High-Fidelity Thermal-Hydraulic Simulation and Modeling for Realistic Blockage Formation in Wire Wrapped Fuel Assemblies

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ABSTRACT:

This study aims to advance the understanding of thermo-hydraulic behaviors and safety implications of blockages in wire-wrapped fuel assemblies (WWFAs) in Liquid Metal Fast Reactors (LMFRs). One critical aspect of LMFR safety is the behavior of coolant flow within fuel assemblies, especially in the presence of blockages. These blockages, formed from particle aggregation, thermal expansion, corrosion, or operational debris, can elevate cladding temperatures, reduce heat transfer efficiency, and compromise reactor safety. Unlike spacer grids that allow blockages to grow radially into a plate-like formation, WWFAs restrict blockages to axial growth. This axial confinement makes WWFAs less prone to blockage risks. Even though WWFAs can mitigate the damage of the blockage, the formation and its impact on the safety of the LMFRs still need to be carefully investigated. Blockages in WWFAs are difficult to detect because their effect on flow resistance is minimal, yet they can significantly increase cladding temperature. To address this gap, our study employs a multi-scale and reduced-order modeling approaches, combining high-fidelity simulations with high-resolution micro computed tomography and 3D CAD reconstructions to model realistic blockages formation. This approach enables a detailed examination of the interactions between coolant flow and blockages, allowing for the assessment of effects on pressure drop, cladding temperature, and overall heat transfer efficiency. The study integrates results from microscopic, mesoscopic, and macroscopic scales to evaluate blockage behavior across the entire reactor system. Using the representative elementary volume and random pore network model, microscale findings on permeability and thermal conductivity inform larger-scale models. These insights are applied within system codes to simulate the broader thermal-hydraulic performance of the reactor and assess safety impacts under various operational scenarios. Furthermore, machine learning surrogate model will be develop to accelerate pressure calculations, thereby reducing overall simulation time. This research will provide critical data for LMFR design optimization and safety assessments, addressing blockage challenges by informing design improvements, such as optimizing reactor inlet filter sizes to minimize clogging risks. Through this comprehensive and integrated modeling approach, the study will support the development of advanced LMFRs with improved efficiency, safety, and sustainability, contributing to a new generation of low-emission, high-performance reactors as part of a sustainable energy solution.