Project Report
2009 TRRF05 *Fuel Cell Technology*
December 05, 2009, Lund, Sweden

Review of Flow maldistribution in channels of PEMFC stacks

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ABSTRACT

PEM fuel cell stacks are widely studied for their own advantages. The flow maidistribution during unit cells may severely influence the fuel cell stack performance. The researches on flow maidistribution in PEMFC stacks are limited, and investigation results are unsystematic, scattered, and some even contrary. So it is necessary to review and summarize the previous concerned papers, and try to get some methods or guidelines for reducing the flow maldistribution in channels of PEMFC stack. In this project, the previous literatures concerned flow maidistribution in PEMFC stacks are reviewed. The effects of the arrangement of flow configurations, design parameters and operation conditions on flow maidistribution are summarized. Some suggestions are presented to reduce the flow maidistribution in PEMFC stacks.

INTRODUCTION

Fuel cell devices offer technical and environmental advantages such as high performance characteristics, reliability, durability and clean power when compared to conventional thermal power systems. Polymer Electrolyte Membrane (PEM) fuel cells, which operate at low temperatures (around 80 ◦ C), have a theoretical efficiency which is much greater than that of conventional internal combustion engines, quick start-up compared to other fuel cells operating at high temperature and zero toxic emissions if hydrogen is available. Thus, they offer an attractive alternative to internal combustion engines for transportation applications. A single PEM fuel cell can only offer a voltage of ~ 0.6–1.0V. In order to increase the voltage sufficient for practical operations, many single cells are serially connected to fabricate the fuel-cell stack.

Under ideal conditions, a fuel cell stack performance is simply the sum of the performance of individual cells. However, this linear correlation is not achieved in practice. This is due to many reasons including poor distribution of reactants among different cells of the stack. Due to this flow maldistribution, if the highest flow rate is adjusted at design value, other cells starve for fuel. Whereas, if the lowest flow rate is adjusted at the design value, other cells waste away the fuel. Hence, there is need to have accurate study of flow maldistribution in a fuel cell and take remedial measures to reduce loss of output due to this flow deficiency.

PROBLEM STATEMENT

At the stack level, flow maldistribution is more severe due to the multi-duct (individual cells are sometimes referred to as ducts) configuration. However, due to the complexity of the problem and the lack of an experimental technique to measure the instantaneous flow distribution, the investigations reported for the stack level maldistribution are very limited. Previous researchers using different methods investigated this problem, and obtained their own conclusions. But these conclusions are unsystematic, scattered, and some even contrary. So it is necessary to review and summarize the previous concerned papers, and try to get some methods or guidelines for reducing the flow maldistribution in channels of PEMFC stack.

LITERATURE SURVEY

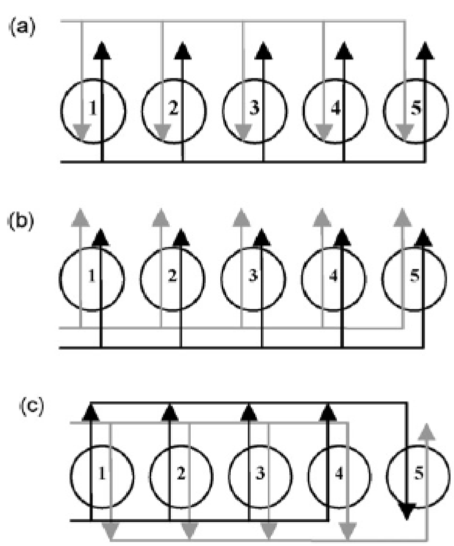
Generally, a fuel cell stack is built from a number of individual cells. These individual cells are normally electrically connected in series to provide a useful stack output voltage. The internal gas distribution system is required to supply fresh reactants to the cells and to subsequently remove reaction products from the cells.

Three different approaches in fuel cell stack gas flow configuration are possible: a parallel gas flow configuration where each cell is supplied with identical input gas streams; a serial gas flow configuration where the output gas stream of one cell is utilized as input gas stream of the downstream cell; and finally a mixed gas flow configuration where some of the cells are installed in a parallel, and some of the cells are installed in a serial gas flow configuration.

Most fuel cell stacks in the medium and high output power range are either based on a fully or at least partially parallel gas flow configuration, where the fuel cell stack inlet gas stream is divided into more or less identical gas streams that are fed to the individual cells. Alternatively, certain aspects associated with the maldistribution of reactants in a parallel gas flow configuration can be reduced or even completely eliminated if a serial gas flow configuration is applied where the gas flow of multiple cells is forced through each of the unit cells installed in the serial configuration. A serial gas flow configuration is, for instance, inevitably linked to higher gas flow rates and pressure differentials because the reactants required by the whole line of serially connected cells has to be transported through the upstream cells. This makes a complete blocking of one of the cells (e.g. due to water slugs) less probable than with a parallel gas flow configuration.

The gas flow configuration is an important aspect in the design of a fuel cell stack, as the supply of educts as well as the removal of reaction products have a significant impact on cell and stack operation and performance. The gas flow configuration therefore has to be carefully chosen and optimized with respect to the requirements of a specific application in order to provide an efficient and uniform operation of each individual cell of a fuel cell stack.

Friedl et al.[1] experimentally analyzed different internal gas flow configurations for a PEMFC stack. In their study, six stack setups were presented, as shown in Figure 1. Their results, as showed in Figure 2, show that, of the six stack setups investigated, the two mixed gas flow setups 3 and 4 show the highest average cell output voltages in the majority of measurements. The two all-parallel gas flow stack setups 1 and 2 (parallel gas flow configuration of five cells in counter-/co-flow mode) show slightly smaller average cell output voltages, whereas the all-serial stack setups 5 and 6 have the lowest average output voltages. Qian et al.[2] reported that, in serial configurations, higher pressure-drop occurred as a result of the longer traveling length for the stream. The reactant distribution is normally not uniform from cell to cell along the reactant feed path. But the continuous flow without any bypass is beneficial for product gas and water removal. The parallel configuration has lower pressure-drop, but can result in non-uniform reactant distribution flow between cells due to uneven product gas bubbles and water droplets formed in the channels of each of the cells. In the worst case, non-uniform cell-to-cell reactant distribution can lead to low cells and cell reversal. Mohamed and Jenkins[3] designed a fuel cell stack using genetic algorithms, and the optimal design parameters, which were number of stack cells in series, number of stack cells in parallel, were 21 and 1, respectively.



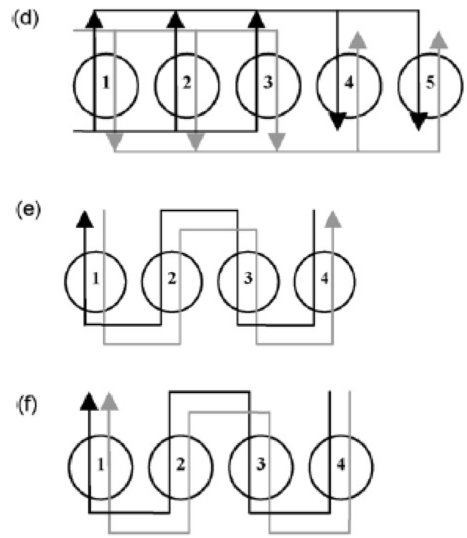


Fig. 1. Schematic view of the six different internal stack gas flow configurations (black arrows corresponds to the anode flow direction; grey arrows correspond to the air flow direction). Stack setup 1: all-parallel gas flow configuration of five cells, counter-flow mode. (b) Stack setup 2: all-parallel gas flow configuration of five cells, co-flow mode. (c) Stack setup 3: serial gas flow configuration of four parallel and one single cell in counter-flow mode. (d) Stack setup 4: serial gas flow configuration of three and two parallel cells in counter-flow mode. (e) Stack setup 5: all-serial gas flow configuration of four cells, counter-flow mode. (f) Stack setup 6: all-serial gas flow configuration of four cells, co-flow mode[1].

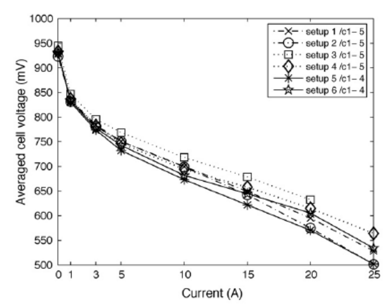


Fig.2 Comparison of averaged cell output voltages for stack setups 1-6[1].

Although a serial gas flow configuration presents better performance on fuel cell stacks confirmed by the above researches, it is only particularly interesting option with small fuel cell systems, e.g. designed for portable applications in consumer electronics, to avoid high pressure drop. In greater fuel cell stacks in order to supply more power, the parallel channels configurations are always adopted. More investigations have been carried out on the parallel configurations. The parallel configurations always can be either a U-shape (reverse flow) where the outlet gas flows in opposite direction to the inlet gas, or a Z-shape (parallel flow) where the directions of the inlet and outlet gas-flows are the same, as showed in Figure 3. In both cases, the inlet and outlet manifold flows are perpendicular to the gas-flow through the channels on the electrodes. In some references, the flow maldistributions in the two different configurations are compared.

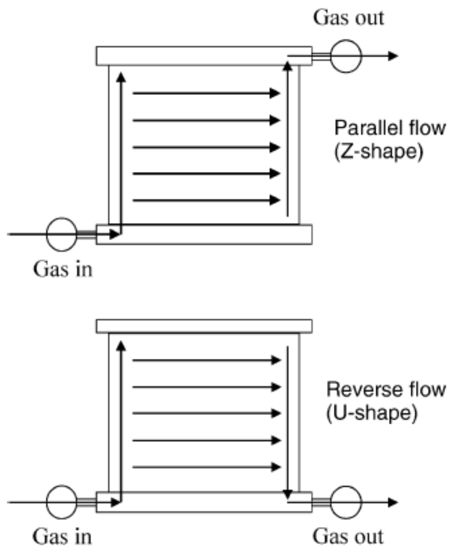


Fig.3 Schematic of two different types of parallel configurations in fuel-cell stacks[7].

Baschuk and Li [4] formulated a mathematical model of a PEMFC stack based on a hydraulic network Approach. Based on the model, they compared the performance of a single PEM fuel cell operating independently with U and Z configuration stacks consisting of 50 cells, and they found the Z configuration stacks had a better performance than the U configuration stacks, as shown in Figure 4. Chang et al. [5] presented a PEMFC stack model which incorporated flow distribution effects and a reduced dimensional unit cell model. They found that, in the Z-Type manifold stack, there was a greater spread in the flow distribution compared to the U-Type manifold, and this was reflected in the somewhat greater spread in cell voltage shown in Figure 5 and Figure 6. Therefore, U-Type manifolds are preferable on a performance basis, in addition to the packaging basis. Park and Li [6] pointed that, the effect of flow distribution on the stack performance was found to be considerably less for the Z configuration. It is suggested that the Z configuration is hence preferable when the sufficient flow uniformity cannot be ensured. In the literatrue of Koh et al. [7], the results showed that the flow distributions in U and Z configuration stacks were similarly non-uniform. The measurement results of Mustata et al.[8] showed Z configurations provided a more uniform mass flow distribution. Karimi et al. [9] reported that, although a Z-configuration stack was preferable to U-configuration, simulation results had revealed that a symmetric double inlet–single outlet topology provided excellent performance with reasonably low compressor requirement demand and minimum voltage spread.

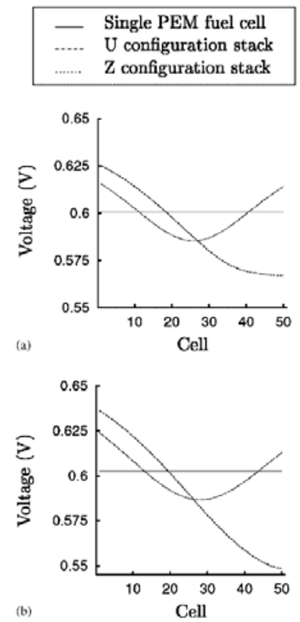


Fig. 4 Voltage of each cell in 50 cell U and Z configuration stacks operating with (a) H2/air reactants and at the current density of 0.41 A cm^{-2} and (b) reformate/air reactants and at the current density of 0.32 A cm^{-2} [4] .

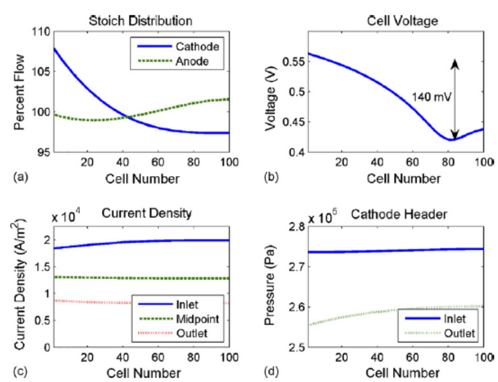


Fig. 5. (a) Calculated flow distribution, (b) average voltage distributions, (c) current density distribution, and (d) cathode header pressures as functions of cell number for a U-Type manifolded stack on a certain condition[5].

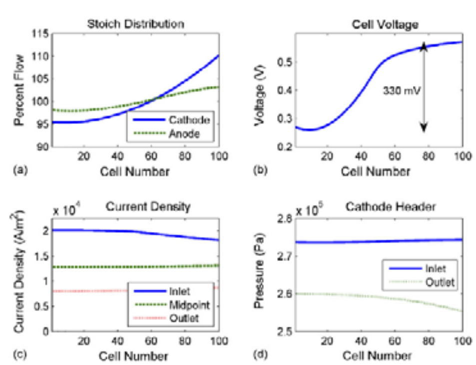


Fig.6 Same functions of cell number for a Z-Type manifolded stack on the same condition[5].

According to the above researches, it seems that there is no prccise conclusion about which is better one in U and Z configuration.

Many researchers have investigated the flow distribution of both U configuration and Z configuration, respectively. The flow distribution can usually be influenced by geometrical design factors and operation conditions. The geometrical design factors of internal manifold stacks include manifold structure, size, number of manifolds, overall gas-flow pattern, gas channel depth, active area for electrode reactions, and so on. The shapes of manifold holes can be circular, rectangular, or oblong. The cross-sectional area of the holes is important because it determines the linear velocity of gas-flow through the manifolds for a given flow rate of the inlet gas. The operation conditions always include the feed gas rate, kinds of reactants, stoichiometry rates of the air input gas stream, relative humidity of the fuel and air input gas streams and so on. In this project the review will be divided in to two sections: research on U configuration and research on Z configuration. Both sections will be discussed from geometrical design factors and operation conditions, respectively. The subsections will be organized both experimental study and model or simulation study.

Research on U configuration

Design parameters

First the references using experimental methods to investigate the design parameters for U configuration in PEMFC stacks are reviewed.

Hensel et al. [10] used MEMS (micro-electro-mechanical systems) micro-valves to control cell-to-cell flow distribution to reduce fuel maldistribution. Figure 7 shows the conventional common manifold stack fuel configuration, and Figure 8 and Figure 9 are new systems presented in this paper. Their results demonstrated more uniform flow distribution and better performance of fuel cell stack by using the new systems. Rodatz et al. [11] pointed that, the flow distribution was strongly coupled to the flow resistance in the channels and the cells. The flow resistance is primarily influenced by restrictions in the cross-section of the flow channels. These may be caused by variations in the flow channel depth and width due to fabrication tolerances, the intrusion of the gas diffusion electrode, or an accumulation of water droplets. A non-uniform temperature distribution may arise from varying flow resistance in the flow channel of the cooling media, air pockets in the channel, or variations in the membrane resistance and a resulting variation in local heat generation.

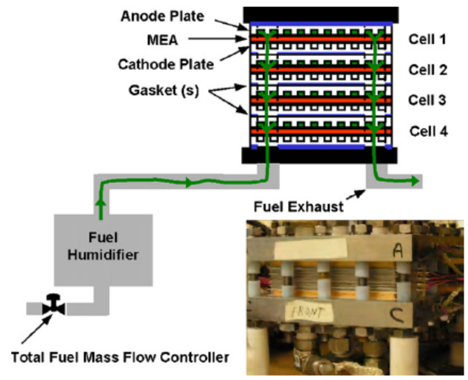


Fig. 7. Conventional common manifold stack fuel configuration and photo[10].

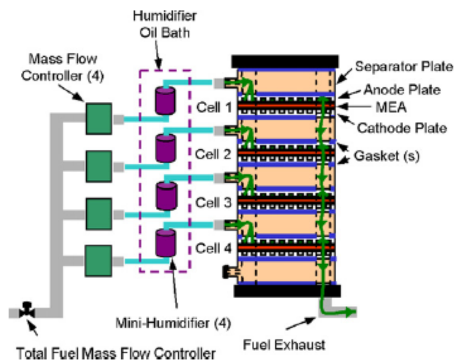


Fig. 8. Diagram of the mass flow control fuel delivery system[10]

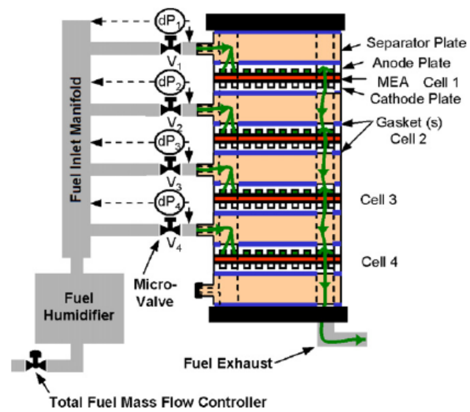


Fig. 9. Diagram of the micro-valve fuel control system with isolated cell stack[10].

Next the references are reviewed, which are model or simulation investigation of design parameters for U configuration in PEMFC stacks.

Koh et al. [7] found that, pressure variation in fuel-cell stack manifolds was influenced not only by manifold size but also by manifold geometry. The effect of manifold geometry can be modeled with additional pressure-losses to that experienced with a straight smooth wall. When the geometry of the manifold flow junction of this fuel-cell stack is modeled as a fully-open gate-valve or sudden contraction with a geometrical loss coefficient of 0.2, certain non-uniformity of the flow distribution is observed in either a reverse flow (U-shape) or a parallel flow (Z-shape). The non-uniform distribution is more significant at the cathode where a large amount of excess gas enters the stack, than at the anode where gas utilization is sufficiently high to allow a relatively small amount of total gas flow. Chen et al.[12] investigated the effect of channel flow resistance and manifold width on flow distribution in stacks. The channel flow resistance was varied by changing the permeability of porous media. Their results show, channels with large flow resistance contribute more pressure drop, and then cause a more uniform flow distribution; while manifold widths increase, a more uniform flow distribution will be achieved. Wang [13] presented a mode considering the friction effect or inertial effect on the flow and pressure distribution in U-type fuel cell stacks. Parameter Sensitivity is analyzed through two general characteristic parameters representing geometrical structures and flow conditions for the flow performance of the fuel cell stack. It is found that friction and momentum effects work in opposite directions, the former tending to produce a pressure drop and the latter a pressure rise. The proper balance of the two effects can result in less non-uniformity and an optimal design. Kim and Kim [14] investigated the effect of cathode inlet manifold configuration on the overall performance of a 10-cell PEMFC, considering different types of manifolds with a 90° turn, as shown in Figure 10 and Figure 11. The improved manifolds of Types 2–4 provide more uniform flow distribution and better performance, compared with the Type 1 manifold. The improved manifold yields increased cell potential, increased power output, and higher fuel cell efficiency.

Based on their own model, Baschuk and Li [4] found that, strategies for performance improvement rely on obtaining a uniform reactant distribution within the stack, and include increasing stack manifold size, decreasing the number of gas flow channels per bipolar plate, and judicially varying the resistance to mass flow in the gas flow channels from cell to cell. Chang et al. [5] investigated the effect of design parameters (manifold, flow configuration and friction factor) on fuel cell stack performance. In general, higher channel friction factors lead to a more uniform flow distribution; lower header

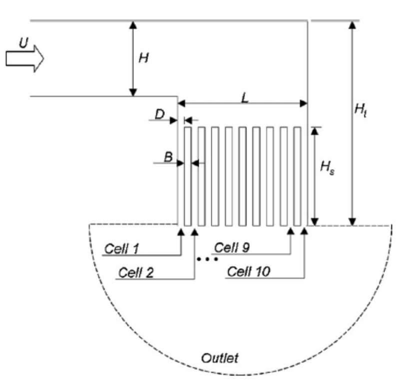


Fig.10 Schematic of problem and calculation domain[14].

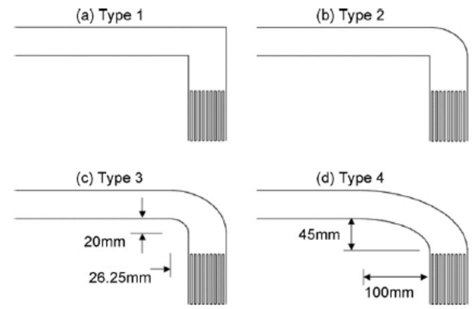


Fig. 11. Cathode inlet manifold configurations[14].

resistances lead to a more uniform flow distribution. Park and Li [6] reported that, flow uniformity could be ensured by enlarging manifold diameter and reduced flow channel sizes. Giddey et al. [15] investigated the PEM fuel cell stack performance in stages of different cell configurations. Mackie et al. [16] developed a flow network model to estimates of the flow distribution as a function of stack dimensions including header and unit cell geometry, based on the observations in the CFD simulations, and three fitting parameters were introduced to account for effects of surface roughness of the headers, reduced effective header area in the outlet header, and pressure drop in the unit cell.

Operation conditions

Friedl et al. [1] carried out the experiments for internal stacks over a wide range of operating conditions (i.e. stoichiometry rates of the air input gas stream, relative humidity of the fuel and air input gas streams). Experimental results revealed the complex interdependence between reactant supply, membrane drying and electrode flooding that governs operation and performance of the individual cells and the fuel cell stack assembly, respectively. Mennola et al. [17] investigated the effect of two different air supply methods on the fuel cell stack performance. They found that, on the free convection, the ohmic losses in individual cells were close to each other and lower, compared to forced convection.

Chen et al.[12] reported that lesser air feed promotes more uniform flow distribution than higher air feed. Bansode et al. [18] carried out the numerical simulation of effects of flow maldistribution on heat and mass transfer in a PEMFC stack. This study clearly shows that in the low velocity ducts, the water vapor removal rate is less which eventually results in earlier occurrence of uniform temperature than the ducts with high velocity; for given channel cross section and flow rate, with the variation in port diameter different types of maldistribution evolve. Baschuk and Li [4] noticed that, the average voltage of the cells in the stack was lower than the voltage of the cell operating individually, and this difference inreactants when compared to the H2/O2 reactants. Chang et al. [5] reported control of operating conditions (reactant flow rate, cell temperature, etc.) was important to ensure uniform performance in a stack as well as manufacturing processes. Park and Li [6] pointed that, the effect of temperature is dominant on the cell voltage variance when the flow variance was small for sufficiently uniform distribution of reactant flow among the cells in the stack; the flow and temperature distribution had a different influence on the stack performance, and a judicial matching of their distribution can provide the ideal uniform cell voltage distribution.

Research on Z configuration

Design parameters

Nguyen and Knobbe [19] carried out a new method using the sequential exhaust or purging of individual cells in fuel cell stack. Two devices were made to control the sequential exhausting: one was a simple rotating manifold distributor, shown as Figure 12; another was an electromechanical valve, shown as Figure 13. Using the two devices, the performance of the fuel cell stack markedly improved.

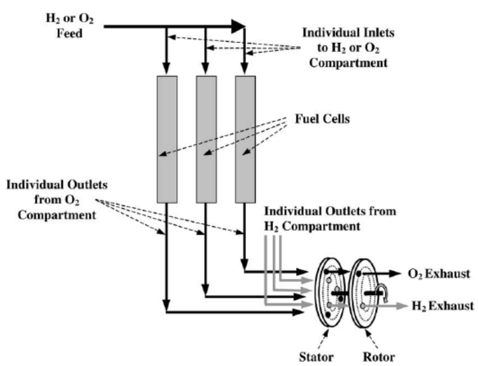


Fig.12 Fuel cell stack with sequential exhaust system employing a rotating device[19].

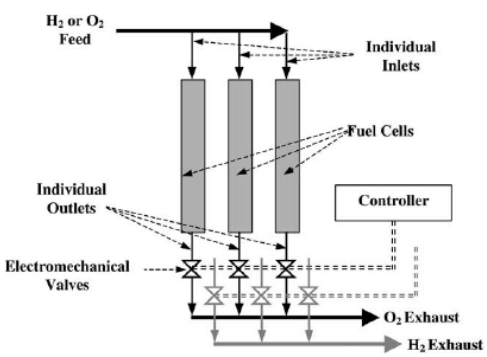


Fig.13 Fuel cell stack with sequential exhaust system employing a electromechanical valve[19].

Karimi et al. [9] reported that the size and the number of flow channels carved on the bipolar plate were very important to the flow distribution in fuel cell stack. Flow channels with smaller cross-sectional area and longer lengths increased the compressor power demands considerably without improving the stack voltage spread appreciably. The analysis by Mohan et al. [20] showed that, maldistribution parameter was directly proportional to the area ratio of channel to port and number of channels and inversely proportional to channel friction coefficient. An increasing channel friction coefficient indicates increase in the flow resistance throughout the core of the PEMFC, which results in better distribution. Increase of port dimension reduces the flow maldistribution. Cheng and Lin[21] presented numerical simulation of transport phenomena in a six-cell PEM fuel cell stack by adjusting the gas channel size of individual cells to obtain evenly distributed cell voltages. Results show that an even distribution in cell voltages can be obtained simply by adjusting the channel width ratios and channel heights for individual cells. The analysis by Ito et al. [22, 23] shows, the larger maldistribution can be seen with larger the total cross sectional area ratio of the flow channel to the manifold augment; the friction factors in the individual unit cells strongly influences the maldistribution; the bipolar plate with low number of flow channels can improve the maldistribution in the unit cell; the maldistribution in the cathode influences the performance of the stack more than in the anode.

In geometry and flow pattern, some microchannel reactors are very similar to the fuel cell stack. Some investigation results concerning microchannel reactors maybe supply useful suggestions to structure design of fuel cell stack. Commenge et al. [24] presented the optimal design for flow uniformity in microchannel reactors, and found that when the wall of inlet distributing chamber was regular, a slight curvature could appear along the wall of output collecting chamber if flow uniformity was to be realized between microchannels. Tonomura et al.[25] carried out optimal design of manifold in plate-fin microdevices by using CFD. Simulation results show that longer branched channels enable fluid to be distributed equally into each channel. Also demonstrated is the fact that the magnification of the outlet manifold area makes the flow distribution uniform. Pan et al. [26] also presented optimal design of complex manifold geometries for uniform flow distribution between microchannels in microreactors. The optimal design results showed that, in order to obtain uniform flow distribution, the microchannel depth becomes larger with larger microchannel width, and at the same time the microchannel number becomes comparatively larger; the area ratio increases with the increasing microchannel width; the area ratio of two manifolds becomes bigger with the larger microchannel depth.

Operation conditions

The studies on operation conditions for Z configuration in PEMFC stacks are few. The references [1, 4, 5, 6, 18], which researched on operation conditions for both U and Z configurations, have be reviewed in above section in the paper.

The analysis by Mohan et al. [20] showed that, maldistribution was dependent on flow rate of the fluids and fluid property. With the increase in fluid velocity, maldistribution increases. Hydrogen gives a uniform distribution, while air has got the highest flow maldistribution.

At recent, Kandlikar et al. [27] reported a novel technique based on the entrance region pressure drop measurements for monitoring fluid flow maldistribution in individual channels. The technique had also been applied in an in-situ experimental setup to obtain the flow maldistribution under electrochemical reaction conditions in the presence of two-phase flow in the cathode side gas channels. In the future there will be more and more methods to accurately measure the flow maldistribution so that the flow maldistribution problem will be better solved.

PROJECT DESCRIPTION

The literatures above all researched the flow maldistribution in the channels of PEMFC stack using different methods. Their results showed not only the effect of flow maldistribution on the fuel cell stack performance, but also some influencing factors on flow maldistribution. Some methods or guidelines for reducing the flow maldistribution in parallel channels of PEMFC stacks, can be obtained from the literatures.

CONCLUSIONS

A serial gas flow configuration can reduced the maldistribution of reactants although it will cause bigger pressure drop. a mixed gas flow configuration, where some of the cells are installed in a parallel and some of the cells are installed in a serial gas flow configuration, is confirmed to make better fuel cell stack performance. But as great pressure drop, the serial gas flow configuration is just adopted in small stack systems. For a high power stack system, the parallel channels configurations are always adopted. The parallel configurations always can be either a U-shape (reverse flow) where the outlet gas flows in opposite direction to the inlet gas, or a Z-shape (parallel flow) where the directions of the inlet and outlet gas-flows are the same. By reviewing the previous studies, it is not sure that which one will be better in the two different channel configurations. The flow distribution in parallel configurations can usually be influenced by geometrical design factors and operation conditions. From the previous studies, some conclusions can be concluded to reduce the flow maldistribution in fuel cell stack.

(1) Some new systems, such as micro-valve fuel control system and sequential exhaust system can improve the fuel cell stack performance.

(2) For the design parameters, these arrangements listed below can reduce the flow maldistribution: lower area ratio of channel to port (including larger manifold size/ cross-sectional area (widths)); lower flow channel sizes; lower manifold resistances; lower number of channels; lower number of gas flow channels per bipolar plate; larger channels flow resistance (varied by changing the permeability of porous media) and larger flow channel lengths.

(3) For operation conditions, lower feed gas rate/ velocity and using the H2/O2 reactants can improve the flow distribution and get a better fuel cell stack performance. There is no linear relationship between stoichiometry rates and relative humidity and the flow distribution.Project major findings and experience gains.

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