Numerical investigation of dimensions and arrangement of obstacle on the performance of PEM fuel cell

A. A. Ebrahimzadeh, I. Khazaee∗, A. Fasihfar

Faculty of Mechanical and Energy Engineering, Shahid Beheshti University, A.C., Tehran, Iran

E-mail addresses: lmankhazaee@yahoo.com, i_khazaeei@sbu.ac.ir (I. Khazaee).

Abstract

The fuel cell is an electrochemical energy converter which converts the chemical energy from a fuel into electricity and heat and has been able to introduce itself as a source of clean power in the world over the past few decades. One of the major technical challenges in the development of PEM fuel cell technology is to achieve high and stable efficiency. One of the key parameters in designing this type of fuel cell is the shape and dimensions of reactors flow field channels on the bipolar plates. In this research, the obstacle is simulated by selecting the obstacle geometry in the channel path, and after choosing the best range (height), the best obstacle width is analyzed to have better performance. The simulation is done for the non-obstacle case and obstacles with 0.5, 1, 1.5 and 2 mm heights and 0.9, 1.8, 2.7 and 3.6 mm widths, respectively. The obtained results for PEMFC show that the height of 1.5 mm and the width of 3.6 mm have the highest impact on the fuel cell efficiency regarding species consumption, pressure drop and current density. Once the proper dimensions of the obstacle have been determined, different arrangements of the obstacle and their effect on the fuel cell efficiency are investigated, and the best arrangement is selected.

Keywords: Electrochemistry, Energy, Mechanics
1. Introduction

There are many problems caused by continuous using of fossil fuels, which currently provide 82% of the energy consumption [1]. The global warming trend will increase due to increased burning of fossil fuels to generate electricity, caused by the explosion of the world’s population. In addition to health and environmental concerns, the global fossil fuel reserves are rapidly decreasing. The world needs a power source that would have low pollutant emissions, high-efficiency energy, and unlimited reserves for the growing population of the world. Fuel cells have been known as one of the most promising technologies to achieve these goals [2].

Studding of flow field effect on improving PEMFC performance is a new issue that is taken into consideration by many researchers [3, 4, 5].

In 1970, regarding the evaluation performed by the German Ministry of Defense, it was found out that the PEM fuel cell (PEMFC) is the most effective solution for use in submarines due to its high power density, high efficiency, short start-up time and low operating temperature [6]. One of the determinant factors in the fuel cell performance is to determine the appropriate flow field. The gas flow channels are designed to direct and distribute the reactors with various designs such as parallel, serpentine, pinned, helicoid, etc., which also can be single-channel or multi-channel. The pressure drop, the way of distributing species concentration, flow velocity, the way of water removal etc., are important factors that should be considered in determining the proper flow field. These channels are usually formed as tracks on bipolar plates in a fuel cell stack [2]. Ferng et al. [7] have studied the effect of the flow channel patterns on PEM fuel cell performance in an experiment a three-dimensional numerical model. The studied fields have been parallel and serpentine, respectively. The obtained results show that the serpentine channel has higher efficiency over parallel channels.

Other results of this study are to investigate the effect of channel depth on parallel and serpentine channels, which have a significant effect on the performance of the fuel cell in parallel channels; however, on serpentine channels, it does not have significant impact on the performance of fuel cell. They have not paid attention to the other aspects of the channel. Scholta et al. [8] has studied a model with parallel flow channel field which is not at the same direction with 100 cm² active area. In this research, the effect of rib and channel width on the performance of a fuel cell is studied using a base flow field. The values between 0.7 and 1 mm are selected as the optimal values for either channel or rib width. In general, narrow channel is preferred for high current density; however, wider dimension is better at low current density. Yan et al. [9] has studied the effect of reducing the outlet channel flow areas in a multi serpentine flow field with an active area of 29.5 cm² on the performance of fuel cell and local transport phenomena. They have found that the reductions of
the outlet channel flow areas increase the reactant velocities in these regions, which enhance reactant transport, reactant utilization and liquid water removal. However, the pressure drop increases and the total performance of the fuel cell decreases. When the pressure losses are also taken into account, the optimal performance is obtained at a height contraction ratio of 0.4 and a length contraction ratio of 0.4 in the present design. In two similar works [10] and [11], an optimization method for a single serpentine fuel cell has been presented with 5 channels and 81 mm² active area by varying the height of flow channel. This geometric variable is used only in the cathode which is slightly similar to the anode flow channel in order to maintain the channel’s cross-section. The optimized geometry allows the power of the outlet cells to reach by 11.9 percent more than a cell with direct flow channels. The optimal model is compared with three narrowed channel and the final divergent channel of the convergent channel improves the major flow of channels and the sub-rib displacement. In this way, the local oxygen transfer rate and local current density increase. The channel divergence reduces the intrusion of reactants in the outlet channel. Rahimi et al. [12] has numerically studied the type of serpentine flow field on PEM fuel cell. They have improved water management by reducing the number of channels at the end of the flow field. The active area of the fuel cell is 25 cm² and channel dimension has also optimized. They have ignored the issue of lifetime in their research. However, they have only performed the study numerically. Liu et al. [13] has studied the role of flow field type on the performance of fuel cell experimentally. They have investigated different types of flow fields such as serpentine, parallel, pin, interdigitated and spiral. They have reported that the serpentine field has better performance compared with other fields. Accordingly, they have presented four new serpentine fields and studied their performance in a stack with four fuel cells. Finally, they have reported that the symmetric serpentine field has better performance over other fields. Khazae and Sabadbafan [14] have studied the effect of humidity and direction of the flow of reactant gases on fuel cell efficiency in 4-serpentine and 1-serpentine flow channel. They have reported that the cell performance at lower voltages increases with increasing humidity in cell with 4-Serpentine flow channel and also in cell with 1-Serpentine flow channel, cell performance at all voltages increases with increasing humidity. Also, the parallel input and output direction is more suitable for cell performance. They have reported that 4-Serpentine flow channel has better efficiency over 1-Serpentine flow channel at the same condition. Kahraman and Orhan [15] have reviewed different types of flow fields and flow field plates as well as their advantages and disadvantages. In addition, they have performed the modeling and optimizing processes for one sample with parallel and direct field. Perng et al. [16] have numerically studied the cross rectangular blocks in the PEM fuel cell flow channel and found out that the efficiency of the fuel cell has been increased. Han et al. [17] has studied the effect of sinusoidal flow channel’s wall on the performance of PEM fuel cell numerically and experimentally and found out that the concentration loss induced by unstable mass transfer.
is delayed and the fuel cell’s performance was improved by 5.76% in the experiment and 5.17% in the numerical analysis. Bilgili et al. [18] has studied the efficiency of PEM fuel cell with baffles at cathode and anode channels and showed that the baffles increase the gas density along channel and higher cell voltages are obtained in high flow densities. Heidary and Kermani [19] have studied the effect of heat exchange caused by partial blockage of flow field channels of a fuel cell and showed that the heat exchange between channel walls and original flow depends on the number of blocks along the lower wall. Ghanbarian et al. [20] has studied the effect of block in channel on the performance of fuel cell. They have used various types of blocks such as square, semicircular and trapezoid and reported that in high flow densities, the effect of block is so significant. Also, the trapezoid blocks have shown more increase in the net power. Ashorynejad and Javaherdeh [21] have studied the effect of sine field on the performance of fuel cell in a two-dimensional single-phase model considering only the cathode channel by using Boltzmann method. They have reported that the sine field increases the performance of the fuel cell with higher wavelength. Heidary et al. [22] has studied the effect of partial or full block placement of channel along both anode and cathode channels on the performance of fuel cell. Blockage in the channel of flow-field diverts the flow into the gas diffusion layer and enhances the mass transport from the channel core part to the catalyst layer. They have used a two-phase 3D model with a single channel. They have studied the effect of blocks number, their arrangement and their placement in cathode and anode channels and they have reported 30% performance increase for a sample with full blockage of cathode with 5 blocks. Heidary et al. [23] has used blockage in the flow field channel to increase the efficiency of fuel cell. They have used two types of in-line and non-linear or zigzag blockage. According to their reports, the presence of blockage increases the gas penetration and is particularly useful in the area of concentration loss. Also, the compressive loss caused by these blockages can be neglected against efficiency increase.

In previous studies, there is not any comprehensive resource to study the obstacle, pattern and its types. Most of them have studied the effect of a type of an obstacle on a different frequency domain or examine several obstacles in a steady state on the fuel cell efficiency. In this research, the PEM fuel cell is simulated three dimensionally with two-channel serpentine flow field with an obstacle to investigate the effect of obstacle on fuel cell performance and species distribution. At first, a square obstacle with different depth and width is studied, and once its appropriate dimension is selected, the domain and frequency of the obstacle are studied in the gas flow field.

2. Calculation

The fluid-flow, heat and mass transfer, electrochemical reactions and electrical charge transfer processes in the PEM fuel cell are presented by mass, momentum,
energy, chemical species transfer and charge transfer equations. Here, the super-
scripts (g), (l), (s) and (m) denote the properties associated with the gas, liquid, solid
and membrane, respectively. In this way, (c) denotes any quantity associated with
capillary pressure. The equations of mass, momentum, energy and intra
membrane phenomena are expressed as Eqs. (1), (2), (3), (4), (5), (6), (7), and (8) [24]. In these
equation $C_p^{(g)}$ (J K$^{-1}$ kg$^{-1}$) is, Special heat capacity of the mixed gas, \( \bar{m}_{H_2O} \) (kg mol$^{-1}$ s$^{-1}$) is Mass transfer caused by water condensation or evaporation, \( k \) (W m$^{-1}$ K$^{-1}$), is thermal conductivity, \( u, v, w \) and \( U \) (m/s) are velocities, \( \lambda \) is water
content, \( \varepsilon \) is porous coefficient, \( \omega_i^{(g)} \) is species mass fraction, \( \rho \) kg m$^{-3}$, is density, \( T \)
(K), is temperature, \( s \) is Saturation fluid and \( S \) are source terms

\[
\text{Mass (gas)} \quad \frac{\partial}{\partial t}(\rho^{(g)}u^{(g)}) + \nabla \cdot (\rho^{(g)}u^{(g)}s) = \dot{m}_{H_2O} - \dot{m}_{H_2O}
\]

\[
\text{Mass (liquid)} \quad \frac{\partial}{\partial t}(\rho^{(l)}u^{(l)}s) = \dot{m}_{H_2O}
\]

\[
\text{Momentum} \quad \frac{\partial}{\partial t}(\rho^{(g)}u^{(g)}) + \nabla \cdot (\rho^{(g)}u^{(g)}u^{(g)}) = \nabla \cdot \sigma - \frac{\mu^{(g)}}{k}u^{(g)}
\]

\[
\text{Energy} \quad (\rho C_p)^{\text{eff}} \frac{\partial}{\partial t}T + \nabla \cdot (\rho C_p)^{\text{eff}}u^{(g)}T = \nabla \cdot (k^{\text{eff}}\nabla T) + S_{\text{temp}}
\]

\[
\text{Species} \quad \frac{\partial}{\partial t}(\rho^{(g)}\omega_i^{(g)}) + \nabla \cdot n_i^{(g)} = S_i
\]

\[
\text{Membrane water content} \quad \frac{\partial}{\partial t} \left( \frac{\rho^{(m)}M_{H_2O}\lambda}{M^{(m)}} \right) + \nabla \cdot n^{(m)} = S_{\lambda}
\]

\[
\text{Membrane potential} \quad \nabla \cdot j^{(m)} = S_{\text{pot}}
\]

\[
\text{Solid potential} \quad \nabla \cdot j^{(s)} = -S_{\text{pot}}
\]

In the above equations, the gas and liquid phases are coupled in the phase change
source term, \( \dot{m}_{H_2O} \).Since the porous flow field is considered in this study, the Darcy
term (the last term in Eq. (3)) is applied in the flow field. The energy equation is
shared among phases; therefore, the phase mixture properties are determined by
effective parameters.

Eq. (6) is only solved in the membrane and catalyst layer, and the source term
applied in the catalyst layer couples water flux with Eq. (5). The mass flux of species,
current density, liquid water velocity, and total stress tensor are defined as Eqs. (9),
(10), (11), (12), (13), and (14): In these equations \( \Omega^{(m)}(V) \), is Ionic phase potential,
\( \Phi^{(s)}(v) \) is Solid phase potential, \( \sigma \) is total stress tensor and \( \mu \) (kg m\(^2\)s\(^{-1}\)) is dynamic slab.

\[ n_i^{(s)} = \rho^{(s)} u^{(s)} \omega_i^{(s)} - \rho^{(s)} D_{i,\text{eff}}^{(s)} \nabla \omega_i^{(s)} \quad (i = H_2, O_2, H_2O, N_2) \]  

\[ n_{H_2}^{(m)} = \frac{n_d M_{H_2} O_i^{(m)}}{F} - \frac{\rho^{(s)} M^{(m)} M_{H_2} O D_{H_2,\text{eff}}^{(s)}}{M^{(m)}} \nabla \lambda \]  

\[ i^{(m)} = -\sigma^{(m)}_{\text{eff}} \nabla \Phi^{(m)} \]  

\[ i^{(s)} = -\sigma^{(s)}_{\text{eff}} \nabla \Phi^{(s)} \]  

\[ u^{(l)} = \begin{cases} u^{(g)} S - D^{(c)} S \nabla S & (ff) \\ -D^{(c)} \nabla S & (gdl, cl) \end{cases} \]  

\[ \sigma = -F^{(g)} I + \mu^{(g)} \left[ \nabla u^{(g)} + \left( \nabla u^{(g)} \right)^T \right] - \frac{2}{3} \mu^{(g)} \left( \nabla u^{(g)} \right) I \]  

In this model, the equations are solved for all components such as hydrogen, oxygen, water, and nitrogen in the whole areas.

The flux of water in the membrane, Eq. (9), is calculated by the membrane water content, \( \lambda \), which is obtained by the electroosmotic drag and diffusion is expressed by a phenomenological model. Eqs. (10) and (11) represent the electrical density for electron and hydrogen ions, respectively. In Eq. (12), the liquid velocity in the gas flow field is considered as similar to the gas velocity in addition to the capillarity contribution caused porous field. At the gas diffusion layer and catalyst layer, it is assumed that the liquid flow is caused by capillary diffusion. In Eq. (13) the total stress tensor is obtained for compressible gases according to the pressure, viscous and volume dilation.

The source terms are given by Eqs. (15), (16), (17), (18), and (19): In these equations \( F \) (C mol\(^{-1}\)) is Faraday constant, \( R \) (J mol\(^{-1}\)K\(^{-1}\)) is gases global constant, \( J \) (A/m\(^2\)) is convertor current density, \( \sigma^{(s)} \) (sm\(^{-1}\)) is Electrical conductivity, \( \sigma^{(m)} \) (sm\(^{-1}\)) is Proton conduction, and \( M_i \) (kg mol\(^{-1}\)) is species molecular mass.

\[ S_{\text{mass}} = \begin{cases} -\frac{M_O J_c}{4F} + \frac{M_{H_2} O J_c}{2F} - \nabla n_{H_2,\text{O}}^{(m)} & \text{(cathode cl)} \\ -\frac{M_{H_2} O J_a}{2F} - \nabla n_{H_2,\text{O}}^{(m)} & \text{(anode cl)} \\ 0 & \text{(elsewhere)} \end{cases} \]
The source term for mass conservation, $S_{\text{mass}}$, includes both mass consumption and production according to the electrochemical reactions and the water transfer through the membrane, whereas the source term for species conservation, $S_i$, includes phase change of mass transfer from water and interphase water transfer in addition to species consumption and production. In the catalyst layer, $\lambda$ is obtained according to Eqs. (20) and (21) which is coupled with Eq. (6) by the source term, $S_\lambda$.

$$\lambda = \begin{cases} 0.043 + 17.81a - 39.85a^2 + 36.0a^3 & a \leq 1 \\ 1 + 1.4(a - 1) & 1 < a \leq 3 \end{cases}$$  

(20)

*a* is the amount of water acidity, calculated as:

$$a = \frac{p_{H_2O}^{(s)}}{p_{H_2O}} + 2s$$  

(21)
Two first terms in Eq. (19) are the reversible and irreversible entropic heat generated by the electrochemical reaction; the third and fourth terms represent ohmic heating, also the last term is the energy transfer caused by interphase mass transfer, where \( H_{vap} \) is the heat of water vaporization. In Eq. (19), \( j(A/m^3) \) represents the volumetric current densities and is obtained for anode and cathode as Eqs. (22) and (23): \( C_{i,ref} \) (mol m\(^{-3}\)) is molar capacity of the reference species and \( \alpha \) is transfer coefficient.

\[
j_{an} = j_{an}^{ref} \left( \frac{C_{H_2}}{C_{H_2}^{ref}} \right)^{\gamma_{an}} \left( \exp \left( \frac{\alpha_{an}F\eta_{an}}{RT} \right) - \exp \left( - \frac{\alpha_{an}F\eta_{an}}{RT} \right) \right) \tag{22}
\]

\[
j_{cat} = j_{cat}^{ref} \left( \frac{C_{O_2}}{C_{O_2}^{ref}} \right)^{\gamma_{cat}} \left( \exp \left( - \frac{\alpha_{cat}F\eta_{cat}}{RT} \right) - \exp \left( \frac{\alpha_{an}F\eta_{cat}}{RT} \right) \right) \tag{23}
\]

where \( \eta(V) \) is the extra potential expresses in anode and cathode as Eqs. (24) and (25):

\[
\eta_{an} = -\varnothing_e \tag{24}
\]

\[
\eta_{cat} = V_{cell} - \varnothing_e - V_{oc} \tag{25}
\]

where \( V_{oc}(V) \) is the open circuit voltage, obtained as Eq. (26):

\[
V_{oc} = 1.23 - 9 \times 10^{-4}(T - 298) \tag{26}
\]

### 2.1. Boundary conditions

The inlet velocities, temperature and mass fraction of chemical species are determined as the operating parameters of the fuel cell. Before solving the governing equations, the rate of flow channels’ inlet mass and mass fraction of chemical species are measured by the mean current density values, stoichiometry ratio, temperature, pressure, and other parameters.

The inlet mass flow rate of hydrogen in anode gas channel is obtained as Eq. (27):

\[
\dot{m}_{H_2} = \omega_{an} \frac{I_m M_{H_2} A}{n_{e,an} F} \tag{27}
\]

The inlet mass flow rate of oxygen in cathode gas channel is calculated as Eq. (28):

\[
\dot{m}_{O_2} = \omega_{cat} \frac{I_m M_{O_2} A}{n_{e,cat} F} \tag{28}
\]

where \( \omega_{an/cat} \) is the stoichiometry ratio at anode/cathode side; \( I_m \) is the mean current density; \( M_{H_2/O_2/air} \) is the molecular mass of hydrogen/oxygen/air; \( A \) is the catalyst active area; \( n_{e,an/cat} \) is the number of electrons at each reaction in anode/cathode
side; \( r_{O_2} \) is the oxygen weight ratio in the inlet air. The amount of humidity present in the mixture of gases at the inlet of the flow channels is calculated by the relative humidity. The relative humidity is the maximum water vapor that can be present in the gas in certain conditions and is calculated by the ratio of the partial pressure of the water vapor contained in the gas mixture to the saturation pressure of water vapor.

The humidity amount in the cathode channel inlet airflow is calculated as Eq. (29):

\[
\dot{m}^{\text{cat}}_{H_2O} = \frac{M_{H_2O}}{M_{O_2}} \frac{\Phi P_{\text{sat}}}{(P - \Phi P_{\text{sat}})} \dot{m}_{O_2}
\]

The humidity amount in the anode channel inlet hydrogen is calculated as Eq. (30):

\[
\dot{m}^{\text{an}}_{H_2O} = \frac{M_{H_2O}}{M_{H_2}} \frac{\Phi P_{\text{sat}}}{(P - \Phi P_{\text{sat}})} \dot{m}_{H_2}
\]

The inlet flow rate of anode and cathode gases is calculated as Eq. (31):

\[
\begin{align*}
\dot{m}^{\text{in}}_{\text{an}} &= \dot{m}^{\text{an}}_{H_2O} + \dot{m}_{H_2} \\
\dot{m}^{\text{in}}_{\text{cat}} &= \dot{m}^{\text{cat}}_{H_2O} + \dot{m}_{O_2}
\end{align*}
\]

The mass fraction of chemical species in inlet anode channel is calculated as Eq. (32):

\[
Y^{\text{an}}_{H_2O} = \frac{\dot{m}^{\text{an}}_{H_2O}}{\dot{m}^{\text{in}}_{\text{an}}}
\]

\[
Y^{\text{an}}_{H_2} = \frac{\dot{m}_{H_2}}{\dot{m}^{\text{in}}_{\text{an}}}
\]

The mass fraction of chemical species in inlet cathode channel is calculated as Eq. (33):

\[
Y^{\text{cat}}_{H_2O} = \frac{\dot{m}^{\text{cat}}_{H_2O}}{\dot{m}^{\text{in}}_{\text{cat}}}
\]

\[
Y^{\text{cat}}_{O_2} = \frac{\dot{m}_{O_2}}{\dot{m}^{\text{in}}_{\text{cat}}}
\]

The boundary condition of outlet channel flow

At the outlet of open-ended gas channels of PEM fuel cell, the flow is considered as fully developed. The outlet boundary condition is as Eq. (34) for the anode and cathode gas channel in the open end conditions and cooling fields.
\[ P = P_{\text{ref}}, \quad \frac{\partial V}{\partial n} = 0, \quad \frac{\partial T}{\partial n} = 0, \quad \frac{\partial Y_i}{\partial n} = 0, \quad \frac{\partial s}{\partial n} = 0 \]  

(34)

**Outlet boundary conditions**

All outer plates of PEM fuel cell, except for terminals, are defined as the outlet boundaries of the fuel cell. The terminals are the upper and lower plates of the fuel cell, where the electric current enters and exits. The zero flow field conditions are considered for the outlet boundaries as Eq. (35).

\[ \frac{\partial \phi_s}{\partial n} = 0, \quad \frac{\partial \phi_m}{\partial n} = 0 \]  

(35)

If a fixed voltage is considered for current calculation, the boundary condition for anode terminal is calculated as Eq. (36):

\[ \phi_s = 0, \quad \frac{\partial \phi_m}{\partial n} = 0 \]  

(36)

And the boundary condition for cathode terminal is calculated as Eq. (37):

\[ \phi_s = V_{\text{cell}}, \quad \frac{\partial \phi_m}{\partial n} = 0 \]  

(37)

### 2.2. Validation and mesh independency

**Fig. 1** illustrates the dimensional features of channel as well as the width and depth of the obstacle. In this figure, a, b, y, w represents the obstacle’s length, depth or height, width, and slope, respectively. Also, in **Fig. 2**, the problem geometry and its mesh structure designed in GAMBIT is shown. A mesh with a regular structure is used to solve. In order to perform a mesh independent solving for a known geometry at a known voltage, the current density variations are studied. The obtained results show that there is a negligible difference about 0.8% between 0.3 mm and 0.25 mm meshes spacing. Therefore, 0.3 mm meshes spacing with approximately 1400000 meshes is used for measurement. The number and size of the mesh are shown in **Fig. 3**. It must be noted that to obtain the best solution, it is necessary to apply an appropriate number of mesh into the gas diffusion layer, catalyst layer and membrane along Y.

Once the modeled mesh independency has been insured, it is validated by the experimental results of Jong Won Choi [24]. **Fig. 4** represents the performed validation. It is observed that the given model is compatible with the experimental results of Jong Won Choi and the computing model applied in this research has acceptable performance.

In this research, the simulation has been performed by FLUENT ANSYS 16.2. The given geometry has been simulated as 3D and by assuming slow flow,
incompressible and static manner. Also, the electrode has been considered as catalyst layer and homogenous membrane. The given fuel cell has 27.3 cm² active area, and its working temperature is 343K. The solution has been done as two phases with 1 bar pressure and 1.5 stoichiometry for anode (hydrogen) and cathode (oxygen) at

![Diagram](https://example.com/diagram1.png)

**Fig. 1.** (a) Channel dimensional features, (b) channel size, (c) obstacle depth and width.

![Diagram](https://example.com/diagram2.png)

**Fig. 2.** (a) Anode and cathode gas flow field with an obstacle, (b) regular mesh in GAMBIT software.
1.26 $\text{A cm}^{-2}$ flow density with 0.4 voltage and for a quite wet inlet gas. It is worth noting that the total contact resistance of 130 m$\Omega$.cm$^2$ has been considered at the contact surface between gas diffusion layer and current collector plate and also between gas diffusion layer and catalyst layer [25]. Other physical features of the PEM fuel cell are listed in Table 1.

3. Results & discussion

In this section, at first, the results obtained from simulation of the fuel cell with different obstacle height and width is given. Then, the results obtained from different obstacle arrangements are presented, and finally, the best geometry is introduced.
3.1. Results obtained from different obstacle heights

In this section, the effect of obstacle height on the fuel cell efficiency is studied. For example, Fig. 5 shows the geometry of gas flow field simulated with 1.5 mm obstacle height. The simulation has been done for a flow field with 2 mm channel depth without an obstacle and with obstacles with 0.5, 1, 1.5 and 2 mm. The results related to an obstacle with 2 mm height are given at the end of this section due to a difference at its range.

In Fig. 6, the average diagram of velocity regarding different obstacle heights has been shown for 0.8 and 0.4 V voltages at the middle of anode and cathode gas flow channel. Diagrams represent that the flow pressure drop increases as the height of obstacle increases and as a result the velocity would be reduced. These variations

| Description                                                                 | Units | Value   |
|-----------------------------------------------------------------------------|-------|---------|
| Anode and cathode gas diffusion layer thickness                             | mm    | 0.25    |
| Anode and cathode catalyst layer thickness                                  | mm    | 0.01    |
| Membrane thickness (Naphion 112)                                            | mm    | 0.05    |
| Anode and cathode gas channel thickness                                     | mm    | 2       |
| Current collector thickness                                                 | mm    | 2.2     |
| Anode and cathode gas diffusion layers’ effective porous                     |       | 0.17    |
| Anode and cathode catalyst layers’ effective porous                         |       | 0.17    |
| $\varepsilon_{mc}$ Ionomer volume fraction at anode and cathode catalyst layer |       | 0.2     |
| $K$ The permeability of the anode and cathode gas diffusion layer           | m²    | $1.1 \times 10^{-14}$ |
| $\bar{a}_{l,0}^{ref}$ Exchanged current density x anode side specific level | A/m³  | $1 \times 10^9$   |
| $\bar{a}_{c,0}^{ref}$ Exchanged current density x cathode side specific level| A/m³  | $2.5 \times 10^9$ |
| $C_{H_2,ref}$ Hydrogen reference molar density                             | mol/m³| 40.88   |
| $C_{O_2,ref}$ Oxygen reference molar density                                | mol/m³| 40.88   |
| $\alpha_a$, $\alpha_c$ Anode and Cathode transition coefficient for hydrogen oxidation reaction |       | 1       |
| $\alpha_a$ Cathode transition coefficient for oxygen reduction reaction      |       | 1       |
| $\rho_{dry,mem}$, dry membrane density                                      | kg/m³ | 1980    |
| EW membrane equivalent weight                                               | kg/mol | 1.1   |
| Faraday coefficient, $F$                                                    | C/mol | 96457   |
| Hydrogen mass diffusion                                                     | m²/s  | $1.1028 \times 10^{-4}$ |
| Oxygen mass diffusion                                                       | m²/s  | $3.2348 \times 10^{-5}$ |
| Water mass diffusion                                                        | m²/s  | $7.35 \times 10^{-5}$ |
are more observed at the lower voltage (Fig. 6b) due to higher velocity and species’ inlet flow rate. Velocity variations at higher voltage represent a fixed trend due to the species’ lower inlet flow rate.

In Fig. 7, the oxygen density contour is shown at the middle of the cathode gas flow channel for four states at 0.4 V voltage. As this figure shown, at the beginning of the route, oxygen has the maximum density and decreases along the gas flow channel due to participation in the chemical reaction and consumption. According to this figure, we try to get more oxygen in the reaction by considering an obstacle and have a more efficient result for the fuel cell. To better understand, the variations in oxygen concentration is shown in Fig. 8 along the cathode gas flow channel at 0.4 V voltage. As shown in figure (b), the height of 1.5 has less oxygen concentration over other heights which shows higher oxygen reaction rate and the inverse state is observed in figure (a) for hydrogen.

Another important factor in designing a fuel cell is to study the pressure. The pressure distribution at the middle of the cathode gas flow channel is shown in Fig. 9 for

![Fig. 5.](image)

(a) 3d geometric design of gas flow field with an obstacle, (b) geometry of an obstacle with 1.5 mm height.

![Fig. 6.](image)

(a) Mean velocity at 0.8V voltage; (b) mean velocity at 0.4V voltage at the middle of the anode and cathode gas flow channel.
Fig. 7. Oxygen concentration dispersion at the middle of cathode gas flow channel for (a) zero obstacle height; (b) 0.5 obstacle height; (c) 1 obstacle height; and (d) 1.5 obstacle height at 0.4 V.

Fig. 8. Variations in oxygen concentration at 0.4 V voltage along cathode gas flow channel.
Fig. 9. Pressure distribution at the middle of cathode gas flow channel for (a) zero obstacle height; (b) 0.5 obstacle height; (c) 1 obstacle height and (d) 1.5 obstacle height at 0.4 V.

Fig. 10. (a) Pressure variations along anode gas flow channel, (b) pressure variations along cathode gas flow channel at 0.4 V voltage.
0.4 V voltage. In Fig. 5, the maximum pressure for models (a), (b), (c) is 41, 44 and 52 Pa, respectively. In model (d), the contour guide is given due to different pressure where its maximum pressure is 190 Pa. As this figure shown, the pressure drop reduces along this path. Furthermore, by considering an obstacle, the pressure drop increases in the channels where the pressure variation at the gas flow field of Fig. 10 represents this fact.

In Fig. 11, the diagram of temperature variations is shown along the anode and the cathode gas flow channel for different obstacle heights for 0.4 V voltage. As the figure shown, the maximum temperature and variations is observed for height = 1.5 mm. The High temperature suitable but in a way that it does not cause membranes to dry and burn. According to the figure, for the heights of zero and 0.5 mm, the temperature variations are stable and uniform, however, for 1 mm and 1.5 mm heights, the temperature of fluid decreases when it hits the obstacle, and later it increases, and this behavior continues until the end of the path. For the height of 1.5, the temperature has the higher value at the inlet part, while in other heights, the temperature increases towards outlet, which is due to increasing of friction coefficient and pressure in this height.

Since the results and the range of variations for 2 mm height is different from other given models in previous sections, the results of an obstacle with 2 mm height are presented in this section, separately. In fact, in this section the height of the obstacle is equal to the depth of gas flow channel and making this obstacle leads to the blockage of the gas channel. Fig. 12 represents the velocity distribution, reactant concentration and pressure at the middle of the anode gas channel for 0.4V voltage. As it can be seen, there is not any significant velocity distribution due to channel blockage and a less value that can be seen is due to the forced passage of flow from the porous part of gas diffusion layer. The species distribution is in a way

![Fig. 11. (a) Temperature variations along anode gas flow channel, (b) temperature variations along the cathode gas flow channel at 0.4 V.](image-url)
that the maximum concentration is seen at the middle of gas flow field and the maximum pressure drop is seen in this model the previous model due to the blockage of the gas flow channel.

**Fig. 13** represents the polarity diagram for different heights. As it can be seen, by increasing the height up to 1.5 mm, an improvement has been shown in this diagram. At 2 mm height, according to this fact that an entire blockage is caused at the channel path, a significant reduction is observed at the performance. Therefore, according to the lower pressure drop and higher consumption rate of species, 1.5 mm height is considered as an optimal height to follow.
3.2. Results obtained from different obstacle widths

According to this fact that in the previous section, 1.5 mm height has been selected as an appropriate height, here we study the effect of obstacle width on the efficiency of the fuel cell. For example, in Fig. 14, a simulated geometry of an obstacle with 1.5 mm height and 3.6 mm width is shown.

The simulation is done for gas flow field with 2 mm depth and 0.9, 0.8, 2.7 and 3.6 mm widths. Fig. 15 shows the oxygen concentration distribution at the middle of cathode flow channel at 0.4 V voltage. It is observed that the oxygen distribution at the beginning of the path has the highest value and goes through a decreasing trend along flow channel due to participation in the chemical reaction and consumption.

The diagram of hydrogen and oxygen concentration variations is shown in Fig. 16 along anode and cathode gas flow channel at 0.4V voltage. As figure shown, for

![Fig. 13. Polarity diagram for heights = 0, 0.5, 1, 1.5 and 2 mm.](http://creativecommons.org/licenses/by-nc-nd/4.0/)

![Fig. 14. (a) Geometry of the gas flow channel with an obstacle with 1.5 mm height and 3.6 mm width, (b) geometry of an obstacle with 1.5 mm height and 3.6 mm width.](https://doi.org/10.1016/j.heliyon.2018.e00974)
Fig. 15. Oxygen concentration dispersion at the middle of cathode gas flow channel for (a) 0.9 mm obstacle width; (b) 1.8 mm obstacle width; (c) 2.7 mm obstacle width; (d) 3.6 mm obstacle width at 0.4 V voltage.

Fig. 16. (a) Hydrogen concentration variations, (b) oxygen concentration variations at 0.4V along anode and cathode gas glow channel.
an obstacle with 3.6 mm width, the hydrogen and oxygen concentration is less than other widths which represent a higher rate of species reaction in this width. Therefore, by increasing the width of an obstacle, a higher delay is seen in hydrogen and oxygen consumption trend in the fuel cell which is desirable for better efficiency of the fuel cell.

Also, the pressure distribution is studied at the middle of anode and cathode gas flow channel for 0.4V voltage. In this case, the pressure drop is seen along gas flow channel where for models (a), (b), (c), (d) the maximum pressure is 110, 137, 128 and 172 Pa. To better understand the fluid behavior, the diagram of pressure variations is shown in Fig. 17 along anode and cathode gas flow channel for 0.4V voltage which confirms the accuracy of the results given in the previous section.

The diagram of temperature variations is shown in Fig. 18 along the anode and the cathode gas flow channel for different widths. The maximum temperature and variations are seen for an obstacle with 3.6 mm width. As the figure shown, the fluid

![Fig. 17. (a) Pressure variations along the anode gas flow channel, (b) pressure variations along the cathode gas flow channel at 0.4V.](https://doi.org/10.1016/j.heliyon.2018.e00974)

![Fig. 18. (a) Temperature variations along the anode gas flow channel, (b) temperature variations along the cathode gas flow channel at a 0.4V voltage.](https://doi.org/10.1016/j.heliyon.2018.e00974)
temperature decreases as hitting the obstacle and then increases and this behavior continuous until the end of the path. It must be noted that a high temperature does not lead to the burning or dryness of the membrane which is an important fact in designing a fuel cell.

The current density distribution at the shared surface of the catalyst layer and anode gas diffusion layer at 0.4V and 0.8V represents that the current density increases over other models as the obstacle’s width increases to 3.6 mm. This is due to the high rate and velocity of the reactors at 0.4V. At high voltages, there is not a significant difference among the current densities at different widths which is due to lack of generating high water and ignoring the water removal and management at these voltages. The mean current density at the best state for 0.4 V, and 0.8 V, namely model (d), with 3.6 mm width is $25502 \ \frac{\text{A}}{\text{m}^2}$ and $506 \ \frac{\text{A}}{\text{m}^2}$, respectively. Also, the current density distribution at the shared surface of the catalyst layer and cathode gas diffusion layer at the best state for 0.4 V and 0.8 V, model (d), with 3.6 mm width is $19232 \ \frac{\text{A}}{\text{m}^2}$ and $436 \ \frac{\text{A}}{\text{m}^2}$. According to the obtained results, 3.6 mm width has the best current density in terms of models’ pressure drop and would be the best choice where the polarity diagram in Fig. 19 represents this fact for different widths.

3.3. Results obtained from different obstacle arrangements

According to this fact that the proper height and width of 1.5 mm and 3.6 mm have been obtained from the previous sections, here we study different obstacle

![Fig. 19. Polarity diagram for obstacles with 0.9, 1.8, 2.7 and 3.6 mm.](https://doi.org/10.1016/j.heliyon.2018.e00974)
arrangements in terms of the following figures. **Fig. 20** represents the four arrangements studied in this section. As it can be seen, in arrangements 1 and 3, three and two obstacles with a regular arrangement have been made along the width of fuel cell two-path flow channel and in arrangements 2 and 4, two and three obstacles have been made along the width flow channel where their arrangement is zigzag. The oxygen concentration dispersion is given in **Fig. 21** for four arrangements at 0.4 V where its quantitative diagram in **Fig. 22** represents that the concentration of species decreases along gas flow channel which suggests the consumption of species. The obtained results show that the arrangement 4 has lower concentration over other arrangements which suggests higher rate of reaction in both oxygen and hydrogen.

In **Fig. 23**, the diagram of mean pressure value for different arrangements at 0.8 and 0.4 V is shown at the middle of the anode and cathode gas flow channel for different obstacle arrangements. As shown, by making more obstacles at the channel path, arrangements 1 and 4 represent higher pressure increase due to higher drops at the flow movement path caused by friction coefficient increase or opposing force where this increase at 0.8 V has lower value because of lower flow rate. In fact, the higher pressure represents high power consumption for to pump fluid into channels which requires more cost. As a result, pressure drop should be considered to select and design optimally. According to the obtained results, arrangements 2 and 3 could be selected as economical arrangements in terms of pressure drop, however other factors such as current density must also be considered.

**Fig. 20.** Four different simulated arrangements with square obstacles with 1.5 mm height and 3.6 mm width.
Fig. 21. Oxygen concentration dispersion at the middle of the cathode gas flow channel for (a) arrangement 1, (b) arrangement 2, (c) arrangement 3 and (d) arrangement 4 at 0.4V.

Fig. 22. (a) Hydrogen concentration variations, (b) oxygen concentration variations at 0.4V along anode and the cathode gas flow channel.
Fig. 23. (a) Mean pressure value at 0.8 V, (b) mean pressure value at 0.4 V, at the middle of anode and cathode gas flow channel.

Fig. 24 represents the diagram of pressure variations along anode and cathode gas flow channels for 0.4 V. The obtained results show that arrangements 2 and 3 has lower pressure drop over other arrangements, since there are more obstacles in arrangements 1 and 4 among the path and arrangement 3 has the lowest pressure drop over other arrangements.

The temperature distribution at the middle of the membrane is shown in Figs. 25 and 26 for 0.4 and 0.8 V. As figure shown, the temperature distribution under the effect of gas flow channel has the lowest temperature at the inlet and it has the highest temperature at the outlet. In Fig. 18, the membrane surface is approximately at 343 K uniform temperature due to performance at high voltage and low rate of reactants.

Fig. 27 shows the diagram of temperature variations along the anode and the cathode gas flow channel for 0.4 V. It can be seen that a higher temperature is produced due to higher consumption rate of species at low voltage and increases toward outlet. In fact, the peak and valley created in diagrams results from passing through obstacles.

Fig. 24. (a) Pressure variations along the anode gas flow channel, (b) pressure variations along cathode gas flow channel at 0.4 V.
Wherever an obstacle is created, because of the compulsion to cross a narrower section and the greater diffusion of species in the gas diffusion layer, and as a result of the reaction of most species, there is a higher heat which is called peak and the path from a channel without obstacle has low temperature according to the above mentioned descriptions, which is called valley.

The current density distribution at the shared surface of the catalyst layer and anode gas diffusion layer is also studied. Voltage decrease leads to increasing of the produced current density over higher voltage that is due to high rate and velocity of reactants at 0.4 V. The obtained results show that the mean current density at the best state with 0.4V and 0.8V voltage for arrangement 3 is $25575 \frac{A}{m^2}$ and $514 \frac{A}{m^2}$. Also, the results for current density distribution at the shared surface of the catalyst layer and cathode gas diffusion layer represent that the mean current density at the best state with 0.4V and 0.8V voltage for arrangement 3 is $25611 \frac{A}{m^2}$ and $514 \frac{A}{m^2}$. Fig. 28 represents the mean current density at 0.8 and 0.4V for different obstacle arrangements. Fig. 29 shows the polarity diagram for different obstacle arrangements. It can be seen that the current density values are very close to each other, where by closer examination,
arrangements 3 and 4 have the highest produced current density. In this way, according to the observed pressure drop at the computing area and species consumption rate, finally the arrangement 3 with lower pressure drop and high consumption rate of species is the most suitable choice for design.

Fig. 26. Temperature distribution at the middle of the membrane for (a) arrangement 1, (b) arrangement 2, (c) arrangement 3 and (d) arrangement 4 at 0.4V.

Fig. 27. Temperature variation diagram, (a) along anode gas flow channel, (b) along cathode gas flow channel at 0.4 V.
4. Conclusion

In this research, the effect of obstacles along the gas flow field on the efficiency of the fuel cell is studied. At first, a state without obstacle and a state with obstacles having 0.5, 1, 1.5 and 2 mm heights have been studied. The obtained results show that although the obstacle height of 1.5 mm generated higher pressure drop over other obstacles with 0.5, 1 and 1.5 mm heights. According to the studied cases, 1.5 mm
height is the best height for the obstacle. After selecting the suitable height of 1.5 mm, the appropriate width of the obstacle has been studied. In 3.6 mm width, it has been observed that the concentration of hydrogen and oxygen in the flow field in terms of the fuel cell performance is less than other widths. Furthermore, the generated current density is better in this width at both high and low voltages, although it has higher pressure drop. As a result, 3.6 mm obstacle width has been selected as the best width. In the following, different obstacle arrangements have been studied by finding the appropriate height and width of the obstacle. Four arrangements including two regular and two zigzag arrangements have also been studied. Two regular and zigzag arrangements are different only in the number of obstacles along a path. In the third arrangement (arrangement c in Fig. 20), the concentration of hydrogen and oxygen species has significant decrease along the channel and as a result, the species consumption rate is higher than other arrangements. Also, the generated current density of the third arrangement is higher and has the lowest pressure drop over others. According to the mentioned cases, the third arrangement has been selected as the best obstacle arrangement. In forthcoming paper we focused on the shape of obstacles and the optimal shape of it will be presented.

Declarations

Author contribution statement

Aliakbar A. Ebrahimzadeh, Iman Khazaee: Conceived and designed the analysis; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Ahmad Fasihfar: Conceived and designed the analysis; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
References

[1] Word Energy Consumption, 2011. Available from, http://en.wikipedia.org/wiki/World_energy_consumption.

[2] F. Barbir, PEM Fuel Cells: Theory and Practice, Academic Press, 2013.

[3] Youcef Kerkoub, Ahmed Benzaoui, Fadila Haddad, Yasmina K. Ziari, Channel to rib width ratio influence with various flow field designs on performance of PEM fuel cell, Energy Convers. Manag. 174 (2018) 260–275.

[4] Andrea Baricci, Riccardo Mereu, Mirko Messaggi, Matteo Zago, Fabio Inzoli, Andrea Casalegno, Application of computational fluid dynamics to the analysis of geometrical features in PEM fuel cells flow fields with the aid of impedance spectroscopy, Appl. Energy 205 (2017) 670–682.

[5] Mohammad Ziauiddin Chowdhury, Yahya Erkan Akansu, Novel convergent-divergent serpentine flow fields effect on PEM fuel cell performance, Int. J. Hydrogen Energy 42 (2017) 25686–25694.

[6] A. Psoma, G. Sattler, Fuel cell systems for submarines: from the first idea to serial production, J. Power Sources 106 (1–2) (2002) 381–383.

[7] Ferng Yuh-Ming, SuAyandLu Shao-Ming, Experiment and simulation investigations for effects of flow channel patterns on the PEMFC performance, Int. J. Energy Res. 32 (2008) 12–23.

[8] J. Scholta, G. Escher, W. Zhang, L. Küppers, L. Jö rissen, W. Lehnert, Investigation on the influence of channel geometries on PEMFC performance, J. Power Sources 155 (2006) 66–71.

[9] Wei-Mon Yan, Hung-Yi Li, Po-Chiao Chiu, Xiao-Dong Wang, Effects of serpentine flow field without let channel contraction on cell performance of proton exchange membrane fuel cells, J. Power Sources (2008) 174–180.

[10] Lin Lin, XinXin Zhang, Hu Ting Feng, Xiao-Dong Wang, Optimization of a serpentine flow field with variable channel heights and widths for PEM fuel cells, Sci. China Technol. Sci. 53 (2010) 453–460.

[11] Kap-Seung Choi, Hyung-Man Kim, Sung-Mo Moon, Numerical studies on the geometrical characterization of serpentine flow-field for efficient PEMFC, Int. J. Hydrogen Energy 36 (2011) 1613–1627.

[12] M. Rahimi-Esbo, A.A. Ranjbar, A. Ramiar, E. Alizadeh, Improving PEMFC performance using a novel flow field, Int. J. Hydrogen Energy 37 (2016) 2490–2497.
[13] Hong Liu, Peiwen Li, Daniel Juarez-Robles, Kai Wang, Abel Hernandez-Guerrero, Experimental study and comparison of various designs of gas flow fields to PEM fuel cells and cell stack performance, Front. Energy Res. 2 (2014) 1–8.

[14] I. Khazaee, H. Sabadbafan, Effect of humidity content and direction of the flow of reactant gases on water management in the 4-serpentine and 1-serpentine flow channel in a PEM (proton exchange membrane) fuel cell, Energy 101 (2016) 252–265.

[15] H. Kahraman, Mehmet F. Orhan, Flow field bipolar plates in a proton exchange membrane fuel cell: analysis & modeling, Energy Convers. Manag. 133 (2017) 363–384.

[16] S.W. Perng, H.W. Wu, Effects of internal flow modification on the cell performance enhancement of a PEM fuel cell, J. Power Sources 175 (2008) 806–816.

[17] S.H. Han, N.H. Choi, Y.D. Choi, Simulation and experimental analysis on the performance of PEM fuel cell by the wave-like surface design at the cathode channel, Int. J. Hydrogen Energy 37 (2012) 1613–1627.

[18] M. Bilgili, M. Bosomoiu, G. Tsotridis, Gas flow field with obstacles for PEM fuel cells at different operating conditions, Int. J. Hydrogen Energy 40 (2015) 2303–2311.

[19] H. Heidary, M.J. Kermani, Performance enhancement of fuel cells using bipolar plate duct indentations, effect of nano-particles on forced convection in sinusoidal-wall channel, Int. J. Hydrogen Energy 38 (2013) 5485–5496.

[20] A. Ghanbarian, M.J. Kermani, Enhancement of PEM fuel cell performance by flow channel indentation, Energy Convers. Manag. 110 (2016) 356–366.

[21] H.R. Ashorynejad, K. Javaherdeh, Investigation of a waveform cathode channel on the performance of aPEM fuel cell by means of a pore-scale multi-component lattice Boltzmann method, J. Taiwan Inst. Chem. Eng. 000 (2016) 1–11.

[22] H. Heidary, M.J. Kermani, B. Dabir, Influences of bipolar plate channel blockages on PEM fuel cell performances, Energy Convers. Manag. 124 (2016) 51–60.

[23] H. Heidary, M.J. Kermani, S.G. Advani, Ajay K. Prasad, Experimental investigation of in-line and staggered blockages in parallel flow field channels of PEM fuel cells, Int. J. Hydrogen Energy 41 (2016) 688–693.
[24] W.Ch. Jong, H. Yong-Sheen, W.C. Suk, S.K. Min, Experimental study on enhancing the fuel efficiency of an anodic dead-end mode polymer electrolyte membrane fuel cell by oscillating the hydrogen, Int. J. Hydrogen Energy 35 (2010) 12469—12479.

[25] M. Ghasemi, A. Ramiar, A.A. Ranjbar, S.M. Rahgoshay, A numerical study on thermal analysis and cooling flow field’s effect on PEMFC performance, Int. J. Hydrogen Energy (2018) 1—19.