Trans. of the Korean Hydrogen and New Energy Society, Vol. 32, No. 5, 2021, pp. 331~339
DOI: https://doi.org/10.7316/KHNES.2021.32.5.331

KHNES
pISSN 1738-7264 • eISSN 2288-7407

딤플 패턴 최적화를 통한 고체산화물 연료전지 분리판의 흐름 균일도 향상

쿠엔[1,2] · 이동근[1] · 안국영[1,2] · 김영상[1,2,†]

[1]한국기계연구원 청정연료발전연구실, [2]과학기술연합대학원대학교 환경에너지기계공학과

Enhancing Flow Uniformity of Gas Separator for Solid Oxide Fuel Cells by Optimizing Dimple Patterns

THAI-QUYEN QUACH[1,2], DONG KEUN LEE[1], KOOK YOUNG AHN[1,2], YOUNG SANG KIM[1,2,†]

[1]Department of Clean Fuel and Power Generation, Korea Institute of Machinery & Materials (KIMM), 156 Gajeongbuk-ro, Yuseong-gu, Daejeon 34103, Korea
[2]Department of Environment and Energy Mechanical Engineering, University of Science and Technology (UST), 156 Gajeongbuk-ro, Yuseong-gu, Daejeon 34103, Korea

†Corresponding author :
yskim@kimm.re.kr

Received 8 October, 2021
Revised 18 October, 2021
Accepted 20 October, 2021

Abstract >> This study presents a novel way to enhance uniformity of the gas flow inside the solid oxide fuel cell (SOFC), which is critically important to fuel cell performance, by using dimples. A pattern of dimple, which works as a flow distributor/collector, is designed at the inlet and outlet section of a straight channel gas separator. Size of the dimples and the gap between them were changed to optimize the flow uniformity, and any change in size or gap is considered as one design. The results show that some dimple patterns significantly enhance the uniformity compared to baseline, about 4%, while the others slightly reduce it, about 1%. Besides, the dimple pattern also affects to the pressure drop in the flow channel, however the pressure drop in all cases are negligible (less than 26.4 Pa).

Key words : Fuel cell(연료전지), SOFC(고체산화물연료전지), Separator(분리판), Flow uniformity(흐름 균일도), Pressure(압력)

1. Introduction

Planar solid oxide fuel cell (SOFC) is of great interest because of its high energy transformation efficiency, versatility, and fuel flexibility. SOFCs directly convert chemical energy to electricity by using a variety of hydrocarbon fuels, such as natural gas, synthesis gas, and bio gas. Owing to operate at high temperature (above 700℃), SOFCs can be easily integrated with other systems, e.g., hybrid power generation system, combined heat and power system, and energy storage system, to obtain a high overall efficiency up to 90%[1)]. However, the cost of the stack, which is mostly restricted by performance and lifetime of the stack, is remaining challenge[2,3]. The performance and lifetime of the stack are strongly affected by temperature gradient, current density distribution, and flow uniformity in the channel of the stack. Increase of the flow uniformity not only can increase the stack performance[4] but also can reduce impact of these two others. The flow channel, normally, is governed by interconnector, therefore design the interconnector is one of the key points of the SOFC stack development.

There are innumerable channel types designed and published in the literature, however, parallel channel, single serpentine channel, and multi-serpentine channel are the most popular designs since they are easy to manufacture leading to a lower manufacturing cost. Among them, multi-serpentine interconnector showed highest performance. Saied et al.[5] calculated stack performance with difference interconnector designs by using a 3D mathematical model. His results showed that the multi-serpentine interconnector achieves a higher current, about 5.18%, compared to single serpentine and parallel type. Jiang et al.[6] reported that multi-serpentine channel not only enhanced stack performance, but also reduced thermal stress inside the stack by flattening the temperature distribution, especially at high current density (above 6,330 A/m^2). Nevertheless, these researches did not use current collector in their designs, as shown in the left side of Fig. 1. If the current collector layer was used, which is normally high porosity, the advantage of serpentine channel might be collapsed since fuel/air could primarily flow through this porous layer instead of the channel. Therefore, in the case of using current collector, simple parallel channel that is less affected by porous media, is preferable.

Regarding to the current collectors, they can be metal woven mesh or metal foam. The use of current collectors takes a variety of advantages. The current collector layer can not only reduce the ohmic loss between layers of the fuel cell, but also bring a reliable compressibility for the stack which is beneficial to engineering point of view[7,8]. In addition, a properly use of current collector layers can significantly improve performance of the stack. Canavar et al.[9,10] reported that SOFC stack using a proper porous flow field, which works as current collector, can obtain higher voltage compared with the case merely using channel because of the reduction in the ohmic loss. Furthermore, by combining metal mesh/foam and the gas channel, the stack performance can further be improved. As a result, stack designs with both channel and the porous current collector are favorable nowadays. These above types design are presented the Fig. 1 in sequence of the stack performance.

It seems that the combination of parallel channel and current collector layer in the SOFC stack is one of the reasonable choices for both performance and manufacturing points of view. However, researchers

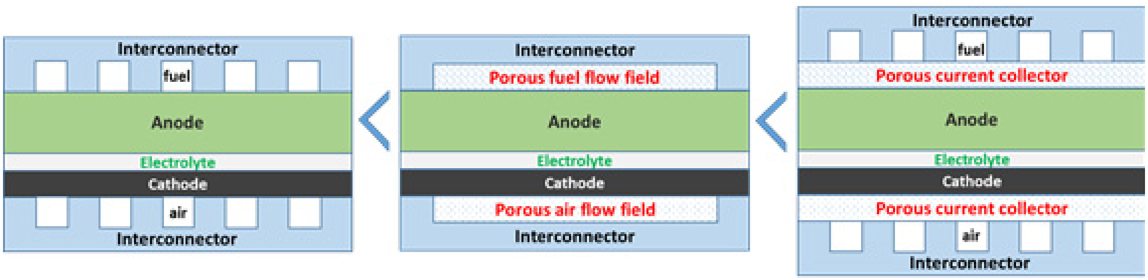

Fig. 1. Comparison of stack designs in term of cell voltage

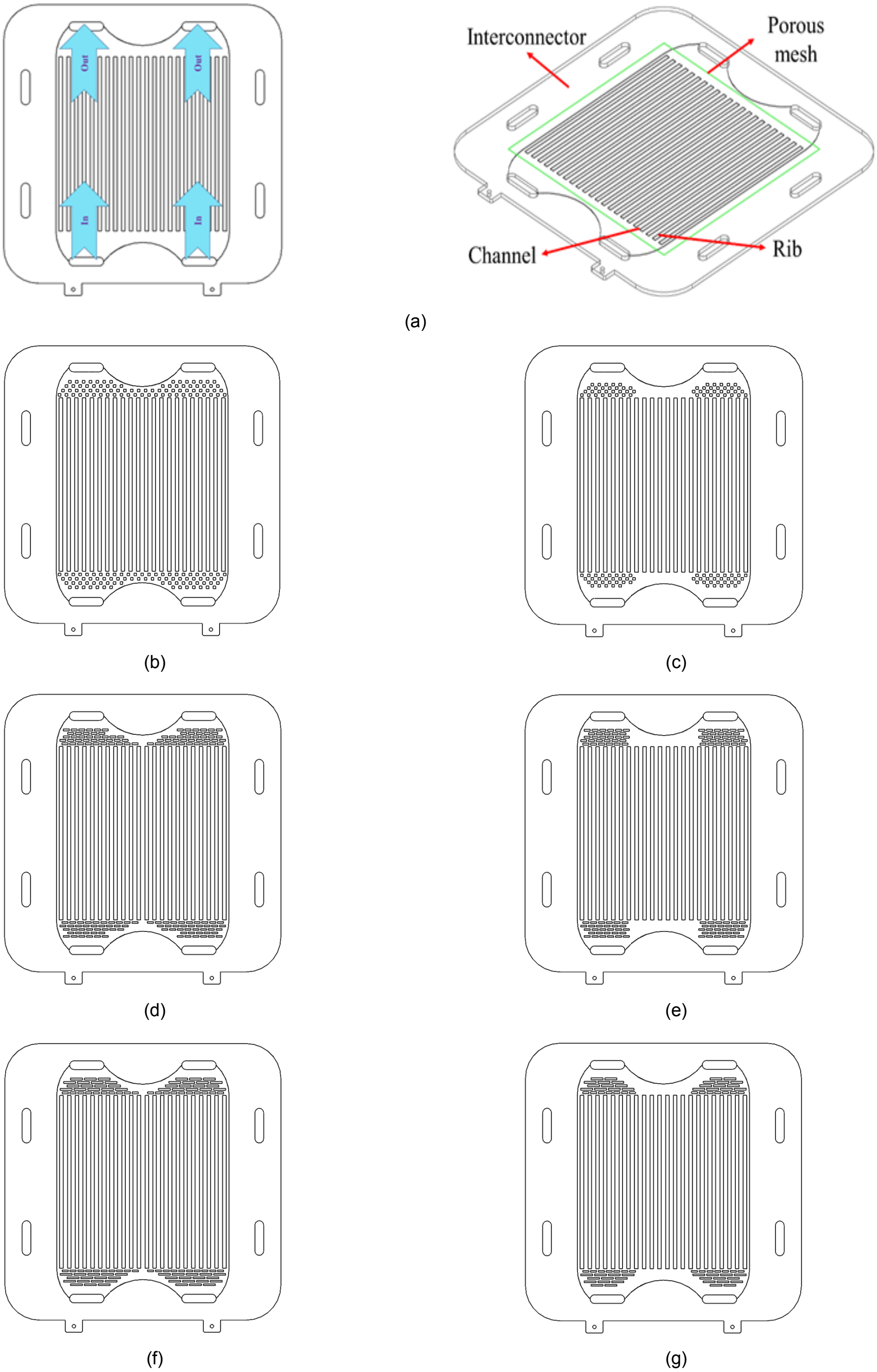

Fig. 2. Interconnector designs considered in the study. (a) Base design, (b) design 1, (c) design 2, (d) design 3, (e) design 4, (f) design 5, (g) design 6

are continuing to enhance performance of these kind of designs. To improve flow uniformity of the parallel channel, Huang et al.[4] conducted a set of guide vanes in the entrance and the outlet section of the interconnector, resulting in an increase of the uniformity of approximately 10% and pick power density of 11%. Ashraf et al.[11] designed a pattern of dimples (or circular guiding vanes) and compared with the typical rectangular rib design. Unfortunately, his results revealed that the uniformity (between cells) of the dimple pattern design is 0.88 while that of the rectangular design is approximately 0.98. However, the design using dimple demonstrated more uniform temperature and current density distribution as well as higher cell efficiency than rectangular interconnector. Whether, as a combination of the two above researches, by using dimple pattern in the entrance and outlet area of the interconnector with rectangular channel, the flow uniformity can be increase or not. In addition, so far there is no attempt to try other shapes of dimple in those areas.

In this study new designs of the interconnector with rectangular-shape dimple patterns in the inlet and outlet sections are proposed. By conducting a simple computational fluid dynamics (CFD) calculation of the interconnector at typical working conditions of the SOFC stack, the uniformity and pressure drop are calculated. Sizes of the dimple are changed to find out the optimal design based on flow uniformity in the channel. Results show that an appropriate dimple pattern design can significantly increase the flow uniformity of the SOFC stack while keep the pressure drop over the channel in an acceptable range.

2. Design descriptions

There are seven designs considered in this study, one is based design which has no dimple pattern for comparison, and the others are proposed designs with dimple pattern, as presented in Fig. 2. The interconnector is 160×160 mm^2 that will be used for the cell with active area of 100×100 mm^2. The gas comes in from two holes, goes through parallel channels, and then goes out of the interconnector by two other holes. The channel high is 0.4 mm. A metal porous mesh that is 110×110×0.36 mm^3 is used as a current collector layer. The porosity of the metal mesh varies from 0.6 to 0.9 depending on the structure of the mesh. In this study, we assume the porosity of the mesh of 0.8. Note that all designs in the study are cross-flow type gas separator, and only anode side is considered since the study focuses on gas flow uniformity only. There are no chemical or electrochemical effects are taken into account, therefore the result should be similar for both sides in term of flow uniformity.

In the proposed designs, design 1 to design 6, the dimple patterns are located at the inlet and outlet area of the gas separator. As illustrated in Fig. 2 (b)-(g), not only the dimple sizes but also the dimple patterns are changed from designs to optimize flow uniformity. Design 1, 3, and 5 are using patterns which cover all channels while the others are conducting partial dimple pattern. Categorization of dimple pattern in those designs are summarized in Table 1.

Table 1. Categorization of dimple patterns

	Pattern type	Mixed size	Sizes (mm × mm)
Design 1	Full	No	1.5×1.5
Design 2	Partial	No	1.5×1.5
Design 3	Full	No	1.0×3.5
Design 4	Partial	No	1.0×3.5
Design 5	Full	Yes	1.0×3.5; 1.0×7.0
Design 6	Partial	Yes	1.0×3.5; 1.0×7.0

The other dimensions of the gas separator and the mesh sizes are identical to the based case.

3. CFD calculation

Interconnector designs were simulated in Fluent software (ANSYS, Canonsburg, Pennsylvania, The United States of America) in which the typical continuity equation, momentum equation, and energy equation of the gas flow are solved. All hexahedral meshes were created using nonconforming mesh technique. Approximately two million mesh elements are generated for the entire calculation domain (fluid domain and porous mesh).

The main assumptions in the simulation are as follow: 1) the gas is assumed as an ideal gas, 2) the flow is considered as laminar, 3) the simulations are performed under steady-state conditions, and 4) the gauge pressure is set to 0 Pa for both anode and cathode outlets.

In the course of simulation, the gas is pure hydrogen (H_2) at 973 K. The mass flow rate is 6.4×10^{-7} kg/s, which is similar to previous in-house experiment condition[12]. A heat flux of 60 W/m^2 is applied to the current collector layer surface (porous mesh) to cover the thermal effect of the gas. To investigate flow uniformity in the channels, a typical formula is used as follow[13]:

$$\Gamma = 100 \times \left\{ 1 - \left\{ \frac{1}{n} \sum_{i=1}^{n} \left[\frac{(u_i - \overline{u})}{\overline{u}} \right]^2 \right\}^{1/2} \right\} \quad (1)$$

where n=24 represents the total number of rectangular rib-channels, u_i is the velocity at ith rib-channel, and $\overline{u}$ is the averaged mean velocity, respectively.

4. Results and discussion

The most concerning thing in gas separator design is that the gas flow is well distributed into channels so that get high flow uniformity. For the based design, the flow uniformity and pressure drop are 94.8% and 14.0 Pa, respectively. It is clear from Fig. 3 that the flow is distributed more in the side-channels, resulting in higher velocity in the channel 1-9 and 16-24 than channels in the center of the interconnector. The non-uniform distribution is attributed to the difference in pathways of the gas. The side-channels

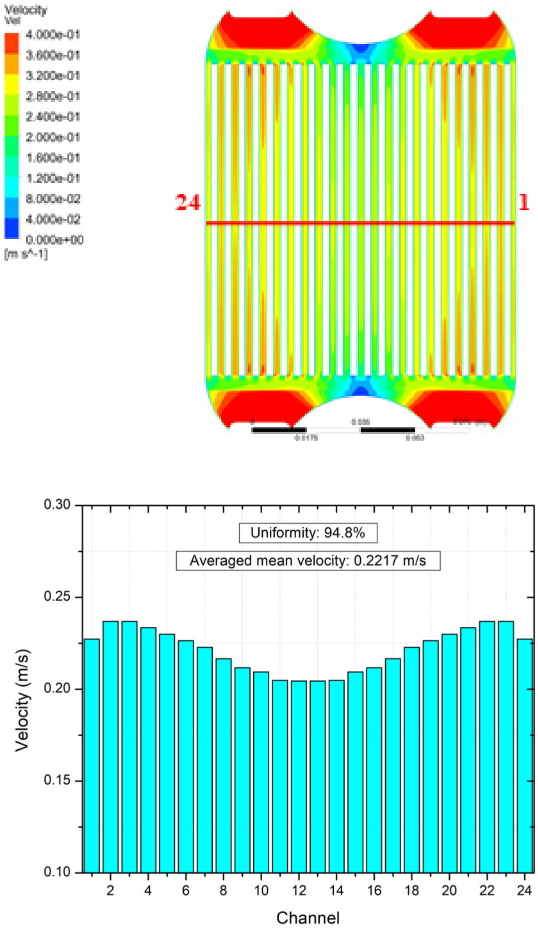

Fig. 3. Velocity distribution in the interconnector and velocity at the middle of the channel of base design

have shorter pathway while those of center ones are longer, leading to difference in local pressure drop between channels. This brings an idea of using dimple pattern to compensate the gas pathway of all channels.

Fig. 4 displays the velocity distribution of the dimple pattern designs. By using dimples, the flow is distributed more to the center area, resulting in more uniform flow distribution, especially in design 3, 4, 5, and 6. However, to quantitative evaluate the improvement of the flow distribution, velocity profile in channels and the flow uniformity have to be considered.

Fig. 5 shows the velocity profile in the channels and the uniformity of all designs with dimple pattern. While design 1, 2, 3, and 5 show a similar distribution to the based case, design 4 and 6 show a more uniform velocity. Those difference can be seen

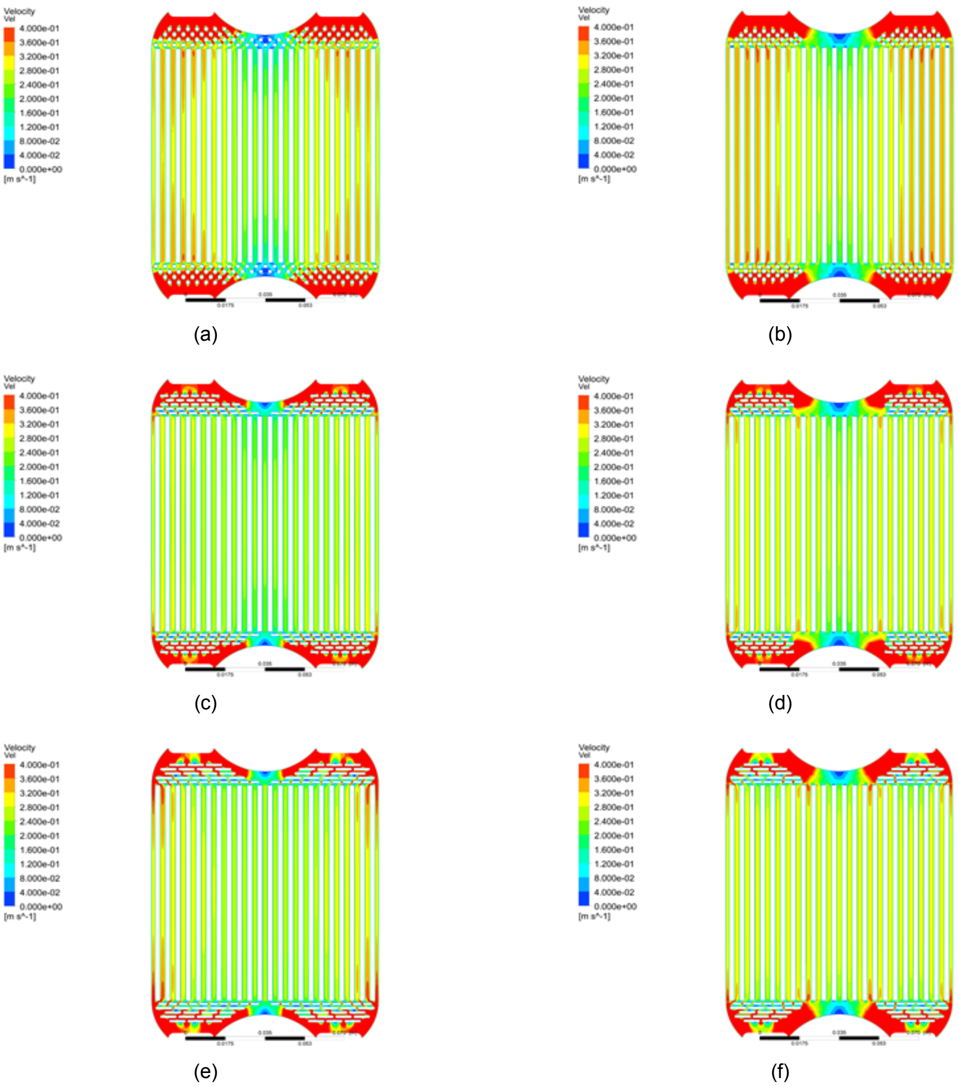

Fig. 4. Velocity distribution in the gas separator designs with dimple pattern. (a) Design 1, (b) design 2, (c) design 3, (d) design 4, (e) design 5, (f) design 6

in flow uniformity value, which are 93.4%, 94.5%, 95.9%, 94.9%, 97.4%, and 98.7%, respectively. The velocity profile of design 4 and 6 are almost flat, as presented in Fig. 5(d), (f). The improvement of the

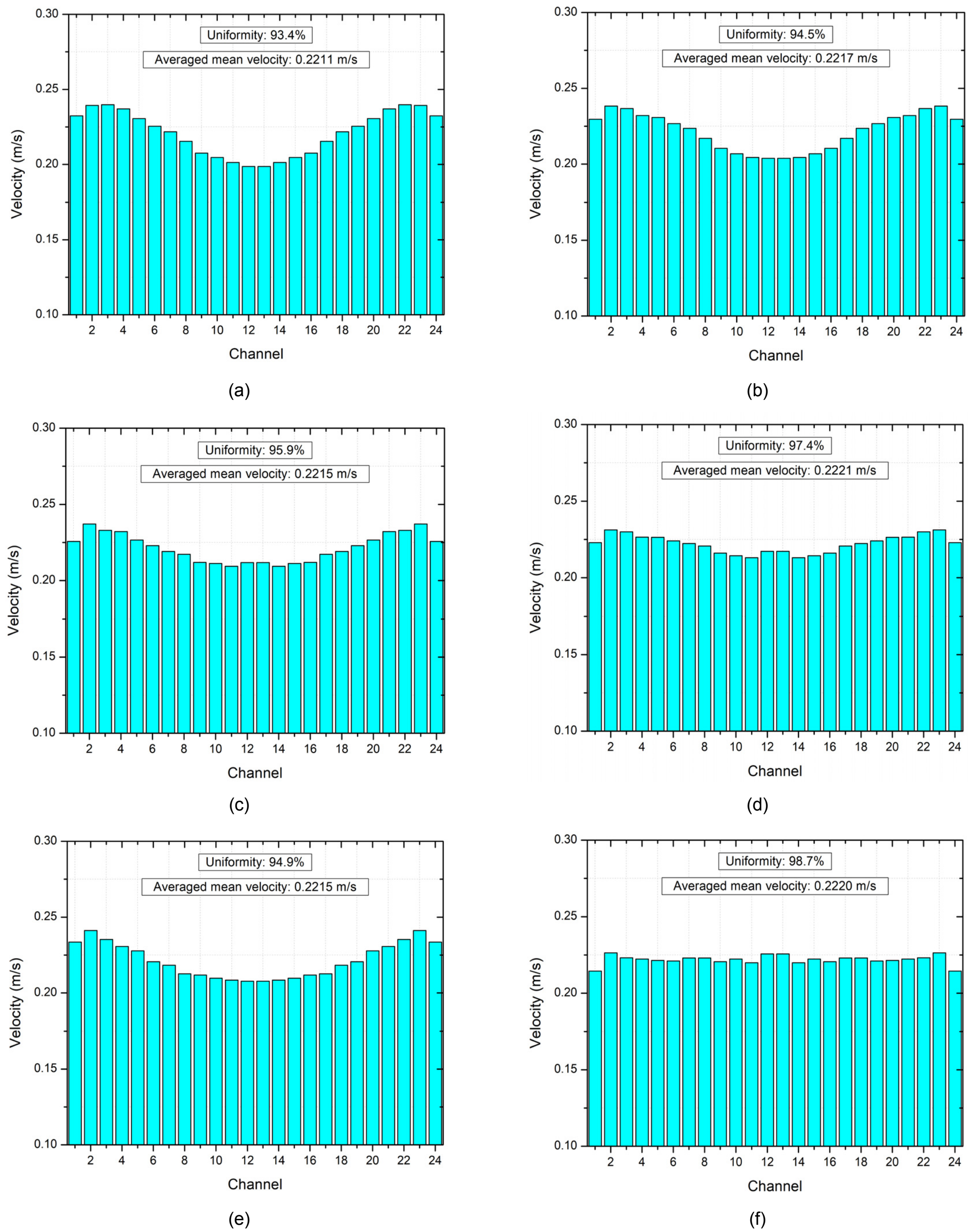

Fig. 5. Velocity profile at the middle of the channel of the designs with dimple pattern. (a) Design 1, (b) design 2, (c) design 3, (d) design 4, (e) design 5, (f) design 6

design 4 and 6 attributes to the increase of gas pathway of the side-channels, resulting in more gas flowing via center channels. In these two designs, although the velocity in channel number 1 and 24 are a little bit lower than the other channels, these two dimple patterns are appropriate for the current interconnector design. In addition, also from Fig. 5, the averaged mean velocity of these designs are similar, about 0.222 m/s, therefore similar pressure drops in these designs could be expected.

Regard to pressure drop from input to output of the interconnector, it varies from 15.5 Pa in design 2 to 26.4 Pa in design 4. The difference in pressure drop is small, therefore it can be neglected. The comparison of pressure drop at all cases are in Fig. 6. It is obvious that increase in pathway of the gas results in an increase in the pressure drop. However, design 6 shows not only highest flow uniformity, about 4% higher than based case, but also a relatively low pressure drop compared to others. Thus, design 6 is the best candidate for current interconnector design and the concept of using dimple can be adapted for designing gas separator.

5. Conclusions

In this paper, a method to enhance flow uniformity in the parallel channel-type interconnector was introduced. A dimple pattern was design at the inlet and outlet section of the interconnector to compensate the gas pathway between channels, therefore the pressure drop at all channels could be similar. A simple CFD calculation, which takes into account to heat flux to the interconnector and flow in a porous media, was done for 3D models of the interconnector. The uniformity calculated at the middle of the channels were increased from 94.8% in the based case to 98.7% (design 6) while the pressure drop varied from 14.0 Pa to 26.4 Pa. The following conclusions were drawn by summarizing our calculation results of all dimple pattern designs: 1) by using an appropriate dimple pattern at the inlet and outlet section of the interconnector, the flow uniformity can be significantly enhanced. 2) The change of pressure drop over the interconnector during optimizing the dimple pattern is negligible. And 3) design 6 shows the best performance in the current interconnector design.

These above results bring a promising method to enhance flow uniformity of the gas separator for the SOFC stack. However, a comprehensive simulation, which takes into account to electrochemical reaction and heat transfer with environment as well as between cells, is necessary to optimize the shape and size of the dimple pattern.

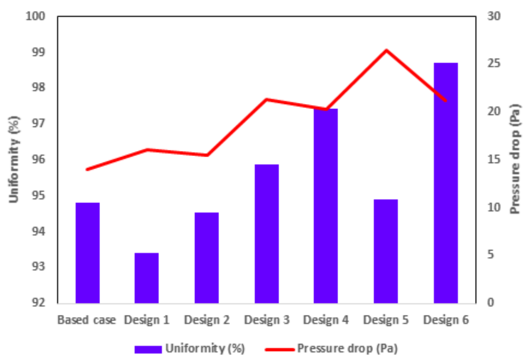

Fig. 6. Comparison in pressure drop and flow uniformity

Acknowledgment

This research was financially supported by the Ministry of Trade, Industry and Energy (MOTIE) and Korea Institute for Advancement of Technology (KIAT) through the National Innovation Cluster R&D program (P00015272_Development of Manufacturing Technology for Improving High Temperature Durability and Efficiency of Metal Bipolar for SOFC).

References

1. D. W. Wu and R. Z. Wang, “Combined cooling, heating and power: a review”, Progress in Energy and Combustion Science, Vol. 32, No. 5-6, 2006, pp. 459-495, doi: https://doi.org/10.1016/j.pecs.2006.02.001.
2. V. T. Giap, Y. D. Lee, Y. S. Kim, and K. Y. Ahn, “Techno-economic analysis of reversible solid oxide fuel cell system couple with waste steam”, Trans Korean Hydrogen New Energy Soc, Vol. 30, No. 1, 2019, pp. 21-28, doi: https://doi.org/10.7316/KHNES.2019.30.1.21.
3. Y. Yi, S. J. Shin, S. J. Park, M. S. Kim, H. J. Kim, J. H. Kim, I. Kim, and Y. S. Kim, “Long term operation and improvement reliability for SOFC system”, Trans Korean Hydrogen New Energy Soc, Vo. 28, No. 5, 2017, pp. 502-511, doi: https://doi.org/10.7316/KHNES.2017.28.5.502.
4. C. M. Huang, S. S. Shy, H. H. Li, and C. H. Lee, “The impact of flow distributors on the performance of planar solid oxide fuel cell”, Journal of Power Sources, Vol. 195, No. 19, 2010, pp.6280-6286, doi: https://doi.org/10.1016/j.jpowsour.2010.04.073.
5. M. Saied, K. Ahmed, M. Nemat-Alla, M. Ahmed, and M. El-Sebaie, “Performance study of solid oxide fuel cell with various flow field designs: numerical study”, International Journal of Hydrogen Energy, Vol. 43, No. 45, 2018, pp. 20931-20946, doi: https://doi.org/10.1016/j.ijhydene.2018.09.034.
6. C. Jiang, Y. Gu, W. Guan, M. Ni, J. Sang, Z. Zhong, and S. C. Singhal, “Thermal stress analysis of solid oxide fuel cell with Z-type and serpentine-type channels considering pressure drop”, Journal of the Electrochemical Society, Vol. 167, No. 4, 2020, pp. 044517, doi: https://doi.org/10.1149/1945-7111/ab79aa.
7. A. Nakajo, F. Mueller, J. Brouwer, and D. Favrat, “Mechanical reliability and durability of SOFC stacks. Part II: modelling of mechanical failures during ageing and cycling”, International Journal of Hydrogen Energy, Vol. 37, No. 11, 2012, pp. 9269-9286, doi: https://doi.org/10.1016/j.ijhydene.2012.03.023.
8. S. Lee, Y. H. Jang, H. Y. Shin, K. Lee, M. Bae, J. Kang, and J. Bae, “Reliable sealing design of metal-based solid oxide fuel cell stacks for transportation applications”, International Journal of Hydrogen Energy, Vol. 44, No. 57, 2019, pp. 30280-30292, doi: https://doi.org/10.1016/j.ijhydene.2019.09.087.
9. M. Canavar and Y. Kaplan, “Effects of mesh and interconnector design on solid oxide fuel cell performance”, International Journal of Hydrogen Energy, Vol. 40, No. 24, 2015, pp. 7829-7834, doi: https://doi.org/10.1016/j.ijhydene.2014.11.101.
10. M. Canavar and B. Timurkutluk, “Design and fabrication of novel anode flow-field for commercial size solid oxide fuel cells”, Journal of Power Sources, Vol. 346, 2017, pp. 49-55, doi: https://doi.org/10.1016/j.jpowsour.2017.02.020.
11. M. A. Ashraf, K. Rashid, I. Rahimipetroudi, H. J. Kim, and S. K. Dong, “Analyzing different planar biogas-fueled SOFC stack designs and their effects on the flow uniformity”, Energy, Vol. 190, 2020, pp. 116450, doi: https://doi.org/10.1016/j.energy.2019.116450.
12. J. Lee, I. T. Pineda, V. T. Giap, D. Lee, Y. S. Kim, K. Y. Ahn, and Y. D. Lee, “Performance prediction model of solid oxide fuel cell stack using deep neural network technique”, Trans Korean Hydrogen New Energy Soc, Vol. 31, No. 5, 2020, pp. 436-443, doi: https://doi.org/10.7316/KHNES.2020.31.5.436.
13. C. M. Huang, S. S. Shy, and C. H. Lee, “On flow uniformity in various interconnects and its influence to cell performance of planar SOFC”, Journal of Power Sources, Vol. 183, No. 1, 2008, pp. 205-213, doi: https://doi.org/10.1016/j.jpowsour.2008.04.059.