current intensity distribution of a fuel cell is an important factor that determines its performance. A contactless method that does not affect the fuel cell and can accurately and quickly assess internal cell conditions is required to measure the current distribution. Therefore, this study proposes a simplified method to measure current distribution based on four magnetic field measurements. The proposed method demonstrates that the purge control performed in flooding during constant-current operation results in non-uniform current distribution, despite effective voltage recovery. This study shows that the method is useful to eliminate the non-uniformity of current distribution for improving long-term operation of fuel cells.

Keywords: Fuel cell, magnetic sensor, control, failure detection

1. INTRODUCTION

The current distribution in a fuel cell is important for determining its performance. Conventionally, it has been measured using contact-type devices such as printed circuit boards (PCBs). Recently, non-destructive, contactless measurement methods have been studied to predict current distribution using magnetic sensors placed around the fuel cell [1], [2]. However, most of the proposed methods use measurements from multiple sensors to improve accuracy, which is computationally time-consuming. Therefore, the current distribution cannot be predicted in real time. Consequently, these methods are typically used as a posteriori diagnosis.

According to our research, the number of measurement points can be reduced and evaluated by inserting them in an air-cooled fuel cell [3]. We have also previously demonstrated that the system can be used for control as it enables real-time identification of faults such as flooding or dry-out by considering the measurements from at least two magnetic sensors, but only the current distribution at the time of the fault [4].

In this study, we present a method to calculate the intensity, which is fundamentally a simple current distribution, in real time from the magnetic fields at four points, and the change in the current intensity distribution when switching between flooding and dry-out.

2. EXPERIMENTAL AND CALCULATION METHOD

2.1 PEMFC system and conditions

Based on the experimental data in [4], a method to calculate the current intensity distribution the magnetic field at four points is presented in this study. The experiment was performed using a 5-cell PEMFC stack with a constant current of 15 A for 1 h and an un-humidified hydrogen and air supply. Flooding and dry-out were alternately simulated by controlling the hydrogen and air supply and the speed of the fan. Flooding was a dead-end operation, i.e., the hydrogen outlet was closed, and the experiment was performed at a low temperature of 45°C. During dry-out, the hydrogen outlet was opened, and the operating temperature was increased to a maximum of 80°C. When switching from flooding to dry-out operation, the hydrogen outlet valve was opened, and the system was purged by increasing the air flow rate. When switching from dry-out to flooding operation, the fan continued to operate until the temperature reached 50°C.

A small 2 mm-square sensor was inserted in the cooling hole of the proton exchange membrane fuel cell (PEMFC) stack and output the magnetic field according to the current. It collected measurements every 0.5 seconds during operation at four measurement points between the inlet and the outlet of the fuel cell, as shown Fig.1.

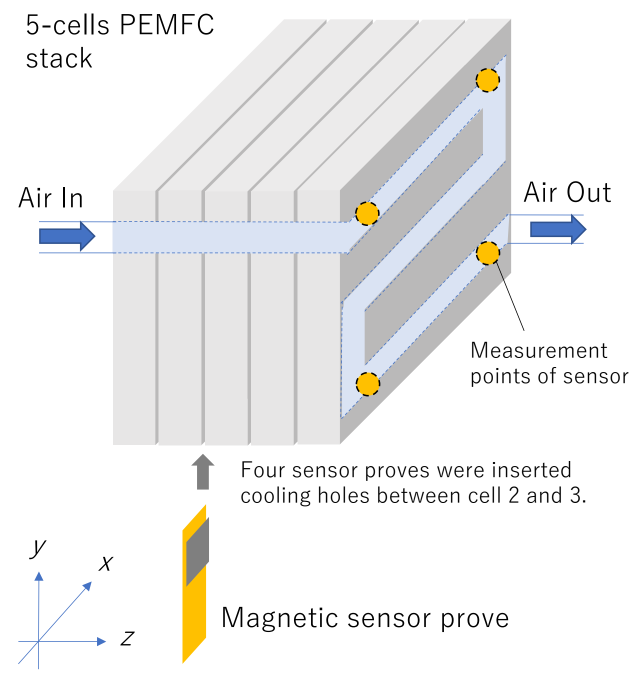


Fig. 1 Schematic diagram of the measurement point

2.2 Calculation of current intensity distribution based on 4-points magnetic field measurement

The magnetic field in the air-cooled PEMFC stack was measured using a probe equipped with a magnetic sensor. According to Biot-Savart's law, the magnetic field from the current is expressed as follows:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_r}{4\pi}\int_{V_s}\frac{\mathbf{r_s}-\mathbf{r}}{\left|\mathbf{r_s}-\mathbf{r}\right|^3}\times\mathbf{j}(\mathbf{r_s})\,dV_s \tag{1}$$

The direction of the vector is determined by the relationship between the measuring and calculation point. When the fuel cell is operated at a constant current, the total current at the start of operation ***J*** and the total current at the time of calculation ***J'*** are constant.

$$\sum_{i=1}^{n}\mathbf{J} = \sum_{i=1}^{n}\mathbf{J}' = const. \tag{2}$$

Furthermore, in the presence of a current distribution, as in a fuel cell, the current flows in the direction perpendicular to the distribution plane (z-direction in Fig. 1). According to Ampere's law, the magnetic fields induced by the current exist only in the x and y directions. Therefore, the current ***Jx, Jy*** due to each component of the magnetic field in the case of the four measurement points are expressed as follows:

$$\begin{pmatrix} J_{1x} \\ \vdots \\ J_{4x} \end{pmatrix} = \begin{pmatrix} a'_{11x} & \cdots & a'_{14x} \\ \vdots & \ddots & \vdots \\ a'_{41x} & \cdots & a'_{44x} \end{pmatrix}^{-1} \begin{pmatrix} B_{1x} \\ \vdots \\ B_{4x} \end{pmatrix} \tag{3}$$

$$if\ \ k = n:$$
$$a'_{knx} = 0$$

$$else:$$
$$a'_{knx} = \frac{(r_{xn} - r_{xk})}{\sqrt{(r_{xn} - r_{xk})^2 + (r_{yn} - r_{yk})^2}}$$

$$k, n = 1\ to\ 4$$

$$\begin{pmatrix} J_{1y} \\ \vdots \\ J_{4y} \end{pmatrix} = \begin{pmatrix} a'_{11y} & \cdots & a'_{14y} \\ \vdots & \ddots & \vdots \\ a'_{41y} & \cdots & a'_{44y} \end{pmatrix}^{-1} \begin{pmatrix} B_{1y} \\ \vdots \\ B_{4y} \end{pmatrix} \tag{4}$$

$$if\ \ k = n:$$
$$a'_{kny} = 0$$

$$else:$$
$$a'_{kny} = \frac{(r_{yn} - r_{yk})}{\sqrt{(r_{xn} - r_{xk})^2 + (r_{yn} - r_{yk})^2}}$$

$$k, n = 1\ to\ 4$$

The diagonal matrix is assumed to be approximately zero, this approximate current value is called “current intensity” and is used to calculate the distribution. The current intensity at the four measurement points can be expressed as the sum of each component as follows:

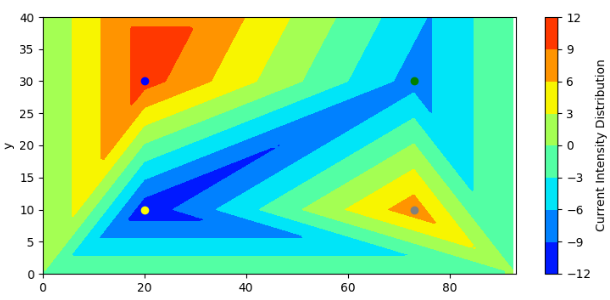
$$J_n = J_{nx} + J_{ny} \tag{5}$$
$$n = 1\ to\ 4$$

The value of the current intensity at these four points and four boundary points are used to estimate the current intensity distribution. The difference of the current intensity distribution from its initial state at each measurement point is calculated. Although only four points are required to calculate the current intensity distribution, resolution can be improved if more measurement point data are included. The calculation can be handled by increasing the matrix by one row and one column for a unit increase in the number of measurement points.

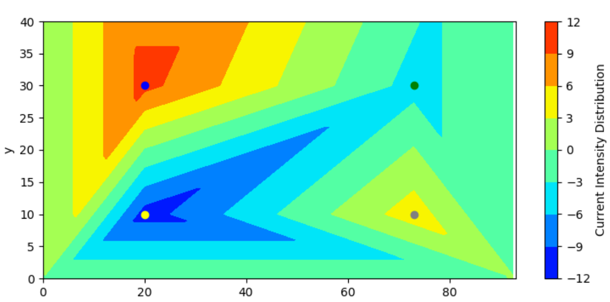
3. RESULTS AND DISCUSSION

3.1 Switching from Flooding to Dry-Out

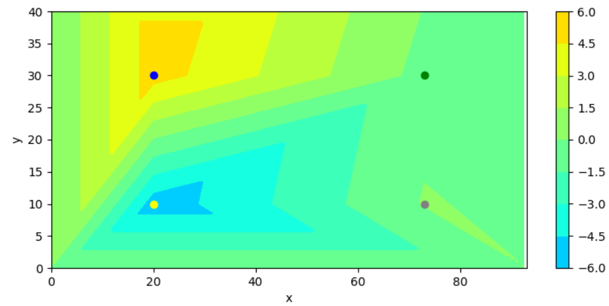
Figure 2(a) shows the current intensity distribution before purge control. The upper left and lower right correspond to the air inlet and outlet sides, respectively. The current distribution at the air inlet side is higher compared with its initial condition. In contrast, the blue coloration in the middle section indicates that the current is lower compared with its initial condition. Purge control was performed for the period of operation from 760-780 seconds, and the voltage was recovered. In Fig. 2(b), the current distribution at the inlet side remains high and that in the middle is low, as shown in Fig. 2 (a). This indicates that the purge control has effectively removed water from the channel. However, a small quantity of water remains in the membrane-electrode assembly MEA of several cells. At this point, the current distribution is expected to remain low. Fig. 2 (c) and (d) show the current intensity distribution at 850 and 900 seconds, which gradually becomes uniform. These results indicate that although power generation can be recovered by purge control, achieving in-plane uniformity is time-intensive.



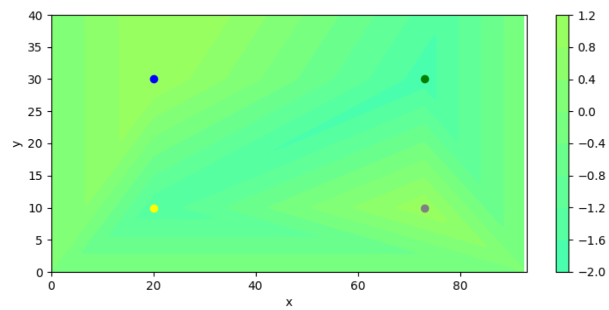
(a) 750 sec.



(b) 800 sec.



(c) 850 sec.

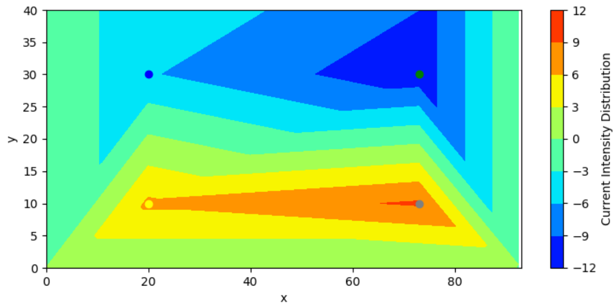


(d) 900 sec.

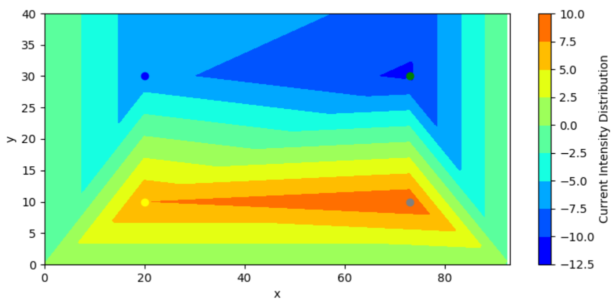
Fig. 2 Current intensity distribution before and after purging

3.2 Switching from Dry-Out to Flooding

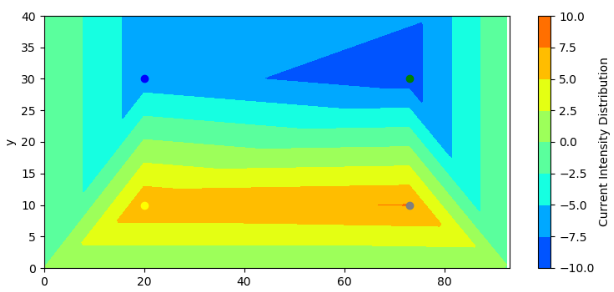
Figure 3(a) shows the current intensity distribution before cooling. Before control by dry-out, it was lower at the inlet and larger at the outlet side. This is consistent with the theoretical consideration that the current distribution decreases at the inlet due to dry air and increases at the outlet side due to increased moisture from generated water. Cooling control was performed for the period of operation from 1063 to 1195 sec. As shown in Figs. 3 (b) and (c), the current distribution remains unchanged. Moreover, equalizing the entire stack by fan cooling took a long time. Current intensity distribution becomes uniform as shown in Fig. 3 (d) similarly to that in the purge control in flooding operation.



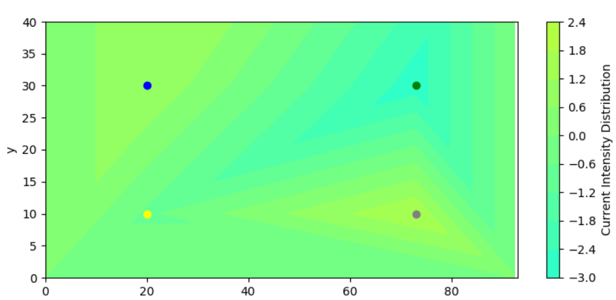
(a) 1050 sec.



(b) 1100 sec.



(c) 1150 sec.



(d) 1200 sec.

Fig. 3 Current intensity distribution before and after cooling

4. CONCLUSIONS

In this study, a method to calculate the current intensity distribution was proposed and evaluated during switching between flooding and dry-out operations. Typically, the performance is evaluated in terms of voltage and current. However, the proposed method demonstrates that the current distribution remained non-uniform during purge control, despite voltage recovery. Furthermore, cooling after dry-out was shown to be time-intensive. In addition, after cooling, the current distribution returned to a uniform state. These results verify that the method is useful to eliminate the non-uniformity of current distribution for improving long-term operation of fuel cells.

ACKNOWLEDGEMENT

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