Influences of Bipolar Plate Channel Blockages on PEM Fuel Cell Performances

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Abstract: In this paper, the effect of partial- or full-block placement along the flow channels of PEM fuel cells is numerically studied. Blockage in the channel of flow-field diverts the flow into the gas diffusion layer (GDL) and enhances the mass transport from the channel core part to the catalyst layer, which in turn improves the cell performance. By partial blockage, only a part of the channel flow is shut off. While in full blockage, in which the flow channel cross sections are fully blocked, the only avenue left for the continuation of the gas is to travel over the blocks via the porous zone (GDL). In this study, a 3D numerical model consisting of a 9-layer PEM fuel cell is performed. A wide spectrum of numerical studies is performed to study the influences of the number of blocks, blocks height, and anode/cathode-side flow channel blockage. The results show that the case of full blockage enhances the net electrical power more than that of the partial blockage, in spite of higher pressure drop. Performed studies show that full blockage of the cathode-side flow channels with five blocks along the 5 cm channel enhances the net power by 30%. The present work provides helpful guidelines to bipolar plate manufacturers.

Keywords: Computational Fluid Dynamics; PEM fuel cells; Flow-field channels; Blockage; Pressure drop.

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1. Introduction

With the limitations of fossil fuel resources and crises in environmental pollution, recent attention to alternative power sources for various applications has been very serious. Proton Exchange Membrane Fuel cells (PEMFCs) with high efficiency and high environmental compatibility have attracted considerable interest within academic and industrial area as a potential power source for transportation and other mobile applications [1-2].

Bipolar plates (BPP) employ various patterns of grooves or flow-field channels to feed reactant gases to the electrode of PEM fuel cells. Several numerical and experimental investigations have attempted to visualize and quantify the characteristics of different flow-field designs [3-8]. For example, Spornjak et al. [8] compared water content and dynamics by simultaneous neutron and optical imaging for three PEM fuel cell flow-fields: parallel, serpentine, and interdigitated. They concluded that the serpentine flow-field showed stable output across the current range and the highest limiting current in comparison to parallel and interdigitated flow-fields which exhibited substantially higher water contents. However, the serpentine flow-field also experienced the highest pressure drop. Li and Sabir [9] presented a review of the flow-field layouts developed by different companies and research groups and their associated pros and cons. Manso et al. [10] also reviewed recent works related to the influence of geometric parameters of flow channels on overall PEMFC performance. Based on this work, homogeneous gas distribution in the gas flow channel can provide a uniform current density throughout the active area and, hence, a uniform temperature distribution, causing less mechanical stresses in MEA and increasing the PEMFC lifetime.

In this paper, a method to improve fuel cell performance is introduced by inserting blockages into the BPP flow-field channels. This method draws its inspiration from heat transfer enhancement techniques employing blockages. Blockages can be considered as passive control devices to enhance forced convection heat transfer. According to Guo et al. [11] and He and Tao [12], blocks make synergy between convection and conduction terms in heat transfer, and increase the heat transfer between the wall and the core flow. This is explained as follows. Consider the energy equation and its advection term, $\vec{V} \cdot \nabla T \equiv (u \partial T / \partial x + v \partial T / \partial y)$,

Heat-Transfer:
$$\underbrace{u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}}_{= \vec{V} \cdot \nabla T} = \alpha \nabla^2 T \quad (1)$$

where $\vec{V} = (u \hat{i} + v \hat{j})$ is the local velocity vector, ∇T is the temperature gradient and α is thermal diffusivity respectively. In the case of no blocks (Fig. 1a), ∇T is almost in transverse direction, and $\vec{V}$ is along the channel. Hence the intersection angle between $\vec{V}$ and ∇T is almost 90° and $\vec{V} \cdot \nabla T$ is at its minimal value (≈ 0). Placement of blocks within the channel (Fig. 1b), induces a velocity component in transverse direction. Hence, the intersection angle between $\vec{V}$ and ∇T will reduce and $\vec{V} \cdot \nabla T$ can, therefore, begin to move away from almost zero value. As a result, convection between the wall and the core flow should also start to increase by the channel blockage.

Several papers have investigated the effect of blockages on the improvement of forced convection heat transfer [13-15]. For example, Heidary and Kermani [14] computed the hydrodynamics and heat transfer enhancement in a channel containing one or more rectangular blocks that partially filled the channel cross-section, and

reported a 60% improvement in convective heat transfer. Similarly, Huang et al. [15] computed the heat transfer enhancement due to the installation of multiple heated blocks in channels filled with porous media and showed that flow modification via the blocks can significantly enhance convective heat transfer.

From the analogy between heat and mass transfer phenomena in dynamically similar problems, in a mass transfer problem, it is expected that channel blockage enhances the mass exchange between the channel core part and, say a catalyst layer at the top boundary of Fig.1c. Considering the mass concentration equation as:

Mass-Transfer:
$$\underbrace{u \frac{\partial C_A}{\partial x} + v \frac{\partial C_A}{\partial y}}_{=\vec{V} \cdot \nabla C_A} = D_{A,eff} \nabla^2 C_A \quad (2)$$

Here ∇C_A is the concentration gradient and $D_{A,eff}$ is effective binary diffusivity of the reacting species. It is noted that by the blockage of the channels, the intersection angle between $\vec{V}$ and ∇C_A will reduce from 90° and $\vec{V} \cdot \nabla C_A$ similar to $\vec{V} \cdot \nabla T$ will start to move from almost zero value. Indeed, such a placement of blocks in PEMFC flow channels can facilitate over-block convection, thereby driving reactant gas convectively into the gas diffusion layer and delivering reactant species directly to the catalyst sites. Over-block convection also aids the removal of reaction products from the gas diffusion layer into the channel which can further improve performance [16].

The literature contains only a few studies that have investigated the effect of blockages in PEM fuel cell flow-field channels. Heidary and Kermani [17-18] numerically investigated the effect on heat transfer of partial blockages and the corrugated wall in the flow-field channels of a fuel cell and showed that the heat exchange between the

channel walls and the core flow strongly depends on the number of blocks along the bottom wall and shape of corrugation. Kuo et al. [19] performed numerical simulations to investigate the performance characteristics of PEMFCs with wave-like gas channels. Perng and wu [20] also numerically investigated the installation of transverse trapezoidal baffles in the flow channel of PEMFCs and found that the fuel cell performance was enhanced. Wu and Kuo [21] developed a three-dimensional model to analyze PEMFC performance using multiple transversely-inserted rectangular cylinders along the channel axis, and found higher performance with a reasonable pressure drop. Tiss et al. [22] have presented a numerical model investigating the mass transport in a PEM fuel cell with partial blocks inserted in the gas channel. Bilgili et al. [23] have studied the performance of PEM fuel cells containing baffles in PEMFC flow channels and shown that such baffles enhance gas concentration along the channels and higher cell voltages are obtained at high current densities.

Belchor et al. [24] compared experimentally the PEMFC performance of parallel-serpentine-baffle and parallel-serpentine flow channels. They showed that under low humidity conditions, the parallel-serpentine-baffle configuration exhibited better performance due to improved water retention in the flow-field channels. Han et al. [25] studied the effect of wall waviness of the flow channel on PEMFC performance and concluded that concentration loss induced by unstable mass transfer was delayed, and the fuel cell's performance was improved by 5.76% in their experiment, and by 5.17% in their computational study. Ku and Wu [26] investigated a novel design consisting of rectangular parallelepiped within an interdigitated flow-field by simulation and experiment, and reported that the presence of baffles increased the rate of

electrochemical reaction and net power by up to 26%. Ghanbarian and Kermani [27] have studied the effect of the partial blockage of flow channels in a parallel flow field and shown that blockage provides performance enhancements over 25% at some specific cases. Heidary et al. [28] have investigated experimentally the effect of two types of full blockage configurations within a parallel flow-field and resulted that the staggered configuration enhances cell performance by up to 28% over the baseline case, and by 18% when compared to the in-line case.

In published papers, blocks were installed in anode and cathode side flow channels simultaneously. Therefore individual effect of blockages in each side has not been discussed. In this paper, we have investigated the blockage effect in anode/cathode side individually. Alongside the investigation of blockage on cell performance, the effect of two types of blockage is also investigated in this study: partial and full blockage. In partial blockage, a part of the flow channel is shut off, while in full blockage, flow channel is blocked completely and the only avenue left for the gas is to undergo over-block convection through the porous zone (GDL) as it transits from the inlet to the outlet. To the best of our knowledge no paper in literature studied the effect of partial and full blockage and also compared the presence of blocks in flow channels of anode and cathode-side of PEMFCs. We want to understand if full blockage with a greater pressure drop gives better cell performance. Also, the effect of blocks number installed along the flow channel is studied. To meet the goal of the present study, the following parametric studies are performed in present studies include:

- The effect of blockage along the cathode-side flow channel;
- The effect of blockage along the anode-side flow channel;

- The effect of blocks height (either partial or full blockage of the channel height);
- The effect of blocks number installed along the flow channel;

The noted set of computations was performed using a 3D numerical simulation of a 9-layer PEM fuel cell and optimized blocks installation along its flow channel. The computations performed here can provide helpful guidelines to the manufacturers of PEM fuel cell bipolar plates.

2. Governing equations

Figure 2 illustrates schematic of a flow-field configurations investigated in this study. Figure 2a shows schematic of three-dimensional computational units used in the present study. The computational domain includes nine layers in total as: the current collectors, gas flow channels, gas diffusion layers (GDLs), catalyst layers (CLs) in the cathode and anode side, and a membrane layer in the core. Structured types of grids (in the form of hexahedral elements) are used for each of the mentioned nine layers. Flow directions of anode and cathode sides are as counter-flow. Figure 2b shows the channel symmetric plane in the computational domain, as shown by ABCD in Fig. 2a. Figures 2c to 2e show sample of the computed geometries studied in this paper; Fig. 2c includes anode/cathode-side blockage of PEMFC; Fig. 2d shows different geometries to investigate different blocks height and Fig. 2d includes different blocks number (N) on cathode-side of PEMFC. It is noted that the present computations deal with a single channel, as a representation of a set of parallel channels. The active area in the present

study is $w \times L$, where w is the repeating unit of the cells and L is the length of the channel. The active area is scalable via the addition of repeating units.

In this section the PEMFCs' governing equations are described. The assumptions that are made on the model are listed as follows:

- The PEMFC operates under steady-state and isothermal conditions;
- Based on Reynolds number calculation, laminar flow in the gas flow channels is considered in this model;
- Isotropic and homogeneous porous zone is assumed;
- Multi-component diffusion is considered in this model [29];
- Water exists in the entire fuel cell only in vapor phase.

Transport equations-The governing equations used in this work included the mass conservation equation, the Navier-Stoke's equations, and species transport equations which are expressed as:

$$\nabla \cdot (\rho \vec{V}) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi \quad (3)$$

where ϕ is the transported quantity (mass, momentum, and species mass fraction), ρ is the mixture density, $\vec{V}$ is the velocity vector, Γ is the transported quantity diffusivity, and S_ϕ is the source term. The variables used as the transport quantity in mass, momentum, and species equations are 1, velocity in each direction, and mass fraction of each specie, respectively.

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179 **Electrochemical modeling**-The most significant electrochemical aspects in PEMFCs
 180 are the reactions of oxygen reduction in the cathode side and hydrogen oxidation in the
 181 anode side. The driving forces for these reactions are the surface over-potentials which
 182 are the differences between the solid phase potential (ϕ_s) and the membrane phase
 183 potential (ϕ_m). Therefore, two potential fields are needed to be solved for the entire fuel
 184 cell; one equation for electron transport through the solid materials, current collector and
 185 the porous GDL, and another equation for proton H^+ transport:

$$\nabla \cdot (\sigma_s \nabla \phi_s) = -R_s, \quad \nabla \cdot (\sigma_m \nabla \phi_m) = -R_m \quad (4)$$

186 In Eq. (4), R_s and R_m are the volumetric sink/source terms for the transport of
 187 electrical currents, σ is the electrical conductivity [$S \cdot m^{-1}$], and s and m represent the
 188 solid and membrane phases, respectively. The source terms R_s and R_m in Eq. (4) are
 189 non-zero only inside the catalyst layers and are defined as:

- 190 • For the solid phase, $R_s = -R_a$ on the anode side and $R_s = +R_c$ on the cathode
 191 side,
- 192 • For the membrane phase, $R_m = +R_a$ on the anode side and $R_m = -R_c$ on the
 193 cathode side, where R_a and R_c are determined from the Butler-Volmer equations:

$$R_a = \zeta_a i_a^{ref} \left(\frac{[H_2]}{[H_2]_{ref}} \right)^{\gamma_a} \left(e^{\alpha_a F \eta_a / RT} - e^{-\alpha_c F \eta_a / RT} \right) \quad (5)$$

$$R_c = \zeta_c i_c^{ref} \left(\frac{[O_2]}{[O_2]_{ref}} \right)^{\gamma_c} \left(-e^{\alpha_a F \eta_c / RT} + e^{-\alpha_c F \eta_c / RT} \right)$$

194 here $[H_2]$ and $[O_2]$ are the hydrogen concentration in the anode catalyst layer and
 195 oxygen concentration in the cathode catalyst layer, respectively. $[H_2]_{ref}$ and $[O_2]_{ref}$ are
 196 the reference hydrogen concentration and reference oxygen concentration. Also i_a^{ref}
 197 and i_c^{ref} are the anode and cathode volumetric reference exchange current densities [A
 198 m^{-2}], respectively, α_a and α_c are the anode and cathode transfer coefficients,
 199 respectively, γ_a and γ_c are the anode and cathode concentration dependence
 200 exponents, respectively, and η_a and η_c are the anode and cathode over-potentials,
 201 respectively. These over-potentials are the local potential difference between the solid
 202 and membrane phases in the three phase boundaries within the catalyst layer, which
 203 are the driving forces for the reactions in catalyst layers. The over-potentials η_a and η_c
 204 are defined as:

$$\begin{aligned} \eta_a &= (\phi_s - \phi_m), \\ \eta_c &= (\phi_s - \phi_m - V_{oc}) \end{aligned} \tag{6}$$

205 where ϕ_s is the local electric potential, ϕ_m is the local protonic potential, V_{oc} is the open
 206 circuit voltage.

207 The ionic conductivity of the membrane phase in Eq. (4) is computed by [30]:

$$\sigma_m = (0.00514\lambda - 0.00326)e^{1268 \left(\frac{1}{303} - \frac{1}{T} \right)} \tag{7}$$

208 The water content, λ , that appears in the preceding property computations are obtained
 209 using Springer et al. correlation [30],

$$\lambda = \begin{cases} 0.043 + 17.18a - 39.85a^2 + 36a^3 & a < 1 \\ 14 + 1.4(a - 1) & a > 1 \end{cases} \quad (8)$$

210 here a is the water activity that is defined as,

$$a = \frac{P_{wv}}{P_{sat}} \quad (9)$$

211 where P_{wv} is the partial pressure: $P_{wv} = x_{H_2O} P$ and x_{H_2O} is the vapor molar fraction and
 212 P is pressure. In Eq. (9), P_{sat} is the saturation pressure expressed in terms of the
 213 temperature:

$$\log_{10} P_{sat} = -2.1794 + 0.02953(T - 273.17) - 0.000091837 (T - 273.17)^2 + 0.00000014454 (T - 273.17)^3 \quad (10)$$

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216 **3. Boundary conditions and numerical procedures**

217 Fuel cell dimension of the model is listed in table 1. After the geometries were
 218 generated, they required to be discretized into fine cells. Very fine discretizing causes
 219 accurate results, but requires a long computational time. Therefore, a grid independent
 220 test can obtain the best grid number. In this study, the grid independent analysis of each
 221 layer of the model was performed. After the grid independency test, it was found that
 222 the best number of cells lined in the deep, in current collectors, flow channels, GDL, CL,

and membrane used in this model were 8, 8, 5, 5 and 5 respectively, resulting in the total of 228,000 hexahedral cells. Finally, the generated grids were imported into ANSYS® FLUENT® software package to compute by using the add-on module.

In this study, cell operating pressure was taken 1 atm on channel exit and cell operating temperature were considered 80°C. Because the real application usually uses air as the oxidant due to its convenience that no space is required for oxidant storage, air was used as cathode-side fluid in this study. Anode/cathode flow rates were 10^{-4} and 10^{-3} gram per second respectively with 10%/90% relative humidity in H₂/Air inlets, respectively. Fuel cell materials, operating conditions and boundary conditions are listed in table 2. A control volume method has been used to solve the governing equations and perform parametric studies in the present paper. The solution procedure used to solve in all cases was based on SIMPLE (Semi-Implicit Method for Pressure Linked Equation) algorithm. The calculation was in the double precision for achieving accurate results and algebraic multigrid (AMG) method was also used to improve the convergence rate. Finally, to prevent the oscillation of the solution by adding an artificial diffusion term, a second-order upwind discretization scheme was selected as a numerical scheme.

4. Results and Discussion

Figure 3 depicts a comparison between the simulation from the present computation and the previous published results [31]. As shown in this figure, there is a good agreement for polarization curves. The influences of the blocks height, blocks

number, and also Anode/Cathode blockage are studied in this paper. The results of the computations are shown in Figs. 4 to 9.

Figures 4a to 4d show the polarization curve and power density curve for the cases studied here: anode full blockage and cathode blockage with different blocks height, 0, 50%, 90% and 100%. In each case, four blocks ($N = 4$) were considered. As shown in Fig. 4a, placement of blocks along the anode-side flow channel does not enhance the cell performance. Because fuel cell losses are typically lower on the anode side of PEM fuel cells and therefore we do not need blockage to make-up losses. On the other hand, hydrogen diffusivity is substantially more than that of oxygen; reference diffusivity of O_2 and H_2 are $3.2 \times 10^{-5} \text{ m}^2/\text{s}$ and $11.0 \times 10^{-5} \text{ m}^2/\text{s}$, respectively. So hydrogen as anode-side reactant can diffuse easily into GDL and CL without any need to blockage. Therefore, no blockages of the anode-side channels are considered for all cases in the present study.

As depicted in Fig. 4b, the addition of blockages along the cathode-side flow channels improves cell performance especially at higher current densities; it is evident that the blockages help to mitigate mass transport limitations at high currents resulting from reactant species depletion and water flooding.

Figures 4c and 4d show the effect of blocks height along the cathode side flow channel. As depicted in these figures, cathode-side full blockage (100% blockage) enhances cell performance much better than partial blockage (50 and 90% blockage). Because with partial blocks, reacting species can escape from the gap above the blocks in the flow channel without diffusing into GDL and catalyst layer; whereas with full

blockage, species are pushed into GDL and catalyst layer, so the cell performance enhances further. Also, full blockages increase pressure drop through the flow-field more than partial blockages. Therefore, operating pressures throughout the cell will be increased further. An increase in cell operating pressure results in higher cell potential due to the Nernst equation and an increase in exchange current density. Exchange current density is proportional to surface concentration which in turn is directly proportional to pressure [32].

As seen in Fig. 4d, partial blockage improves cell performance at higher current densities and maximum power does not change considerably; while with full blockage, maximum power improves significantly alongside the enhancement of limiting current density (i_L).

Figure 5 shows the variation of oxygen molar concentration along the GDL/CL boundary with 4 blocks along the cathode-side flow channel (line EF in Fig. 2b). As shown in this figure, with permeating through the GDL and reacting in the catalyst layer, oxygen is consumed and therefore oxygen molar concentration decreases along the channel. As depicted in these figures, due to increased velocity over blocks, O_2 molar concentration also experiences four picks compared to smooth configuration and with blocks height, peak value increases due to more effective over-rib convection. But in case of full blockage, because blocks close the flow channel completely, more species push into GDL/catalyst layer, therefore pick values in case of full blockage is much more than that of partial blocks. With velocity contours of different cases, the reason will be explained obviously as follows.

Sample of the computed results showing the velocity field in the middle section area of computational domain (section ABCD of Fig. 2a) are illustrated in Fig. 6. As explained before, in the case of without block, flow transport is smooth as seen in Fig. 6a. While in blocked cases, species velocity increases above the blocks and with blocks height, velocity over blocks increases considerably; in the case of 50% blockage, maximum velocity is nearly 5m/s, whereas in the case of 90% blockage, maximum velocity is more than 15m/s. Because priority for fluid pathway is flow channel instead of the porous zone (GDL) and in the case of higher blocks height, the space of the flow channel over blocks would be tighter. So, in two cases of partial blockage, species velocity in GDL/CL boundary increases a little over the blocks (see cathode-side in Fig. 6b and c). But in the case of full blockage, its trend is completely different. With the blockage of the flow channel, reactant species are forced into the porous zone (GDL), therefore species velocity increases in GDL/CL boundary significantly over the blocks (see Fig. 6d).

Figures 7a and b show the effect of blocks number N (0 to 5) in the cathode-side flow channels for the case of full blockage of channels cross sections. Generally speaking, as blocks number (N) increases along the channel, the cell performance, and in turn the limiting current density (i_L) improves. Table 3 reports a sensitivity analysis of the effect of N on i_L . This table shows the improvements in i_L in terms of local and cumulative values. For the cases studied here (channel length $L = 5$ cm), it is observed that for $N \leq 5$, sensible improvements in i_L are achievable. For a given L , further additions of blocks (i.e. reducing of the spacing between two consecutive blocks) do not introduce significant improvements. This is explained as follows. Increasing N , instead

of introducing excessive disturbances to the core flow, generates a recirculating region between two neighboring blocks with the flow between the blocks being trapped in these regions. Hence, the main core flow does not feel each block individually as a disturbance generator; instead it assumes a single and longer block that is stretched along the channel (for more details, see Heidary and Kermani [17]). As shown in Fig. 6 and noted in Table 3, the present study shows that the optimized block number ranges from 3 to 5. Beyond which, i_L does not improve and is not recommended. In addition, they impose excessive and unnecessary pumping power to the system.

Figure 8a shows the effect of the blocks number N (0 to 5) on the variation of O_2 molar concentration along the GDL/CL interface for different cell voltages; 0.2, 0.4 and 0.6V. As shown in this figure, with species reacting along the channel and consumption of species, O_2 molar concentration decreases along the channel. Also, as cell voltage increases, less species is consumed and therefore O_2 molar concentration is more in higher cell voltages.

As depicted in Fig. 8, O_2 molar concentration follows a smooth trend in the case of smooth channel, while in blocked cases, profiles experience some picks due to increased over-rib convection. It can be also seen that with more blocks number, peak values of molar concentration increases.

Figure 8b shows the effect of blocks number on variation of local current density along the GDL/CL boundary for $V_{cell} = 0.4V$. As shown in this figure, with species reacting along the channel and consumption of species, current density decreases along the channel. Local current density profiles follow the similar trend with O_2 molar

concentration profiles. For example, profiles follow a smooth trend in the case of smooth channel, while in blocked cases, profiles experience some picks due to increased over-rib convection and increased O_2 concentration in regions right above the blocks. At the end of channel length especially far from blocked regions, current density drops considerably with more blocks number due to the reduced O_2 concentration.

Figure 9 shows the effect of blocks number on net power in different cell voltages, 0.1, 0.4, and 0.7. The presence of blocks increases the pressure drop along the flow channel. Therefore, while blockage are beneficial in terms of improving performance, there is a penalty in terms of the higher pumping power required to drive the reactant gas flow through the flowfield. So the pressure drop and required pumping power at $V_{\text{cell}}=0.4V$ are also indicated alongside. The pumping power is obtained by multiplying the pressure drop by the air flowrate, and the net power is obtained by subtracting the pumping power from the gross power. Figure 9 indicates that the cell power at $V_{\text{cell}}=0.7$ and $0.1V$ is low compared to $V_{\text{cell}}=0.4V$. The cell voltage of $0.4V$ shows maximum power density for all cases. Although the pumping power is quite small in comparison to the electrical power produced by the cell, but in $V_{\text{cell}}=0.7$ and $0.1V$, power enhancement due to the blockage is not as much as required excessive power, therefore blockage does not improve cell performance in these cell voltages. But in maximum cell power ($V_{\text{cell}}=0.4V$), its trend is completely different. With blocks, cell power increases significantly. For example, with 1-5 blocks, net power improves 5%, 12%, 19%, 24% and 30% respectively.

It should be noted that employment of the blocks within the channels adds extra obstacles in front of the existing (or produced) liquid water and therefore, liquid water

experiences harder time to be purged out, and causes flooding. That in turn decreases the permeability of oxygen into the porous zone (GDL and CL). But this point can have a positive effect at high air flow rate values or lower relative humidity cases, where the membrane dehydrates. At these cases, some of the liquid water already existing upstream of the blocks can help to keep the membrane hydrated for better protonic conductivity.

5. Conclusions

In this paper, partial/full blockage along the parallel flow-field channels of a PEM fuel cell are numerically investigated to optimize cell performance and pressure drop. For this purpose, the effect of the blocks number and blocks height along the anode and cathode-side flow channels is studied. The main findings are as follows:

1. It is observed that the presence of blockages drives reactant gases into the GDL and enhances oxygen molar concentration over the catalyst layer, which increases cell performance, especially in the mass-transport limited region of polarization curve. The performed parametric studies show that indented cathode-side flow channel with five blocks and 100% blockage each enhances the net power up to 30%.
2. Because fuel cell losses are typically lower on the anode side, and hydrogen diffusivity is substantially more than that of oxygen, hence, anode blockage does not provide any benefit. In addition, they unwantedly require excessive pumping power. As a result blockages of the anode channels are avoided.

3. Placement of partial blocks improves cell performance, especially in concentration loss region of the polarization curve. But it has less effect on cell performance compared to fully blockage. Because in case of partial blockage, there is a space over the blocks which species can pass through the flow channel without diffusing into the porous zone. But in case of full blockage, the only avenue left for the gas is to undergo over-block convection through the porous zone (GDL/CL) as it transits from the inlet to the outlet which causes the performance of the full blockage to improve when compared to the partial blockage.
4. Partial blockage imposes lower pressure drop along the flow channel compared to fully blockage; therefore it requires less pumping power. But in the sum, the net power gained due to full blockage is more than that in partial blockage cases.
5. Generally speaking, as the blocks number (N) along the channel increases, the cell performance, and in turn the limiting current density (i_L) improves. Table 3 reports a sensitivity analysis of the effect of N on i_L . This table shows the improvements in i_L in terms of local and cumulative values. For the channel length $L = 5$ cm studied in this paper, it is observed that for $N \leq 5$, sensible improvements in i_L has been achievable. Further additions of blocks do not introduce disturbances to the core flow, hence, cannot improve the cell performance.
6. Channel blockage adds extra obstacles in front of the existing liquid water, and can cause flooding and decrease the permeability of oxygen into porous zones (GDL and CL). But at high flowrate and low relative humidity cases, channel blocking can help to retain liquid water within the channels, which enhances the membrane hydration and improves membrane protonic conductivity.

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(b) Enhanced convective heat transfer in a straight channel with block

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Fig. 1. Schematic figures showing synergy between convection and diffusion mechanisms of heat and mass transfer; (a) heat transfer in a straight channel with no block, (b) heat transfer in a straight channel with block, (c) mass transfer in a straight channel with block.

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(a) 3D schematic figure of computational domain

(b) schematic figure of ABCD plane

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Fig. 2. Schematic figures of the PEMFC domain studied in the present computation.

Fig. 3. Validation Test: comparisons of the polarization curve obtained from the present study and literature [31].

(a) The effect of anode flow channel blockage on polarization and power density curves in the present numerical study;

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Fig. 5. Sample of the computed results at $V_{\text{cell}} = 0.4\text{V}$ showing blockage effects (block height) on oxygen molar concentration in cathode GDL/CL interface (Line EF in Fig. 2b).

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Fig. 6. Effect of different types of blockage (blocks height) on velocity contours in middle plane of PEMFC (plane ABCD) at $V_{\text{cell}} = 0.4V$.

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Fig. 7. The effect of blocks number on; (a) polarization curve, (b) power density curve. 100% blockage is considered here.

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(a) Distribution of oxygen concentration in cathode-side catalyst layer boundary;

(b) Distribution of current density in cathode-side catalyst layer boundary;

Fig. 8. Effect of blocks number on (a) distribution of oxygen concentration in cathode-side catalyst layer boundary for $V_{\text{cell}} = 0.2, 0.4$ and 0.6 V , (b) distribution of current density in cathode-side catalyst layer boundary and $V_{\text{cell}} = 0.4 \text{ V}$.

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Table 1. Geometrical parameters of PEM fuel cell studied here.

Property	Value	Unit
Cell length	50	mm
Channel height	0.8	mm
Channel width	0.8	mm
Rib width	0.8	mm
Channel to land ratio	1	-
BP thickness	1.6	mm
GDL thickness	0.19	mm
CL thickness	0.015	mm
Membrane thickness	0.05	mm
Block length	1.0	mm
Block width	0.8	mm

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Table 2. Operating conditions, material and physical properties of PEM fuel cell studied here

Property	Value	Unit
Boundary condition		
Anode inlet temperature, T_{in}	80	$^{\circ}\text{C}$
Cathode inlet temperature, T_{in}	80	$^{\circ}\text{C}$
Anode inlet relative humidity, RH	10	%
Cathode inlet relative humidity, RH	90	%
Anode mass flow rate	10^{-7}	kg s^{-1}
Cathode mass flow rate	10^{-6}	kg s^{-1}
Operating temperature, T	80	$^{\circ}\text{C}$
Operating Pressure, P	1	atm
Gas Diffusion Layer		
Porosity, ε	0.55	-
Permeability, K	1.0×10^{-12}	m^2
Catalyst Layer		
Porosity, ε	0.475	-
Permeability, K	1.0×10^{-12}	m^2
Surface to volume ratio, ζ	2×10^5	$\text{m}^2\text{-Pt m}^{-3}$
Membrane		
Thermal conductivity	0.16	$\text{W m}^{-1} \text{K}^{-1}$
Equivalent weight of dry membrane	1100	kg kmol^{-1}
Reaction parameters		
Anode concentration exponent, γ_a	0.5	-
Cathode concentration exponent, γ_c	1	-
Open circuit voltage, V_{oc}	0.95	V
Anode Reference concentration, $[H_2]_{ref}$	1	kmol m^{-3}
Cathode Reference concentration, $[O_2]_{ref}$	1	kmol m^{-3}
Anode charge transfer coefficient, α_a	2	-
Anode reference current density, i_a^{ref}	0.75×10^4	$\text{A m}^{-2}\text{-Pt}$
Cathode charge transfer coefficient, α_c	2	-
Cathode reference current density, i_c^{ref}	20	$\text{A m}^{-2}\text{-Pt}$

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Table 3. Sensitivity analysis of effect of blocks number on limiting current density.

Blocks number N	¹ Local improvement in the Limiting current density	² Cumulative improvements in the Limiting current density
0	-	-
1	7.1	7.1
2	5.4	12.9
3	3.8	17.1
4	2.1	19.6
5	0.8	20.6

1 Local improvement in the Limiting current density $\frac{(i_{L_N} - i_{L_{N-1}})}{i_{L_{N-1}}} \%$,

2 Cumulative improvements in the Limiting current density $\frac{(i_{L_N} - i_{L_{Smooth-Channel}})}{i_{L_{Smooth-Channel}}} \%$.

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