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Analysis of Axial Shape Index and Peaking Factors Considering Flexible Operation for Boron-free i-SMR Core

Seunghwan Jun[a,b], Bum Hee Jo[b], Ser Gi Hong [a*]
[a]*Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[b]*KEPCO Nuclear Fuel, 242, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea*
[*]*Corresponding author: hongsergi@hanyang.ac.kr*

1. Introduction

In the case of small modular reactors (SMRs), they have been equipped with enhanced flexibility performance requirements compared to large-scale nuclear plants, as outlined in EPRI URD Revision 13 [1]. Therefore, enhanced flexibility performance has been established as a fundamental developmental objective for Innovative-Small Modular Reactor (i-SMR).

Axial Shape Index (ASI) is an indicator of how the axial power distribution in the core is skewed towards the upper or the lower regions. The ASI limit is being utilized as a basis for the initial conditions of transient analysis and the limiting condition for operation. However, since the i-SMR core is structurally and systemically different from the conventional nuclear power plants and is designed with a boron-free core, the ASI limit used for the conventional nuclear power plant cannot be directly applied. Therefore, an ASI analysis considering various power and operating conditions is necessary.

In this paper, an analysis on the power-dependent ASI was conducted considering various operating conditions, including design requirements related to flexible operation of i-SMR such as daily load following operation, unexpected power change, and xenon transient condition power change. Furthermore, the sensitivity analysis of ASI and peaking factors was conducted with respect to power variations under xenon transient conditions induced by reactivity uncertainty. This allowed for the assessment of the impact of reactivity uncertainty on ASI and peaking factors.

2. Methods and Results

2.1 Computational Methods

Assembly burnup calculations for two-group cross-section generation were computed by KARMA (Kernel Analyzer by Ray-tracing Method for fuel Assembly) [2][3] which is a two-dimensional multi-group transport theory code using 190 group and 47 group cross section library based on ENDF/B-VI.8. ASTRA (Advanced Static and Transient Reactor Analyzer) code was used for 3D core calculation [4]. ASTRA is a multi-dimensional nuclear reactor simulator based on a nodal diffusion theory to facilitate the nuclear design of PWR cores and developed by KEPCO NF (KEPCO Nuclear Fuel) based on the reactor physics technologies. It adopts a semi-analytical nodal method (SANM) coupled with a coarse mesh finite difference method (CMFD) of which the accuracy and efficiency were proven itself as an excellent neutronic solver for the reactor core analysis. [5][6]

2.2 Daily Load Following Operation

The i-SMR specifies the following as the top requirements for daily load following operation: the ability for operating at the rated power levels of at least 100%-20%-100%. Additionally, the time required for ramping down from full power to partial power and returning from partial power to full power should be within 2 hours each. The duration of maintaining partial power is set to be between 4 and 10 hours. The rate of change of inlet temperature remains constant at 6.8℃/hr within the power change.

The daily load following operation meeting the above specified requirements was simulated for three cycles: the initial core cycle, the transition core cycle, and the equilibrium core cycle (cycles 1, 2, and 8). For each cycle, the simulations were conducted at the beginning of cycle (BOC), the middle of cycle (MOC), and the end of cycle (EOC). The simulations involved ramping down the power from full power to 20% within 2 hours, maintaining it for either 4 or 10 hours, and then ramping back up to full power within 2 hours.

Fig. 1 shows the simulated results of maintaining a 20% power for 4 hours during 100-20-100% daily load following operation (2-4-2-16 hours). The control rod positions and ASI variations are presented in Fig. 1. Compensation for power defect and reactivity variations due to Xenon is achieved solely through the regulating control rods.

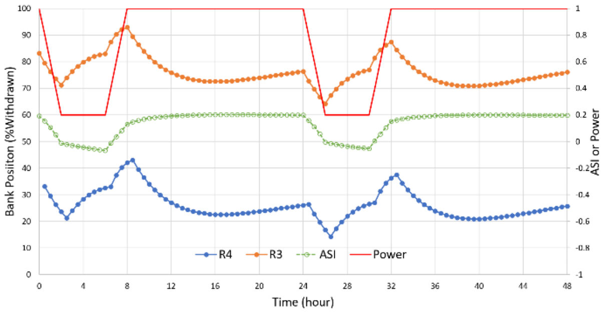

Fig. 1. Control Rod Positions and ASI during Daily Load Following Operation (BOC, Cycle 8, 2-4-2-16)

Fig. 2 shows the ASI categorized by power levels for daily load following operation. At full power, the ASI ranges from -0.26 to 0.28, expanding to -0.37 as power decreases. It was observed that the ASI range expanded negatively by 12% and positively by 2% compared to the ASI range of -0.14 to 0.26 during full power operation. Since i-SMR shows significant negative MTC values, reactivity tends to be inserted into the upper region as the power decreases, resulting in an upward bias in the power.

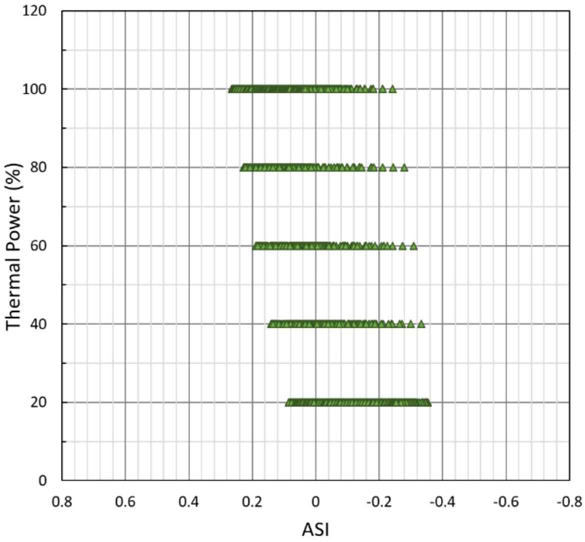

Fig. 2. Axial Shape Index for each Power Level (Daily Load Following Operation)

2.3 Unexpected Power Change

The i-SMR specifies the following as the top requirements for unexpected power change: the ability to handle step changes of ±10% and ramp changes at a rate of 5% per minute, both within the range of 20% to 100% of the power level.

The ramp changes were simulated for cycles 1, 2, and 8. For each cycle, the simulations were conducted at the beginning of cycle (BOC), the middle of cycle (MOC), and the end of cycle (EOC), progressing at a rate of 5% per minute from 20%, 40%, 60%, and 80% power until reaching full power. Conversely, instances of power decrement were simulated, reducing power at a rate of 5% per minute from full power, 80%, 60%, and 40% power, until reaching 20% power. Furthermore, to simulate step changes of ±10%, instantaneous power increments (e.g., 20% to 30%, 50% to 60%, 90% to 100%) and decrements (e.g., 100% to 90%, 60% to 50%, 30% to 20%) were established and simulated.

Fig. 3 shows the ASI categorized by power levels for unexpected power changes. At full power, the ASI ranges from -0.27 to 0.28, expanding to -0.36 as power decreases. The ASI expanded negatively by 13% and positively by 2% compared to the ASI range of -0.14 to 0.26 during full power operation.

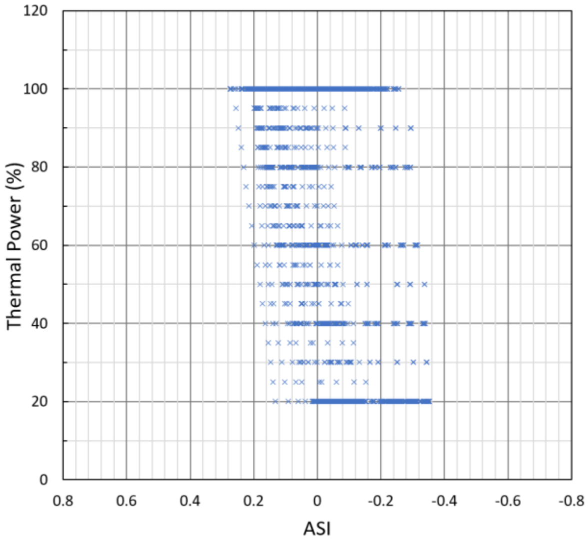

Fig. 3. Axial Shape Index for each Power Level (Unexpected Power Change)

2.3 Xenon Transient Condition Power Change

Because the 20% power functions as the lower bound of the operating range, power changes were initiated from xenon equilibrium state at 20% power. The calculations were conducted for critical control rod position and axial power distribution while incrementally increasing the power by 5% from 20% to analyze the effects of xenon changes. To assess the impact of reactivity uncertainty, power changes were simulated considering reactivity uncertainties of 0 pcm, -300 pcm, and -500 pcm.

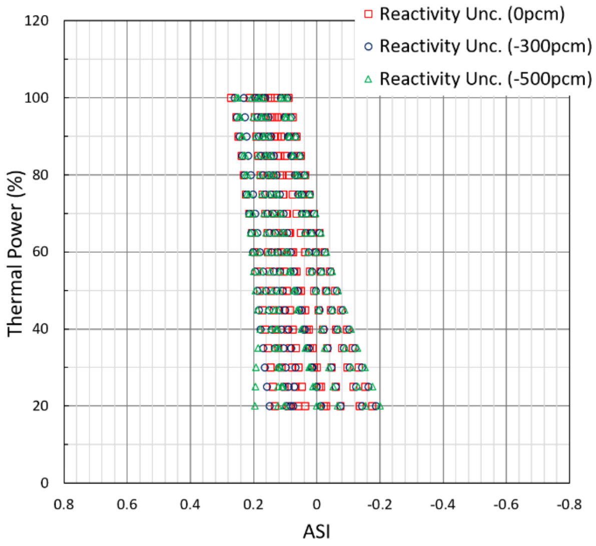

Fig. 4. Axial Shape Index for each Power Level (Xenon Transient Condition Power Change)

Fig. 4 shows the ASI categorized by power levels for xenon transient condition power changes in response to changes in reactivity uncertainty. At full power, the ASI range remains similar in response to changes in reactivity uncertainty, however, as power decreases, it can be observed that the ASI range widens with increasing reactivity uncertainty.

Table I summarizes the peaking factors as reactivity uncertainty in the simulated power changes. The peaking factors in the table represent the maximum values across all power levels. The maximum F_r was not significantly affected by reactivity uncertainty, whereas the maximum F_q showed an increment of approximately 7.5% when reactivity uncertainty is -500 pcm.

Table I. Peaking Factors for Reactivity Uncertainties

Parameters	Reactivity Uncertainty		
	0 pcm	-300 pcm	-500 pcm
F_r	1.754	1.757	1.758
F_q	2.423	2.540	2.603

3. Summary and Conclusions

An analysis of the ASI is requisite to establish the initial conditions for transient analysis and the limiting conditions for operations of the i-SMR. Calculations of ASI were conducted considering various power and operational conditions such as daily load following, unexpected power change, and xenon transient condition power change.

The ASI calculated for each power level are shown in Fig. 5. At full power with planed and unexpected power changes, the ASI ranges from -0.28 to 0.28, expanding to -0.36 as power decreases.

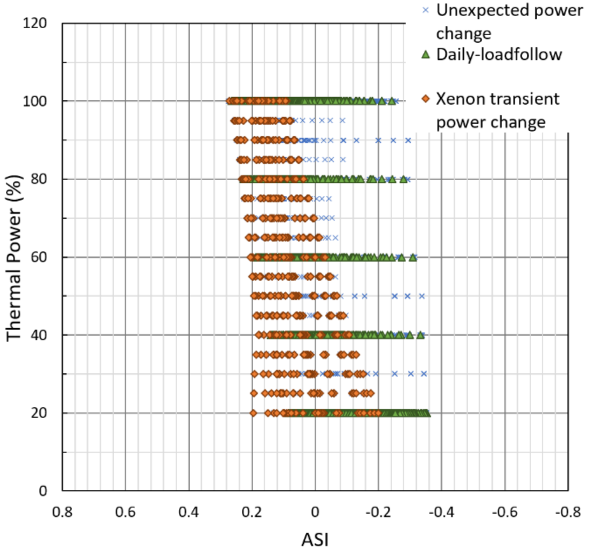

Fig. 5. Axial Shape Index for each Power level

Furthermore, it was observed that the ASI range widens and the peaking factors increases with increasing reactivity uncertainty.

It is evaluated that the ASI of the i-SMR core should be controlled within ±0.4. The results of this study could be utilized in setting the initial conditions for safety analysis and defining the operational ranges during future design processes.

The KARMA/ASTRA code used in this study did not consider the microscopic XS changes in isotopic composition due to control rod insertion. Therefore, it will be necessary to evaluate the effects of control rod insertion in the future to reflect its impact.

ACKNOWLEDGEMENT

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