Fractal Flow Fields: A New Design of Gas Flow Channels in Polymer Electrolyte Fuel Cells

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ABSTRACT.

A new type of gas flow field in the anode and cathode gas chambers of polymer electrolyte fuel cells is proposed where the separator plate has no flow channel grooves but solely the flat sheet separating the anode and cathode gas diffusion layers (GDLs). The GDL layer is successively cut into subsections (fractals) of identical form, and assembled in a cofacial arrangement so that the electrode surface contacts these subsections. The gas is introduced directly into each portion of the GDL from the lateral direction. When the gas is forced to flow through the GDL, the gas diffuses to the catalyst layer and reacts there. The exhaust gas flows through the GDL in a lateral direction to a manifold. The pressure drop across the inlet and outlet of the gas flow field is several kPa for 20-40 mm fractal, which is ca. 10 times higher than the normal serpentine flow fields. However, the net power density per unit volume or weight of fuel cell is ca. 2 times higher in the fractal flow field than in serpentine flow field. In view of the uniformity in current density and temperature, the size of 20 mm for fractal is optimized.

INTRODUCTION

Polymer electrolyte fuel cells (PEFCs) are attracting more and more attention as a power generator in the field of zero-emission vehicles, stationary applications, and so on (1, 2). Because of high power, quick response and low operation temperature, PEFC has much merit as a power source to mobile applications. In order to be so, the power density (kW/L or kW/kg) of the current PEFC should further be improved.

In PEFCs, the power is mainly determined by the cathode performance because of the sluggish cathode reaction and mass transport, and this result in a high overpotential. Especially at high current densities, the power is limited by the availability of oxygen at the cathode catalyst surface. Also emerged water at the cathode catalyst layer counteracts oxygen diffusion. Water should be eliminated efficiently so that there is no hindrance of oxygen diffusion towards the catalyst surface. Design of gas flow channels is thus a crucial factor that determines the overall performance of PEFCs.

Conventional design is the serpentine flow field where the anode or the cathode gas flows through a zigzag patterned groove machined on the surface of carbon plate (3). The problem of this design is that under the rib the gas distribution is low and also water
flooding tends to occur at high current density. High cost for machining the gas flow channels on the carbon plate is another drawback.

Recently, T. V. Nguyen et al. developed a new design of flow field where a pair of comb like grooves, inlet and outlet channels, are carved with dead-end design on separator carbon materials (4). This design has an advantage of realizing a forced gas flow from one channel to the other through the gas diffusion layer, and effective supply of oxygen and removal of generated water are made possible.

In this work we report a new flow field that can eliminate the flow channel groove in the separator, makes it into a mere thin sheet and thus improves drastically the volume and weight power density of the PEFC system. This design is called fractal flow field, because it is based on the repetitive patterns of same geometric form, subdivided into smaller ones, as shown in Fig. 1. As repetitive patterns square or hexagonal patters are also possible, but in this report triangular patterns are tested for the first time.

EXPERIMENTAL

Pressure Drop Measurement through the Gas Diffusion Layer

The triangular gas diffusion layer (GDL) was tested for the pressure drop measurement using a carbon paper sheet (TORAY TGP-H-120, 0.35 mm thick, 76% porosity) through which oxygen gas was flowed from one apex to the opposite base or to the reversal direction. The size of GDL was 12.5, 17.7, 25 and 35.4 mm at the sides of vertical corner. As the gas inlet mode, 45 ° apex inlet mode or 90 ° apex inlet mode were tested (Fig. 2). The gas flow rate was controlled and pressure measured with a mass flow controller (MKS Instruments, Type M100B and Type 223) as shown in Fig. 3.

Effect of the Size of GDL on Polarization Performances

The size of the triangular pattern is optimized by measuring the current density at 25 °C for several sizes of single cells with MEA made of Nafion 112 membrane, 50 wt% Pt/C catalyst (Tanaka Kikinzoku Kogyo K.K., TEC10E 50E, 0.3 mg Pt cm⁻²) and TORAY carbon paper. At the same time, the heat generated from the cathode side end plate (Au foil as a current collector put on an acrylic resin block) was measured by a thermo-tracer (NEC TH5104) through a MgF₂ window.

Polarization Measurement with Single Cells

Power measurement with single cell was performed for 17.7x17.7 mm cell with fractal flow field at 50 °C. H₂ and O₂ gas were flowed with 70% ad 40% utilization rate, respectively, at 1 atm and humidified through the 60 °C gas bubblers. The polarization curves were measured also for the serpentine type cell with 5 cm² electrode area to compare the performances.

Performance Evaluation by Use of a Fuel Cell Simulator

The current density distribution, pressure and gas concentration distribution with either the fractal flow field or the serpentine flow field are simulated using a PEFC simulator P-Cell, developed by Fuji Research Institute Co. Ltd, Tokyo. H₂ and O₂ gas were introduced into the cell at 70% ad 40% utilization rate, respectively. After the current is maintained at 0 A cm⁻² and the cell is stabilized, the current is increased linearly with time (0.01 A/cm² per second) maintaining the gas utilization rate, until the
current reaches 1 A/cm². In the fractal flow field, the reversal mode of the gas flow is also simulated.

RESULTS AND DISCUSSION

The Pressure Drop through DGL in the Fractal Flow Field
The size and the gas flow mode in the triangular GDL are tested. As shown in Fig. 4, the pressure drop experiment showed a linear dependence on the gas flow rate, and in the 90° apex inlet mode, the pressure drop was about half of that of the 45° apex inlet mode. The size dependence was found to be small. This fact indicated that most of the pressure drop occurred around the inlet apex where the gas flow line was very crowded.

To cope with this problem, the inlet apex of 12.5 mm size GDL was cut into the width of 3 mm and tested in the same way. The pressure drop in this case was reduced by 30% where the decrease in the GDL area was only 3%. Thus a larger opening of the gas inlet could be very effective in reducing the pressure drop.

Simulation of Unit Cells made of Fractal Flow Fields and the Serpentine Flow Fields
Figure 5 depicts the simulated results of current distribution at 0.5 A/cm² in fractal flow fields. The current is localized at the anode gas inlet, because the generated water at the cathode diffuses to the anode side at the cathode downstream portion, and decreases the membrane resistance there. When the electrode area is increased at constant average current density, the local current is especially lowered at the inlet of the cathode gas.

After comparing performances of the 90° apex inlet mode and the outlet mode, it is seen that supplying the gas from the base side of a triangle is preferable in view of the uniformity of current density, as shown in Fig. 6. Increasing the current density caused a localization of the current at the inlet part of the gas. Thus the current density should be less than 0.3 A/cm². At this current density, the size effect was not large.

Polarization Measurements with different size of Fractal GDL
From the pressure drop measurements it is concluded that by modification of the inlet apex the problem of a large pressure drop can be solved. Then the size of the fractal subsection should be determined from the viewpoint of the uniformity of the current density across the electrode surface.

Polarization curves of various electrode area are measured at 25 °C. The results in Fig. 7 show that the best value of power density at 0.6 V was attained around 0.08 W/cm² with a size of 17.7x17.7 mm cell, and this value decreased to about half for the 50x50 mm cell. This is because of the non-uniform gas flow pattern for larger cell sizes.

The thermograph also supported the results, and non-uniform heat generation on the end plate was observed for cells larger than 20x20 mm size. In this case the heat was localized to the area where the anode and the cathode gas concentrations are both high. Comparing with the result of the computer simulation of a unit cell, a good correlation of heat distribution and the current distribution was confirmed.

Comparison of Polarization Behaviors with Serpentine Flow Fields
The single cell experiments were performed at 25 °C with 17.7x17.7 mm size of unit cell made of fractal flow fields. Polarization performances are compared in Fig. 8.
together with those of a unit cell made of serpentine flow fields. The current at 0.6 V was about 17% less in fractal flow field than that in serpentine flow field. Table 1 summarizes the projected power density of fuel cells made of fractal and serpentine flow fields, as expressed in the power per unit electrode area and that per unit volume.

At 50 °C, the difference in the polarization behaviors between fractal and serpentine flow fields was small, as indicated in Fig. 9. The power of 0.11 W/cm² for the fractal flow field and 0.12 W/cm² for the serpentine flow field per electrode area, respectively, were projected at 0.6 V operation. However, when the performance was expressed as volume power density, it was calculated to be 0.85 kW/L for fractal flow field in comparison with 0.49 kW/L for serpentine flow field, because in the former case the separator can be made thinner (0.5 mm) than in the latter case (2 mm).

CONCLUSIONS

A new flow field called the fractal flow field is proposed where the GDL of a PEFC is divided into smaller subsections of similar shapes, and in each subsection the gas is forced to flow through the GDL in lateral direction. In this way the gas delivery in GDL is improved and the thickness of a unit cell is reduced dramatically. This results in not only the increase in the volume power density of the cell stacks but also the cost reduction owing to the elimination of gas flow channels in the carbon separators.

Triangular fractals are tested either experimentally or with computer simulation, and it is found that this new flow field has a high potentiality as compared with conventional serpentine flow fields. One of the weak points of the triangular fractal flow fields is that the streamline of gases is localized at the inlet apex, which causes a high pressure drop and a non-uniform current distribution. However, in terms of the power density per unit volume or unit weight, fractal flow fields are very attractive option in the PEFC design. Further study is required for other types of fractals, such as square of hexagonal fractal flow fields, where the uniformity in the gas flow will be much improved as compared with the triangular fractal flow fields.

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Figure 1. (a) Serpentine flow field and (b) fractal flow field of triangular patterns. Each of the anode and the cathode gas diffusion layer has the same patterns, but oriented in perpendicular position.

Figure 2. (a) 45° apex inlet mode and (b) 90° apex inlet mode of triangular fractal flow field.
Figure 3. Pressure drop measurement system of triangular GDL.

Figure 4. Pressure drop versus $O_2$ gas flow rate through the GDL of various sizes in the $45^\circ$ apex inlet mode and $90^\circ$ apex inlet mode.
Figure 5. Current density distribution of (a) 25×25 mm cell and (b) 11.2×11.2 mm cell at the average current density of 0.5 A/cm². The contour lines are drawn for every 0.01 A/cm².

Figure 6. Current density distribution of 17.7×17.7 mm cell at the average current density of 0.3 A/cm². (a) 90° apex inlet mode and (b) base inlet mode.
Figure 7. Polarization curves of unit cell of fractal flow fields of various sizes measured at 25 °C.

Figure 8. Comparison of unit cell performances with 17.7×17.7 mm size triangle fractal flow fields and 22.4×22.4 mm serpentine flow fields measured at 25 °C.
Figure 9. Comparison of unit cell performances with triangle fractal flow fields of various sizes and 22.4×22.4 mm serpentine flow fields measured at 50 °C.

Table 1. Comparison of unit cell performances with triangle fractal flow fields of various sizes and 22.4×22.4 mm serpentine flow fields measured at 25 °C and 50 °C.

| Thickness (mm) | Flow fields          | Serpentine | Fractal |
|----------------|----------------------|------------|---------|
|                | Anode GDL           | 0.17       | 0.35    |
|                | Membrane + Catalyst layer | 0.10       | 0.10    |
|                | Cathode GDL         | 0.17       | 0.35    |
|                | Separator           | 2.00       | 0.50    |
|                | Total               | 2.44       | 1.30    |
| Power at 0.6V  | per unit area (mW/cm²) | 95         | 79      |
| at 25 °C       | per unit volume (mW/cm³) | 389       | 607     |
| Power at 0.6V  | per unit area (mW/cm²) | 120        | 110     |
| at 50 °C       | per unit volume (mW/cm³) | 492       | 846     |