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Structure optimization of anode parallel flow field for local starvation of proton exchange membrane fuel cell

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HIGHLIGHTS

- Optimizing the anode flow field to improve the behavior of PEMFC in starvation.
- Using segmented cell technology to observe the vacuum effect in starvation.
- Comparing the results of simulation with starvation experiment.

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ABSTRACT

The structure of the flow field can directly affect the gas distribution in the fuel cell. The uneven distribution of gas can lead to local starvation, which might cause cell performance degradation, cell reversal, and seriously affect the cell durability. This paper proposes two structure optimization schemes of parallel anode flow field through simulation, and chooses the better optimization scheme to conduct an experiment. The results show that, with the same operating conditions, the anode current density distribution uniformity of the optimized parallel flow field single cell is significantly better than that of the original parallel flow field single cell. And in deep starvation, the vacuum effect of optimized parallel flow field single cell occurs under lower hydrogen stoichiometry. It further demonstrates that the structure optimization of anode flow field can improve performance of proton exchange membrane fuel cell when starvation happens.

1. Introduction

Starvation describes the operation condition of fuel cells in sub-stoichiometric fuel or oxidant feeding [1]. Fuel cell could not exhibit its best performance when starvation happens. Severe starvation of anode will cause cell reversal, and seriously affect the cell's life [2] [3]. It is important to avoid the starvation. Since the structure of the flow field can directly affect the gas distribution in the fuel cell. And the uneven distribution of gas can lead to local starvation. This paper attempts to improve the behavior of PEMFC in starvation by optimizing the structure of anode parallel flow field.

Fuel cell starvation has been studied by several researchers. Liu [1] had researched behaviors of PEMFC in starvation. The different kinds and degrees of starvation were observed and analyzed by both simulation and experiment. Particularly, the vacuum effect was explained in their study. Several groups have reported current density distribution measurement results of fuel cell under starvation condition. In Yoon's paper [4], Hakenjos's paper [5] and Kim's paper [6], the experimental cell's current density distribution in starvation was discussed. The current density distribution is a very suitable characterization way to investigate the local starvation of fuel cell. However, they just used it to analyzed the mechanism of starvation but did not propose any optimization solutions.

On the other hand, the structure of flow field has also been studied by many researchers. In Cooper's paper [7], the width of channels and lands of parallel flow field were optimized to improve the cell's raw power and limiting current density. Bachman [8] has investigated the effect of channel length on performance and water accumulation in a PEMFC parallel flow field. In Guo's paper [9], SA Atyabi's paper [10] and B. Timurkutluk's paper [11], the CFD simulation was used to optimize the geometric construction of parallel flow field to obtain a better flow distribution. Especially in B. Timurkutluk's work, convergent and divergent parallel flow fields have been designed, which has the same optimization concept as the wedge structure in this paper.

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However, these paper did not make experiment of optimizing flow field. Tong [12] has proposed a parallel flow field design with parallel flow field design with external two-valve regulation on cathode channels, which could improve the power density. And several researchers [13] [14] have made bionics optimization of flow field structure. Besides, in Dong-soo ko's paper [15], the effect of channel flow pattern on internal properties distribution of PEMFC for cathode starvation conditions has been studied. L. An [16] [17] has discussed the effect of flow field on the transfer phenomena of fuel cells. In the same way as this paper, DH Wen [18] also used both simulation and experiment to optimize the flow field for fuel cell efficiency. However, none of them have optimized the structure of anode flow field to improve the fuel cell's behavior in starvation.

In this paper, two optimization schemes of anode parallel flow field structure have been designed. At first, The CFD simulation was used to analyse the hydrogen distribution of different flow field and find the better scheme. Then, the segmented cell technology [19] was used in single cell starvation experiment, which could help to observe the current density distribution in anode starvation directly. Through this way, the vacuum effect was also verified according to unusual current density distribution. The results showed that, with the same operating conditions, the anode current density distribution uniformity of the optimized parallel flow field single cell was significantly better than that of the original parallel flow field single cell. And under deep starvation, the vacuum effect of optimized parallel flow field single cell occurred under lower λH_2 (hydrogen stoichiometry, all of the hydrogen stoichiometry below are indicated by λH_2).

2. Experimental

2.1. Optimization and simulation of parallel flow field single cell

2.1.1. Optimization schemes

The structure of the original flow field (all of the original flow field below are indicated by Ori) is shown in Fig. 1a. The selected anode flow field is a typical parallel one with 25 cm^2 active area. It has 2 main channels and 25 shunt channels, and all of them is 1 mm deep. Specifically, the main channels are 2 mm wide, the width of the shunt channels on both sides is 1.5 mm, and the width of the remaining shunt channels is 1 mm. Besides, the lands are 1 mm wide. The diameters of the holes for the inlet and the outlet are both 2 mm. In the starvation experiment of the original parallel flow field single cell, the low current density area mainly appeared in the middle part of the active area and the hydrogen outlet area [10] [11]. Which meant there was less hydrogen in those shunt channels of such area. In order to make the distribution of hydrogen more uniform in each shunt channel, two optimization schemes of main channels were proposed.

In the two optimization schemes, only the structure and size of main channels were changed. As shown in Fig. 1b, the width of main channels are linearly expanded from 2 cm to 4 cm in the Opt1 (optimized scheme 1, all of the optimized scheme 1 below are indicated by Opt1). As shown in Fig. 1c, the width of main channels are linearly are linearly tapered from 4 cm to 2 cm in the Opt2 (optimized scheme 2, all of the optimized scheme 1 below are indicated by Opt2).

2.1.2. Hydrogen distribution simulation

The simulation in this paper was the hydrogen distribution of the unipolar side of the anode flow field. The unusual high current density areas were really difficult to be simulated in a full size flow field model. In order to simplify the model, the electrochemical reaction was not involved. Since the structure of the flow field could directly affect the gas distribution in the fuel cell. The uneven distribution of gas can leaded to local starvation. Therefore, the results of hydrogen distribution simulation could be used to choose the better optimization scheme. Although, hydrogen distribution might be affected by local reaction, the flow field structure was the main research object of hydrogen distribution in this paper.

As shown in Fig. 2, the unipolar model had 3 main parts, which were flow field, GDL (Gas diffusion layer) and CL (Catalyst layer). The distribution of hydrogen in CL-GDL-interior was needed in the analysis.

First of all, some assumptions needed to be made. All fluids are incompressible fluids and ideal gases. Fluid flow Reynolds is high since the big amount of channels, so it should be turbulent. The phase transition and the electrochemical reaction are not considered.

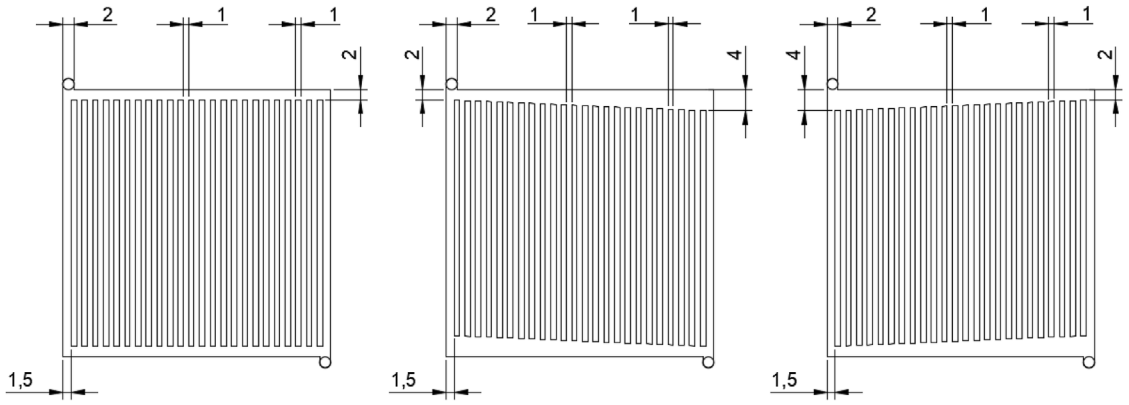
Based on these assumptions, the governing equations included mass conservation equation (1) and momentum conservation equation (2).

$$\nabla\cdot(\varepsilon\rho U) = S_m \tag{1}$$

In mass conservation equation (1), ρ is fluid density; U is speed vector. ε is the porosity of the porous medium. In the flow channel, $\varepsilon = 1$; and ε is less than 1 in the GDL and the CL, respectively 0.5 and 0.6. S_m is the source term of mass. In flow field, $S_m = 0$. Normally, in GDL and CL, S_m is equal to the sum of the changes in the reactants and products. However, $S_m = 0$ in GDL and CL of this unipolar model, since the electrochemical reaction are not considered.

$$\nabla\cdot(\varepsilon\rho UU) = -\varepsilon\nabla p + \nabla\cdot(\varepsilon\mu_{\text{eff}}\nabla U) + S_u \tag{2}$$

In momentum conservation equation (2), p is fluid pressure. The source term of the momentum transfer equation in a porous medium such as GDL and CL is $S_u = \frac{\mu^{\text{eff}}\varepsilon u}{K}$. The permeability K is very small and other items can be neglected, that is, the pressure drop in the porous unit is proportional to the velocity of the mixture. Thus, the equation at this time is the ordinary Darcy equation. The S_u in the flow channel is 0,



a. Ori b. Opt1 c. Opt2

Fig. 1. Parallel flow field diagrams (mm).