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Kesit alan geometri etkisinin PEM yakıt hücresinin performansı üzerine incelenmesi

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ÖZ

Bu çalışmada, düşük sıcaklıklarda çalışan tek kanallı bir proton değişim membranlı yakıt hücresi modellenmiştir. Hazırlanan model deneysel verilerle karşılaştırılmış ve doğruluğu kanıtlanmıştır. Bu model kullanılarak, kanal yüksekliği sabitken kanal genişliğindeki değişimin hücre performansına etkisi ve kanal kesit alanı sabitken kanal geometrisindeki değişim araştırılmıştır. Reaktantın difüzyon tabakası ile temas ettiği alanın büyütülmesinin performans artışı sağladığı tespit edilmiştir. Ancak düşük voltajlarda çalışırken taban açısı ve kanal genişliğinin artmasıyla artan konsantrasyon kayıplarının azaldığı gözlemlenmiştir.

Anahtar Kelimeler: PEM yakıt pili, kesit alanı, kanal geometrisi, modelleme

Investigation of the cross-section area geometry effect on the performance of PEM fuel cell

ABSTRACT

In this study, a proton exchange membrane fuel cell operating at low temperatures with a single channel is modeled. The prepared model has been compared with experimental data and its accuracy has been proved. Using this model, the impact of the change of the channel width on the cell performance with the channel height being constant and the change of the channel geometry with the channel cross-sectional area being constant was investigated. It has been found that the enlargement of the area where the reactant contacts the diffusion layer provides an increase in performance. However, when working at low voltages, it has been observed that increasing concentration losses decrease with increasing base angle and channel width.

Keywords: PEM fuel cell, Cross-section area, Channel geometry, Modeling

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1. INTRODUCTION

The increase in the world population, industrialization, and technological developments cause a rapid increase in energy consumption. Many problems are encountered in fossil fuels used to meet energy needs. These problems can be listed as the gradual decrease in fossil fuel reserves and the possibility of being exhausted shortly (or its extraction and processing would not be economically beneficial) and the negative environmental impacts caused by the toxic gases resulting from burning these fuels. For this reason, it has become necessary to focus on clean and renewable energy sources that will meet the energy needs [1]. The fuel cell (FC) stands out among other approaches to reducing the use of non-renewable energy sources and is seen as a promising tool to reduce the discharge of pollutant gases such as CO_2, SO_2. Lots of fuel cell types can be found in the literature which is classified with electrolyte type and operating temperature [2].

The most widely used type of fuel cell today is low-temperature proton exchange membrane fuel cells (PEMFC). By feeding pure hydrogen by the anode and oxygen or air as oxidants by the cathode, they generally operate in the temperature range of 60-85 °C. Feed channels are an area that needs special attention to facilitate the distribution of reactants and to increase their diffusion. For this reason, there are channels in the literature created using different cross-sectional areas.

Ahmed, D. H. and Sung, H. J. modeled a single cell flat fuel cell in 3 dimensions using three-channel section (rectangular, trapezoidal, and parallelogram) configurations in their study. The primary purpose of this study is to examine the cell performance of cells with different duct cross-sectional geometric configurations. First of all, the same boundary conditions, same channel height, same cross-sectional area, and active surface area were kept constant for all three cross-sectional geometries. As a result of simulations using these channel cross-section geometries, they obtained that the fuel cell with rectangular channel section geometry gave higher cell voltages, but the fuel cell with parallelogram channel section geometry obtained minimum potential. In the fuel cell with trapezoidal channel cross-section geometry, smoother reactant gas and current density lines were obtained [3].

Khazae shows the experimental results of the proton exchange membrane fuel cell performance graph to search the effect of flow channel modification on the fuel cell performance for rectangular, triangular, and elliptical channel cross-sectional geometries. All parameters give that for all voltage conditions, the impact of flow channel modification on performance curves is significant. The results pointed that when the geometry of the channel is rectangular, the overall cell performance is higher, but when the geometry of the channels changes to triangular and elliptical, the cell performance decreases [4].

Khazae experimentally investigated the effect of channel section geometry on the performance in a single cell proton exchange membrane fuel cell with a serpentine channel structure. Elliptical quadrilateral and triangular geometries are considered channel cross-section geometry. Polarization curves are given for five different operating temperatures for three cross-section geometries. The result obtained as a result of repeated studies has shown, when the cell geometry is rectangular, it is clear that the overall performance of the cell is better than elliptical and triangular geometry. The biggest difference in the performance of these conditional rectangle and elliptical section geometries is approximately 12%, and the maximum difference between rectangular and triangular geometries is 18% [5].

Khazae and Sagadbafan used 3-D and non-multiphase models to analyze the impact of increasing the number of serpentine channels in 2-pole plates and enhance the depth and section geometry of the proton exchange membrane fuel cell with triangular, elliptical, and rectangular channel structure. They numerically investigated the different barriers' effect for different aspect ratios on gas concentration, current density, and performances are compared the results with the experimental results of the triangular channel cross-section geometry polymer electrolyte membrane fuel cell. Also, they examined the effect of channel depth for each channel cross-section geometry. They stated that the increase in the number of passes and the decrease in the channel height have an improving effect on fuel cell performance [6].

Wang et al. The 3D model with parallel structured channels was created and the performance effect of the cross-section geometry of the cathode side flow channel of the model was investigated. They verified the model they created with experimental data in the literature. They considered rectangular, triangular, trapezoidal, and circular structures as channel cross-section geometry. He compared the polarization curves, current density distributions, velocity and oxygen concentration distributions in the cathode channel, and local liquid water saturation distributions for different channel sections. They stated that the change in the cross-section geometry affects the performance more prominently at low operating potentials. The local current density for the triangular duct section is higher than for the rectangular, trapezoidal, and semicircular ducts. They achieved the maximum performance in the fuel cell with the triangular section geometry channel and the minimum performance in the fuel cell with the rectangular section geometry channel [7].

Harun, Z. and Etminan, A. examined the performance of PEM-in with two different geometries in their study. Two different geometries have been applied to the PEM design to see how rectangular and triangular channel sections affect the performance of these geometries. The study includes the effect of humidity and inlet gas temperature as the 2 effective parameters on PEM operation. Also, different flow directions (parallel and reverse) are discussed in the study. We know from the results that the high temperature and humidity of the inlet gas produces much higher output voltage with different current densities in all simulations. Moreover, both cross-sectional areas show almost the same output voltage under the same conditions with less than a 2% difference. This shows that the difference between the cross-sectional areas (triangle and quadrilateral) does not significantly affect the performance of the PEM. Under these conditions, when we consider the difference to the benefit, the triangular section channel shows higher performance compared to the rectangle. Also, the difference between the types of flows (reverse and parallel) causes a deviation in the output voltage for the same conditions. In general, the counter-flow type produces higher output voltage compared to parallel flows, and this becomes more pronounced in the triangular cross-sectional area [8].

Wang et al. examined parallel and intertwined designs with different aspect ratios in their study, and a 3-dimensional digital model was used in the analysis. This study highlighted the influence of the aspect ratio of the flow channel and the cross-sectional area of the flow channel. Interlocking design provides better cell performance than parallel design for all conditions considered. When cell voltages are smaller than 0.7 V, electrochemical reaction rates are high. Depending on this situation, oxygen consumption and liquid water production are also high. And therefore, the aspect ratio of the channel cross-section and the channel cross-sectional area have little effect on cell performance in all various cathode flow field designs. Thus, as the aspect ratio of the cross-sectional area of the channel cross-section increases, cell performance first increases and then decreases [9].

Mohammadi, A. et al. 30 types of duct cross-sectional designs are considered, including 25 innovative and 5 well-known configurations. The 30 configurations of the channel cross-sectional area are compared with configurations with a rectangular channel cross-section, configurations with a trapezoidal channel cross-section, configurations with an inverted trapezoid bottom, semi-elliptical bottom configurations, and inverted semi-elliptical bottom configurations. The maximum power densities of their configurations are integrated into all designs. In the 30 configurations, all conditions are the same [10].

Cooper et al., experimentally investigated the effect of the channel width, channel height, and the distance between channels of the current collecting plate on the anode side of a PEM fuel cell with a parallel channel structure. As a result of their investigations, they stated that the decrease in channel height and channel cross-sectional area increased the battery performance and the amount of net power obtained [11].

Ionescu and Buzbuchi investigated the effect of the ratio of channel width to current collector plate interchannel width on fuel cell performance in the two-dimensional model they created. With the help of the model they created, they obtained the distribution of reactant gases, current density, and electric potential. According to the findings they obtained, it was stated that a more homogeneous hydrogen and oxygen distribution was obtained with an increase in the ratio of the channel width to the interchannel width of the current collecting plate, but a more unbalanced current density distribution was obtained. Since the shoulders of the current collector plate are the only parts in contact with the gas diffusion layer, they stated that the ohmic resistance in the battery increases with the increase of the channel width ratio. They stated that if the contact area is small enough, these ohmic losses will cause a reduction in battery performance [12].

Shimpalee and Vanzee investigated the effect of channel sizes on fuel cell performance in a serpentine bipolar plate with the model they developed. They made separate examinations according to whether the fuel cell is active or stationary. They stated that in cases where the fuel cell is stationary, the narrow channels and the distance between the channels affect the performance positively, and the opposite is the case when the fuel cell is active [13]

In their study, Khazaee and Ghazikhani modeled the fuel cell in three dimensions to examine the effect of channel depth on battery performance in a single-cell rectangular channel cross-sectional fuel cell. The researchers verified the model they created with experiments. They used four 34 different duct sizes and three different air stoichiometry ratios as variable parameters. In the study, polarization curves, current density, the mole ratio of oxygen, and water content distributions of the membrane were examined. They observed that the battery performance increased with the increase in air stoichiometry. They stated that the highest cell performance is in the fuel cell with 1.5 mm anode channel depth and 1 mm cathode channel depth. They observed that the performance was the lowest in the geometry where the anode and cathode channel depths were 1 mm [14]

Muthukumar et al. In their study, investigated the effect of scale size on battery performance in a single-cell fuel cell with a square-section flow channel. For the parameters they examined, the length of the fuel cell and the membrane electron pair thickness were kept constant. The side length and membrane width of the channel (3a) were used as variable parameters, and the side length and membrane width of the channel was increased at the same rate. The side lengths of the channel are taken as 0.5, 1.0, 1.5, and 2.0 mm. It was observed that the increase in the edge length negatively affected the battery performance. The maximum power was obtained at 0.5 mm edge length and 0.4 V battery potential [15].

Liu et al. In their study investigated the performance of the fuel cell with increasingly narrow flow channels and the transfer of reactant gases. As the reactive gas in the conical channel is accelerated and forced to pass through the gas diffusion layer due to the decrease in channel depth along the flow direction. indicated that fuel cell performance improved. In their study, they also considered the effect of liquid water formation on the transport of reactant gases [16].

Mahmoudimehr and Daryadel modeled the PEM fuel cell in their study to examine the effect of channel height and channel width on fuel cell performance under different operating conditions. In the results they obtained, they stated that the optimum channel sizes vary with the operating conditions [17].

Eker and Taymaz modeled the fuel cell in three dimensions using the PEMFC module of the FLUENT package program to examine the effect of channel width and operating temperature on the performance of the PEM fuel cell. With the help of the model they created, the polarization curves and current density distributions were examined. As a result, they stated that increasing the channel width and decreasing the operating temperature negatively affect the battery performance [18].

Lobato et al. In their study, they modeled a high-temperature polymer electrolyte membrane fuel cell with an active area of 50 cm2 in three dimensions and made analyzes for three different channel structures (four-step serpentine, parallel and needle-like). Since the reactant gases could not distribute properly along the electrode, they achieved lower performance in parallel channel structures. They achieved similar performance in serpentine and needle-shaped channel structures [19].

In this study, a low-temperature PEMFC is modeled using the finite element method with Comsol Multiphysics 5.5. The prepared model has been verified with the experimental results obtained from the literature. After this verification, the effect of change of channel width on cell performance was investigated, with channel depth remaining constant. As a second study, the cross-sectional geometry was converted into an isosceles trapezoidal form by keeping the channel cross-sectional area and depth constant, and the effect of this situation on performance was investigated. In this study, especially the channel structures that can be created with CNC were taken into consideration. Contrary to the use of rectangular or square cross-section ducts, which are often used, the effect of different sections to be created on the performance is examined. Contrary to previous studies, the focus was directly on the cross-sectional area and shape of the bipolar plate.

2. MATERIAL AND METHOD

In this study, a model was created using a single channel of a polymer electrolyte membrane fuel cell. The model's data is coming from experimental studies in the literature and the model was validated using these data. The model is 3D, non-isothermal. A schematic view of the prepared model is shown in Fig. 1. Various parameters of the fuel cell model are given in Table 1.

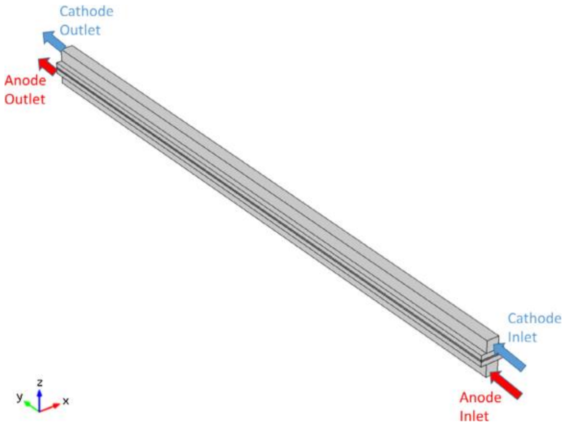

Figure 1. Prepared model schema

Table 1 Parameters of the model

Parameter name	Value (unit)
Width of Channel	1 (mm)
Depth of Channel	1 (mm)
Length of Channel	10 (mm)
Gas Diffusion Layer Thickness	380 (μm)
Gas Diffusion Layer Conductivity	150 (S/m)
CL Thickness	15 (μm)
CL Porosity	0.5
CL Specific area	$1x10^4$ (1/m)
CL Conductivity	1000 (S/m)
CL Permeability	$2.36x10^{-12}$ [m^2]
Membrane Thickness	120 (μm)
Membrane Permeability	$1.8x10^{-18}$ (m^2)
Membrane Charge concentration	$1.2x10^3$ (mol/m^3)
Anode platinum loading	0.4 (mg/cm^2)
Anode carbon loading	0.6 (mg/cm^2)
Cathode platinum loading	0.4 (mg/cm^2)
Cathode carbon loading	0.6 (mg/cm^2)
Operating temperature	338.15 (K)
Anode pressure	1 (atm)
Cathode pressure	1 (atm)
RH of fuel	100 (%)
The anodic stoichiometric flow ratio	1.2
The cathodic stoichiometric flow ratio	2.0
Anode inlet flow	0.2 (l/s)

The model has some assumptions. Which are:

- ❖ The presented model operates at a stationary mode.
- ❖ All gases are ideal gas.
- ❖ All fluids are incompressible.
- ❖ Mechanical deformations are ignored.
- ❖ The membrane is permeable for only water and ions.
- ❖ All materials are isotropic and homogenous.
- ❖ In the flow channels, GDLs and CLs, one-phase flow is used.

Initially, 1 mm was taken as the channel width, then 0.5 and 1.5 mm measurements were also examined. At this stage, the depth of the channel was kept constant. In the second stage, the cross-sectional area of the duct was kept constant, but the rectangular duct of 1 mm width was compared with two different isosceles trapezoids. The lower base lengths of these trapezoidal trapezoids are respectively 1.5 and 1.75 mm, and the upper base lengths are 0.5 and 0.25 mm, respectively (Figure 2).

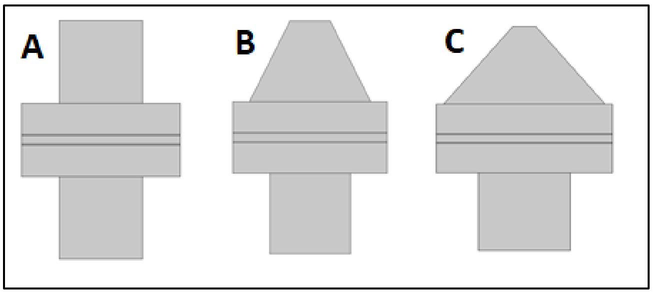

Figure 2. Views of the cross-section areas (A:1x1mm, B:0.5x1.5x1mm, C:0.25x1.75x1mm)

3. RESULTS

In Fig. 3, the prepared model is compared with the experimental data in the literature. Experimental values, which are used in the model, were procured from a reference article [20]. Concerning the experiments, the active area is 25 cm^2. Anode side catalyst loading is 0.6 mg/cm^2 for carbon and 0.4 mg/cm^2 for platinum. Cathode side catalyst loading is the same as the anode. The stoichiometric value of H_2 was 1.2, the stoichiometric value of air stoichiometry was 2, the operating temperature was 65 °C. In Fig. 3, the results of the presented model are perfectly matched with experimental data. It has been observed that when higher current densities are used, the current densities decrease more rapidly due to mass transfer resistance.

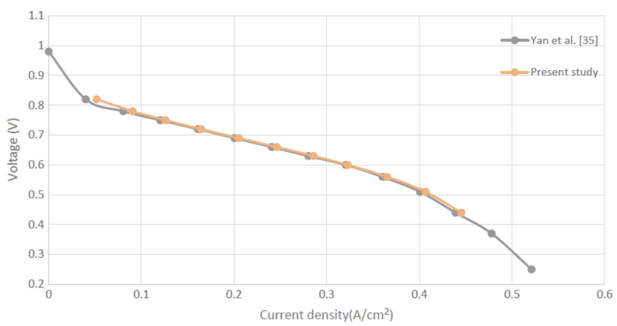

Figure 3. Model validation

After the model verification process was carried out, the channel width was changed by keeping the channel depth constant. The results are compared on the polarization curves in Figure 4.

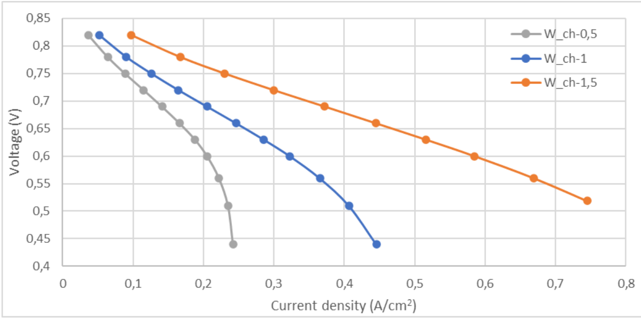

Figure 4. Polarization curves depending on the width change

In the second part of the study, rectangular geometry and two different isosceles geometries are compared with each other by using the fixed channel cross-sectional area. The results of the fixed cross-sectional analysis are given in Figure 5.

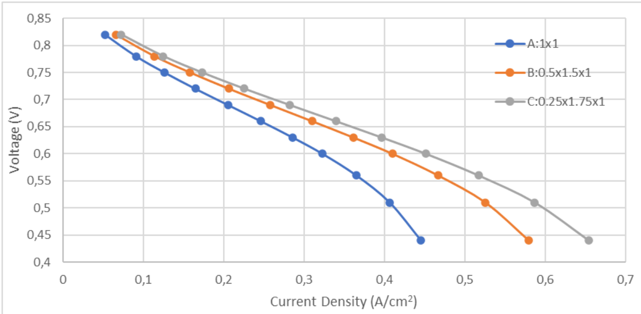

Figure 5. Polarization curves of geometries with a constant cross-section

As can be understood from Figure 5, it shows a higher performance than the cross-section geometry being isosceles. This performance increased as the lower base length of the isosceles increased. This indicates an increase in the penetration of hydrogen into the diffusion layer. However, the reduction in the length of the upper sole affects the increase in performance as the flow is concentrated in the regions close to the lower sole.

4. CONCLUSION

In this study, a 3-dimensional, non-isothermal model for low-temperature proton exchange membrane fuel cells was developed using the finite element method. The model has been compared and validated with experimental data from Mississippi State University.

In the study, the effect of channel width and channel geometry on cell performance was investigated. Accordingly, the increase in the channel width, provided that the channel height is constant, increases the fuel cell performance. However, while the channel cross-sectional area is constant, the more the surface where the reactant touches the diffusion layer, the higher the performance. Especially, as the base angles of the trapezoidal structure increase, it has been observed that the performance increases. In addition to this study, it is possible to obtain a correlation between performance increase and base angle with parametric analysis.

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REFERENCES

[1] A. C. Turkmen, C. Celik, “The effect of different gas diffusion layer porosity on proton exchange membrane fuel cells,” *Fuel,* 222, pp. 465-474, 2018.

[2] A. C. Turkmen, “Determination of thermal conductivity coefficient in gas diffusion layers and development of the nonisothermal model of proton exchange membrane fuel cell,” *Master thesis*, Kocaeli University, Turkey, 2018.

[3] D. H. Ahmed, H. J. Sung, “Effects of channel geometrical configuration and shoulder width on PEMFC performance at high current density,” *Journal of Power Sources,* 162(1), pp. 327-339, 2006.

[4] I. Khazaee, “Experimental investigation and numerical comparison of the performance of a proton exchange membrane fuel cell at different channel geometry,” *Heat and Mass Transfer*, 51, pp. 1177–1187, 2015

[5] I. Khazaee, “Improvement the equation of polarization curve of a proton exchange membrane fuel cell at different channel geometry, *Heat and Mass Transfer,* 51, pp. 1681–1689, 2015.

[6] I. Khazaee, H. Sabadbafan, “Numerical study of changing the geometry of the flow field of a PEM fuel cell*,” Heat and Mass Transfer,* 52, pp. 993–1003, 2015.

[7] X. D. Wang, G. Lu, Y. Y. Duan, and D. J. Lee, “Numerical analysis on performances of polymer electrolyte membrane fuel cells with various cathode flow channel geometries,” *International Journal of Hydrogen Energy,* 37(20), pp. 15778-15786, 2012.

[8] Z. Harun, A. Etminan, “Numerical Simulation of a Proton Exchange Membrane (PEM) Fuel Cell with Rectangular and Triangular Cross-Section Area Channels,” *The International Journal of Advanced Technology,* 9(4), pp. 282-288, 2020.

[9] X. D. Wang, Y. Y. Duan, W. M. Yan, and X. F. Peng, “Effects of flow channel geometry on cell performance for PEM fuel cells with parallel and interdigitated flow fields,” *Computational Thermal Sciences,* 53(16), pp. 5334-5343, 2008.

[10] A. Mohammedi, S. Youcef, B. H. Moussa, “3D investigation of the channel cross-section configuration effect on the power delivered by PEMFCs with straight channels,” *Fuel,* 263, pp. 1167-1195, 2019.

[11] N. J. Cooper, T. Smith, A. D. Santamaria, J. W. Park, “Experimental optimization of parallel and interdigitated PEMFC flow - field channel geometry,” *International Journal of Hydrogen Energy*, 2016.

[12] V. Ionescu, N. Buzbuchi, “PEMFC Two-dimensional FEM Model to Study the Effects of Gas Flow Channels Geometry on Reactant Species Transport,” *Energy Procedia*, 2017.

[13] S. Shimpalee, J. Vanzee, “Numerical studies on rib and channel dimension of flow-field on PEMFC performance”. *International Journal of Hydrogen Energy*, 2007.

[14] I. Khazaee, M. Ghazikhani,<“Numerical Simulation and Experimental Comparison of Channel Geometry on Performance of a PEM Fuel Cell,” *Arabian Journal for Science and Engineering*, 2012.

[15] M. Muthukumar, P. Karthikeyan, M. Vairavel, C. Loganathan, S. Praveenkumar, A. S. Kumar, “Numerical studies on pem fuel cell with different landing to channel width of flow channel,” *Procedia Engineering*, 2014.

[16] H. C. Liu, W. M. Yan, C. Y. Soong, F. Chen, H. S. Chu, “Reactant gas transport and cell performance of proton exchange membrane

fuel cells with tapered flow field design". *Journal of Power Sources*, 2006.

[17] J. Mahmoudimehr, A. Daryadel, "Influences of feeding conditions and objective function on the optimal design of gas flow channel of a PEM fuel cell". *International Journal of Hydrogen Energy*, 2017.

[18] E. Eker, I. Taymaz, "Akış kanalı genişliğinin pem tipi yakıt hücresi performansına etkisinin incelenmesi," *Sakarya Üniversitesi Fen Bilimleri Dergisi*, 2013.

[19] J. Lobato, P. Cañizares, M. A. Rodrigo, F. J. Pinar, E. Mena, D. Úbeda, "Three-dimensional model of a 50 cm^2 high temperature PEM fuel cell. Study of the flow channel geometry influence". *International Journal of Hydrogen Energy*, 2010.

[20] Q. Yan, H. Toghiani, H. Causey, "Steady-state and dynamic performance of proton exchange membrane fuel cells (PEMFCs) under various operating conditions and load changes," *J Power Sources*, 161, pp. 492-502, 2006.