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The Effect of the Holes Size Change of Lower-Support-Structure-Bottom Plate on the Reactor Core Thermal-Hydraulic Design

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1. Introduction

Because the APR+ (Advanced Power Reactor Plus) had more fuel assemblies (241EA→257EA) and the design of some internal structures was changed (from those of APR1400), the core-inlet flow-rate distribution for a 1/5 scaled-down reactor model was measured and high flow-rates were found especially near the outer region of the reactor core [1,2]. Such a result may be undesirable in terms of both the mechanical integrity of fuel assembly and the core thermal-margin. To solve the above-mentioned problem, additional tests with a 50% blockage of the flow holes in the outer region of the Lower-Support-Structure-Bottom Plate (LSSBP) were conducted under the 4-pump balanced flow condition, and the measured data were compared with those of the original LSSBP [3].

In this study, to examine the effect of the holes size change (i.e. smaller diameter) in the outer region of the LSSBP, not a 50% blockage of the flow holes, on the reactor core thermal-hydraulic design, simulations were conducted with the commercial CFD (Computational Fluid Dynamics) software, ANSYS CFX R.15. The predicted results were compared with those of the original LSSBP.

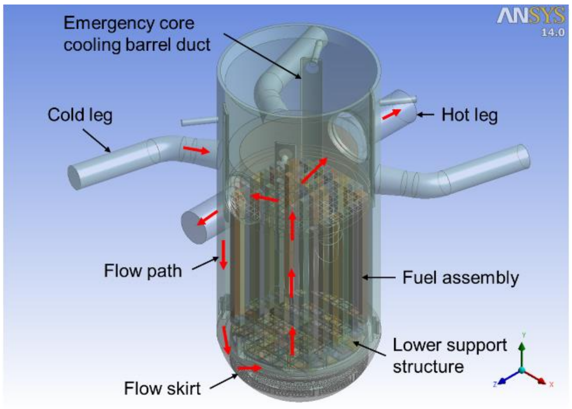
2. Analysis model

2.1 APR+ Flow Distribution Test Facility

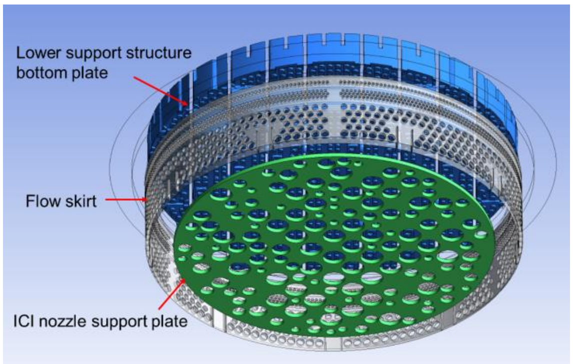
APR+ Core Flow & Pressure Test Facility (ACOP), installed in the KAERI (Korea Atomic Energy Research Institute), is a 1/5 scaled-down model of APR+. It consists of a reactor vessel with two coolant loops (i.e., four cold legs and two hot legs). The internal structures of the reactor model (e.g., flow skirt and upper/lower core structures) had almost the same shapes as those in the original APR+, and satisfied geometrical similarity [1,2]. The core-inlet flow-rate distribution could be obtained by measuring the differential pressure and discharge coefficients at the venturi region of each core simulator. A total of 257 core simulators, which corresponded to the fuel assemblies, were installed in the reactor model. The upper head of the reactor, and some core-bypass flow-paths were neglected in the reactor model because these parts were expected to have little influence on the core-inlet flow-rate distribution. The criteria of the allowable data scattering for each core simulator inlet flow-rate distribution was ±1.5% [1].

2.2 Test Conditions

The test matrix consists of three flow conditions, i.e., the symmetric or asymmetric flow conditions for 4-pumps operation, and the flow condition for 3-pumps operation. In this study, CFD simulation was conducted under the symmetric flow condition for 4-pumps operation. Under this condition, the Reynolds number was about 8.6×10^5 in the downcomer.



(a) Full geometry



(b) Details of lower support structure

Fig. 1. The computational domain.

2.3 Geometry Modeling

2.3.1. Porous medium assumption. APR+ reactor internals are complex structures which support fuel assemblies, control rods and measuring instruments. The internal structures, especially those located in the upstream of the reactor core, may have a significant influence on the core-inlet flow-rate distribution;

depending on both their shapes, and the relative distance between the internal structures and the core inlet [4]. Therefore an exact representation of these internal structures is needed for CFD simulation of the core-inlet flow-rate distribution. However, such an approach requires a great deal of computing resources to analyze the real-flow phenomena inside a reactor.

In this study, as shown in Fig. 1, among the reactor internal structures located upstream of the reactor core, the real geometries of a flow skirt, LSSBP and ICI nozzle support plate, were considered because these internal structures could significantly influence the flow-rate distribution at the core inlet.

Meanwhile, to reduce total numbers of elements and thus minimize the required amount of computation, fuel assemblies and some internal structures (e.g., control-element guide tubes) were simply considered as each bulk volume (porous domain). Then, in order to reflect the velocity field and pressure drop occurring in the real-flow region; porosity and Isotropic Loss Models [5] were applied to the porous domain.

Porosity is the ratio of the volume of fluid region to total volume; including both fluid and solid regions. It has an effect on flow acceleration in the porous domain. In this study, the porosity was determined by considering the real geometry of the reactor internal structures. A momentum source was used to model the momentum loss in the porous domain; which corresponds to a pressure drop in real reactor vessel. Loss coefficients were adjusted to match the magnitude of the pressure drop found in the porous domain, with those of the measurement.

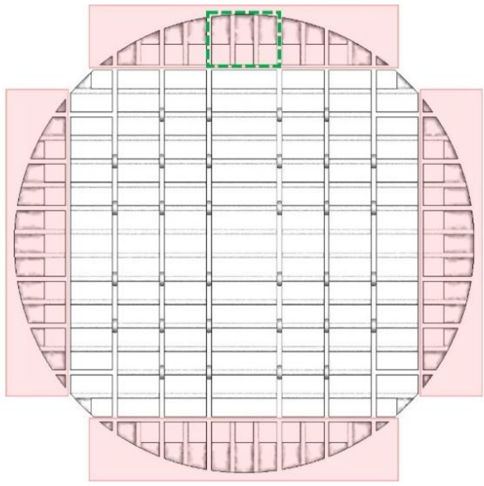
2.3.2. LSSBP holes pattern. With the aid of a flow skirt, the LSSBP plays a significant role in a uniform flow-rate distribution at core inlet. In general, holes size in the center region of the LSSBP are smaller than those in the outer region to prevent the flow from building up in the core center region.

In this study, in order to examine the appropriateness of the original LSSBP holes pattern and the effect of holes size change of LSSBP on the reactor core thermal-hydraulic design, the original LSSBP holes pattern was modified. As shown in Fig. 2, holes size in the outer region of the LSSBP, represented by four rectangular boxes in red, was reduced. The diameter ratio of a hole in the original LSSBP to those in the modified LSSBP was about 1.414 and 1.826, which corresponded to 50% and 70% reduction in the flow area per a hole. In case of several holes with small diameter, a hole size was not changed.

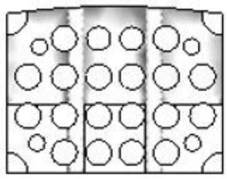
3. Numerical modeling

3.1 Numerical Method

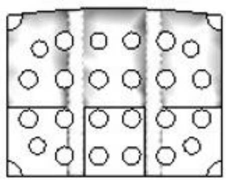
The flow inside the scaled-down APR$^+$ model was assumed to be steady, incompressible, isothermal and turbulent. High resolution scheme was used for both the convection-terms-of-momentum equations and -turbulence equations. The solution was considered ‘converged’ when the residuals of the variables were below 3×10^{-4}, and the variations of the target variables were small. Simulation was conducted with the commercial CFD software, ANSYS CFX R.15.



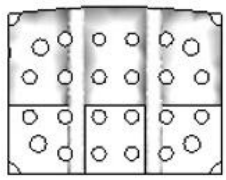
(a) Regions of the LSSBP holes pattern change



(b) Original



(c) 50% flow area reduction



(d) 70% flow area reduction

Fig. 2. LSSBP holes pattern.

3.2 Turbulence Model

The k-ε model, which is one of the most prominent Reynolds Averaged Navier-Stokes (RANS)-based turbulence models, was used to simulate the turbulent flow inside the scaled-down APR$^+$. The reason is that this model has proven to be numerically stable and has offered a good compromise in terms of accuracy and robustness. In a previous study [6], turbulence models available in ANSYS CFX R.13, for example k-ε model, Shear Stress Transport (SST) model, and SSG (Speziale, Sarkar and Gatski) Reynolds Stress model, were used to examine the turbulent flow inside the scaled-down APR+. Although the reactor internal-flow pattern differed locally; depending on the turbulence models used, the k-ε model showed the best agreement with the experimental data. More detailed descriptions of the k-ε model can be found in the ANSYS CFX-solver modeling guide [5].

3.3 Grid System

As shown in Fig. 3, a hybrid mesh, made up of tetrahedrons, pyramids and prisms, was generated to prevent the oversimplification of the geometry, and to have more efficient mesh distribution. Prism layers were used to get higher resolution in the near-wall region.

Fig. 3. Grid system; Lower support structure (original LSSBP).

Detailed information for two grid types is shown in Table 1. Total number of elements are independent of LSSBP holes pattern and therefore, are nearly same for each type.

Because the average difference of the normalized, flow-rate at the core-inlet plane between two grid types was about 0.4%, the predicted results with grid Type1 was explained in this study.

Table 1: Grid information for the modified LSSBP.

Domain	**No. of elements**	
	Type1	**Type2**
Downcomer	4.2×10^6	9.3×10^6
Lower support structure	7.0×10^6	1.4×10^7
Fuel assembly	3.9×10^6	7.8×10^6
Others	2.6×10^7	4.4×10^7
Total	4.1×10^7	7.5×10^7

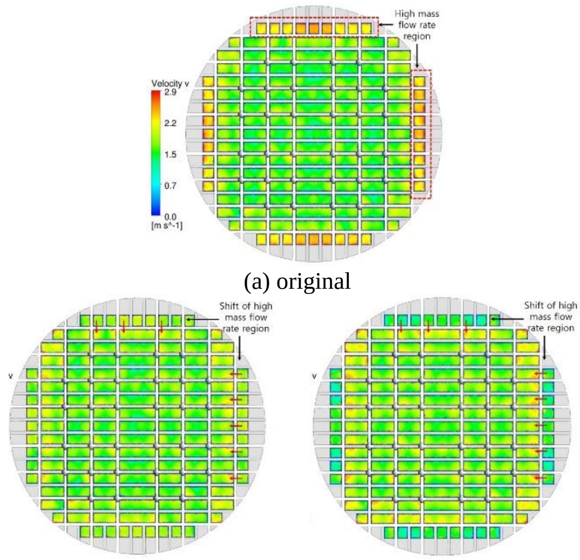
3.4 Boundary Conditions

By referring to the test condition [1,2]; an inlet flow-rate of 135 kg/s was imposed at each cold leg. Turbulence intensity at the inlet was assumed to be 5 %. Light water at 60℃ was used as the working fluid. The 'average pressure over the whole outlet' option; with a relative pressure of 0 Pa, was used at each hot leg as an outlet-boundary condition. A no-slip condition was applied at the solid wall. To model the flow in the near-wall region, scalable wall functions were applied.

4. Results and Discussion

4.1 General flow pattern

Fig. 4 shows the contour of velocity component normal to the core inlet plane. For the original LSSBP holes pattern, high velocity (or flow-rate) were found especially near the outer region of the reactor core. As the magnitude of flow area reduction increases, high velocity zones shift from the outer region to the inner region of the reactor core.



(a) original

(b) 50% flow area reduction (c) 70% flow area reduction

Fig. 4. Contour of velocity component normal to the core inlet plane.

4.2 Hydraulic uplift force on a fuel assembly

Hydraulic uplift force on a fuel assembly is generated by reactor coolant flow and is balanced by hold-down spring, located at the upper part of a fuel assembly, to fix a fuel assembly. Therefore, to design hold-down spring, correct estimation for a hydraulic uplift force on a fuel assembly is essential.

For the design purpose, the hydraulic uplift force is calculated at the lowest permissible temperature for full-flow condition. Because of the density effect, the resulting magnitude may be the largest for all operating conditions.

To prevent the fuel assembly movement by pressure pulsations, a jitter allowance is added to the calculated uplift force. The effect of corrosion product deposit, namely 'crud', is to increase the pressure drop across the fuel assembly. Therefore, an allowance for crud effect should be incorporated in the calculated uplift force. Then, statistically determined allowance for all uncertainties in data, used to calculate the design uplift force, is added as follows;

$$F_{up}^{d} = F_{up}^{be} + jitter\ allownace + crud\ allownace + uncertanties$$

where F_{up}^{d}, F_{up}^{be} is the design and the best estimated uplift force on a fuel assembly.

Table 2 shows the calculated uplift force on a fuel assembly. By reducing the holes size in the outer region of the LSSBP, design uplift force was smaller than that of the original LSSBP holes pattern. From the nuclear regulatory perspective, this kind of the design change of the holes pattern in the outer region of LSSBP may be desirable in terms of improving the mechanical integrity of fuel assembly. However, as the magnitude of flow area reduction increased from 50% to 70%, design uplift force also increased, which was undesirable for the mechanical integrity of fuel assembly. Therefore it is necessary to determine the optimal magnitude of flow area reduction in the outer region of the LSSBP.

Table 2: The calculated hydraulic uplift force (unit: *lbs*)

Conditions	**Hole pattern**		
	Original	**50% area reduction**	**70% area reduction**
Best estimated	2,936.3	**2,741.5**	2,787.4
Design	3,071.3	**2,862.2**	2,911.4

4.3 Thermal analysis results

4.3.1. Overpower penalty. For APR$^+$, simple thermal margin model will be used to monitor the real time DNBR (Departure from Nucleate Boiling Ratio) and benchmarked to calculate the DNBR conservatively against the DNBR results with the detailed subchannel analysis code. Under the operating conditions of COLSS (Core Operating Limit Supervisory System)/CPC (Core Protection Calculators), overpower penalty will be calculated for the limiting assembly candidates.

In this study, 0.2% of overpower penalty was obtained for the original LSSBP holes pattern. There was no overpower penalty for the modified LSSBP. This result shows that the hole area reduction in the outer region of LSSBP may be desirable in terms of improving core thermal margin.

4.3.2. MDNBR at hot assembly. In this study, fuel assembly with the minimum core-inlet flow-rate and the maximum rod power was selected as a target candidate for the hot assembly. Because MDNBR (Minimum Departure from Nucleate Boiling Ratio) is mostly found in the inner region of the reactor core, MDNBR was calculated for the hot assembly in this region. Table 3 shows the operational condition for the MDNBR calculation.

Table 3: Operational condition for the MDNBR calculation.

Operational condition	Pressure (*psia*)	Temp. (℉)	Mass flux ($Mlb_m/hr\text{-}ft^2$)	Axial power distribution
Nominal	2,250	557	2.4956	Cosine

Table 4: The calculated MDNBR.

Parameter	**Hole pattern**		
	Original	**50% flow area reduction**	**70% flow area reduction**
MDNBR	1.454	1.459	1.464

Table 4 shows the calculated MDNBR. As the magnitude of flow area reduction increased, MDNBR also increased. The reason may be that a more uniform distribution of the flow-rate at the core-inlet plane for the modified LSSBP hole pattern guarantee the increased thermal margin.

5. Conclusions

In this study, to examine the effect of the holes size change (smaller diameter) in the outer region of the LSSBP on the reactor core thermal-hydraulic design, simulations were conducted with the commercial CFD software, ANSYS CFX R.15. The predicted results were compared with those of the original LSSBP. The major conclusion can be summarized as follows:

(1) A more uniform distribution of the flow-rate at the core-inlet plane could be obtained by reducing the holes size in the outer region of the LSSBP.

(2) By reducing the holes size in the outer region of the LSSBP, design uplift force was smaller than that of the original LSSBP holes pattern. However, it is necessary to determine the optimal magnitude of flow area reduction in the outer region of the LSSBP.

(3) 0.2% of overpower penalty was obtained for the original LSSBP holes pattern. There was no overpower penalty for the modified LSSBP. As the magnitude of flow area reduction increased, MDNBR also increased.

(4) Therefore, this kind of the design change of the holes pattern in the outer region of the LSSBP may be desirable in terms of improving both the mechanical integrity of fuel assembly and the core thermal margin.

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