Numerical Analysis of Temperature Distributions in Single Cell of PEFC by Heat Transfer Model Considering Vapor Transfer

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Abstract: Polymer Electrolyte Fuel Cell (PEFC) is required to be operated at temperature at 100 °C for fuel cell vehicle applications during the period from 2020 to 2025 in Japan. It is expected that micro porous layer (MPL) and thinner polymer electrolyte membrane (PEM) would enhance the power generation performance of PEFC at this temperature. The key objective of this study is to analyse the impact of MPL and thickness of PEM on the temperature distributions of interface between the PEM and catalyst layer at the cathode (i.e., the reaction surface) in a single PEFC. A 1D multi-plate heat transfer model, considering vapor transfer, which is based on temperature data of separator measured using thermograph in power generation process. It is developed to evaluate temperature at the reaction surface. This study is investigated the effect of flow rate and relative humidity of supply gases on temperature distribution on reaction surface. The study reveals that the impact of flow rate of supply gas on temperature distribution on reaction surface is smaller with and without MPL. It is observed that the even temperature distribution on reaction surface as well as higher power generation performance can be obtained with MPL irrespective of thickness of PEM and relative humidity conditions.

Key words: PEFC, heat transfer model, vapor transfer, temperature distribution, high temperature, relative humidity condition, thickness of PEM, MPL.

1. Introduction

According to NEDO road map 2017 in Japan [1], polymer electrolyte fuel cell (PEFC) is desired to be operated at around 100 °C for fuel cell vehicle (FCV) and dynamic loading applications during the period from 2020 to 2025. However, the current PEFC has Nafion membrane and it is usually operated within the temperature range between 60 °C and 80 °C [2, 3]. When the PEFC is operated at higher temperature, the following advantages can be achieved: (1) enhancement of electrochemical kinetics for both electrode reactions, (2) simplification in the cooling system due to increase in temperature gradient between the PEFC stack and coolant for FCV application, (3) increase in tolerability of CO and allowing the PEFC to use lower quality reformed hydrogen [4]. However, uneven temperature distribution especially at operation temperature around 100 °C would cause the degradations of polymer electrolyte membrane (PEM) and catalyst layer since they are easy to be dried. Water’s behaviour (humidity level) influences the performance of the PEM, gaseous flows in gas diffusion layer (GDL) and catalyst layer. Therefore, it is important to understand the temperature distribution in single cell of PEFC in order to improve the power generation performance and realize the long operating life time. It is the aim of this study.

The characteristics of PEFC up to 200 °C have already reported in Refs. [5-28]. However, most of them have focused on development of new material [6,
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9, 10, 13, 14, 18, 23, 24, 27], the performance through current density distribution, voltage change [5, 8, 12, 15-17, 21, 22, 25, 26], and durability [7, 11]. Though some researches have reported the temperature distribution in the single cell of PEFC operated at higher temperature [19, 20, 28], they have not investigated the temperature near the interface between the PEM and catalyst layer at the cathode, which is termed as a reaction surface in the paper. Therefore, the heat and mass transfer characteristics of PEFC, which dominantes the power generation performance, operated at higher temperature around 100 °C, are not investigated yet.

Nishimura et al. [29] have conducted to measure the temperature distributions on separator’s back of single cell of PEFC by thermograph. Since there has been no disturbance of heat and mass transfer due to non-destruction measurement, the temperature distribution under power generation conditions could be measured more accurately. An empirical model to predict the temperature distribution on reaction surface has developed using the measured data. Though the authors have surveyed the literatures, there has been no precious study to estimate the temperature distribution on reaction surface from measuring the temperature data at separator’s back. If a heat transfer model, which can predict the temperature distribution on the reaction surface with the measured separator back’s temperature, needs to be developed, the temperature distribution could be estimated easily without any difficult and complex temperature measurement in future.

Nishimura et al. [30-32] have conducted the studies in which a 1D multi-plate heat transfer model using the temperature data at separator’s back, measured by thermograph under power generation, has developed in order to estimate the temperature distribution inside single cell of PEFC. Since the single cell of PEFC consists of some components having plate shapes such as PEM, catalyst layer, GDL and separator, Nishimura et al. [30-32] proposed the heat transfer model assuming the heat transfer through multi-plates for these components of the cell. The reaction surface temperature \( T_{\text{react}} \) has calculated using the heat transfer model. It is a new approach to clarify the heat transfer mechanism in single cell of PEFC by means of the data measured by the thermograph and the presented model. Comparing the model [30-32] with the other models [33-35], there have been some differences. For example, the 1D model developed by Khandelwal and Mench [33] considered the heat transfer from the PEM, catalyst layer, anode/cathode diffusion media, and backing plate based on Fourier’s thermal conduction equation. It has used the heat sources such as the Joule heating from the PEM, entropic loss, activation and concentration over-potential, and Joule heating in the catalyst layer [33]. However, it has confirmed that the temperature gradients for the targeted regions under the similar operational conditions have been almost the same [30]. Additionally, Nishimura et al. [36] have already investigated 3D model using commercial CFD software to predict the distribution of \( T_{\text{react}} \). The 3D model calculated the equations such as conservation equations of mass, momentum and energy in porous region as well as electrochemical reaction. According to the comparison of the results predicted by the 3D model with that by the 1D model proposed in this study under the several operation conditions, the differences of \( T_{\text{react}} \) between two models were from 0.1 K to 1.5 K. Consequently, the study considers that the proposed 1D should be validated with the 3D model. Additionally, the advantages of proposed 1D model can be evaluated as follows: (1) The proposed 1D model can predict the temperature distribution on reaction surface without complex simulation using the 3D model and temperature measurement with higher accuracy; (2) The proposed 1D model can provide a new procedure predicting the temperature distribution on the reaction surface using the measured temperature data of the separator back without disturbing the heat and mass transfer phenomena as well as power generation
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operation in PEM, catalyst layer and GDL; (3) It can save the time to clarify the mechanism of PEFC with a simple model.

Though the 1D model, proposed in this study, is considered to be reasonable, vapor transfer process is not considered. The heat transfer mechanism is influenced by vapor transfer, and it is considered to estimate the effective thermal conductivity of components of single cell of PEFC. It is a new approach to predict the temperature distribution on the reaction surface.

The objective of the work is to develop and validate a heat transfer model for predicting the temperature distribution on the reaction surface as well as to analyse the desirable operational condition under operation temperature at 100 °C. This study focuses on the impact of micro porous layer (MPL) with the thickness changes of PEM in order to investigate the desirable operation condition under higher temperature operation. The MPL can reduce the liquid saturation in the GDL and increase the oxygen diffusion in the catalyst layer [37]. In addition, the MPL can increase the water flux from the cathode to the anode [37]. Therefore, it is expected that temperature distribution on the reaction surface can be influenced by the MPL.

Moreover, Penga et al. [38] have reported that the thinner PEM, whose thickness has 10 μm, provided the lower ohmic resistance as well as better hydration of the anode H₂ due to the increased back diffusion, when operated at 60 °C. It can be expected that the positive effects of thinner PEM can be promoted the power generation performance of PEFC at higher temperature operation. The study is evaluating three types of PEM to investigate the impact of their thickness on the temperature distribution on reaction surface. In addition, the work is investigating the effects of MPL, flow rate, relative humidity of supply gases on temperature distribution on reaction surface.

2. Calculation Procedures

2.1 1D Multi-plate Heat Transfer Model

The multi-plate single cell PEFC module used in this study is illustrated in Fig. 1 [39]. In the module, the separator’s back is the opposite side of surface contacting GDL. The separator’s back surface temperatures $T_{surf,c}$ and $T_{surf,a}$ are measured by using the thermograph. The separator, which has 5 flow serpentine channels, is used for thermograph [29] in the power generation process in order to obtain the temperature data.

Fig. 1  1D multi-plate heat transfer module.
The heat transfer across the module is considered in 1D direction only. In the module, the cell is divided into a gas channel and a rib part. In Fig. 1, the upper and the lower parts represent rib part and channel part, respectively. For both parts, the heat transfer is assumed to be through-plane direction. The heat generated on reaction surface is transferred to the cathode and anode sides separately. Although the gas flowing through the gas channel from the inlet to the outlet of the cell carries away some heat, the amount of heat taken is less than 1% of the estimated reaction heat of approximately 20 W [30]. Therefore, the heat carried away by the gas flow is neglected in the study.

Additionally, the mass flow rate of gas flowing through the gas channel is very small ranging from 10⁻⁸ to 10⁻⁶ kg/s, and it is resulting that the thermal conduction of gas in the gas channel is considered to be static. Also, in the study, the heat pipe effect due to phase change of water is not considered. However, the other studies conducting the numerical simulation by 3D model have considered the phase change of water [40, 41], reported that the temperature difference between $T_{\text{react, rib}}$ under the rib and that under the channel is relatively small, which is approximately within 1 °C at 70-80 °C.

Therefore, it is considered the heat pipe effect that assists heat removal under the channel is small.

2.2 Reaction Heat Generation Rate

The reaction heat generation rate $H_{\text{react}}$ is calculated as follows [32, 39]:

$$H_{\text{react}} = E_i - W_E$$  \hspace{1cm} (1)

where, $E_i$ is the ideal (total) energy generation rate by the water formation from H₂ and O₂ based on the higher heating value ($q_{\text{HHV}}$). $W_E$ is the electric work generated by PEFC. $E_i$ and $W_E$ are expressed as follows:

$$E_i = m_{H_2} \times q_{\text{HHV}}$$  \hspace{1cm} (2)

$$W_E = I \times V$$  \hspace{1cm} (3)

where, $I$ is the total current obtained by the experiment (= 20 A). In the study, the power generation data corresponding to load current at 20 A (= 0.80 A·cm⁻²) are used for the heat transfer modeling. $V$ is the voltage and obtained through the experiment. $m_{H_2}$ is the molar flow rate of supplied H₂, which is equal to the ideal reaction consumption rate of H₂ required for the generation at 20 A, i.e., the stoichiometric ratio (s.r.) of 1.0. Here, s.r. is the ratio of the feed amount of H₂ and O₂ to that required to generate a current of 20 A. The flow rate of supply gas (H₂) at s.r. of 1.0 is defined as follows:

$$m_{H_2} = I/nF$$  \hspace{1cm} (4)

where, $m_{H_2}$ is the molar flow rate of supplied H₂ (mol·s⁻¹); $n$ is the valence of ion (= 2 for H₂); $F$ is the Faraday constant (= 96,500 C·mol⁻¹). $m_{O_2}$ is the molar flow rate of supplied O₂ (mol·s⁻¹) and it is calculated as follows:

$$H_2 + 1/2O_2 = H_2O$$  \hspace{1cm} (5)

The actual s.r. of supply gases is used for the mass flow controller installed at the inlet of the single cell. The mass flow meter is installed at the outlet of the cell in the power generation experiment [29].

2.3 Heat-Balance Equations for Calculating Reaction Surface Temperature

The heats transferred in the proposed model are expressed as Eqs. (6)-(10) and they are described in Ref. [39]:

$$H_{\text{rib,c}} = K_{\text{rib,c}} \cdot A \cdot (T_{\text{react,rib}} - T_{\text{surf,c}})/2$$  \hspace{1cm} (6)

$$H_{\text{chan,c}} = K_{\text{chan,c}} \cdot A \cdot (T_{\text{react,chan}} - T_{\text{surf,c}})/2$$  \hspace{1cm} (7)

$$H_{\text{rib,a}} = K_{\text{rib,a}} \cdot A \cdot (T_{\text{react,rib}} - T_{\text{surf,a}})/2$$  \hspace{1cm} (8)

$$H_{\text{chan,a}} = K_{\text{chan,a}} \cdot A \cdot (T_{\text{react,chan}} - T_{\text{surf,a}})/2$$  \hspace{1cm} (9)

$$H_{\text{react}} = H_{\text{rib,c}} + H_{\text{chan,c}} + H_{\text{rib,a}} + H_{\text{chan,a}}$$  \hspace{1cm} (10)

where, $H_{\text{rib,c}}$ is the heat flux to cathode side under rib (W); $K_{\text{rib,c}}$ is the overall heat transfer coefficient for cathode side under rib (W·m⁻²·K⁻¹); $A$ is the heat transfer area which is the active area of MEA, i.e., power generation area (= 0.0025 m²); $T_{\text{react,rib}}$ is the reaction surface temperature under rib (K or °C); $T_{\text{surf,c}}$ is the separator’s back surface temperature at cathode (K or °C); $H_{\text{chan,c}}$ is the heat flux to cathode side under channel (W); $K_{\text{chan,c}}$ is the overall heat transfer coefficient for cathode side under channel (W·m⁻²·K⁻¹);
$T_{react,chan}$ is the reaction surface temperature under channel (K or °C); $H_{rib,a}$ is the heat flux to anode side under rib (W); $K_{rib,a}$ is the overall heat transfer coefficient for anode side under rib (W m⁻² K⁻¹); $T_{surf,a}$ is the separator’s back temperature at anode (K or °C); $H_{chan,a}$ is the heat flux to anode side under channel (W); $K_{chan,a}$ is the overall heat transfer coefficient for anode side under channel (W m⁻² K⁻¹). $K_{rib,c}$, $K_{chan,c}$, $K_{rib,a}$ and $K_{chan,a}$ are defined as follows:

$$
\frac{1}{K_{rib,c}} = \frac{\delta_{cat}}{k_{cat}} + \frac{\delta_{MPL}}{k_{MPL}} + \frac{\delta_{GDL}}{k_{GDL}}
$$

$$
+ \frac{\delta_{rib}}{k_{rib}} + \frac{\delta_{sep}}{k_{sep}}
$$

$$
1/K_{chan,c} = \frac{\delta_{cat}}{k_{cat}} + \frac{\delta_{MPL}}{k_{MPL}} + \frac{\delta_{GDL}}{k_{GDL}}
$$

$$
+ \frac{\delta_{chan}}{k_{chan,c}} + \frac{\delta_{sep}}{k_{sep}}
$$

$$
1/K_{rib,a} = \frac{\delta_{PEM}}{k_{PEM}} + \frac{\delta_{cat}}{k_{cat}} + \frac{\delta_{MPL}}{k_{MPL}}
$$

$$
+ \frac{\delta_{GDL}}{k_{GDL}} + \frac{\delta_{rib}}{k_{rib}} + \frac{\delta_{sep}}{k_{sep}}
$$

$$
1/K_{chan,a} = \frac{\delta_{PEM}}{k_{PEM}} + \frac{\delta_{cat}}{k_{cat}} + \frac{\delta_{MPL}}{k_{MPL}}
$$

$$
+ \frac{\delta_{GDL}}{k_{GDL}} + \frac{\delta_{chan}}{k_{chan,a}} + \frac{\delta_{sep}}{k_{sep}} = (14)
$$

where, $\delta_{cat}$ is the thickness of the catalyst layer (m); $k_{cat}$ is the thermal conductivity of the catalyst layer (W m⁻¹ K⁻¹); $\delta_{MPL}$ is the thickness of MPL (m); $k_{MPL}$ is the thermal conductivity of MPL (W m⁻¹ K⁻¹); $\delta_{GDL}$ is the thickness of GDL (m); $k_{GDL}$ is the thermal conductivity of GDL (W m⁻¹ K⁻¹); $\delta_{rib}$ is the thickness of the separator rib (m); $k_{rib}$ is the thermal conductivity of the separator rib (W m⁻¹ K⁻¹); $\delta_{sep}$ is the thickness of the separator excluding rib part (m); $k_{sep}$ is the thermal conductivity of the separator excluding rib part (W m⁻¹ K⁻¹); $\delta_{chan}$ is the thickness of the channel of separator (m); $k_{chan}$ is the thermal conductivity of the mixture gas in the channel of separator (W m⁻¹ K⁻¹); $\delta_{PEM}$ is the thickness of PEM (m); $k_{PEM}$ is the thermal conductivity of PEM (W m⁻¹ K⁻¹).

In Table 1, the effective thermal conductivities of porous media $k$, are from Refs. [29, 33]. Since the effective thermal conductivities, given in Table 1, are obtained when the cell component pores are filled with air at room temperature, the corrected effective thermal conductivities are calculated for the cell component pores filled with H₂ and O₂, and H₂O at 100 °C, at the initial operating temperature of cell ($T_{ini}$).

In addition, the vapor transfer from the catalyst layer at the cathode is considered. The water is produced by electro-chemical reaction to the outside of the single cell by gas diffusion. Fig. 2 illustrates 1D multi-plate vapor transfer model and $\varepsilon$ is porosity (-).

The vapor concentration in catalyst layer at the cathode is calculated by adding the H₂O produced by electro-chemical reaction to the vapor. It is mixed with the supplied gas to the cell, and it is used in estimating the relative humidity of supply gas. The cell is divided into twenty segments as explained later. The amount of H₂O produced by electrochemical reaction is divided into the twentieth, and it is assumed to be added with gas flows through segments. Since H₂ and O₂ are consumed by electro-chemical reaction in the anode and cathode, respectively, the concentration of H₂ and O₂ in catalyst layer, at the anode and cathode, respectively, is decreased from the inlet to the outlet of the cell through segments by twentieth. Finally, the vapor concentration in catalyst layer at the cathode is calculated by considering the change in vapor and O₂. It is important to analyze the diffusivity of vapor in each component of the cell. Table 2 lists diffusivity of vapor, which is used in this study. It is assumed that a binary diffusion of H₂O, and H₂ or O₂ is occurred in each component except for PEM. As in PEM, the vapor is transferred via electro-osmotic drag with H⁺, which is influenced by water content in PEM [43]. The relationship between the relative humidity of supply gas and diffusivity of vapor in PEM is based on Ref. [43]. The vapor transfer is estimated by Eqs. (15)-(26).
\[ \omega_1 = -D_{\text{H}_2\text{O}-\text{O}_2}(C_1 - C_{\text{cat}})/\delta_{\text{MPL}}\epsilon_{\text{MPL}} \quad (15) \]
\[ \omega_2 = -D_{\text{H}_2\text{O}-\text{O}_2}(C_2 - C_{\text{cat}})/\delta_{\text{GDL}}\epsilon_{\text{GDL}} \quad (16) \]
\[ \omega_3 = -D_{\text{H}_2\text{O}-\text{O}_2}(C_3 - C_{\text{cat}})/\delta_{\text{Rib}}\epsilon_{\text{Rib}} \quad (17) \]
\[ \omega_4 = -D_{\text{H}_2\text{O}-\text{O}_2}(C_4 - C_{\text{cat}})/\delta_{\text{sep}}\epsilon_{\text{sep}} \quad (18) \]
\[ \omega_5 = -D_{\text{H}_2\text{O}-\text{O}_2}(C_5 - C_{\text{cat}})/\delta_{\text{PEM}}\epsilon_{\text{PEM}} \quad (19) \]
\[ \omega_6 = -D_{\text{H}_2\text{O}-\text{H}_2}(C_6 - C_{\text{cat}})/\delta_{\text{cat}}\epsilon_{\text{cat}} \quad (20) \]
\[ \omega_7 = -D_{\text{H}_2\text{O}-\text{H}_2}(C_7 - C_{\text{cat}})/\delta_{\text{MPL}}\epsilon_{\text{MPL}} \quad (21) \]
\[ \omega_8 = -D_{\text{H}_2\text{O}-\text{H}_2}(C_8 - C_{\text{cat}})/\delta_{\text{GDL}}\epsilon_{\text{GDL}} \quad (22) \]
\[ \omega_9 = -D_{\text{H}_2\text{O}-\text{H}_2}(C_9 - C_{\text{cat}})/\delta_{\text{Rib}}\epsilon_{\text{Rib}} \quad (23) \]
\[ \omega_{\text{cathode}} = (C_{\text{cat}} - C_{\text{IV}})D_{\text{H}_2\text{O}-\text{O}_2}/(\delta_{\text{GDL}}\epsilon_{\text{GDL}} + \delta_{\text{Rib}}\epsilon_{\text{Rib}} + \delta_{\text{sep}}\epsilon_{\text{sep}} + \delta_{\text{MPL}}\epsilon_{\text{MPL}}) \quad (24) \]
\[ \omega_{\text{anode}} = (C_{\text{cat}} - C_{\text{IV}})/\delta_{\text{MPL}}\epsilon_{\text{MPL}}D_{\text{PEM}} + (\delta_{\text{cat}}\epsilon_{\text{cat}} + \delta_{\text{GDL}}\epsilon_{\text{GDL}} + \delta_{\text{Rib}}\epsilon_{\text{Rib}} + \delta_{\text{sep}}\epsilon_{\text{sep}} + \delta_{\text{MPL}}\epsilon_{\text{MPL}})/(D_{\text{H}_2\text{O}-\text{O}_2}) \quad (25) \]

where \( D_{\text{H}_2\text{O}-\text{O}_2} \) is the binary diffusivity of \( \text{H}_2\text{O} \) and \( \text{O}_2 \) \((\text{m}^2\text{s}^{-1})\), \( C_1 \) is the vapor concentration on the interface between MPL and GDL at the cathode \((\text{kg} \cdot \text{m}^{-3})\), \( C_{\text{cat}} \) is the vapor concentration in catalyst layer at the cathode \((\text{kg} \cdot \text{m}^{-3})\), \( C_2 \) is the vapor concentration on the interface between GDL and separator rib or separator channel at the cathode \((\text{kg} \cdot \text{m}^{-3})\), \( C_{\text{III}} \) is the vapor concentration on the interface between separator rib or separator channel and separator excluding rib part at the cathode \((\text{kg} \cdot \text{m}^{-3})\), \( C_4 \) is changed by 20% RH, 40% RH, 60% RH and 80% RH to evaluate the impact on the temperature distribution on reaction surface. In the calculation, the thermal conductivity of each gas is estimated by the above described vapor transfer \([45]\).

In order to solve Eqs. (6)-(9), the temperatures are measured using the thermograph and substituted into
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Table 1 Specifications of PEFC components referred from the manufacturing catalog and previous studies [29, 37-39, 42].

<table>
<thead>
<tr>
<th>Parts</th>
<th>Size</th>
<th>Characteristics</th>
<th>Porosity (–)</th>
<th>Effective thermal conductivity (W m⁻¹ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer electrolyte membrane (PEM)</td>
<td>50.0 mm × 50.0 mm × 0.127 mm (Nafion 115), 50.0 mm × 50.0 mm × 0.051 mm (NRE-212) or 50.0 mm × 50.0 mm × 0.025 mm (NRE-211)</td>
<td>Nafion 115, NRE-212 or NRE-211 (produced by Du Pont Corp.)</td>
<td>0.28</td>
<td>0.195</td>
</tr>
<tr>
<td>Catalyst layer</td>
<td>50.0 mm × 50.0 mm × 0.01 mm (attached with PEM)</td>
<td>Pt/C (20 wt% Pt loading)</td>
<td>0.78</td>
<td>0.27</td>
</tr>
<tr>
<td>Micro porous layer (MPL)</td>
<td>50.0 mm × 50.0 mm × 0.003 mm (attached with GDL)</td>
<td>Mixture of carbon black and PTFE</td>
<td>0.60</td>
<td>1.0</td>
</tr>
<tr>
<td>Gas diffusion layer (GDL)</td>
<td>50.0 mm × 50.0 mm × 0.19 mm (TGP-H-060)</td>
<td>Carbon paper (TGP-H-060 produced by Toray Corp.)</td>
<td>0.78</td>
<td>1.7</td>
</tr>
<tr>
<td>Separator</td>
<td>75.4 mm × 75.4 mm × 2.00 mm (thickness of rib part: 1.00 mm) (gas supply area: 50.0 mm × 50.0 mm)</td>
<td>Carbon graphite, serpentine</td>
<td>0.15</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2 Diffusivity of vapor to consider the vapor transfer in the cell [43, 44].

<table>
<thead>
<tr>
<th>Component</th>
<th>Diffusivity (m²·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O-H₂</td>
<td>9.27 × 10⁻⁵</td>
</tr>
<tr>
<td>H₂O-O₂</td>
<td>3.57 × 10⁻³</td>
</tr>
<tr>
<td>PEM (40% RH)</td>
<td>3.958 × 10⁻⁷</td>
</tr>
<tr>
<td>PEM (80% RH)</td>
<td>1.166 × 10⁻⁶</td>
</tr>
</tbody>
</table>

Table 3 Operating conditions of power generation for temperature measurement by thermograph.

<table>
<thead>
<tr>
<th>Anode</th>
<th>Cathode</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>O₂</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gas type</th>
<th>H₂</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of supply gas at inlet (°C)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Relative humidity of supply gas (% RH)</td>
<td>40, 80</td>
<td>40, 80</td>
</tr>
<tr>
<td>Pressure of supply gas at inlet (absolute) (MPa)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Flow rate of supply gas at inlet (NL·min⁻¹) (stoichiometric ratio (–))</td>
<td>0.280 (2.0)</td>
<td>0.140 (2.0)</td>
</tr>
</tbody>
</table>

These equations as $T_{surf,c}$ and $T_{surf,a}$. The operation conditions, used for power generation in order to measure temperatures with thermograph, are given in Table 3. Analysis using 1D multi-plate heat transfer is carried out by means of the data obtained under these conditions. In the power generation process, the current density is kept at 0.80 A·cm⁻² in order to obtain the temperature data by thermograph, so the cell temperature could be kept higher than the initial temperature with no heat input from the electric heater required [29, 42]. Therefore, the temperature distribution data caused by reaction heat only at separator back could be obtained. The experimental procedure for measuring the temperature during power generation has been explained in Refs. [29, 41].

In order to use the temperature data measured by thermograph in 1D multi-plate heat transfer model, the image of in-plane temperature distribution is divided into segments of 10 mm × 10 mm each, as shown in Fig. 3. Although the power generation area is 50 mm × 50 mm, and the observation area is set to be 40 mm × 50 mm to prevent a gas leak through observation window in the experiments. The gas channel width and the rib width, of investigated separator, are 1.0 mm; and the number of gas channel is 5. The segment includes the area consisting of five pairs of rib and gas.
channel. The average temperature in each segment at anode and cathode is used for the separator’s back temperature in 1D multi-plate heat transfer model. The segment is named as A to T along the gas flow direction (Fig. 3).

Regarding the segment A and T, the insulators covering the gas pipes interfere with the thermograph measurement in some area of the segment as it can be seen in Fig. 3. In this study, the effective temperature of segment A and T is obtained by removing the temperature data that are interfered by the insulator from the total temperature data in each segment. In the heat transfer analysis, it is assumed that \( T_{\text{surf,c}} \) on the rib side is equal to \( T_{\text{surf,c}} \) on the channel side as well as \( T_{\text{surf,a}} \) because the difference between them could not be recognized by the measured data.

Considering the above described assumptions and Eqs. (6)-(14), the reaction surface temperature \( T_{\text{react}} \) is expressed as follows:

\[
T_{\text{react}} = T_{\text{react,rib}} = T_{\text{react,chan}} = \frac{2H_{\text{react}}/A + (K_{\text{rib,c}} + K_{\text{chan,c}})T_{\text{surf,c}} + (K_{\text{rib,a}} + K_{\text{chan,a}})T_{\text{surf,a}}}{(K_{\text{rib,c}} + K_{\text{chan,c}} + K_{\text{rib,a}} + K_{\text{chan,a}})} \tag{27}
\]

3. Results and Discussion

3.1 Impact of Flow Rate of Supply Gas and Relative Humidity of Room on Temperature Distribution

It is considered that flow rate of supply gas at inlet influences the heat and mass transfer as well as power generation performance from the viewpoint of gas diffusion and water transfer. In addition, it is necessary to investigate the impact of relative humidity of air surrounding single cell of PEFC on temperature distribution on reaction surface, calculated by the proposed model. Tables 4-6 list temperature distribution on reaction surface for use of Nafion 115 without MPL and simulated by the proposed heat transfer for the stoichiometric ratio (s.r.) of supply gas of 1.5, 2.0 and 3.0, respectively. The relative humidity of supply gas is 80% RH at the anode and 80% RH at the cathode (A80%RH, C80%RH). The relative humidity of air surrounding single cell of PEFC is changed by 20% RH, 40% RH, 60% RH and 80% RH. In these tables, \( T_{\text{react}} \) is calculated by the proposed model and compared with \( T_{\text{react}} \) which is calculated by the heat transfer model without considering vapor transfer, which is displayed by W/O in these tables.

According to Tables 4-6, it is known that the impact of s.r. on temperature distribution on reaction surface is smaller, and it is confirmed under the condition with MPL. The reason could be that the gas supply is sufficient for power generation even at s.r. = 1.5 [40]. Since the power generation characteristics/performances, obtained by experiment in this study, are almost the same among different s.r., the results for s.r. = 1.5 are shown in the following section since they can represent the characteristics of different s.r.

In addition, it is obvious that the impact of relative humidity of air surrounding single cell of PEFC on temperature distribution on reaction surface is also small, which is confirmed under the condition with MPL. The digit of value of \( C_{\text{cat}} \) is 2 to 4 times as large as that of \( C_{\text{IV}} \). It is thought that the impact of relative humidity of air surrounding single cell of PEFC, i.e., \( C_{\text{IV}} \) on temperature distribution on reaction surface is smaller. The annual mean relative humidity of air in Tsu city, Japan in 2019 where the authors are working is 63% RH [46]. The results obtained by assuming \( C_{\text{IV}} \) of 60% RH are shown in the following section.
Table 4  Effect of relative humidity of air surrounding single cell of PEFC on distribution of $T_{\text{react}}$ using Nafion 115 for s.r. = 1.5 (A80%RH, C80%RH).

<table>
<thead>
<tr>
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<th>60% RH</th>
<th>80% RH</th>
<th>W/O</th>
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Table 5  Effect of relative humidity of air surrounding single cell of PEFC on distribution of $T_{\text{react}}$ using Nafion 115 for s.r. = 2.0 (A80%RH, C80%RH).

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<thead>
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$T_{\text{react}}$ is calculated by the proposed model and compared with $T_{\text{react}}$ calculated by the heat transfer model without considering vapor transfer. The $T_{\text{react}}$ calculated by the proposed model is higher by 0.1-0.2 °C. This tendency is also confirmed under the condition with the MPL. The effective thermal conductivity of each component in the cell is reduced since the thermal conductivity of gas phase in each component is reduced by the increase in the amount of vapor, and it is resulting in the decrease in the overall heat transfer coefficient as shown in Eqs. (11)-(14). Consequently, $T_{\text{react}}$ calculated by the proposed model becomes relatively higher.  

3.2 Impact of Relative Humidity of Supply Gas on Temperature Distribution

Figs. 4-6 show the impact of relative humidity of supply gas on temperature distribution on reaction surface with MPL using Nafion 115, Nafion NRE-212 and Nafion NRE-211, respectively. These figures show the results for that A80%RH, C80%RH, the
relative humidity of supply gas of 80% RH at the anode and 40% RH at the cathode (A80%RH, C40%RH), the relative humidity of supply gas of 40% RH at the anode and 80% RH at the cathode (A40%RH, C80%RH), and the relative humidity of supply gas of 40% RH at the anode and 40% RH at the cathode (A40%RH, C40%RH), respectively. Since the power generation is not carried out using Nafion 115 for A40%RH, C40%RH, the results are not shown in Fig. 4.

According to Figs. 4-6, it is observed that the impact of relative humidity of supply gas on temperature distribution on reaction surface is smaller irrespective of thickness of PEM. Since MPL performs to reduce the liquid saturation in GDL and increase the oxygen diffusion in the catalyst layer as well as the water flux from the cathode to the anode [37], it is thought that the difference in temperature distribution among different relative humidity conditions is smaller.

In addition, it is revealed that the temperature distribution on reaction surface is nearly flat irrespective of relative humidity of supply gases. Since the gas diffusion and water transfer are promoted due to MPL, it is believed that the power generation occurs from the inlet to the outlet uniformly, resulting in the even temperature distribution on reaction surface.

3.3 Impact of PEM on Temperature Distribution

Figs. 7-9 show the impact of thickness of PEM on temperature distribution on reaction surface for the different relative humidity conditions.

![Fig. 4 Impact of relative humidity of supply gas on $T_{\text{react}}$ with MPL using Nafion 115.](image)

![Fig. 5 Impact of relative humidity of supply gas on $T_{\text{react}}$ with MPL using Nafion NRE-212.](image)
Fig. 6  Impact of relative humidity of supply gas on $T_{\text{react}}$ with MPL using Nafion NRE-211.

Fig. 7  Comparison of $T_{\text{react}}$ among different PEMs with MPL for A80%RH, C80%RH.

Fig. 8  Comparison of $T_{\text{react}}$ among different PEMs with MPL for A80%RH, C40%RH.
According to Figs. 7-9, it is observed that the impact of thickness of PEM on temperature distribution on reaction surface is smaller irrespective of relative humidity conditions. Since the gas diffusion and water transfer are enhanced due to MPL, it is believed that the power generation occurs from the inlet to the outlet uniformly irrespective of thickness of PEM, resulting in the even temperature distribution on the reaction surface.

3.4 Impact of MPL on Temperature Distribution

Fig. 10 shows the impact of MPL on temperature distribution on reaction surface using Nafion 115 for the different relative humidity conditions. The results with MPL are indicated by W, while those without MPL are indicated by W/O. Since the power generation is not carried out using Nafion 115 without MPL for A40%RH, C80%RH, the results are not shown in Fig. 10. $T_{\text{react}}$ without MPL is higher by approximately 5 °C than that with MPL for A80%RH, C80%RH. In addition, $T_{\text{react}}$ without MPL is higher by approximately 1-2 °C than with MPL for A80%RH, C40%RH. Since the power generation is smaller without MPL, $H_{\text{react}}$ increases as shown by Eq. (1), and it is resulting that $T_{\text{react}}$ becomes higher according to Eq. (27). It is noticed from Fig. 10 that the temperature distribution on reaction surface with MPL is almost flat. Since the gas diffusion and water transfer are enhanced due to MPL, the power generation would occur from the inlet to the outlet uniformly. As a result, the even temperature distribution on reaction surface is obtained.
It is observed that MPL is effective to obtain even temperature distribution on reaction surface as well as high power generation performance. It is confirmed irrespective of thickness of PEM, flow rate and relative humidity of supply gases. However, it is considered to investigate the impact of MPL on temperature distribution with the change in thickness of GDL and separator. Since these components have larger thickness compared to PEM, it is considered that they might influence not only temperature distribution on reaction surface but also power generation performance. It will be investigated in the near future.

4. Conclusions

The temperature distribution on reaction surface is calculated by the 1D multi-plate heat transfer model considering the vapor transfer, which is considered in the study under operational temperature of 100 °C. In this work, the investigation of the impact of thicknesses of PEM is analyzed for temperature distribution on reaction surface for the different flow rates, relative humidity of supply gases. As a result, the following conclusions have been drawn from the obtained results.

The impact of flow rate of supply gas on the temperature distribution is not significant under the condition with and without MPL. Since the gas diffusion and water transfer are enhanced along the gas flow from the inlet to the outlet of the cell due to MPL, the impact of relative humidity of supply gas as well as thickness of PEM on temperature distribution on reaction surface is smaller, which causes the even temperature distribution on reaction surface irrespective of relative humidity of supply gas as well as thickness of PEM. With MPL, \( T_{\text{react}} \) becomes lower and the temperature distribution on reaction surface is nearly flat compared to the condition without MPL. It is concluded that MPL is effective to obtain even temperature distribution on reaction surface as well as high power generation performance irrespective of thickness of PEM, flow rate and relative humidity of supply gases.

Acknowledgments

This work is supported by Mie Prefecture Industrial Research Institute and the authors gratefully acknowledge.

References


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