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Numerical and experimental study of two-phase flow uniformity in channels of parallel PEM fuel cells with modified Z-type flow-fields

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ABSTRACT

The aim of this study is to improve two-phase flow uniformity of proton exchange membrane fuel cells (PEMFCs) with parallel flow-fields. Therefore, a series of experiments are performed to find the relevance of cathode stoichiometry ratio, unsteady distribution of water coverage ratios and power of a PEMFC with Z-type flow-field. The experimental results indicate that at high cathode stoichiometry ratios, the power and efficiency are stable but their magnitudes are low. In addition, the fuel cell later reaches to its stable power and efficiency. However, the duration of this stability is higher than low cathode stoichiometry ratios. A 3D numerical model is proposed in order to simulate two-phase flow in channels of parallel flow-fields. This model, which is validated by the experimental results, considers the microstructure of gas diffusion layers. By using this model, a modified flow-field with uniform distribution of single-phase and two-phase flow is introduced. Unlike the simple flow-field, the plugs do not exist in the modified flow-field. It has lower two-phase pressure drop than the simple flow-field. The simulation results show that the parasitic power for the air supply system of this modified flow-field is lower than the simple flow-field and therefore its overall efficiency is higher.

1. Introduction

Proton Exchange Membrane Fuel Cell (PEMFC) is a highly efficient system of power generation to convert chemical energy into the electrical energy with heat and water as only byproducts [1,2]. Multiscale and Multiphysics phenomena occur in this clean device [3,4]. Proper water management is one of the key issues for stable and efficient operation of PEMFCs [3,5–8]. Flow-fields must be designed in a manner that both flooding and dehydrating of PEMFCs do not occur [8,9]. The design of the flow-field is not straightforward due to the highly coupled interaction between heat, mass, and electrochemical phenomena which are involved in the PEMFCs [10] and the most common methodology for this purpose is trial and error [11]. In the PEMFCs, many different types of flow-fields such as parallel, serpentine, multi-serpentine, pin-type interdigitated channels and biomimetic were used to improve heat and mass transfer for better water management [5,12–14]. The single serpentine flow-field has no flow distribution problems because only one channel exists for purging of liquid water. However, this configuration has higher pressure drop than the parallel flow-field due to the longer length of its channels [15]. This undesirable phenomenon decreases the total efficiency due to the high parasitic power and increases mechanical stress because of high pressure differences between the inlet and outlet [11]. In addition, the fabrication of parallel flow-field is easier because of its simpler structures. However, this configuration suffers from the maldistribution problem, which reduces the performance of PEMFCs [16,17].

The water management in channels of parallel flow-fields was investigated in several studies. Taner [18,19] performed an exergy and energy analyze on the performance of PEMFCs and found that by controlling the voltage of PEMFCs, the water management system can be managed easily. Kandlikar et al. [20,21] designed an ex-situ parallel PEMFC in order to investigate two-phase flow distribution. They found that the dominant flow regime at low superficial velocities is slug which leads to uneven distribution of water. While, the film flow is the dominant at high superficial velocities which results in decrease of pressure drop. Heidary et al. [22] added staggered or in-line obstacles within the channels of parallel flow

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field and compared with the simple parallel flow-field. Their experiments revealed that the staggered obstacles enhance the performance of the fuel cell even with considering the parasitic power of the air supply system. Spernjak et al. [23] analyzed the water content of parallel, serpentine, and interdigitated flow-field by neutron imaging. Their results exhibited that serpentine flow-field has lower water content and higher pressure drop than the other flow-fields. Jithesh et al. [24] investigated the parallel, single serpentine and multi serpentine flow-fields. Their simulations showed that the liquid water tends to accumulate in the middle channels of parallel flow-field. They concluded that the water removal rate of the serpentine flow-field is higher than the parallel flow-field. They introduced a mixed flow-field, which has better efficiency and capability of water removal than the other flow-fields. Ferng and Su [25] studied the effect of channel depth on the performance of serpentine and parallel flow-fields. They concluded that the effect of this parameter on the performance of the parallel flow-field is high while the serpentine flow-field is insensitive. Su et al. [26] concluded that the flooding in the channels of parallel flow-field decreases by fitting the streamline patterns and the flow-field. Wang et al. [27] examined the effect of different channel configurations on the performance of the parallel PEMFCs. They showed that the flooding increases when the cross section of channels and their aspect ratio increase. Zhang et al. [28] studied two-phase flow in the PEMFCs with the parallel channels. Their experimental results showed that high gas velocities are needed in order to avoid two-phase flow mal-distribution. Lu et al. [29] studied the channel orientation effects on the performance of a parallel flow-field. They showed that the gravity helps to formation of slug in the horizontal orientation, while in the vertical orientation gravity assists in film formation, which is better for improvement in water management. Guo et al. [30] showed that two-phase flow regimes in channels of PEMFCs are changed in microgravity conditions. Cooper et al. [31] investigated the geometrical parameter of the parallel flow-fields. Their statistical analysis revealed that the most important factor in both the power and current density is the width of channels and ribs in the parallel flow-field. They showed that the width of channels could be decreased to a specific point for improvement in the performance. Saco et al. [32] investigated the performance of different flow-fields. They proposed a straight zig-zag flow-field which has better performance than the serpentine and simple straight flow-fields, but their numerical simulation does not consider the two-phase flow regimes in channels of flow-field which greatly affect the performance of parallel PEMFCs.

The unsteady distribution of two-phase flow affects the unsteady performance and efficiency of PEMFCs, which are not considered in the previous experimental works. Moreover, the unsteady formation of two-phase flow patterns in the channels of parallel flow-field was not surveyed in the previous studies. All of these concerns are studied in the present study.

Several models were suggested for improvement of airflow uniformity in the channels of the parallel flow-fields. Wang et al. [33] proposed a theoretical model to solve the pressure and momentum distribution in the parallel Z-type flow-field. They [17] improved the performance of convectional parallel flow-field by introducing multi-U types to enhance the flow uniformity. Sajid Hossain et al. [34] used a numerical simulation to improve single-phase flow uniformity in PEMFCs with Z-type and U-type flow-fields. They showed that the flow uniformity decreases with increase of channel width Maharudrayya et al. [35,36] analyzed flow distributions in channels of U-type, and Z-type parallel flow-fields. They proposed multiple U-type and Z-type for improvement in flow uniformity, but these configurations increase the pressure drop. By using an analytical model, Zhang et al. [37] founded that uniform distribution of reactants in the parallel channels is provided by changing the cross-section area of channels. Xiao et al. [38] presented a hydrodynamic model to analyze the distribution of air flow in the parallel flow-fields. They found that the flow non-uniformity increases with the increase of airflow rates. They showed that the inlet header size greatly affects the flow uniformity of channels. Carton and Olabi [39] compared the performance of serpentine-parallel and open pore cellular foam flow-fields. Their results showed that the thermal management and flooding control of open pore cellular foam flow-field is better than the serpentine-parallel flow-field. Sasmito et al. [40] indicated that the serpentine flow-field has better thermal and water management, but its parasitic power is higher than the other flow-fields leading to decrease of the overall efficiency of the PEMFC.

However, the models presented in the literature did not consider the two-phase flow uniformity and its effects on the parasitic power losses, which are investigated in the present simulations.

Due to the complexity of two-phase flow in the channels of PEMFCs, numerical simulations together with experiments are used for the perdition of two-phase flow behavior in the channels of PEMFCs [41]. The volume of fluid (VOF) method is more utilized among of various methods for simulations of two-phase flows in the channels of PEMFCs. Jiao et al. [42] investigated two-phase flow in microchannels of a PEMFC with parallel flow-field using the VOF method. Their results showed that uneven distribution of water in the channels leads to blockage of outlet manifold. They proposed inlet and outlet manifolds with gradually reduced and increased cross-section areas, respectively to solve this problem. Ferreira et al. [43] studied two-phase flow in a single channel of anode side. They understood that the increase of hydrogen mass flow rate leads to increase of two-phase pressure drop. Ashrafi et al. [44] simulated the effects of gravity on the parasitic power loss of a single serpentine flow-field. Their numerical model illustrated that the pressure drop and the resulting parasitic power are low when the channels are horizontal and the inlet manifold is placed on the upper part of the flow-field. They also [45], suggested a tapered channels for the parallel flow-fields to improve the water removal and decrease of pressure drop and pressure fluctuations. In another simulation [46], they studied the effect of surface roughness of carbon paper gas diffusion layers (GDLs) on the droplet dynamics in microchannels of PEMFCs. They found that the height and density of roughness have great impact on the detachment velocity of droplet from the surface of GDLs in the microchannels. Hou et al. [47] simulated the gas-liquid two-phase flow in an elbow. Their results revealed that the water removal in the serpentine channels of anode is easier than the cathode side under similar operating condition. Carton et al. [48] performed a VOF simulation in double-serpentine PEMFCs. Their results indicated that the slugs are formed in low airflow velocities. They stated that the slugs lead to high pressure fluctuations in the PEMFCs.

However, the previous numerical models do not consider the two-phase flow patterns and their effects on the pressure drop for a full-scale Parallel PEMFCs. Therefore, a numerical model for prediction of two-phase flow distributions is essential. This model can be used to improve two-phase flow uniformity in the channels of parallel flow field.

In the present study, the effects of flow uniformity on the water coverage ratio (WCR) of each channel, the unsteady power, and the unsteady efficiency are investigated. A simple Z-type parallel flow-field with transparent flow-fields is tested experimentally by direct visualization method [9,49]. The relation of normalized mass flow rate (NMR) of each channel with its WCR is elucidated. The effects