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Reduced Order Modeling of Heat and Fluid Flow: Multi-Scale Modeling of Advanced Reactors to Enable Faster Deployment

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ABSTRACT:
Several advanced reactor concepts are currently being pursued in the U.S., with dozens of companies proposing unique designs. Crucial for their deployment is the analysis of reactor transients (e.g., a protected loss of flow), which is an essential part of the evaluation of thermal margins and the overall safety case. The objective of this project is to accelerate parametric and long-transient thermal-hydraulics analysis, with a focus on mixed convection within sodium-fast reactor (SFR) assemblies as a challenge problem. We propose a multiscale simulation approach that combines data from high-fidelity large-eddy simulations (LES) on DOE's exascale computers with recent advances in reduced order models (ROMs) for turbulent flow simulation. The ROMs are derived as projections of the governing Navier-Stokes and energy equations onto low-dimensional approximation spaces that are derived from proper-orthogonal decomposition (POD) or similar data compression of the LES solutions. Typical ROMs can run long-time transients in a matter of minutes on a laptop, for a variety of parametric conditions. Their utility depends crucially on establishing stability and accuracy of the ROM solutions for relevant quantities of interest, which is a central objective of this project.

Research tasks include exploration of novel ROM stabilization approaches, alternative bases, and cost-mitigation strategies to permit larger approximation spaces for improved accuracy. Another task will be to couple reactor- or assembly-scale ROM simulations with boundary-layer resolving LES to provide accurate heat transfer estimates in critical regions. A fundamental task will be to develop a suite of LES benchmark data for mixed-convection in SFR assemblies and upper plena, which will be used for construction and for validation of the ROMs as well as providing insight for these cases.

The high-fidelity studies will be conducted with the open source code Nek5000/RS, which uses high-order spectral elements to realize accurate thermal transport and boundary-layer resolution. The project will further development of NekROM, which is a new suite of utilities designed to interface with Nek5000/RS that supports the development of ROMs and their deployment for parametric modeling. Error indicators are provided to guide in the parametric development. For example, one can combine multiple POD bases (p-type refinement) or use independent bases (h-type refinement) when building a model to cover the parametric domain of interest. These error indicators will be extended to support turbulent flows and quantities of interest relevant to long-time transients in SFR applications. Nek5000/RS/ROM will be coupled to Cardinal to provide a direct interface to systems analysis codes.

This proposal aims to deliver a tool for accurate and inexpensive prediction of key thermal-hydraulic phenomena in SFRs, whose operation, safety, and design are impacted by several critical factors, including thermal stratification, mixing in large enclosures, and mixed convection. The lack of adequate modeling capability for these phenomena leads to high uncertainty, which limits the reactor's overall performance by requiring excessive margins. The proposed methods have the potential to help reduce these margins, leading to better economics. The project has the potential to significantly advance the state-of-the-art of ROMs for challenging turbulent flow problems and to enable a transformative change in the way thermal-hydraulic simulations are performed.