Preliminary Investigation of Pressure Similarity in the i-SMR Steam Generator Using CFD

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1. Introduction

Small modular reactors (SMRs) have gained significant attention as next-generation nuclear reactors due to their enhanced safety, economic efficiency, and operational flexibility. Ensuring the reliability of newly developed SMR designs requires a Comprehensive Vibration Assessment Program (CVAP) to evaluate the structural integrity of reactor internals [1]. During the implementation of the CVAP, it is essential to design a scaled-down test facility that accurately replicates the fluid dynamic and structural interactions of the prototype. This study develops a CFD model for the steam generator (SG) simulation section and conducts a preliminary analysis of the pressure characteristics between the scaled-down test facility and the prototype. The results establish fundamental data for designing the SG section in scaled-down test facilities.

2. Materials and Methods

2.1. Innovative small modular reactor

The i-SMR under development is an integral pressurized water reactor that incorporates key primary system components, including a pressurizer, helical steam generators, and reactor coolant pumps (RCPs), within a single reactor vessel (Fig. 1). The reactor is designed to generate 170 MWe per module and is equipped with four RCPs per module. The steam generator is installed inside the reactor vessel and utilizes a helical-type tube structure [2].

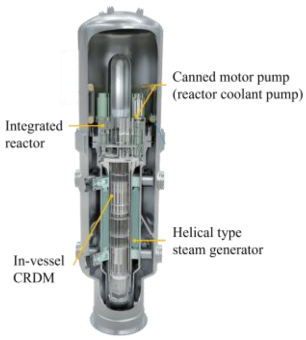


Fig. 1. Structural layout of the i-SMR

2.2. CFD model and methodology

Fig. 2 illustrates the three-dimensional CFD model used for the preliminary analysis of the SG simulation section. The model includes the flow path from the RCP discharge to the downstream section of the steam generator. The scaled-down SG simulation section was modeled considering the helical-type tubes. A structured grid system was constructed, with the first cell height set between 0.3 mm and 0.5 mm to maintain a Y+ value below 100. The total grid count for the CFD analysis was approximately 68 million.

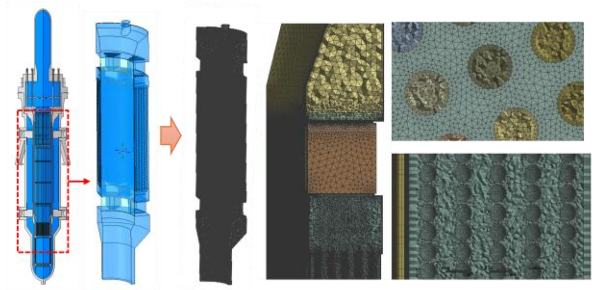


Fig. 2. 3D CAD model and computational grid of the SG section in the i-SMR

Steady-state CFD simulations were performed to evaluate pressure similarity in the upstream and downstream regions of the steam generator. Pressure similarity refers to the condition in which the non-dimensional pressure distribution, typically expressed using a pressure coefficient or normalized pressure, is preserved between the scaled-down model and the full-scale prototype. This ensures that the pressure-driven flow characteristics remain consistent across geometrically and dynamically similar systems, even under different operating scales. The flow field was computed using the continuity and momentum equations, and turbulence effects were modeled using the Shear Stress Transport (SST) k-ω turbulence model.

Three cases were analyzed:

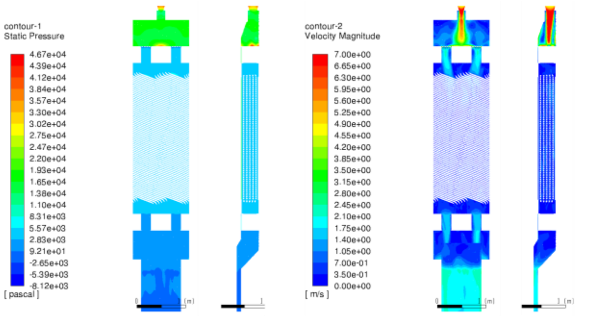
- Case 1: Using the scaled-down geometry and applying experimental conditions aligned with similarity laws.
- Case 2: Using full-scale geometry and its corresponding operating conditions.

- Case 3: Modeling the SG tubes as a porous medium, approximating the pressure drop without fully resolving the tube geometry.

The boundary conditions were established based on the i-SMR design specifications. In the computational domain, the inlet boundary was defined at the discharge of the RCP and imposed as a velocity inlet. The outlet boundary was located at the downstream section of the steam generator and specified as a pressure outlet with a static pressure set to zero. Symmetry boundary conditions were applied to the lateral (left and right) planes of the computational domain, while all other surfaces were treated as no-slip walls (Fig. 2 (a)).

3. Results

The three-dimensional CFD analysis yielded insights into the fluid flow and pressure distribution in the steam generator region of the i-SMR. Fig. 3 presents the pressure and velocity distributions in the scaled-down model. Pressure similarity was evaluated by dividing the analysis domain into 83 equally spaced cross-sections and comparing the average pressure. The total pressure was normalized based on the inlet pressure of Case 1 (Fig. 4). The results show that applying the similarity ratio resulted in a pressure distribution in the scaled-down model that closely matched the full-scale prototype.



(a) Static pressure (b) Velocity magnitude

Fig. 3. Static pressure and velocity magnitude distributions

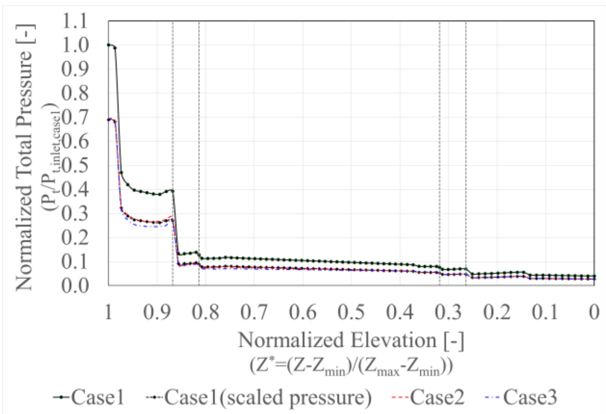


Fig. 4. Comparison of normalized total pressure distributions for different cases

4. Conclusions

This study conducted a preliminary CFD analysis to evaluate the pressure similarity of the scaled-down SG simulation section of the i-SMR. The CFD analysis results confirmed that the pressure distributions of the scaled model and the prototype exhibited similarity and provided comparative data for the design of the scaled-down test facility. Future studies will focus on experimental validation and further refinement of the numerical modeling approach to improve the accuracy of scaled-down test facility designs.

ACKNOWLEDGEMENT

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