Design and Development of Proton Exchange Membrane Fuel Cell using Open Pore Cellular Foam as Flow Plate Material

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Abstract

This paper reports the design and development of a Proton Exchange Membrane (PEM) fuel cell using open pore cellular metal foam as the flow plate material. Effective housing designs are proposed for both hydrogen and oxygen sides and through the application of Computational Fluid Dynamic (CFD) modelling and analysis techniques the flow regime through the open pore cellular metal foam flow plate are identified.

Based on the CFD results the best anode housing design was selected and manufactured. The fuel cell was assembled and tested and the findings are reported.

Keyword: Proton Exchange Membrane (PEM), Fuel Cell, Open Pore Cellular Foam (OPCF), Flow Plate.

1. Introduction

Fuel cells are devices that produce electricity through a chemical reaction between a fuel and an oxidant. Their high efficiency and low environmental impact have made them a promising alternative to conventional power sources. Fuel cells already have applications in, but are candidates to revolutionise, the transport, stationary power, and electronic industries. Different types of fuel cells have been developed over the last few decades such as Alkaline fuel cell (AFC), Direct Methanol fuel cell (DMFC), Phosphoric Acid fuel cell (PAFC), Molten Carbonate fuel cell (MCFC), Solid Oxide fuel cell (SOFC) [1,2], and Proton Exchange Membrane (PEM) fuel cell. PEM fuel cells are low temperature fuel cells that use a solid polymer in the form of a solid phase proton conducting membrane as an electrolyte. PEM fuel cells have many advantages over the other fuel cell types; including low temperature operation, high power density, fast start up, system robustness, flexibility of fuel type (with reformer) and reduced sealing, corrosion, shielding or leaking concerns [3]. A conventional PEM fuel cell consists of a Membrane Electrode Assembly (MEA), which contains a proton exchange membrane, an electrically conductive porous Gas Diffusion Layer (GDL) and an electro-catalyst layer, sandwiched between two flow plates. A conventional flow plate has flow channels that distribute the fuel and oxidant to the reactive sites of the MEA. One of the key strategies for improving the performance of the PEM fuel cell is the effective design of the flow plate. The efficient distribution of the fuel and oxidant to the catalyst layer, can increase the utilization of catalyst, improve the water management through the cell and provide effective collection of the produced current [23]. Various designs for the flow field were proposed by the researchers including pins, straight channels, serpentine channels [4], integrated channels, interdigitated channels [5, 6] and bio-inspired flow fields [7]. A detailed review for all flow field configurations was introduced by Manso et al. [8]. The various types of flow channels have common drawbacks such as; large pressure losses, high cost of manufacturing and low mechanical strength; which increase the weight and volume of the fuel cell. In addition, the flow channels can cause unequal distribution of the electrochemical reactions which lead to irregular utilization of the catalyst [9].

As an alternative to conventional flow plates, researchers [9-12] have identified that Open Pore Cellular Foam (OPCF) materials can provide several advantages over the conventional flow plates such as better gas flow through the fuel cell, lower pressure drop from inlet to outlet.

It was identified by Tsai et al. [10] that the flow field with metal foam has an impact on the performance of the PEM fuel cell. The authors completed an experimental programme to study the effect of flow field design on the performance of a PEM fuel cell. The authors concluded that the flow field can play a key role in the design and development of PEM fuel cells with either conventional or foam flow plates. In many experiments however, researchers have placed foam materials in the channels of conventional flow plates, as completed by Kumar & Readdy [21]. This retrofitting of a flow plate is crude and may not allow for the full benefits of OPCF materials to be exploited.

In spite of these advantages an effective flow plate design has not being well enough developed to allow foam materials to be effectively housed inside PEM fuel cells. New tailored housings with the required data, such as pressure analysis, flow regimes and velocity profiles have not been gathered.

In conventional flow plates the flow behaviour of oxygen and hydrogen inside the fuel cell and through the flow plates can be effectively predicted and analysed by employing the Computational Fluid Dynamic (CFD) modelling tool. Many researchers [13-20] employed the CFD tool in their studies to develop and optimize the bipolar flow plates. Detailed information about the flow regime is provided by the CFD simulations such as flow distribution, pressure pattern, and pressure drop. This information can aid in the geometric design of flow plates and flow fields and their suitability for a PEM fuel cell.

Generally speaking, the uniform flow distribution of oxygen or hydrogen and pressure over the GDL is an essential requirement in the PEM fuel cell to insure the balanced use of catalyst and thus achieving a better cell performance. The conventional flow plates deliver and distribute the hydrogen and oxygen/air to the reactive sites of the MEA via channels. The flow distribution across these channels can easily be identified using the CFD analysis and through inspecting the pressure and velocity field along the flow plate as completed by [15, 19-20].

In the present paper, a PEM fuel cell with using an OPCF flow plate, with suitable manifolding was designed and developed. Several manifold designs were proposed and tested numerically using CFD analysis. The most effective design is identified to improve the fuel cell performance. The fuel cell is prepared and tested, with the experimental results and performance reported.

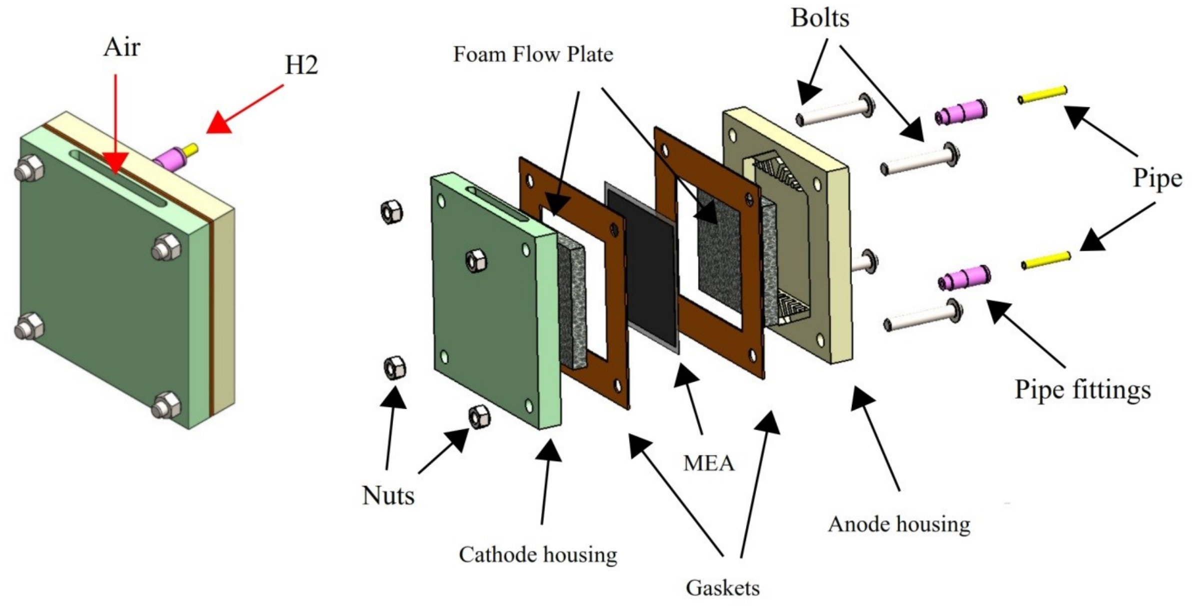
2. Modelling and simulations

2.1 Fuel cell design

In the current study, the conventional flow plates are replaced with metal foam flow plates. Two different housings were designed to accommodate the foam flow plates on the anode and cathode sides.

The OPCF on the cathode side is air breathing allowing air convection from the surrounding atmosphere. The OPCF on the anode side is supplied with pressurised hydrogen through appropriate fittings, and gaskets are used to seal the cell.

All components are assembled together using bolts with nuts. The use of metal foam eliminated the need for some supplementary components such as current collectors which used with the conventional flow plate. Fig 1 shows the fuel cell components and final assembly.



Fuel Cell Aseembly

Fuel Cell Components

Fig 1: PEM fuel cell components and assembly

2.2 3-D CFD Modelling

Many designs of the anode housing were suggested in the current study to provide the adequate flow of hydrogen to the OPCF and the MEA. All of the proposed housing designs have manifold channels to deliver the hydrogen to OPCF as shown in Fig 2.

Computational Fluid Dynamic (CFD) techniques through FLUENT software were used to analyse effective housing designs. Since the electrochemical reaction in a PEM fuel cell requires low flow rates of oxygen and hydrogen in the flow plates, the single-phase, steady state, laminar flow module in FLUENT was used to perform the flow simulations. The laminar flow module was also used by researchers [15, 20, and 22]. The model was imported into the commercial software and boundary conditions, as shown in Table 1, were applied. The mesh used hybrid elements by specifying the minimum edge length, Fig 3. The final models contained between 30,000 and 50,000 elements course enough not to exceed the limit or computational power or time available but fine enough to give acceptable results, clarified by grid independence analysis.

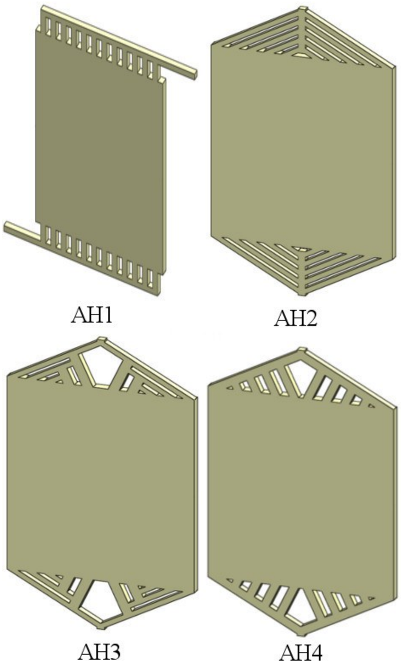


Fig 2: Anode housing flow configurations.

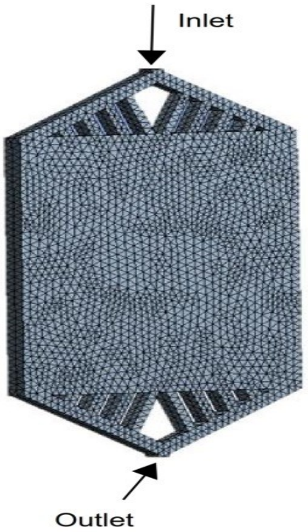


Fig 3: The CFD model mesh with flow region

Table 1: Simulation parameters & Boundary conditions

Modeller	Ansys DM
Mesher	Ansys Meshing
Mesh	Mixed Tet & Quad
Size function	Fixed
Smoothing	Medium
Transition	Slow
Elements	37,997
Solver	Fluent 3-D Double Precision
Solver type	Pressure based
Model flow	Laminar
Fluid	Hydrogen
Solid (walls)	Aluminium
Temperature	Constant
Porous GDL	N/A
Inlet velocity (m/s)	1
Pressure outlet (Pa)	0 (relative)
Scheme	Simple
Gradient	least squares cell based
Pressure	Standard
Momentum	Power law
Compute from	Inlet
Monitors	Mass flow Continuity Velocity
Iterations	150

3. Experiments

3.1 Material & Assembly

Table 2 summarises the material properties of the fuel cell components used in this study and Fig 4 shows the assembly steps of the PEM fuel cell. The optimised OPCF flow plate housing was machined and wiped thoroughly using isopropyl alcohol to ensure that the housing is clean and no dust or grease present. The flow plate housing is placed horizontally in a flat position. OPCF was polished using silicon carbide grinding paper on a polishing wheel. The OPCMF is placed inside the housing and bolts are placed through the housing as shown in Fig 4, photo 2. A gasket is then placed into position as shown in Fig 4, photo 3. The MEA is positioned onto the housing as shown in Fig 4, photo 4. A second gasket is then placed onto the MEA as shown in Fig 4, photo 5. A second OPCF flow plate is placed into a second housing as shown in Fig 4, photo 6. The second housing is then placed onto the bolts of the first housing. The MEA and gasket positions are checked and both housings are closed. Nuts are placed on the bolts and they are tightened. The push-in fittings for hydrogen pipes are placed in their positions. The final assemble fuel cell is shown in Fig 4, photo 7.

Table 2: Material properties of the fuel cell component

Fuel cell component	Material	Properties
OPCF housing	Acetal	Supplier: Impact Ireland
MEA	Nafion 212	active area: 5×5 (cm*cm), Catalyst loading: 0.4mg/cm2 Pt/C, GDL: Sigracet SGL 24BC, 0.55g.cm-3 Bulk density. Supplier: EES ltd UK
Flow plate	OPCMF	24 Pores/cm , thickness: 6.35 (mm)
Gaskets	Silicon	Thickness: 0.8 (mm)

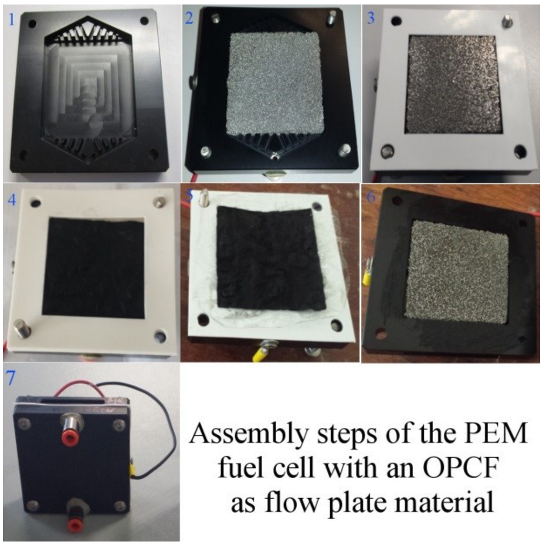


Fig 4: Assembly steps of the PEM fuel cell

3.2 Experimental Set-up and procedure

The experimental setup is similar to Carton & Olabi [23]. The reactant gas, hydrogen, is stored in a compressed cylinder. A specialised hydrogen pressure controls the hydrogen gas flow pressure. The gas then passes through volumetric flow meters. The flow controllers are calibrated for the hydrogen gas and air. The flow controllers are controlled by the data acquisition (DAQ) software (Lab View). Both air and hydrogen gases were humidified as stated by the manufacturer of the MEA. The open circuit voltage and the fuel cell operating voltage are detected by the DAQ hardware and analysed through the software. The open circuit voltage reading is also double checked at the anode and cathode using a multimeter (Fluke 8808A digital multimeter). The fuel cell current is measured using a multimeter (Fluke 8808A digital multimeter) in series with the external load.

Every effort was made to keep parameters constant during the experiments to ensure that the values of resistance, pressure and flow were not changed from one experiment to the next. These parameters were checked throughout the experiment to identify any unwanted errors. The only effect on the performance was that of the flow plate design.

4. Results and discussion

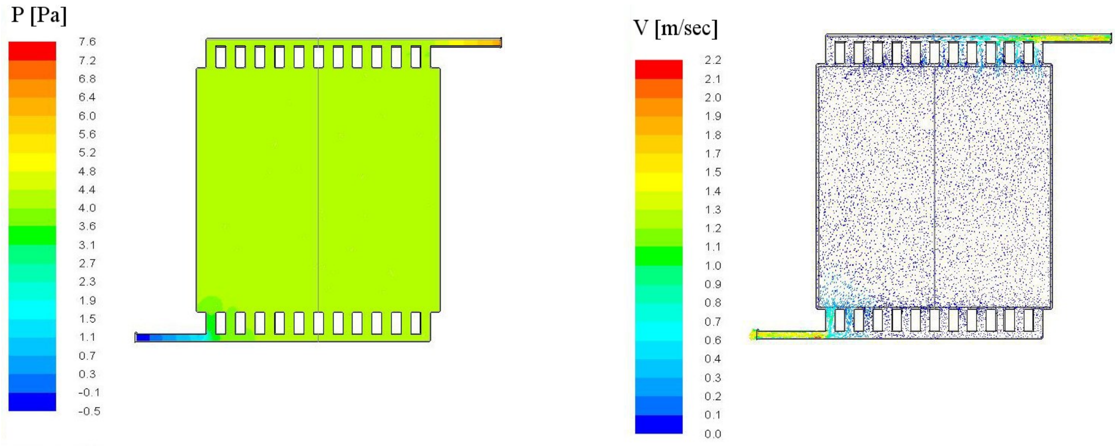
4.1 Analysis of the Anode housing configurations

As mentioned in the introduction, the optimisation and analysis of various flow field configurations can be carried out through the analysis of velocity, flow regimes and pressure distribution. The optimal design should provide an even flow and pressure distribution over the GDL and minimised pressure drop from inlet to outlet.

4.1.1 Anode Housing Design 1 (AH1)

The AH1 configuration is shown in Fig 2. This design was created to allow flow spread over the OPCF through many channels which are perpendicular to the main inlet channel. The downstream collector was designed similarly to upper collector.

Fig 5(a) shows the pressure distribution through the AH1 model, which indicates that there is a high inlet pressure and low out put pressure but even pressure distribution along the central region of the flow plate, corresponding to where the OPCF is housed. This even pressure is promising but the fluid flow velocity in Fig 5(b) may be an issue for this flow plate design. Fluid flow is confined by the channels and therefore there may be an increased possibility that low flow regions exist to the right and left side of the flow plate. This can cause possible dead zones and water accumulation as shown by Carton et al. [24]. This could dramatically reduce the performance of the fuel cell as only about one third of the active area of the cell would have convective air flow.



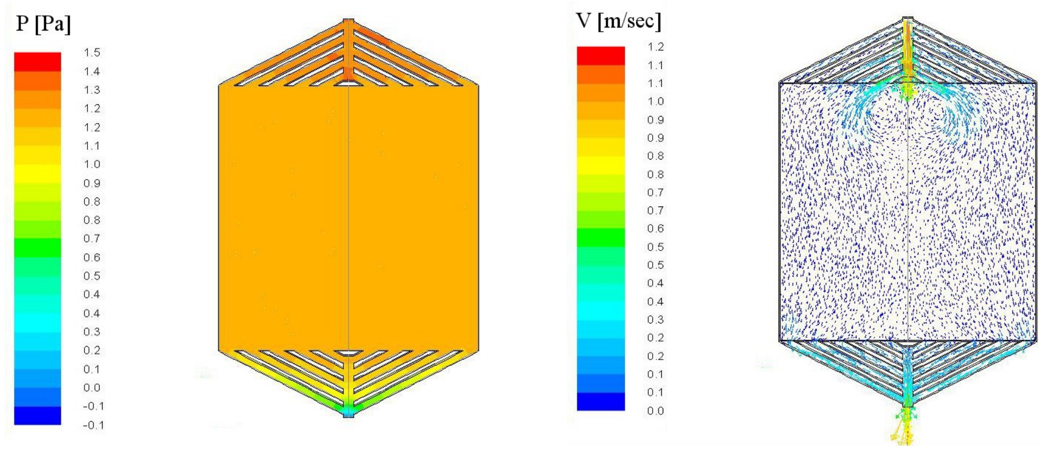
(a) (b)

Fig 5: Numerical simulation results of AH1: (a) - Pressure distribution (pa), (b) - Velocity vectors (m/s)

4.1.2 Anode Housing Design 2 (AH2)

The AH2 configuration is shown in Fig 2. The main inlet and outlet are aligned to the center of the design. The flow is deigned to spread through the OPCF through many channels which are diagonal to the main inlet channel. Fig 6(a) shows the pressure distribution through the AH2 model. The pressure distribution is even with only a low pressure drop from inlet to outlet.

The velocity profile through this housing is shown in Fig 6(b). A low velocity is noticed at the inlet when compared to other designs, as flow travels straight through this design with few restrictions by the channels. Large eddy currents are also noticed while the edges of the flow plate have minimal flow, that may correspond to stagnant flow areas where water may accumulate and the effective active area of the MEA could be reduced. This could dramatically reduce the performance of the fuel cell.



(a) (b)

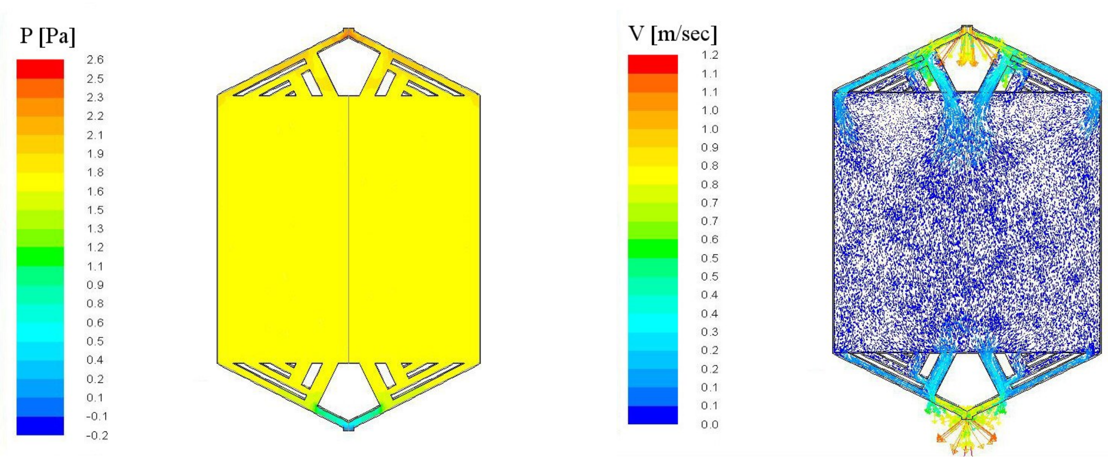
Fig 6: Numerical simulation results of AH2: (a) - Pressure distribution (pa), (b) - Velocity vectors (m/s)

4.1.3 Anode Housing Design 3 (AH 3)

The AH3 configuration is shown in Fig 2. This design has an obstruction placed close to the inlet which aims to split the flow into two branches. The design is aimed to then split that flow and spread over the foam material.

Fig 7(a) shows the pressure distribution through the AH3 model. The pressure distribution is even with only a low pressure drop from inlet to outlet.

The velocity profile through this housing is shown in Fig 7(b). The distribution of velocity flow is more even than previous models however large eddy currents are also noticed creating dead zones, that may correspond to stagnant flow areas where water may accumulate as demonstrated by carton & olabi [24], reducing the effective active area of the MEA. This design was unsuccessful and could dramatically reduce the performance of the fuel cell.

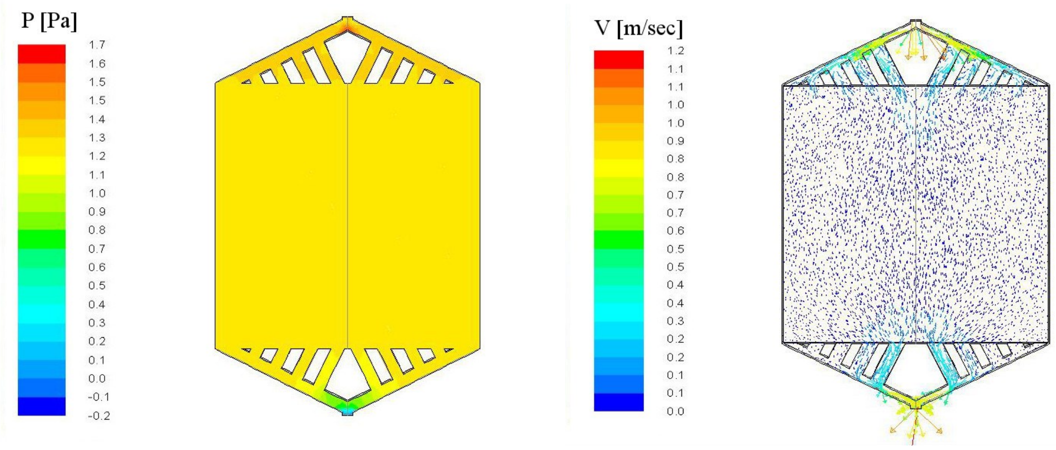


(a) (b)

Fig 7: Numerical simulation results of AH3: (a) - Pressure distribution (pa), (b) - Velocity vectors (m/s)

4.1.4 Anode Housing Design 4 (AH 4)

The AH4 configuration is shown in Fig 2. This design is similar to the previous design (AH3), however the flow is diverted evenly into two branches and then sub channels which are perpendicular to the main channels direct the flow over the OPCF. The width of main channels is larger than the sub channels with the objective of capturing and directing the flow evenly across all channels. Fig 8 (a) shows the pressure distribution, which indicates there, is a high inlet pressure and low out put pressure and even pressure distribution along the entire housing but most importantly across the central region of the flow plate, corresponding to where the OPCF is housed. The velocity flow is shown in Fig 8 (b). The modified housing channel design directs the flow evenly across the entire flow plate, with no eddy currents noticed which would significantly reduce stagnant areas in the PEM fuel cell. This Anode Housing Design (AHD 4) has the flow regime and pressure results required by the fuel cell.



(a) (b)

Fig 8: Numerical simulation results of AH4: (a) - Pressure distribution (pa), (b) - Velocity vectors (m/s)

4.2 Comparison of conventional and Foam flow plate

To prove the advantage of using OPCF flow plate, CFD analysis was also carried out on the conventional flow plate design, as shown in Fig 9. It can be seen that large pressure drops are viewed with serpentine flow plates. Velocity disturbances at the bends can affect flow.

Boundary layers of lower velocity fluid flow are noticed at the bends & channel edges.

In contrast the OPCF Anode housing design 4, as shown in Fig 8, low pressure drops are viewed and velocity disturbances are minimal with an even flow regime visible.

The I-V and power density curves of the conventional and OPCF flow plate are shown in Fig 10. It is clear that OPCF flow plates outperformed the conventional serpentine flow plate, recording 0.7 (V) at 0.09 (A/cm2). While approximately 0.7 (V) was recorded at 0.05 (A/cm2) for the standard double serpentine flow plate.

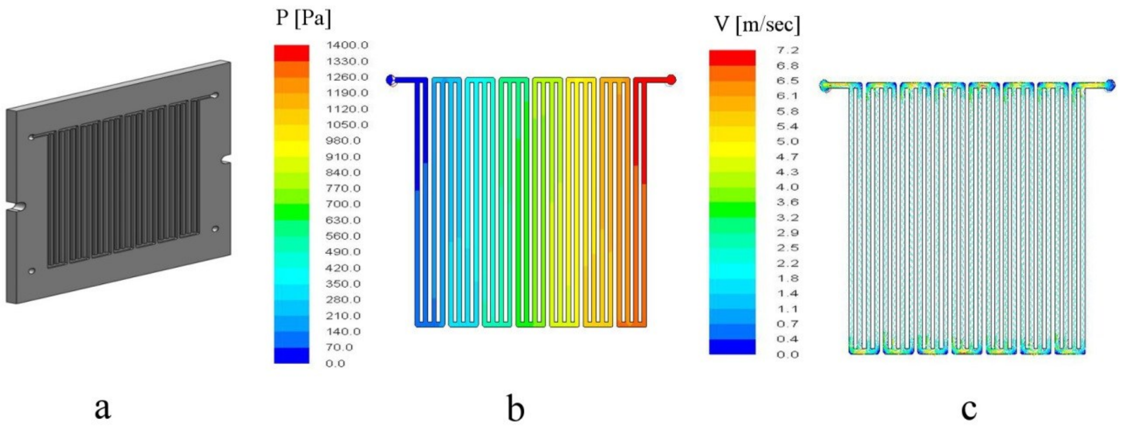


Fig 9: Numerical simulation results of the conventional flow plate: (a) - 3D Model, (b) - Pressure distribution (pa), (c) - Velocity vectors (m/s)

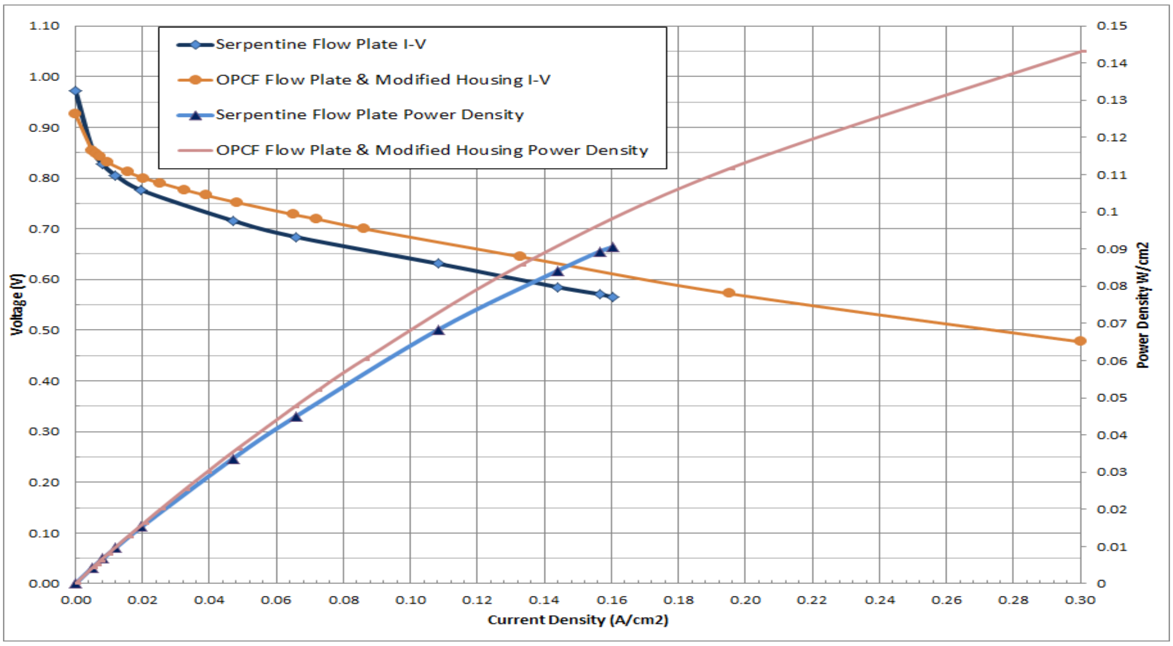


Fig 10: Polarisation curve comparison for serpentine flow plate and OPCF flow plate.

5. Conclusion

In this paper, Open Pore Cellular Foam (OPCF) materials were evaluated and tested as a potential material to replace conventional flow plates.

Through a combination of mechanical and Computational Fluid Dynamic (CFD) modelling and analysis effective flow plate designs, flow field configurations and materials are analysed and new cell designs are proposed. It was found that a suitable OPCF housing design was required to ensure increased support and effective fluid flow through the OPCF. With an optimised design OPCF materials can ensure better gas flow through the fuel cell, lower pressure drop from inlet to outlet and increased PEM fuel cell performance. The ultimate goal of this body of work is to improve the performance of PEM fuel cells by simplifying their design, allowing fuel cells to offer a promising, possibly green, alternative to traditional power sources, in many applications, without air polluting issues [25, 26].

6. References

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