QUANTITATIVE NEUTRON RADIOGRAPHY OF LIQUID-METAL FLOW: IMAGING, INFERENCE, AND MULTIPHYSICS MODELING

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Abstract

Liquid metals (Li, LiPb, LBE, Ga and others) are used for fusion reactor cooling and breeding due to their thermophysical properties. They can manage intense heat loads in blankets and divertors while facilitating tritium breeding. On the other hand, challenges arise like corrosion, magnetohydrodynamic (MHD) pressure drops, and other safety risks. Quantitative characterization of liquid-metal flows remains a central challenge in nuclear thermal-hydraulics due to optical opacity, high density, and complex particulate interactions. Integrated experimental–computational framework combining time-resolved neutron radiography (NR) with high-fidelity computational fluid dynamics (CFD) to investigate liquid metal flows laden with cadmium microparticles in canonical geometries. The objective is to establish a validated, uncertainty-aware modeling workflow capable of predicting particle concentration fields, slip velocities, and turbulence–particle interactions in liquid-metal systems relevant to advanced reactor technologies and nuclear materials processing. A dedicated loop with interchangeable pipe and square-duct test sections has been developed for beamline deployment (IEA-R1/IPEN). High-speed NR (≥200 fps, L/D≈500) enables quantitative extraction of path-integrated particle concentration through calibrated neutron attenuation models, leveraging the strong neutron absorption cross-section of cadmium to enhance phase contrast. Beyond conventional attenuation analysis, an advanced image post-processing pipeline is implemented to enable velocity-field reconstruction via neutron-based particle image velocimetry (nPIV) and particle tracking velocimetry (nPTV). The work includes flat/dark-field correction, beam non-uniformity normalization, scatter compensation, spatial deconvolution based on measured modulation transfer function (MTF), contrast enhancement, and adaptive filtering to improve signal-to-noise ratio at high frame rates. Sequential cross-correlation (multi-pass interrogation with window deformation) is then applied to extract two-dimensional velocity fields, while centroid-based tracking provides Lagrangian particle statistics. The combined approach allows simultaneous determination of Eulerian velocity maps and dispersed-phase kinematics, with target accuracies below ±3% (particle volume fraction) and ±5% (mean velocity). Parallel CFD studies employ RANS and LES formulations for the carrier phase, coupled with Eulerian–Lagrangian and Eulerian–Eulerian multiphase approaches to model particle transport, including drag, lift, turbulent dispersion, and particle–wall interactions. Closure relations are systematically assessed and calibrated against NR-derived observables such as concentration profiles, velocity vector fields, particle clustering metrics, slip velocity distributions, and near-wall accumulation trends. Bayesian inference is applied to quantify parameter uncertainty and reduce predictive variance in extrapolated operating conditions. The combined dataset and calibrated models provide new insight into turbulence–particle coupling, preferential concentration, and deposition behavior of high-absorption microparticles in dense liquid metals. The proposed experiment–model–data-assimilation loop establishes a reproducible methodology for high-fidelity validation of particulate CFD in opaque fluids, supporting improved predictive capability for reactor-relevant configurations such as vertical risers, bends, and sudden expansions.