ETM0015

A Design Improvement for Suitable Gas Inlet and Outlet of a Polymer Electrolyte Fuel Cell with a Hybrid Serpentine-Interdigitated Flow Field

Nuttapol Limjeerajarus[1,2,*] and Thatphong Santiprasertkul[1,2]

[1] Research Center for Advanced Energy Technology, Faculty of Engineering, Thai–Nichi Institute of Technology
[2] Automotive Engineering Program, Faculty of Engineering, Thai–Nichi Institute of Technology
1771/1 Pattanakarn, Suan Luang, Bangkok 10250, THAILAND
*Corresponding Author: Email: nuttapol@tni.ac.th, Tel.: +66-2763-2600 Ext. 2922, Fax.: +66-2763-2600 Ext. 2900

Abstract

It has been widely known that a well-design flow field in PEFC requires well balancing in gas distribution, water management, electron transport and pressure drop, which directly affect cell performance and durability. According to our previous work, although the proposed hybrid serpentine-interdigitated flow field was very promising, it still had the low oxygen concentration area, which can be improved. In this work, the design improvement aims to adjust the position and the number of inlet and outlet of gas flow channels in a 50 cm^2 PEFC with a hybrid serpentine-interdigitated flow field. An investigation on the cell performance and other transport behaviors has been carried out using CFD techniques via ANSYS FLUENT software. The results revealed that the new inlet and outlet gas flow channel pattern design can provide lower pressure drop, power requirement in anode and cathode side and better water management, as compared with those of the original hybrid serpentine-interdigitated flow field, which could consequently lead to the longer cell lifetime; beside it can provide the better oxygen mass faction distribution which could avoid the cold spot area in cell. Furthermore, these results gave a better understanding that the shorter channel length can provide not only lower pressure drop but also the better water management since the gases can bring the water out more efficiently through the shorter channel length.

Keywords: PEFC, CFD, Flow field designs, Hybrid Serpentine-Interdigitated Flow Field

1. Introduction

The Polymer Electrolyte fuel cell (PEFC) is one of the most popular energy convertors because it operates at low temperature and provides high energy density. In a typical fuel cell, hydrogen and oxygen are fed into anode electrode and cathode electrode, respectively, and then the reactant gasses flow pass through the flow field in the bipolar plate into the reaction zone. The variety of the flow field designs can cause differences in transport behavior and power of density peak up to 300% between the equivalent systems [1]. Since the configuration of flow field affects transport behaviors, the well-design flow field reflects long cell lifetime and high cell performance. According to our previous study [2], the novel design called "Hybrid Serpentine-Interdigitated (HSI) Flow Field" had been proposed and compared with the conventional single-channel serpentine flow field. The result revealed that the hybrid serpentine-interdigitated flow field outperformed the single channel serpentine flow field by providing the better heat and water management as well as the net power output. However, the hybrid serpentine-interdigitated flow field still had the defect point which was the low oxygen concentration area near the oxygen outlet on the cathode side [2]. The low oxygen concentration reflected low chemical reaction rate and high amount of liquid water in this area, therefore the hybrid serpentine-interdigitated flow field still needs to be improved.

A numerical investigation by Seungjae Lee et al. revealed that the multi-inlet serpentine design achieved a higher oxygen concentration and a more uniform water distribution than the conventional single-channel serpentine [3]. In this study, the hybrid serpentine-interdigitated flow field has been modified by increasing the inlet and outlet of gas flow channel so-called ‘’2-IO hybrid serpentine-interdigitated flow field (2-IO-HSI)’’, as depicted in Fig. 1. The transport behavior and cell performance were investigated by using a computational fluid dynamics (CFD) simulation by comparing with the hybrid serpentine-interdigitated flow field. The result would provide a useful information about the effect of the multi-inlet/outlet and the modified hybrid serpentine-interdigitated flow field would be promising to be a popular flow field in real applications.

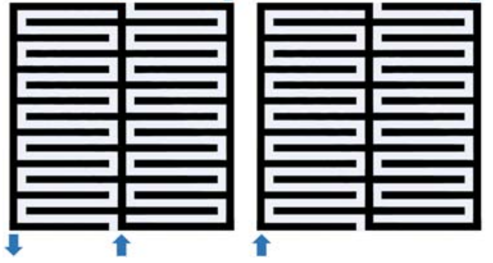

(a) (b)

Fig. 1 Inlets and outlets of (a) 2-IO-HSI (b) HSI

Table. 1 Material properties and model parameters used in the simulation [2]

Parameter	HSI	2-IO-HSI
Number of inlets	1	2
Number of outlets	1	2
Cell active area (cm^2)	48.067	
Channel cross section (width x depth (mm))	0.80×0.80	
Porosity;		
Gas diffusion layer	0.6	
Catalyst layer	0.4	
Electric conductivity ($1\ \Omega^{-1}\ m^{-1}$)	280	
Density ($kg\ m^{-3}$)	321.5	
Surface to volume ratio ($m^2\ m^{-3}$)	1.127×10^7	
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.16	
Equivalent weight of dry membrane ($kg\ kmol^{-1}$)	1,100	
Anode exchange current density ($A\ m^{-2}$)	7.17	
Cathode exchange current density ($A\ m^{-2}$)	7.17×10^{-5}	
Anode flow rate (kg/s)	2.87×10^{-6}	
Cathode flow rate (ml/min)	3.87×10^{-5}	

2. Computational fluid dynamics modeling

In this work, the 3-dimensional CFD models of PEFC with 2-IO-HIS and HIS flow fields were developed by ANSYS WORKBENCH. After finishing the geometries, both models were imported into ANSYS ICEMCFD for discretizing into small computational cells. To stably solve the problem and avoid inaccurate solution, the hexahedral cells had to be used as they do not create highly skewed cells [4]. The electrochemical reaction and transport phenomena were numerically solved by using ANSYS FLUENT PEMFC add-on module based on the finite volume method. The equations solved in this work included the equations of conservation of electric current, mass conservation of gas species, Navier–Stokes equation, energy balance, and a set of several equations. These equations are a combination of theoretical and experimental derived equations which were described in detail in previous study [5].

To solve the stated equations, suitable boundary conditions have to be specified. In order to achieve maximum accuracy for the result in this study, our main boundary conditions were obtained from experimental work, which were already well validated in previous studies [6 - 7]. The information about properties and parameter taken from our previous work [2] are given in Table 1. The simulations, the operation was solved under steady state condition while the non-isothermal condition was used to examine heat generation phenomena. The pressure at the outlet of gas flow channels was set at 1 atm as the cell operated under the atmospheric pressure. The temperature was 333.15 K at the inlet surfaces of the anode/cathode gas flow channels and also both anode and cathode terminal surfaces. The flow rates of reactant gases were set constant based on Reynolds number calculations which were considered to be in the laminar flow regime. In this model, multi-component diffusion, water transports inside the membrane, liquid water formation and transport were considered [8]. Note that the operating boundary conditions were set the same in both models in this research.

3. Results and Discussion

After the numerical simulation of both 50 cm^2 3-dimensional CFD models of 2-IO-HSI and HSI flow fields had been done, the polarization curves were used to compare cell performance. The numerical polarization and power curves of both flow fields are shown in Fig.4, the result was clearly revealed that the PEFC performance of 2-IO-HSI configuration was significantly higher than that of HSI configuration when current density was about 1.6 A cm^{-2}. However, considering at the practical voltage of 0.6 V [5], the overall performance of both models was almost equivalent. In other words, the 2-IO-HIS can perform and provide the power as well as the HIS under the real operating condition.

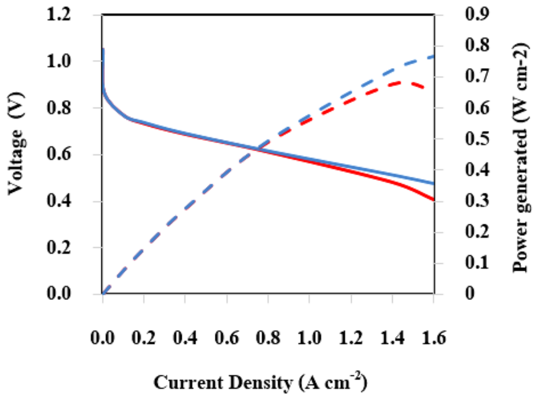
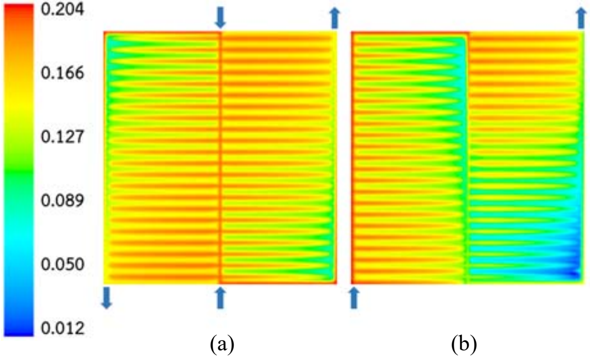


Fig. 2 The numerical polarization of (━) 2-IO-HSI and (━) HSI flow fields voltage; and power curves of (‒ ‒) 2-IO-HSI (‒ ‒) and HSI flow fields.

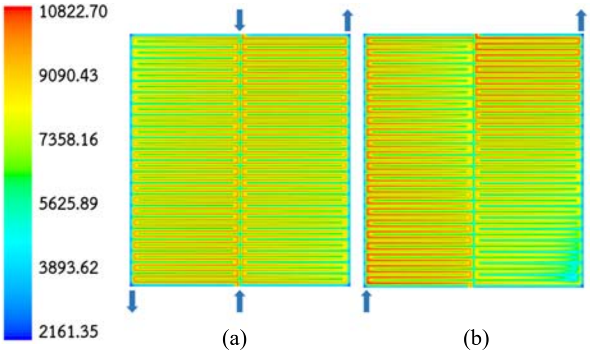
The purpose of this work was to investigate not only the cell performance, but also the distribution behavior of current density, water content, water saturation, especially the mass fraction of oxygen on the interface between the cathode catalyst and gas diffusion layer which is the major disadvantage of the previous HSI flow field. The distributions of transports in the cell indicated not only ability of water and heat management of the cell, but also cell durability and material degradation, hence the investigation of transport behaviors was also conducted and discussed.

Note that the investigation of transport behaviors was carried out for the practical voltage of 0.6 V, which was at current density of about 0.8 A cm^{-2}.



(a) (b)

Fig. 3 Oxygen mass fraction distribution on the interface between the cathode catalyst and gas diffusion layer of (a) 2-IO-HSI (b) HSI flow fields.



(a) (b)

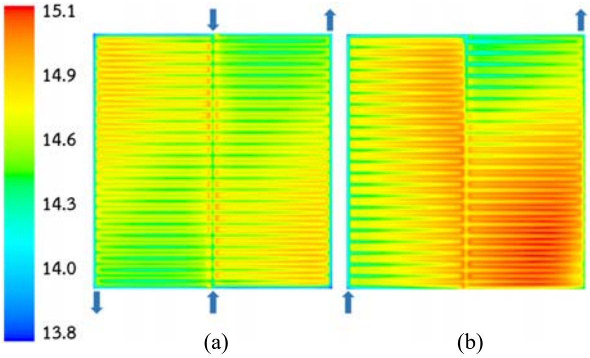
Fig. 4 Current density distribution on the interface between the cathode catalyst and gas diffusion layer of (a) 2-IO-HSI (b) HSI flow fields.

3.1 Oxygen concentration

As mentioned earlier, the previous HSI configuration had the defect point which is the low oxygen concentration area near the oxygen outlet on the cathode side (see Fig.3b) that could lead to the non-uniform distribution of current density, the acceleration of cell degradation and the decrease in cell durability. The comparison of oxygen mass revealed that with the 2-IO-HIS configuration, the oxygen concentration around the HIS defect point was increased and the distribution of oxygen mass fraction was obviously more uniform than the HSI case. As summarized by Seungjae Lee et al., increasing inlet of gas flow channel can accomplish a higher oxygen concentration, which leads to decreases in the over-potential and ohmic loss, and thus the higher cell performance [3]. Similarly, the current density distribution of the 2-IO-HSI configuration was more uniform than the HSI configuration, as shown in Fig. 4. It can imply that oxygen could be better fed into the HIS defect point (low oxygen concentration area) by increasing gas flow inlet at the middle of the flow field, hence the reaction rate of electrochemical reaction was obviously increased.

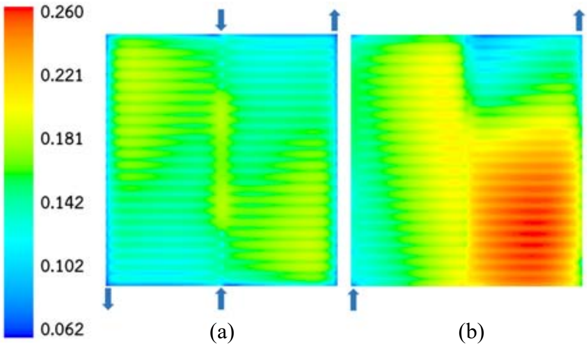
3.2 Water management

As concluded by many researchers [9 - 11], a major problem that affects cell performance and durability is water flooding in the catalyst layers and gas diffusion layers. Therefore, a well-designed of flow field must provide a uniform distribution of water concentration and good water management. According to our previous work [2], although HSI could provide a better water management than the conventional single channel serpentine flow field, but it was not good enough as it caused high membrane water content (water content>14) which indicated that the membrane was full of liquid water. Fig. 5 presents the comparison of water content distribution between 2-IO-HSI and HSI configurations. It was clearly seen that the 2-IO-HSI configuration can offer a more uniform water distribution than the HSI configuration. However, it is worth to mention that the water concentration in the membrane (water content) was still higher than 14. As the result, it can imply that at a particular current density in the range of 0.8-1.6 A cm^{-2}, the cell voltage of the 2-IO-HSI configuration was higher than that of the HSI configuration because the protonic resistance was reduced due to the lower water content in the membrane.



(a) (b)

Fig. 5 Water content distribution on the interface between the membrane and the cathode catalyst layer of (a) 2-IO-HSI (b) HSI flow fields.



(a) (b)

Fig. 6 Water saturation distribution on the interface between the cathode catalyst and gas diffusion layer of (a) 2-IO-HSI (b) HSI flow fields.

Fig. 6 a and b present the water saturation distribution on the interface between the cathode catalyst and gas diffusion layer of both flow fields. The liquid water in the 2-IO-HSI configuration was obviously lower than that in the HSI configuration, since the former could force liquid water out through the cell more efficient than the latter, which resulted from its gas flow inlet and outlet arrangement that reduced the distance of gas flow in GFCs. From this result, it can be concluded that the new arrangement of gas flow inlet and outlet of 2-IO-HSI provided a better water management in the catalyst layer and the gas diffusion layer as well as in the membrane.

3.3 Pressure drop and net power generation

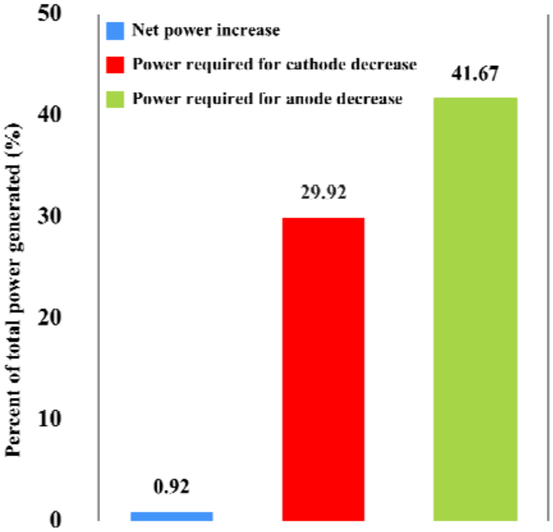


Fig. 7 Water content distribution on the interface between the membrane and the anode catalyst layer of (a) 2-IO-HSI (b) HSI flow fields.

The pressure drop affected directly the cell performance since the power requirement for the flowing of the reactants in cathode and anode side directly deducted the net power output. The simulation results indicated that the 2-IO-HSI configuration contributed to pressure drop lower than the HSI configuration by 3000 Pa approximately which lead to the decrease in power requirement by 41.67% and 29.92% in anode side and cathode side, respectively due to its shorter channel length. As the result, the net power output increased by 0.2 W (0.92%) as compared with that of the 50 cm^2 HIS configuration. However, in an automotive application, it would need up to 113 kW of PEFC-stack cell. Therefore, this design improvement of 2-IO-HIS configuration would contribute to the increase in the net power output of 986 W. More importantly, the much more uniform distributions provided by the new design would make the PEFC lifetime much longer.

Since the comparisons of both models had been done, the 2-IO-HSI configuration was performed a more uniform distribution of oxygen mass fraction, water content in MEA, water saturation, and current density than the HSI configuration. Furthermore, the 2-IO-HSI configuration was required the power for the flowing of the reactants lower than the HSI configuration. The 2-IO-HSI configuration was very expected flow field for PEMFC to challenging in global energy market. However, this flow field need the experimental examination for reliability, therefore it should be carried out and is ongoing in our research group.

4. Conclusion

The effects of the modified inlet/ outlet configuration on the performance and transport behaviors of a 50 cm^2 PEFC had been examined using CFD calculation via ANSYS FLUENT software. The objective of the current study was to demonstrate the feasibility of using new inlet and outlet gas flow channel pattern to improve the performance of PEFCs. The result revealed that the 2-IO-HSI configuration outperformed the HSI configuration in the viewpoints of the oxygen mass fraction distribution, water management, and also the power requirement in cathode and anode sides while it offered the performance as same as the HSI configuration (at the current density was 0.8 A cm^{-2}). This made the 2-IO-HSI configuration contributed 0.92% more net power output and longer cell durability than the HSI configuration.

5. Acknowledgement

The authors would like to express their gratitude to Thai-Nichi Institute of Technology for providing a financial support for this research (ID: 1610/A009).

6. References

[1] Arvay, A., French, J., Wang, J.-C., Peng, X.-H., and Kannan, A.M. (2013). Nature inspired flow field designs for proton exchange membrane fuel cell, *International Journal of Hydrogen Energy*, vol.38(9), March 2013, pp. 3717 - 3726.

[2] Charoen-amornkitt, P., Santiprasertkul, T., Munprakobkij, P. and Limjeerajarus, N. (2015). Numerical Study of a Polymer Electrolyte Fuel Cell with a Hybrid Serpentine-Interdigitated Flow Field Design, paper presented in *The 6th TSME International Conference on Mechanical Engineering*, Hua-Hin, Thailand.

[3] Seungjae, L., Taeyoung, K., Heekyung, P. (2011). Comparison of multi-inlet and serpentine channel design on water production of PEMFCs, *Chemical Engineering Science*, vol.66(8) April 2011, pp. 1748–1758.

[4] Versteeg HK., Malalasekera W. (2007). An introduction to computational fluid dynamics: the finite volume method. 2nd ed. Pearson Education; ISBN: 978-0-13-127498-3, Bell & Bain Limited, Glasgow.

[5] Limjeerajarus, N. and Charoen-amornkitt, P. (2015). Effect of different flow field designs and number of channels on performance of a small PEFC, *International Journal of Hydrogen Energy*, vol.40(22), June 2015, pp. 7144 - 7158.

[6] Limjeerajarus N., Nishiyama Y., Ohashi H., Ito T., Yamaguchi T. (2009). Modeling for PEFC MEAs based on reaction rate on Pt surface and microstructures of catalyst layers. *Journal of chemical engineering of Japan*, vol.42(8), August 2009, pp. 616-631.

[7] Limjeerajarus N., Yanagimoto T., Yamamoto T., Ito T., Yamaguchi T. (2008). Quantitative analysis of oxygen-containing species adsorbed on the Pt surface of a polymer electrolyte fuel cell membrane electrode assembly electrode using stripping voltammetry, *Journal of Power Sources*, vol.185(1), October 2008, pp. 217-221.

[8] ANSYS® Academic Research, Release 14.0, Help system, fuel cell modules manual. ANSYS, Inc.

[9] Pasaogullari, U. (2009). Heat and water transport models for polymer electrolyte fuel cells, In: Vielstisch W, Yokokawa H, Gasteiger HA, editors. Handbook of fuel cells, Chichester, UK: John Wiley.

[10] Manso, A.P., Marzo, F.F., Barranco, J., Garikano, X., and Garmendia Mujika, M. (2012). Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell. A review, *International Journal of Hydrogen Energy*, vol.37(20), October 2012, pp. 15256 - 15287.

[11] Xianguo L. and Sabir, I. (2005). Review of bipolar plates in PEM fuel cells: flow field designs, *International Journal of Hydrogen Energy*, vol.30(4), March 2005, pp. 359 - 371.