

Enhancing the Technical and Economic Performance of Proton Exchange Membrane Fuel Cells Through Three Critical Advancements

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ABSTRACT

Proton Exchange Membrane (PEM) fuel cells are gaining traction in automotive applications due to their efficiency and environmental benefits, but they face challenges such as high costs, degradation rates, and limited hydrogen availability. To address these issues, novel operational methods have been developed, focusing on customized designs rather than traditional uniform configurations. These advancements include the variable temperature flow field, which maintains high relative humidity without external humidification by leveraging internally generated water and heat, and graded catalyst loading, which enhances current density distribution. Additionally, complex flow fields have been designed using 3D metal printing to mitigate liquid water accumulation. These innovations have shown significant performance improvements, particularly when combined, demonstrating a 260% increase in current density at 0.6 V. These advancements hold promise for overcoming the limitations of conventional PEM fuel cell designs and enhancing their viability for commercial applications.

Keywords: PEM fuel cells, Computational Fluid Dynamics, Variable Temperature Flow Field, Graded Catalyst Design, 3D Metal Printed Flow Field

INTRODUCTION

Proton exchange membrane (PEM) fuel cells are steadily gaining momentum in automotive applications. Besides their formidable benefits such as low operating temperature, high efficiency, zero emissions and low noise, there are several drawbacks such as high price, unreliable degradation rates and very limited availability of hydrogen, as well as poor dynamic power output. To tackle these issues, we have developed several novel methods for operation of PEM fuel cells. These methods are based on designing the PEM fuel cell in a custom way to fit the application, instead of using uniform design with fully humidified reactants which is common practice. Throughout our research over a span of several years we have started to address the issue of liquid water accumulation and transport inside the cell, which is consequence of cell operating at the constant temperature with usage of fully humidified hydrogen at the anode and air

at the cathode. The humidification of reactants was thought to be a necessity, since the proton conductivity of the Nafion membrane is directly proportional to its water content. However, since PEM fuel cell generates large quantities of water during operation at elevated current densities, using fully humidified reactants is detrimental to its performance since the generated water remains in liquid form and is unable to evaporate and thus accumulates in the diffusion layers and sometimes in the reactant channels, which causes uneven current density and heat transfer distribution. The first method we have developed to tackle these issues is variable temperature flow field, shown in references [1-3]. This method is based on usage of ambient air and dry hydrogen for feeding of the cell. High relative humidity is achieved by establishing and maintaining a precise temperature profile along the cell which in ensures almost 100% humidified reactant gases along the active area of the cell using water generated by the cell. To establish and maintain this specific

temperature profile coolant fluid is used. Coolant enters the cell at temperature of 30°C and gradually increases its temperature to 60°C while absorbing internally generated heat. Variable temperature flow field has shown that it is possible to achieve higher performance using this method and basically dry reactants contrary to the isothermal operation with fully humidified reactants, which indicates its potency towards the development for commercial applications. This method was further enhanced together with another method, which was developed by Xing et al. research group [4,5], utilizing graded catalyst loading which further enhances the current density distribution of the cell by controlling of the chemical rates of reaction along the active area of the cell. Graded catalyst design was combined with variable temperature flow field in [4] and compared to fully humidified isothermal operation. It was demonstrated experimentally that using variable temperature flow field combined with graded catalyst design leads to 260% increase in current density at 0.6 V which was astounding. Our research also focused in the direction of developing complex flow fields which utilize pressure gradients to expel the liquid water, which tends to accumulate near the cathode outlet. This method has also demonstrated that it is possible to achieve significant improvements in the performance at elevated current densities. We call these three methods - three critical advancements. They are described in more details in the continuation of this work.

1 CRITICAL ADVANCEMENTS

Coolant Induced Variable Temperature Flow Field

Traditional Proton Exchange Membrane (PEM) fuel cell operation relies on maintaining an isothermal temperature profile across the cell, which necessitates external humidification systems to ensure high membrane water content. However, this conventional approach introduces increased system complexity, higher parasitic energy losses, and greater cost. The critical challenge in PEM fuel cell operation is maintaining optimal membrane hydration while preventing flooding that can block reactant transport pathways. Conventional isothermal approaches struggle to achieve the delicate balance between membrane hydration and preventing excess water accumulation in the gas diffusion layer (GDL) and catalyst layer (CL). This excess water can block oxygen transport to reaction sites, especially at higher current densities, leading to reduced performance. External humidification has been the standard solution but introduces significant system complications.

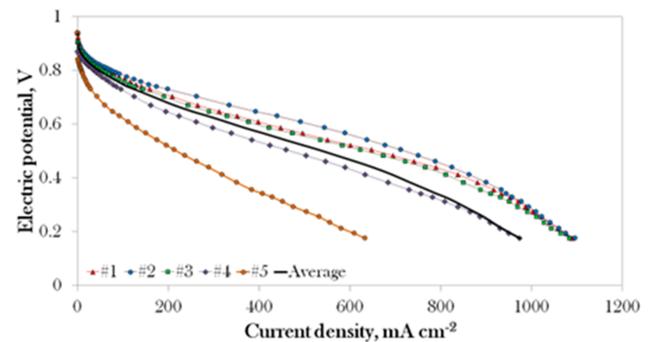
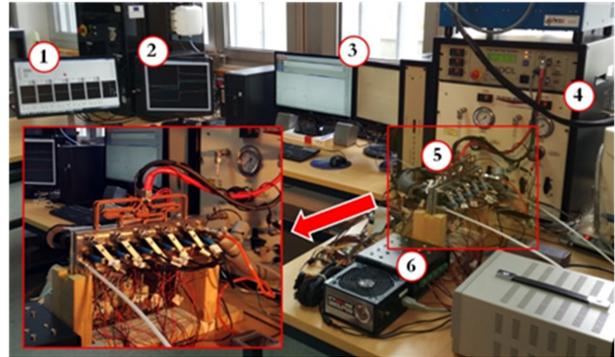


Figure 1. Experimental investigation of variable temperature flow field and polarization curves for each segment.

Željko Penga's innovative variable temperature flow field (VTFF) concept represents a significant advancement in addressing these challenges. The VTFF approach creates a controlled temperature gradient along the flow field by gradually increasing the coolant temperature as it passes through the PEM fuel cell. This strategic temperature management leverages internally generated water and heat to maintain relative humidity close to 100% along the entire flow field of both anode and cathode sides without requiring external humidification. The VTFF concept operates on the principle that water generated during fuel cell operation can be effectively utilized for internal reactant humidification when properly managed with a temperature gradient. By carefully controlling the temperature profile, the water vapor partial pressure can be maintained just below saturation pressure throughout the reactant channels. This prevents liquid water condensation while ensuring high membrane hydration, effectively addressing the dual challenges of membrane drying and electrode flooding that plague conventional designs. Penga validated this concept through extensive computational fluid dynamics (CFD) modeling and experimental testing using a custom-designed segmented PEM fuel cell setup, shown in Figure 1. The experimental apparatus provided critical insights into membrane water transport, temperature distribution on current collectors and inside channels, and current density distribution along the cell. This segmented approach allowed for precise monitoring of conditions at different

positions along the flow field, confirming the theoretical predictions of the VTFF concept. The experimental results demonstrated that PEM fuel cells operating with dry reactants under the VTFF concept achieved performance comparable to or better than conventional isothermal configurations with fully humidified reactants. Polarization curve comparisons revealed that the VTFF approach particularly excelled in reducing mass transport losses at higher current densities. This improvement stems from the VTFF's ability to maintain optimal hydration while preventing liquid water accumulation by evaporating generated water into the reactant streams. The most significant contribution of the VTFF concept is its ability to eliminate the need for external humidification while simultaneously enhancing high-current performance.

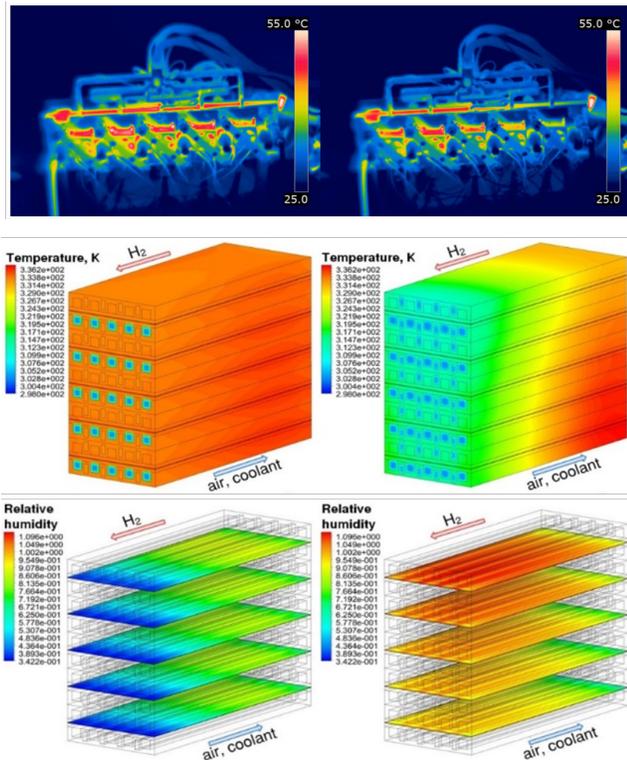


Figure 2. Isothermal (left) vs. variable temperature flow field (right) operation. Exp. vs. CFD results (above vs below) for temperature and relative humidity distributions.

By maintaining high relative humidity without condensation, the VTFF concept minimizes the problematic accumulation of liquid water that typically restricts reactant transport at higher current densities. This results in extended operational ranges and improved overall efficiency. Furthermore, the VTFF concept offers substantial system-level benefits, including reduced complexity, lower parasitic power losses, and decreased weight and volume requirements due to the elimination of external humidifiers. This makes the approach particularly

valuable for mobile and portable applications where system simplicity and efficiency are paramount. The concept has been demonstrated to be applicable to PEM fuel cell stacks, as shown in Figure 2, further extending its practical utility for commercial applications.

Variable Temperature Flow Field with Graded Catalyst Design

Traditional Proton Exchange Membrane (PEM) fuel cell designs typically employ a uniform distribution of functional components throughout the membrane electrode assembly (MEA), including consistent platinum catalyst loading, ionomer content, and porosity distributions. However, this uniform approach fails to account for the highly non-uniform distribution of current density, reactant concentration, and water content that naturally occurs during operation. This mismatch between uniform design and non-uniform operating conditions leads to suboptimal performance, excessive platinum utilization in low-activity regions, and heterogeneous degradation patterns. The cost of platinum-based catalysts remains a significant barrier to widespread PEM fuel cell adoption, with catalyst layers accounting for approximately 40% of the total system cost. Additionally, the durability issues stemming from non-uniform current distribution continue to impede commercial deployment. These challenges create a pressing need for more sophisticated design approaches that can optimize material utilization and performance simultaneously. Lei Xing's research has pioneered the concept of functionally graded porous electrode design, which strategically varies the distribution of key components along both through-plane and in-plane directions. This approach recognizes that different regions of the MEA experience vastly different local conditions during operation, requiring tailored properties to optimize performance. By creating spatial gradients of functional components such as platinum loading, ionomer content, and porosity, the graded design approach can significantly enhance performance while reducing material usage. The graded design strategy addresses the trilemma of performance, durability, and cost that has long challenged PEM fuel cell commercialization. For cells operated under varying loads, different regions require different catalyst activities and mass transport rates due to non-uniform reactant and product distribution. A rational graded design helps reduce precious material usage, improve overall cell performance, and achieve more uniform distributions of current density and heat generation.

A key innovation in Xing's work is the development of sophisticated hybrid modeling approaches that combine physics-based simulation with machine learning techniques. This methodology first establishes detailed multi-physics models that capture the complex interactions between electrochemical reactions, heat transfer, and mass transport. After experimental validation, these

models generate comprehensive databases that inform data-driven machine learning algorithms, creating powerful surrogate models capable of rapid multi-objective optimization. This hybrid approach overcomes the limitations of purely physics-based or purely data-driven methods. The physics-based foundation ensures accurate representation of fundamental processes, while the machine learning integration enables efficient exploration of vast design spaces that would be computationally prohibitive with traditional methods. This combination has proven particularly effective for optimizing multiple interconnected variables involved in graded electrode design. Xing's research has demonstrated significant improvements through graded catalyst designs, particularly in homogenizing current density distribution and enhancing performance at high current densities. By strategically varying platinum loading and gas diffusion layer porosity along in-plane directions, these designs achieve more uniform reaction rates and improved reactant transport to under-represented regions. The optimized graded designs have shown superior performance compared to uniform designs while using less platinum catalyst overall. Multi-objective optimization techniques have been employed to balance competing performance metrics such as maximum power density, platinum utilization efficiency, and current density homogeneity. These approaches have identified optimal grading profiles that represent the best compromises between different objectives, providing valuable design guidelines for practical implementation. The research has clearly established that properly designed graded structures can simultaneously address cost, performance, and durability challenges. By using a combination of variable temperature flow field and graded catalyst design, it was demonstrated that at 0.6 V the current density can be 260% higher when compared to isothermal operation with constant catalyst loading which is highly favourable for wide range of fuel cell applications because it addresses most of its current issues. The experimental rig where variable temperature flow field and graded catalyst design were used is shown in Figure 3.

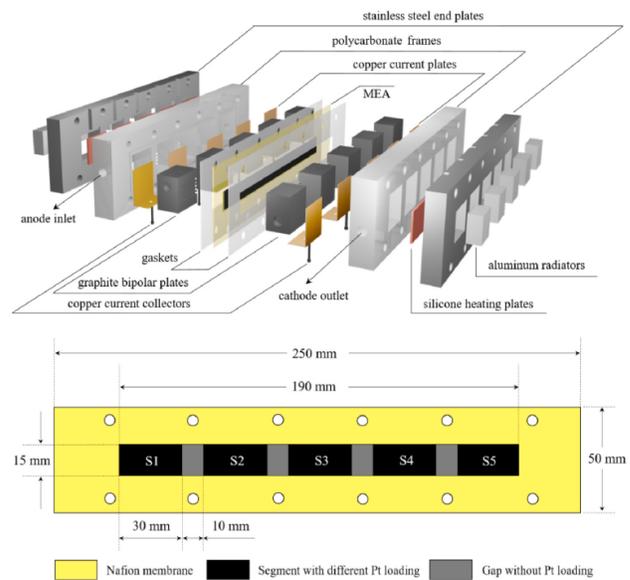


Figure 3. Segmented fuel cell with temperature control of each segment and segmented membrane-electrode assembly with different catalyst layer concentration on each segment.

3D Metal Printed Flow Fields

Conventional flow field designs in PEM fuel cells face significant challenges related to reactant distribution and water management, particularly in regions directly beneath the ribs of bipolar plates. These under-the-rib areas typically suffer from lower oxygen concentration and more severe water flooding than areas beneath the channels, creating performance bottlenecks that limit overall cell efficiency. The design of flow field geometry thus becomes critical for optimizing the balance between electrical conductivity and mass transport. Traditional manufacturing methods have imposed significant constraints on flow field designs, often limiting innovation to simple channel geometries that fail to address these under-the-rib transport issues. The emergence of advanced manufacturing techniques, particularly three-dimensional (3D) metal printing, has opened new possibilities for creating complex flow field geometries previously impossible to fabricate using conventional methods. Research by Penga, Xing, and colleagues has explored innovative flow field designs that leverage 3D metal printing capabilities to address under-the-rib transport limitations. These designs feature auxiliary channels equipped with through-plane arrayed holes strategically positioned to improve oxygen transport and water removal from under-the-rib regions. The auxiliary channels create additional pathways for reactant delivery and product removal, while the through-plane holes facilitate direct transport between the main channel and the electrode surface beneath the rib. These novel designs represent sophisticated modifications of traditional

serpentine and parallel flow field patterns. By integrating auxiliary structures without compromising the mechanical integrity or electrical conductivity of the bipolar plate, these designs achieve a careful balance between competing requirements. The number, placement, and dimensions of auxiliary channels and holes have been systematically optimized to maximize performance benefits while minimizing pressure drop penalties.

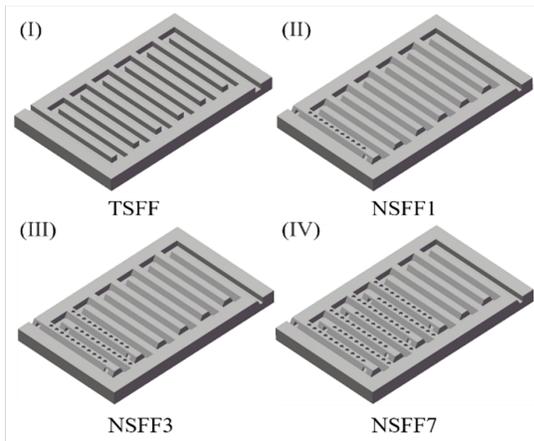
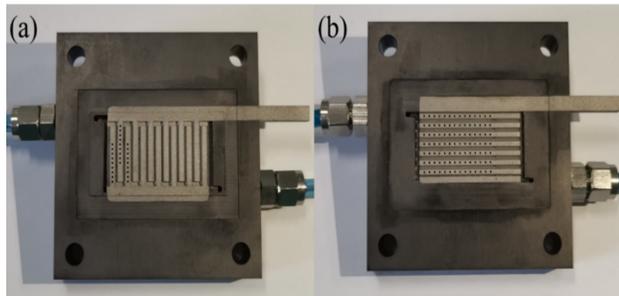
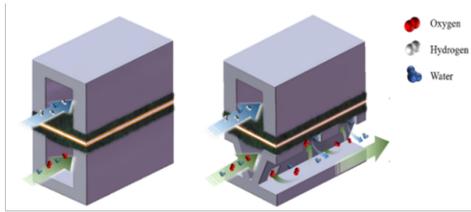


Figure 4. Isothermal (left) vs. variable temperature flow field (right) operation. Exp. vs. CFD results (above vs below) for temperature and relative humidity distributions.

The implementation of these complex flow field designs has been enabled by advances in 3D metal printing technology, as shown in Figure 4, which allows for the fabrication of intricate features with high precision. This additive manufacturing approach overcomes the limitations of traditional machining methods, enabling the creation of structures with internal passages, overhanging features, and precise dimensional control that would be difficult or impossible to achieve through conventional means. The 3D printing process for these flow fields

involves selective laser melting of metal powders, building the structure layer by layer according to a digital design. This approach offers significant advantages in terms of design freedom,

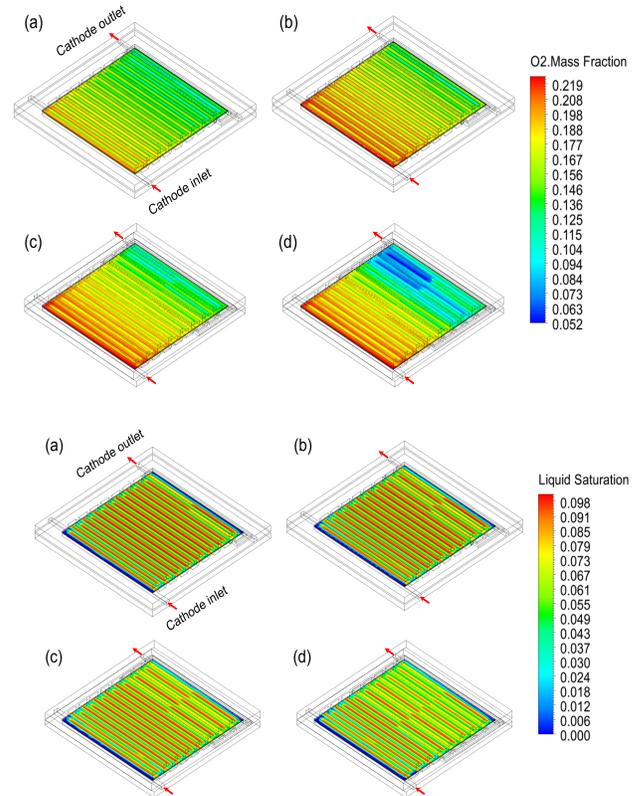


Figure 5. Isothermal (left) vs. variable temperature flow field (right) operation. Exp. vs. CFD results (above vs below) for temperature and relative humidity distributions.

The technology has reached sufficient maturity to produce functional bipolar plates with the required dimensional accuracy, surface finish, and material properties for practical fuel cell applications. Experimental and numerical evaluations, Figure 5, of the 3D printed novel flow fields have demonstrated significant performance improvements, particularly at high current densities where mass transport limitations typically dominate. Cells equipped with optimized auxiliary channel designs showed reduced ohmic resistance and enhanced mass transport capabilities compared to conventional designs. The performance gains were achieved through the improved oxygen supply and water removal from under-the-rib regions, preventing local flooding and reactant starvation. Perhaps most significantly, these novel flow field designs successfully address what the researchers describe as the "trilemma" of performance, pressure

drop, and manufacturability. Conventional designs typically force compromises between these competing factors, but the combination of innovative geometry and advanced manufacturing technology has enabled solutions that excel in all three dimensions. The optimal designs achieve enhanced performance without excessive pressure drop penalties, while the 3D printing approach makes their manufacture commercially viable.

CONCLUSIONS

The innovations in variable temperature flow fields, graded catalyst designs, and 3D metal printed flow structures represent significant advancements in PEM fuel cell technology. Željko Penga's variable temperature flow field concept eliminates the need for external humidification while maintaining optimal membrane hydration and reducing mass transport losses. Lei Xing's graded catalyst approach optimizes material utilization and performance through strategic variation of functional components guided by sophisticated hybrid modeling. The collaborative work on 3D metal printed flow fields addresses critical under-the-rib transport limitations through novel geometries enabled by advanced manufacturing techniques. Together, these innovations address key barriers to widespread PEM fuel cell adoption by enhancing performance, reducing cost, increasing durability, and simplifying system design. The integration of these approaches offers a promising pathway toward more efficient, cost-effective, and commercially viable PEM fuel cell systems for a variety of applications, from transportation to stationary power generation. As these technologies continue to mature, they will likely play an increasingly important role in the transition to clean energy systems and contribute significantly to global decarbonization efforts. In this work, we have demonstrated that the performance of conventional PEM fuel cell designs—characterized by isothermal operation, constant catalyst loading, and standard flow field configurations—can be significantly enhanced through the application of our proposed methods. The integration of these approaches has the potential to enable the development of a novel class of PEM fuel cells, tailored in every aspect to meet specific application requirements. However, the combination of these methods introduces a vast array of input and output parameters, necessitating the development of an advanced AI model to guide and optimize this process, which will be the focus of our future research.

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