Polymer-based bipolar plates for fuel cells: design, simulation, and manufacturing

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Abstract

This paper presents the optimization of bipolar plates for polymer-based fuel cells designed for small-scale applications like drones and portable devices. The fuel cell uses an open-cathode system, where air from the environment is the oxidant, reducing weight and complexity. Three initial design concepts were created, and the counter-flow design was selected for further development due to its higher performance potential. The plate geometry was optimized with semi-circular channels on the anode side to improve hydrogen flow and U-shaped channels on the cathode side for better water removal. Flow and pressure distributions were analyzed using Computational Fluid Dynamics (CFD). Although early results showed uneven distribution, further adjustments led to a new design, which improved manufacturability and reduced deformation. After testing different gas inlet configurations, a final design was developed, showing more uniform flow and better performance for lightweight applications.

Keywords

proton exchange membrane fuel cell, computational fluid dynamics, channel design, optimization

1 Introduction

Fuel cells have become a promising technology for portable and stationary applications due to their high energy density and environmental friendliness [1]. Proton-exchange membrane fuel cells (PEMFCs) are particularly suitable for portable applications, as they offer a lightweight and compact solution, making them ideal for drones, electric scooters, and portable electronics [2]. A key component of PEMFCs is the bipolar plate, which serves multiple functions: it distributes gases evenly across the electrodes, conducts electrical current within each cell, and manages water and thermal output [3].

In recent years, open-cathode PEMFC designs have gained attention for portable applications, where air from the environment is used as the oxidant instead of pure oxygen. This approach simplifies the system by eliminating the need for oxygen tanks, valves, and regulators, making it lighter and more suitable for portable uses. However, this design introduces gas distribution and water management challenges, which can affect the fuel cell's performance and durability [4].

Bipolar plates play a critical role in addressing these challenges. The geometry of the flow channels on the anode and cathode sides significantly impacts the uniformity of gas distribution, pressure drop, and water removal. Several studies have explored different flow channel configurations to optimize these factors[5]-[7].

Parallel channels, which are simple to design and manufacture, are commonly used but may suffer from uneven gas distribution and significant pressure differences between the anode and cathode. To overcome these limitations, researchers have proposed various bipolar plate designs, such as counter-flow and hybrid flow configurations. Counter-flow designs can offer better cell performance by promoting more uniform gas distribution. However, they are often more complex to manufacture and may still result in uneven flow distribution, requiring further optimization [8].

Bipolar plates are traditionally made from metal or graphite due to their excellent electrical and thermal conductivity. However, in recent years, polymer composites have become increasingly accepted for use in fuel cells. These materials offer several advantages: lower density, better corrosion resistance than metals, easier fabrication, and greater design flexibility than graphite. However, polymers have lower electrical and thermal conductivity than metals and graphite [9]. To overcome this, conductive fillers can be added to the polymer matrix to improve thermal and electrical conductivity. The most commonly used conductive fillers are carbon-based materials, which come in various forms: graphite, carbon black, carbon nanotubes (single-walled or multi-walled), carbon fiber, and graphene. By carefully selecting and combining these fillers, polymer composites can achieve the necessary conductivity for use in fuel cells while also benefiting from the advantages of lighter weight, better corrosion resistance, and easier fabrication [10].

Thermoplastic polymer-based bipolar plates are typically produced using compression or injection molding. However, combining the two manufacturing methods can offer significant advantages, particularly in precision. With the help of injection-compression molding, precise manufacturing and reduced shrinkage of the bipolar plates are possible [11].

In this work, we present a comprehensive optimization of the bipolar plate geometry for a polymer-based fuel cell designed for small portable applications. Three initial designs were evaluated through CFD simulations, focusing on flow uniformity, pressure drop, and manufacturability. The selected design was further refined through CFD analysis and injection molding simulations, leading to an optimized version that balances performance and ease of production.

2 Geometry for the bipolar plates

We aimed to develop a polymer-based fuel cell for powering smaller vehicles (drones, scooters, exoskeletons) and portable devices. For these applications, an open-cathode fuel cell is typically used. This design uses ambient air on the cathode side instead of pure oxygen. This approach makes the system lighter, smaller, and less complicated, eliminating the need for an oxygen tank and its associated components.

During the design phase, we aimed to develop a bipolar plate with dimensions of 150x50x3 mm, featuring an open-cathode design with a parallel channel layout. The parallel layout offers simplicity, more even gas distribution, and a smaller pressure difference between the cathode and anode sides, which is essential for protecting the membrane due to its vulnerability. Based on these criteria, we created three concepts, shown in Figure 1.

- Concept (a): This crossflow solution offers simplicity and ease of manufacturing. It is straightforward to produce and does not require complex tooling. However, it has poor velocity distribution along the cathode channels, which can result in inefficient gas flow. Additionally, the structure is less stiff, which may lead to durability issues under operating conditions.
- Concept (b): A hybrid design where air is not directly drawn from the environment, making it less of an open-cathode system. This design is compact and easy to manufacture. However, compared to concept (a), it suffers higher pressure loss and uneven gas distribution, which can negatively affect fuel cell performance. The balance between a compact design and efficiency is a key to this concept.
- Concept (c): A counter-flow design offers better fuel cell performance than the crossflow system. This design can deliver higher power output due to the more efficient flow arrangement. However, its downside is a more complex design, which complicates manufacturing and increases the potential for uneven gas distribution.

After analyzing the advantages and disadvantages, we selected option (c) as the basis for further development (V1).

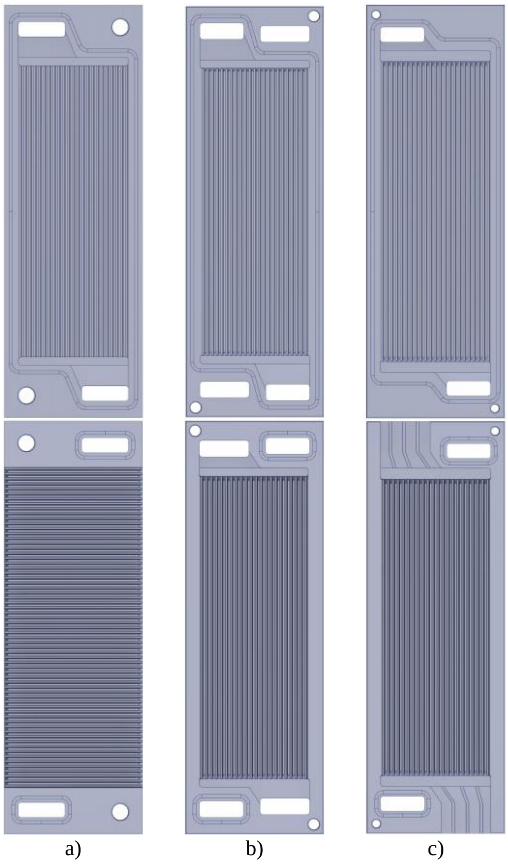


Fig 1. Different concepts for open cathode parallel channel bipolar plates (up: hydrogen (anode) side, down: air (cathode) side)

2.1. Channel Geometry

On the hydrogen (anode) side, we used semi-circular channels. This shape allows for higher pressure drop, leading to better hydrogen utilization and, thus, higher performance. We chose U-shaped channels on the air (cathode) side because they remove water more effectively than semi-circular or rectangular ones.

2.2 Channel Dimensions

For parallel designs, wider channels are preferable, as they provide a larger surface area for the reactive gases to contact the gas diffusion layer (GDL), enhancing diffusion. While literature offers no definitive conclusions on optimal channel dimensions, studies often examine the impact of the channel width-to-rib width ratio on cell performance, with values ranging from 0.5 to 2. Based on this, we selected a channel width of 1.2 mm and a rib width of 0.6 mm for the cathode side and 1 mm and 0.75 mm, respectively, for the anode side. The channel depth was 0.5 mm for the anode (due to the semi-circular cross-section) and 1.25 mm for the cathode.

3. Bipolar plate design verification by numerical simulations

Using Autodesk CFD software, we conducted CFD simulations to analyze the pressure drop and velocity distribution. We applied a volume flow rate of 5 l/min at the inlet and set zero pressure at the outlet. The mesh settings are detailed in Table 1, with a total element count of 3.3 million. We used the Modified Petrov-Galerkin (ADV 5) advection scheme for solving the energy, velocity, and pressure equations.

Table 1 Parameters used in the meshing of CFD simulations

Property	Value
Resolution factor	1
Edge growth rate	1.1
Minimum points on edge	2
Points on longest edge	10
Surface limiting aspect ratio	20
Volume growth rate	1.35

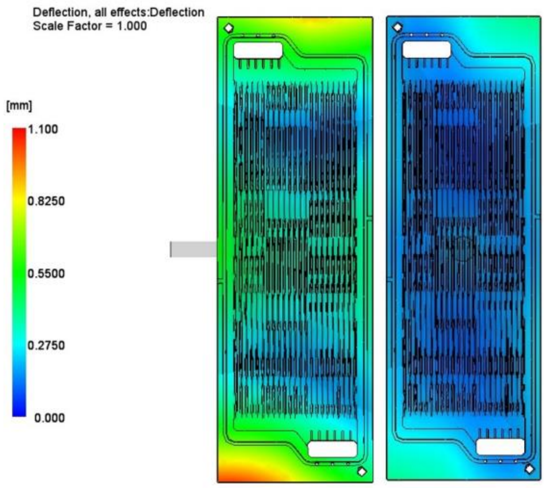
The velocity and pressure distribution on the anode side of the V1 concept show significant non-uniformity along the channels. This uneven distribution negatively impacts hydrogen utilization and overall cell performance. Optimizing the channel design or improving the gas flow distribution could enhance the system's efficiency. Similar to the anode side, the cathode's velocity and pressure distribution are also uneven in the V1 design. This imbalance can prevent efficient water removal, leading to potential flooding. Further optimization of the cathode channels is required to achieve more even gas distribution and maintain stable performance under varying conditions.

To analyze the manufacturing process of the bipolar plate, we used Autodesk Moldflow Insight 2023 injection molding simulation software. The material we plan to use is a graphite- and carbon-filled thermoplastic. These fillers provide good electrical conductivity but significantly reduce the material's processability. As we developed our own material, exact data was not yet available, so we selected the closest match from the Moldflow database (HT1 Reference). This material had similar thermal conductivity and viscosity to our developed material. We used 3 mm tetrahedral elements with a total element count of 550,000. The main parameters are shown in Table 2.

Table 2 Key parameters for the simulation of injection compression molding

Property	Value
Material	HT1 Referenz
Melt temperature [°C]	340
Mold temperature [°C]	150
Compression distance [mm]	3
Compression speed [mm/s]	5

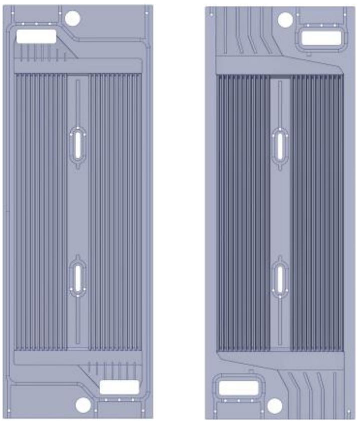
We examined the impact of gate location on the plate's deformation. This plate geometry only allows the gate to be located on the sides of the plate. However, this led to uneven shrinkage, causing warpage, as shown in Fig 2a.



a) b)

Fig 2. Bipolar plate deformation in the case of injection molding (a) the gate on the side of the product, (b) the gate in the middle of the product

If we could place the gate in the center of this geometry, it would minimize warpage (Fig. 2b), so we designed a bipolar plate geometry (V2) that allows the gate to be located in the center of the plate (Figure 3). The anode gas channels have ribs that help guide the gases for more even velocity and pressure distribution and support the seal of the hydrogen channel.



a) b)

Fig 3. Optimal design from a manufacturing point of view (a) anode side (b) cathode side

We performed additional CFD simulations to analyze the velocity and pressure distributions. The V2 concept displays improvements in flow distribution compared to V1, yet the velocity and pressure patterns are still irregular, particularly near the inlet and outlet. These irregularities suggest further adjustments, especially in the inlet and outlet design, to achieve better flow control and minimize pressure losses. On the cathode side of V2, while flow uniformity has improved compared to V1, the distribution is still not ideal. This could result in inefficient air (oxygen) delivery to the active area, reducing the overall reaction rate. Further channel geometry and positioning optimization are needed to enhance performance while ensuring the design remains suitable for efficient injection molding.

To address this, we tested various concepts on the hydrogen's inlet channel to further optimize the velocity distributions in the channels (Figure 4).

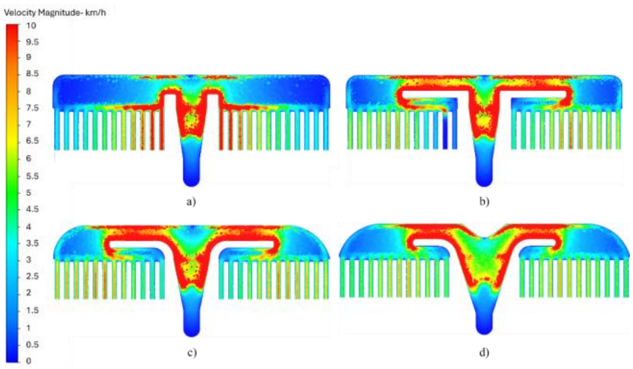
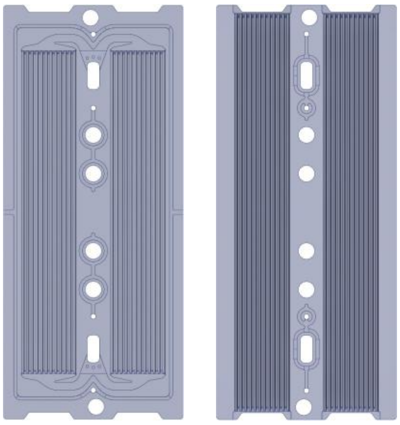


Fig 4. Velocity distribution of anode side

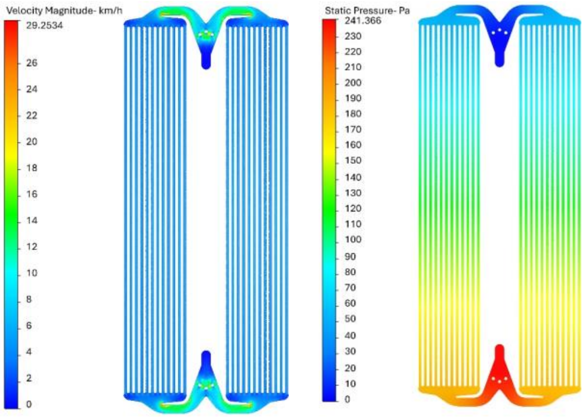
With a continuous trial-and-error method, we optimize the inlet area to reach a uniform velocity distribution through the channels. Based on the simulation results, we redesigned the bipolar plate (V3, Figure 5).



a) b)

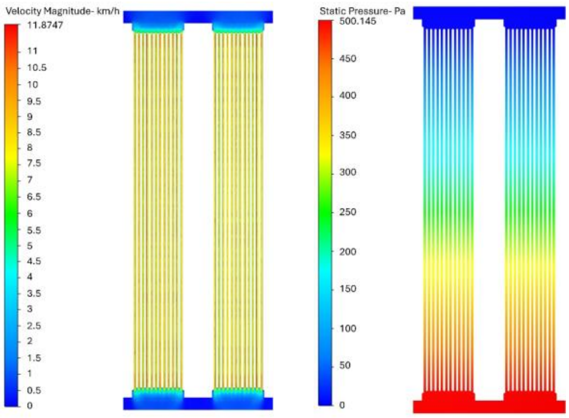
Fig 5. V3 concept (a) anode side and (b) cathode side

We validated the completed design using CFD simulations, examining the velocity and pressure conditions (Figures 6 and 7).



a) b)

Fig 6. V3 anode side (a) velocity distribution and (b) pressure distribution



a) b)

Fig 7. V3 cathode side (a) velocity distribution and (b) pressure distribution

The V3 concept demonstrates a more uniform velocity and pressure distribution on both sides compared to previous versions. The gas flows more smoothly, helping to use hydrogen better and reducing problems caused by uneven flow. This balance is critical for ensuring efficient water removal and maintaining optimal oxygen supply for the cathode side. The improvements seen in V3 suggest that this design is closer to achieving the desired performance levels for practical fuel cell applications.

4 Conclusion

In this work, we demonstrated the optimization of the bipolar plate design for open-cathode fuel cells. This represents a key step in improving the performance and manufacturability of polymer-based fuel cells. By iteratively refining the design, significant improvements in gas flow distribution, both in the anode and cathode channels, were achieved. The improved velocity and pressure balance across the channels lead to better hydrogen utilization, more efficient water removal, and a higher overall fuel cell performance.

Future work could focus on refining the material development for the bipolar plates, exploring alternatives that could further reduce weight while maintaining or improving conductivity and mechanical strength. Additionally, further optimization of the flow field designs through advanced simulations and final tests on fuel cell assemblies can provide deeper insights into performance improvements. Extending this research to mass production or integrating it with hybrid energy solutions could open new opportunities in sustainable energy applications beyond small vehicles and portable devices. This project lays the foundation for future advancements in the design and application of polymer-based fuel cells.

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