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PEM POWER GENERATION UNDER HIGH-TEMPERATURE CONDITIONS : EXPERIMENTS AND SIMULATIONS

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1. ABSTRACT

This paper describes three points : “① Experiments in power generation under high-temperature conditions”, “② Visualization of PEM power generation conditions (temperature surface distribution measurement)” conducted in collaboration with Mie University, and “③ PEM three-dimensional modeling simulation (distribution of temperature, gas, formed water)”, which is a part of our on going investigation of high-temperature PEM engineering development trends.

1) Power generation experiments under high-temperature conditions

Power generation experiments were performed under high-temperature conditions. The power generation performance (cell voltage) decreased and the cell resistance increased as the cell temperature was increased.

2) Visualization of PEM power generation states

The regular PEM power generation state was visualized by using thermography to measure the surface temperature distribution in the cell when power is generated. From this result, it is thought that the reaction phenomena inside the cell are mostly near the fuel gas inlet.

3) PEM 3-Dimensional Model Simulation

Using the 3-dimensional cut model of the single PEFC cell, distribution of the temperature, gas, and formed water were simulated for when a regular PEM generates electricity. From this result, it confirms the validity of the model and is considered applicable to high-temperature PEM too.

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2.1 Introduction

For the sake of the long-term goal of reducing the half level of global greenhouse gases emissions from 2008 by 2050, the “Cool Earth - Energy Technology Program” was drawn up in Japan in March 2008 and 21 innovative energy technologies were selected to concentrate on. Among these, stationary fuel cells are positioned as an innovative technology from the perspective of expanded use of reduced carbon energy in the consumer sector.

Stationary fuel cells have high electrical power generation efficiency and low CO_2 emissions, so this is technology that can contribute to reducing the load on the environment. Much is expected of stationary fuel cells as an energy source that can cover a variety of applications and scales, from portable equipment to automobile, residential, and industrial cogeneration systems. Two types are being developed: polymer electrolyte fuel cell (PEFC) and solid oxide fuel cell (SOFC) for residential use.

Toho Gas has been working on the development of PEFC systems for residential cogeneration since the latter half of the 1990s and started commercialization of these systems in 2009 under the product name of “ENE·FARM”. On the other hand, manufacturers are moving forward with the development of technology to improve equipment performance and cut the cost of equipment. This also includes basic research, for example into high-temperature PEMs. Given these circumstances, in order to grasp the PEFC system technology development trends and to clarify the technical issues to the tackled, Toho Gas too has its eyes on high-temperature PEMs in particular, is obtaining development articles from manufacturers, and is proceeding with tasks such as evaluating performance for high-temperature operation.

This paper discusses the survey of high-temperature PEM technology development trends undertaken by our company.

2.2 Outline of residential PEFC Systems

Residential PEFC systems use a fuel such as city gas to produce electricity and heat. They are comprised a power generation unit and a hot water supply unit (See Fig. 1). The power generation unit is comprised the reformer that generates reformed hydrogen-rich gas from the city gas, the stack that reacts hydrogen in the reformed gas with oxygen in the air to generate electricity and gas, etc. The hot water supply unit is comprised the hot water tank that accumulates the hot water recovered from the power generation unit and the backup water heater to heat the water when the hot water from the hot water tank is insufficient.

The electrical power generated by the power generation unit used for the residential electrical power load. On the other hand, the recovered waste heat is used for hot water loads such as the kitchen, bathing tub, etc. as hot water and is used for heating etc.

The stack, which is at the center of the power generation unit, is comprised layers of PEM and electrodes (See Fig. 2). If PEM can be given durability even under conditions of high temperatures, then improved performance through catalytic activation can be expected.

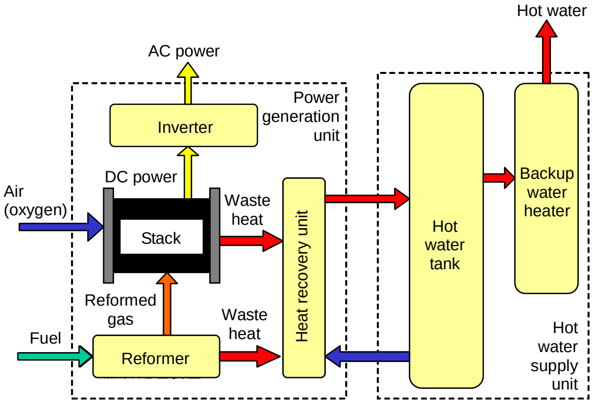


Fig. 1: Outline of Residential PEFC System

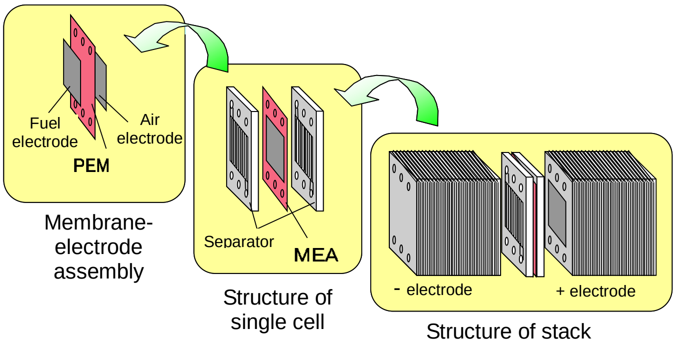


Fig. 2: Outline of Stack

2.3 Contents of Activities

Toho Gas is tackling the clarification of power generation mechanisms and grasping the performance of high-temperature PEM as the investigation of trends in high-temperature PEM technology development. Currently, as the first step toward grasping performance, Toho Gas is tackling establishing the evaluation method for high-temperature PEM and for clarifying the power generation mechanism, Toho Gas is aiming to establish PEM power generation state visualization and simulation technology. This paper introduces three points concerning the establishment of evaluation techniques: "① Experiments in power generation under high-temperature conditions", "② Visualization of PEM power generation conditions (temperature surface distribution measurement)" conducted in collaboration with Mie University, and "③ PEM three-dimensional modeling simulation (distribution of temperature, gas, formed water)".

2.3.1 Experiments in power generation under high-temperature conditions

In order to establish the evaluation technique for high-temperature PEM, power generation experiments were conducted under high temperature (>100˚C). Following is a summary of the experiments.

✓ An MC-25SC-NH from Micro Cell Technology was used for the PEFC cells (regular PEMs) (See Fig. 3).

✓ Compact cell evaluation devices made by CHINO corporation are used as the evaluation devices (See Fig. 4).

✓ For the provided gas, humidified hydrogen and humidified air are used and the relative humidity is controlled at the humidification tank temperature and the flow is controlled with the mass flow controller (See Fig. 5).

✓ The load current is controlled to the desired value by the electronic load device and the cell voltage values are obtained with the logging PC.

✓ PEFC cells are controlled temperature by the rubber heater attached to the end block.

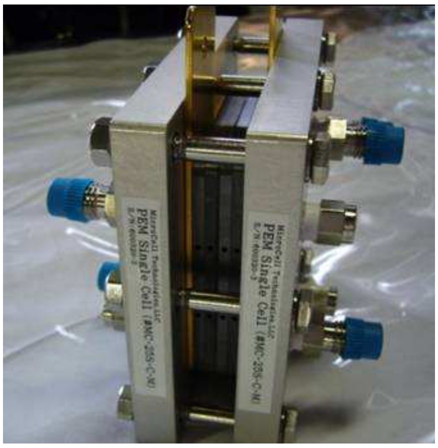


Fig. 3: Appearance of PEFC Cells

Fig. 4: Appearance of Compact Cell Evaluation Device

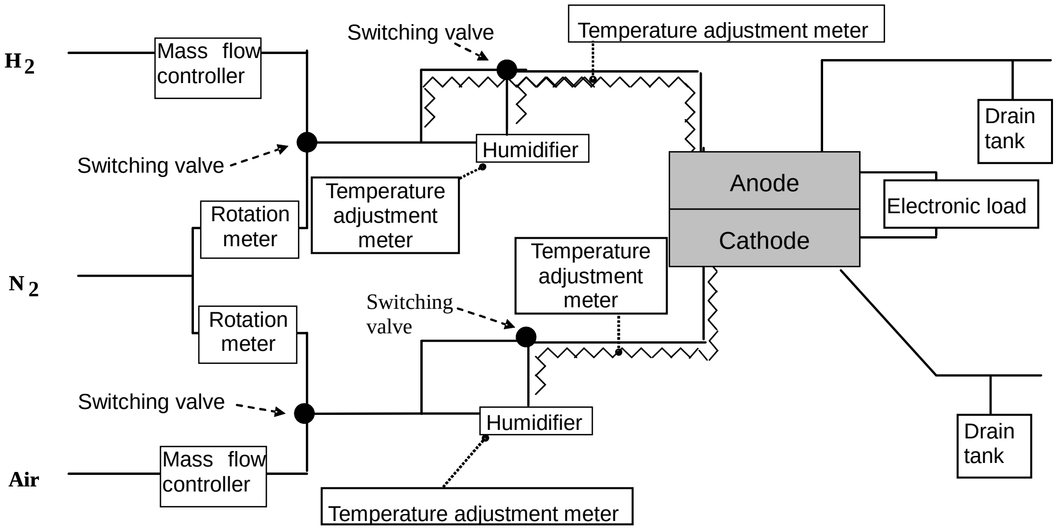


Fig. 5: Flow Diagram for Compact Cell Evaluation Device

Table 1 shows the experiment conditions and Fig. 6 shows the results of the experiment (cell voltage and cell resistance for each current density). The hypothesis before the experiment was that as the cell temperature rises, due to improved performance of Pt and other catalysts, ① The power generation performance (cell voltage) will rise and ② The reaction resistance will decrease and the cell resistance (electrolyte membrane resistance + reaction resistance) will also decrease. However, in the experiment results, as the cell temperature rises, ① The power generation performance (cell voltage) decreases and ② The cell resistance increases. These results were the exact opposite of the hypothesis. The cause for this is that when the cell temperature is raised at a constant relative humidity (RH40%), the partial pressure of the water vapor in the fuel gas on the cathode side rises (the oxygen partial pressure falls).

Since the point to improve in the experimental technique was identified as above, as the countermeasure, a method was considered in which N_2 is mixed in with the fuel gas and as the partial pressure of water vapor increases, the amount of N_2 mixed in is decreased to hold the partial pressure of oxygen constant. This countermeasure will be executed in future experiments and the essential PEM performance grasped.

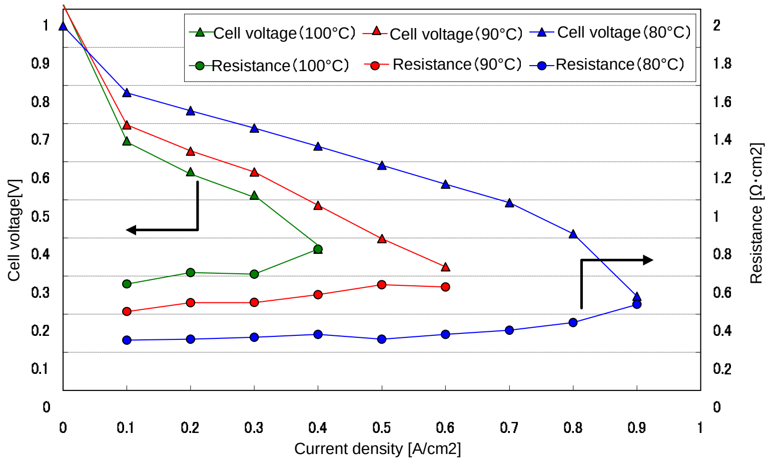


Fig. 6: Results of Power generation Experiments Under High-Temperature Conditions

Table 1: Setting the Conditions for the Power generation Experiments

Item	Settings
Cell temperature	80, 90, 100°C
Relative humidity	40%
Fuel gas	Hydrogen/ Oxygen
Gas usage	Anode 70% Cathode 40%
Calculation method	Calculated from the last minute of the output stabilization time (5 min)

Also, in parallel with the power generation experiments with regular PEM, development articles of PEM were obtained from two companies manufacturing PEMS and their power generation performance under the conditions recommended by the manufacturers was checked. Figure 6 shows the results of these experiments. It was confirmed that the high-temperature PEMs under development (by Company A and Company B) had output densities under high-temperature conditions about 30% higher than regular PEMs (See Fig. 7). The main cause of the superiority of the high-temperature PEMs was their higher H_2 ion conductivity under high-temperature conditions.

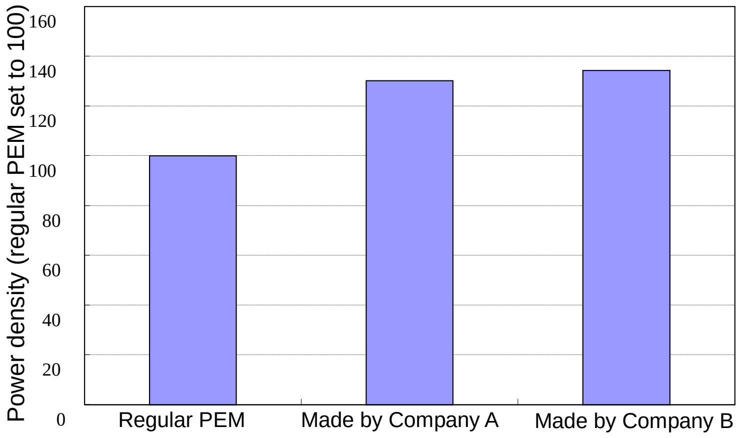


Fig. 7: High-Temperature PEM Power Density

2.3.2 Visualization of PEM power generation states

The PEM power generation conditions was visualized by opening an observation window in PEFC cells (with regular PEMs mounted) and using thermography to measure the surface temperature distribution in the cell when power is generated. The surface temperature distribution in the cell was shot with thermography when power was generated with a current load of 20 A (0.8 A/cm^2). Fig. 8 and Fig. 9 show the results of these experiments. The temperature near the fuel gas inlet was approximately 2˚C higher in the observation region. In the open circuit voltage (OCV) state, because such a temperature distribution does not occur, it is judged that the temperature distribution caused by the heat generated from power generation. From this result, it is thought that the reaction phenomena inside the cell are mostly near the fuel gas inlet.

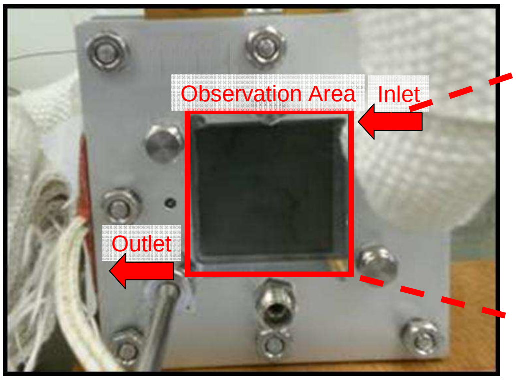


Fig. 8: Appearance of PEFC Cells (with observation window)

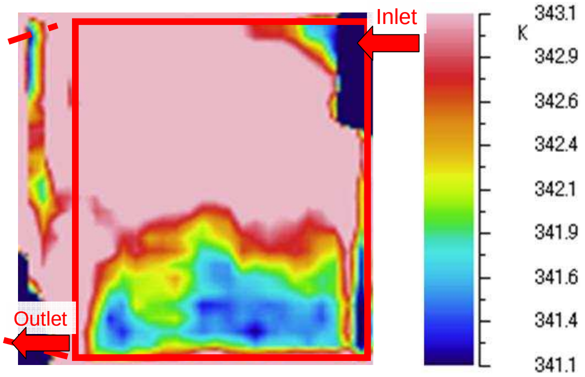


Fig. 9: Cell Temperature Distribution during Power Generation

2.3.3 PEM 3-Dimensional Model Simulation

The experimental results in (2) and the general CFD-ACE+ software (from Wave Front) were used to construct the 3-dimensional cut model of the single PEFC cell shown in Fig. 10. This cut model is 2.5 mm high, 2.0 mm wide, and 0.1 mm thick and it has 800,000 calculation nodes in the mesh. Pure hydrogen and pure oxygen were used in the fuel gas and were set to flow parallel to the direction of gas flow. Using this cut model, the temperature, gas, and generated water distribution were simulated for when a regular PEM generates electricity. Fig. 11 shows one example of the results (Temperature distribution during power generation by regular PEM: gas flow direction along the axis perpendicular to the paper surface from front to rear). At a cell temperature of 80˚C, the center section along the PEM membrane thickness direction has the greatest temperature rise (about 1˚C). Comparing these results with the results of previous research also shows the validity of this simulation model.

Also, data was obtained on high-temperature PEM properties and applied to the cut model to run a high-temperature PEM 3-dimensional simulation. In the experimental results and simulation results, the same trend was confirmed (The power generation performance was improved on the three points of ① Cell temperature rise, ② Fuel gas relative humidity rise, and ③ Cathode fuel gas change from air to O_2). Therefore, this cut model is considered applicable to high-temperature PEM too.

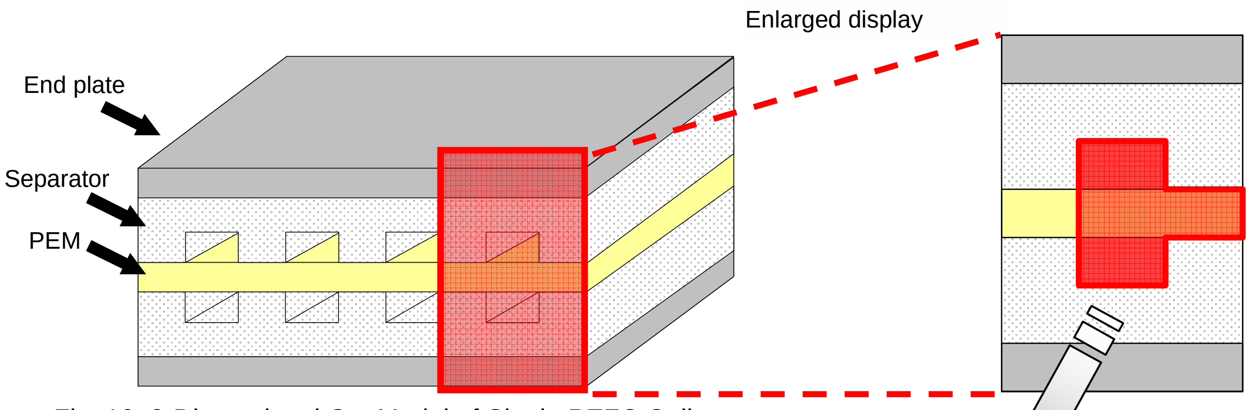


Fig. 10: 3-Dimensional Cut Model of Single PEFC Cell

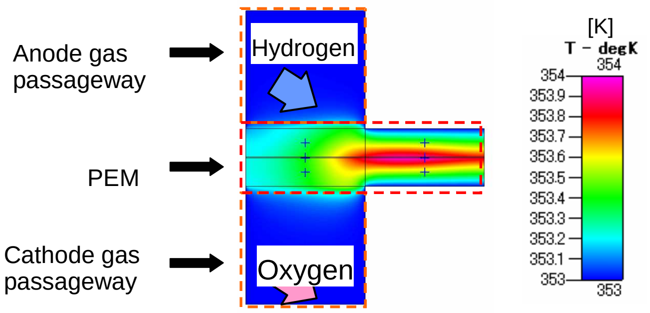
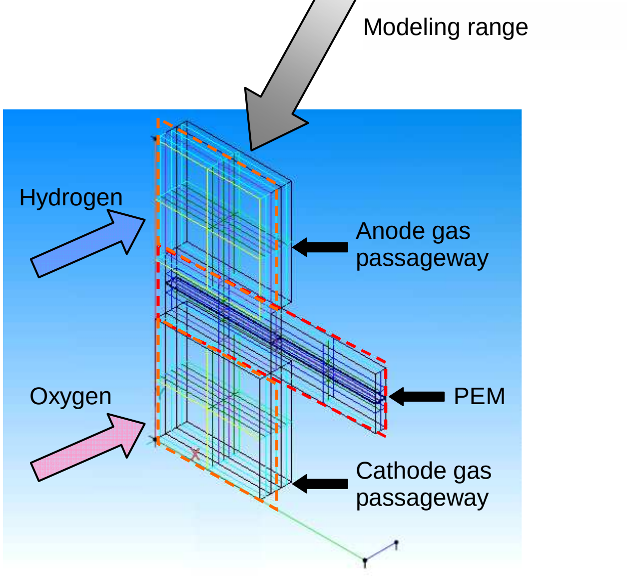


Fig. 11: Example of Simulation Results



2.4 Future Issues

Plans for the future are to improve the precision of simulation based on the experimental data, to extend the range of the simulation, and to link this to clarification of the high-temperature PEM power generation mechanism.

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