

Sensitivity Analysis of Thermal Margin of Water Cooled Integrated SMR Fuel Assembly as Axial Power Peaking and Thermal-Hydraulic Conditions

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1. Introduction

Small Modular Reactors (SMRs) are being developed based on compact and modularized designs compared with conventional nuclear power plants, and in Korea, the innovative Small Modular Reactor (i-SMR), a light-water-cooled SMR, is currently under development [1]. The i-SMR is an integral-type modular pressurized water reactor, and its safety assessment should account for design and thermal-hydraulic characteristics that differ from those of conventional large-scale pressurized water reactors.

In pressurized water reactors, when the surface heat flux of a fuel rod reaches the critical heat flux (CHF), departure from nucleate boiling (DNB) may occur, resulting in a rapid degradation of heat transfer performance. The departure from nucleate boiling ratio (DNBR) is defined as the ratio of the critical heat flux to the local heat flux, and the minimum DNBR (MDNBR) in the core is a key parameter for evaluating thermal margin [2]. Lee et al. (2025) [3] evaluated the thermal margin of i-SMR fuel using the subchannel thermal-hydraulic code CTF [5] with the Groeneveld CHF Look-up Table (LUT) [4] and analyzed the thermal margin for axial power distributions at the beginning of cycle (BOC) and end of cycle (EOC). Even under the same total power condition, the thermal margin can vary with changes in axial power peaking and major thermal-hydraulic conditions. The previous study showed that the minimum DNBR occurred near the maximum power peaking location and that the overall DNBR trend was closely related to the axial power distribution [3]. A sensitivity analysis of DNBR with respect to changes in the axial power distribution is required. In this study, a CTF [5] subchannel analysis model was developed based on the analysis conditions of Lee [3], and the axial DNBR distribution and MDNBR location under the reference condition were compared with the results of the previous study. Subsequently, the sensitivity of DNBR to changes in axial power peaking was analyzed based on the BOC and EOC axial power distributions of the i-SMR, and variations in the MDNBR with changes in mass flux and system pressure were evaluated. Through these analyses, this study aimed to examine the trend in the thermal margin of Water Cooled Integrated SMR fuel assembly with changes in the axial power distribution and major thermal-hydraulic conditions using an existing CHF correlation.

2. Preliminary Analysis of Water Cooled Integrated SMR Fuel Assembly

2.1 Analysis Model and Conditions

For evaluation of the DNBR of the Water Cooled Integrated SMR fuel assembly, the subchannel thermal-hydraulic code CTF was used. Prior to the sensitivity analysis, a reference CTF input model was developed based on the Water Cooled Integrated SMR fuel assembly geometry and normal operating conditions adopted by Lee [3]. The major analysis conditions are summarized in Table 1.

Table 1. Operating parameters at normal condition [3]

Parameter	Value
Power[MWt]	520
No. of Assembly	69
RCS Pr. [kg/cm ²]	158.19
Linear Power [kW/m]	12.077
Lattice Type	17 X 17
No. of Fuel Rod	260
Water Hole per Assembly	29
Height [mm]	2400
Mass Flow [kg/s]	54.18

2.2 Reference Case Results and Comparison

The axial power distributions at BOC and EOC presented in the previous study were adopted as the reference power distributions. The critical heat flux was calculated using the Groeneveld CHF Look-up Table (LUT)[4] implemented in CTF, and the MDNBR and its axial location were compared based on the calculated axial DNBR distributions. The results of the reference model were compared with those of Lee [3]. Since the previous study presented the DNBR and axial power distributions in normalized form, the comparison focused on the overall trend of the axial DNBR distribution and the location of the MDNBR rather than on a direct quantitative comparison of absolute MDNBR values. For this purpose, each distribution was normalized by its own maximum value and plotted together in Fig. 1.

The normalized DNBR distributions obtained in this study showed overall agreement with the previous study for both BOC and EOC conditions. Therefore, the reference model was subsequently used as the baseline model for the sensitivity analyses.

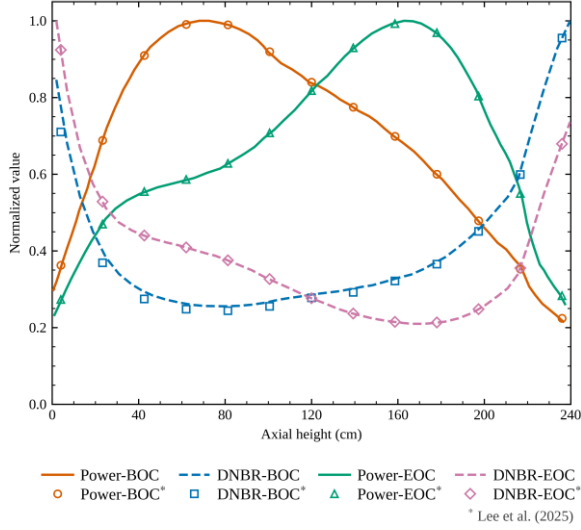


Fig 1. Axial power distributions and axial DNBR distributions at BOC and EOC

3. Sensitivity Analysis

3.1 Effect of axial Power Peaking

At both BOC and EOC, the minimum DNBR was observed to occur near the location of the maximum axial power peak. Therefore, a sensitivity analysis was performed by varying the axial power peaking factor for the BOC and EOC power distributions to investigate the effect of axial power peaking on DNBR.

To vary only the magnitude of the power peak while maintaining the same total power and peak location, the power at each axial position was adjusted by the same scaling factor about the mean value of the reference power distribution. The modified power distribution was calculated as follows.

$$f(z) = \bar{f} + a[f_0(z) - \bar{f}]$$

- $f_0(z)$: the reference axial power distribution
- $\bar{f}$: the mean axial power
- a : adjustment factor

The adjustment factor was calculated as follows.

$$a = \frac{F_{z, target} - 1}{F_{z0} - 1}$$

This method preserves the axially integrated power while changing only the magnitude of the power peak without altering its axial location. The reference peaking factors for BOC and EOC were 1.432 and 1.480, respectively. Based on these values, the peaking factors were increased by 5% and 10%.

Table 2. Axial power peaking factors for the sensitivity cases

Condition	BOC F_z	EOC F_z
Reference	1.432	1.480
Peak +5%	1.504	1.554
Peak +10%	1.575	1.628

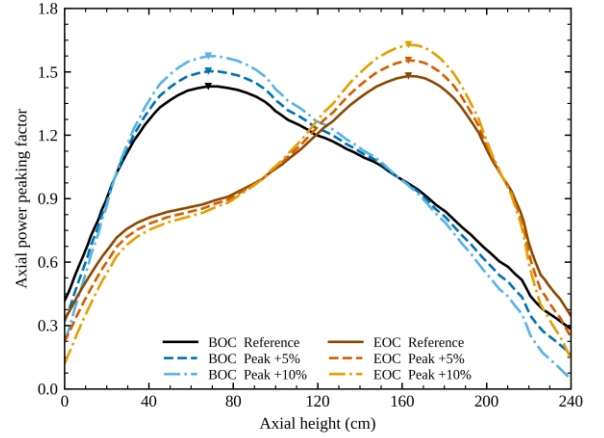


Fig 2. Normalized axial power distributions for BOC and EOC.

3.2 Effect of Mass Flux and System Pressure

To evaluate the effects of major thermal-hydraulic conditions other than axial power peaking on DNBR, sensitivity analyses were performed for mass flux and system pressure. Since the Groeneveld CHF Look-up Table implemented in CTF calculates CHF as a function of equilibrium quality, pressure, and mass flux[4], mass flux and system pressure were selected as the sensitivity parameters in this study. The analysis conditions are summarized in Table 3.

Table 3. Thermal-hydraulic sensitivity cases

Case	Mass flux	System pressure
Reference	100%	100%
Mass flux (−10%)	90%	100%
Mass flux (−20%)	80%	100%
Pressure (−10%)	100%	90%
Pressure (−20%)	100%	80%

For each condition, the axial DNBR distribution was calculated, and the MDNBR and its axial location were compared to evaluate the effects of changes in mass flux and system pressure on DNBR.

4. Results

The DNBR analysis results for variations in axial power peaking are shown in Fig. 3. Even under the same total power condition, the MDNBR decreased as the axial power peaking increased. When the axial power peaking factor was increased by 10%, the MDNBR decreased by 9.3% at BOC and 9.1% at EOC. This indicates that the local concentration of the axial power distribution, in addition to the total power, is an important factor affecting the thermal margin of Water Cooled Integrated SMR fuel assembly.

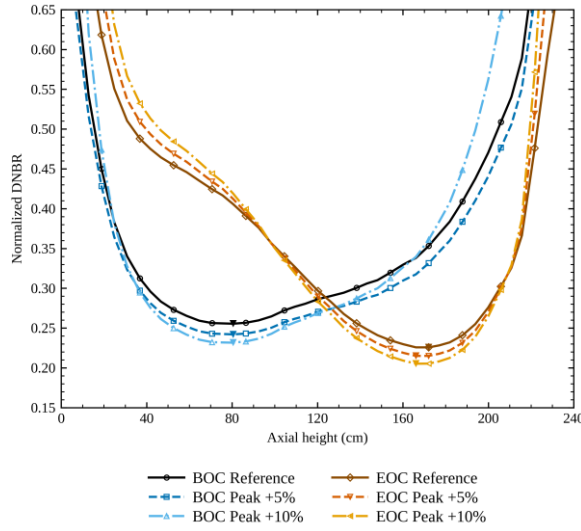


Fig 3. Axial DNBR distributions for different power peaking

The DNBR analysis results for variations in mass flux and system pressure are shown in Fig. 4. When the mass flux and system pressure were each decreased by 20%, the MDNBR decreased by 9.9% and 2.2%, respectively, indicating that DNBR was relatively more sensitive to variations in mass flux within the range considered in this study. A decrease in mass flux can increase the heat input per unit mass of coolant under the same thermal power condition, resulting in a greater enthalpy rise and an increase in equilibrium quality [7]. Since both mass flux and equilibrium quality are key thermal-hydraulic parameters used to determine CHF in the Groeneveld CHF LUT [4,7], these changes can affect the CHF and are therefore considered to have contributed to the decrease in DNBR observed in the present analysis [6].

5. Conclusions

In this study, changes in the thermal margin of the Water Cooled Integrated SMR fuel assembly were evaluated through sensitivity analyses using CTF, and the corresponding variations in DNBR were investigated. The results showed that both the axial power distribution and coolant flow conditions affect the thermal margin of Water Cooled Integrated SMR fuel assembly. In particular, within the range investigated in this study, DNBR was more sensitive to variations in mass flux than to variations in system pressure. This result suggests that the dependence of CHF on mass flux should be carefully considered in the development of new CHF correlations

applicable to Water Cooled Integrated SMR operating conditions. In addition, since the present study employed the Groeneveld CHF LUT, further studies should apply various CHF correlations to investigate differences in the predicted thermal margin of Water Cooled Integrated SMR fuel assembly among the correlations.

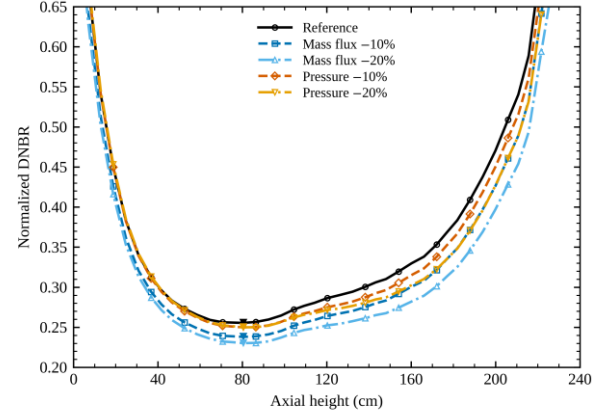


Fig 4. Axial DNBR distributions for different mass flux and system pressure conditions.

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