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Feasibility Study to Apply the Full Core Subchannel Analysis to Thermal-Hydraulic Design

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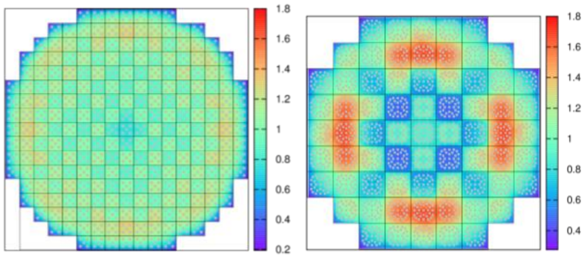
1. Introduction

The core TH(Thermal-Hydraulic) design establishes the DNBR(Departure from Nucleate Boiling Ratio) design limit, which is one of the most important safety limits in the nuclear power plant, and provides a generic thermal margin analysis model for safety analysis and core protection system design. The flow and thermal field analysis have been conducted on the basis of the core analysis model for the quarter core using the subchannel analysis code, THALES(Thermal-Hydraulic AnaLyzer for Enhanced Simulation) [1]. Currently, the core analysis model for TH design consists of subchannels in the hot node(1/4 assembly) and assembly channels in other areas, which causes to not consider the radial power distribution and inlet flow distribution in the whole core at once. Thus, the hot node is selected based on the peak of the radial power factors at each burnup case, which is no problem for the quarter core because the radial power distribution is symmetric as shown in Fig. 1. However, since the inlet flow distribution is not symmetric as shown in Fig. 2, the quadrant has to be selected. In TH design, the quadrant with the lowest inlet flow factor in the hot node is set conservatively. Using the combination of the hot node, burnup case, and inlet flow distribution quadrant, the LHF(Limiting Heat Flux) is calculated and then LAC(Limiting Assembly Candidate)s are selected.



a) APR1400 Plant b) i-SMR Plant

Fig. 1. Radial Power Distribution

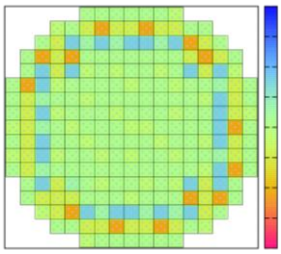


Fig. 2. Inlet Flow Distribution in APR1400 Plant

A LAC is a combination of the node and burnup case, which means a candidate of the most limiting radial power distribution in the current cycle in the viewpoint of DNBR. The LACs are very important that all the thermal designs are performed with them. However, the method to select the hot node with the peak of the radial power distribution results in the selection of the less limiting nodes in the aspect of the DNBR. Additionally, the inlet flow distribution affects the DNBR more sensitively than the radial power distribution, especially in the bottom-skewed axial power distribution. As the LACs are closely related to the thermal margin, KNF(*KEPCO Nuclear Fuel Co. Ltd.*) has developed the methodology to apply the full core subchannel analysis to the selection of LACs to take into account the effects of the radial/axial power distribution and inlet flow distribution at once.

This paper introduces the full core subchannel analysis developed by KNF and shows the calculation results for APR1400 and i-SMR plants. Also, the possibility of increasing AOPM(Available OverPower Margin) is described through the full core subchannel analysis.

2. Methods and Results

2.1 Full Core Subchannel Analysis

The full core subchannel analysis is able to reflect the effect of the radial power distribution and inlet flow factor for the flow and heat field calculation at once. Also, the same governing equation, thermal-hydraulic models, and assumptions can be applied to the whole core. Thus, the full core subchannel analysis helps evaluate the flow and heat fields in the core more realistically and removes the conservatism associated with TDC(Thermal Diffusion Coefficient), cross flow, etc. for the lumped channels.

For the full core subchannel analysis, all channels in the core are composed of the subchannels surrounded by fuel rods and guide tube as shown in Fig. 3. The number of channels and rods for the full core subchannel analysis are shown in Table 1. A large number of channels and rods increases the size of the matrix for analyzing the flow and heat field, which leads to a long calculation time and a large amount of memories in the computer server. Thus, KNF optimized the dynamic memories in THALES and introduced the Aitken relaxation method[2,3] for the stable convergence.

Table. 1. Number of Channels and Rods

	i-SMR	OPR1000	APR1400
No. of channels	20248	44908	61036
No. of rods	17940	41772	56876

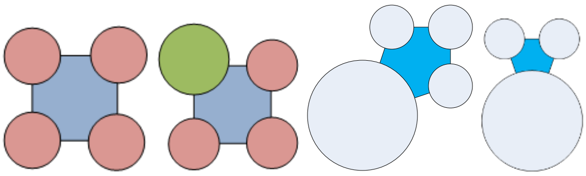


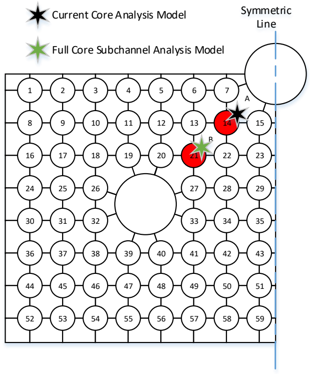
Fig. 3. Various Types of Subchannels for APR1400 and i-SMR Plants' Reactor Cores

2.2 Calculation Results

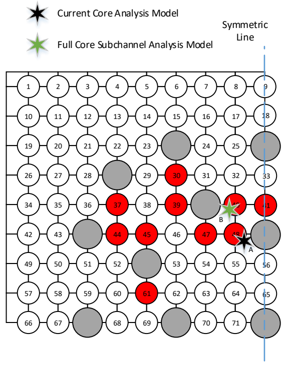
In this section, the calculation results for APR1400 and i-SMR plants are described. The radial power distribution for APR1400 and i-SMR plants are used as shown in Fig. 1. For APR1400 plant, the radial power distribution under the ARO condition is used, which means the control rod is not inserted. On the other hand, since i-SMR plant adopts the soluble boron free operation, the control rod remains to be inserted to control the reactivity. Thus, the radial power in the center region is low due to the control rod as shown in Fig. 1 b). The inlet flow distribution for APR1400 plant is used as shown in Fig. 2. The inlet flow distribution for i-SMR plant is assumed based on OPR1000 plant because the inlet flow distribution test has not been performed yet. After performing the THALES calculation using the current core analysis model and full core subchannel analysis model, the channels where the minimum DNBR(mDNBR) occurs are marked in Fig. 4. The rods filled with the red color mean the hot rod. In Fig.4, the mDNBR occurs in the channel adjacent to the hot rod. However, the mDNBR channels depend on the core analysis models.

For the detailed analysis, the enthalpy, mass flux, void fraction, and DNBR along the axial length are compared as shown in Figs. 5 and 6. Channels A and B mean the channels where the mDNBR occurs for the current core analysis model and full core subchannel analysis model, respectively. Figures 5 and 6 show that the enthalpy, mass flux, and void fraction are different depending on the core analysis models, which causes the mDNBR to occur on different channels. The cross flow between the subchannels are calculated based on the pressure loss between channels; however, the cross flow between the subchannel and lumped channel is evaluated using Hetsroni[4] equation which calculates the cross flow conservatively. Thus, the current core analysis model predicts the enthalpy, mass flux, and void fraction conservatively as shown in Figs 5 and 6. In case of the full core subchannel analysis, the cross flow can be evaluated reasonably by applying the same equation in the whole core excluding Hetsroni equation.

Also, the hot node which is located on the symmetric plane can affect the flow behavior. The channel B in Fig. 4 is more realistic than channel A in the viewpoint of DNBR. It is confirmed that the full core subchannel analysis evaluates the thermal-hydraulic behavior appropriately and helps eliminate conservatism by comparison with the current core analysis model.

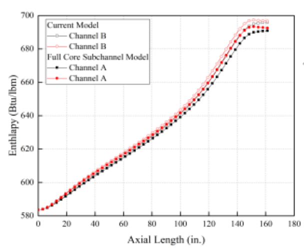


a) APR1400

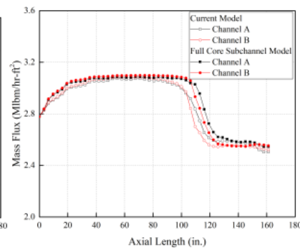


b) i-SMR

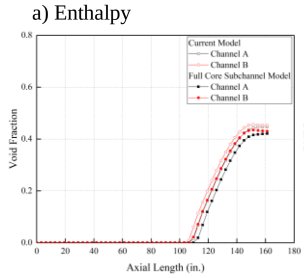
Fig. 4. mDNBR Channels for APR1400 and i-SMR Plants



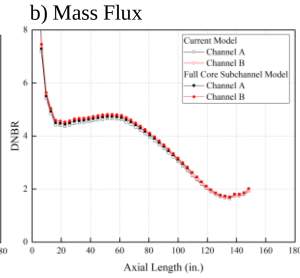
a) Enthalpy



b) Mass Flux

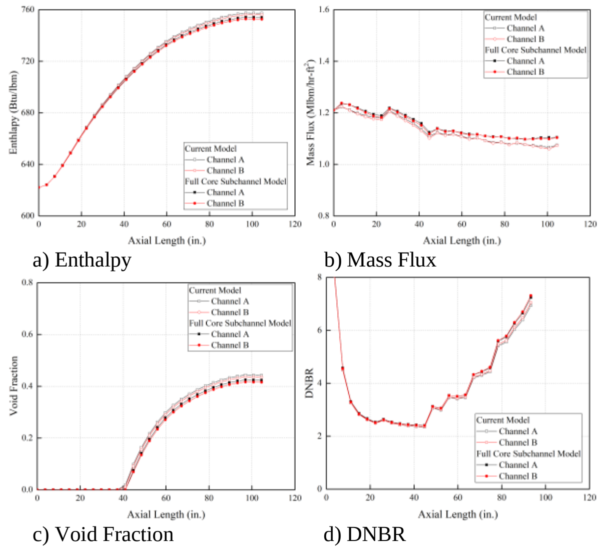


c) Void Fraction



d) DNBR

Fig. 5. Comparison of Enthalpy, Mass Flux, Void Fraction, and DNBR in Channels A and B for APR1400 Plant

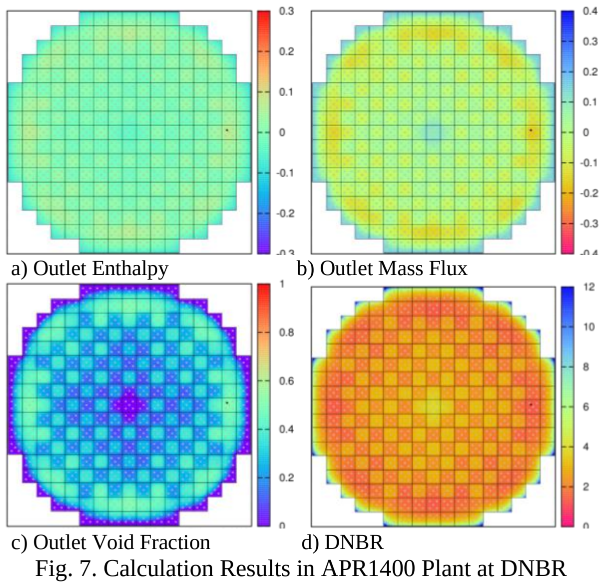


a) Enthalpy b) Mass Flux

c) Void Fraction d) DNBR

Fig. 6. Comparison of Enthalpy, Mass Flux, Void Fraction, and DNBR in Channels A and B for i-SMR Plant

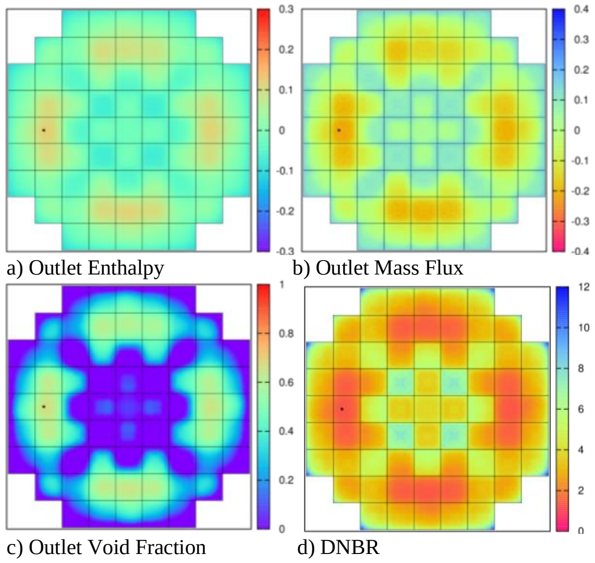
Figures 7 and 8 show the calculation results at the DNBR SAFDL(Specified Acceptable Fuel Design Limit) condition for the whole core. The black square in the outlet enthalpy, outlet mass flux, outlet void fraction and DNBR distribution means the channel where the minimum DNBR occurs. These figures help understand the calculation results at once and select the limiting channels in the viewpoint of DNBR. Based on the limiting channels in Figs. 7 and 8, the AOPM will be evaluated in the next section.



a) Outlet Enthalpy b) Outlet Mass Flux

c) Outlet Void Fraction d) DNBR

Fig. 7. Calculation Results in APR1400 Plant at DNBR SAFDL Condition



a) Outlet Enthalpy b) Outlet Mass Flux

c) Outlet Void Fraction d) DNBR

Fig. 8. Calculation Results in i-SMR Plant at DNBR SAFDL Condition

2.3 AOPM Evaluation

AOPM calculations are performed using the calculation results in the previous section. For all the APR1400 and i-SMR plants, it is checked that AOPM increases when selecting the LACs through the full core subchannel analysis as shown in Fig. 9. $AOPM_{current}$ is the value calculated using the LACs through the existing core analysis model. $AOPM/AOPM_{current}$ means the increase of the AOPM. This result only reflects changes in the core analysis model and the AOPM can be further enhanced if the full core subchannel analysis is applied to the selection of the LACs. The increase of the AOPM affects the DNBR design limit and a generic thermal margin analysis model, which can contribute to improving the thermal margin of the nuclear power plants.

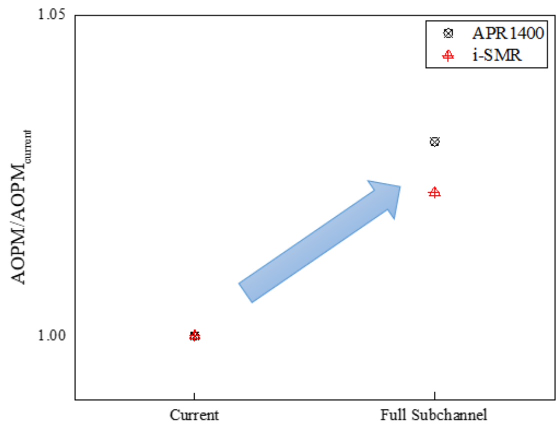


Fig. 9. AOPM Enhancement

3. Conclusions

In this paper, the full core subchannel analysis methodology being developed by KNF is described. Through the calculations for APR1400 and i-SMR plants, it is confirmed that the full core subchannel analysis produces the calculation results more reasonably. Also, the LACs selected from the full core subchannel analysis make it possible to increase the AOPM, which will be able to help improve the thermal margin of the nuclear power plants. The full core subchannel analysis will be used in the various ways, such as the DNBR analysis in the SCEAW(Single CEA Withdrawal) accident and TH behavior evaluation in various radial/axial power distributions due to the soluble boron free operation in i-SMR plant.

Acknowledgement

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