Flow Field Design of PEMFC

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Climate change and the major threat it poses to the environment and human lives is the major challenge the world faces today. To overcome this challenge, it is recommended that future automobiles have zero carbon exhaust emissions. Even though battery electric vehicles reduce carbon emissions relative to combustion engines, a carbon footprint still remains in the overall ecosystem unless the battery is powered by renewable energy sources. The proton exchange membrane fuel cell (PEMFC) is an alternate source for automotive mobility which, similar to battery electric vehicles, has zero carbon emissions from its exhaust pipe. Moreover, the typical system level efficiency of a PEMFC is higher than an equivalent internal combustion powertrain.

proton exchange membrane fuel cell
computational fluid dynamics
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serpentine

1. Parallel Flow Field Channels

The parallel and serpentine flow field channels are the most common flow field patterns for fuel cells [1]. Parallel flow fields, despite being straightforward and having minimal production costs, have reportedly been found to function worse than serpentine flow fields due to the reactant's uneven distribution [2]. Localised hot areas are frequently caused by the reactant being distributed unevenly. Furthermore, it is documented that parallel flow fields may lead to flooding in cells, particularly under the ribs, where the lowest pressure of the cell is found [3]. However, parallel flow channels do have a low pressure drop. As opposed to parallel flow fields, serpentine flow field channels have a greater pressure drop, which increases reaction activity and improves the reactant's migration to the GDL at the expense of additional parasitic pumping power. Additionally, this channel design enhances water removal by increasing the pressure drop of cell and reducing the flooding effect. To improve the uniformity of reactant distribution, parallel flow fields' size and patterns have been changed in a number of research studies [4].

In order to optimise the flow distribution, Bi et al. [5] narrowed the dimensions of the flow field channel at the channel entrance region, which improved the performance of the parallel flow field pattern. The authors claimed that by making the entrance channel narrower, minimal liquid water was seen on the cathode side of the flow field channels, while water was evenly dispersed across the channels of the anode. At the fuel cell stack level, Ramos-Alvarado et al. [6] and Liu et al. [7] investigated how to improve the flow distribution in parallel flow field channels through manifold design. Bifurcation design for a parallel flow field channel was investigated by Ramos-Alvarado et al. [6] though varying the channel size to better use the active area and flow distribution. The authors successfully developed a parallel flow field design with bifurcation that generated higher efficiency than a serpentine flow field design. It has also been found that a parallel flow field with bifurcation required less pumping power than serpentine flow fields. It has also been demonstrated that improving the parallel flow field design with bifurcation produces a more uniform flow distribution. In 2017, Lim et al. [8] published an analysis on the distribution of reactant in modified parallel flow field channels. The authors asserted that the modified parallel flow field produces a more consistent pressure and reactant distributions as compared to a conventional parallel flow field pattern. The impacts of two major designs with two modified headers on the distribution and uniformity of air in a PEMFC's parallel channel flow were quantitatively examined by Sajid Hossain et al. [9] using Z-type Z-U-type parallel channel topologies.

Lim et al. [10] modelled a PEMFC with a parallel flow field using a 3-D (three-dimensional) computational fluid dynamics (CFD) model. Flow characteristics, current density, temperature and water dispersion were considered in the model. The numerical results demonstrated that modified parallel flow field channels, where the reactant is distributed uniformly throughout the flow field, offer evenly distributed current density generation. Karthikeyan et al. [11] conducted experimental tests on a PEMFC with a parallel serpentine flow field for an effective cross-sectional area of 25 cm^2. Using a computational method, Saco et al. [12] evaluated a scaled-up PEMFC with a variety of flow channel designs to maximise the production of power through efficient water management. The authors used four distinct flow channel designs for their numerical investigation. In the first configuration, a parallel serpentine flow channel that has a cross-sectional area of 25 cm^2 was primarily expanded to 225 cm^2. By resolving the equations relating to the governing principles of mass, momentum, energy, species and electrochemistry, the three-dimensional flow through the PEMFC was simulated. The power density created by the straight flow channel with the zigzag flow route was determined to be 0.3758 W cm^{-2}, the highest of the designs taken into consideration. This is because the water was managed well with little pressure loss. A 3-D, two-phase PEMFC model with wave parallel flow field was investigated by Chen et al. [13]. The findings showed that wave parallel flow field channels are generally superior to conventional parallel flow fields in facilitating the transit of reactant gases, eliminating the liquid water collected in microporous layer and preventing the accumulation of thermal stress in the membrane. The gas flow velocity in wave parallel flow field channels is more uniform than that of a conventional parallel flow field because of the periodic geometric properties of the wave flow field channel. Additionally, the results demonstrated that increasing the wave parallel flow fields' large amplitude and short-wave duration can increase PEMFC output power. Specifically, the maximum power output in the wave parallel flow field was 34.75% greater than that of the traditional parallel flow field at an operating voltage of 0.6 V.

According to experimental findings, Henriques et al. [14] suggested that parallel plus transversal flow field design enhances the performance of fuel cell by 26% over conventional designs. Comparative studies of the three-dimensional PEMFC as a dual-cell, quad-cell and hexa-cell stack were conducted by Lim et al. [15] based on a modified parallel flow field. In order to investigate how the performance of a PEMFC stack changes as the number of cells rises, series connections between dual-, quad- and hexa-cell stacks were made. To investigate how a PEMFC stack generates current density, a CFD model was employed. The findings showed that the current density falls as the number of cells in a stack increases. Using CFD, Selvaraj and Rajagopal [16] examined how the flow fields and humidification of reactants affected the performance of a scaled-up PEMFC, validating results for parallel and counter serpentine flow channels of 24.8 cm^2 with data from the literature. By altering the flow field channel parameters, such as width and length of the channel, Martin et al. [4] ran numerical simulations on a parallel flow channel PEMFC in order to investigate the flow physics of the PEMFC. The authors proposed a redesigned PEMFC architecture with parallel flow channels that maximise pressure drop while assuring uniform distribution of flow throughout the PEMFC. Afshari et al. [17] quantitatively evaluated the performance of PEMFCs using metal foam as a distributor and a cathode with a limited flow channel. The three different types of flow field channels—parallel flow field, flow field with flow-restricting baffles and flow channel with metal foam distributor—were computationally examined with the use of the finite volume approach. The authors noticed that the performance and reaction rate for the flow field with baffles were enhanced by uniform distribution of the oxygen in the GDL and catalyst layer. The flow channel with metal foam ensures that current density and oxygen are distributed uniformly throughout the PEMFC's performance by enhancing the cathode catalyst layer.

The multiphase numerical simulation of a PEMFC was performed by Atyabi and Afshari [18] using a parallel and sinusoidal flow field pattern to analyse the performance of the PEMFC. The investigation was conducted utilising a finite volume technique and the steady state, multiphase and non-isothermal PEMFC model. Ion exchange, pressure, power density, water and thermal management of the PEMFC are some of the characteristics which were compared between the sinusoidal flow field channel and the parallel flow channel. The highest power density was discovered to have been visible for the parallel flow field and the sinusoidal flow field channel. A study was conducted by Ferng et al. [19] to analyse the effects of various flow channel configurations on PEMFC performance. The authors concluded that the step-wise depth design and parallel flow channel considerably improved PEMFC performance. In order to evaluate the local transport properties of a PEMFC, Ghanbarian et al. [20] examined a number of geometrical parameters, such as the channel height and breadth, the number of ribs between two adjacent channels, the number of parallel channels and serpentine twists. Zehtabiyan-Rezaie et al. [21] introduced a series of convergent divergent channels to the parallel flow field design to study the impact of cross-section area. According to the authors, two divergent neighbours were fed by the converging channels because of the pressure.

2. Serpentine Flow Field Channels

The majority of industrial and automotive applications employ the serpentine flow channel [22]. This is due to the improved reactant and oxidizer distribution that the serpentine flow channel can demonstrate at the anode side and cathode side GDLs, respectively. However, the disadvantage of the serpentine flow field configuration is that, in comparison to parallel flow channels, the pressure loss across it is significantly larger [23].

Karvelas et al. [24] conducted a comparison of the flow route designs of parallel, interdigitated and serpentine flow-fields. The authors found that smoothening was significantly more successful in lowering the pressure drop in serpentine geometry than it was in interdigitated or parallel flow fields. A numerical investigation with innovative chaotic structure for serpentine flow channels was carried out by Dong et al. [25], considering the impact of temperature, number of bends and flow channel corner angle on PEMFC performance. It was claimed that the new chaotic structure increased energy efficiency by 6.26% to 8.40%, while also ensuring that the flow channels have a consistent temperature distribution. Through numerical analysis, Selvaraj and Rajagopal [26] looked at how the land to channel (L:C) ratio and flow field affect PEMFC performance. The straight-zig-zag flow field with a 2:2 L:C ratio was determined to have a maximum power density of 0.3250 W cm^2 at 0.4 V. In comparison to a straight-zig-zag PEMFC, the oxygen consumption in the cathode flow channels of a serpentine-parallel, a serpentine-zig-zag and a straight-parallel PEMFCs was 77.08%, 10.41% and 42.70% lower, respectively. With a L:C ratio of 2:2, the pressure drops in the flow channels of a serpentine-parallel, a serpentine-zig-zag and a straight-parallel flow field were 78.18%, 95.81% and 48.33% higher, respectively, than those of straight-zig-zag flow fields. Yousef et al. [27] conducted a numerical analysis of the performance of PEMFCs with different flow field configurations including serpentine, parallel and compound channel topologies. The authors compared the numerical results for the aforesaid models based on the polarisation curves of the reactants, the reactant flow distribution and the water molecules in the membrane electrolyte. Their results showed that serpentine and compound flow field channels performed better than PEMFCs with parallel flow field channels.

Khazaee et al. [28] numerically simulated a PEMFC with four-serpentine, single serpentine and two other channel designs with a 24.8 cm^2 active area. Their investigation focused on the channel design, gas flow direction, humidity and pressure. The authors took into account three separate relative humidity (RH) ranges, with corresponding values of 100%, 50% and 10%. Additionally, the cross- and counter-flowing gas flow paths were studied. The authors showed that the four-serpentine and single-serpentine flow channels performed better when the reactant had a greater relative humidity. When compared to cross- and counter-flow channels, the PEMFC with serpentine channel performed better. Rostami et al. [29] conducted a numerical analysis of a PEMFC with a serpentine channel with different-sized bends. In order to investigate the effects of the pressure differential and current densities, the bend diameters of the flow field channel were varied between 0.8 and 1.2 mm. It was observed that the serpentine flow field channel gives the optimal performance due to a more uniform distribution of reactants. In order to determine how 25 channels and a 5.1 × 5.1 cm area of a PEMFC performed in relation to the geometric layouts and dimensions of the flow field, Youcef et al. [30] employed a three-dimensional model. Three designs, namely serpentine, interdigitated and parallel with six channel-to-rib width ratios were investigated. Performance was improved in PEMFCs with serpentine configurations; compared to interdigitated and parallel, it rose by 4.6% and 39.1%, respectively. Additionally, rib width expansion and channel narrowing both enhanced cell function. When the channel-to-rib width ratio varied from 2.66 to 0.25, the cell function increased by 120%, 45% and 23% for serpentine, interdigitated and parallel flow field configurations, respectively. Shimpalee et al. [31] examined the impact of the number of gas flow pathways on reactant transport and cell performance in a 200 cm^2 PEMFC using a serpentine flow field configuration. It was reported that the local distributions of water content, temperature and current density become more uniform with shorter path lengths or larger number of channels. The performance of PEMFCs was examined by Wang et al. [32] in relation to the influence of design factors in the bipolar plates, such as the number of flow channels in serpentine configuration, the number bends of flow channel and the flow channel width ratio. According to their findings, the single serpentine flow field configuration performed better compared to the double and triple flow field configuration.

Current distribution measurement was employed by Lobato et al. [33] to examine the effects of four flow field designs on PEM fuel cell performance, these were: step serpentine, parallel, pin type and interdigitated. The findings show that the use of pure oxygen can result in a maximum power gain of up to 25% for pin-type or serpentine flow field configurations. Experimental research on the impact of channel and rib widths for a serpentine flow field with an aspect ratio of height/width ranging from 0.5 to 2 has been performed by Hsieh et al. [34]. Shimpalee et al. [35] studied the effects of cross-sectional areas of ribs and channels on the distribution of reactants on the performance of a 25 cm^2 PEMFC with a serpentine flow field configuration. The authors showed that the performance of the fuel cell was improved by narrow channels with broad rib spacings. In serpentine flow field design, the impact of the channel cross-section aspect ratio was examined by Manso et al. [36]. It was discovered that the PEMFC performance at high operating voltages is significantly impacted by the channel cross-section aspect ratio. In order to better understand the effect of the single and triple serpentine flow field configuration on the efficiency of PEMFCs, Wang et al. [37] developed a 3=D model. The authors discovered that a lowered channel aspect ratio boosted the gas inlet flow velocity at low operating voltages, enhancing liquid water removal and improving cell performance. A modified serpentine flow field provided by Kahraman and Orhan [38], that divides the route into connected segments, considerably influenced the current study. The uniformity of reactant distribution and cell performance were compared in the current study, which also designed several innovative modified forms. In the research presented by Nam et al. [39], Baz et al. [40] and Abdulla et al. [41], the impacts of under-rib convection flow were the basic premise for building efficient serpentine-type flow fields by maximising the difference in route length between neighbouring channels. According to the aforementioned studies, the under-rib convection and the transfer of reactants to GDL are the two key strategies for enhancing PEMFC performance.

3. Interdigitated Flow Field Channels

The interdigitated flow field channel was initially suggested by Nguyen [42] to improve the transfer of liquid water out of the gas diffusion layer. Reactant is forced from the channel to the GDL through a convection process in an interdigitated flow channel, resulting in improved reactant transportation and water removal [43]. Hu et al. [44] assessed how the interdigitated flow field design affected PEMFC performance. According to their findings, the interdigitated cathode side in the flow field design reduced the liquid water content and increased the oxygen concentration in the gas diffusion layer when compared to straight flow. The interdigitated design is advantageous because it increases reaction activity and improves the performance of the cell, according to Yi et al. [45], who studied the impact of various flow channel designs on the performance of PEM fuel cells. In contrast to diffusion, the convection process is far more effective in overcoming the water flooding effect, and as a result, interdigitated PEMFCs function better than straight-channel PEMFCs. According to Manso et al. [22], a drawback of the interdigitated flow field configuration is the higher consumption of energy to pump the gas, which raises the power requirement to feed the reactants in their respective flow channels and thus lowers efficiency at the system level.

4. Bio-Inspired Flow Field Channels

An alternative approach was taken by Roshandel et al. [46], who created a bio-inspired pattern for the flow fields within a PEMFC. In comparison to more traditional patterns like parallel and serpentine flow paths, the results obtained utilising the bioinspired flow filed pattern showed that the gas distribution was more uniform in the case of this novel design; thus, high voltage and power density can be reached. The author also identified areas where the design had room for improvement. Using Murray's Law, which connects the dimensions of the parent channel to the dimensions of the daughter channels, was one method used for designing bio-inspired flow fields [47][48]. Fuel cells [23][49] and microfluidic devices [50][51] have both used this method. Guo et al. [52] created a series of flow field designs for fuel cells that were influenced by the venation structure of a tree leaf and utilised Murray's Law to establish the correlation between channel dimensions. Murray's Law was used by Arvay et al. [49] to create certain bio-inspired flow field topologies. Their goal was to create a flow channel arrangement that could maintain a balanced gas distribution across the reaction region and maximise the pressure drop inside the flow channels. According to the findings of their work, using flow field designs that are inspired by nature makes it feasible to disperse the reactants more efficiently with a little pressure drop. In networks with circular cross-sections, Zografos et al. [53] predicted the ideal ratio between the diameters of the parent and daughter vessels using Murray's Law; as a result, it offered a better design. Ozden et al. designed and investigated the performance of a bio-inspired flow field-based DMFC (direct methanol fuel cell) [54]. The serpentine (anode) and second leaf design (cathode) had the highest peak power density, at 888 W m^{-2}. For contrast, when the serpentine flow field was applied to the anode and cathode, a peak power density of 824 W m^{-2} was attained.

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