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Optimization and Reliability Enhancement of Solid Oxide Fuel Cells through Advanced Numerical Modeling

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Abstract

Solid Oxide Fuel Cells (SOFCs) are gaining increasing attention as a viable solution for addressing the global need for energy security and environmental sustainability. When powered by clean energy sources such as green hydrogen, which is produced through electrolysis using renewable energy, SOFCs have the potential to significantly reduce greenhouse gas emissions and contribute to a sustainable energy future. Despite their advantages, including high efficiency and fuel flexibility, SOFCs face several challenges that hinder their widespread commercialization. A major concern is performance degradation, influenced by complex multi-physics interactions within the system, including thermal stresses, chemical reactions, and mechanical deformations. Current studies have mainly focused on enhancing efficiency; however, addressing degradation and reliability issues is crucial for the long-term success of SOFC technology. Key parameters such as operating temperature, fuel composition, material properties, and thermal management play critical roles in determining SOFC longevity and performance. Effective thermal management strategies can alleviate thermal stresses that contribute to material fatigue and failure while optimizing fuel composition can mitigate issues such as electrode delamination and enhance overall efficiency. Additionally, improving the microstructural design of cell components, such as porosity optimization in electrodes and tailored electrolyte thickness, can increase mechanical stability and reduce degradation rates. This research focuses on leveraging Computational Fluid Dynamics (CFD) to analyze and optimize SOFC performance. CFD simulations facilitate the identification of hotspots and regions prone to failure, enabling the development of targeted strategies to mitigate degradation. Advanced multi-physics modeling has allowed for detailed analysis of correlations between thermal, fluid, and electrochemical behavior. Through parametric studies, critical design and operational parameters have been identified to enhance power density, fuel utilization, and thermal stability. Moreover, the computational framework has been validated based on an experimental model developed at the Energy Mechatronics Laboratory (EML) at the University of Alberta. This experimental setup replicates real-world operating conditions and provides high-fidelity data to benchmark the simulation results, ensuring accuracy and reliability. The insights gained from this study are expected to contribute significantly to the development of robust operational strategies that mitigate degradation issues and extend the operational lifespan of SOFCs. By identifying optimal operating conditions and enhancing predictive capabilities, this research supports the transition toward more sustainable energy solutions.