

Technology for Estimation of Fuel Cell Stack Temperature Using Transient Heat Transfer Simulation in Cell Stacking Direction

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ABSTRACT

A simulation of transient heat transfer in the cell stacking direction was developed that makes it possible to estimate the temperature of the MEA at different arbitrary stacking positions within the stack, including the case components and the end cells, at a high level of accuracy under all operating conditions that can be assumed for the vehicle environment. With regard to factors that have a considerable effect on the temperature of the MEA but necessitate a high volume of calculations, the introduction of a correction term based on fundamental data measured in a stack while generating power simplified the calculations. In addition, by contrast with conventional simulation technology, factors that have little effect on the temperature of the MEA were identified and omitted. These initiatives have made it possible to conduct coupled calculations for the constituent components of the stack without any decline in the accuracy of temperature estimations. It was verified that the simulation of transient heat transfer in the cell stacking direction was able to realize the target figure for temperature estimation accuracy of within $\pm 5\%$ against actual measurements for both steady-state stack generation conditions and stack warm-up mode, including transient states.

1. Introduction

Honda is advancing the development of the fuel cell vehicle (FCV) as a technology able to respond to the twin issues of CO₂-driven global warming and the securing of energy with the depletion of fossil fuel resources⁽¹⁾.

Figure 1 shows the structure of the fuel cell stack fitted in the 2016 model year CLARITY FUEL CELL (termed “the stack” below). The stack is composed of layered fuel cells (termed “cells” below) and stack case components (termed “case components” below). The membrane electrode assembly (MEA) inside the cells generates heat as a result of factors, including energy loss in cell reactions, but the flow of coolant between the cells cools the system and controls it to the correct temperature.

The cells in contact with the case components (termed “the end cells” below) are susceptible to the effect of heat released from the cells to the case components and atmosphere, as shown in Fig. 2. Figure 3 shows the temperature distribution of the cells positioned in the center of the cell stacking direction (termed “the center cells” below) and the end cells when the stack is started with the case components at low temperature.

The temperature of the end cells is lower than that of the center cells. When the MEA temperature differential between the center cells and the end cells (ΔT_{MEA}) becomes high, the volume of condensate in the end cells becomes higher than it is in the center cells. This

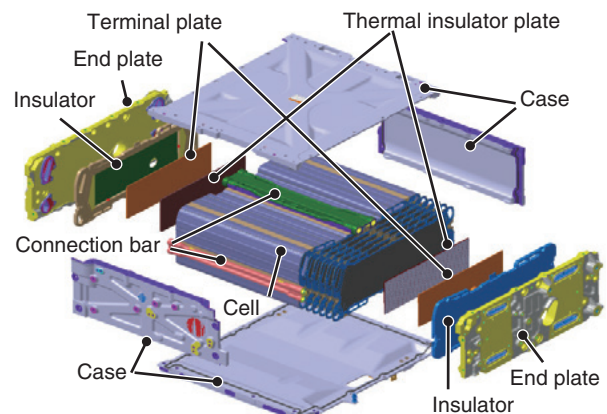


Fig. 1 Structure of fuel cell stack

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phenomenon is one of the causes of instability in cell voltage behavior⁽²⁾.

In order to lower ΔT_{MEA} during stack warm-up, it is necessary to both increase the insulation performance of the case components and supply the appropriate level of heat to the cells by means of heat exchange with the coolant and heat generation by the current-carrying components. As this implies, not only cooling of each cell by the coolant, but also control of the temperature of the end cells to the appropriate level under all operating conditions, are important factors in the thermal design of the stack.

Honda has worked to develop a simulation technology able to estimate the internal environment of the cells during power generation by making original modifications to market software^{(3), (4)}. However, because the purpose of this simulation technology, like standard fuel cell simulation technologies⁽⁵⁾⁻⁽⁸⁾, is to estimate the in-plane environment of the center cells (parameters including pressure, temperature, and MEA water content), it presented the issue of necessitating a high volume of calculations for parameters other than temperature.

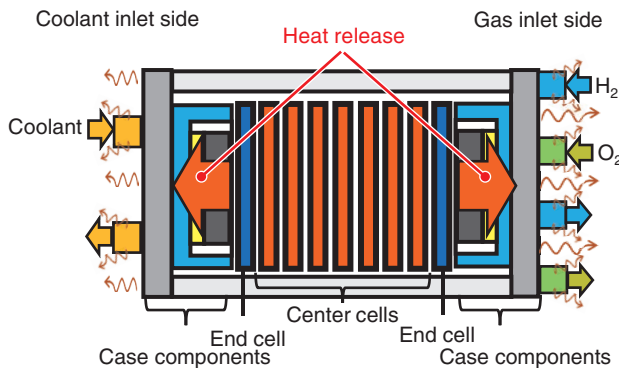


Fig. 2 Schematic image of heat release from case components

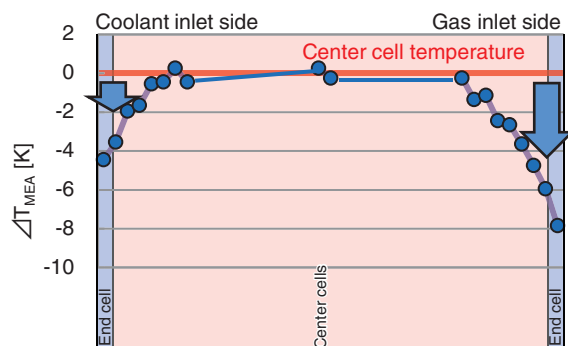


Fig. 3 Relationship between ΔT_{MEA} and position in stacking direction

Two methods can be considered for the estimation of ΔT_{MEA} using conventional simulation technologies. The first of these, for single-cell calculations, is to add a heat release term to the input parameters in the cell stacking direction, thus considering the cell being focused on as an end cell. The second method is to conduct coupled calculations for all the cells forming the stack and the case components (termed “stack coupled calculations” below). Because the first method does not consider reduction in the temperature of contiguous cells, it is not suitable for high-accuracy estimation. The second method was able to estimate reduction in the temperature of the end cells with a high degree of accuracy, but it necessitated large-scale calculations.

The development goal for the simulation technology discussed in this paper was to estimate the temperature of the MEA at different arbitrary stacking positions within the stack to a high level of accuracy without large-scale calculations.

2. Examination of Calculation Methods

2.1. Effect of Each In-cell Heat Exchange Factor on MEA Temperature

Figure 4 shows the flow directions of the various fluids in the stack fitted in the CLARITY FUEL CELL. The structure of the stack sees air and coolant flowing in the same direction, while H_2 flows in the opposite direction.

Anode gas (H_2), cathode gas (air), and coolant are assumed to be the factors that are able to be used for heat exchange within the cells in relation to the heat generated from the MEA during power generation. The dominant heat exchange factors for power generation at current densities of 0.03 A/cm^2 , 0.1 A/cm^2 , 0.3 A/cm^2 , 0.7 A/cm^2 , and 1.5 A/cm^2 , representing generation conditions assumed to occur within the vehicle environment, were identified by calculating the amount of heat exchange from the degree of change in temperature at the inlet and outlet and physical property values (heat capacity and flow rate)

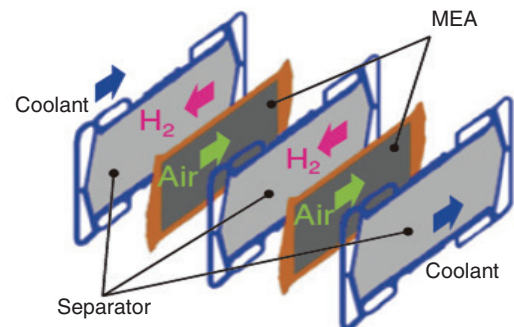


Fig. 4 Flow directions of anode gas, cathode gas, and coolant

for each factor. Figure 5 shows the ratio of amount of heat exchange for each fluid with the amount of heat exchange for the coolant as the benchmark. These results show that the amount of heat exchange for the gases (H_2 and air) is $\pm 3\%$ or less in relation to the amount of heat exchange for the coolant. The ratio of the heat exchange amounts for the gases and the coolant differs depending on the stack current per unit area because the inlet temperature and flow rate of the coolant and the gases differ. In addition, the fact that H_2 heat exchange occurs on the heat release side is due to the structure of the stack, which causes H_2 to flow in the opposite direction to the direction of coolant flow, the dominant heat exchange factor.

2.2. Effect of MEA In-plane Heat Conduction on MEA Temperature

The transfer of MEA heat is assumed to be effected through heat conduction and heat transfer in the cell stacking direction orthogonal to heat conduction. Figure 6 shows an image of heat exchange when in-plane heat

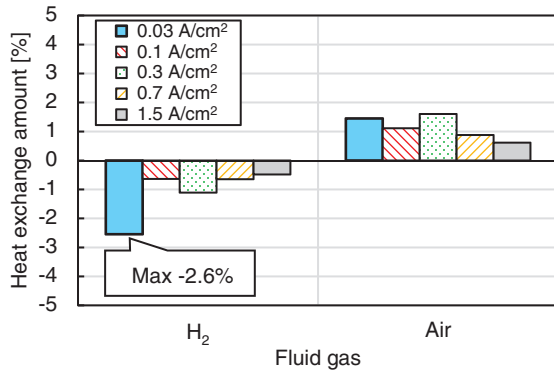


Fig. 5 Heat exchange amount for each fluid with coolant as benchmark

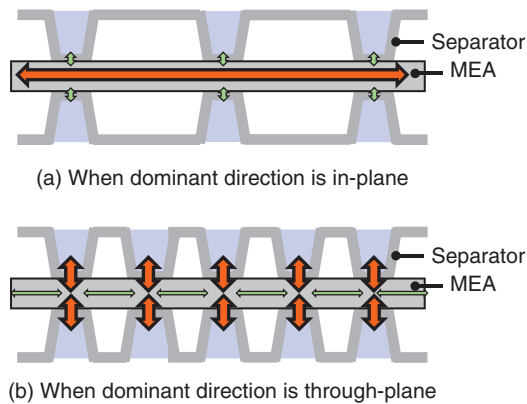


Fig. 6 Schematic image of heat exchange in cell in in-plane direction and through-plane direction

conduction is dominant and when heat transfer in the cell stacking direction is dominant. It is assumed that when the effect of heat conduction in the MEA in-plane direction is greatest, the in-plane MEA temperature distribution is uniform, irrespective of the temperature gradient of the coolant flowing from the stack inlet to the stack outlet. Conversely, it is assumed that when heat transfer in the cell stacking direction is dominant, the MEA in-plane temperature distribution follows the temperature gradient of the coolant flowing from the stack inlet to the stack outlet.

Given this, temperature measurements were conducted at the three center cell MEA in-plane temperature measurement positions shown in Fig. 7 (at the coolant inlet, at the center of the cell, and at the coolant outlet) under power generation conditions of 0.1 A/cm^2 , which are representative of stack warm-up mode. Figure 8 shows a graph of temperature differentials ($\Delta T_{\text{cool in-out}}$) with coolant inlet temperature as the benchmark. These results indicate that the temperature distribution in the MEA in-plane direction is identical to the coolant temperature distribution. In other words, heat exchange between the coolant and the MEA can be considered to be more strongly correlated with MEA temperature than heat conduction in the MEA in-plane direction.

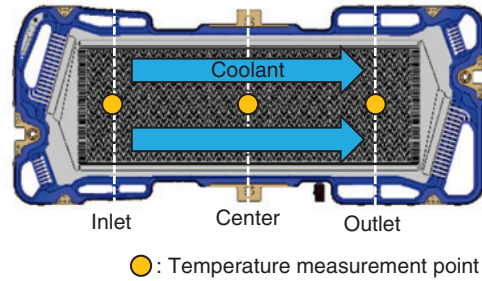


Fig. 7 Temperature measurement points for inlet, outlet, and center cell

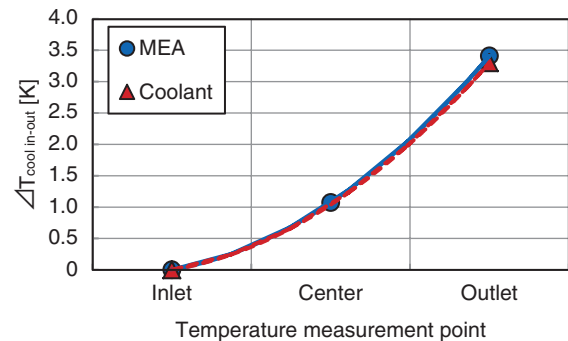


Fig. 8 Temperatures of MEA and coolant

2.3. Concept of Calculation Method

Based on the results discussed above, it was considered that calculation of the heat exchange between H_2 and air and MEA in-plane heat conduction could be omitted because their influence on the temperature of the MEA was minimal. In addition, focusing on the fact that the effect of MEA in-plane heat conduction was minimal made it possible to limit the calculation position for each component to one point in the cell plane. While the conventional simulation technology is a tool for the estimation of cell in-plane temperature distribution, as Fig. 9 shows, the distinctive feature of the simulation technology under consideration in this paper is the ability to estimate temperature distribution in the cell stacking direction, including the case components. The technology makes it possible to arbitrarily set calculation points in the cell plane, and by conducting calculations for multiple in-plane points, it is possible to accurately estimate the temperature distribution for the stack as a whole.

When creating simulations of the cell stacking direction, there are factors on which the three-dimensional structure of the cells has a considerable effect, such as Reynolds number, an indicator of the degree of turbulence. Because of this, estimative accuracy is insufficient when only the cell stacking direction is simulated. However, conducting detailed calculations for factors affected by the three-dimensional structure of the cells would enormously increase the calculation volume. Therefore, it was decided, in addition to general theoretical equations and physical property values, to introduce a correction term (a correlation coefficient) based on fundamental data measured in a stack while generating power. This addition made it possible to reduce the calculation volume in the simulation technology discussed in this paper without any reduction of estimative accuracy.

Based on the range of variation in actual measurements, taking sensor errors and variations between components into consideration, the target value for temperature estimation accuracy was set at within $\pm 5\%$ of actual measurements. This target value represented the same estimation error as the conventional cell in-plane simulation technology.

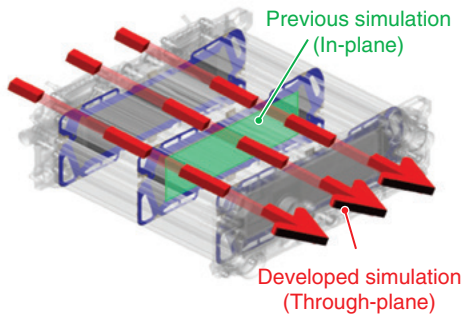


Fig. 9 Roles of developed simulation and conventional simulation

3. Simulation Creation of Transient Heat Transfer in Cell Stacking Direction

3.1. Heat Transfer within Components

The heat transfer within component A [Fig. 10(a)], considered by the simulation of transient heat transfer in the cell stacking direction, is assumed to be made up of heat conduction, heat transfer (heat release to the air, heat exchange with the coolant), and internal heat generation, as shown in Figs. 10(a), (b), and (c) and Eq. (1). The meanings of the symbols in the equation are shown in a list of symbols at the end of this paper.

$$mC \frac{dT_n}{dt} = Q_c - Q_t + Q_h \quad (1)$$

The terms related to heat conduction in Eq. (1) are expressed as Eqs. (2)-(4).

$$Q_c = Q_{n-1} - Q_n \quad (2)$$

$$Q_{n-1} = \frac{\lambda}{l} (T_{n-1} - T_n) A_c \quad (3)$$

$$Q_n = \frac{\lambda}{l} (T_n - T_{n+1}) A_c \quad (4)$$

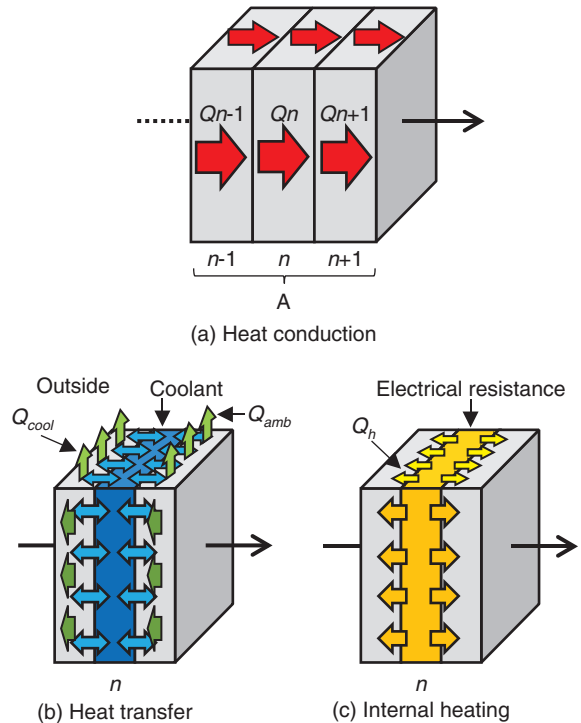


Fig. 10 Schematic image of heat flux in components

The terms related to heat transfer in Eq. (1) are expressed as Eqs. (5)-(8). Here, the heat transfer coefficient of the coolant in the coolant heat exchange expressed by Eq. (7), h_{cool} , is a value that fluctuates due to the coolant flow velocity and the effect of three-dimensional structures, such as the shape of the cell flow channels. Due to this, it is not easy to express h_{cool} using a theoretical equation. Given this, a relational expression for the correlation coefficient α and the coolant flow rate, determined experimentally in the actual cell shown in Fig. 11, was employed as the h_{cool} correction term in the simulation of transient heat transfer in the cell stacking direction. This made it possible to express the fluctuations in h_{cool} due to fluctuations in the coolant flow rate for a specific cell shape without any increase in the volume of calculations.

$$Q_t = Q_{amb} + Q_{cool} \quad (5)$$

$$Q_{amb} = h_{amb} A_{amb} (T_n - T_{amb}) \quad (6)$$

$$Q_{cool} = \alpha h_{cool} A_{cool} (T_n - T_{cool}) \quad (7)$$

$$\alpha = f(v_{cool}) \quad (8)$$

Different equations are employed for internal heat generation in general components and the MEA in Eq. (1). Equation (9), which considers Joule heat, is employed for general components, while Eq. (10), which considers heat loss in the chemical reactions occurring in the fuel cells, is employed for the MEA.

$$Q_{h\ parts} = I^2 R \quad (9)$$

$$Q_{h\ MEA} = I \Delta E \quad (10)$$

3.2. Heat Transfer between Components

The movement of heat at the interface between

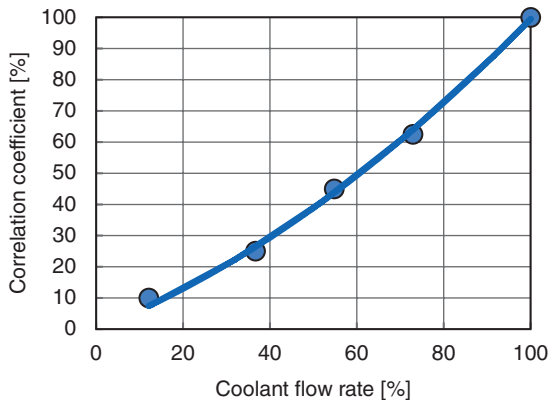


Fig. 11 Relationship between correlation coefficient and coolant flow rate

components A and B (Fig. 12) considered by the simulation of transient heat transfer in the cell stacking direction was set as the heat transfer between components and the heat generated by interface resistance, as expressed by Eqs. (11)-(13).

$$Q_B = Q_{A-B} + Q_{hs} \quad (11)$$

$$Q_{A-B} = h_{A-B} A_c (T_A - T_B) \quad (12)$$

$$Q_{hs} = I^2 R_s \quad (13)$$

By applying the above equations to each of the component parts of the stack and inputting their respective physical property values and dimensions as parameters, it was possible to create a model of the stack components.

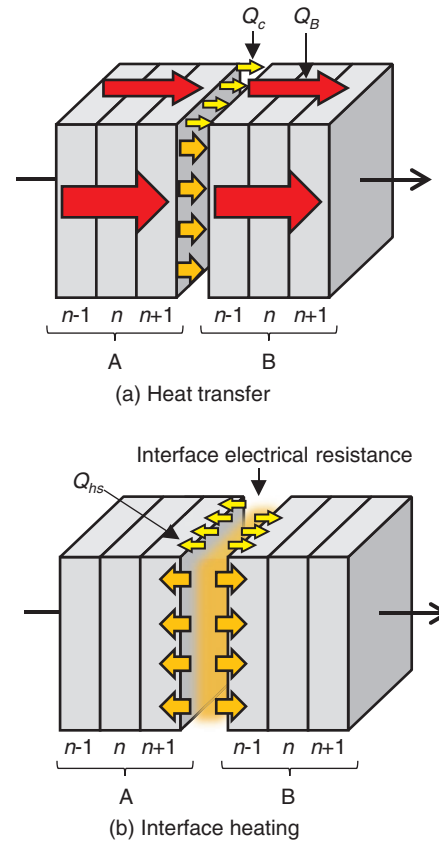


Fig. 12 Schematic image of heat flux between components A and B

4. Simulation Results and Verification of Accuracy

4.1. Verification of Temperature Estimation Accuracy in Different Generation Modes

Calculations were conducted for power generation at

current densities of 0.03 A/cm², 0.3 A/cm², 0.7 A/cm², and 1.5 A/cm², representing generation conditions assumed to occur within the vehicle environment. Actual measurements and calculation results were compared, with the center cells, the end cells, and the end plates, the outermost of the case components, as the targets of the evaluation (Fig. 13). The maximum temperature estimation error during steady state operation for each operating condition was 3.7% against the actual measurements, indicating that the target figure was realized. These results verified that the simulation of transient heat transfer in the cell stacking direction is not restricted to specific modes, but is applicable to stack temperature estimation across a wide range of generation modes, from low loads to high loads.

4.2. Verification of Temperature Estimation Accuracy in Stack Warm-up Mode

Figure 14 shows an image of stack warm-up mode, the mode in which it is assumed that the temperature differential between the MEA in the center and end cells (ΔT_{MEA}) reaches its peak in the vehicle environment. This mode is a sequence of modes, in which the stack is started in a state in which the cell temperature has declined in the external air temperature due to a long soak, and the cell temperature begins to increase due to idling generation (transient phase) until the temperature becomes constant (steady-state phase). In this mode, the case components, which possess a high heat capacity but a limited tendency to follow the temperature of other components, are prone to the development of a heat differential with the end cells. As a result, the heat release from the end cells to the case components increases, increasing ΔT_{MEA} . The accuracy of temperature estimation in transient states was verified by comparing actual measurement data and calculation results for this mode.

Figure 15 shows the temperature transition of actual measurements and calculation results for the center cells,

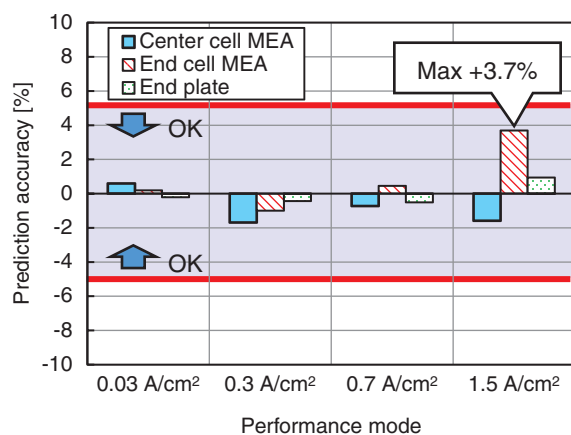


Fig. 13 Simulation and measurement results for fuel cell stack part temperatures during steady-state operation

end cells, and end plates in a transient state in stack warm-up mode. The temperatures in this graph are expressed as ratios, with the external temperature as the benchmark

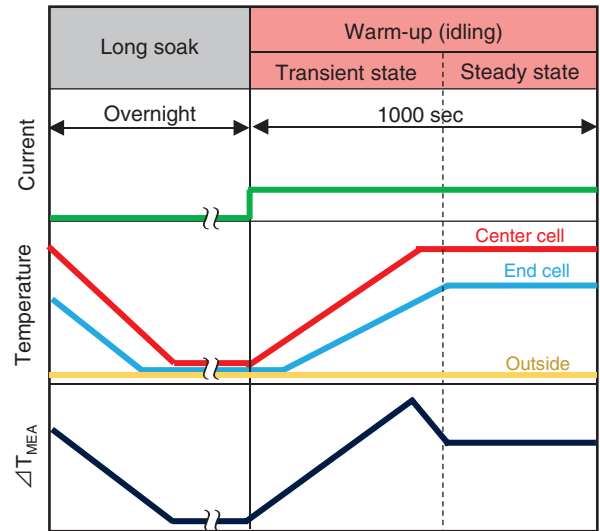


Fig. 14 Schematic image of warm-up mode

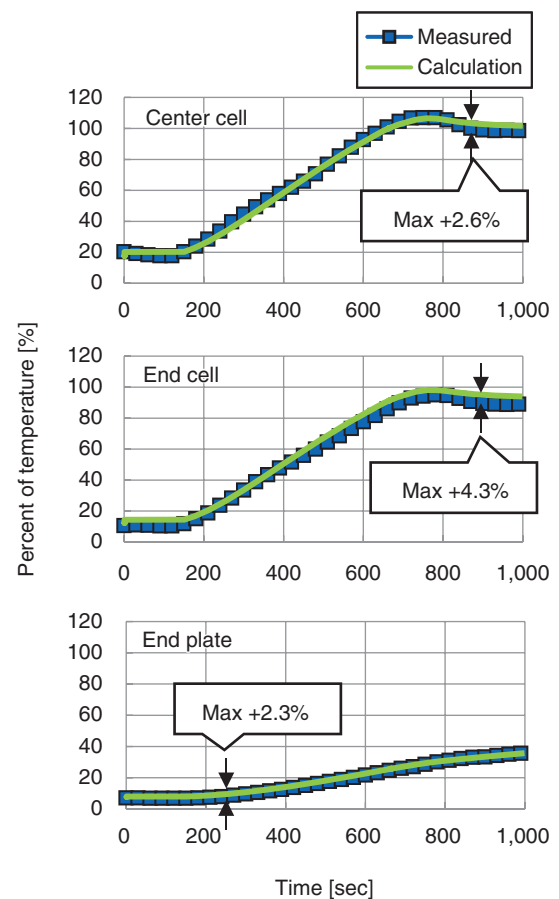


Fig. 15 Simulation and measurement results for fuel cell stack part temperatures in transient state during warm-up mode

and the temperature of the center cells after 1000 sec has elapsed as the maximum temperature. These results verified that the simulation technology is capable of reproducing the process of temperature increase in each component from a state in which the temperature of the cells had declined in the external air temperature after a long soak. In addition, the temperature estimation error was a maximum of 4.3% against measurement results, demonstrating that the simulation also realized the target value in stack warm-up mode, which includes transient states. This verified the fact that the simulation of transient heat transfer in the cell stacking direction could also be applied to the estimation of stack temperature, including transient states.

4.3. Verification of Calculation Speed

Using the conventional simulation technology, when a work station-level calculation resource was employed, calculation time for stack warm-up mode was several days or more for only one center cell. By contrast, using the simulation technology discussed in this paper, when a laptop computer-level calculation resource was employed, calculation time for stack warm-up mode was 60 sec. Even when calculations were conducted for multiple in-plane points, it was possible to complete the calculations in a matter of several minutes. This demonstrates that the development of the simulation of transient heat transfer in the cell stacking direction has made it possible to estimate the temperature distribution for the entire stack with a practical calculation time, even when standard calculation resources are employed.

5. Conclusion

A simulation of transient heat transfer in the cell stacking direction was developed that makes it possible to estimate the temperature of the MEA at different arbitrary stacking positions within the stack at a high level of accuracy and without large-scale calculations. With regard to factors that have a considerable effect on the temperature of the MEA but necessitate a high volume of calculations, the introduction of a correction term based on fundamental data measured in a stack while generating power reduced the calculation volume. At the same time, by contrast with the conventional simulation technology, a method of identifying and omitting factors that have little effect on the temperature of the MEA was developed. Temperature estimation error under steady-state stack generation conditions was a maximum of 3.7% against actual measurement results. In addition, temperature estimation error in stack warm-up mode including transient states was a maximum of 4.3% against actual measurement results. These results demonstrate that the temperature estimation accuracy of the simulation of transient heat transfer in the cell stacking direction achieved the target value for estimation error of within $\pm 5\%$ against actual measurement results.

References

- (1) Kimura, K., Kawasaki, T., Ohmura, T., Atsumi, Y., Shimizu, K.: Development of New Fuel Cell Vehicle CLARITY FUEL CELL, Honda R&D Technical Review, Vol. 28, No. 1, p. 1-8
- (2) Chiba, H., Iwasawa, C.: Optimization of Fuel Cell Generation Environment by Water Observation using Neutron Radiography, Honda R&D Technical Review, Vol. 25, No. 1, p. 122-131
- (3) Yoneda, M., Tago, Y., Suzuki, K., Takimoto, M., Ejiri, E.: Macroscopic Modeling and Simulation for Polymer Electrolyte Membrane Fuel Cells, ECS Transactions, Vol. 3, Issue 1, p. 1105-1114, (2006)
- (4) Nagumo, K., Inoue, M.: Numerical Prediction of Water Content Distribution of Catalyst Coated Membrane of Fuel Cell Stack using Simulation, Honda R&D Technical Review, Vol. 28, No. 1, p. 26-33
- (5) Yoneda, M., Yoshimura, H., Takayama, T., Motegi, H., Takayama, R., Kariya, N.: Prospects of Modeling and Simulation for Polymer Electrolyte Fuel Cell, Mizuhohosoken Giho, Vol. 6, No. 1, p. 51-58, (2014) (in Japanese)
- (6) Nonoyama, N., Ikogi, Y.: PEMFC model development for designing MEA: Model Validation and a Parameter Study for Low Humidity Operations, ECS Transactions, Vol. 16, Issue 2, PART 1, p.13-21, (2008)
- (7) Yamamoto, K., Fujita, Y., Yasumoto, E., Sugawara, Y.: Multiscale Simulation for Fuel Cell, Panasonic Technical Journal, Vol. 63, No. 1, p. 72-77, (2017) (in Japanese)
- (8) Takayama, T., Yoshimura, H., Tsukamoto, T., Motegi, H., Takayama, R., Yoneda, M.: Kotaikobunshigata Nenryodenchi Shimyureta "P-Stack4.0" Furusutakkuseino Kaisekio Jitsugensuru Senyosofutouea, Kurinenerugi, Vol. 26, No. 1, p. 1-8, (2017) (in Japanese)

List of Symbols

A_{amb}	Heat transfer area of external air [m^2]
A_c	Heat conduction area [m^2]
A_{cool}	Coolant heat transfer area [m^2]
C	Heat capacity [J/(kg·K)]
h_{A-B}	Coefficient of heat transfer between A and B [W/(K· m^2)]
h_{amb}	Heat transfer coefficient of external air [W/(K· m^2)]
h_{cool}	Heat transfer coefficient of coolant [W/(K· m^2)]
I	Current [A]
l	Length [m]
m	Mass [kg]
t	Time [sec]
T_A	Surface temperature of A [$^{\circ}C$]
T_B	Surface temperature of B [$^{\circ}C$]
T_{amb}	External air temperature [$^{\circ}C$]

T_{cool}	Coolant temperature [°C]
T_n	Temperature of n components [°C]
T_{n+1}	Temperature of $n+1$ components [°C]
Q_{A-B}	Amount of heat transfer between A and B [W]
Q_B	Amount of heat conduction in B [W]
Q_{amb}	Amount of heat release to external air [W]
Q_{cool}	Amount of heat exchange with coolant [W]
Q_c	Amount of heat conduction [W]
Q_h	Amount of internal heat generation [W]
$Q_{h\ parts}$	Amount of internal heat generation for general components [W]
$Q_{h\ MEA}$	Amount of internal heat generation for MEA [W]
Q_{hs}	Amount of heat generation at interface [W]
Q_{n-1}	Amount of heat conduction for $n-1$ [W]
Q_n	Amount of heat conduction for n [W]
Q_i	Amount of heat transfer [W]
R	Specific electrical resistance [Ω]
R_s	Interface electrical resistance [Ω]
v_{cool}	Coolant flow rate [L/min]
α	Correlation coefficient [-]
λ	Thermal conductivity [W/(m·K)]
ΔE	Voltage drop [V]

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