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Effective Convergent-Type Flow Slab in Proton Exchange Membrane Fuel Cells

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Keywords: Convergent-type serpentine flow slab; Proton Exchange Membrane fuel cells; conventional flow slab; numerical simulation; concentration polarization; Computational flow design

ABSTRACT

Proton Exchange Membrane (PEM) fuel cells employing modified convergent-type serpentine flow slabs (TS) were designed for the estimation of fuel cell performance enhancement in accordance with some optimization studies. Numerical simulation was used to create cell models with modified convergent serpentine flow slabs of four different channel widths such as TS28, TS36, TS44 and TS52 and performance comparison was done with a common serpentine flow slab (OS) PEM fuel cell. All the cells had the same reaction area of 25.7×24 mm and rib ratio of 51%. The TS fuel cells produced similar voltage ranging from 1-1.1 V, power density of 650 to 675 mW/cm^2 and current density of 2550 to 2700 mA/cm^2. The OS PEM fuel cell produced similar voltage (1.1 V) and power density (660 mW/cm^2) compared to TS fuel cells but very less current density (1861 mA/cm^2) output was observed. The experimental results evidenced that the modified flow slabs were superior in controlling the cell performance compared to traditional flow slab irrespective of their channel width. This was due to the fact that improper fuel mixing was eradicated and the flow slab effectively postponed concentration polarization. Therefore, these findings would provide progressive insights for future applications of PEM fuel cells.

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INTRODUCTION

Proton exchange membrane fuel cells (PEMFCs) are highly innovative type of alternative clean energy generators. They are highly advantageous as they are portable for static applications due to their very low emission capability, operation in low temperatures, high power efficiency, and quick start-up (Chakraborty, 2016, Liu, 2017, Martin, 2017, Fontana, 2011). Though considerable research has been undertaken with PEMFCs and various fuel cell types have been successfully proved their electrochemical reactions and transport phenomena, there are still certain drawbacks which need serious consideration and effective research solutions (Arvay, 2013). Considerable improvements in design of catalyst layer (Marr, 1999), gas diffusion layer (Radhakrishnan, 2011, Jayakumar, 2017) flow field plate (Palaniswamy, 2016) in PEMFC were extensively studied by researchers globally. In that, flow field plate has an immensely vital part in PEMFC fuel transport. A well-organized PEMFC flow slab can effectively inhibit the non-uniform fuel flow, which will result in power performance enhancement and manufacturing cost reduction (Fontana, 2011).

Numerical Simulation is a beneficial and cost-effective technology which can be employed for physical modeling, construction and operation of various reactors. It is highly beneficial as it can predict the chemical and biochemical reactions inside a reactor and analyze of the effects of parameters on reactor performance, thus aiding parameter optimization (Janajreh, 2017, Lan, 2016). A deep understanding of the advantages and disadvantages along with features of flow field plates is very important. So, numerous analyses by comparing different flow field plate types have been performed by researchers.

Serpentine inter-digitated, bionic and parallel types are studied more often (Wang, 2017). The effects of aspect ratio, length and width of parallel, inter-digitated and serpentine flow slabs on PEMFCs has been keenly investigated (Chiu, 2012). They have reported that the PEMFCs had increased performance when serpentine type flow slabs with lesser width and height were employed. Reports have indicated that the employment of serpentine type flow slabs resulted in more uniform flow rate and better power performance when compared to the other types (Wang, 2010, Manso, 2011, Cooper, 2016, Liu, 2013). A review has been published on the research studies focused on effects of variations of serpentine type flow slabs on PEMFC performance (Manso, 2012). They have reported that at persistent current output, PEMFCs with wide flow slabs produced low power performance and the flow slab width was inversely proportional to power production in PEMFCs. These research studies have specified the flow slab design significance and the importance to improvise overall performance of PEMFCs.

More research emphasis has been provided for studies on the effects of the convergent flow slab depth rather than its width on the PEMFC performance. Therefore, this research study was focused to investigate the width effects in convergent serpentine flow slabs on reactor performance. Common serpentine type flow slab was compared with four different convergent type serpentine flow slabs in terms of enhancing the performance of PEMFC. Uneven electricity output in the catalyst layer is mainly due to non-uniform fuel flow. This would probably decrease the fuel cell durability and which can be prohibited by the optimization of serpentine flow slab designs. Thus, by doing so, the concentration polarization can be greatly reduced at maximum current densities and the power production would be enhanced.

METHODOLOGY

In this research work, commercialized software Computational flow design (CFD) was used for the numerical simulation of PEMFC model. Reactor performance estimation was done by the application of various geometries of the convergent serpentine flow slabs. Various assumptions were considered in numerical simulation such as (1) The system was considered to be in steady-state (2) All gas mixtures were considered as ideal gas and Newtonian fluid (3) Laminar flow (4) catalyst layer, gas diffusion layer and the membrane were all considered to be homogeneous and uni-directional, porous and with constant porosity and permeability (5) the thermal and electrical resistances were neglected (6) all reactants and products were gases and the gravity effects were disregarded. The detailed governing equations and numerical methods are available in our previous research work (Wang, 2017) and were not presented here.

One common serpentine flow slab (OS) and four different convergent-type serpentine flow slabs (TS28, TS36, TS44, TS52) with similar reaction area of 25.7 mm×24 mm and a rib ratio of 51% were used. The OS was the serpentine flow field without changes in width. TS28 designated the width of convergent serpentine flow slab with a constant reduction of 0.2 mm, and eight channels designed in flow slabs. The schematic models of common serpentine flow slab and four convergent-type serpentine flow fields are shown in Figure 1. The black part represented the fluid distribution in flow slabs of PEMFC, and the triangle arrows signposted the fluid flow direction. The grid numbers in the grid test were set to 196,980 before starting the numerical runs (Wang, 2017).

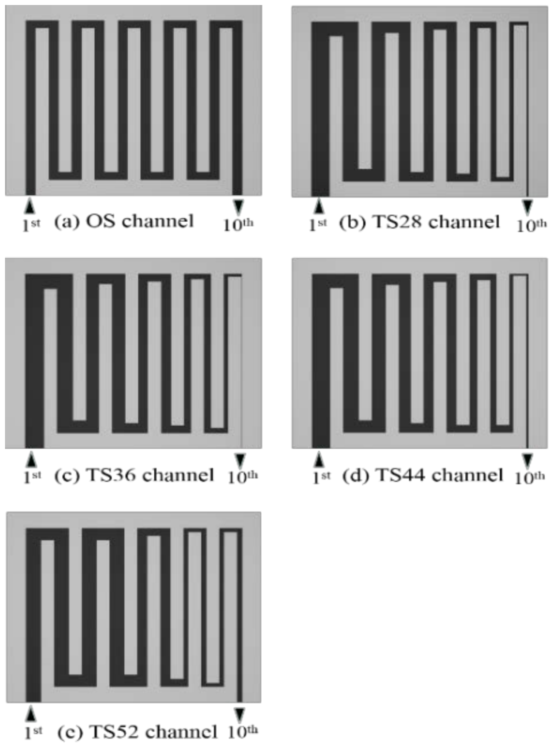

Fig. 1. Various flow field designs employed in the study

Boundary conditions were fixed (the flux equal to zero). The anode and cathode flow slab walls had constant pressure and devoid of chemical reactions. Practical properties of GDL and CL with different size of porosity, permeability and conductivity were utilized and the PEM fuel cell with convergent serpentine flow was expected to be better compared to the common serpentine flow slab of constant channel width. It was also confirmed by a series of study-cases.

The related parameters and fuel conditions of the PEMFC were set as constant and have been listed in Table. 1 and Table. 2 respectively.

Table 1. PEM fuel cell parameters

Parameter	Value
Porosity of GDL and CL	0.4
Porosity of Membrane	0.28
Permeability of GDL and CL (m^2)	$1.76x10^{-11}$
Permeability of Membrane (m^2)	$1.8x10^{-18}$
GDL CL layer conductivity ($\Omega^{-1}\cdot m^{-1}$)	100
Membrane conductivity ($\Omega^{-1}\cdot m^{-1}$)	$1x10^{-20}$
GDL CL layer thermal conductivity (W/m·K)	1.3
Membrane layer thermal conductivity (W/m·K)	0.455
Transfer coefficient at anode	0.5
Transfer coefficient at cathode	1.5
Concentration dependence at anode	0.5
Concentration dependence at cathode	1.5
Reference current density at anode (A/m^3)	$9.2272x10^8$
Reference current density at cathode (A/m^3)	$1.5x10^6$

Table 2. Fuel conditions used in the present study

Parameter	Value
Reference (atm)	1
Anode inlet Velocity (m/s)	2
Cathode inlet Velocity (m/s)	6
Temperature (K)	323
Fuel concentration of Anode	H_2：73%、H_2O：27%
Fuel concentration of Cathode	O_2：100%

The geometric values of PEMFCs and channel width for various convergent serpentine flow slabs are tabulated in Table. 3 and Table. 4 respectively (Wang, 2017).

Table 3. Geometric values of elements in serpentine flow slab PEMFCs

Parameter	Value
Channel depth of electrodes (mm)	1
Anode and cathode of the electrode (mm)	1
Channel rib width of electrodes (mm)	1.3
Diffusion layer thickness (mm)	0.35
Catalyst layer thickness (mm)	0.005
Membrane thickness (mm)	0.035
Surface to Volume ratio (m^{-1})	1000

Table 4. Channel width of PEMFCs with different serpentine flow slabs

Ch. Model	Channel Width (mm)										Rib area ratio	Exit aspect ratio
	1	2	3	4	5	6	7	8	9	10		
OS	1	1	1	1	1	1	1	1	1	1	51.2	1
TS28	1.8	1.6	1.4	1.2	1.0	1.0	0.8	0.6	0.4	0.2	50.9	0.2
TS36	1.9	1.6	1.3	1.3	1.0	1.0	0.7	0.7	0.4	0.1	50.9	0.1
TS44	1.6	1.6	1.2	1.2	1.2	0.8	0.8	0.8	0.4	0.4	51.0	0.4
TS52	1.5	1.5	1.5	1.5	1.0	1.0	0.5	0.5	0.5	0.5	51.0	0.5

RESULTS AND DISCUSSION

The predicted results (Figure 2a and b) of PEMFC performance with various convergent serpentine flow slabs like OS, TS28, TS36, TS44, and TS52 were similar to that of our previous study (Wang, 2017). The PEMFC performance in this study was evaluated as open circuit voltage (OCV), power and current density generation. The TS type flow slab fuel cells produced similar OCV of 1 V to 1.1 V, power densities of 650 to 675 mW/cm^2 and current densities of 2550 to 2700 mA/cm^2. But the traditional flow slab fuel cell produced OCV similar to that of the TS flow slab fuel cells at low current densities, but at high current density values the OCV production dropped suddenly. Nevertheless, the power and current density of the TS-type were much better than the OS-type. At maximum current densities, the reactor fuel was utilized more speedily and thus the fuel concentration in the flow slabs reduced. This phenomenon caused high concentration polarization and had negative impacts on the PEMFC constancy and robustness (Wang, 2018). Concentration polarization happened more frequently in the OS-type and this reduced the power density, which was obvious from the results. Convergent-type serpentine flow slabs employed in this research study, possessed the ability of deferring the concentration polarization at maximum current density values.

Further justification was provided by (Wang, 2008) where they described that the PEMFC performance with serpentine flow slabs was not affected by the fuel flow at minimum current densities, but at maximum values, significant differences occurred. (Wang, 2010) have also indicated that the fuel concentrations at the inlet varied greatly with that at the outlet of the PEMFC with serpentine flow slab and this was much high compared to the other flow slabs types. The distribution of current density inside serpentine flow channels of PEMFC was studied in detail. It was reported that fuel flow arrangements and geometry inside the reactor were important in maintaining homogenous power distribution along with PEMFC performance (Alaefour, 2012, Alaefour, 2011).

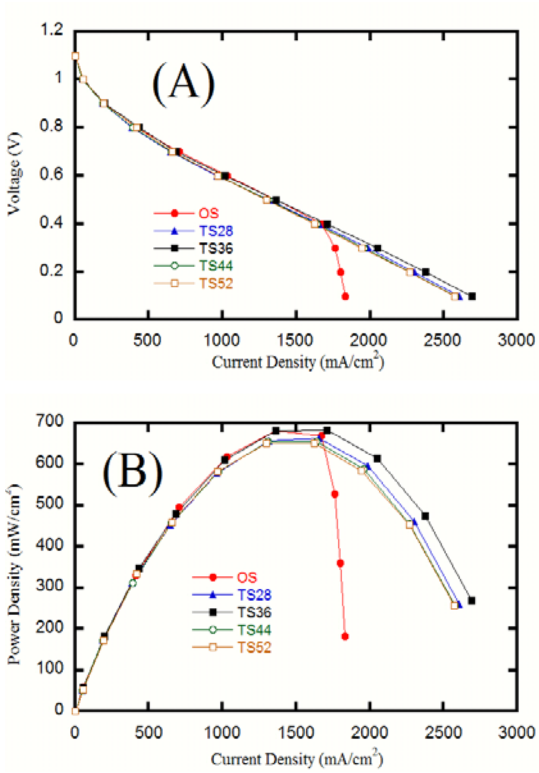

Fig. 2. Polarization and power density curves in the PEMFCs

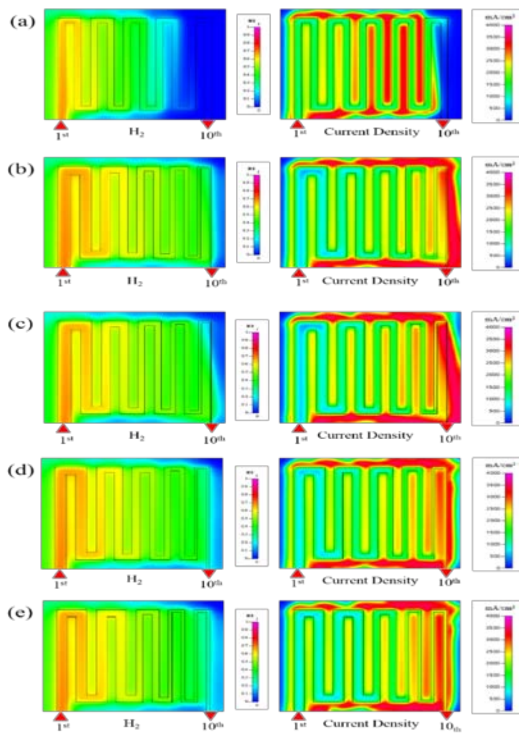

Fig. 3. H$_2$ concentration and current density distributions at V=0.3 V for different flow field designs (a) OS, (b) TS28, (c) TS36, (d) TS44, (e) TS52.

This was in accordance to the results of this study, where the serpentine type flow slab had prohibited the non-homogeneity of fuels at maximum current density values. If the fuel concentration in the flow slab was unevenly distributed, this might have resulted in uneven power output and decreased PEMFC performance. The current density in TS36 system was 2959.2 mA/cm^2 which was about 1.59 times higher than the OS-type system. This was due to the high fuel flow speed in the flow slab downstream of the convergent flow slab (Marr, 1999, Huang, 2018). This phenomenon might have prohibited the fuel shortage in the flow slab downstream which might have resulted in concentration polarization postponement (Lan, 2018). The detailed hydrogen concentration and distribution of current density at a loading of 0.3 V for various flow field designs is presented in Figure 3. From the figure it is obvious that the reduced performance was observed in PEMFC with common serpentine flow field (OS-type), whereas convergence in the flow channel width improved the performance.

CONCLUSIONS

In this research work, the effects of various convergent serpentine flow slabs on PEMFC performance were examined in details. Results indicated that convergent serpentine flow slab (TS-type) was more beneficial than the common serpentine flow slab (OS-type) in enhancing the irregular fuel flow distribution in flow slab terminal at maximum current densities. In this TS-type, the limiting current density produced was 2959.2 mA/cm^2, which was 1.59 times higher than that of the OS-type. Thus, the optimized flow slab reactor in this present study was TS36 PEMFC. So, prominent accomplishments of the better flow slab designs in PEMFCs have prodigious potential to progress their power output and significant possibilities in their forthcoming applications.

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REFERENCES

Arvay, A., French, J., Wang, J. C., Peng, X.H., & Kannan, A.M. “Nature inspired flow field designs for proton exchange membrane fuel cell.” *Int. J. Hydrog. Energ*, 2013, 38, 3717-3726.

Alaefour, I., Karimi, G., Jiao, K., & Li, X. “Measurement of current distribution in a proton exchange membrane fuel cell with various flow arrangements–a parametric study.” *Appl. Energ*, 2012, 93, 80-89.

Alaefour, I., Karimi, G., Jiao, K., Al Shakhshir, S., & Li, X. “Experimental study on the effect of reactant flow arrangements on the current distribution in proton exchange membrane fuel cells.” *Electrochim. Acta*, 2011, 56, 2591-2598.

Chakraborty, U. “Fuel crossover and internal current in proton exchange membrane fuel cell modeling.” *Appl. Energ*. 2016, 163, 60-62.

Chiu, H.C., Jang, J.H., Yan, W.M., Li, H. Y., & Liao, C.C. “A three-dimensional modeling of transport phenomena of proton exchange membrane fuel cells with various flow fields.” *Appl. Energ*, 2012, 96, 359-370.

Cooper, N.J., Smith, T., Santamaria, A.D., & Park, J.W. “Experimental optimization of parallel and interdigitated PEMFC flow-field channel geometry.” *Int. J. Hydrog. Energ*, 2016, 41, 1213-1223.

Fontana, É., Mancusi, E., Da Silva, A., Mariani, V. C., De Souza, A. A. U., & de Souza, S.M.G.U. “Study of the effects of flow channel with non-uniform cross-sectional area on PEMFC species and heat transfer.” *Int. J. Heat. Mass. Trans*, 2011, 54, 4462-4472.

Huang, K.D.; Sangeetha, T.; Cheng, W.F.; Lin, C.; Chen, P.T. “Computational fluid dynamics approach for performance prediction in a Zinc–air fuel cell.” *Energies* 2018, *11*, 2185.

Jayakumar, A., Singamneni, S., Ramos, M., Al-Jumaily, A. M., & Pethaiah, S. S. “Manufacturing the Gas Diffusion Layer for PEM Fuel Cell Using a Novel 3D Printing Technique and Critical Assessment of the Challenges Encountered.” *Materials*, 2017, *10*, 796.

Janajreh, I., ElSamad, T., & Hussain, M.N. “Intensification of transesterification via sonication numerical simulation and sensitivity study.” *Appl. Energ*, 2017, 185, 2151-2159.

Liu, Y., Fan, L., Pei, P., Yao, S., & Wang, F. “Asymptotic analysis for the inlet relative humidity effects on the performance of proton exchange membrane fuel cell.” *Appl. Energ*. 2017, 213, 573-584.

Lan, T.H., Wang, C.T., Yang, Y.C., & Chen, W.T. “Multi-effects of gravity and geometric flow channel on the performance of continuous microbial fuel cells.” *Int. J. Green. Energ*, 2016, 13, 1483-1489.

Liu, H., Li, P., & Wang, K. “Optimization of PEM fuel cell flow channel dimensions—Mathematic modeling analysis and experimental verification.” *Int. J. Hydrog. Energ*, 2013, *38*, 9835-9846.

Lan, T.H.; Wang, C.T.; Sangeetha, T.; Yang, Y.C.; Garg, A. “Constructed mathematical model for nanowire electron transfer in microbial fuel cells.” *J. Power Sour.* 2018, *402*, 483–488.

Martin, S., Garcia-Ybarra, P.L., & Castillo, J.L. “Long-term operation of a proton exchange membrane fuel cell without external humidification.” *Appl. Energ*, 2017, 205, 1012-1020.

Marr, C., & Li, X. “Composition and performance modelling of catalyst layer in a proton exchange membrane fuel cell.” *J. Power. Sources*, 1999, 77, 17-27.

Manso, A. P., Marzo, F. F., Mujika, M. G., Barranco, J., & Lorenzo, A. “Numerical analysis of the influence of the channel cross-section aspect ratio on the performance of a PEM fuel cell with serpentine flow field design.” *Int. J. Hydrog. Energ*, 2011, *36*, 6795-6808.

Manso, A. P., Marzo, F. F., Barranco, J., Garikano, X., & Mujika, M. G. “Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell. A review.” *Int. J. Hydrog. Energ*, 2012, 37, 15256-15287.

Palaniswamy, K., Marappan, M., & Jothi, V.R. “Influence of porous carbon inserts on scaling up studies for performance enhancement on PEMFC.” *Int. J. Hydrog. Energ*, 2016, 41, 2867-2874.

Radhakrishnan, V., & Haridoss, P. “Effect of GDL compression on pressure drop and pressure distribution in PEMFC flow field.” *Int. J. Hydrog. Energ*, 2011, 36, 14823-14828.

Wang, C. T., Ou, Y. T., Wu, B. X., Thangavel, S., Hong, S. W., Chung, W. T., & Yan, W. M. “A modified serpentine flow slab for in Proton Exchange Membrane Fuel Cells (PEMFCs).” *Energ. Proc*, 2017, *142*, 667-673.

Wang, C.T., Hu, Y.C., & Zheng, P.L. “Novel biometric flow slab design for improvement of PEMFC performance.” *Appl. Energ*, 2010, 87(4), 1366-1375.

Wang, C. T., Ou, Y. T., Wu, B. X., Thangavel, S., Hong, S. W., Chung, W. T., & Yan, W. M. “A modified serpentine flow slab for in Proton Exchange Membrane Fuel Cells (PEMFCs).” *Energ. Proc*, 2017, *142*, 667-673.

Wang, C.T.; Sangeetha, T.; Zhao, F.; Garg, A.; Chang, C.T.; Wang, C.H. “Sludge selection on the performance of sediment microbial fuel cells.” *Int. J. Energ. Res.* 2018, 42, 4250–4255.

Wang, X. D., Duan, Y. Y., Yan, W. M., & Peng, X. F. “Local transport phenomena and cell performance of PEM fuel cells with various serpentine flow field designs.” *J. Power. Sourc*, 2008, 175, 397-407.