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CFD Analysis of Core Flow Distribution in the APR1000 Reactor and Experimental Validation

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1. Introduction

In this study aims to establish a reliable CFD analysis technique to accurately analyze the coolant flow rate distribution at the core inlet of the APR1000 reactor and to verify it with experimental data. Through this, the thermal-hydraulic performance under reactor design and operating conditions is evaluated, and an optimized analysis method is presented. The main objectives of the study include performing CFD analysis for both the scaled-down and full-scale models, verifying the reliability of the CFD method through comparison with experimental data, and evaluating performance under various design variables and operating conditions. Additionally, the study seeks to acquire coolant flow distribution data at the core inlet under different conditions and build a database for use in reactor thermal-hydraulic design and operational optimization.

This study will contribute to a deeper understanding of the coolant flow characteristics in the APR1000 reactor through CFD analysis results, improving the safety and efficiency of reactor design and operation.

2. Methods and Results

2.1 APR1000 Reactor Model

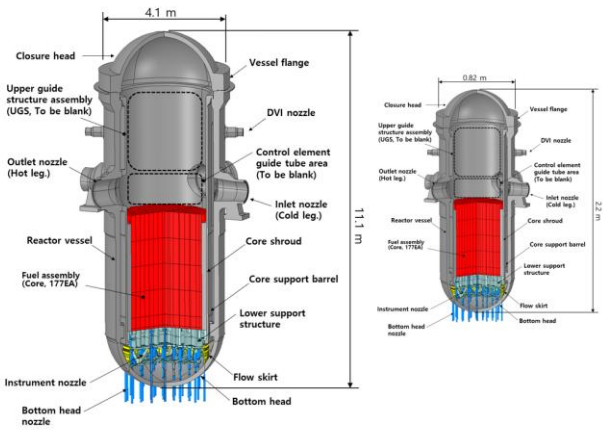
The APR1000 reactor is designed as a pressurized water reactor (PWR) for efficient heat removal. Its key components include the cold leg, downcomer, lower plenum, fuel assemblies, upper plenum, and hot leg. Coolant enters through the cold leg, descends through the downcomer, and is evenly distributed across the fuel assemblies in the lower plenum. An Emergency Core Barrel Duct (ECBD) is installed above the downcomer to supply additional coolant to the core during emergencies.

The core consists of 177 fuel assemblies arranged in a 15×15 array. The coolant absorbs heat from the fuel rods and exits through the upper plenum and hot leg.

2.2 CFD Analysis Model and Grid System

Based on the design data of the APR1000 reactor, a three-dimensional full-scale geometric model was created for CFD analysis (Fig. 1(a)). When creating this model, it was constructed to reflect almost 100% of the geometric details of the structure. The region containing the 177 fuel assemblies, the tube bank region, and the upper guide structure (UGS) within the core was not geometrically considered because a porous medium model was used.

A scaled-down model was created at a 1/5 scale, identical to the 1/5 scaled-down model used in the experiments by Kim et al. [1,2], and was linearly scaled (Fig. 1(b)). The grid system for the full-scale CFD analysis was developed using this 3D full-scale model. For consistency, the grid system for the scaled-down model was scaled from the full-scale system. To determine the grid system for the reactor core flow distribution analysis, three grid systems (Coarse, Medium, Fine) were created, and a sensitivity analysis was conducted. As a result, the coarse grid system was selected.



(a) Full scale model (b) 1/5 scaled-down model

Fig. 1. CFD analysis model for APR1000 reactor

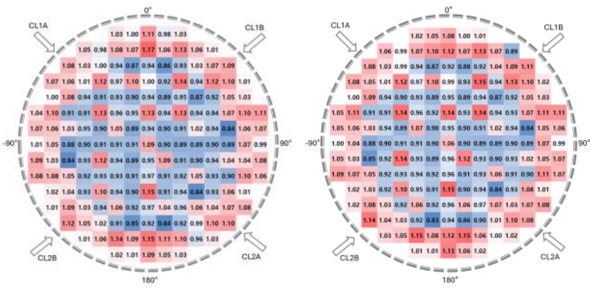
2.3 CFD Analysis Conditions and Numerical Method

The full-scale model reflects actual reactor operating conditions, with coolant entering through four cold legs at totaling 15,308 kg/s. The outlet flow through two hot legs is balanced at 7,654 kg/s. The coolant inlet temperature is 295.8°C, and the outlet pressure is 15.5 MPa. The core bypass flow includes paths like alignment keys and nozzle gaps, with 2% of the total flow bypassing the core. The coefficients of inertia in axial and lateral directions in the porous medium region are set respectively. It is assumed that no heat is released from the fuel assembly. The scaled-down model used conditions based on the experiments of Kim et al. This device does not include core bypass flow.

CFD analysis was performed using continuity, momentum and energy equations. The standard k-ε turbulence model was applied. CFX used a Pressure-Based Coupled Solver with High Resolution Scheme. To ensure accuracy and stability, the convergence criterion was set to a residual less than 10^{-3}.

2.4 Results

The flow distribution results at the core inlet from both the full scale model, 1/5 scaled-down model, and experiments are shown in Fig. 2 (CFD) and Fig. 3 (Exp.). In all cases, the flow at the edge was relatively high and tended to be distributed lower toward the center of the core. The analysis results showed greater flow variability than the experimental results but showed similar distributions. It is difficult to accurately predict local flow changes in the core flow distribution. Nevertheless, the CFD analysis effectively captured the overall flow trend and provided reasonable results within the experimental constraints.



(a) Full scale model (b) 1/5 scaled-down model

Fig. 2. Core inlet flow distribution according to turbulence models

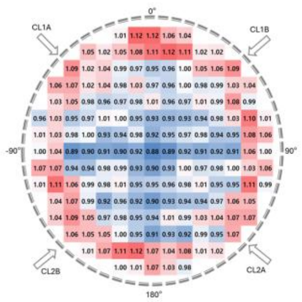


Fig. 3. Core inlet flow distribution from the 1/5 scaled-down model experiment [2]

The comparison between the analytical and experimental results of the scaled-down model showed that the 1/5 scaled-down model exhibited greater flow rate variability. The relative Deviation values indicated a generally consistent flow trend with the experiment, though local flow differences existed. The coefficient of variation (COV) and the relative deviation (RD) were evaluated to compare flow variability and similarity among the models and experimental results. These metrics were calculated using the following equations:

$$COV = \frac{\sigma}{V_{avg}} \times 100 \quad (1)$$

Where σ is the standard deviation of flow rate and V_{avg} is the mean flow rate.

$$RD = \frac{1}{n}\sum_{i-1}^{n}\left|\frac{F_{i,EXP} - F_{i,CFD}}{F_{i,EXP}}\right| \quad (2)$$

Where F_i is the flow rate at location i.

In comparison with the full-scale model, similar trends were observed, with higher flow variability than the experiment (Table I). These results suggest that while the full-scale model exhibited similar flow characteristics, local variability was larger, highlighting the importance of continuously verifying model reliability against experimental data.

Table I: Comparison of core inlet flow distribution between CFD and experimental results

		Full scale model	1/5 scaled-down model	Exp. [2]
Flow	Coefficient of Variation (COV) [%]	8.214	8.370	5.694
Similarity	RD [-]	0.047	0.049	-

3. Conclusions

The CFD analysis methodology established in this study was evaluated as a reliable tool for analyzing the core inlet flow distribution of the APR1000 reactor. There was a high degree of similarity between the CFD analysis results and the experimental data. These findings offer essential foundational data for optimizing reactor design and safety assessments and confirm the high reliability of the full-scale model analysis through comparisons with scaled-down experimental results. The CFD analysis methodology developed in this study can be extended to other reactor designs and analyses, serving as a critical guideline for the design and analysis of complex thermal-fluid systems.

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