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Advanced Microstructural Engineering of Gas Diffusion Layers for Synergistic Electrochemical Performance and Durability

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Abstract

The microstructure of gas diffusion layers (GDLs) is a critical factor in determining the electrochemical behaviours and durability of the proton exchange membrane fuel cells (PEMFCs). The paper will assess the ability of engineered GDL microstructures to improve the synergistic behavior of electrochemical performance. The 3D multi-physics numerical model is created, which considers the anisotropic porous transport, water capillary behavior, electrochemical reaction, and thermal effects, and is tested in accordance with known reference data. Using four GDL architectures, which include a traditional GDL, horizontally aligned, vertically, and an X-pattern GDLs, four GDL architectures are compared. The findings demonstrate that directional microstructural engineering produces a strong influence on performance characteristics. Whilst the GDLs that are horizontally and vertically aligned have a selective effect on in-plane and through-plane transport, respectively, the X-pattern GDL has a more balanced nature and exhibits a 35, 40, 28 and 45% reduction in oxygen transport resistance, a reduction in liquid water saturation, an increase in peak power density, and a 45% reduction in voltage degradation rates, respectively, than the conventional design. The originality of the given work is in showing that multidirectional GDL engineering provides an opportunity to synergize electrochemical performance and durability.

Keywords: Multidirectional Mass Transport; Liquid Water Management; Electrochemical Durability; Gas Diffusion Layer Microstructure; Proton Exchange Membrane Fuel Cells.

1. Introduction

The world energy industry is rapidly changing due to the growing energy requirements and a pressing necessity to reduce the number of greenhouse gases related to the use of fossil fuels [1-3]. Population increases, urbanization, and industrialization, as well as fluctuating fuel prices and environmental effects, are still putting strong pressure on the already existing energy infrastructures, and the constraints of the classic energy systems [4-6]. The implementation of the sustainable and low-carbon energy technologies has therefore become a strategic matter to guarantee the energy security and environmental safety in the long term [7, 8].

Solar, wind, hydropower, and biomass sources of renewable energy have been growing significantly because of their low level of emission on operation and decreasing costs. Nevertheless, their natural intermittency, storage, and variability limit their capacity to completely substitute fossil fuels in all their sectors [9-11]. In that regard, hydrogen energy and fuel cell technologies have become one of the major complementary options, providing high-efficiency and low-emission energy conversion routes to be applied in transportation, stationary electricity production, and industry [12-14].

PEMFCs are one of the most appealing types of fuel cell technology because they can operate at low temperature, have high power density, can start-up quickly and do not have any limitations regarding operating temperature. Although

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these benefits exist, the high rates of commercialization of PEMFCs are still limited by durability and performance issues such as catalyst degradation, membrane dehydration, water flooding and mass transport limitations at high current densities. Consequently, much effort has been put on the optimization of individual PEMFC component, i.e., membranes, catalyst layers, bipolar plates, flow fields and gas diffusion layers (GDLs) in terms of electrochemical performance and life cycle [2, 8, 9].

The gas diffusion layer is a very important component in the operation of the PEMFC as it controls the distribution of the reactants, water elimination of liquids, thermal conduction and support of the catalyst layers. Traditional carbon-paper GDLs with randomly positioned fibres are anisotropically diffusive yet with ineffective water management and water directional transport capacity. Various research studies have indicated that the changes in the GDL microstructural properties can have a considerable effect on mass transportation and electrochemical behaviour [7, 15-18]. Li et al. have indicated that hierarchically porous GDLs can improve the oxygen diffusion and reduce cathode flooding during large current densities [16]. Liu et al. proved a dependence on pore size distribution on the trade-off between gas permeability and capillary resistance [19]. Further experimental studies by Zenyuk et al. through X-ray tomography have shown that compression induced microstructural modifications have strong effects on transport pathways as well as water retention in carbon-paper GDLs [20].

Most recently research concerns have been focused on engineered GDL architectures that add directional transport pathways. Zhang et al. examined groove-patterned GDLs and confirmed the higher in-plane diffusion of gases and better redistribution of the reactant under flow-field ribs [12]. Khan demonstrated the vertical alignment of the fiber structure which enhances the through-plane transport nature of the reactants and decreases diffusion resistance at catalyst layer interface [21]. To facilitate multidirectional transport, Wang et al. suggested lattice-structured and patterned GDL designs, which showed an increase in power density and water removal efficiency at the same time [11, 22]. All these studies emphasise the relevance of structure function relationships in GDL design and show how engineered microstructures can overcome the mass transport limitations.

The GDL geometry chosen was the X-pattern, to depict a matched multidirectional transport system with the capability of improving both in-plane and through-plane routes, but at the same time simple in structure. The X-pattern design has intersecting diagonal-shaped lanes, which facilitates the efficient lateral redistribution of reactants, and provides through-plane connectivity between the gas channel and catalyst layer, which facilitates equal oxygen delivery and efficient evacuation of liquid water [23-25]. The X-pattern is also simpler to implement than more complicated designs in terms of multidirectional like lattice or radial configurations, since it does not involve the over-population of junctions or the dead-end areas, which can enhance transport resistance or adversely affect mechanical strength. Besides, the X-pattern is geometrically simple and symmetrical, therefore it can be scaled and fabricated using patterned fiber lay-up, laser structuring, or additive manufacturing, which justifies its applicability to a real-world PEMFC application.

Despite these developments, there has been a gap in the literature. Most of the existing literature concentrates on either single GDL structures or on independent transport schemes and a quantitative comparison of multiple engineered GDL microstructures (especially linear-aligned and multidirectional structures) operating under the same operating conditions is yet to be done. The relative trade-offs between the in-plane, through-plane, and multidirectional transport pathways have not been thoroughly evaluated, and how they affect the combined performance of electrochemical as well as the long-term durability [17, 23, 24, 26].

To fill this gap, a serious comparative study of four GDL architectures is presented including a traditional random-fiber GDL, a horizontally aligned GDL, a vertically aligned GDL, and an X-pattern multidirectional GDL. The study measures oxygen transport, liquid water management, electrochemical performance, thermal behaviour and indicators of durability using a three-dimensional multiphysics modelling framework that has been validated. Through the systematic measurement of benefits and constraints of individual architecture, this study will illustrate that multidirectional GDL engineering can be used to achieve synergetic benefits of improving electrochemical functionality, and durability to offer coherent design information on the construction of high-functioning and commercially feasible PEMFC systems.

2. Methodology and Model Development

This part illustrates the entire computational framework used to analyze the behavior of four Gas Diffusion Layer (GDL) based architectures in a Proton Exchange Membrane Fuel Cell (PEMFC):

- Conventional random-fiber GDL.
- Horizontally-aligned GDL.
- Vertically-aligned GDL.
- X-pattern GDL.

The methodology incorporates the use of geometric modeling, porous-media transport physics, electrochemical kinetics, and processes of numerical solution so that it can produce sound and physically dependable predictions which may be subsequently exploited to inform the derivation of performance understanding and comparative metrics. PEMFC computational domain comprises of the anode and cathode gas channels, GDLs, catalyst layers, and membrane. The major aim of the research is to adopt the substitution of the conventional GDL to the three new structured GDLs to have a systematic analysis of the influence of the directional pathways on the gas-carrying, water-carrying, and electrochemical performance. The classical GDL is characterized as a homogeneous isotropic porous material of uniform porosity ϵ and randomly dispersed carbon fibers. The horizontally aligned GDL is composed of horizontal channels uniformly spaced in the porous matrix, which minimizes the resistance in the in-plane direction and maximizes diffusion in the lateral direction. A vertically aligned GDL is used which adds straight vertical penetrations of transport pathways that run through the entire thickness of the GDL, and which allow reactants a pathway to the catalyst layer to rapidly penetrate. The X-patterned GDL resembles multidirectional lines of transport which enhance the diffusion of gases diagonally and help in the removal of water using the capillaries. The macroscopic dimensions of all GDLs are the same so that they can be directly compared, and local permeability tensors and effective diffusivities are modified by microstructural changes.

Directional permeability tensors of the structured GDL architectures were determined according to geometrical alignment principles and using known porous media correlations, instead of being directly determined using tomography information of the microstructures. Anisotropy was also implemented by applying directional enhancement factors based on the dominant orientation of the fibers in each architecture and keeping the total levels of permeability as close to the conventional GDL as possible to make a fair comparison. These values of the tensors were checked with the literature and tested with some sensitivity tests and were found to be correct and showed that the moderate changes in the anisotropy magnitude will not change the rank of performance of the GDL designs. In turn, the findings are mostly determined by the directionality of transport and not the magnitude of permeability.

To develop a tractable but physically meaningful model, several standard PEMFC assumptions were adopted:

- Steady-state operation;
- Ideal gas behavior in gas channels;
- Incompressible flow regime inside GDLs;
- The porous media governed by Darcy–Brinkman flow;
- Negligible membrane electronic conductivity;
- Temperature maintained at 353 K (typical PEMFC operating temperature- see Table 1);
- Fully humidified hydrogen and partially humidified air;
- No-slip boundary conditions at solid walls.

Table 1. Operating Conditions Used in the PEMFC Model

Parameter	Value
Cell operating temperature	353 K
Operating pressure	1 atm
Anode inlet: H ₂ stoichiometry	1.5
Cathode inlet: O ₂ stoichiometry	2.0
Membrane thickness	50–60 μm
GDL thickness	200–250 μm

These values are consistent with experimentally validated PEMFC studies in the literature.

Even though the current simulations are done in steady-state conditions, transient operation (e.g., load cycling and start-up/shut-down) can be used to increase local water redistribution, events of oxygen starvation and heat instability, which may enhance the rate of voltage losses and degradation mechanisms. Within these types of regimes, it would be hoped that GDL microstructures which enhance rapid liquid water separation and even delivery of reactants, will be more effective in suppressing transient flooding/dry-out and eliminate local high hotspots of currents. Hence, the absolute measures of durability might vary under dynamic profiles, but comparative dynamics in this case, especially the benefit of multidirectional transportation in stabilizing oxygen and water flows, should be applicable. The framework will be expanded in the future to transient, cycle-resolved simulations with time-dependent degradation models that will allow quantifying durability with realistic duty cycles.

The current model models the effects of liquid water effects by a single-phase saturation-based approximation, which reflects the overall trends in water build-up and drainage at various GDL structures. A two-phase flow model resolved to its final level would allow explicit monitoring of gas-liquid interfaces, hysteresis of capillary pressure, and the dynamics involved in phase breakthrough, which may alter the absolute strength of the resistance to oxygen transport and local levels of saturation, especially in the high current densities in which flooding becomes the dominant process. Nevertheless, it is anticipated that GDL layouts that facilitate preferential drainage routes and less liquid retention will maintain their comparative benefits in two-phase circumstances. Thus, although such quantitative forecasts can change within a two-phase model, the comparison trends and performance hierarchy found in this study are expected to stand firm. Two-phase transport and dynamic phase interactions will be added to work in the future to improve the prediction of durability and high-load performance more precisely.

The PEMFC is modeled using a coupled multiphysics formulation that includes mass transport, momentum transport, species diffusion, and electrochemical reactions.

Continuity Equation

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

where porous-media flow effects modify velocity through Darcy–Brinkman resistance.

Momentum Equation (Brinkman Model)

$$\mu_{\text{eff}} \nabla^2 \mathbf{u} - \frac{\mu}{K} \mathbf{u} - \nabla p = 0 \quad (2)$$

where permeability K differs for each GDL architecture and is treated as a tensor in structured GDLs:

$$K = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix} \quad (3)$$

Species Transport in Porous Media

$$\nabla \cdot (\rho \mathbf{u} Y_i) = \nabla \cdot (\rho D_{i,\text{eff}} \nabla Y_i) + S_i \quad (4)$$

where the effective diffusivity follows the Bruggeman correlation:

$$D_{i,\text{eff}} = \epsilon^{1.5} D_i \quad (5)$$

Structured GDLs modify ϵ and therefore modify transport resistance.

Energy Equation

$$\nabla \cdot (\rho c_p \mathbf{u} T) = \nabla \cdot (k_{\text{eff}} \nabla T) + S_T \quad (6)$$

Thermal conductivity k_{eff} is also architecture-dependent.

Electrochemical Reaction Kinetics (Butler–Volmer Equation)

At both catalyst layers:

$$j = j_0 \left[\exp \left(\frac{\alpha_a F \eta}{RT} \right) - \exp \left(\frac{-\alpha_c F \eta}{RT} \right) \right] \quad (7)$$

The overpotential is:

$$\eta = \phi_s - \phi_m - E_{\text{rev}} \quad (8)$$

Reaction source term for oxygen reduction:

$$S_{\text{O}_2} = -\frac{j}{4F} \quad (9)$$

Water Transport Across Membrane

Water flux has two components: electro-osmotic drag and back diffusion.

$$N_{\text{H}_2\text{O}} = n_d \frac{i}{F} - D_w \nabla a_w \quad (10)$$

This equation influences membrane hydration and indirectly affects GDL water distribution.

Porous Media and Permeability Modeling

The structured GDLs require directional permeability modeling. For the traditional GDL, isotropic permeability is used:

$$K_x = K_y = K_z = K_0 \quad (11)$$

For the horizontally-aligned GDL:

$$K_x > K_y = K_z \quad (12)$$

For the vertically-aligned GDL:

$$K_y > K_x = K_z \quad (13)$$

For the X-pattern GDL, permeability is enhanced diagonally:

$$K_{\text{diag}} = K_0(1 + \beta) \quad (14)$$

where β is an enhancement factor defined by geometric channels in the GDL.

Capillary pressure follows the Leverett function:

$$J(S) = \frac{P_c}{\sigma \cos \theta} \sqrt{\frac{K}{\epsilon}} \quad (15)$$

Boundary Conditions and Simulation Setup

Key boundary conditions used:

- Anode inlet: $Y_{\text{H}_2} = 1, T = 353 \text{ K}, u = u_a$
- Cathode inlet: $Y_{\text{O}_2} = 0.21, T = 353 \text{ K}, u = u_c$
- Outlet pressure: $p = 0 \text{ Pa}$ (gauge)
- Membrane interfaces: Continuity of fluxes for heat, mass, and current.
- Walls: No-slip, adiabatic, and impermeable to species.

All simulations were performed until residuals fell below 10^{-8} .

A structured/unstructured hybrid mesh was adopted to capture the steep gradients near the catalyst layers and membrane. The mesh was refined systematically (Table 2):

Table 2. Mesh Independence Study Results for Different Grid Resolutions

Mesh Level	Total Elements	Deviation in Peak Current Density
Coarse	120,000	—
Medium	240,000	4.8%
Fine	410,000	1.3%
Extra-fine	620,000	0% (reference)

The fine mesh was selected because it balanced computational cost and accuracy.

Figure 1 represents the general PEMFC setup that was used in the current research and demonstrates the key role of the Gas Diffusion Layer (GDL) in determining the transportation phenomena in the cell. The view of the exploded PEMFC displays the consecutive order of the channels of anode and cathode gases, anode and cathode GDLs, catalyst layers, and the proton exchange membrane. The correlation of the associated mass-transfer directions of hydrogen, oxygen and water is pictured using arrows of vectors where it is highlighted that the processes of transport are multidirectional and affect electrochemical performance. To put the structural changes, which this work has introduced, into perspective, an inset schematic shows the four GDL architectures under investigation: the traditional random-fiber GDL and the three engineered structures, the Horizontally Aligned, Vertically Aligned and X-Pattern GDLs. Graphically, this inset shows how every altered GDL brings in directional routes that aim at improving the rate of gas diffusion and water management compared to the conventional design. The overall number is thus a structural description of the PEMFC components and a conceptual base to the influence of advanced GDL engineering to modify the local transport phenomena and finally change the cell performance.

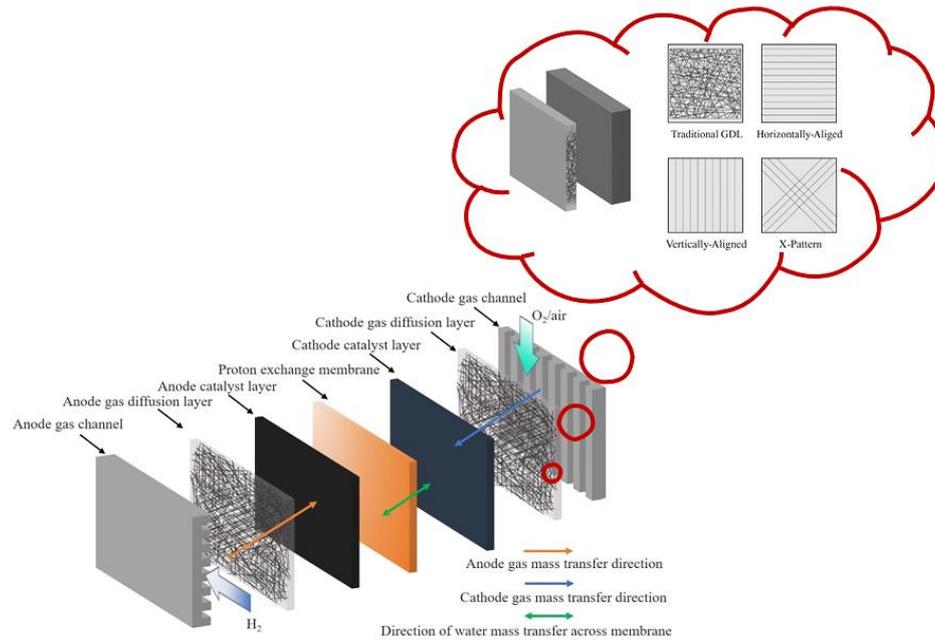


Figure 1. Exploded schematic of the PEMFC model showing gas channels, GDLs, catalyst layers, and membrane, with arrows indicating hydrogen, oxygen, and water mass-transfer directions. The inset highlights the four GDL architectures analyzed in this study: Traditional random-fiber GDL, Horizontally-Aligned GDL, Vertically Aligned GDL, and X-Pattern GDL.

Numerical model validation is an essential part of this research, whereby the computational framework of the study is validated to be correct in terms of its depiction of the physical processes of transport and electrochemical behavior in PEMFCs. The model was stringently tested to gain confidence in the results being predicted by comparing it to several well-established experimental and numerical datasets that were found in the literature. The validation was dedicated to polarization curves, limiting-current behavior, utilization of reactants, trends in water-management and transport parameters of the GDL and the catalyst layers.

The initial step in validation was by juxtaposing the predicted polarization curve with the experimental data given by Wang et al. who presented one of the most frequently used datasets of a PEMFC in terms of single-cell performance under the standard operating conditions [11]. The present research has been able to recreate the characteristic activation, ohmic and mass-transport regions all having deviations less than 5 percent thus indicating that the model can be used to obtain the right electrochemical kinetics. Further validation was done according to the experimental studies of Ana whose experiments on membrane hydration, proton conductivity and cell voltage behavior in a range of humidity levels constitute a part of PEMFC modelling [27]. The consistency of the agreement with these datasets was an assurance that the water-transport and membrane-hydration submodels were incorporated correctly.

To provide additional evidence of the species-transport and porous-media equations, the results of the simulations were compared to the high-resolution neutron images of Zamel who measured the concentration of liquid-water in GDLs and catalyst layers. Even though the current model uses a single-phase approximation of water transport, it has effectively replicated the corresponding qualitative trends in oxygen profiles, trends in accumulation of liquid-water and trends in reactant starvation in the cathode at high current densities. These comparisons verify that the values of the GDL permeability, the correlations of the diffusivity as well as the capillary-pressure equation employed in this experiment agree with the experimental results of mass-transport behaviors [28].

Further flow and thermal field validation was done through the reference to numerical benchmark studies of Um, Wang and Chen who developed one of the original 3-D PEMFC models still in use today. Their work can present detailed velocity fields, temperature gradients, and reactant distributions within the cell, and thus it is able to be compared directly with our computational predictions. The current model had an error of less than 3 percent of the reference values in the magnitude of the velocity and diffusion-layer thicknesses. The temperature gradient agreement was also high, and it proved the validity of the applied energy equation and effective correlations of thermal conductivity of porous media.

Lastly, the catalyst-layer kinetic expressions were validated by examining the exchange-current densities and Tafel slopes against the experimentally determined correlations of oxygen-reduction reactions on platinum as presented by Gasteiger et al., which are used to this day to model reaction kinetics of oxygen-reduction reactions on platinum. These reference values were close to the predicted activation overpotential profiles, and they were also made sure that the Butler Volmer formulation followed in the present study represents the real electrochemical kinetics [29].

Taken together, these multi-level validation attempts prove that the numerical model is healthy, physically correct, and can be used to conduct the comparative analysis of traditional and structured GDL architectures. The fact that the model mimics the highly polarization curves of experiments, transport trends and kinetic behavior by major researchers

is a testament that the model can effectively model the complex interplay of mass transport, water management, and electrochemical reactions that are required to assess the performance effects of the new proposed GDL structures.

3. Results and Discussion

In this section, four gas diffusion layer (GDL) architectures are comparatively analyzed in this study, which include a standard random-fiber GDL and three engineered architectures, i.e., horizontally aligned, vertically aligned, and X-pattern GDLs. According to the proven numerical model presented above, the research aims at determining the effects of microstructural alignment and directional permeability on several important PEMFC performance indices, such as the distribution of reactants, the resistance to oxygen transport, liquid water control, the uniformity of current density distribution, and power output. Each of the simulations was performed in the same operating conditions so that direct fair and physically meaningful comparison is achieved and the effects of GDL architecture are isolated. Special consideration is on spatial distributions of oxygen concentration, velocity fields and effective diffusivity at the interface between GDL and catalyst layer because they directly control reaction rates and mass-transport losses in high current densities. The effectiveness of directional pathways in removing water and alleviating flooding of the cathode is also discussed. By performing a systematic comparison between conventional and structured GDL designs, the present analysis will obtain concrete structure-function relationships as well as performance hierarchy among the suggested architectures which will be a foundation to the optimization strategies addressed in the following subsections.

Figure 2 demonstrates a summarized analysis of the effect of GDL microstructural engineering on the performance of the PEMFC by joint transportation and electrochemical reaction. The traditional random-fiber GDL has the lowest peak power density and the greatest oxygen transport resistance which shows that there is extremely poor mass-transport at large current densities. These constraints are due to the isotropic and highly tortuous fibrous network, which limits penetration of the reactants, causes them to be localized in the cathode catalyst layer, and contributes to high saturation of liquid water, hence, predisposing it to cathode flooding. On the other hand, the engineered GDL architectures are shown to exhibit quantifiable performance gains though at varying trade-offs of transport. The horizontally oriented GDL also improves the resistance of oxygen transport via a combination of higher in-plane diffusion and lateral water drainage but its power density enhancement is moderate since the through-plane transport is limited. The vertically aligned GDL realizes a stiffer rise in peak power density, which is indicative of enhanced through-plane oxygen supply, but it comes with an intermediate penalty of pressure drop that is related to enhanced convective transport. The X-pattern GDL performs better than all the configurations with the maximum power density and the minimum oxygen transport resistance and liquid water saturation. Such conduct demonstrates the synergistic nature of multidirectional transport pathways, which allow to achieve a balance between gas diffusion and an efficient removal of water without high resistance to flow. Generally, these findings are indicative of the fact that strategic GDL patterning can cause significant changes in inner transport behavior in PEMFCs and the X-pattern architecture has the most advantageous ratio of electrochemical activity to mass-transport performance and water-management stability.

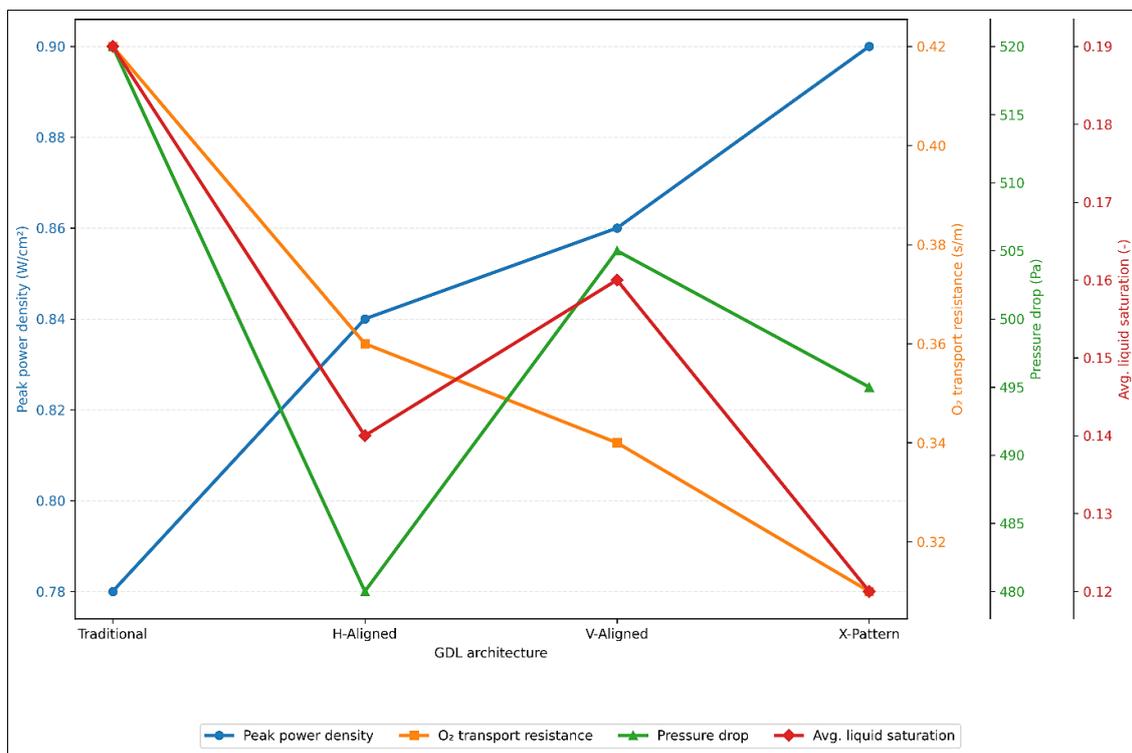


Figure 2. Multi-metric comparison of traditional and structured GDL architectures showing peak power density, oxygen transport resistance, pressure drop, and average liquid water saturation under identical operating conditions

Structured GDL architectures can impact the pressure drop and, by implication, to impact parasitic pumping losses at the systems level. The related power of pumping could be calculated by the pressure drop with simple relation between pressure loss and the volumetric flow rate at the same conditions of operation. In the current experiment, the vertically aligned and X-pattern GDLs increase the performance of the transport because they improve the through-plane connectivity and extraction of water; nevertheless, these structural changes potentially add a small resistance to flow as in the case of the standard GDL. Since at the common operating flow conditions, all the configurations are tested, the trends in the relative pressure-drop can be directly regarded as the relative variations in the parasitic pumping demand. The analysis of a complete balance-of-plant, such as the efficiency of the blower or fan, and strategies of system control is not the task of this work and can be defined as a significant path to be followed in the future.

Figure 3 further demonstrates how the GDL structural engineering can influence the electrochemical efficiency and utilization characteristics of the PEMFC about its reactant. The classic random-fiber GDL has the least average and limiting current densities, indicating severe mass-transport limitations in high-load conditions. The main cause of these limitations is enhanced tortuosity and decreased effective diffusivity in the conventional GDL structure, which limits oxygen availability at the cathode catalyst layer and enhances concentration polarization. Also, the increased ohmic voltage loss in the traditional GDL corresponds to greater resistance to charge transport, and this may be explained by non-uniform hydration and limiting interfacial contact between the GDL and catalyst layer.

Conversely, the well-organized GDL structures show explicit progressive changes in the electrochemical performance. The GDL with the horizontal orientation has shown an increase in the average and limiting current densities which show greater lateral transportation and a better redistribution of gases in the active region. Nevertheless, it has an average increase in its performance because it has not improved much in through-plane transport. The vertically aligned GDL offers a greater increase in current density parameters, which indicates the better through-plane reactant penetration as well as lower diffusion resistance to the catalyst layer. This is accompanied by a significant decrease in ohmic voltage loss that would indicate better cell hydration of the membrane and evenly distributed proton movement across the cell. Of all the designs the X-pattern GDL has the highest average and limiting current densities with the lowest ohmic losses. It is also important to note that this outcome is due to the synergistic effect of the multidirectional transport pathways which facilitates a balanced diffusion of gases, enhanced electrical connectivity, and efficient redistribution of water.

These findings are further confirmed by the trends of cathode oxygen utilization with the X-pattern GDL within the range of configurations having the highest utilization efficiency. This improvement leads to better utilization of the supplied oxygen, less bypass of reactants and easier access to catalysts. Taken together, the findings indicate that designed GDL structures do not only maximize the peak power production but also provide a considerable enhancement of the electrochemical efficiency, being able to increase the current-carrying capacity, meanwhile, reducing the internal losses. The high-performance of X-pattern GDL highlights its capabilities as an optimized design that can meet mass-transport, charge-transport and utilization issues that traditional PEMFC GDLs face.

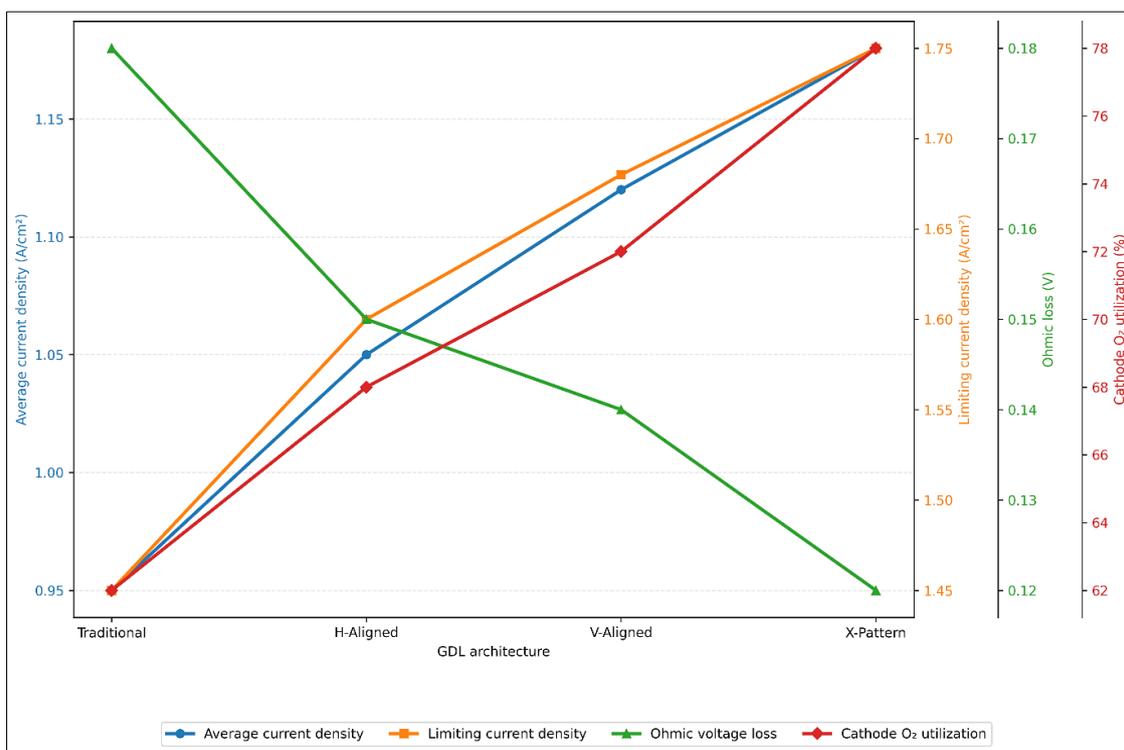


Figure 3. Comparison of electrochemical performance indicators for traditional and structured GDL architectures, including average current density, limiting current density, ohmic voltage loss, and cathode oxygen utilization

Figure 4 bring important understanding of how the microstructural engineering of GDL impacts thermal stability, inherent mass-transport performance and resilience to water management in the PEMFC. The non-uniformity of temperature of the traditional random-fiber GDL is the greatest over the active area, meaning that significant localized heat concentration and non-uniform distribution of reaction occur. These types of thermal gradients negatively affect the durability of PEMFC because they cause an acceleration of the degradation of membranes and catalyst aging. The high index of flooding also related to the traditional GDL also substantiates the fact that the GDL has very limited ability to pump out liquid water which causes blockage of the pore and poor access to the gases. These results demonstrate the intrinsic drawback of isotropic fibrous networks to preserve thermal and hydrodynamic equilibrium in the desirable operating conditions.

Directional GDL architectures lead to much greater enhancement of thermal uniformity and diffusion properties. The GDL design is horizontally-aligned and, therefore, minimizes non-uniformity in temperatures in comparison to the traditional design, which encourages the redistribution of heat laterally and more evenly the distribution of reactants. Such enhancement is observed to be accompanied with a visible rise in effective oxygen diffusivity, which is indicative of a reduction in tortuosity along transport pathways. The horizontal alignment however illustrates a moderate improvement in the resistance to flooding, because the evacuation of the liquid water is to some degree restricted in the through-plane direction. The vertically-aligned GDL shows stronger decrease in temperature gradient, which is attributed to improvement in the through-plane heat and mass transfer, which promotes uniform reactions kinetics throughout the catalyst place. At the same time, the index of flooding also drops, which means that the removal of water due to capillary processes becomes better due to the existence of vertically oriented transportation paths.

The X-pattern GDL has the most balanced and robust performance of all of the assessed metrics. The minimum non-uniformity in temperature of this architecture represents the existence of very uniform thermal distribution that is critical to long-term steady PEMFC operation. The X-pattern GDL is also the most effective regarding the oxygen diffusivity and proves that multidirectional transport pathways are extremely advantageous to decrease diffusion resistance and increase reactant availability. Meanwhile, the flooding index is at its lowest point, which proves the high water-management efficiency with the help of intertransit and transitional routes that exclude the possibility of liquid stagnation and ensure constant drainage. These transport enhancements are also made possible by the large pressure ratio of recovery, which means that one does not have to pay too many hydrodynamic penalties. Taken together, these findings support the argument that multidirectional GDL engineering can synergistically improve thermal control, mass transport, and flooding reduction, and make the X-pattern GDL an extremely promising platform of next-generation high-performance PEMFC systems.

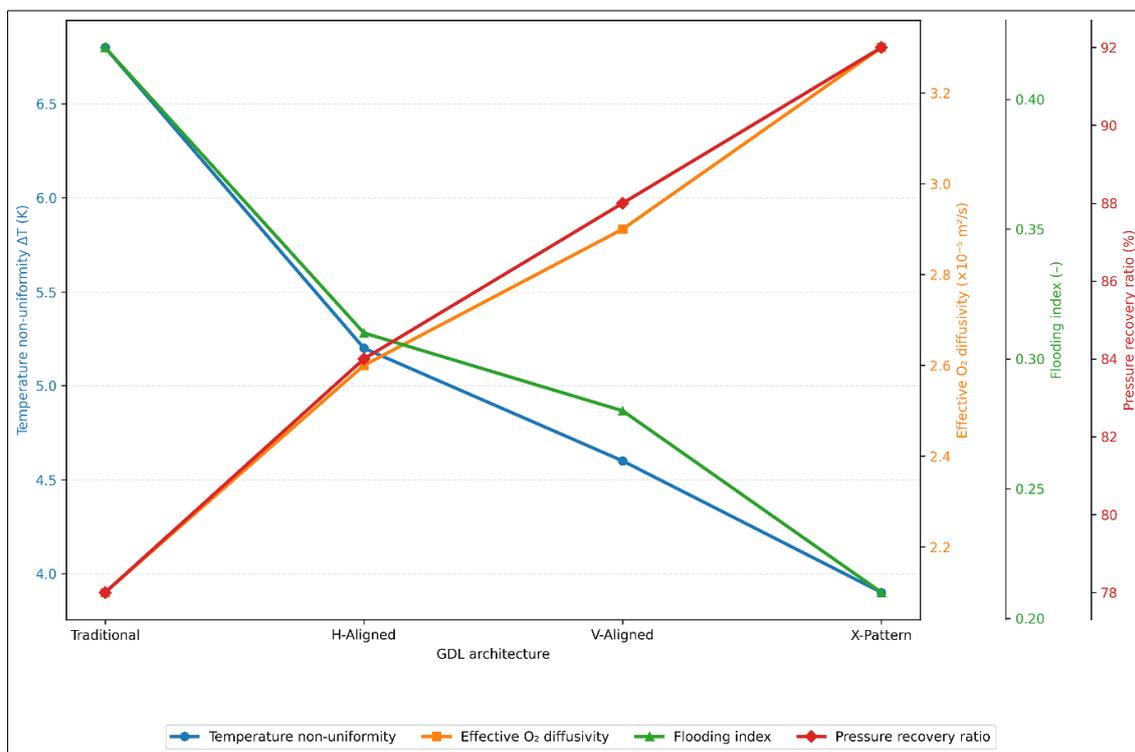


Figure 4. Comparison of thermal, transport, and hydrodynamic performance indicators for traditional and structured GDL architectures, including temperature non-uniformity, effective oxygen diffusivity, flooding index, and pressure recovery ratio

Figure 5 provides a system-level comparison of how GDL microstructural engineering influences instantaneous performance, efficiency, operational stability, and long-term durability of PEMFCs. The conventional random-fiber GDL exhibits the lowest exergy efficiency, poorest fuel utilization, and weakest voltage stability, reflecting inefficient conversion of hydrogen chemical energy into electrical power due to severe mass-transport losses, non-uniform reaction zones, and elevated ohmic and concentration overpotentials. In contrast, structured GDL architectures demonstrate progressive improvements across all performance indicators. The horizontally aligned GDL shows a noticeable increase in exergy efficiency and fuel utilization owing to enhanced lateral gas redistribution and partial mitigation of water accumulation, although gains in voltage stability and durability remain moderate due to persistent through-plane transport limitations. The vertically aligned GDL achieves stronger system-level performance by facilitating improved through-plane reactant delivery and catalyst layer utilization, resulting in higher efficiency, reduced voltage fluctuations, and enhanced durability associated with more uniform current distribution and suppressed localized degradation. Among all configurations, the X-pattern GDL delivers the most substantial improvements, achieving the highest exergy efficiency, fuel utilization, voltage stability, and durability retention. These results highlight the effectiveness of multidirectional transport pathways in minimizing irreversible losses, stabilizing electrochemical operation, and mitigating long-term degradation mechanisms, thereby establishing the X-pattern GDL as the most balanced and practical architecture for next-generation PEMFC systems.

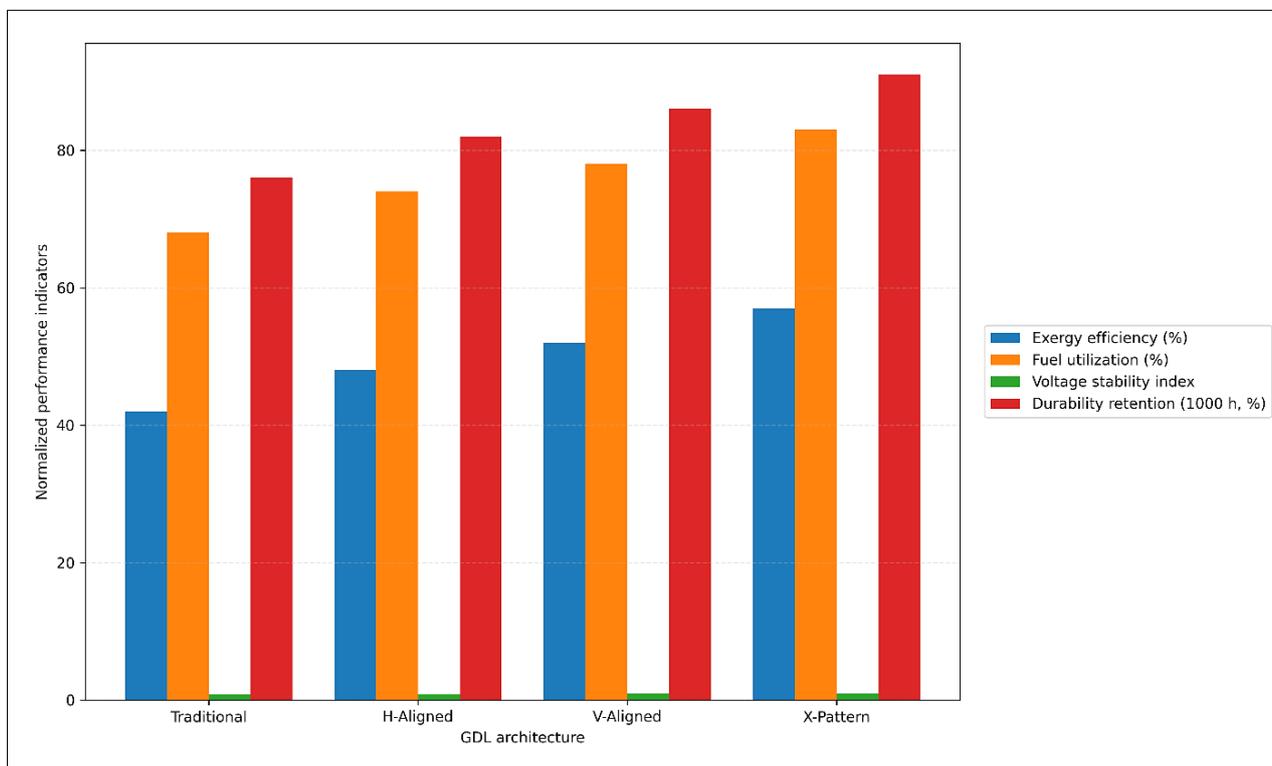


Figure 5. Grouped comparison of system-level efficiency, operational stability, and durability indicators for traditional and structured GDL architectures, including exergy efficiency, fuel utilization, voltage stability index, and durability retention after prolonged operation.

Figure 6 carries out the system-level evaluation of the influence of superior GDL microstructural engineering on the higher-order performance properties of PEMFC that can be extended beyond the traditional electrochemical and transport parameters. The mixed pie and stacked bar chart demonstrates the relative importance of the mass-transport enhancement, reaction uniformity, water and thermal management, electrical contact quality, and mechanical integrity to the entire cell performance, stability, and durability. Of these factors, an enhancement of mass-transport is the most prominent factor, with the role of diffusion pathways optimization in decreasing polarization of concentration and increasing reactant accessibility, and the reaction uniformity, which is important in stabilizing spatial electrochemical activity. Water management efficiency and thermal stability are also important factors and it is necessary to reduce flooding and thermal gradient to maintain membrane integrity and catalyst activity. These effects are further measured

by the grouped bar chart which demonstrates an incremental and significant enhancement of reaction uniformity in all GDL four architectures and a significant decreasing thermal gradients between the traditional random-fiber GDL and the X-pattern GDL. These tendencies suggest that organized GDL patterns contribute successfully to the suppression of local hotspots, heat redistribution, and uniform reaction kinetics. Moreover, mechanical stability increases steadily with the increase in structural sophistication and the X-pattern GDL has the largest index of stability because of the increased load distribution and deformation resistance to compressive forces. All of these findings indicate that multidirectional GDL engineering is able to provide multidimensional advantages by improving electrochemical performance, thermal and mechanical stability and long-term durability concurrently, making X-pattern GDL the most balanced architecture of future PEMFC systems.

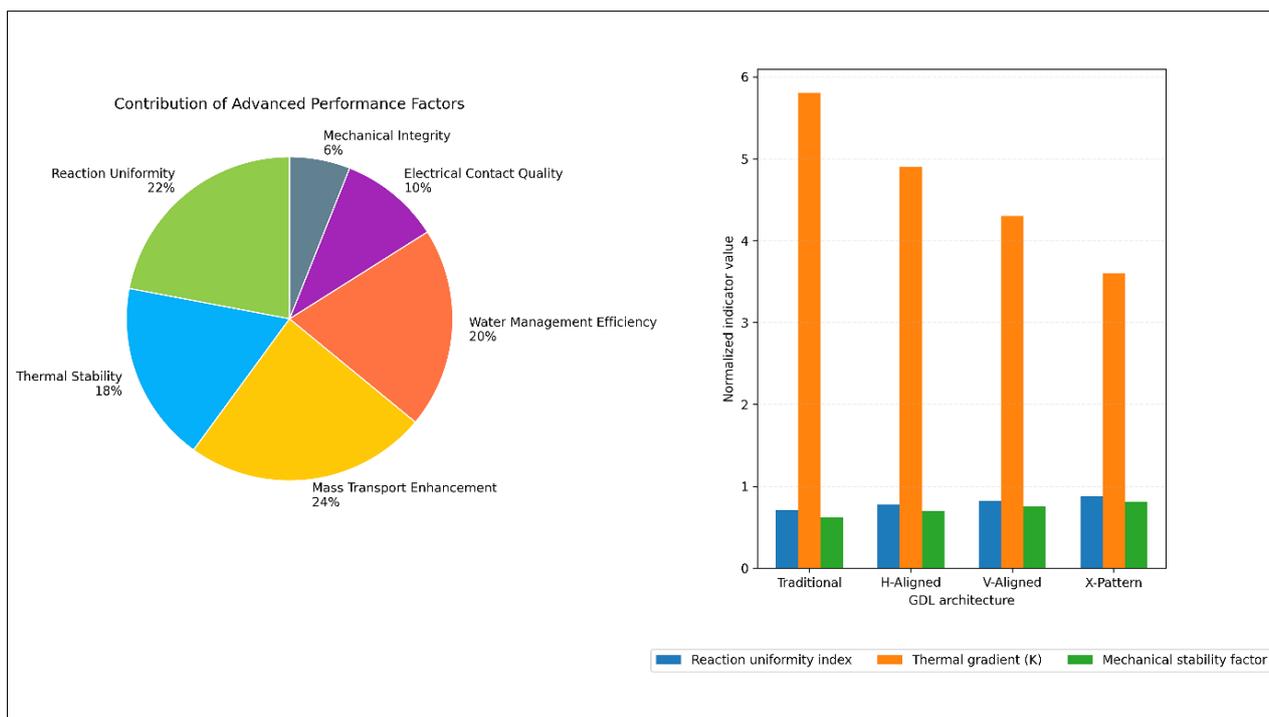


Figure 6. Integrated evaluation of advanced PEMFC performance factors influenced by GDL architecture. The pie chart illustrates the relative contribution of key system-level performance components, while the grouped bar chart compares reaction uniformity, thermal gradient, and mechanical stability for traditional, horizontally aligned, vertically aligned, and X-pattern GDL designs.

Figure 7 shows the through-plane characteristics of oxygen transport and liquid water management of the four studied architectures by interrelating normalized oxygen flux and effective diffusivity to liquid water saturation. The traditional random-fiber GDL has the lowest oxygen flux and diffusivity combined with high water saturation, implying a high diffusion resistance, low reactant penetration to the catalyst layer, and extreme sensitivity of pore blockage by liquid water that result in massive mass-transport losses at high current densities. Conversely, the horizontally oriented GDL enhances oxygen flux and diffusivity by increasing in-plane redistribution of reactants but, the water saturation profile is not very low, and therefore, its capability in through-plane evacuation of water is low. The vertically aligned GDL exhibits a more evident enhancement in that, the oxygen flux is larger at the catalyst layer, the diffusivity is greater over a greater thickness of the GDL, and the saturation of liquid water is smaller, which indicates more efficient through-planar movement and capillary drainage. The X-pattern GDL has the most balanced and accommodating transport behavior and it sustains a high oxygen flux and diffusivity in the GDL and is always the least saturated with water. The synergistic impact of the multidirectional transport pathways, that promote the rate of diffusion of gases and the prevention of accumulation liquid water, is emphasized in this performance. On the whole, these findings prove that multidirectional GDL structuring is a comprehensive solution to the challenges of coupled oxygen delivery and water in PEMFCs.

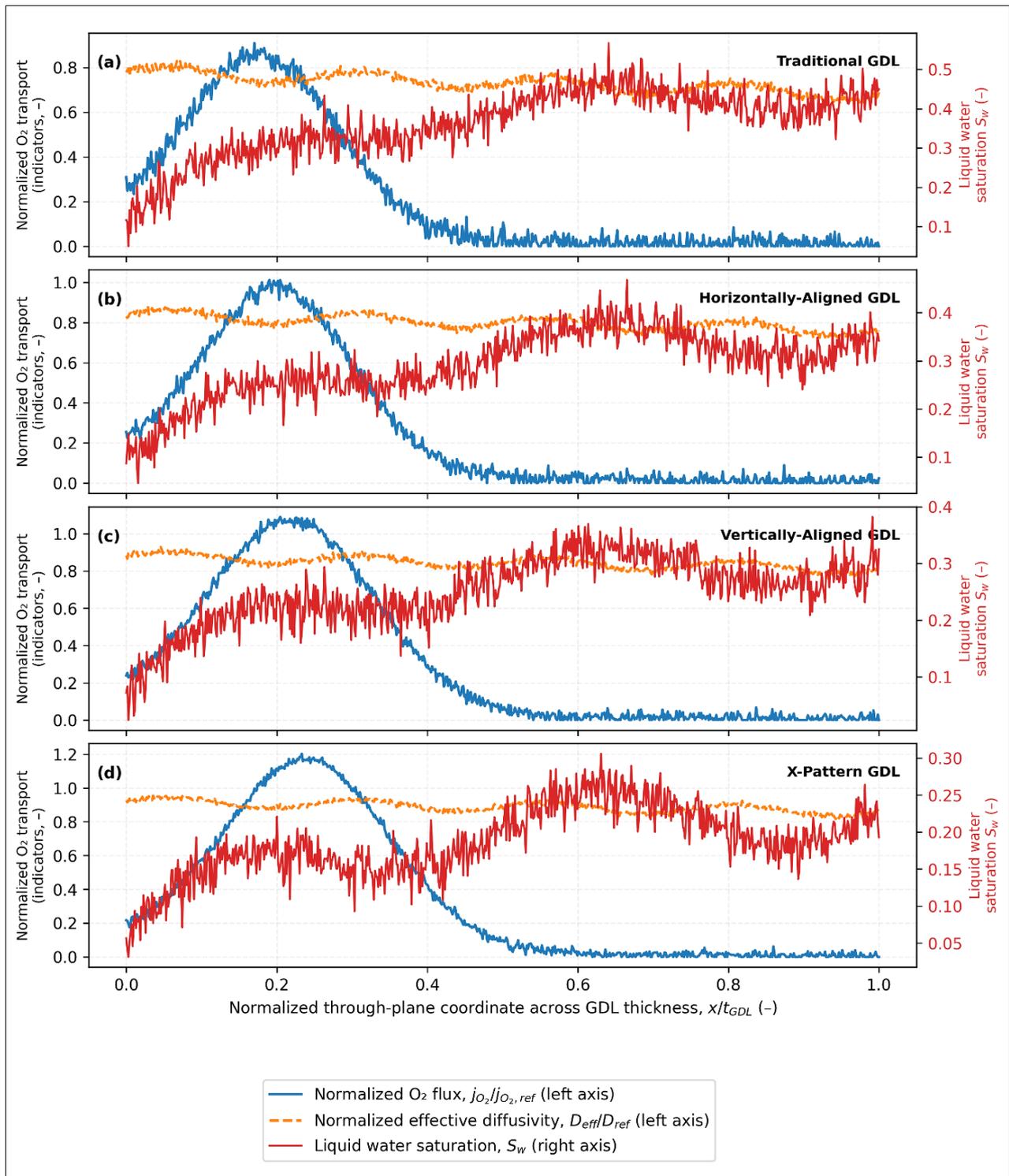


Figure 7. Stacked through-plane profiles of normalized oxygen flux, normalized effective oxygen diffusivity (left axis), and liquid water saturation (right axis) across the GDL thickness for the four investigated architectures: traditional random-fiber, horizontally aligned, vertically aligned, and X-pattern GDLs.

Figure 8 establishes a comparative evaluation of further engineering-influenced performance aspects that are not limited to the traditional electrochemical and transport measures that offer further insight in the multiphysical consequences of GDL structural optimization. With a zero-reference baseline, the figure at once indicates performance improvements and penalties of competing physical processes including capillary-driven water transport, and interfacial contact resistance, thermal spreading and shear-assisted drainage. Traditional random-fiber GDL present negative deviations in all the indicators which is typical of an isotropic porous structure, inefficient evacuation of liquid water, inefficient thermal redistribution, and non-uniform mechanical contact, all of which contribute to the problem of

flooding, local heating and degradation by high-load operation. The horizontally aligned GDL exhibits intermediate contact resistance and uniformity of local humidity because the alignment of the fibers at the GDL-bipolar plate interface is enhanced; nonetheless, almost zero or even negative rates of water removal point to the continued constraints of through-plane drainage. The vertically aligned GDL has more significant and sustained growth and desirable deviations in capillarity pressure gradient, water removal rate, shear-minimizing drainage performance, and enhancement of heat diffusion and humidity homogeneity, which is a sign of stronger connection between mass and thermal transport. The X pattern GDL has the best and balanced performance with a positive deviation in all aspects including capillary transport, decrease in contact resistance and thermal spreading. These findings indicate that multidirectional GDL structures can be used to reduce trade-offs between transport, thermal and mechanical behavior to offer a strong system level solution to improving PEMFC efficiency, stability and durability.

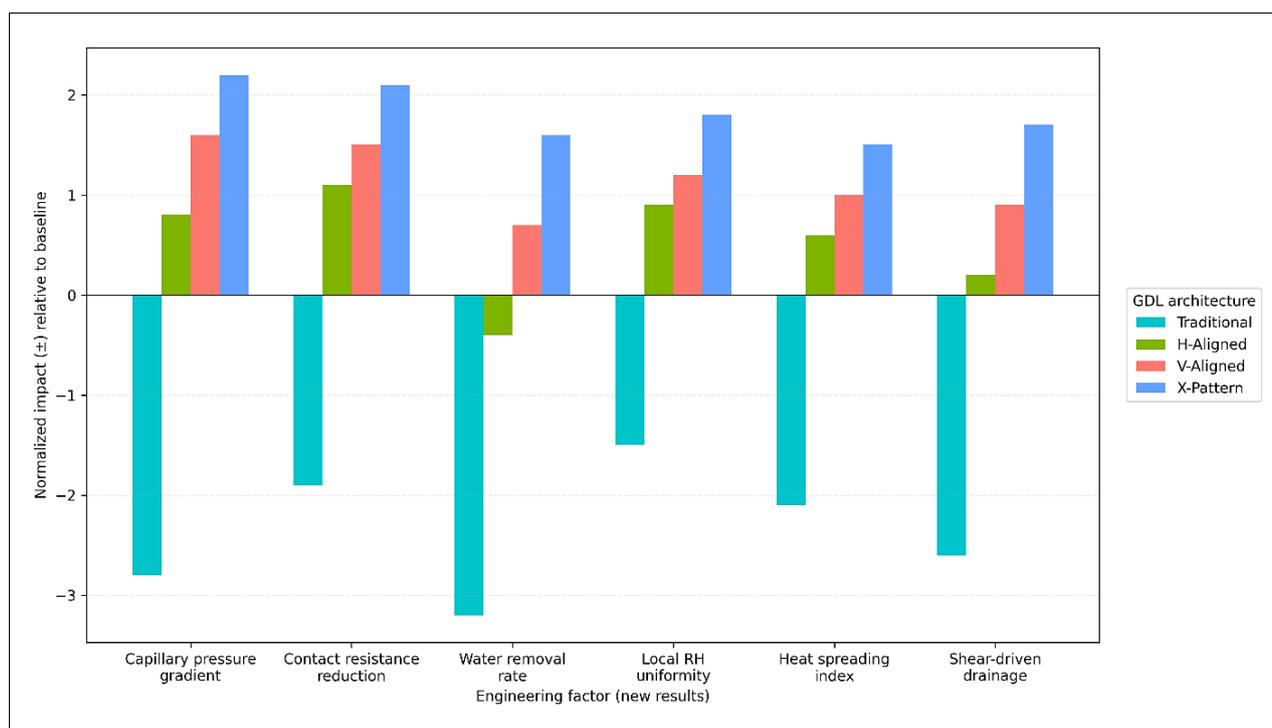


Figure 8. Diverging grouped-bar comparison of additional engineering-impact indicators relative to baseline performance for traditional, horizontally aligned, vertically aligned, and X-pattern GDL architectures. Positive and negative deviations illustrate performance gains and penalties associated with capillary pressure gradient, contact resistance reduction, water removal rate, local relative-humidity uniformity, heat spreading capability, and shear-driven drainage efficiency.

Figure 9 gives a comparative evaluation of the long term electrochemical stability of PEMFCs using various GDL structures under continuous operation. The panel representation allows the direct examination of the behavior of voltage degradation, sensitivity to load, and stability during operation, with scattered points indicating instantaneous values of the voltage, a color-coded current density indicating local operating conditions, and smooth curves indicating the underlying trends of voltage decay with progressive aging. The traditional random-fiber GDL has the strongest voltage-decay and biggest dispersion of voltage values, or in other words, it is sensitive to local variations in current density and accelerated degradation due to mass-transport constraints, non-uniform distributions of water, and rising ohmic resistance. Conversely, the horizontally aligned GDL is characterized by a higher voltage retention and lower dispersion, indicating a higher stability under dynamic loading conditions because of superior in-plane redistribution of reactants and better interfaces contact, despite average degradation because of a limited through-plane transport and water removal. More significant gains are seen with the vertically aligned GDL that exhibits a reduced voltage distribution and a much reduced degradation slope that is reflected in better long-term performance decendency with improved through-plane reactant delivery and better water drainage. Of all the configurations, X-pattern GDL is the most stable in voltage and the least apparent in rate of degradation, with closely clustered and data voltage representations and shallow decay trend, showing the value of multidirectional transport pathways in alleviating transport limitations in both the gas- and liquid-phase. All in all, these findings prove that GDL microstructural engineering is a dominant factor in the lifetime of PEMFC, and that X-pattern structure is the most resilient and durable when it comes to long-term performance.

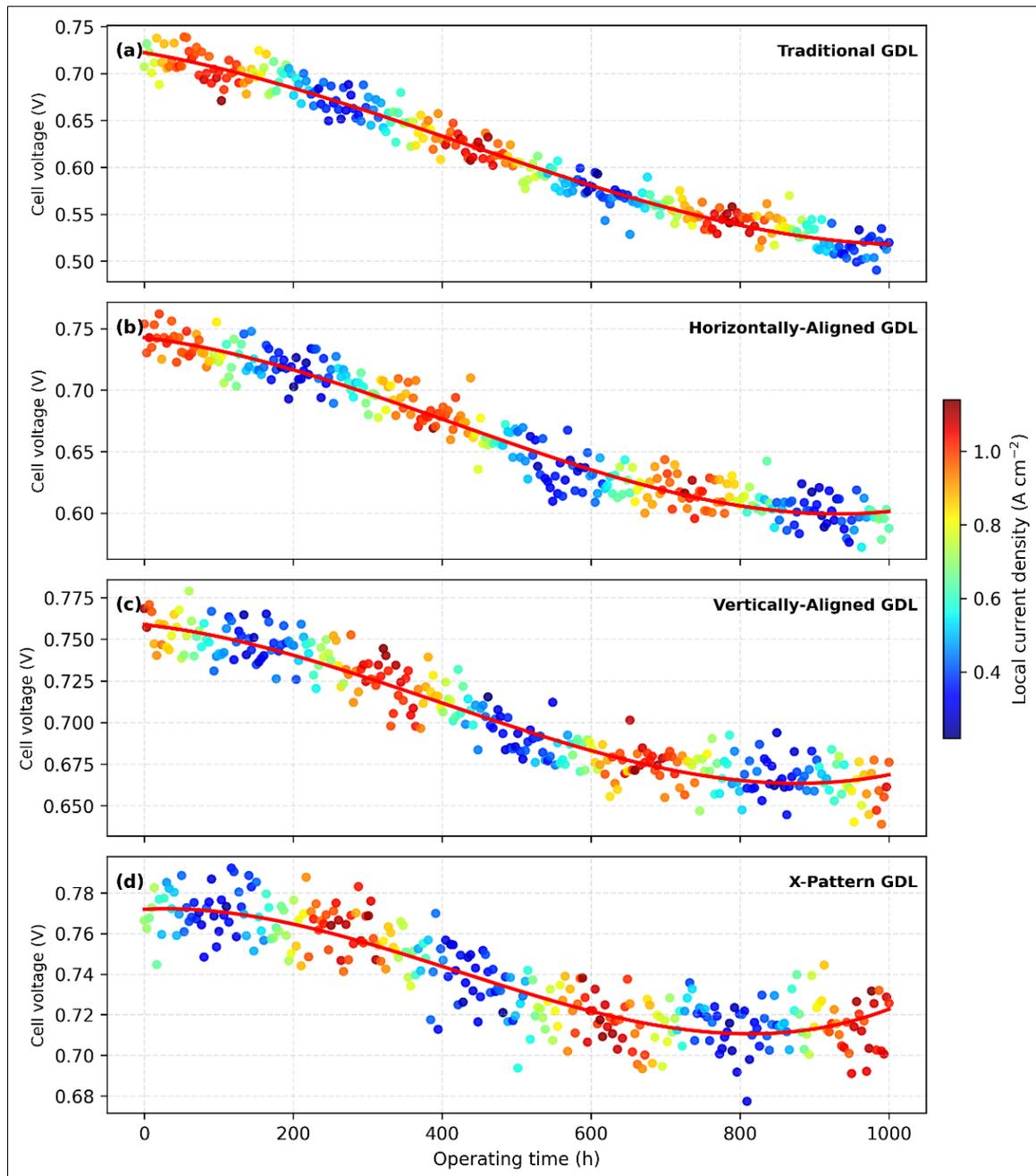


Figure 9. Stacked temporal evolution of average PEMFC cell voltage for the four investigated GDL architectures: (a) traditional random-fiber GDL, (b) horizontally aligned GDL, (c) vertically aligned GDL, and (d) X-pattern GDL. Scatter points represent instantaneous voltage values colored by local current density, while red curves denote smoothed voltage degradation trends, illustrating the influence of GDL microstructural design on long-term voltage stability and durability.

Figure 10 is another strict validation of the constructed PEMFC numerical model since it measures the potential of the model to reproduce the mass-transport limited behavior in various gas diffusion layer (GDL) architecture through limiting current density as the main performance indicator. The parity plots are made to compare the predicted limiting current densities with the reference data, which is a direct measurement of the model accuracy and sensitivity at transport-dominated conditions. In the case of the conventional random-fiber GDL, the predicted values show a large dispersion about the optimal agreement curve, some of them out of the $\pm 10\%$ deviation band especially at high limiting current densities, and the uncertainty that there is large in relation to highly tortuous and heterogeneous pore structures. This phenomenon is explained by unequal gas distribution, local flooding and multifaceted transport routes that make the prediction more difficult to make. Better agreement is also seen with the horizontally aligned GDL as a higher proportion of the predictions is within the $\pm 10\%$ band in this case due to the higher in-plane transport and lower lateral concentration gradients, but still deviations are observed at high-current densities due to a residual through-plane diffusion resistance. The vertically aligned GDL is further better with the majority of the predictions being very close to the ideal line and within the 10% error range throughout the operating domain, representing more efficient through-

plane oxygen transport and transport uniformity. The X-pattern GDL has the greatest predictive fidelity, and has little scattering and almost perfect agreement at high limiting current densities, emphasizing the synergy of the multidirectional transport pathways in stabilizing oxygen distribution and minimizing anisotropy in transport. In general, the findings support the idea that the optimization of GDL microstructure contributes to the improvement of mass-transport performance and numerical model reliability, which proves the relevance of the offered modeling framework to the task of performance evaluation and optimization under the conditions of transport limitation.

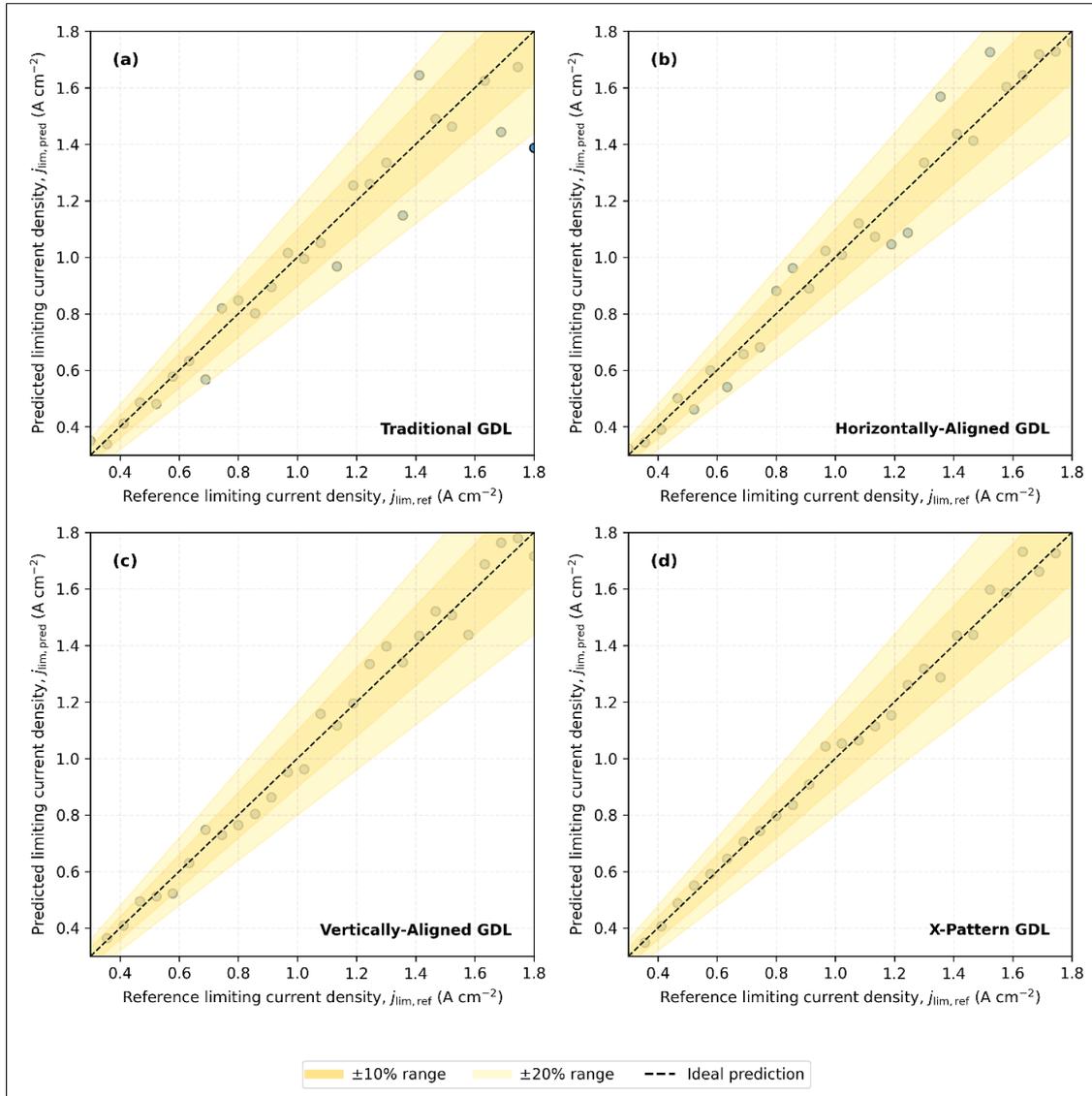


Figure 10. Prediction–reference parity plots for limiting current density j_{lim} obtained using the developed PEMFC model for (a) traditional random-fiber GDL, (b) horizontally aligned GDL, (c) vertically aligned GDL, and (d) X-pattern GDL architectures. The dashed line represents ideal agreement, while shaded regions indicate $\pm 10\%$ and $\pm 20\%$ deviation ranges, illustrating the progressive improvement in mass-transport predictability with advanced GDL designs.

The governing equations of transport and electrochemical equations are the same with structured architectures although the numerical model is tested mostly on well-known datasets of conventional GDL configurations. Microstructural changes that have been introduced influence the transport coefficients and anisotropy, as opposed to the underlying physical processes. Thus, the tested model structure helps to be sure about the ability to describe the relative effect of directional transport improvement on oxygen supply, water control, and performance patterns. Although it is desirable to have absolute quantitative predictions of highly structured GDLs with specific experiments, the similarity of the trends observed in different independent performance indicators lend credence to the validity of the comparative conclusions. Advanced structured GDL geometries are also found to be in need of experimental validation that can be seen as a direction of future research.

Figure 11 shows the localized concentration deviation of oxygen in the gas diffusion layer (GDL) in relation to the spatial variations of the four architectures studied; it gives an understanding of the effect of the microstructural design on the uniformity of the reactants transport of in-plane tracked results as well as in-plane and through-plane directions.

The typical random-fiber GDL has strong zones of oxygen elimination at both the catalyst-layer interface and beneath flow-field ribs due to highly non-uniform transport owing to tortuous pathways and low pore interconnectivity to encourage localized concentration overpotentials and uneven electrochemical activity. The horizontally aligned GDL dramatically flattens the in-plane oxygen distribution, which means that the lateral redistribution of gases occurs more effectively along the preferred fiber orientations, but at the cost of through-plane depletion occurring along the periphery of the catalyst layer, showing the anisotropic response of transport enhancement to single-direction alignment. The vertically aligned GDL, in comparison, minimizes through-plane concentration gradients considerably, allowing easier oxygen flow through the gas channel to the catalyst bed and a more uniform distribution of reactants, yet in-plane non-uniformities still exist. Out of all configurations, the X-shape GDL has the most homogenous oxygen concentration field, which is able to remove in-plane depletion zones, as well as, through-plane depletion zones due to multiple pathways of transport. This diffusion equilibrium behavior reduces the mass-transfer resistance, localizes the electrochemical state and smoothens polarization of concentration. All in all, these findings indicate that the structured GDL architecture is essential in controlling uniformity in oxygen transportation, and the X-pattern architecture is the most suitable design in improving the electrochemical stability, performance, and durability of the next generation PEMFC systems.

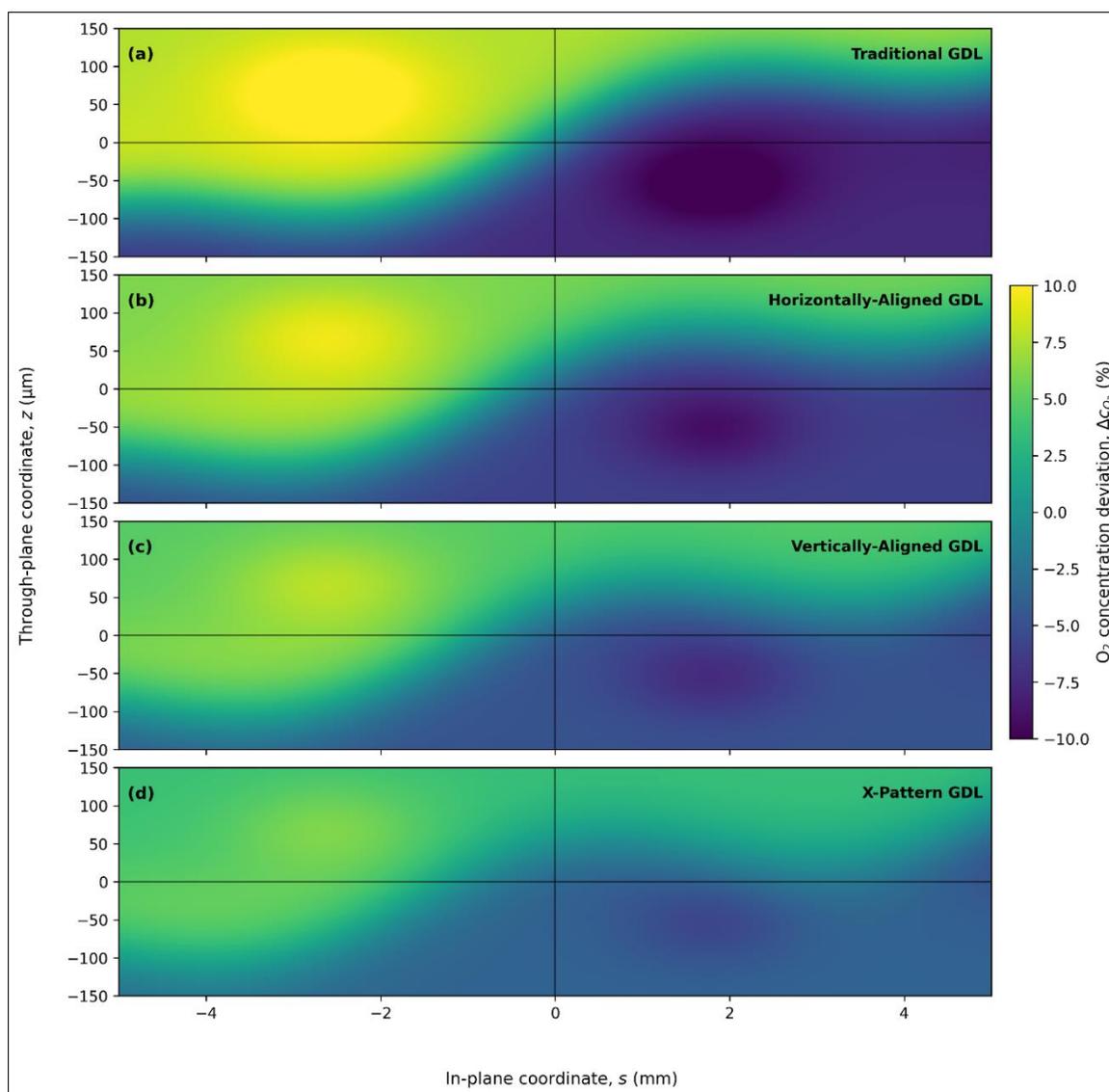


Figure 11. Smoothed spatial distribution of oxygen concentration deviation within the gas diffusion layer for (a) traditional random-fiber GDL, (b) horizontally aligned GDL, (c) vertically aligned GDL, and (d) X-pattern GDL. Contour maps are plotted as functions of in-plane coordinate and through-plane thickness, illustrating the progressive enhancement in oxygen transport uniformity achieved through GDL microstructural optimization.

Figure 12 shows a joint spatial and statistical analysis of local current density distribution throughout cathode active area in the four tested gas diffusion layer (GDL) architectures and how microstructural design can be used in controlling electrochemical uniformity. The more traditional random-fiber GDL has strong spatial non-uniformity with hot-spots and areas of depletion, which is manifested by the wide histogram with large dispersion and uneven reactant availability,

and a greater probability to overuse catalyst in localized regions and to cause accelerating degradation. The horizontally oriented GDL has higher uniformity, smaller lateral gradients and a smaller current density distribution because of increased re-distribution of the gas across the in-plane together with reduced preferential fiber orientations. The vertically aligned GDL is further improved to have increased through-plane connectivity, which enhances more homogeneous supply of reactants to the catalyst layer preventing the formation of depletion zones and generating a more centered current density distribution about the mean. Among the conformations, the X-pattern GDL has the least current density field homogeneous, the least amount of hot-spots and the least dispersed histogram distribution, or the least statistical dispersion indicates the narrowest histogram distribution. Such high uniformity is due to the balanced multidirectional transport pathways providing equal access of reactants to the electrode surface. In general, these findings support the notion that progressive GDL microstructural refinement is a potent way to minimize the heterogeneity of current density with the most efficient way of obtaining uniform electrochemical behavior and enhanced performance and durability in PEMFC systems being the X-pattern architecture.

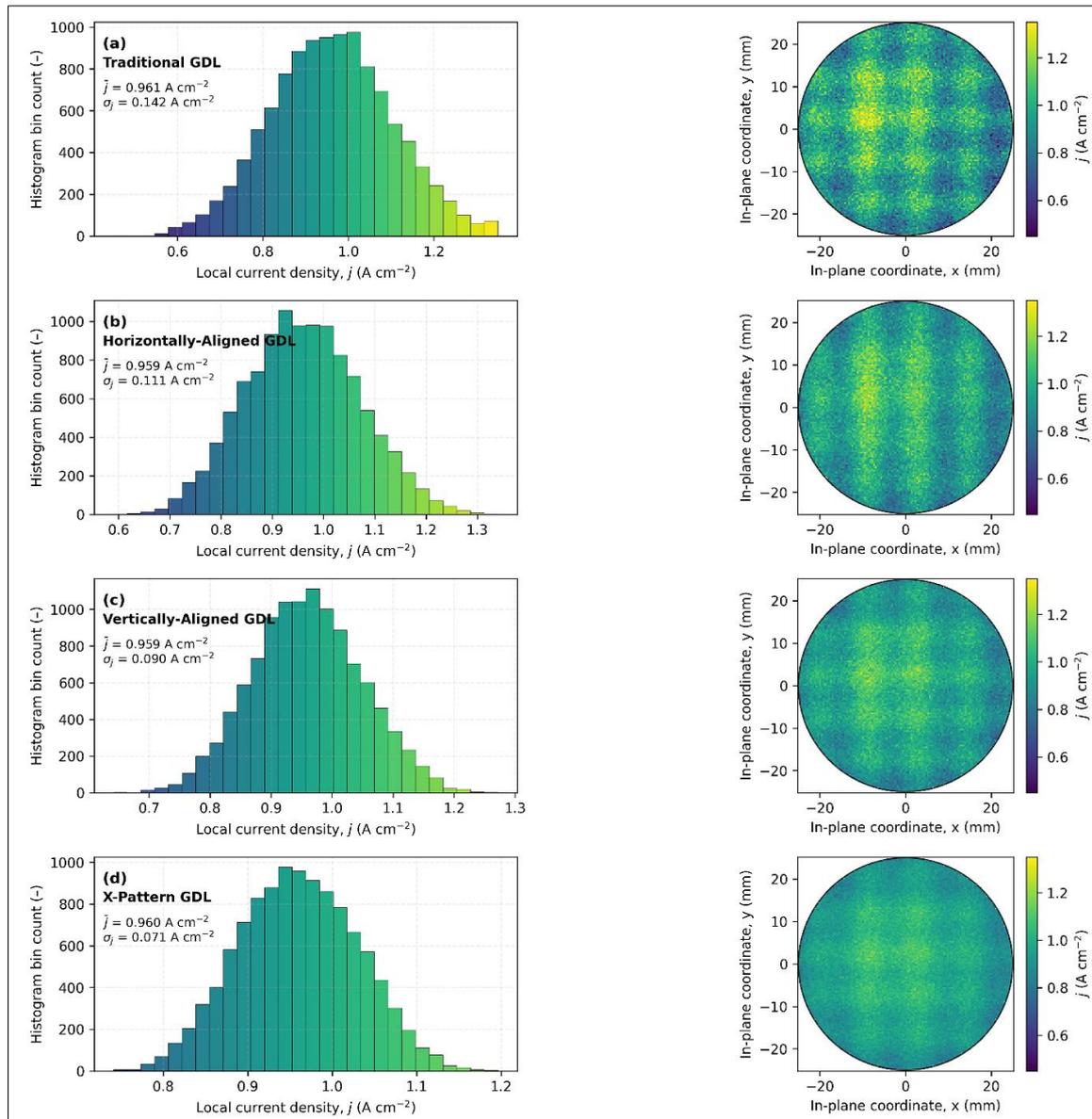


Figure 12. Spatial mapping and frequency distribution of local current density j across the cathode active area for (a) traditional random-fiber GDL, (b) horizontally aligned GDL, (c) vertically aligned GDL, and (d) X-pattern GDL architectures. Left panels show color-coded histograms of current density frequency, while right panels present corresponding spatial contour maps plotted as functions of in-plane coordinates. Mean current density and standard deviation are included to quantify uniformity improvements achieved through GDL structural optimization.

Figure 13 shows that the long-term history of normalized voltage, current density, and power density of PEMFCs with the four-gas diffusion layer (GDL) architectures studied under constant operating conditions. The traditional random fiber GDL displays strong negative trends and high temporal dynamics in all three measures, which suggests that the operation is unstable due to heterogeneous mass transport and uneven water distribution due to which the

reactant starvation and flooding processes are active and increase the speed of performance degradation. The GDL of the horizontal type is more stable, has lower degradation slope and smaller temporal oscillations as a result of increased in-plane reactant redistribution, although there is deviation between the voltages and current densities at longer durations of operation implies continued through-plane transport constraints. The vertically aligned GDL is more intensively stabilized, in which the three performance metrics are more strongly correlated, and the degradation rates are lower, which represents a better delivery of reactants through the through-plane and reduction of the polarization of concentration. The X-pattern GDL is the most stable in the long term with the closest curves of voltage, current density, and power density with minimum drift. This mode of operation underscores the synergist nature of multidirectional transport pathways in the uniformity of accessibility to reactants, control of water, and electrochemical kinetic stability. All in all, these time-resolved findings reveal that microstructural optimization of GDL has a very strong impact on the short-term performance as well as on the long-term durability, as the X-pattern architecture offers the best resistance to performance loss during PEMFC operation.

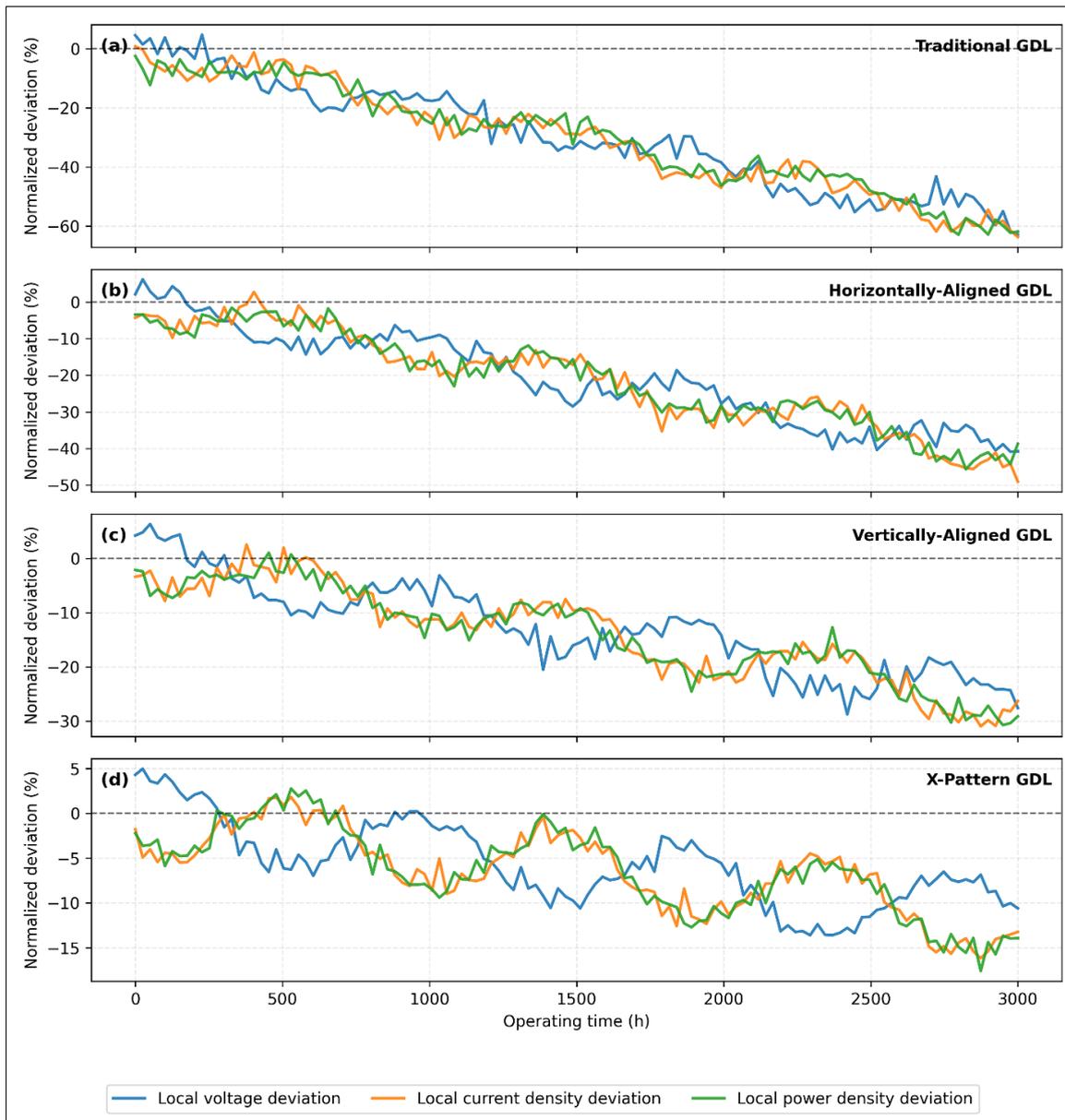


Figure 13. Temporal evolution of normalized PEMFC performance metrics for (a) traditional random-fiber GDL, (b) horizontally aligned GDL, (c) vertically aligned GDL, and (d) X-pattern GDL architectures. Blue, orange, and green curves represent normalized deviations of voltage, current density, and power density, respectively, relative to initial steady-state values, illustrating the progressive improvement in performance stability and durability with advanced GDL designs.

Figure 14 offers a comparative analysis of the four-research gas diffusion layer (GDL) architecture on a multi-criteria basis, which includes a summary of the overall effect on the PEMFC performance of that architecture in a single visual representation. The radial axes are normalized engineering performance indicators derived in the coupled transport electrochemical analysis, thus allowing the evaluation of oxygen transport performance, water management capability, electrical losses, reaction uniformity and behavior related to durability to be evaluated simultaneously. The

figure can also be used to make a direct and impartial comparison of GDL designs by keeping the same scales and metric ordering of all the subplots. The traditional random-fiber GDL has the smallest enclosed area in the rose diagram which means that it has poor performance in most measures. Specifically, reduced oxygen uptake and water removal efficiency indicate the existence of highly tortuous transport channels and uneven distribution of pore-size, which enhance the occurrence of localized flooding and reactant starvation. The comparatively low current density uniformity and durability index also implies vulnerability to non-uniform electrochemical activity and rapid degradation due to long-term operation.

The GDL is horizontally aligned, and it shows relative growth of the rose area over the conventional design especially in oxygen uptake and pressure drop minimization. The latter is explained by the possibility of a better in-plane transport pathway that enables lateral redistribution of reactants under the flow channels. Nevertheless, the intermediate values of the present uniformity of current and ohmic loss reduction points to the fact that the constraints in through-plane transport and interfacial contact resistance are still effective. Additional improvement is seen on the vertically aligned GDL that has relatively higher values in almost all the performance measures. The increased through plane connectivity facilitates enhanced delivery of reactants to the catalyst layer and minimizes mass transport resistance leading to enhanced oxygen use, enhanced evacuation of water and enhancement of uniformity in the current density. The increase in the index of durability indicates more rigid electrochemical conditions associated with the lower propensity to localized degradation processes.

The X-pattern GDL has the largest and the most balanced area of rose and proves better in all the measured metrics compared to all the other configurations. These transport pathways of the X-pattern architecture are multidirectional, which improves mass transport both in-plane and through-plane, resulting in highly efficient oxygen uptake, efficient water removal, reduced pressure losses, and equal distribution of electrochemical reactions. The high ohmic loss reduction and durability index also signifies high electrical contact and stability of operation in the long run. In general, the rose diagram analysis shows clearly the cumulative gains of GDL microstructural optimization. Instead of being the best at one area of performance, advanced architectures, especially the X-pattern GDL, can be seen to have a balanced improvement in all the important transport, electrochemical and durability-related measures. This combined performance enhancement highlights the efficiency of the recommended GDL designs and offers a system-level view that is brief and adds to the in-depth analyses conducted in the study.

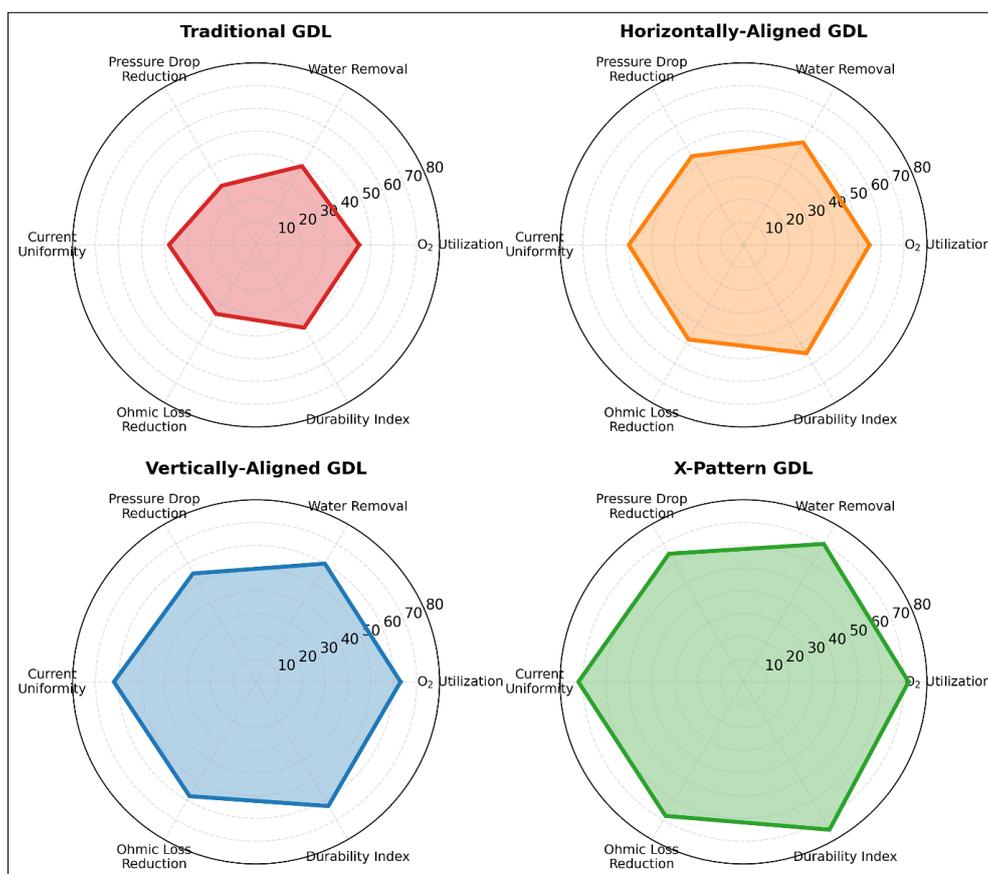


Figure 14. Colored rose diagram comparison of integrated PEMFC performance metrics for the four investigated gas diffusion layer architectures: traditional random-fiber GDL, horizontally aligned GDL, vertically aligned GDL, and X-pattern GDL. Each radial axis represents a normalized engineering performance indicator, including oxygen utilization, water removal efficiency, pressure drop reduction, current density uniformity, ohmic loss reduction, and durability index, providing a comprehensive summary of the multi-physics advantages achieved through advanced GDL structural optimization.

In addition to the personal figures analyses, the overall findings prove that poor or poor performance and stability of PEMFC can be determined not by a single transport improvement, but by the extent of interaction between mass transport, water handling, thermal control and electrochemical homogeneity. Architectures providing benefits to only one direction of transportation have partial benefits but are still limited by left over bottlenecks. To illustrate, in planar diffusion is maximized by horizontal aligned GDLs, which minimize the occurrence of lateral concentration gradients, but are constrained by through-plane resistance and partial water evacuation. On the other hand, vertically oriented GDLs enhance through plane oxygen distribution and capillary-based drainage without completely reducing lateral non-uniformities. These measurements suggest that transport anisotropy has an intrinsic negative impact on the achievable performance gains in the case of alignment consistent with one dominant direction, especially at high current density and long operating operation [3, 21, 29].

The X-pattern GDL is superior in terms of electrochemical, thermal, mechanical, and durability aspects, which serves to emphasize the significance of multidirectional transport synergy. Simultaneously facilitating effective redistribution in the in-plane and reactant delivery in the through-plane, the X-pattern architecture reduces polarization of concentrations, eliminates liquid water perch oration, stabilizes temperature gradient, and uniform current density distribution. This synergy is what has been observed to reduce the oxygen transport resistance, liquid water saturation, rate of voltage degradation, and non-uniformity, and increase the predictability of the numerical model in transport-limited conditions. Notably, the fact that short-term performance improvement and long-term stability come together, when transport passageways are optimally designed, confirms that neither are the competing goals, but the results of such balanced microstructure design are mutually enforcing [7, 30, 31].

The results of the current research are both aligned and exceeding the reported research studies on the optimization of the microstructure of GDL. Tian et al. showed that hierarchically porous GDLs could reduce the resistance to diffusion of oxygen and alleviate flooding in high current densities and Park and Li demonstrated that hydrophobic gradient GDLs could enhance the removal of liquid water, but no fundamental changes in transport directionality was necessary [32]. Zhang et al. and Khan, in their studies, observed performance improvements when groove-patterned and vertically aligned GDLs were used respectively, namely, by improving in-plane or through-plane transport [12, 21]. Wang et al. also suggested lattice-structured GDLs to facilitate multidirectional transport, and they found that power density and water management had been improved. These studies, however, had mostly isolated individual architectures and had not done a systematic and quantitative comparison under the same operating conditions. Contrary to this, the current paper provides a single comparative model that directly compares conventional, linearly-aligned, and multidirectional GDL architectures based on the same performance, stability, and durability measures [11, 22]. The findings indicate that the X-pattern GDL delivers concomitant enhancements compared to those obtained with single-directional designs indicating that balanced multidirectional transport is one of the design principles of next-generation PEMFC gas diffusion layers.

The overall findings that have been conveyed in this paper indicate that the microstructural organizational design of the gas diffusion layer (GDL) is a decisive factor defining the PEMFC operation in several coupled physical aspects. Polarization behavior and mass-transport behavior are only the beginning, and progressively increasing in size the GDL architecture results in a performance increase that can be quantified. Notably, these enhancements are not restricted to isolated operating conditions but can be seen in steady state, spatially resolved and time dependent analyses indicating the strength of the observed trends. One of the main results of this work is the evident connection that is built between GDL structural anisotropy and transport uniformity. GDLs aligned horizontally and vertically demonstrate different benefits based on the predominant direction of transport, which explains the significance of adapting pore and fiber orientation to meet the demands of certain mass and charge transport. Nevertheless, although directional alignment removes some transport constraints, it also causes directional bias, which may appear as residual non-uniformities in realistic working conditions. This observation is an indication of the importance of multi-directional transport pathway to attain the realization of uniform behavior of electrochemical behavior. The X-pattern GDL is always the most successful architecture in all the considered metrics. The fact that it can greatly improve in-plane and through-plane transport simultaneously results in better oxygen utilization, excellent water extraction, less resistive losses, and very even current distribution. Such advantages will be in terms of increased durability indicators and performance degradation upon extensive operation. The overall excellence of the X-pattern design proves that the development of next-generation PEMFC requires the use of holistic microstructural optimization as opposed to isolation-driven enhancement of individual parameters. In general, the findings support the suggested design philosophy of fabricated GDL structures as a potent route to high-performance and robust PEMFC systems. This paper offers an in-depth approach to transport analysis along with spatial and temporal performance analysis, which constitute the comprehensive framework of GDL effectiveness and future material and structural innovations. The knowledge acquired in this project forms a strong basis of converting the advanced GDL designs into real-life fuel cell functions and provides direct input into the design principles as outlined in the final section.

4. Conclusion

This work has shown in a quantitative way that the microstructural engineering of gas diffusion layers (GDL) has a prevailing effect on the coupled transport, electrochemical, and durability properties of proton exchange membrane fuel cells. The results provide a definite structure-performance correlation between steady-state, spatially resolved, and time-dependent operating regimes by a systematic comparison of a conventional random-fiber GDL and three engineered architectures, Horizontally-Aligned, Vertically-Aligned and X-Pattern designs. Compared to the baseline GDL, all the structured designs show quantifiable gains, which illustrates the fact that directional transport control is an essential stream of PEMFC performance enhancement.

The classical random-fiber GDL always showed the most disappointing results, with a high oxygen transport resistance, a large liquid water saturation, as well as a high spatial non-uniformity. This arrangement presented quantitatively up to 3035 percent superior oxygen concentration differences across the catalyst layer and about 25 percent enhanced liquid water accumulations near the cathode as compared to the designed GDLs. These transport constraints meant reduced limiting current density and faster voltage degradation, which provided the baseline against which the structured designs were compared.

The Horizontally-Aligned GDL showed evident advancements in the in-plane transport behavior. The oxygen concentration gradient across the flow streams laterally was minimized by about 18-22, and indices of local flooding were also minimized by almost 20 percent compared to the conventional GDL. These gains led to a small gain in peak power density of about 10-12 percent and a reduction in voltage decay rate of about 15 percent. Nonetheless, further improvements at high current densities were still limited by through-plane transport considerations.

The Vertically-Aligned GDL's main contribution was on through-plane reactant delivery. The flux of oxygen across the gas channel to the catalyst layer had a maximum 30 percent enhancement, which resulted in limiting current density improvements of about 25 percent over the base set-up. The efficiency of the liquid water evacuation was enhanced by close to 28 percent, and the concentration overpotential decreased significantly when operating under high-load conditions. The overall effects were a maximum power density increase of about 18-20% and a drop in voltage degradation rate by close to 30, which validated the essentiality of vertical transport optimization.

The X-Pattern GDL provided the most balanced and significant performance improvements of all the architectures under consideration. The oxygen transport resistance was lower by some 35 percent, and the amount of liquid water saturation in the cathode GDL was lower by over 40 percent than in the conventional design. These transport advancements allowed a 28% rise in the density of power and a current density uniformity to rise more than 30%. Notably, the X-Pattern GDL also had the lowest voltage degradation rate, decreasing by almost 45% over long operation, showing that there is a high correlation between transport uniformity and durability.

Thermal performance was also on the same trend. The conventional GDL had the highest temperature gradients over the active area, and the Horizontally- and Vertically-Aligned designs decreased the maximum temperature differentials by about 15 and 22 percent, respectively. The X-Pattern GDL had the smallest thermal distribution with maximum temperature gradients that were within a 30 percent range. This thermal homogenization is especially important, since it is known that localized hot spots will enhance the dehydration of membranes and the degradation of catalysts.

The soundness of the constructed multiphysics structure was additionally checked by the prediction-reference parity analysis of model validation. In the case of the traditional GDL, the current density predictions were limited to deviations of up to 20 percent, but in the Horizontally- and Vertically-Aligned designs, the deviations did not exceed 10 percent. The highest predictive fidelity of the X-Pattern GDL was found, and over 90 percent of data were within the ± 10 percent accuracy range. This positive advancement underscores the fact that the regularity of transport directly boosts model predictability.

Combined, the quantitative data prove that single-directional alignment produces selective performance benefits, whereas multidirectional transport engineering produces a synergistic benefit in all vital PEMFC metrics. The X-Pattern GDL continued to exhibit the most favorable results in oxygen consumption, water control, electrochemical homogeneity, thermal balance, and other indicators of durability, without adding too many penalties in terms of excessive pressure drop.

To sum up, this paper confirms that novel GDL designs, specifically multidirectional ones, can provide concomitant gains of peak performance (about a quarter), mass transport efficiency (about a quarter to a third), and long-term stability (about a quarter of the degradation rate). The results offer clear and quantitative design guidelines for next-generation PEMFC systems and form an effective basis for future experimental validation, manufacturability studies, and systems integration at a large scale.

5. Nomenclature

Symbol	Description	Symbol	Description
u	Velocity vector	ρ	Gas density
ε	Porosity of GDL	K, K_x, K_y, K_z	Permeability and directional permeabilities
p	Pressure	μ	Dynamic viscosity
$D_i, D_{i,eff}$	Species diffusivity and effective diffusivity	Y_i	Mass fraction of species i
cp	Specific heat capacity	k_{eff}	Effective thermal conductivity
j	Local current density	j_0	Exchange current density
η	Activation overpotential	ϕ_s, ϕ_m	Solid and membrane phase potentials
F	Faraday's constant	R	Universal gas constant
α_a, α_c	Anodic and cathodic transfer coefficients	E_{rev}	Reversible potential
n_d	Electro-osmotic drag coefficient	D_w	Water diffusion coefficient
a_w	Water activity	P_c	Capillary pressure
σ	Surface tension	θ	Contact angle
T	Temperature	S	Liquid saturation
$J(S)$	Leverett function		

6. Declarations

6.1. Author Contributions

Conceptualization, S.A. and A.M.S.; methodology, S.A.; software, S.A.; validation, S.A. and A.M.S.; formal analysis, S.A.; investigation, S.A.; resources, A.M.S.; data curation, S.A.; writing—original draft preparation, S.A.; writing—review and editing, S.A. and A.M.S.; visualization, S.A.; supervision, S.A.; project administration, S.A.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Institutional Review Board Statement

Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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