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NOVEL METAL-FOAM FLOW FIELDS FOR PEM FUEL CELLS WITH ENHANCED PERFORMANCE

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ABSTRACT

Flow fields in bipolar plates of Proton Exchange Membrane fuel cells distribute fuel and oxidant over the reactive sites of the membrane electrode assembly. Bipolar plates are typically graphite with parallel or serpentine channels as flow fields. Drawbacks of graphite include weight, fabrication inaccuracy, cost, porosity, and brittleness. In this paper, open-cell metal foam is experimentally investigated as a flow field for a new bipolar plate design. Using experiments, the performance of the conventional bipolar plate/flow field was directly compared to that of the metal-foam designs at the same operational conditions. Results show that the cell current, voltage and power density were improved and temperature and pressure distribution on the membrane were even. As importantly, the conversion efficiency was higher for the metal-foam design, and the weight was reduced significantly.

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1. INTRODUCTION

A fuel cell is a power-generation system that converts chemical energy of a fuel (usually hydrogen) into DC electricity. The theoretical energy-conversion efficiency of fuel cells is over 80%. Fuel cells operate continuously as long as the reactants (hydrogen and oxygen from air) are supplied. This makes them different from batteries which require re-charging. The only byproducts of fuel cells are heat and water; they have no emissions [1]; in fact, fuel-cell-powered buses reduced greenhouse gas emissions by 62% compared to diesel buses [2]. Fuel cells have been considered for powering cars [3] and portable devices [4]; and as simple and hybrid power plants [5].

Proton Exchange Membrane fuel cells (PEMFC) enjoy few key advantages over other kinds of fuel cells: 1) low-temperature operation (60 to 80 oC compared to 700 oC for solid oxide fuel cells, 2) high power density, 3) fast start up, 4) robustness and 5) less sealing and corrosion issues. The power output and efficiency of PEMFC are higher than those of direct methanol fuel cells. In addition, PEMFC are more compact and weight less. As such they are strong candidates to replace the internal combustion engine in the transport industry [6]. Nonetheless, transportation application has the

most stringent requirements on volumetric and gravimetric power density, reliability and cost. The high cost of this technology represents the biggest challenge for its commercialization.

A single fuel cell produces about 0.7 Volts; for higher power, multiple cells are arranged in series (stacking). The bipolar stack is composed of unit cells that have alternate polarity, and face each other through bipolar plates. Bipolar plates are the most repeated component in a stack; and they are the heaviest and costliest components. Researches have estimated that they account for 40 to 80% of the total weight and 30 to 37% of the cost of a stack [7,8]. In terms of volume, bipolar plates occupy 70% of the volume of a stack [8]. Indeed, bipolar plates are one of the major issues preventing fast and full commercialization of fuel cells as an energy technology.

Heinzel et al. [7] recorded the following key requirements on the material of bipolar plates: low permeability for hydrogen, low cost, low weight, small volume, amenable to mass production techniques and recyclable. No single material has been identified to simultaneously satisfy all the requirements. The most common bipolar plates are made from graphite with micro-channels (flow field) machined on their face with serpentine, maze or parallel flow configurations. The channels provide flow paths to distribute the fuel and oxidant over the entire electrode area uniformly. Graphite exhibits weak flexural strength and is brittle, which is not suitable for transportation applications where serious vibrations and loading occur. The low flexural strength of graphite has prevented a much-needed reduction in the thickness of bipolar plates, limiting them to about 4 to 6 mm. This has resulted in fuel cell stacks with low power density, which is not acceptable for transportation and mobile applications.

Open-cell metal foam is a highly-porous material with a web-like internal structure, Fig. 1. The foam can be made from aluminum, copper, steel and nickel. Manufacturing, properties and applications of metal foam have been covered in [9]. Metal foams can be tailored to alter their properties by varying their internal morphology and the porosity. The foams also can be mechanically compressed. They enjoy good permeability and are excellent media for transporting and distributing gases. Simulations by the current authors have shown considerable enhancements when using metal foams as flow fields in PEMFC [10]. An experiment was conducted to assess these enhancements, as described next.

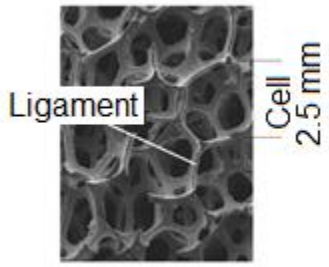

Fig. 1 Internal structure of open-cell aluminum foam having 10 pores per inch

2. Design and Fabrication of Novel Aluminum-Foam/Aluminum Bipolar Plate

Two new flow fields were basically sheets of open-cell aluminum foam made from 6101-T6 aluminum alloy (Duocel aluminum foam by ERG Materials and Aerospace). The starting porosity of the foam was in the range 94 to 96%. To achieve the desired size and porosity, the foam was mechanically compressed as listed in Table 1. Other morphological parameters of the foam are also given in the table.

Table 1 Morphological description of aluminum-foam flow fields

Flow field for	Pore density (ppi)	Cell diameter (mm)	Ligament length (mm)	Porosity (%)
Anode	**20**	1.250	0.520	68.3
Cathode	**40**	0.625	0.250	85.1

The final size of each sheet, after compression, was 1.02 mm X 50.01 mm X 56.59 mm (0.040" x 1.969" x 2.228") with a tolerance of ±0.13 mm. Each sheet could it in a bipolar plate made from aluminum 6101, as shown in Fig 2. The bipolar plate is identical in dimensions and design to those used in the commercial Scribner's fuel cell with 25 cm^2 active area. One plate for the anode side and the other for the cathode.

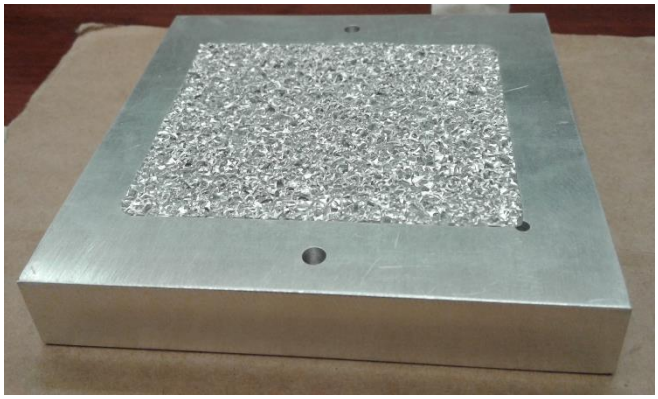

Fig. 2 Photograph of the novel aluminum-foam/aluminum bipolar plate

3. EXPERIMENTAL SET-UP AND PROCEDURE

The test rig, Fig. 3, constituted a fuel cell fixture manufactured by Scriber, three cylinders (hydrogen, nitrogen and air), two flowmeters, a temperature controller, two moisture traps, two back pressure regulators and stainless-steel gas lines. An electronic load recorder (Model ECL450) was used to obtain performance data.

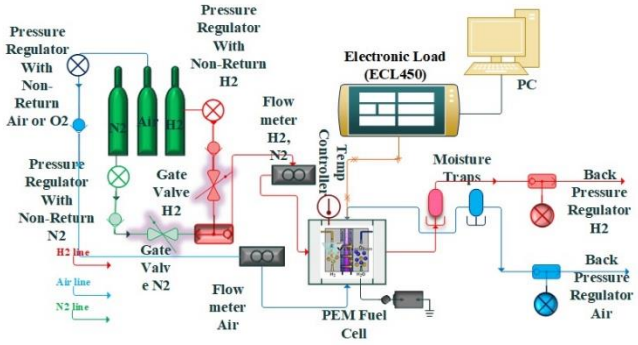

Fig. 3 Schematic of the experimental test rig

The experiment was conducted according to ASME PTC 50-2002 test standard issued by the American Society of Mechanical Engineers. Before each experiment, nitrogen was used for purging the system at a flow of 0.5 L/min at 3 bars for 10 minutes. Then valves and flowmeters were adjusted for air and hydrogen flow according to conditions ASME PTC 50-2002. The experiment took around thirty-five minutes to complete. The voltage, current and flow rates of hydrogen and air were recorded. This procedure was repeated twice-once with the state-of-the-art graphite plate and once with the novel bipolar plate with aluminum foam flow fields at the anode and cathode of the fuel cell.

The accuracies of the current and the voltage were 50 mA and 1 mV, respectively. The flow rates of air and hydrogen had an error of ±2 SLPM. The temperature of the membrane was measured using a thermocouple with accuracy of 0.4°C. The power P was obtained as the product of the current I and the voltage V. The resulting uncertainty in the power was ± 0.78% (calculated according to [11]).

4. RESULTS

Figure 4 shows the operating temperature at the membrane of the fuel cell for the novel aluminum-foam flow fields and the state-of-the-art graphite plate with serpentine micro-channels. The foam flow fields are seen to produce temperatures in the allowable limits for the safety of the membrane: 55 to 90 ^oC. Operating in this range is important for

the endurance of the membrane- an expensive and delicate component indeed. The graphite flow fields (the state of the art) is seen to produce temperatures outside of this allowable range, endangering the membrane.

The polarization curves are shown in Fig. 5. At the same initial maximum voltage, metal-foam flow fields are seen to produce slightly higher voltage and specific power density, as compared to state-of-the-art flow channels in the graphite bipolar plate. The current density j is calculated as

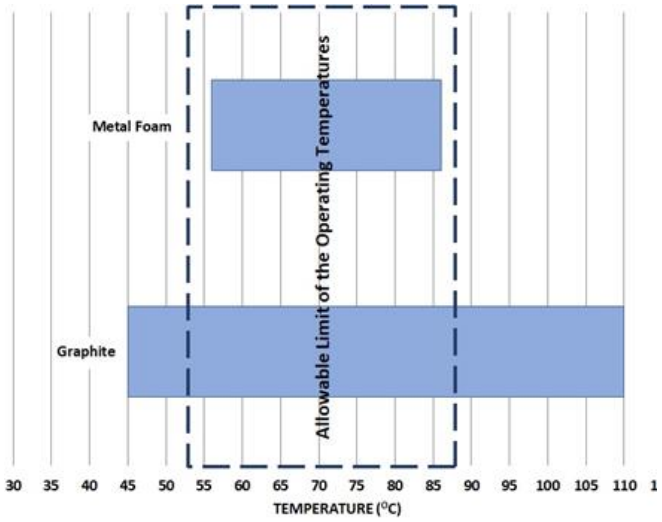

Fig. 4 Membrane operating temperature for metal-foam flow fields and graphite micro-channels- Dotted line represent safe range

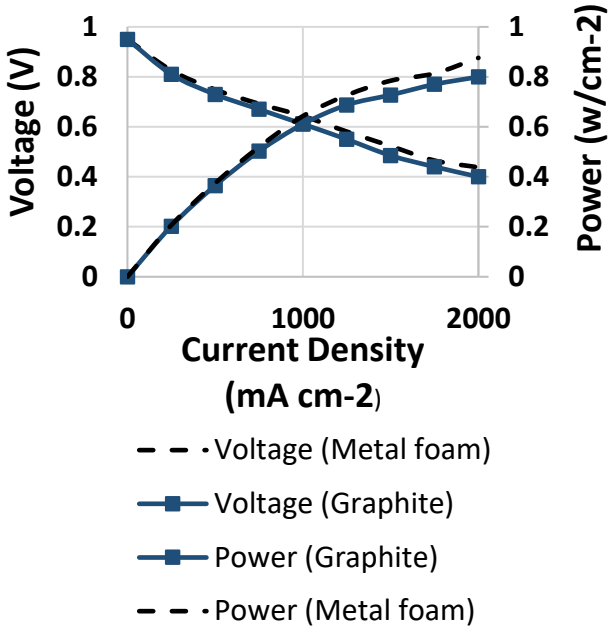

Fig. 5 Voltage and power density for existing and aluminum-foam flow fields

$$j = \frac{I}{A} \quad (1)$$

where I is the current and A is the membrane active area (10.08 cm^2).

The specific power is calculated as j times the voltage V:

$$P_s = jV \quad (2)$$

Figure 6 compares the voltage and power density for the two designs. The power density is calculated as the electric power P divided by the volumetric flow rate of hydrogen $\dot{V}$:

$$\rho = \frac{P}{\dot{V}} \quad (3)$$

It is evident that the metal-foam flow fields outperform the micro-channels flow fields of the existing graphite bipolar plate. The figure indicates that there is an enhancement over the graphite serpentine channels in terms of voltage (about

3.9%), specific power (6.0%) and power density (about 9.9%).

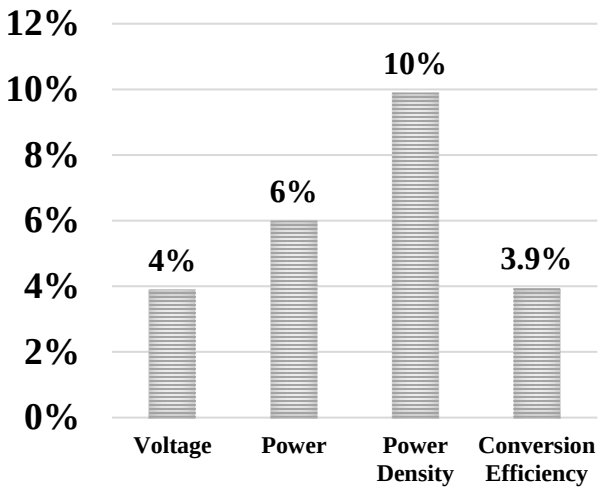

Fig. 6 Enhancements in key performance parameters of aluminum foam flow fields over existing graphite serpentine channels

Based on Fig. 7 the fuel cell with metal-foam flow fields provides better performance with less fuel and less air, as compared to the same cell having the graphite bipolar plate with continuous serpentine channels as flow fields. To further quantify the reduction in fuel and air consumptions, the results are summarized in this figure. Compared to the state-of-the-art, metal-foam flow fields can have up to about 4% reduction in hydrogen consumption and up to about 4.2% of oxygen consumption.

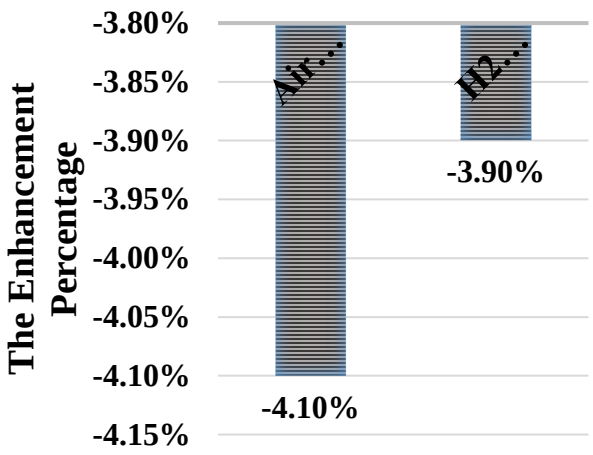

Fig. 7 Consumption reduction in hydrogen and air

Energy conversion efficiency η is the ratio between the actual energy output of a fuel cell and the actual energy input. The maximum conversion efficiency corresponding to the ideal case for hydrogen fuel cell is 83.1% [12]. The actual conversion efficiency is calculated from

$$\eta = \lambda_{feed} \frac{V_{avg}}{1.481} \times 100\% \quad (4)$$

where λ_{feed} is the ratio of the mass hydrogen actually reacted in the fuel cell devided by the mass of fuel input to the cell; $\lambda_{feed} \cong 0.95$ [12]. V_{avg} is the average voltage of the fuel cell in volts and 1.481 volts represents the maximum voltage of an ideal hydrogen fuel cell. The actual efficiencies for all metal-foam design and for the serpentine flow fields were calculated according to Eq. 4. The percent increase in the conversion efficiency for the metal-foam case (41.8%) as compared to the serpentine flow field (40.2%) was 3.9%. The percent increase in efficiency $\%\eta$ was calculated as:

$$\%\eta = \frac{\eta_f}{\eta_s} \times 100\% \quad (5)$$

where η_f is the efficiency of a foam flow field and η_s is the effieincy of the serpentine flow field.

5. Conclusion

Experimental results of the performance of metal-foam flow fields in PEM fuel cells have been presented. The advantages of these flow fields as compared to serpentine channels in graphite bipolar plates can be summarized as follows: metal-foam flow fields maintained safe operating temperature for the membrane, and provided better polarization curves while using less fuel and oxidant. There was an increase in power density of about 9.9%, and enhancement in the conversion efficiency by 3.9% over conventional serpentine channels flow fields. The value of the achieved efficiency for this case was 41.8%. The reduction in weight of the bipolar plate was 27.8%. Further investigations are needed to assess the effect of porosity of metal-foam flow fields on the performance of fuel cells.

6. REFERENCES

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