Investigation of Nodal-Level Effects on the OPR1000 Steam Generator Using CINEMA

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Keywords : CINEMA, Severe Accident, Uncertainty Analysis

1. Introduction

Severe accident scenarios, particularly Loss-of-Coolant Accidents (LOCAs), must be evaluated as part of the safety verification and regulatory licensing process. Notably, Small Break Loss-Of-Coolant Accident (SBLOCA) requires long-term simulations due to its slow accident progression, and accurate modeling considering complex thermal-hydraulic behaviors. Engineering level computer codes are essential and powerful tools for evaluating such accident scenario. The CINEMA (Code for INtegrated severe accident Evaluation and MAnagement) code, which is developed in Korea has been widely utilized such as accident evaluation, and uncertainty analysis [1].

However, engineering level computer code analysis requires considerable computing time due to the complexity of modeling. Specifically, detailed nodalization models can simulate physical phenomena such as core melt, direct containment heating due to corium relocation, and fission product behavior, while, they significantly increase computing costs. Such computational efficiency issues pose a major constraint in field requiring numerous iterative calculations, such as uncertainty analysis and probabilistic safety assessment (PSA). Thus, reducing computational time is an essential task for improving the efficiency of research and development.

This study aims to improve the computational efficiency of OPR1000 SBLOCA analysis using CINEMA. The steam generator region was subdivided into finer nodes to conduct a comparative analysis of two distinct nodalization schemes. The feasibility of an optimized nodalization was assessed based on computation time and the evaluation of thermal-hydraulic behavior throughout accident progression.

2. Methodology

In this study, calculations were performed using version 2.1.0.383 of CINEMA, a comprehensive severe accident analysis code developed in Korea [2]. The accident scenario considered is a 2-inch SBLOCA. This accident analyzes a situation assuming a base case where the reactor automatically shuts down (reactor trip) due to a rapid drop in reactor pressure after coolant leaks outside, and no additional mitigation strategies are applied.

2.1 OPR1000 Nodalization

The existing nodalization of OPR1000 is designed to simulate the main systems and components of a power plant in detail. Each component of this nodalization is subdivided into multiple nodes and junctions to calculate fluid dynamic behavior and heat transfer phenomena. A schematic representation of the nodalization for the entire system of OPR1000 is shown in Figure 1-(a) [3].

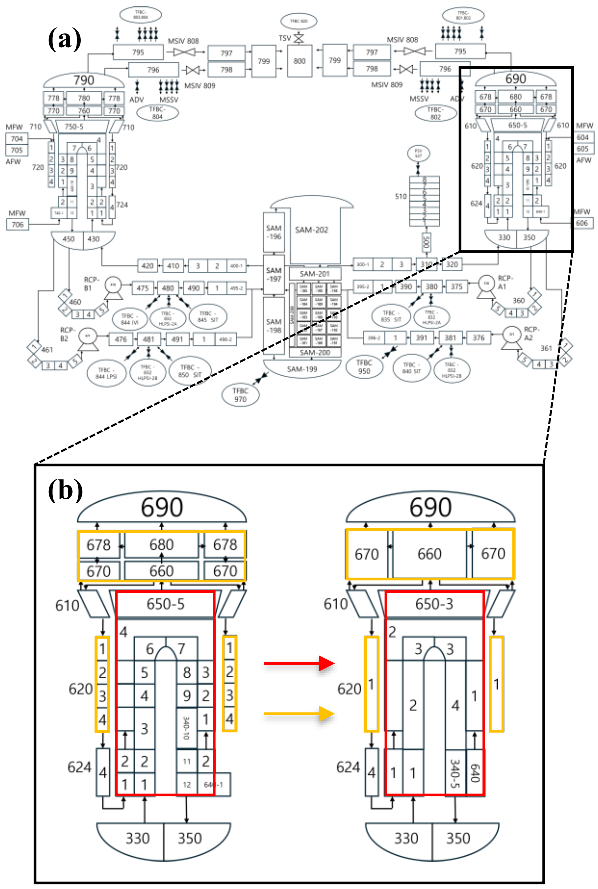

Fig. 1. (a) OPR1000 Nodalization
(b) Steam Generator model

2.2 Steam Generator Nodalization

In the original nodalization (Case 1), the Steam Generator (SG) was modeled in great detail due to its complex structure. Multiple nodes were used to simulate the U-tube and the Secondary side flow path on the shell side. In this study, Simplified SG nodes (Case 2) were developed by applying a method that integrates nodes with similar thermal-hydraulic characteristics from the original nodalization, thereby reducing computation time while maintaining the core physical phenomena.

The primary-side U-tube was simplified from 12 nodes to 5 nodes, the Secondary-side shell from 5 nodes to 3 nodes, the Evaporator from 2 to 1 node, the Downcomer from 4 to 1 node, and the Separator and Dryer areas from 4 to 2 nodes, reducing the total number of nodes from 27 to 12. The original SG nodalization model and the simplified model are shown in Figure 1-(b).

3. Result and Discussion

Table 1 shows the major accident sequences of each case. In the following discussion, the original model before node simplification is designated as Case 1, while the simplified model is designated as Case 2. The results of the two models showed similar trends in most major event occurrence times. Especially, initial accident sequences such as oxidation, and cladding melt occurred at approximately the same time. It indicates that the simplification of the SG node did not significantly affect the initial system responses during the accident. However, minor differences were observed in fuel meltdown, core dry-out, lower head relocation, and RPV failure. It is evaluated that the minor changes in heat transfer area and flow channels within the SG induce the different behavior of primary system.

After 5 to 6 hours from the cladding melted, as shown in Figure 2-3, an increase in pressure in the primary system and a decrease in pressure in the secondary system were simulated. Simultaneously, as shown in Figure 4-5, the discharge flow rate from the break point increased. These phenomena are analyzed as having been caused by complex physical factors. Continuous coolant loss led to core uncover, initiating a zirconium-steam reaction, which generated heat and hydrogen gas, causing the pressure in the primary system to rise. This increased pressure caused the discharge flow rate through the rupture to increase due to the pressure difference. On the other hand, the secondary system shows a continuous decrease in pressure as the heat supply from the primary system decreases. These accident sequence results prove that the node simplified model can sufficiently simulate the accident sequences of previous original model.

Table. 1: Accident Sequences of each Case 1 and 2

Accient Sequences	Set Point	Case 1 (Time, hrs)	Case 2 (Time, hrs)
Reactor trip	-	0	0
Oxidation	1173K	0.79	0.78
Cladding melt	2098K	1.06	1.00
UO_2 melt	2400K	3.91	2.61
Core dry-out	-	6.44	6.94
Relocation to Lower Plenum	-	9.30	10.12
RPV failure	1273.15K	11.01	11.90
Calculation time	-	17.78	15

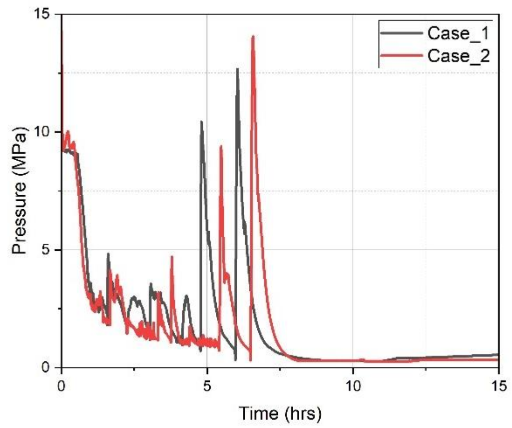

Fig. 2. Primary side Pressure

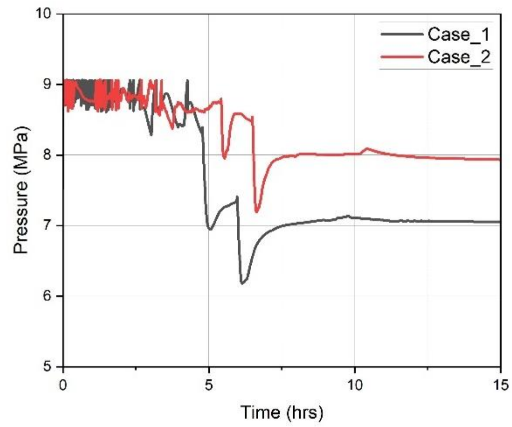

Fig. 3. Secondary side Pressure

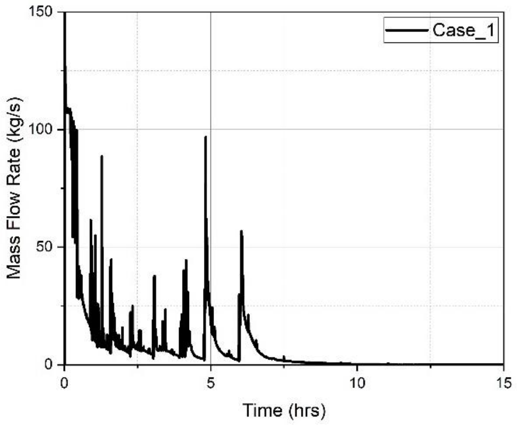

Fig. 4. Break discharge flow rate (Case 1)

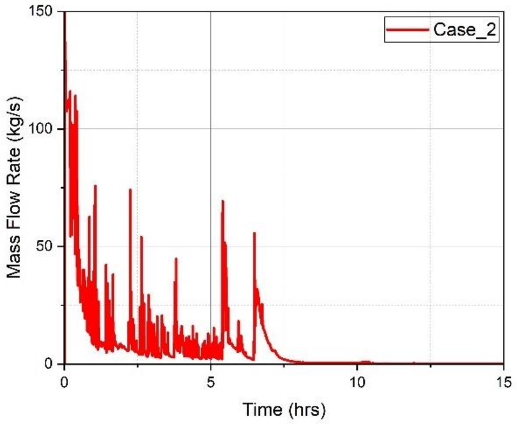

Fig. 5. Break discharge flow rate (Case 2)

To analyze the behavior of thermal-hydraulic variables in the SG section after node simplification, the results for secondary side water level and heat removal rate are compared in Figure 6-9. The simplified model showed slightly lower values than the original model. This difference is induced by the simplification of the total heat transfer area and flow channel characteristics during the node merging process. In the original model, the local heat transfer rate is calculated, however as the nodes are integrated, all sections are combined into one, resulting in the calculation of average heat transfer rate. As a result, the detailed circulation paths that efficiently maintain the heat transfer on the secondary side are not simulated, and the overall flow rate is averaged, leading to a lower evaluation of overall heat removal performance.

Additionally, heat transfer and fluid behavior are inherently nonlinear, and thermodynamic properties also change complexly. If such nonlinear effects are not considered during node integration and only volumes or areas are simply summed, the model may fail to accurately simulate key physical phenomena in accident scenarios. This nonlinearity is particularly pronounced in two-phase flow states where steam and water coexist, such as in SBLOCA.

In conclusion, while simplified models can calculate mass and energy conservation throughout the entire system, compensation on specific local physical processes was unavoidable. A computation time reduction of 16% was achieved, decreasing from 64,000 seconds (17.78 hours) to 54,000 seconds (15hours), however, this simplification led to a difference in the prediction of thermal-hydraulic variables.

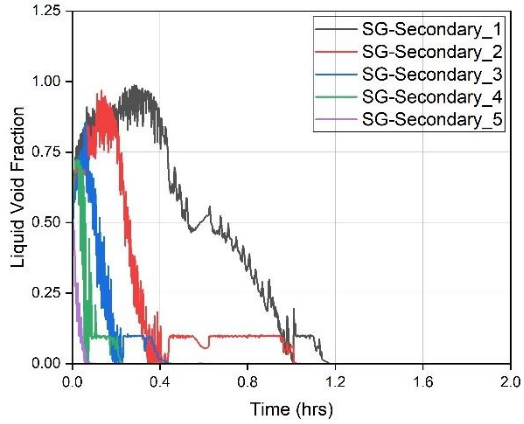

Fig. 6. SG Secondary side Water-Level (Case 1)

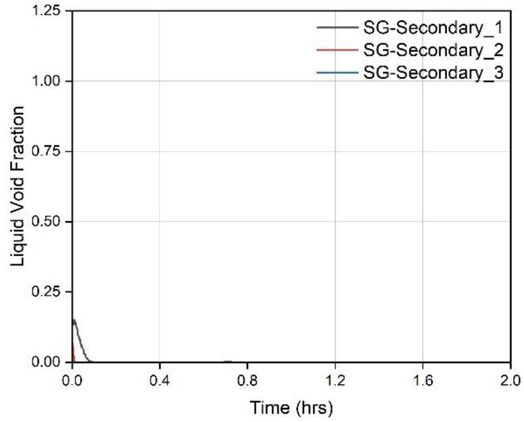

Fig. 7. SG Secondary side Water-Level (Case 2)

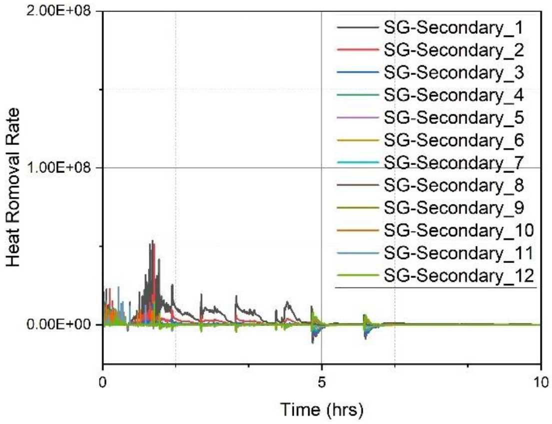

Fig. 8. SG Secondary side Heat Removal Rate (Case 1)

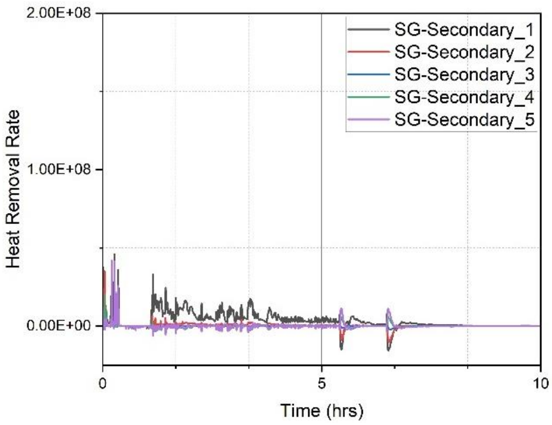

Fig. 9. SG Secondary side Heat Removal Rate (Case 2)

4. Conclusions

In this study, the effect of SG node simplification using the CINEMA code on OPR1000 SBLOCA simulations was analyzed, and the results were compared with original model. The results showed that there were some differences in the thermal-hydraulic variable results. Node simplification has the advantage of reducing computational time, the differences in the thermal-hydraulic variable values indicate there are clear areas for improvement in achieving accuracy. This suggests that future research should focus on improving computational convergence and finding the optimal balance between time-saving efficiency and accuracy. Nevertheless, the computational time reduction demonstrated in this study shows the potential applicability of this technique for fields requiring extensive data-set calculations, such as uncertainty analysis.

In future follow-up studies, it may be possible to further simplify the model by merging other system nodes with similar thermal-hydraulic behavior in addition to the SG, and to conduct research analyzing the resulting computational efficiency and prediction errors. Additionally, by applying the node simplification technique proposed in this study to reactor designs other than the OPR1000, applicability could enhance the efficiency of Severe Accident analysis for various reactor designs.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. RS-2022-00144202).

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