High-Resolution Measurements and Advanced Modeling for Design Optimization of Advanced Small Modular Reactor Steam Generators

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ABSTRACT:

One of the main components of nuclear reactors is the heat exchanger where the thermal power produced in the core is transferred to a secondary flow. Helical Coil Steam Generators (HCSGs) have been proposed for advanced Small Modular Reactors (SMRs) due to its volumetric efficiency, thermal stress flexibility and increase in heat transfer. Unlike typical U-tube heat exchangers (HXs), the HCSG utilizes multiple concentric tube bundles that coil at alternating pitches creating radially-changing tube cross-sections. The shell-side fluid turbulence increases as the cross-flow mixing over the tube bundles increases. While the increase in turbulence is favorable to the increase in heat transfer of the heat exchanger, structural design limitations and the optimal design parameters (geometrical dimensions, spacing, lateral pitch angles, etc.) corresponding to the reactor operating conditions must be considered. An increase in turbulence cause flow-induced vibration (FIV), yielding mechanical failures from fatigue, collision and tube joint failures in designs of tube and shell HXs of SMR HCSG. Therefore, having a greater insight into thermal hydraulic characteristics unique to SMR HCSG design will help develop an optimal, safer and more efficient design.

This proposal seeks to establish a highly coordinated, concurrent experimental and computational effort combining high-resolution turbulence simulations and experiments of single- and two-phase flows to deepen our physical understanding and address critical issues related to flow-induced vibrations appearing HCSG designs. The proposed advanced simulation tool combines the effort and it represents a unique strength of this proposal. It is proposed to acquire targeted measurements and high-fidelity modeling and simulations based on coupled structural, flow and heat transfer, and then use the realized extensive database to derive new models and correlations needed for FIV simulation tool. The specific tasks are:

1. Experimentally investigate isothermal single- and two-phase flows in SMR HCSGs
   a. Leveraging existing test facilities of SMR HCSGs and intensive infrastructure, to obtain high-fidelity measurements for *test-scale conditions* (isothermal, low-temperature/pressure conditions).
   b. Design, based on a scaling analysis, and construct a new HCSG facility for comprehensive tests at *validation-scale conditions* (higher-temperatures/pressures representative of operating conditions).
2. Perform high-fidelity RANS, LES and Hybrid RANS/LES (Nek5000, StarCCM+) coupling structural dynamics (Diablo, Abaqus) using as-built geometries and well-defined boundary conditions from experiments in Objective 1(a), and execute V&V using CFD-graded experimental database.
3. Derive Reduced Order Models (ROMs) based on Kernel-Cell approach and correlations needed for FIV effects using the high-fidelity coupling CFD-FIV results of HCSGs.
4. Perform calculations using developed CFD-ROMs and correlations for the new facility, conduct validations using measurements acquired from Objective 1(b), and propose optimal HCSG designs.

Key outcomes of the proposed work include (1) a unique database of high-fidelity single/two-phase experiments and simulations of the thermal-hydraulic response and FIV effects of SMR HCSG designs, (2) a curated repository of high-fidelity data to support code verification and validation, specifically addressing a significant gap in FIV safety analysis space, and (3) broad collaboration with US universities, industries and international partners. The project outcome will be beneficial several current DOE programs, such as SMR, HTGR, and NEAMS-ART, as well as enhance the collaborations between U.S. universities and the members of OECD NEA Nuclear Education, Skills and Technology (NEST) program.