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Evaluation of a cathode gas channel with a water absorption layer/waste channel in a PEFC by using visualization technique

Kimihiko Sugiura [a,*], Motoki Nakata [a], Tadakatsu Yodo [a], Yusuke Nishiguchi [a], Makoto Yamauchi [a], Yasuhiko Itoh [b]

[a] *Osaka Prefectural College of Technology, 26-12 Saiwai, Neyagawa, Osaka 572-8572, Japan*
[b] *SANYO Electric Co., Ltd., 1-1-1 Sakata, Oizumi-machi, Ora-gun, Gunma 370-0596, Japan*

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Abstract

The polymer electrolyte fuel cell (PEFC) cathode is a performance-limiting component due to the slower oxygen reduction kinetics and mass transport limitations imposed by water generated in an electrochemical reaction. This water assists the performance of the PEFC by preventing drying of the polymer electrolyte. Conversely, the water hinders the transport of the reactant species by blocking the pores in the gas diffusion layer. Moreover, the effective electrode area is decreased, causing the cathode channel to become clogged with supersaturated water from the gas diffusion layer. This problem is overcome by separating the gas channel and the waste channel, and installing a water absorption layer (WAL). The new "WAL type" gas channel has an installed WAL in which the designed waste channel is compared with the gas flow characteristics of a conventional cathode gas channel by using the visualization technique. Gas flowing into the WAL type separator is barely blocked before the WAL absorbs water condensed in the cathode gas channel. Therefore, the WAL type separator effectively improves the PEFC performance.

Keywords: PEFC; Water management; Cathode gas channel; Visualization technique

1. Introduction

In the future, PEFC is expected to become a distributed power source for cars and the like because of its high efficiency and low temperature operation. Therefore, researchers around the world have been conducting research on the improvement of PEFC performance. Many researchers have been conducting research about the gas diffusion layer, the electrolyte membrane, and the separator material. It is understood that the gas channel should be optimized for improving the PEFC performance. If the dew point of steam generated by an electrochemical reaction and steam supplied to the cell rises more than the cell temperature, steam supersaturated in the channel becomes dew condensation. Because this, dew condensation clogs the channel and disturbs the diffusion of the gas, deteriorating the performance of the PEFC. However, there is little reported research on the optimization of the gas channel pattern and the water management comprising the heart of the cell. Recently, the Fraunhofer Institute for Solar Energy Systems [1–2] has made a dynamic study elucidating on the behaviour of cell reactions using the visualization technique. Kumar et al. [3,4] have been studying the numerical analysis of the effect of channel geometry on PEFC performance. However, the mechanism of flooding the flow field with product water in a PEFC has scarcely been experimentally researched [5], and water management is not optimized in the PEFC based on the research of the flooding mechanism. The present paper solves these problems using the following two techniques. First, the flow field-flooding phenomenon with product water is elucidated by using the visualization technique. Secondly, because a water absorption layer (WAL) and waste channel are installed in the channel, flow field flooding caused by product water has been

* Corresponding author. Tel.: +81 72 820 8537; fax: +81 72 821 0134.
E-mail address: sugiura@sys.osaka-pct.ac.jp (K. Sugiura).

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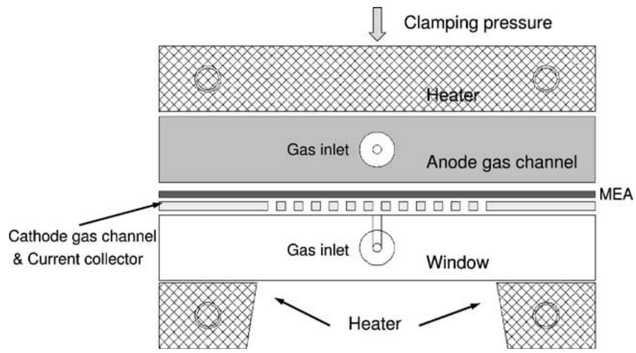

Fig. 1. Schematic diagram of the cell that can observe in cathode gas channel.

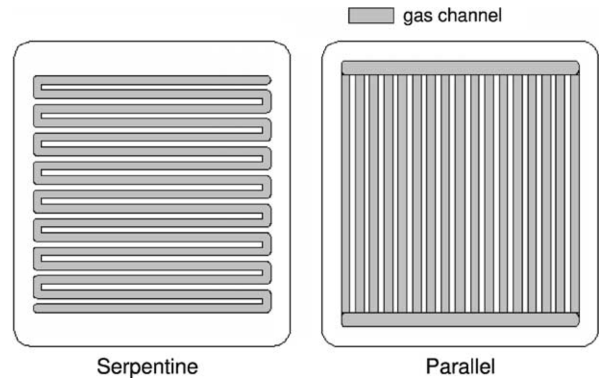

Fig. 3. Analyzed channel pattern.

eliminated. In other words, the supersaturating water is absorbed by installing the WAL in the current collector, and the electrolyte membrane is enriched because water in the WAL is supplied to the electrolyte membrane. Moreover, surplus water in the WAL is efficiently expelled outside the cell by the waste channel set up under the WAL. The effect of the WAL is also confirmed by using the visualization technique. Therefore, emphasis is placed on the optimization of PEFC water management using these two techniques.

2. Experimental

2.1. PEFC cathode gas channel geometry

Flow field flooding with product water is elucidated by observing the inside of the cell using the visualization technique. Fig. 1 shows the schematic diagram of a cell observed in a cathode gas channel. The effective electrode area of this cell is 25 cm^2. Although the anode separator is made of carbon, the cathode separator is made of polycarbonate for image measurements. In addition, the cathode side of the heater plate has an observation window, as shown in Fig. 2. Because polycarbonate, which is an insulator, cannot remove electric current, the cathode gas channel is maintained by carving out a groove for the cathode current collector plate, enabling the electric current to be removed. As shown in Fig. 3, there are two kinds of channel patterns: the serpentine pattern and the parallel pattern. Because the thickness of the current collector plate in the channel is 0.8 mm, the cathode gas channel is 0.8 mm deep. Moreover, all cathode gas channels are 1.6 mm wide. The anode catalyst is Pt-Ru/C, and the cathode catalyst is Pt/C. The gas diffusion layer of both electrodes is conventional carbon paper, the thickness of which is 0.2 mm. The electrolyte membrane is a perfluorosulphonate. Here, this study uses the same MEA in all the experiments to eliminate the influence on the flooding by the difference of the gas channel.

2.2. Water absorption layer and the waste channel

Fig. 4 shows a schematic diagram of the cathode separator with the water absorption layer (WAL) and the waste channel, known as the WAL type separator. The WAL type separator is applied only to a parallel channel. The waste channel is carved for the convex part of the channel (contact face with the electrode), and is 0.5 mm wide and 1.0 mm deep. A WAL

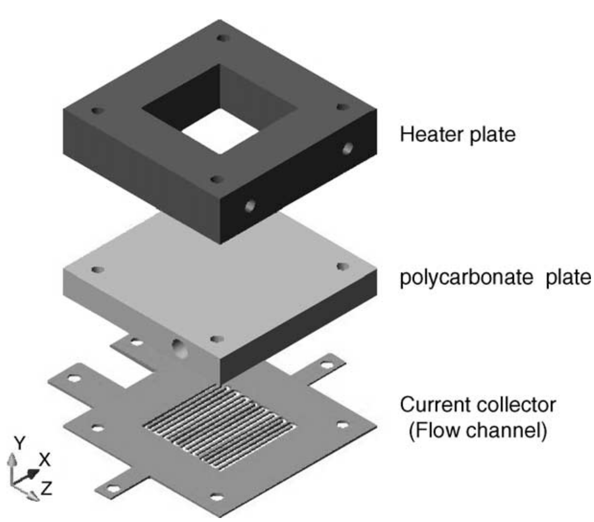

Fig. 2. Structure of cathode channel and the current collector.

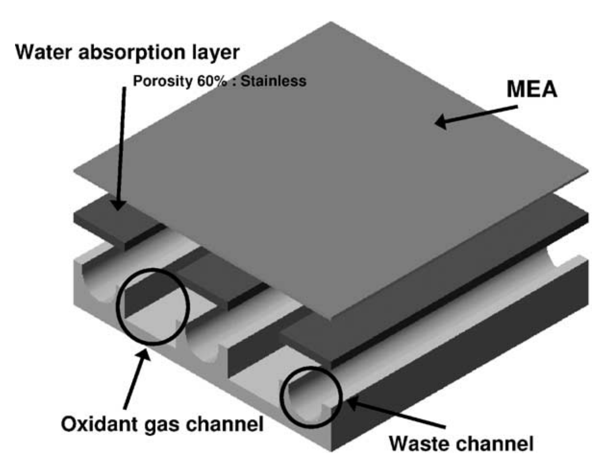

Fig. 4. Schematic diagram of the cathode separator with the water absorption layer and the waste channel.

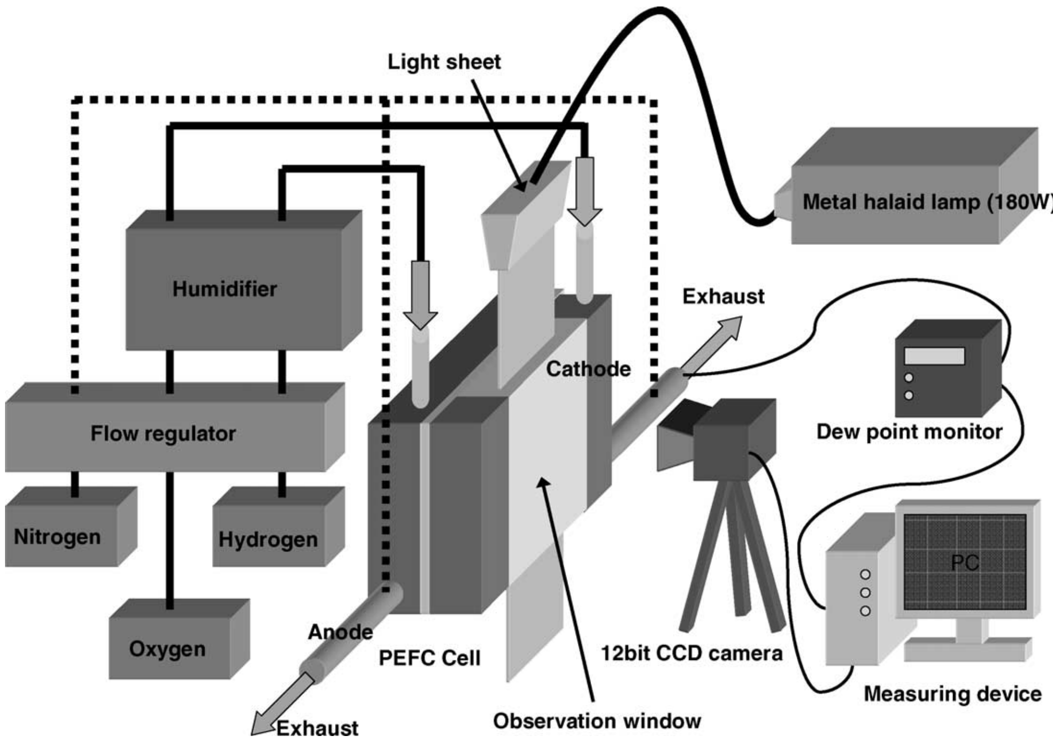

Fig. 5. Schematic diagram of the experimental apparatus.

of 1.2 mm width, 0.8 mm thick, and 50 mm in length is installed on the waste channel, the porosity of which is 60%, the material being composed of stainless steel. Because the electric current cannot be independently removed by the WAL, a current collector, in which a gas channel and the waste channel are installed, touches the WAL and is installed in the gas manifold, and removes the electric current to the outside through the electrode, the WAL, the collector, and the electric current terminal. Surplus water from the waste channel is expelled from the cell through the gas outlet.

2.3. Experimental apparatus and procedure

Fig. 5 shows a schematic diagram of the experimental apparatus. The temperature of the PEFC is maintained at 80 °C by means of a temperature controller. The anode gas and the cathode gas are humidified by passing through the humidifier and being supplied to the PEFC. To prevent the supply gas from being condensed, the piping between the humidifier and the cell is made shorter, and the piping temperature is maintained by a ribbon heater at 85 °C. The cell voltage is measured and recorded by a data logger. Cell resistance is measured by a milliohm meter with AC 4 probes. The light of the metal halide lamp (180 W) is irradiated from the side of the polycarbonate plate for visualization in the cathode gas channel. The image of the cathode gas channel in operation is measured from the front with a high spatial resolution video camera (12 bit). An image picture of 1300 pixels × 1024 pixels spatial resolution is saved directly into computer memory every 2 s.

Table 1
Experimental conditions

Standard condition	Anode	Cathode
Cell temperature (°C)	80	80
Cell pressure (MPa)	0.1	0.1
Supply gas composition (%)	$51H_2/49H_2O$	$51Air/49H_2O$
Humidifier temperature (°C)	80	80
Gas utilization (%)	70	40
Current density (mA cm^{-2})	300	

The experimental conditions are shown in Table 1. The anode gas is supplied to the cell as humidifying gas ($51H_2/49H_2O$) made by passing 100% H_2 into the humidifier at 80 °C. Cathode gas is also supplied to the cell as humidifying gas ($51Air/49H_2O$) made by passing 100% air into the humidifier at 80 °C. Fuel gas utilization is 70%, and oxidant gas utilization is 40%, respectively. The current density is 300 mA cm^{-2}, and the operating pressure is atmospheric.

3. Results and discussion

3.1. Flow field flooding phenomenon with water

Fig. 6 shows the initial *V–I* performance of the cell under standard conditions. Cell performance with a parallel gas channel is worse than that using a serpentine gas channel, because the cathode gas diffusion resistance of the parallel channel is larger than that of the serpentine channel because the Reynolds number ($Re = 152$) of the parallel chan-

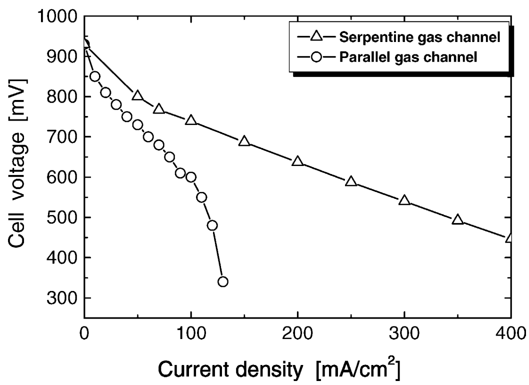

Fig. 6. Initial *V–I* performance of cell under the standard condition.

nel is smaller than that of the serpentine channel (*Re* = 4819). Fig. 7 shows the voltage variation of a PEFC with a serpentine channel and a parallel channel. In this instance, the separators are made of carbon. Operation is carried out under standard conditions, the cell voltage being measured for three hours at a sampling frequency of 1 Hz. Though the mean cell voltage with a serpentine gas channel is about 625 mV with a 300 mA cm^{-2} current density, the cell voltage descends frequently at 10–20 mV like a spike. On the other hand, the mean cell voltage with a parallel gas channel is about 725 mV with a current density of 80 mA cm^{-2}. Here, the current density is established as 80 mA cm^{-2} for cell performance with a parallel gas channel as shown in Fig. 6. Though the cell voltage had not descended frequently like a spike, small voltage variations have occurred for periods of about a minute, and voltage variations of 10–15 mV for periods of 10 min, an effect stemming from the effect of flow field flooding with product water. Therefore, we intend to visualize the cathode channel for elucidating the correlation between

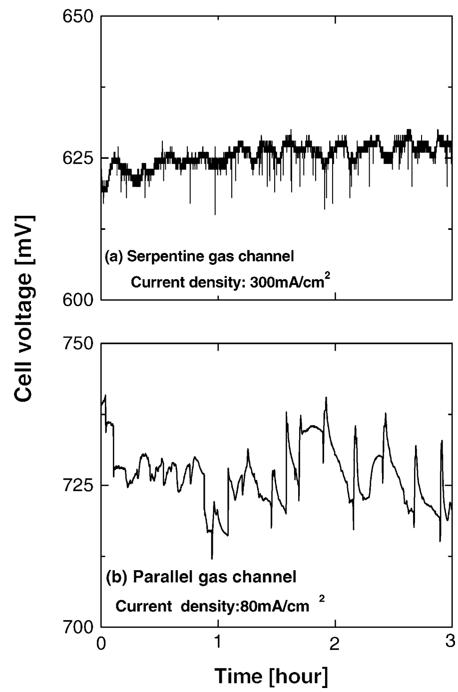

Fig. 7. Voltage variation of PEFC with the serpentine channel and the parallel channel.

cell voltage variations and flow field flooding with product water.

In regard to visualization, Fig. 8 shows the measurement image of a cathode serpentine gas channel. Flow field flooding with the produced water is caused in each part of the channel. If a serpentine channel is clogged by the produced water, gas is not supplied beyond the location of the clog, resulting in the deterioration of the cell performance due to decreasing effective electrode area. Cell performance is improved

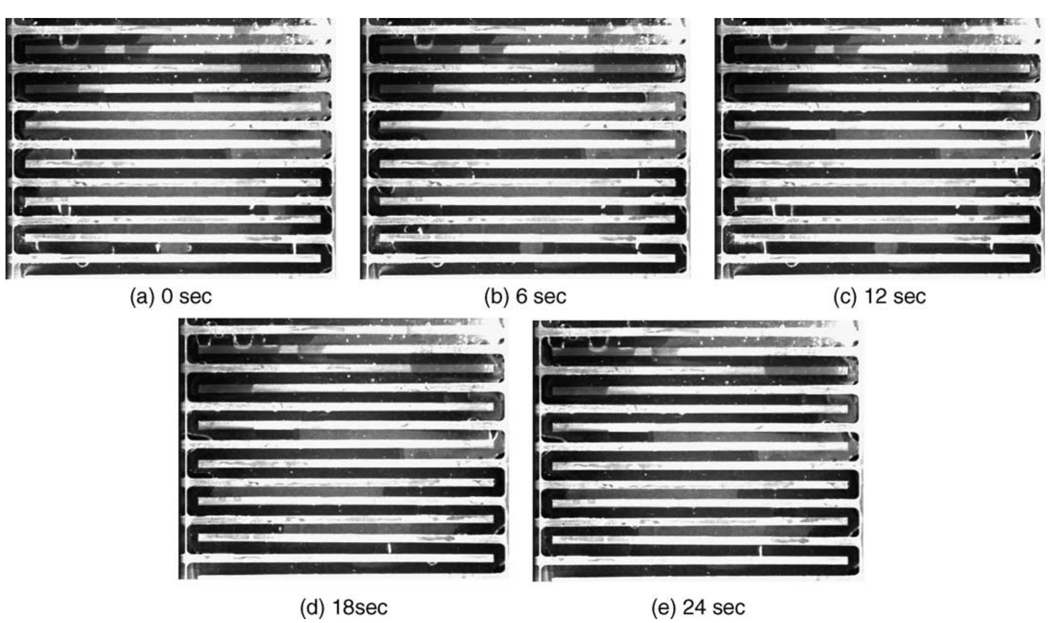

Fig. 8. Measurement image of the cathode serpentine gas channel.

by increasing the effective electrode area if the blockage water is swept downstream. Changes with the elapse of time of the blockage water distribution on the flow field occurred as shown in Fig. 9. Here, the fractional distance of the cathode gas channel is defined by a dimensionless position from inlet to outlet. In addition, the flooding water volume is calculated from the channel size and the channel length blocked by the flooding water. The flooding water in the middle area is swept downstream 18 s later by the rising gas pressure, and is expelled to the exit. It is understandable that cell voltage variation, spike in the serpentine gas channel, is caused by changes in the effective electrode area by the movement of the flooding water. To use the Serpentine channel as the PEFC channel, the following solutions were proposed: (1) to ensure that the blockage water is drained, it is necessary to raise the gas supply pressure; (2) it is necessary to provide a water-repellent treatment to the GDL and the channel.

On the other hand, regarding the cathode parallel gas channel, a part of the channel has been blocked with the produced water, as shown in Fig. 10. Fig. 11 shows the lapse of time changes of blockage water distribution in the flow field. Here, a dimensionless position of the parallel gas channel cannot be defined because not all of the channels are connected. Therefore, the horizontal axis shows a channel number numbered from the left of Fig. 10, and the vertical axis shows the integrated value of the flooding water volume present in each channel. There is hardly any flow field flooding at the central channel, but it does occur at both ends of the channel. The flooding water in the central channel is swept to an outlet 24 s later, the moving floodwater corresponding to small voltage variations. In addition, flooding water at both ends of the channel does not move even if 24 s pass. Because the gasflow in the parallel channel follows the Hargen–Poisseuille law to become a laminar flow state, gas velocity at both ends

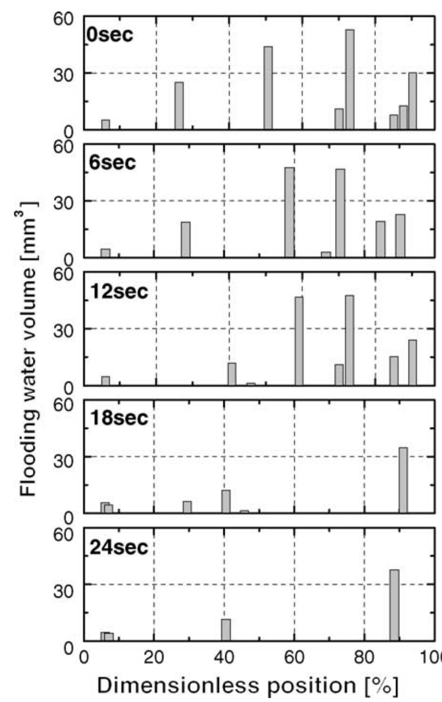

Fig. 9. Lapse of time of the blockage water distribution on the flow field.

of the channel is slow. Moreover, parallel channels, which are different from serpentine type channels, have many channels from inlet to outlet, and the supplied gas avoids the blocked channel and flows to an outlet through other channels. Therefore, if the channel is once blocked, the floodwater scarcely moves in the place and blocking is maintained. Because the floodwater disturbs gas diffusion to the electrode, the electrode is not effective in these locations. Because gas pressure in the channel increases if there is increased clogging of the

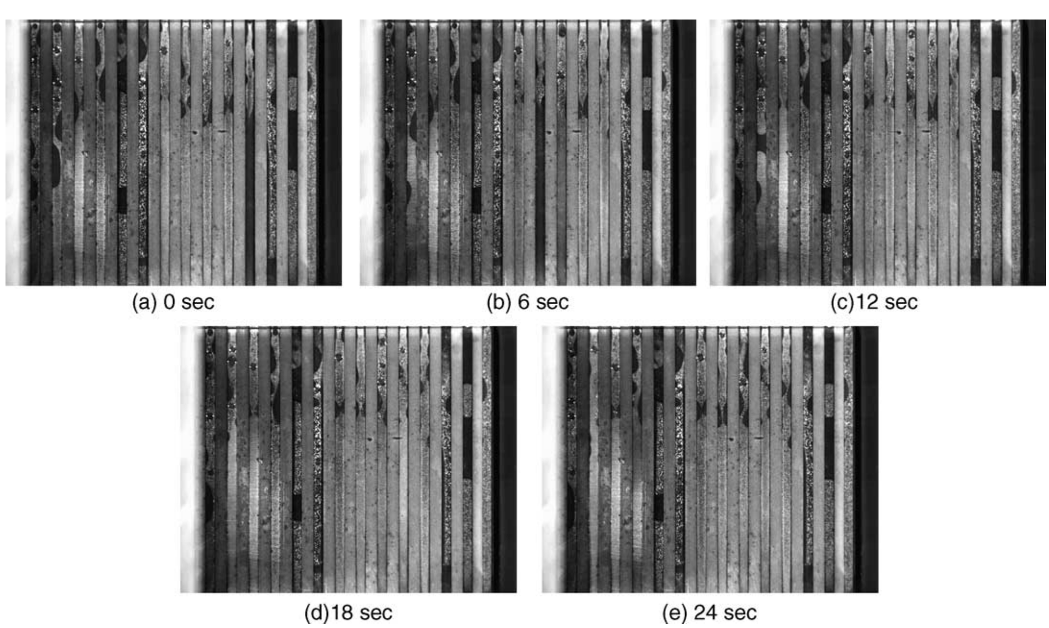

Fig. 10. Measurement image of the cathode parallel gas channel.

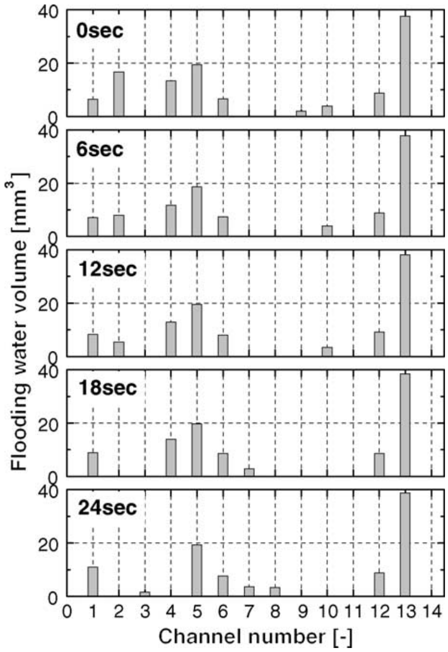

Fig. 11. Lapse of time of the blockage water distribution on the flow field.

channel, the floodwater is swept to an outlet. Moving of the slow floodwaters corresponds to large voltage variations, as shown in Fig. 7, for which reasons the cell performance of the parallel gas channel is bad.

3.2. Effect of the water absorption layer and the waste channel on the flood phenomenon with the water of the channel

The problem of channel blockage by the produced water can be solved if the floodwater is absorbed efficiently by the water absorption layer (WAL), and if the absorbed water is expelled from the cell by the waste channel. Moreover, because the electrolyte membrane can maintain enrichment by supplying water in WAL to the electrolyte membrane, drying of the electrolyte membrane is solved. As the WAL type channel is structurally more easily applied to a parallel type than a serpentine type, a parallel type separator provided with a WAL was made visible for the effect of the WAL to be evaluated. Fig. 12 shows the comparison of the *V–I* performance between a conventional parallel channel and the WAL channel under standard conditions. The cell voltage drop of a WAL is a little large, although it is similar in both cases. In this instance, the cell resistance of a conventional parallel channel is 11 mΩ and that of a WAL channel is 20 mΩ, respectively. It is understood that the reason for the large resistance of the WAL channel is as follows: (1) the contact area with MEA is small as the porosity of the WAL is 60%; (2) absorption of water into the pores of the WAL is resisted. If the difference in the voltage drop is attributable to the difference in cell resistance, the difference in the voltage drop should be a little larger. Cell performance with a WAL channel, however, is

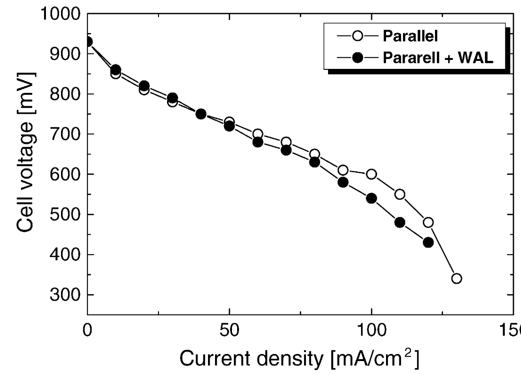

Fig. 12. Comparison of the *V–I* performance between a conventional parallel channel and the WAL channel.

improved by installing the WAL and waste channel. Therefore, to identify the factors for which the WAL improves cell characteristics, the phenomenon of the cathode channel was observed. Fig. 13 shows the measurement image of the WAL type separator. Though the channel of the WAL type separator is blocked in the restricted part, the fraction of the flow field flooding part is less than for a conventional parallel type and a serpentine type. The effect of the WAL is verified by comparing the flooding rates of each channel type. Fig. 14 shows a comparison of flooding rates of each channel type. Here, the flooding rate is defined as the ratio of the blocked area of the channel to the area of all channels. The flooding rate of the WAL type is smaller than for a conventional serpentine type and a parallel type, and its change is small and gradual. Therefore, the installation of the WAL decreases the flooding rate by a factor of 4 or 5. An arbitrary channel image is extracted, and its time variance is evaluated to verify the effect of the WAL in detail. Fig. 15 shows the expansion image of the channel every 0.2 s. Water droplets that adhere to the channel gradually become small, and disappear 0.8 s later. Because the flooding water volume downstream does

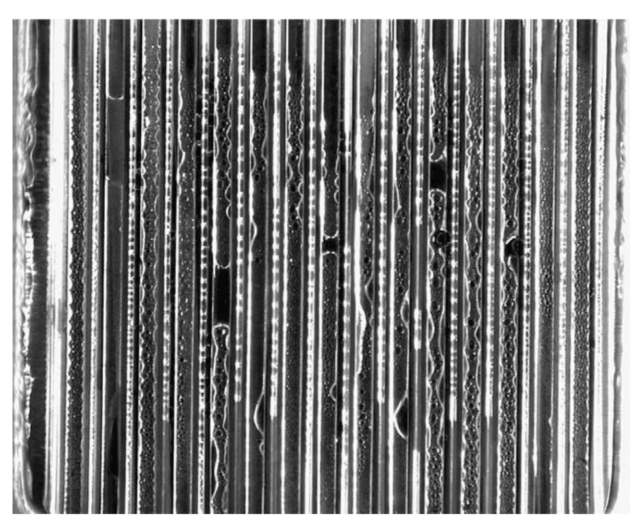

Fig. 13. Measurement image of the WAL type separator.

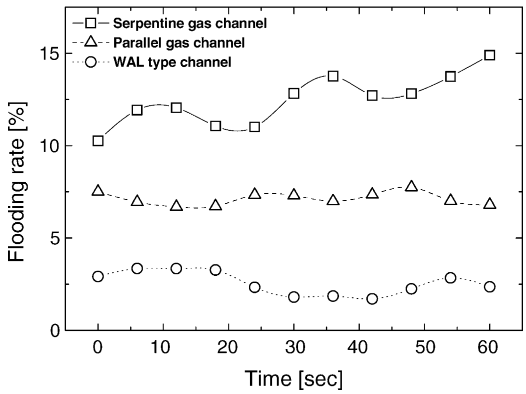

Fig. 14. Comparison of flooding rates of each channel type.

not increase as the upstream water droplets disappear, disappearance of the water droplets does not continue along the channel wall and downstream. Therefore, the WAL has the effect of controlling flow field flooding. Moreover, the electrode part with which the current collector comes into contact is available for cell reaction, because the reactant gas diffuses in the pores in the WAL. It is understood that this factor has the effect of increasing the effective electrode area. However, many water droplets adhere to the channel wall even though the floodwater does not completely block part of the channel. The expansion image of the waste channel as shown in Fig. 16 is then verified to evaluate the effect of the waste channel. Though the absorbed water that becomes a saturated in the WAL is expelled to the waste channel, the expelled water becomes a small drop of water and stays in the waste channel, because the size of the waste channel is small. Therefore, the waste channel does not achieve enough effect, and the waste channel geometry should be optimized.

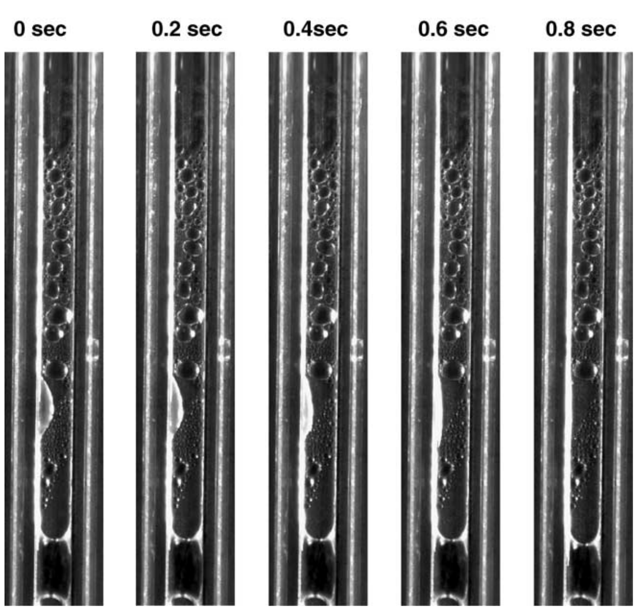

Fig. 15. Effect of WAL.

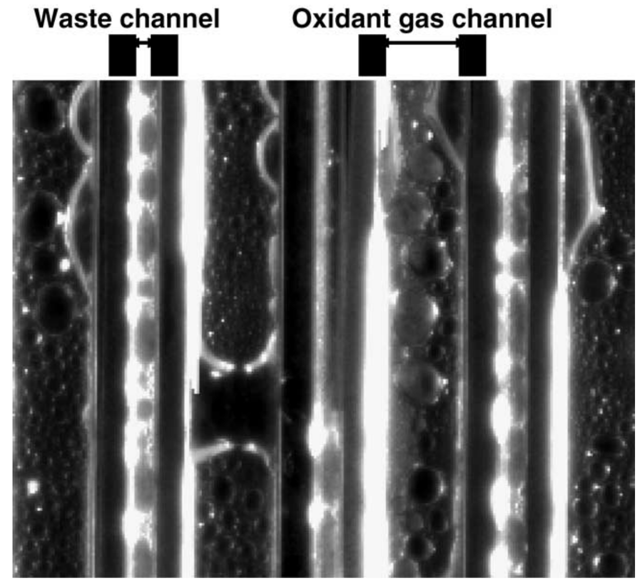

Fig. 16. Expansion image of the waste channel.

From these results, the effects of the WAL and the waste channel installation on the cell performance are understood as follows:

(1) WAL absorbs surplus water of GDL and the gas channel.
(2) The electrode part with which the current collector comes into contact is available for the cell reaction because the reactant gas diffuses in the pore in the WAL. Therefore, if the WAL channel is used in place as a conventional channel, the reaction distribution is made uniform.
(3) We can expect the cooling effect of the cell by the water in WAL to absorb heat according to the cell reaction.

4. Conclusion

The objective of this study was to evaluate the cathode gas channel with a water absorption layer/waste channel in a PEFC using the visualization technique. The results of the study are summarized as follows.

1. A cell voltage drop spike in the serpentine channel is caused by changes in the effective electrode area by the movement of the flooding water.
2. If a parallel type channel was once blocked by the produced water, the floodwater hardly moves in this location and remains blocking. Because the floodwater disturbs the gas diffusion to the electrode, the electrode is not effective in these parts.
3. The installation of the WAL decreases the flooding rate by a factor of 4–5.
4. Water in the waste channel increases fluid resistance and cannot flow to outlet as the size of the waste channel is small. The waste channel geometry should be optimized.

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