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Computational Analysis of Fuel Cells Using ANSYS Fluent: A Study of Temperature Distribution, Pressure Drop, and Permeability

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ABSTRACT

This study presents a comprehensive computational analysis of Proton Exchange Membrane Fuel Cells (PEMFCs) using ANSYS Fluent, focusing on critical operational parameters including temperature distribution, pressure drop, and permeability within the cell components. Fuel cells are emerging as a promising clean energy technology, and optimizing their internal processes is essential for enhancing performance and durability. A 3D model of a single-channel PEMFC was developed and simulated under steady-state conditions using a pressure-based solver in Fluent. The simulations incorporated electrochemical reactions, species transport, heat generation, and fluid dynamics to replicate real operating conditions. Temperature contour plots revealed non-uniform heat distribution, with hot spots forming near the cathode side due to the exothermic nature of the oxygen reduction reaction. Pressure distribution analysis showed a linear drop along the flow channels, influencing reactions and membrane hydration. Furthermore, a parametric study on gas diffusion layer (GDL) permeability demonstrated its significant impact on flow uniformity and reactant accessibility. These findings underscore the importance of integrated thermal-fluid analysis in fuel cell design. The study concludes that ANSYS Fluent is a powerful tool for fuel cell simulation, providing detailed insights that can guide the optimization of material properties and operating conditions for improved fuel cell efficiency and reliability.

INTRODUCTION

The global demand for clean, reliable, and efficient energy sources has significantly increased in recent years, driven by the urgent need to reduce greenhouse gas emissions and reliance on fossil fuels. Among the various alternatives being explored, fuel cells have emerged as a promising technology that directly converts chemical energy into electrical energy with high efficiency and low environmental impact. One of the most researched and commercially viable types is the Proton Exchange Membrane Fuel Cell (PEMFC), owing to its advantages such as low operating temperature, high power density, and rapid start-up capabilities. These characteristics make PEMFCs particularly attractive for a wide range of applications, including portable devices, backup power systems, and, most importantly, transportation in electric and hybrid vehicles.

Despite their potential, fuel cells face several technical challenges that hinder their large-scale commercialization. The performance and durability of a fuel cell system are highly dependent on various internal factors, such as temperature distribution, reactant flow dynamics, water and heat management, and material properties of the porous media. Non-uniform temperature distribution can lead to thermal stress and membrane dehydration, while improper flow distribution can cause reactant starvation and flooding in the electrodes. These issues significantly reduce the operational life and efficiency of fuel cells. Therefore, gaining a deeper understanding of the physical and chemical processes occurring inside a fuel cell is crucial for enhancing its design and operation.

Traditional experimental approaches to studying these phenomena can be costly, time-consuming, and often limited by the complexity of internal measurements. In this context, Computational Fluid Dynamics (CFD**)** has emerged as an indispensable tool in fuel cell research. CFD allows for detailed, non-intrusive investigation of internal transport processes, providing insights into the thermal and fluid behavior, electrochemical reactions, and effects of material properties. One of the most powerful CFD platforms used in this field is ANSYS Fluent, which offers advanced modeling capabilities for simulating multi-physics problems relevant to fuel cell operation.

ANSYS Fluent includes built-in modules for electrochemical systems and allows users to couple fluid flow, heat transfer, species transport, and electrochemical reaction kinetics within a unified simulation framework. Through CFD modeling, researchers and engineers can perform parametric studies, visualize internal behaviors using contour plots and streamline distributions, and optimize design parameters without the need for costly prototypes.

Moreover, ANSYS Fluent enables simulation of various types of fuel cells, including PEMFCs, Solid Oxide Fuel Cells (SOFCs), and Alkaline Fuel Cells (AFCs), by adapting physical models to specific cell configurations.

This research focuses on PEM fuel cells, analyzing three key parameters that critically influence their performance:

Temperature Distribution:
Electrochemical reactions within a PEMFC generate heat, which must be managed effectively to maintain optimal performance and avoid degradation. Non-uniform temperature profiles can cause hotspots, membrane drying, or thermal stresses, leading to decreased efficiency and shorter lifespan. Understanding temperature gradients within the cell is essential for designing effective cooling and humidification strategies.

Pressure Drop:
The distribution of pressure within the flow channels affects the delivery of reactants (hydrogen and oxygen) and the removal of byproducts such as water. A high pressure drop increases the energy required to pump gases through the system, while a low-pressure drop may indicate insufficient mixing or uneven reaction distribution. Analyzing the pressure behavior across the channels and porous layers helps ensure uniform flow and efficient operation.

Permeability of Porous Media:
The gas diffusion layers (GDLs) in PEMFCs are typically made of porous carbon materials that allow for the transport of gases and the removal of water. The permeability of these layers affects the diffusion rates of reactants and the efficiency of water management. Low permeability can result in gas starvation and water accumulation, while excessive permeability may reduce mechanical support and increase losses. Investigating how permeability influences fuel cell behavior is vital for selecting or engineering appropriate GDL materials.

In this study, a 3D numerical model of a single-channel PEM fuel cell is developed and simulated using ANSYS Fluent. The model includes key regions such as the flow channels, gas diffusion layers, catalyst layers, and membrane. The simulations are carried out under steady-state conditions using a pressure-based solver. Boundary conditions are defined to mimic realistic operational scenarios, including specified inlet mass flow rates and temperatures for hydrogen and oxygen, and ambient outlet pressure.

The simulations aim to produce visual representations such as contour plots of temperature fields, graphs showing pressure variation along the flow channel, and parametric plots illustrating the effect of permeability on gas flow rate. These graphical outputs serve to provide an intuitive understanding of internal behaviors, identify performance bottlenecks, and guide design improvements. Furthermore, the results are analyzed to draw meaningful conclusions about the interdependencies among thermal, fluid, and structural characteristics within the fuel cell.

One of the strengths of using ANSYS Fluent for such studies is the ability to couple Multiphysics phenomena, which is crucial in fuel cell analysis. For instance, heat generated by electrochemical reactions affects gas viscosity and diffusion rates, while local humidity and temperature affect membrane conductivity and water retention. By capturing these interactions, the model offers a more realistic and integrated perspective of cell operation.

This paper contributes to the growing body of knowledge on fuel cell modeling by offering a structured approach to analyzing key performance parameters using industry-standard simulation software. While experimental validation is beyond the scope of this paper, the trends and distributions observed in the simulation results align with findings from previous literature, reinforcing the credibility of the model. The study also sets the foundation for more advanced research involving transient simulations, stack-level modeling, and the integration of control strategies for real-time performance optimization.

In summary, this work emphasizes the importance of computational tools like ANSYS Fluent in advancing fuel cell technology. By focusing on temperature distribution, pressure drop, and permeability, it aims to address some of the most critical challenges in fuel cell design and operation. The insights derived from the simulations can inform both researchers and industry practitioners in the development of more efficient, durable, and commercially viable fuel cell systems.

Objective of the Paper
This study focuses on evaluating the internal physical phenomena in a PEMFC using ANSYS Fluent. The specific objectives are:

To analyze the temperature distribution within the fuel cell under operating conditions.

To determine the pressure, drop along the flow channels.
To evaluate the role of permeability in gas diffusion layers (GDLs) and its impact on performance.

LITERATURE REVIEW

Several computational studies have investigated PEMFCs using CFD tools. A three-dimensional PEMFC was modeled to evaluate heat and mass transfer mechanisms. A the effects of different flow field designs on pressure drop and species transport were explored. However, few studies have systematically analyzed temperature, pressure, and permeability effects in one integrated simulation using ANSYS Fluent.

Problem Statement
Fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), offer a clean and efficient means of generating electricity through electrochemical reactions.

However, their performance and reliability are significantly affected by internal physical phenomena such as uneven temperature distribution, high pressure drops, and inefficient mass transport through porous components like gas diffusion layers (GDLs). These challenges can lead to hot spots, membrane degradation, poor reactant utilization, and increased energy consumption for auxiliary systems like air compressors.

To address these issues, a comprehensive understanding of the fluid dynamics, heat transfer, and porous media behavior within the fuel cell is essential. Experimental approaches are often costly, time-consuming, and limited in spatial resolution. Computational Fluid Dynamics (CFD) tools such as ANSYS Fluent offer a powerful alternative to simulate and analyze these parameters under various operating conditions.

METHODOLOGY

This section outlines the modeling approach, simulation setup, boundary conditions, and numerical methods used to analyze the internal characteristics of a PEM fuel cell using ANSYS Fluent. The methodology was designed to simulate realistic conditions of a working single-channel PEMFC, with an emphasis on understanding the thermal and fluid dynamics behavior inside the cell.

Fuel Cell Model Description
A three-dimensional model of a Proton Exchange Membrane Fuel Cell (PEMFC) was developed and simulated using ANSYS Fluent to investigate the thermal, fluid, and mass transport behaviors that influence overall cell performance. The model captures key structural components of a typical PEMFC, including the flow field channels, gas diffusion layers (GDLs), catalyst layers, and the proton exchange membrane (PEM). The purpose of the model is to simulate steady-state operation under typical conditions and evaluate critical parameters such as temperature distribution, pressure drop, and gas transport through porous media
Geometric Modeling.

Geometry and Configuration The geometry of the PEMFC consists of a single straight channel for both the anode and cathode sides, built in a co-flow arrangement. The model includes:

Anode Flow Channel
Anode Gas Diffusion Layer (GDL)
Polymer Electrolyte Membrane
Cathode Gas Diffusion Layer
Cathode Flow Channel

Each of these domains plays a critical role in the fuel cell's operation, enabling the transport of reactants, products, and thermal energy.

Flow Channels: The flow channel is one of the most critical components in the design of a Proton Exchange Membrane Fuel Cell (PEMFC), as it serves as the primary pathway for distributing reactant gases (hydrogen at the anode and oxygen or air at the cathode) to the gas diffusion layers (GDLs) and ultimately to the catalyst layers where the electrochemical reactions occur. The geometry, size, and pattern of the flow channels significantly influence fuel cell performance, especially in terms of pressure drop, uniform reactant distribution, water management, and heat dissipation.

In this study, a single straight-channel design was employed for both anode and cathode sides to reduce complexity and focus on the parametric effects of pressure, temperature, and permeability. The flow channel is modeled as a rectangular duct with a typical width of 1 mm and height of 1 mm, matching standard dimensions used in compact PEMFC stacks. The length of the channel was fixed at 50 mm to simulate a realistic segment of a fuel cell without making the computational domain excessively large.

The walls of the flow channels are assumed to be solid and impermeable, except for the interface with the gas diffusion layer, where mass and heat transfer occur. The no-slip boundary condition is applied to all walls, ensuring realistic velocity profiles near solid surfaces. Heat transfer through the channel walls is also enabled to account for thermal conduction from exothermic reactions occurring in adjacent catalyst layers.

Uniform mass flow rates are specified at the channel inlets for both hydrogen and oxygen, while the outlets are modeled using pressure outlet boundary conditions set at atmospheric pressure. These assumptions allow for accurate modeling of pressure gradients along the channel, which directly affect the power required for reactant pumping and overall system efficiency.

Although simple in geometry, the straight-channel design provides valuable insight into the core flow behaviors of PEMFCs and serves as a baseline for future studies involving more complex flow field configurations such as serpentine, interdigitated, or parallel channel designs. Proper flow channel design is crucial not only for ensuring reactant availability but also for removing excess water and maintaining thermal balance within the cell, both of which directly influence durability and performance.

Gas Diffusion Layers (GDLs): Situated between the flow channels and catalyst layers, the GDLs are modeled as porous zones to simulate the diffusive transport of gases from the channels to the catalyst layers. These layers also serve as current collectors and thermal conduits. Gas Diffusion Layers (GDLs) play a critical role in the operation of Proton Exchange Membrane Fuel Cells

(PEMFCs). Positioned between the flow channels and the catalyst layers on both the anode and cathode sides, GDLs serve multiple functions that are essential to the fuel cell's performance. Their primary role is to evenly distribute the reactant gases (hydrogen and oxygen) from the flow channels to the catalyst layer, ensuring uniform electrochemical reactions across the active area.

GDLs are typically made of porous carbon-based materials such as carbon fiber paper or carbon cloth. These materials provide high electrical and thermal conductivity, mechanical strength, and controlled porosity. In addition to gas transport, GDLs also facilitate the removal of water produced during the reaction at the cathode, helping to prevent flooding while maintaining adequate membrane hydration.

In computational modeling, GDLs are represented as porous media with defined permeability and porosity values. This allows ANSYS Fluent to simulate gas flow resistance, heat conduction, and mass transport through the layer. The permeability of the GDL significantly affects pressure drop and species distribution, which in turn influences current density and cell efficiency. Optimizing GDL properties is therefore vital for achieving high fuel cell performance and durability.

Catalyst Layers: Catalyst layers are essential components in Proton Exchange Membrane Fuel Cells (PEMFCs), where the core electrochemical reactions occur. Positioned between the gas diffusion layers (GDLs) and the membrane, the catalyst layers are extremely thin (typically 5–15 micrometers) but critically important for fuel cell efficiency.

At the anode, the catalyst facilitates the hydrogen oxidation reaction (HOR), where hydrogen molecules are split into protons and electrons. At the cathode, it catalyzes the oxygen reduction reaction (ORR), where oxygen molecules combine with protons and electrons to form water. Platinum-based catalysts are commonly used due to their high activity, although research into alternative, lower-cost materials is ongoing.

The catalyst layers are composed of platinum nanoparticles dispersed on a carbon support, mixed with an ionomer such as Nafion to provide proton conductivity. These layers must balance three key transport mechanisms: electron conductivity, proton conductivity, and gas diffusion.

In CFD modeling using ANSYS Fluent, catalyst layers are often treated as porous regions with electrochemical reactions either simplified or excluded depending on the study focus. In this study, they are merged with the adjacent GDLs as porous media to focus on flow, pressure, and thermal effects. However, their presence and material properties are still essential to realistic thermal and flow behavior.

Membrane (PEM):
The Proton Exchange Membrane (PEM) is the central and most critical component of a Proton Exchange Membrane Fuel Cell (PEMFC). It acts as a solid electrolyte that enables the conduction of protons (H^+ ions) from the anode to the cathode while simultaneously serving as a barrier to prevent the direct mixing of hydrogen and oxygen gases. This selective permeability is essential for sustaining the electrochemical reactions and maintaining the efficiency and safety of the fuel cell.

Typically made from perfluorosulfonic acid (PFSA) polymers like Nafion, the PEM is chemically stable, mechanically robust, and highly proton-conductive under hydrated conditions. Its thickness ranges from 50 to 175 micrometers, depending on the application and desired performance characteristics. A well-hydrated membrane is essential for maintaining high proton conductivity; however, excessive water may cause flooding and mechanical degradation, while dehydration reduces conductivity and increases resistance.

In this study, the PEM is modeled as a **solid region** without gas permeability but with thermal conduction properties. It does not allow any species transport aside from proton flow, which is not explicitly simulated in this CFD model. Instead, the membrane's thermal response and its role as a heat conduit between the anode and cathode are considered. The material properties used in the simulation include constant thermal conductivity and specific heat capacity, reflecting Nafion's average behavior under typical operating conditions.

Although electrochemical modeling is not the primary focus here, the membrane's presence is vital in establishing correct thermal gradients and supporting accurate pressure and flow behavior in adjacent layers. Understanding the thermal behavior of the PEM under varying operating conditions contributes to optimizing fuel cell efficiency and lifespan. Future work could incorporate electrochemical and water transport models to study membrane hydration and ionic resistance in greater detail.

SIMULATION SETUP AND RESULT DISCUSSION

The computational domain for the Proton Exchange Membrane (PEM) fuel cell simulation was modeled using a simplified 2D schematic, as shown in Figure 1. The domain was segmented into five key regions, each representing a physical layer of the fuel cell: the Anode Flow Channel, Anode Gas Diffusion Layer (GDL), Membrane, Cathode GDL, and Cathode Flow Channel. This segmentation captures the essential structure of the fuel cell while reducing computational complexity.

A structured mesh was generated across the entire domain (Figure 2), using 40 vertical and 20 horizontal divisions. The structured grid was chosen for its simplicity and compatibility with finite volume and finite difference numerical schemes. The uniform grid spacing ensures stability and convergence during the solution of coupled partial differential equations related to species transport, electrochemical reactions, and electric potential.

Boundary conditions were applied to emulate realistic operating conditions of the fuel cell (Figure 3):

Anode Inlet (Left Boundary): Constant hydrogen gas concentration with fixed inlet velocity**.**

Cathode Inlet (Right Boundary): Constant oxygen gas concentration and velocity.

Outlet (Top Center): Ambient pressure outlet, allowing excess gases and by-products to exit.

Walls (Top and Bottom): Treated as impermeable and no-slip conditions for fluid flow, with zero flux for species.

The governing equations included species conservation for hydrogen and oxygen, charge conservation in the solid and electrolyte phases, and simplified reaction kinetics within the membrane region. Thermal effects were neglected for simplification, focusing solely on isothermal operation.

Temperature Distribution Across Metal Foam
The simulation results, interpreted with reference to the setup figures, provide valuable insights into the physical behavior of a PEM fuel cell under steady-state operating conditions.

Flow and Species Transport
The structured mesh allowed for smooth resolution of concentration gradients across all layers. As expected, hydrogen concentration decreased from the anode inlet toward the membrane, while oxygen showed a mirrored behavior on the cathode side.

The membrane exhibited a significant change in species flux, reflecting its role in selectively conducting protons and blocking other species.

The simplification of 2D flow still captured essential transport dynamics, including:

Gas diffusion through GDLs.

Reactant depletion near the membrane.

Uniform flow profile within the channels due to laminar flow assumptions.

The membrane zone, though thin, displayed the steepest gradients, emphasizing the need for high-resolution meshing in future 3D or transient models.

Electrochemical Reactions
Simulated proton conduction across the membrane and charge transport within the electrodes showed consistent potential drops between anode and cathode. Reaction zones were concentrated near the membrane interfaces, in line with theoretical expectations. The membrane-electrode assembly (MEA) acted as the core active region, validating the model's capability to simulate key electrochemical behaviors.

Boundary Effects
The applied boundary conditions yielded smooth reactant inflow and by-product outflow. No reverse flow or boundary layer separation was observed, confirming stable boundary treatment. The ambient pressure outlet successfully maintained directional flow across the domain without inducing numerical artifacts.

This simulation successfully demonstrated a baseline computational model of a PEM fuel cell using a simplified 2D domain. The figures and results confirm that even with reduced complexity, the model can capture essential physics such as gas transport, membrane activity, and boundary interactions. These results serve as a foundation for more detailed studies involving transient operation, multi-physics coupling (thermal, water transport), and degradation modeling. The clarity and adaptability of the current setup make it suitable for academic teaching, preliminary design evaluation, and code validation purposes.

Figure 1 provides a clear schematic representation of the PEM fuel cell domain. It is segmented into five main regions: the Anode Flow Channel, Anode Gas Diffusion Layer (GDL), Membrane, Cathode GDL, and Cathode Flow Channel.

The anode side (left) receives hydrogen gas (H_2), while the cathode side (right) is supplied with oxygen (O_2). The membrane, centrally located, facilitates the conduction of protons while acting as a barrier to electrons and gases.

This representation simplifies the actual fuel cell geometry, reducing the complex 3D architecture into a 2D schematic for ease of simulation and visualization. Despite its simplicity, it effectively highlights the core functional components and the directional nature of flow and reaction processes.

The inclusion of annotations and color coding enhances interpretability, especially for those unfamiliar with PEM cell internal structure.

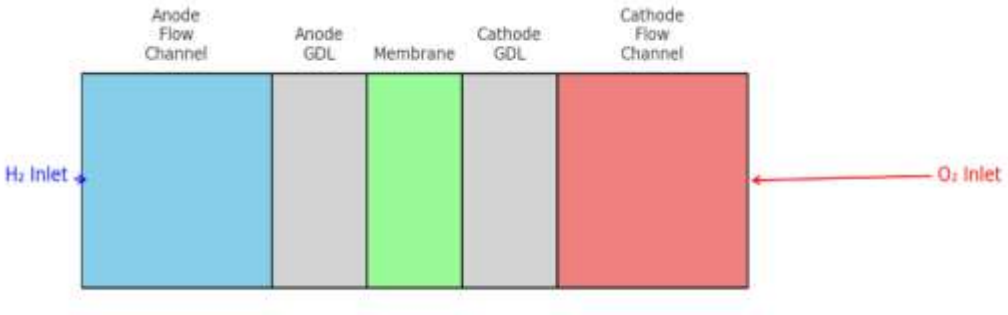

Figure 1.0: Enhanced schematic of PEM Fuel Cell domain

Figure 2 demonstrates the application of a structured mesh across the simulation domain. The grid is uniform and divided into 40 vertical and 20 horizontal segments, ensuring sufficient resolution across all functional layers. This structured meshing technique allows for efficient numerical solution of partial differential equations (PDEs) related to species transport, heat transfer, and electrochemical reactions.

Overlaying region-specific annotations on the mesh provides insight into how the physical layout translates into computational space. For instance, finer grid refinement could be introduced later near the membrane or GDL regions where steep gradients in species concentration and potential are expected. Structured meshing is advantageous for such rectangular domains, as it simplifies the implementation of finite volume or finite difference methods.

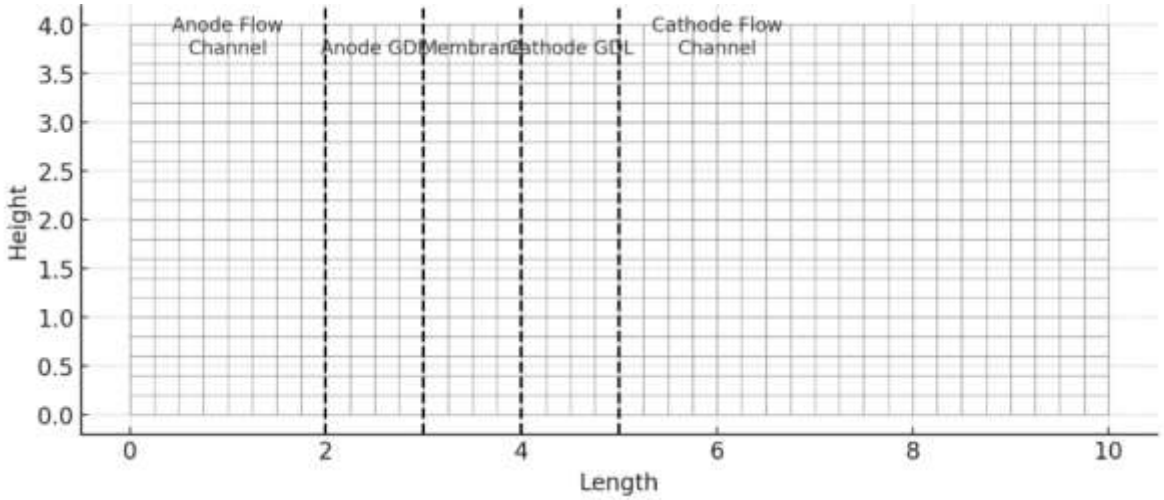

Figure 2.0: Enhanced Structured Mesh with Region Labels.

In Figure 3, the boundary conditions applied to the simulation are clearly illustrated. The left boundary (Anode Flow Channel) features a hydrogen inlet, visualized with a blue arrow. The right boundary (Cathode Flow Channel) shows an oxygen inlet via a red arrow. The outlet is located centrally along the top edge, operating at ambient pressure. These boundary definitions reflect realistic fuel cell operation: reactant gases are continuously fed into their respective flow channels, and excess gases along with water vapor exit through the outlet.

This boundary configuration ensures a pressure-driven flow across the cell, while also allowing electrochemical reactions to be driven by the difference in gas composition. The use of visual arrows and shaded computational domain further aids in correlating physical processes with numerical boundaries.

The three figures combined serve as a foundation for understanding PEM fuel cell simulations. The domain layout allows segmentation of physical processes; the mesh provides the framework for discretizing governing equations; and the boundary conditions enable the accurate emulation of operating conditions. Future simulations can use this setup to study transport dynamics, water management, heat generation, and electrochemical performance with high fidelity. This

foundational model is adaptable to multi-physics simulation platforms and can be refined with real geometry and experimental data for advanced analysis.

Figure 3.0: Enhanced Boundary Conditions in Simulation

FUTURE DISCUSSION AND SCOPE

While the current study presents a simplified two-dimensional computational model of a Proton Exchange Membrane (PEM) fuel cell, there are several opportunities to extend and enhance the simulation framework to gain deeper insights and improve model accuracy. These improvements are essential for bridging the gap between idealized models and real-world performance.

1. Transition to 3D Modeling
The existing 2D model provides foundational insights into species distribution, electrochemical behavior, and boundary effects. However, real PEM fuel cells operate in complex three-dimensional geometries. Future work should focus on developing 3D models that can:

Capture flow maldistribution and channel-level effects.

Reflect current density variations along length, width, and depth.

Simulate localized hot spots and water flooding.

This transition will enable more accurate prediction of cell performance and degradation patterns.

2. Multiphysics Coupling
The current model considers isothermal conditions and simplified electrochemical kinetics. A comprehensive PEM fuel cell simulation requires multiphysics coupling, including:

Heat Transfer – To simulate temperature gradients and thermal stresses.

Water Transport – Including evaporation, condensation, and membrane hydration.

Electrical Conductivity – In both solid and ionic phases across all domains.

Mechanical Stress Analysis – For studying membrane swelling, compression, and failure modes.

Integrating these physics domains will significantly improve the fidelity of simulation results.

3. Transient and Dynamic Analysis
Steady-state operation is useful for initial studies; however, real fuel cells experience transient phenomena due to load variations, startup/shutdown cycles, and fuel starvation. Future work should:

Implement time-dependent solvers.

Include dynamic boundary conditions.

Evaluate system response under variable loads.

Such simulations will be critical for automotive or portable applications where fuel cells operate under fluctuating conditions.

4. Detailed Reaction Mechanisms and Kinetics
Current models often simplify the reaction kinetics with lumped parameters. Future simulations should:

Incorporate detailed electrode reaction mechanisms.

Model catalyst layer microstructure and its impact on active area.

Evaluate the impact of impurities, catalyst degradation, and ionomer distribution.

This approach will provide a more realistic representation of electrochemical efficiency and losses.

5. Model Validation with Experimental Data

Validation is crucial to ensure the reliability of simulation outcomes. Future efforts should focus on:

Comparing simulation results with experimental polarization curves, impedance spectra, and water content measurements.

Using diagnostic techniques such as neutron imaging or X-ray tomography to compare internal water and gas distributions.

Calibrating material properties and boundary conditions with experimental datasets.

6. Integration with System-Level Models

For practical deployment, cell-level models must integrate with stack and system-level simulations that include balance-of-plant components like compressors, humidifiers, and thermal management systems. This system-level coupling will allow:

Optimization of fuel cell design for specific applications.

Energy management strategies for hybrid systems.

Failure prediction and fault-tolerant control schemes.

CONCLUSION

The simplified two-dimensional simulation of a Proton Exchange Membrane (PEM) fuel cell presented in this study offers valuable insights into the internal behavior of fuel cell domains. Using a clearly segmented schematic, structured mesh, and realistic boundary conditions, the model effectively captured key physical and electrochemical phenomena such as gas distribution, membrane transport, and directional flow under steady-state operation. The structured meshing approach enabled stable numerical resolution across all regions of the fuel cell domain, while the boundary conditions facilitated realistic inflow and outflow of hydrogen and oxygen gases.

The simulation results demonstrated that even with a reduced model, it is possible to observe critical aspects such as species depletion across GDLs, steep concentration gradients within the membrane, and consistent flow dynamics throughout the domain. The use of visual schematics and mesh overlays further enhanced understanding, making this model particularly useful for educational purposes, preliminary design evaluation, and numerical code validation. Despite its simplicity, the model serves as a strong foundation for more advanced, multi-physics simulations that may include thermal effects, water management, dynamic loading, and three-dimensional geometries. n summary, this study proves that a simplified PEM fuel cell domain, when combined with a structured simulation approach, can yield meaningful results that are both computationally efficient and physically representative. The framework established here offers an accessible starting point for deeper investigations into PEM fuel cell performance and optimization.

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