

Development of MEA with Built-in Oxygen Sensor for Measurement of Oxygen Concentration around Fuel Cell Cathode Electrode Layer

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ABSTRACT

A membrane electrode assembly with a built-in fiber-optic oxygen sensor able to measure the oxygen concentration around fuel cell cathode electrode has been developed to clarify the effect of a variety of generating conditions on the transport of oxygen to the area around cathode electrode. Changes in the phosphorescence lifetime of an oxygen-sensitive dye coated on the tip of the optic fiber are used to measure oxygen concentration. This paper presents an example of the first-ever simultaneous measurement of the oxygen concentration distribution around cathode electrode and the current density distribution, which expresses the distribution of generation in the active area, in a vehicle-onboard cell during generation. Specifically, it was found that obstruction of transport of oxygen gas to the cathode electrode affects generation output under conditions of high current density operation and generation stability under conditions of low current density operation.

These results, together with the results of neutron radiography observation, indicate that condensed water formed in the gas channels of the cell impede the supply of gases, and can result in a decline in generation performance.

1. Introduction

Against the background of environmental issues including global warming and air pollution, in addition to the instability of the supply of gasoline and other fossil fuels, the development of fuel cell vehicles, which do not emit CO₂ or other pollutants and are considered the ultimate environmentally friendly vehicles, is picking up pace. The ZEV Regulation introduced by the California Air Resources Board (CARB) stipulates that a specific percentage of all the vehicles sold in California by manufacturers that sell more than a specified number of vehicles in the state must be zero emission vehicles (ZEV). From 2018, the state will make the transition to ZEV2.0, which will restrict the ZEV appellation to electric vehicles and fuel cell vehicles. This move increases the importance of development of fuel cell electric vehicles. Honda is proceeding with the development of fuel cell vehicles using polymer electrolyte fuel cells (PEFC), which are able to start at low temperatures and have the potential to be reduced in size. For generation by PEFC, it is necessary to utilize the appropriate amount of water for proton conductivity of polymer electrolyte

membrane (PEM). However, excess water formed in the gas channels and the gas diffusion layers (GDL) is a factor in impeding the supply of gas to the electrode catalysts, the site of the generation reaction. Under conditions of high current density operation, this can reduce output, and under conditions of low current density operation, it can reduce the stability of generation. This makes it necessary to appropriately control the water inside the fuel cell during power generation. The use of a special visualization cell provided with a visualization window, in which the walls of the cathode gas channels have been coated with an oxygen-sensitive dye, and a laser spectrum is available as a method of directly evaluating impediments to gas supply that may cause a decline in generation output or generation stability⁽¹⁾. However, this method of evaluation is restricted to the special visualization cell, and in addition does not enable the oxygen concentration close to the cathode electrode, the reaction site, to be directly measured. In order to address this issue, the research discussed in this paper sought to develop a membrane electrode assembly (MEA) provided with a built-in oxygen sensor.

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2. Necessity for Measurement of Oxygen Concentration

2.1. Fuel Cell

A fuel cell is a power-generating device that produces electricity by means of electrochemical reactions between hydrogen and oxygen. The reactions are a hydrogen oxidation reaction at the anode electrode, shown by Eq. (1), and an oxygen reduction reaction at the cathode electrode, shown by Eq. (2). Water is produced at the cathode as a by-product of the reaction.

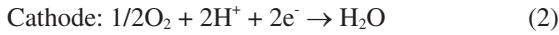


Figure 1 shows a schematic image of a PEFC. The PEFC is made up of a MEA, a catalyst layer (CAT) and a GDL on each side of the PEM, and separators provided with gas and coolant channels. This minimum configuration is termed a single cell. A stack is formed by layering multiple single cells. The PEM conducts protons (H^+) formed by the hydrogen oxidation reaction shown in Eq. (1). The CAT positioned on either side of the PEM respectively catalyze the reactions shown by Eqs. (1) and (2). The GDL diffuse reactant gases to areas not exposed to the gas channels, in addition to conducting electricity. The separators supply reactant gas to the anode and cathode electrodes, isolate the reactant gases from the reactant gases of neighboring cells, cool the cell by supplying coolant, and conduct electricity from the CAT. The cell is also provided with micro-porous layers (MPL) between the CAT and the GDL that further promote the exchange of wastewater and gas from the CAT.

2.2. The Importance of Water Management in Fuel Cells

It is necessary to appropriately control the water in the fuel cell during generation in order to help ensure output and generation stability. The realization of increases in the rate of oxygen use is demanded for fuel cells for automotive use in order to help achieve size reductions, including reduction of the size of the fuel cell system overall, and to limit the power necessary for air pumps and other

equipment. Technologies capable of high current density operation, which produces a higher volume of water, are necessary in order to move towards realizing further reductions in the size of the fuel cell stack.

The fuel cell stacks used in the 2009 model FCX Clarity realized a volumetric power density 50% higher than the stacks used in the 2005 model. In addition, the mass power density of the 2009 stacks was 67% higher than that of the 2005 stacks⁽²⁾.

2.3. Necessity for Measurement of Oxygen Concentration around Cathode Electrode

As discussed above, humidified water supplied to help ensure proton conduction and water produced by power generation condenses and impedes the transportation of reactant gases during power generation. This is referred to as flooding. During power generation, energy loss occurs as a result of the three types of polarization losses shown in Fig. 2. These are activation polarization losses, originating in activation of the catalyst, ohmic polarization losses, originating in proton conduction and electron conduction, and concentration polarization losses, originating in transport resistance of the reactant gases.

The cell voltage is each of the polarization losses divided by the theoretical electromotive force resulting from the difference in electrical potential between hydrogen and oxygen. Theoretical electromotive force corresponds to open circuit voltage (OCV). Flooding accelerates concentration polarization losses, which expresses the transport resistance of the reactant gases, and can reduce cell voltage. Water is produced at the cathode electrode, and water is also transferred to the cathode electrode from the anode electrode as accompaniment water by electro-osmosis, promoting the accumulation of water at the electrode and in the GDL. Because of this, the cathode electrode is more prone to concentration polarization than the anode electrode. The tendency towards flooding is also affected by differences in the wettability of the GDL and electrode materials by water. In addition, as Fig. 3 shows, flooding is more prone to occur in the downstream rather than upstream sections of the gas channels for cathode

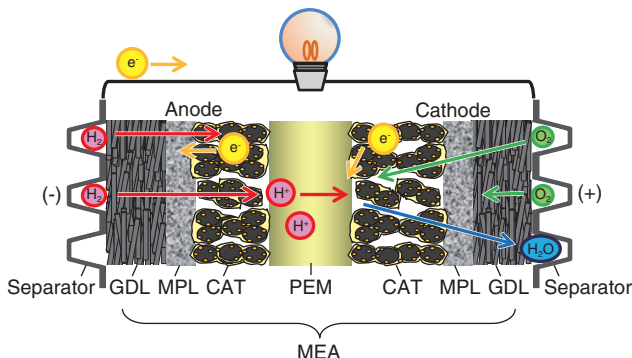


Fig. 1 Schematic image of PEFC

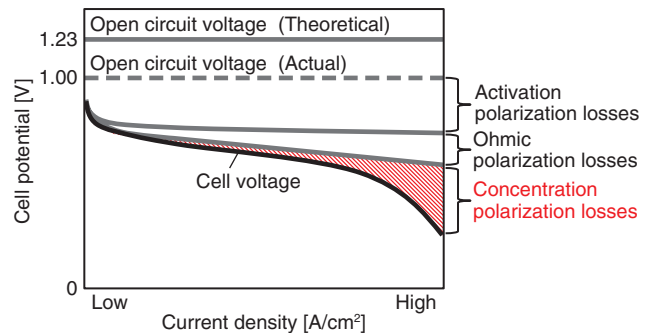


Fig. 2 IV curve and various polarization losses of operating fuel cell

reactant gases located in the active area. This is due to the fact that some of the water produced in the upstream sections of the gas channels by the cathode reactant gases evaporates and becomes water vapor, and the further this vapor travels downstream in the gas channels the more it accumulates and approaches the saturation vapor pressure.

In addition, oxygen present in the air is used as the reactant gas at the cathode electrode; its partial pressure is lower and its molecular weight is higher than the hydrogen employed as the reactant gas at the anode electrode, meaning that it is more easily affected by the diameter of the pores used for gas passage. Concentration polarization at the cathode electrode is therefore more marked under conditions of high current density operation. Transport of oxygen, the cathode electrode reactant gas, within the cell can be broadly divided into:

- (1) Vapor-phase diffusion within the pores of the cathode GDL and MPL;
- (2) Vapor-phase diffusion within the pores of the cathode CAT; and
- (3) Vapor-phase and dissolution diffusion into the cathode CAT electrolyte.

The mode of oxygen diffusion differs depending on the diameter of the pores. The pore diameter of the carbon paper generally used in the GDL mentioned in (1) is around 50-100 μm . The diameter of the pores in the CAT mentioned in (2) and (3) is around 0.01-0.1 μm ⁽³⁾. If the diameter of the pores is sufficiently greater than the mean free path of the gas molecules, molecular diffusion can be regarded as dependent upon collisions between the gas molecules themselves. However, when the pore diameter is low, collisions between the gas molecules and the walls of the pores cannot be ignored, and Knudsen diffusion is dominant⁽⁴⁾⁻⁽⁶⁾. The GDL is dependent on molecular diffusion and the CAT, which has a low pore diameter, is dependent on Knudsen diffusion. Knudsen diffusion is lower the larger the molecular weight of the molecules. Therefore, given that the molecular weight of oxygen is 32 and the molecular weight of hydrogen is 2, the diffusion constant of oxygen in the pores is around one-quarter that

of hydrogen. In addition, because the consumption of reactant gases increases under conditions of high current density operation, the cathode electrode is more prone than the anode electrode to be affected by Knudsen diffusion. In order to verify the effect of Knudsen diffusion, a technology able to measure the oxygen concentration around cathode electrode under a variety of generation conditions is required.

3. Development of MEA with Built-in Fiber-optic Oxygen Sensor

3.1. Selection of Oxygen Concentration Measurement Method

Among standard methods of measuring oxygen concentration are the zirconia sensor type, which uses the electromotive force of concentration cells, the magnetic oxygen meter type, which uses the paramagnetism of oxygen, and the mass spectrometry type, which uses differences in mass number. Based on six considerations, the present research employed a fiber-optic oxygen sensor using an oxygen-sensitive reagent. The six considerations were ability to be built into an MEA, no consumption of gas for sampling, ability to conduct measurements in a gas and liquid two-phase state, electrical insulation performance and explosion-proof performance, rapid transient responsiveness, and ability to conduct multiple-point simultaneous measurement.

It was necessary that the external diameter of the sensor probe should be less than the combined thickness of the CAT and GDL, making a diameter of 250 μm or less desirable. Based on this figure, fiber-optic sensors with external diameters of 90 μm (a core diameter of 50 μm and a cladding layer of 40 μm) and 220 μm (a core diameter of 200 μm and a cladding layer of 20 μm) were manufactured.

3.2. Fiber-optic Oxygen Sensor Probe and Configuration of Measurement Equipment

An oxygen-sensitive dye was employed in measurements of oxygen concentration. A Ru-porphyrin complex was used as the dye. Ru-porphyrin complexes become excited and emit phosphorescence when they absorb light corresponding to the band gap energy⁽⁷⁾. When oxygen molecules exist around the Ru-porphyrin complex, part of the phosphorescent energy emitted is used as excitation energy for the oxygen molecules. Therefore, the higher the oxygen partial pressure, the more the strength of the phosphorescence is reduced, and the shorter the phosphorescence lifetime. Figure 4 shows the relationship between excitation light and the phosphorescence lifetime of the Ru-porphyrin complex.

Given this, measurements of the phosphorescence lifetime of the dye can be converted into oxygen partial pressure and oxygen concentration. Phosphorescence lifetime is converted into oxygen concentration using the Stern-Volmer equation [Eq. (3)].

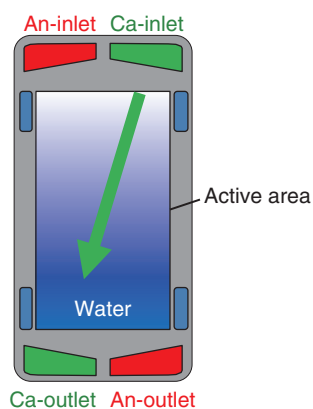


Fig. 3 Water distribution in active area

$$I_0/I = 1 + K_{sv} \cdot [Q] \quad (3)$$

I_0 : Phosphorescent strength in an oxygenless state

I : Phosphorescent strength when oxygen exists

K_{sv} : Stern-Volmer constant (Quenching constant x Phosphorescence lifetime)

$[Q]$: Oxygen partial pressure [Pa] or oxygen concentration [%]

Figure 5 shows a photograph and a schematic of the fiber-optic oxygen sensor manufactured for this research. A multi-mode type with low wavelength selectivity and a large light-transmitting core diameter was selected as the optic fiber. A window was formed in one side of the fiber-optic sensor probe corresponding to the sensing section, and an SMA905 connector was formed on the opposite side for connection to a relay cable. Giving consideration to increasing the light-receiving area and reducing the reflected component of the excitation light, the sensing section window was formed such that its surface displayed a taper angle of approximately 30°. The surface of the window was mirror polished. A polyimide resin coating that had been applied to the fiber-optic cable in order to protect its outer circumference remained in place other than in the window section. The Ru-porphyrin complex was dispersed and fixed in a silica glass membrane using the sol-gel coating technique and used to coat the surface of the window. This coating membrane was a porous membrane with a gas dispersion function^{(8), (9)}.

Figure 6 shows the configuration of the fiber-optic oxygen concentration measurement system. The measurement system consists of an excitation light source, a detector with a built-in lock-in amp synchronized with the light pulse of the excitation light source, a fiber-optic

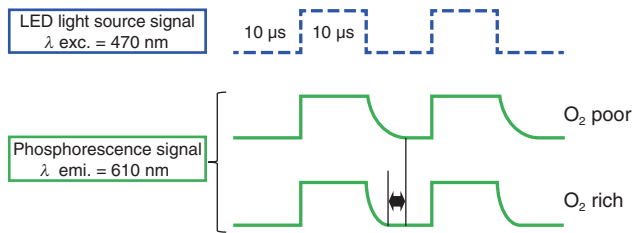


Fig. 4 Relationship between excitation light signal and phosphorescence signal

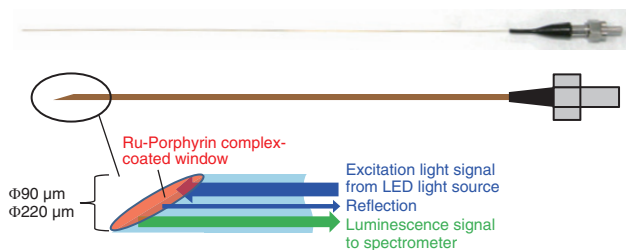


Fig. 5 Schematic image of fiber-optic oxygen sensor probe

oxygen sensor probe and a fiber-optic relay cable. An LED light source with a wavelength of 470 nm, corresponding to the excitation wavelength of the Ru-porphyrin complex, was used as the excitation light source. An optical fiber splitter was used to introduce the excitation light signal to the sensor probe. The two-branched fiber-optic relay cable also fulfilled the function of sending the reflected light signal, which included the phosphorescent component from the sensor probe window, to the detector. The detector was provided with a band pass filter with a wavelength of 610 ± 15 nm, corresponding to the peak wavelength of the phosphorescence. The band pass filter fulfilled the functions of isolating the benchmark phosphorescence signal wavelength and removing the excitation light component. A photo diode was used to detect the phosphorescence signal.

3.3. Characteristics of Oxygen Sensor Operation

As shown in Fig. 4, the excitation light signal was operated at approximately 50 kHz with a pulse width of 10 μs for both on and off. The Ru-porphyrin complex phosphorescence signal, the indicator for measurement of oxygen concentration, was defined as the lifetime from the cessation of the excitation light pulse to the attenuation of the phosphorescence. Figure 7 shows the calibration curve expressing the relationship between oxygen concentration as determined by an actual oxygen

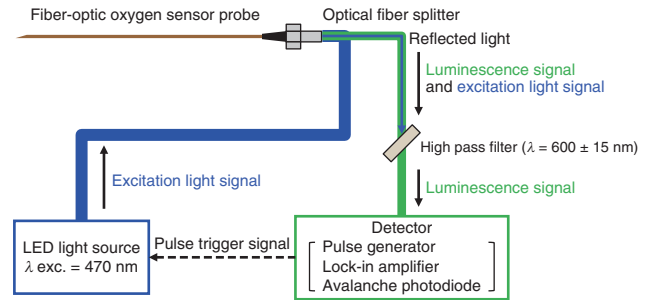


Fig. 6 Block diagram of fiber-optic oxygen sensor system

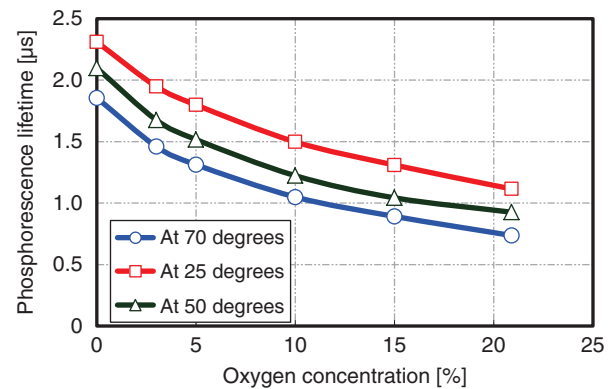


Fig. 7 Relationship between oxygen concentration and phosphorescence lifetime

sensor and the Ru-porphyrin complex phosphorescence lifetime. The phosphorescence lifetime decreases as the partial pressure increases. The phosphorescence lifetime is also dependent on the temperature around the sensor. The temperature-dependent quenching rate of phosphorescence follows Arrhenius' equation⁽⁶⁾. The phosphorescence quenching rate of the Ru-porphyrin complex becomes more rapid as temperature increases, and its phosphorescence lifetime is reduced. When using the Ru-porphyrin complex phosphorescence lifetime in order to measure oxygen concentration, it is therefore necessary to take temperature measurements close to the measurement points and apply temperature correction.

The measured phosphorescence lifetime differed for each sensor. These differences originated in variations in the concentration of the Ru-porphyrin complex and the pore size distribution of the coating membrane that functioned to disperse gas. Because of this it was necessary to obtain calibration curves for all of the oxygen sensors used in measurements.

4. Tests

4.1. Operating Conditions

The developed MEA with built-in fiber-optic oxygen sensor was used in measurements of the oxygen concentration around the cathode electrode during power generation. Specifically, the effects of oxygen transport resistance under conditions of high current density operation and the effect on generation stability of the condensed water produced in the gas channels under conditions of low current density operation, which is frequent, were studied.

4.2. Evaluation Cells

Cells of the type employed in the FCX Clarity were used as the evaluation cells. Figures 8 and 9 show schematics of the evaluation cells. The cells shown in Fig. 9(b) were used in the evaluation.

The flow of reactant gases in the cells for both the anode

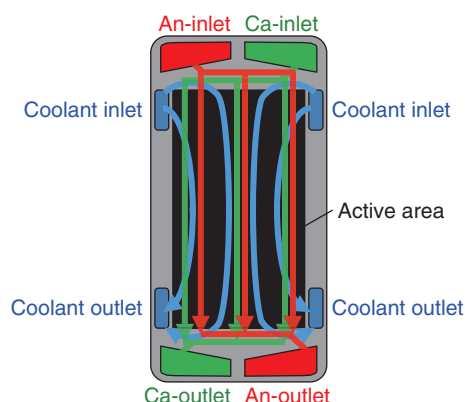


Fig. 8 Schematic image of cell structure

and cathode electrodes is a V-flow that follows the direction of gravity. In addition, in order to reduce size and weight, one cooling structure is employed for each two cells. Because of this there are two types of cell: A Cell, in which the cathode electrode surface is cooled; and B Cell, in which the anode surface is cooled. The smallest unit formed by the combination of A Cell and B Cell was defined as the cell unit complex.

4.3. Oxygen Sensor Measurement Position

Figure 10 shows the load points of the oxygen sensors built into the MEA. The oxygen sensor with an external diameter of 220 μm was employed. Oxygen sensors were positioned at nine points in order to make it possible to

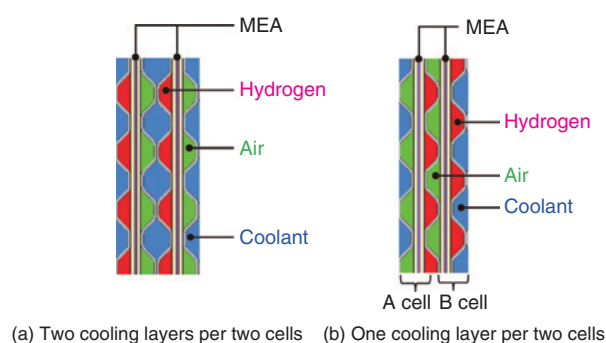


Fig. 9 Schematic images of two modes of stacking

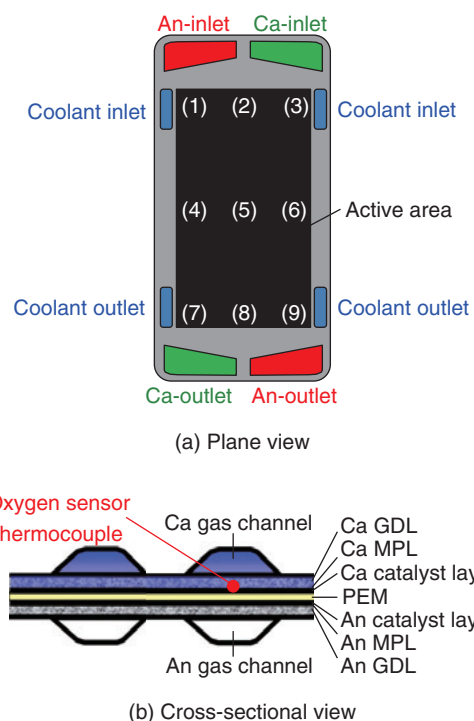


Fig. 10 Schematic image of oxygen measurement positions

measure the trend of distribution of concentration for the entire electrode area (the active area). Thermocouples were also positioned next to the oxygen sensors at these points in order to take temperature measurements for temperature correction. K-type thermocouples with an extra-fine cable coated in Teflon to help ensure electrical insulation were employed as the thermocouples. The oxygen sensor and the thermocouple were separated by a gap of around 5 mm, and positioned directly below the cathode electrode gas channels, as shown in Fig. 10(b). The respective sensors were sandwiched between the cathode electrode MPL and the cathode electrode, and were fixed in place by hot pressing during the bonding of the membrane and the electrode. The foundation layer, which functions to promote exchange of wastewater and gas, also acts as the adhesive that bonds the membrane and the electrode. The formed MEA was fastened between separators to form a cell unit complex. The sections of the sensor that straddled the seal lines formed on the separators to isolate them from gases were coated in a silicon-based liquid seal in order to fasten and cure it and help to prevent gas leaks. One cell unit complex consisting of A Cell and B Cell, each incorporating an MEA with a built-in oxygen sensor and thermocouple, was positioned at the center of a stack for evaluation. Figure 11 shows the position of the cell unit complex with built-in oxygen sensors and thermocouples. Prior to the evaluation of the cell unit complex, the relationship between oxygen concentration and phosphorescence lifetime was studied for single cell units and calibration curves were formulated. In order to calibrate oxygen concentration, calibration curves were obtained by rendering the amount of cathode gas constant under a variety of generation conditions without generating electricity, and mixing oxygen and nitrogen to vary the gas composition.

4.4. Simultaneous Measurement of Oxygen Concentration and Current Density Distribution

A sensor plate for the measurement of current density distribution, which would assist in understanding the distribution of generation in the active areas, was positioned in the stack adjacent to the rear of A Cell in the cell unit complex with built-in oxygen sensor. Figure 11 shows the position of the sensor plate in the stack. Figure 12 shows

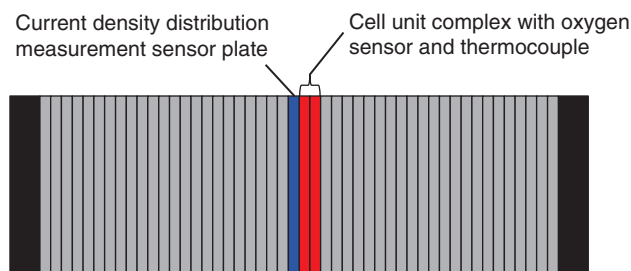


Fig. 11 Schematic image of sensor position in stack

an enlarged view of the positioning of the equipment after installation in the actual stack. The sensor plate was able to divide the active area evenly into a large number of segments and measure the current flowing in each segment with a high degree of accuracy. The greater the amount of current flowing in a segment, the greater the amount of electricity generated. This made it possible to conduct the first-ever simultaneous measurements of oxygen concentration, temperature distribution, and generation distribution around the cathode in the cell active area in the generating environment of an actual stack using a cell for automotive use.

4.5. Condition for Evaluation of Generation

The stoichiometry-dependence of the cathode reactant gases was studied in order to determine the effect of transport resistance of oxygen to the cathode electrode and condensed water produced during generation. In this paper, the gas flow rate will be expressed as stoichiometry. Stoichiometry is determined using Eq. (4), and is a relative value expressed as 1 when the gases necessary for the reactions in the fuel cells are supplied without excess or deficiency.

$$\text{Stoichiometry} = \text{Amount of gas supplied} / \text{Gas quantity required for reaction} \quad (4)$$

The evaluation was conducted with the gas supplied to the anode at a relative humidity (RH) of 60%, and the gas supplied to the cathode at an RH of 95%, which is the level directly before condensed water is formed.

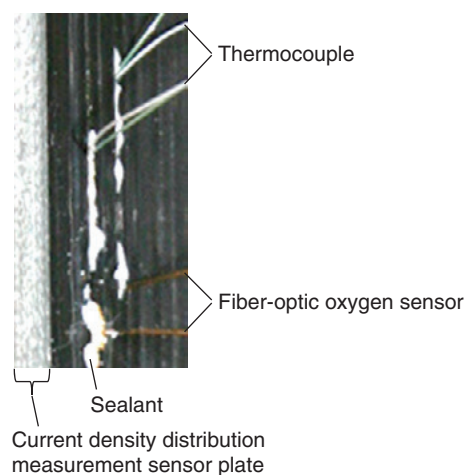


Fig. 12 Enlarged view of sensor position in stack

5. Results

5.1. Verification of Operation of Oxygen Sensor

In order to verify the operation of the oxygen sensor, generation conditions were held constant at 1.0 A/cm^2 , and the sensor's ability to track fluctuations in load was studied.

Figure 13 shows the results of a load fluctuation cycle test in which the load was applied at a rate of $0.1 \text{ A/cm}^2/\text{s}$. Figure 14 shows the results of using current densities from OCV to 1.0 A/cm^2 in multiple steps for fixed time periods. The measured oxygen concentration is from position (5) in Fig. 10(a).

The oxygen concentration measurements taken in the load fluctuation cycle test were able to track the rapid changes in concentration at the cathode electrode due to oxygen consumption during generation. The oxygen concentration measurements taken when holding current density steady for fixed time periods also expressed the differences in oxygen consumption with changes in load. Based on the results discussed above, it was judged that oxygen concentration measurements taken using the developed method made it possible to understand the oxygen concentration environment around the cathode electrode during power generation.

5.2. Evaluation of High Current Density Operation

In order to determine the effect of oxygen transport resistance under conditions of high current density operation, the oxygen concentration distribution and the current density

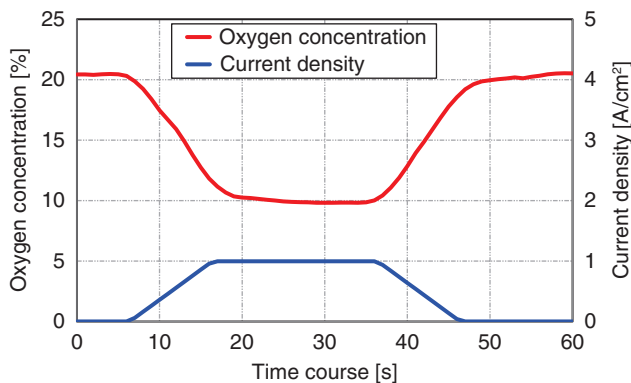


Fig. 13 Change in measured oxygen concentration over time with current density fluctuation

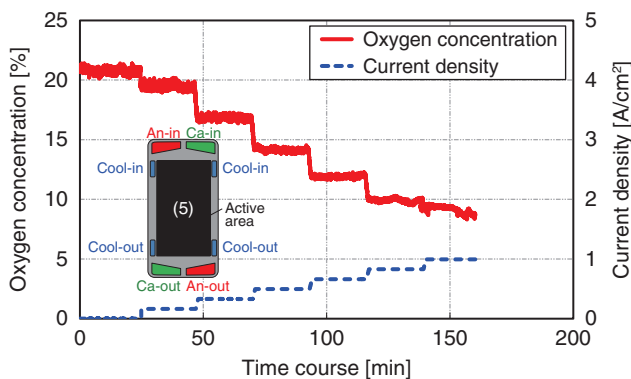


Fig. 14 Measured oxygen concentration at various current density

distribution in the cathode area were compared at 1.0 A/cm^2 and 1.5 A/cm^2 . The results are shown in Fig. 15. The results of comparison of the standard deviation of current density distribution in the cathode area at 1.0 A/cm^2 and 1.5 A/cm^2 are shown in Fig. 16. The decline in oxygen concentration in the midstream and downstream sections of the cathode gas channels is greater at 1.5 A/cm^2 . This is considered to be due to the progression of flooding as a result of the increase in water production and the progression of gas diffusion limitation due to the increase in the consumption of reactant gases for power generation. This is also verified by the expansion of the current density distribution in the active area and the tendency towards a decline in current density in the downstream sections of the cathode gas channels under 1.5 A/cm^2 conditions.

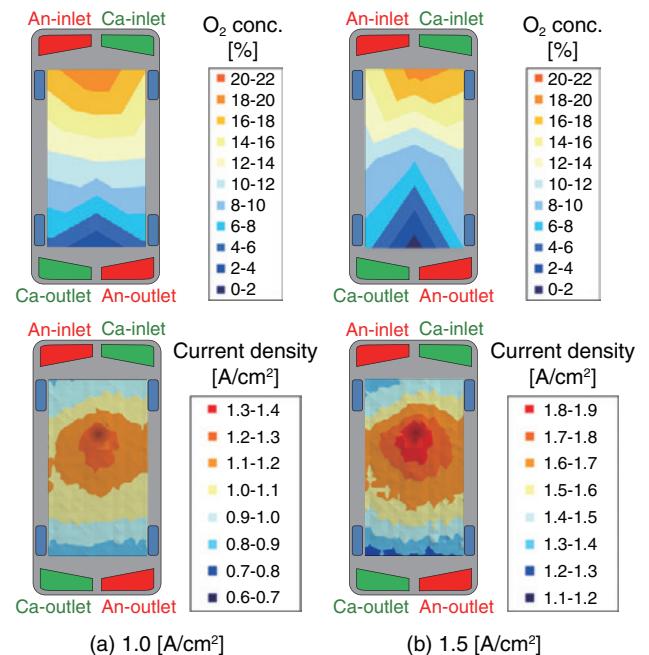


Fig. 15 Oxygen concentration distribution and current density distribution under conditions of high current density

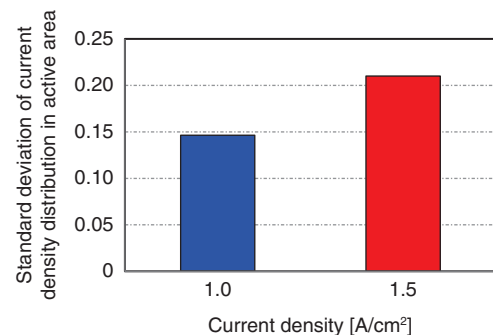


Fig. 16 Comparison of current density distribution at 1.0 A/cm^2 and 1.5 A/cm^2

Local declines in the oxygen concentration in the center of the downstream sections of the cathode gas channels displayed a correlation with the stoichiometry distribution of the cathode reactant gases. Figure 17 shows a comparison of the oxygen concentration distribution in the cathode area and the stoichiometry distribution of cathode reactant gases at the upper extremity of the active area, the point of introduction of cathode reactant gases, under 1.0 A/cm^2 conditions. The stoichiometry distribution for the cathode reactant gases was converted from the flow velocity distribution for each gas channel by means of Particle Image Velocimetry (PIV) using a model of the cathode gas channels in the cell. In concrete terms, in areas in which the stoichiometry of the reactant gases is low when they are supplied, the decline in oxygen concentration due to oxygen consumption is higher.

5.3. Evaluation of Low Current Density Operation

The stoichiometry-dependence of the cathode reactant gases was tested under 0.1 A/cm^2 current density conditions in order to study the effect of oxygen transport resistance under low current density conditions. Figure 18 shows the results of a comparison of oxygen concentration distribution and current density distribution in the cathode area.

The results make it possible to verify that when the stoichiometry of the reactant gases is insufficient when they are introduced, the oxygen concentration of the cathode area positioned in the midstream and downstream sections of the cathode gas channels declines. This tendency is most conspicuous in B Cell. The results also show a decline in current density, indicating a decline in the amount of generation, in the same sections. The areas in which the decline in oxygen concentration occurred correspond to

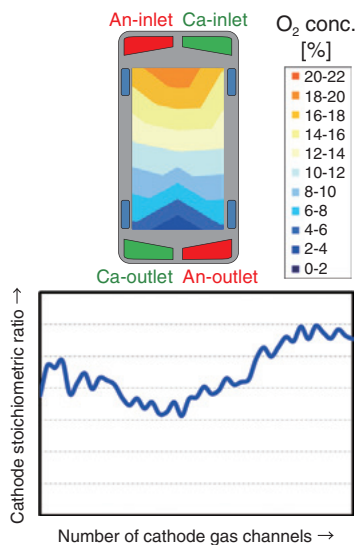


Fig. 17 Comparison of oxygen concentration distribution and cathode stoichiometric ratio distribution in cathode gas channel at 1.0 A/cm^2

areas in which condensed water formed in the gas channels. Figure 19 shows the results of a study, using neutron radiography⁽¹⁰⁾, of areas of the cell in which condensed water forms when the stoichiometry of the cathode reactant gases upon supply is insufficient. More condensed water forms in the areas of the gas channels positioned in the active area for both the anode and the cathode in the case of B Cell. This is related to the fact that the B Cell coolant channel is positioned at the rear side of the anode gas channel.

Because polarization losses are lower in the case of the anode reaction, expressed by Eq. (1), than the cathode reaction, expressed by Eq. (2), it generates less heat. In

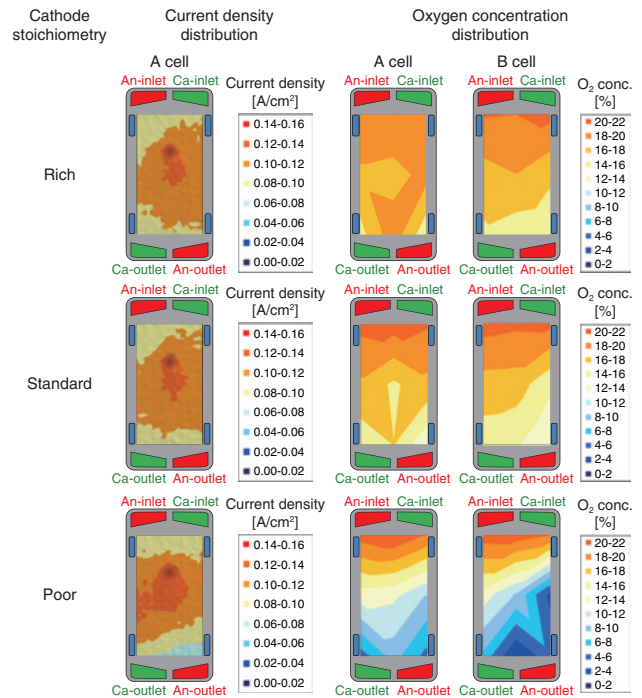


Fig. 18 Cathode stoichiometry-dependence at 0.1 A/cm^2

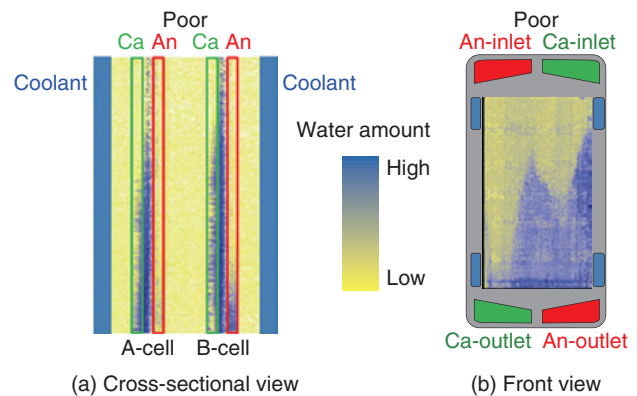


Fig. 19 Neutron radiography images of fuel cell at 0.1 A/cm^2

addition, because the surface of the coolant for B Cell is positioned at the rear of the anode gas channel, in which less heat is produced, its temperature environment is cooler than the surface of the A Cell coolant, which is positioned at the rear of the cathode gas channel. Because of this, B Cell is more prone than A Cell to produce condensed water in both the anode and cathode gas channels⁽¹⁰⁾. There is therefore a difference in the stability of generation in A Cell and B Cell. Figure 20 shows the results of a comparison of the stability of generation as determined from cell voltage. The cell voltage is an enlarged display from a specified potential window. When the stoichiometry of the cathode reactant gases upon supply is insufficient, the stability of generation in B Cell declines, and the decline in the cell's performance also increases.

In addition, the decline is also affected by the fact that, because the flow rate of the introduced reactant gases is lower under conditions of low current density than conditions of high current density, the drainage capacity of the condensed water forming in the gas channels is lower. Figure 21 shows a model of water drainage in a gas flow channel. Two forces tend to promote retention of the condensed water forming in the gas channels. These are the force of adhesion to the walls of the gas channel and the gas pressure acting on the condensed water in the opposite direction to the gas flow. For drainage, it is necessary to overcome these forces promoting the retention of condensed water. As Eq. (5) shows, one method of doing so is by means of the weight of the condensed water itself, and another is to increase the gas pressure produced by the gas flow on the condensed water in the same direction as the gas flow to a level higher than the gas pressure on the condensed water in the opposite direction to the gas flow, which acts to push the condensed water back. The force that

pushes the condensed water out increases in proportion to the flow rate of the gas. Given this, in order to discharge the condensed water in the gas channels that produces instability in power generation, it is necessary to increase the stoichiometry of the reactant gases to help ensure a gas flow rate of a specific level or higher.

$$\text{Water drainage capacity} \propto \text{Pressure 1} - \text{Pressure 2} + \text{Gravity} \quad (5)$$

Figure 22 shows the results of a comparison of the standard deviation of the distribution of oxygen concentration, the voltage difference, and the standard deviation of the current density distribution for Cells A and B.

The results show that when the stoichiometry of the cathode reactant gases falls below the benchmark level, the current density distribution, which expresses the voltage difference and distribution of generation between Cells A and B, becomes broader. This tendency is also true of the

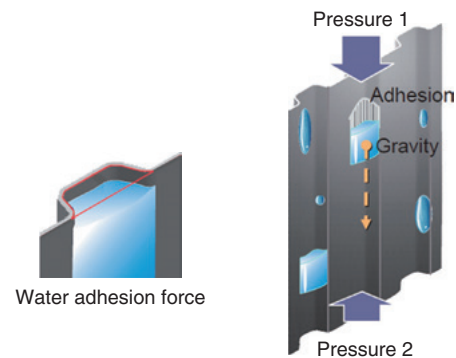


Fig. 21 Water drainage model of gas flow channel

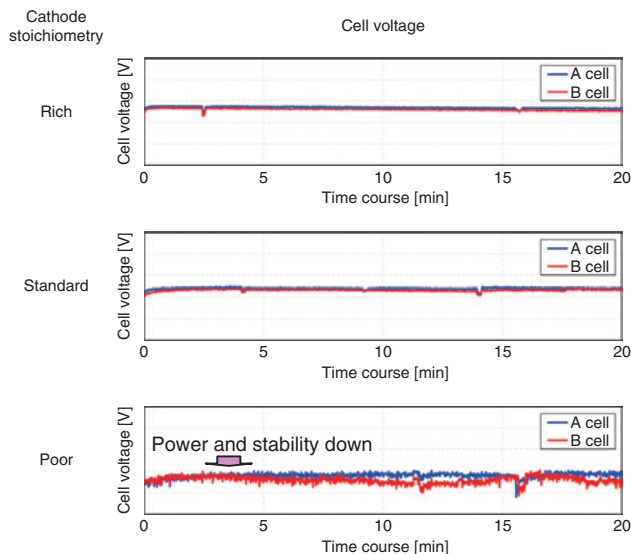


Fig. 20 Cell voltage trend data for A cell and B cell at 0.1 A/cm^2

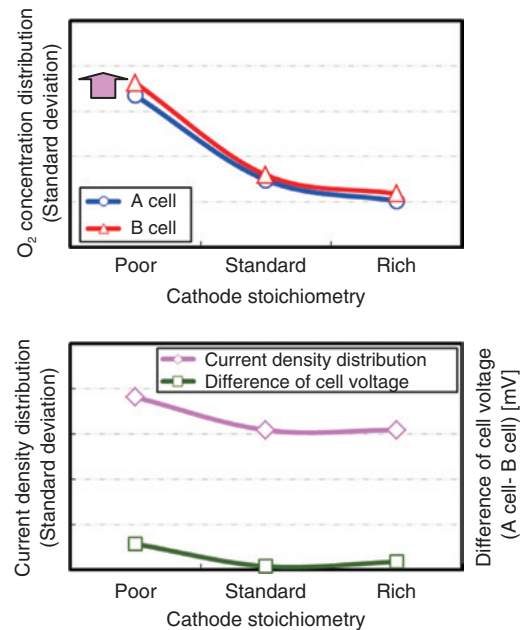


Fig. 22 Cathode stoichiometry-dependence of various parameters at 0.1 A/cm^2

oxygen concentration distribution in the cathode area, and is more conspicuous in B Cell. Based on this, it is considered that the condensed water formed in the gas channel of B Cell produces a resistance, and impedes the supply of cathode reactant gases.

6. Conclusion

A technology for the simultaneous measurement of the oxygen concentration around the cathode electrode during generation and the distribution of generation in the active area in a fuel cell fitted in a vehicle has been developed. The MEA with built-in oxygen sensor developed in the research discussed here can be considered to display merit as an evaluation tool to assist in the determination of fuel cell design guidelines and guidelines for operating conditions to help enable the realization of uniformity in generating environments.

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