

Review of Reactor Core Flow Distribution Research and Perspectives for APR1400

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1. Introduction

Reactor core coolant flow distribution is a key thermal-hydraulic parameter that directly affects CHF (Critical Heat Flux) and DNBR (Departure from Nucleate Boiling Ratio) evaluation, fuel temperature prediction, thermal margin assessment, and reactor protection system setpoints. Because direct measurement of the coolant flow rate for every fuel assembly in an operating plant is practically infeasible, nuclear power plant utilities have traditionally relied on reduced-scale hydraulic experiments and validated CFD (Computational Fluid Dynamics) to predict core inlet flow distribution.

This paper reviews publicly available domestic and international studies relevant to reactor core coolant flow distribution, with emphasis on Korean work for APR+, APR1000, complemented by Korean research reactor studies and international utilities experience. In Korea, systematic investigations have progressed across commercial reactors, OPR1000, APR+, APR1000, and research reactors including HANARO, JRTR and advanced research reactor [1-9]. Notably, KAERI has established reduced-scale hydraulic test facilities such as the ACOP (APR+ Core Flow and Pressure) and subsequent scaled models for APR1000 so experimentally quantify reactor flow characteristics and validate CFD methods [1-6]. Internationally, comparable experiments were executed by Combustion Engineering for the System80 series and Westinghouse for the AP600/AP1000 designs [10,11]. This study considers reactor core flow distribution with the objective of establishing APR1400-specific research outlook and priorities.

2. Review of Core Flow Distribution Studies

2.1 Korean Studies on Commercial Reactor

Korea has systematically advanced reactor core hydraulic technology base through the development of APR+, APR1000, SMART, and etc. Among publicly available Korean studies, ACOP facility is one of the most representative experimental investigations. Built at 1/5 linear scale, the facility measured core inlet flow distribution, core outlet pressure distribution, upper plenum pressure, and sectional pressure drops inside the reactor vessel [1-5]. Experiments for APR+ reactor was performed under balanced flow, 5 % and 15 % unbalanced flow conditions by 4 reactor coolant pumps,

and unbalanced conditions equivalent to a single pump failure. The results showed overall robust flow distribution, while also indicating relatively high peripheral flow, suggesting the need for further improvement in the core support structure design [1,2].

The same methodology was later extended to APR 1000 using a 1/5-scale ACOP facility containing 177 simulated fuel assemblies. Measurements showed that the normalized core inlet flow ranging from 87.9 % to 111.8 % under balanced and 5 % unbalanced flow conditions, and from 87.7 % to 112.0 % under a 15 % unbalanced condition. These results indicate that flow mixing in the lower plenum and the lower support structure play a major role in maintaining a relatively even core inlet flow distribution despite asymmetrical inlet conditions [3-5].

More recent APR1000 CFD studies using validated turbulence models reproduced the measured assembly flow rates generally within about 10 %, confirming the applicability of high fidelity CFD while highlighting a continuing need for improved turbulence modeling in the peripheral core region [6].

2.2 Korean Studies on Research Reactor

Core flow distribution studies have also been performed for research reactors. During HANARO startup testing, an instrumented dummy fuel assembly measured the core inlet flow and confirmed uniformity within about 6 % of the average [7]. A similar instrumented probe fuel methodology was later applied to plate-type fuel research reactors, including a 1/1 real-scale mockup of the advanced research reactor, where full core flow measurements using 22 fuel and 6 fission molybdenum assembly positions showed deviations around 3 ~ 5 % under various hydraulic conditions [8,9].

However, research reactors differ from commercial reactors in core type and are evaluated through real-scale experiments; this is not a methodology directly applicable to the APR1400, which requires scaling analysis and similarity law estimation, although the detailed measurement techniques and instrumentation concepts are worth referencing.

2.3 International Studies

Publicly accessible international literature confirms that lower plenum and core inlet flow management has long been a design concern. For Westinghouse AP600, scale-model studies investigated vortex formation in the

lower plenum and showed that appropriate suppression devices could mitigate such vortical flow [10]. For AP1000, NRC design certification documentation states that CFD analyses of lower vessel hardware and lower core support plate flow-hole geometry were used to improve the core inlet flow distribution, and that a flow skirt was added to obtain a more uniform distribution satisfying design requirements [11].

For System80 and System80+ series, open literature primary data are not readily available. Combustion Engineering is understood to have conducted hydraulic tests during development of System80 and System80+ series, establishing empirical correlations for core flow paths and lower plenum mixing that influenced Korean reactors. A 3/16-scale prototype System80 equipment model used to measure core inlet flow and core outlet pressure distribution.

3. Research Trends and Implication for APR1400

3.1 Comparison of Research Trends

The reviewed studies show a clear methodological transition: earlier work focused mainly on physical hydraulic testing and internal structure optimization, whereas recent studies increasingly combine tests with CFD validation and scale-up analysis. In the Korean case, the progression from CFD studies to APR studies illustrate an evolution from geometry-based numerical analysis to experimentally validated predictive methods. More recent APR1000 CFD studies further show that validated CFD models can reproduce the overall trend of core inlet flow distribution and can be extended to full-scale analysis [6].

3.2 Implications and Research Outlook for APR1400

For APR1400, the key implication is that future work should move beyond generalized statements such as “internal structures affect flow distribution” and instead establish a APR1400-specific framework that connects experimentally anchored CFD, inlet boundary uncertainty, and core thermal-margin evaluation. In particular, uncertainty quantification should be incorporated if CFD is to support safety-relevant decision making or licensing-related applications. OECD/NEA guidance emphasizes that CFD qualification requires verification and validation against experiments, and Uncertainty Quantification (UQ) [12].

Based on the reviewed studies, three research directions are proposed for APR1400 core flow distribution research: (1) Development and validation of APR1400 CFD models using experimentally supported benchmarks; (2) investigation of coupling approaches between vessel CFD and system thermal-hydraulic analyses; (3) incorporation of formal UQ into core flow prediction to support statistically defensible thermal safety margin assessments potentially applicable to future licensing-related evaluations.

4. Conclusions

A comprehensive review of publicly available domestic and international studies indicates that Korean core flow distribution research, documented for APR reactors through reduced-scale ACOP facilities, consistently shows that lower plenum and support structure significantly affect core flow distribution, while strong mixing mitigates flow asymmetry. Based on these findings, three research priorities were identified for APR1400: APR1400-specific experimental and CFD validation, coupling of vessel-scale flow analysis with thermal-hydraulic analyses, and incorporation of UQ into core flow prediction. These research directions may provide a technical basis for future APR1400 core flow distribution studies and subsequent thermal-hydraulic safety margins assessments.

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