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Short communication

Study of the distribution of air flow in a proton exchange membrane fuel cell stack☆

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ABSTRACT

The flow of air to feed oxygen to the cathode of each plate in a proton exchange membrane fuel cell (PEMFC) is studied for a 300 W stack in a realistic 3D configuration. Two configurations for gas income are solved, a "U" shape, where both the inlet and outlet of the air collectors are at the same end plate, and a "Z" shape, where inlet and outlet are at opposite sides of the stack. Under a simplified assumption for the flow of oxygen entering the gas diffusion layer of each cell, detailed mass flow and pressure distributions are shown, including the possibility of a turbulent flow inside the main collectors.

1. Introduction

A correct distribution of the reactant flow through each one of the cells that make up a proton exchange membrane fuel cell (PEMFC) stack is essential to a correct performance of the fuel cell. In particular, a similar distribution of mass flow circulating through each individual cell is desirable, which also helps to guarantee a most important issue: an approximately equal pressure distribution for all plates [1]. It should be reminded that the velocity of the gas reactants entering the gas diffusion layer (GDL) is essentially dependent on the pressure gradient along it, which on its turn depends on the geometry and flow conditions. As all the plates in the stack have the same geometry, then it is the flow conditions which, under an ideal situation (no water flooding, etc.), finally determine the pressure gradient, and eventually, the flow of reactants reaching the catalyst layers.

Some previous works [2,3] have addressed this problem by considering a standard pipe network approach, using for example friction coefficients to calculate both the pressure losses along the main collectors and local losses associated to bends. The main criticism for this otherwise fast approximation is that the "exits" from the collectors to the individual plates are multiple and very close. That disturbs the flow in the main collectors, so for example, in a laminar case in a cylindrical collector, the velocity does not present the typical paraboloidal Poiseuille shape. Something alike happens in the case of a turbulent flow inside the collectors. The consequence is that the real friction coefficient does not match the theoretical one. In fact, the real coefficient depends strongly on the geometry and flow conditions, making this approach dubious.

Another more recent approach [4] considers a 2D approximation where the channels are not represented geometrically, but taken as tubes filled out with porous media.

In this paper, the Navier–Stokes (NS) equations are solved in the main collectors (with a turbulence model) and channels of the plates, with a detailed 3D description and without any extra model for the flow or geometry. The flow through the porous media (GDL) is also solved using the Brinkman–Darcy approximation, as the formulation by Ochoa-Tapia and Whitaker [5].

2. Mathematical formulation

As explained in Section 1, to specify flow and pressure distributions along the stack, including the plates, NS equations are solved, with the needed modifications for the flow in the porous media. In the case of a laminar flow, NS equations are fully solved and no extra model is used. In the case of a turbulent flow, the Standard k–epsilon model is used. Steady-state conditions are considered in both laminar and turbulent configurations.

In the channels of the bipolar plates and the collectors, the 3D steady version of the incompressible Navier–Stokes equations is used, ν being the kinematic viscosity, ρ the density and u_i the $i = 1, 2, 3$ component of the velocity field:

Continuity:

$$\frac{\partial u_j}{\partial x_j} = 0. \tag{1}$$

Momentum:

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j\, \partial x_j}. \tag{2}$$

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For the GDL, it is convenient to distinguish between two types of volume averages of the physical magnitudes of interest inside the porous media [5]:

Superficial average:

$$\langle\cdot\rangle = \frac{1}{V}\int_V \cdot\, \mathrm{d}V. \tag{3}$$

Intrinsic average:

$$\langle\cdot\rangle^\beta = \frac{1}{V_\beta}\int_{V_\beta} \cdot\, \mathrm{d}V_\beta, \tag{4}$$

where β indicates the zone available for the fluid inside the porous media (the "void" part in opposition to the solid part), and V indicates a small enough volume used to calculate the average. In agreement with the notation used, V_β indicates the void part inside the volume V, its fraction being the porosity ε by definition. Hence superficial and intrinsic averages are related through $\langle\cdot\rangle = \varepsilon\langle\cdot\rangle^\beta$.

It can be shown [5] that under appropriate conditions, the superficial averaged velocity is the matching quantity to the flow velocity and that the intrinsic averaged pressure is the matching quantity to the flow pressure inside the porous media. However to simplify the notation, $\mathbf{u}$ and p will be directly written for equations inside the porous media. For a steady state approximation, the conservation equations are

Continuity inside GDL:

$$\frac{\partial u_j}{\partial x_j} = 0. \tag{5}$$

Momentum inside GDL:

$$\frac{1}{\varepsilon^2} u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\nu}{\varepsilon}\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\nu}{K} u_i, \tag{6}$$

where ε is the porosity and K is the permeability, assuming an isotropic and homogeneous porous medium. The second term on the right hand side of Eq. (6) is known as the Brinkman approximation, and the third one reflects the contribution of Darcy's law. One can observe that Eq. (2) are recovered in the case of porosity in the channels equal to unity and infinite permeability. Using simplifying assumptions [5], Eqs. (5) and (6) can be used throughout the whole domain without the need of any"internal" boundary conditions.

In this paper the configuration considered consists of a stack with the collectors and the cathodic side of 24 bipolar plates. In order to solve the equations, appropriate boundary conditions are to be prescribed at the inlet and outlet of the collectors as well as at the outlet of each cathodic GDL. Actually, the flow at the latter boundaries is affected by the other components of the fuel cell. However, in an ideal case, the stoichiometric flow can be considered as a good approximation and this can be imposed by specifying a constant (and equal in magnitude for all plates) pressure boundary condition at a certain distance from the end of each GDL. Furthermore, in the case studied, only oxygen is considered as a reacting gas, meaning that following the usual practice of injecting two times the stoichiometric flow and the fact that oxygen is only a fifth of volume air, the flow at the outlet collector – the one which has not reacted – would be one order of magnitude bigger than the sum of the outlet flows at the GDL exits—the ones consumed by reaction. Therefore this approximate pressure condition at the GDL exits should not greatly affect the flow through the collectors and the cathodic channels. Obviously, the simulation assumes a stable operation of the fuel cell stack.

Notice that this approximation differs from the ones using a pipe-network approach, as the flow is allowed to enter the GDL, which is much more realistic.

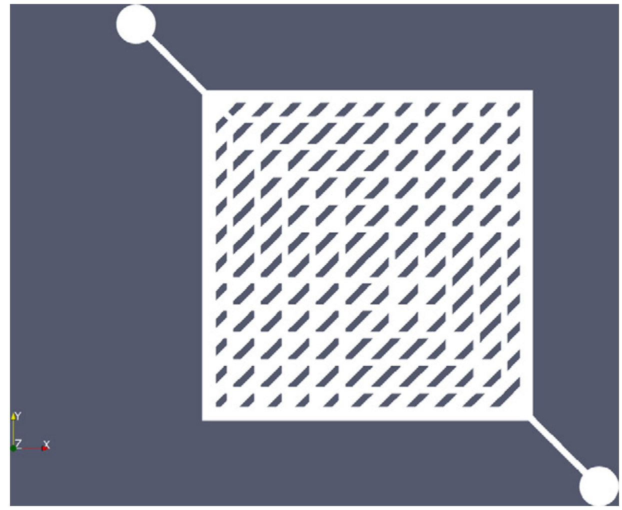

Fig. 1. Transversal cut through the mid-plane of a bipolar plate of the fuel cell stack depicting the cascade design of the channels. This is common to all the bipolar plates that were used for simulations.

2.1. Computational parameters

2.1.1. Numerics

Eqs. (5) and (6) have been discretized with a finite volume method on a 4 M cell hexahedral mesh. The numerical calculations have been carried out using OpenFOAM software (version 1.4.1), with the SIMPLE scheme. For solving the linear systems of equations, a bi-conjugate gradient scheme for velocities and an algebraic multi-grid one for pressure have been used. The code is ran in a parallel environment through domain decomposition. The convergence time on a Beowulf with 8 Opteron (64 bits processor) and 96 GB RAM lasted no longer than a few hours.

2.1.2. Design and physical conditions

As mentioned above, the parts of the PEMFC simulated are the collectors and the cathodic side of 24 bipolar plates. Each bipolar plate is designed to obtain a cascade-type flow pattern, as shown in the cut throug its mid-plane (see Fig. 1), with an active area of 5 cm × 5 cm, that is 2500 mm^2. The collectors are cylindrical in shape with an inner diameter of 6 mm and the external I/O stack connectors, also included in the domain, have an inner diameter of 4 mm. The connectors in betweeen the collectors and each bipolar plate (input and exit ducts for each plate) have a cross section of 1 mm^{2}and the channel height in the bipolar plates is of 1 mm. The GDL thickness is 0.3 mm. The gas is air at 80 C, which has a density $\rho = 0.996\,\mathrm{kg\,m^{-3}}$ and a kinematic viscosity $\nu = 2.05\times 10^{-5}\,\mathrm{m^2\,s^{-1}}$. The porosity of the GDL is taken to be $\epsilon = 0.75$ with a permeability $K = 8.69\times 10^{-12}\,\mathrm{m^2}$. The flow outlet velocity is fixed at 0.9× flow inlet velocity, following the reasonings given above.

The size and number of bipolar plates has been chosen such that the cell will produce 12 V considering a current density of 1 A cm^{-2}, each plate giving 0.5 V.

The cases that have been studied are synthesized in Table 1. The total power of the stack is 300 W (Cases II and III). For Case I, a flow

Table 1
Numerically simulated cases. Case I corresponds to a laminar flow in the collectors while Cases II and III to turbulent flows.

Case	Configuration	Inlet velocity (m s^{-1})	*Re*
I	U	3.4067	664.7
II	U	34.067	6647
III	Z	34.067	6647

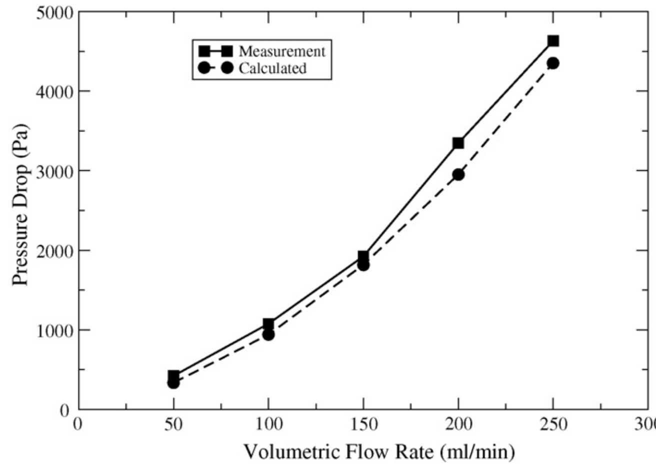

Fig. 2. Comparisons between numerical and experimental data of pressure drop between the entry and exit of a bipolar plate for different flows.

10-fold smaller was considered, so that laminar conditions in the collectors are attained and studied.

3. Results and discussion

3.1. *Pressure drop at the bipolar plates*

First of all, and in order to test the numerical code, a set of comparisons with simple experimental data has been carried out for the flow circulating through the channels of a plate, for the "cascade" configuration studied in this paper. To measure the pressure drop in the plate, two branches of a differential inclined-tube manometer are connected to the inlet and outlet ducts. For both experimental measurements and numerical simulations no flow through the GDL is considered. As Fig. 2 depicts, there is an excellent agreement between the pressure drop measured and simulated, even for the low values of drop detected in the cascade configuration, which proves the good behaviour of this geometrical pattern (and of the numerical schemes).

It could be at first surprising the low pressure drop through the bipolar plates compared with the one taking place at the entry (and exit) ducts to the collectors (see the following figures). Naturally, the reason lies on the verly low value of the velocity of the air circulating through the channels.

3.2. *U and Z configuration stack*

The laminar situation would be the ideal one due to the lower pressure drops. Fig. 3 depicts a transversal cut through the stack in U configuration in the laminar case (I). One can observe that the pressure profile does not remain uniform along the collector transversal sections, meaning that the velocity profile does not preserve its paraboloidal shape. As a consequence, the friction coefficient for a laminar flow in a circular section duct cannot be applied.

As previously mentioned it is desirable that the flow in the collectors be laminar. However, our condition for the flow to be injected in the stack geometry imposes relatively high Reynolds (*Re*) numbers. Thus, as mentioned above, some kind of turbulence modeling is needed for Cases II and III and we chose, in the RANS framework, the Standard *k*–epsilon model, as it has been mentioned above.

Note that at low *Re*, this model recovers the NS equations, as required, because as it can be seen, the flow in the connecting ducts between the bipolar plates and the collectors, as well as the flow through the bipolar plates themselves is laminar. This can be observed in Fig. 4, where it can be seen that the flow, although turbulent in the main part of the collectors, transforms rapidly into laminar in the connecting ducts and the bipolar plates where it has a typical paraboloidial shape. As it is expected in a porous media, there is a sudden pressure drop across the GDL. It can be seen in Fig. 5 the rapid decay in the mass flow in the inflow collector due to the multiple outlets towards the bipolar plates. The typical paraboloidal shape for the velocity field in laminar flows is however recovered inside the small entry (and exit) ducts to each plate.

The pressure drop takes place mostly at the entry (and exit) ducts to the bipolar plates. This is due both to the 90° bend and to the relatively high velocity and very small cross section of those ducts (see Figs. 4, 6 and 7). The flow in the bipolar plates is almost uniform and with a very small pressure drop, just what it is to be desired for

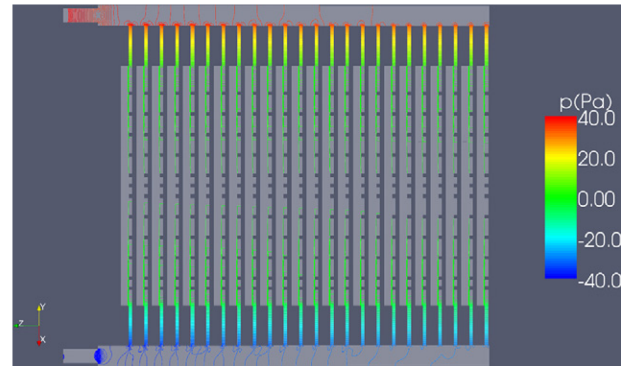

Fig. 3. Transversal cut for the U configuration of the stack in the laminar case (I). It is observed that the pressure contour pattern in the collectors is not consistent with a laminar flow in a duct.

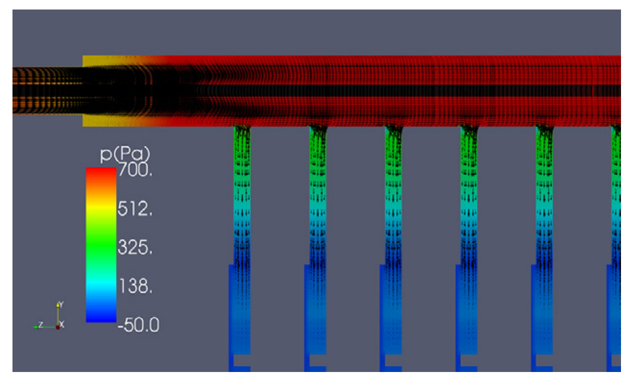

Fig. 4. Detail of the flow at inlet collector-bipolar plate for the Z configuration in the turbulent case. Pressure map and velocity vectors.

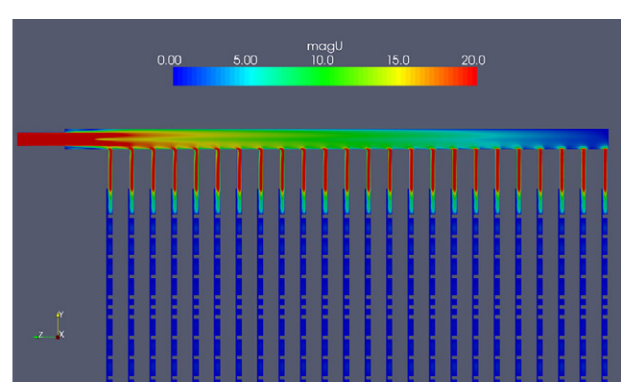

Fig. 5. Flow at inlet collector-bipolar plate for the Z configuration in the turbulent case. Velocity details.

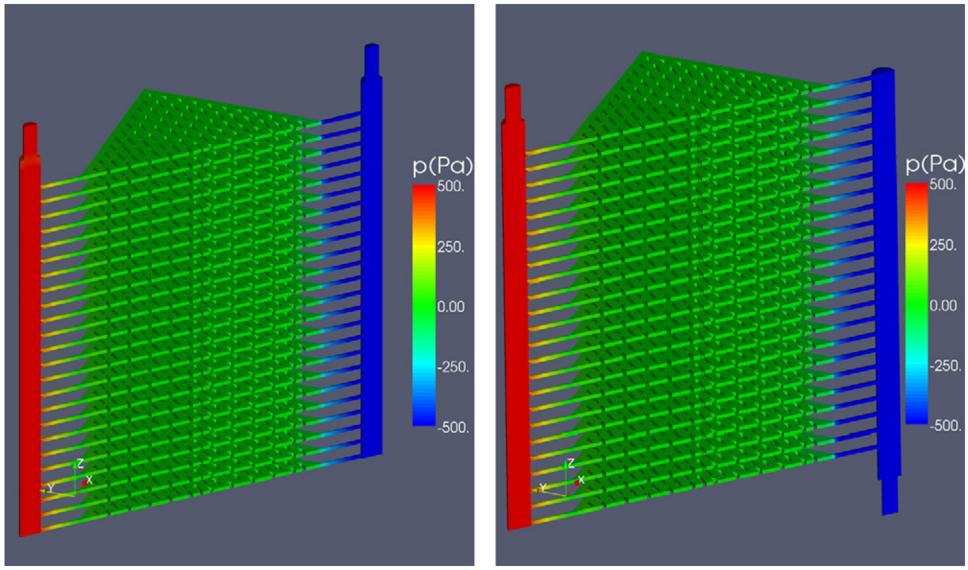

Fig. 6. Transversal cut of the stack for turbulent flow both for the U configuration Case II (a), and Z configuration Case III (b).

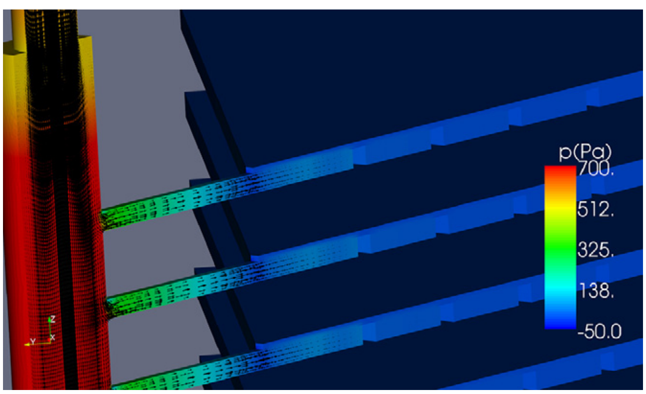

Fig. 7. 3D detail of collector-connector-bipolar plate-GDL for the Z configuration and turbulent case (III).

a correct operation of the stack. This is typical to the cascade design [1] and this can be also seen in Fig. 6 where both configurations are presented.

In Fig. 7 a 3D detail of the flow for the stack in Case III is presented. One can observe the typical pressure drop in the GDL. This effect is relatively small due to the small values of the component of the velocity orthogonal to the interface between the channels and the porous media.

In Fig. 8 the mass flow rate through each one of the bipolar plates is presented for both U and Z configuration in the turbulent case (II and III). In principle the Z configurations provides a more uniform mass flow distribution. However, as it can be noticed in the figure, the effect is not as important as to prevent the use of the U configuration when required.

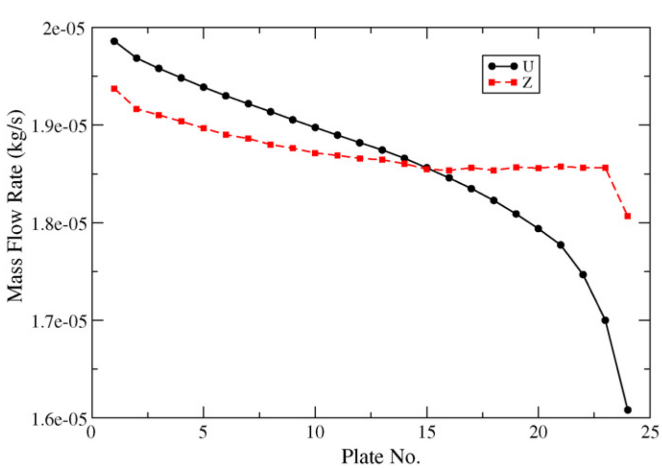

Fig. 8. Mass flow distribution along the bipolar plates inlets for both U and Z configurations.

4. Conclusions

In the present paper it has been demonstrated the possibility and interest of numerical simulations of the full air flow inside a 300 W PEM fuel cell under simplified working conditions. The flow of air has been studied for the whole stack, including the GDL, considering full 3D geometry and full NS equations, with no flow modelling assumptions, other than a Standard k–espsilon closure for the turbulence which exists in the main collectors. The flow in the GDL has been also included in the simulations, using a Brinkman–Darcy approximation for porous media.

It has been shown that the limitations of pipe-network approximations make them inappropriate for the use to calculate gas flows in PEMFC stacks. The main reason is the large number of exits to (and from) the plates, which forces the flow in the collectors not to follow the typical pattern inside a cylindrical duct.

On the contrary, the full NS approximation proves to be adequate while not expensive computationally, allowing a detailed in-space description of the flow and pressure fields. For example it can be seen that most of the pressure drops take place at the small ducts entering and exiting each plate, not in the GDL, the channels of the plates or the main collectors.

Two basic configurations with turbulent flow in the collectors have been studied (U and Z). To complete the study, a full laminar configuration in U has been also studied. In all cases the flow pattern is adequate, although the Z configuration is preferable.

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