

Sensitivity Analysis of Radial Nodalization on Reactor Natural Circulation in an Integral PWR-type SMR Using MARS-KS

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1. Introduction

Integral PWR-type Small Modular Reactors have attracted considerable attention due to their enhanced safety and the adoption of passive safety systems. SMRs adopt an integrated reactor vessel configuration in which the reactor core, steam generators, pressurizer, and primary coolant pumps are located within a single pressure vessel. This design significantly reduces the possibility of large-break loss-of-coolant accidents while enhancing passive safety performance. During design basis accidents (DBAs) or beyond design basis accidents (BDBAs), passive heat removal systems and natural circulation can play a crucial role in maintaining core cooling and removing decay heat. Therefore, accurate prediction of natural circulation behavior is essential for evaluating the thermal-hydraulic performance and safety of SMRs.

Thermal-hydraulic system codes such as MARS-KS are widely used for safety analysis of nuclear reactors. Previous studies have reported that nodalization schemes can affect the predictive accuracy of thermal-hydraulic system codes, particularly in modeling of helical-coil steam generators in SMRs [1] and the reactor upper regions of PWRs. [2] However, relatively few studies have investigated the influence of radial nodalization on reactor natural circulation behavior in SMRs under accident conditions.

This study investigates the sensitivity of natural circulation in the reactor vessel to radial nodalization using the MARS-KS code. Two reactor coolant system (RCS) models with different radial nodalization schemes were developed, and their thermal-hydraulic characteristics were compared under steady-state and SBO conditions.

2. Methods and Results

This section describes the analysis procedure and the MARS-KS nodalization of the RCS. The RCS consists of the reactor core, riser, pressurizer, steam generator, and downcomer.

2.1 Analysis procedure, MARS-KS Nodalization and System Model

Two different radial nodalization schemes were considered for the reactor riser: a conventional single-column (N1) model and a detailed five-column model with crossflow junctions (N5). Steady-state calculations were performed to verify that both models reproduced the reference design operating conditions. Subsequently, SBO transient analyses were conducted to investigate the effects of radial nodalization on natural circulation behavior. The major thermal-hydraulic parameters were normalized with respect to the reference design values. [3]

Figure 1 shows the analysis procedure used in this study. Steady-state analyses were first carried out to evaluate the effect of radial nodalization on the temperature profile, pressure, and mass flow rate. Based on the steady-state results, SBO transient analyses were performed. Based on a sensitivity analysis of the residual heat removal system (RHRS) mass flow rate, a value corresponding to 3% of the normal feedwater mass flow rate was selected for the transient analysis. Subsequently, sensitivity analysis of radial nodalization was performed by comparing the transient thermal-hydraulic responses, including temperature, pressure, mass flow rate, and void fraction.

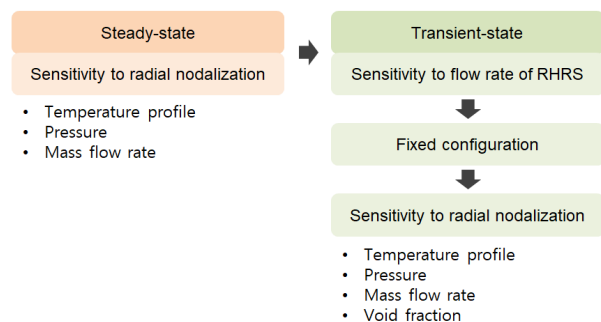


Fig. 1. Flowchart of the nodalization sensitivity analysis.

Figure 2 illustrates the MARS-KS nodalization developed for the N5 Model SMR reactor coolant system. The RCS consists of the reactor core (110, 120),

lower plenum (100), lower/middle/upper riser (200~224), upper plenum (300), pressurizer (310), and steam generator (400). To investigate the influence of radial nodalization on natural circulation, the riser was discretized into five parallel channels coupled through crossflow junctions, while the reactor core was represented by two parallel channels. The two core channels are connected to the five lower riser channels through a branch component. This modeling approach enables the simulation of radial coolant mixing and the resulting thermal-hydraulic behavior under normal operation and SBO conditions.

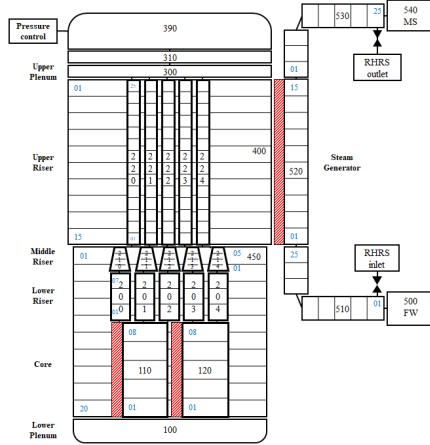


Fig. 2. MARS-KS nodalization of SMR reactor coolant system with N5 Model.

2.2 Results of sensitivity analysis in steady-state

Table I presents the normalized steady-state results predicted by the N1 and N5 model. Both models reproduce the design operating conditions with nearly identical temperature, pressure, feedwater mass flow rates, and reactor power. A slight difference is observed in the primary coolant mass flow rate. Overall, the steady-state results demonstrate that both models provide comparable initial conditions for the subsequent SBO transient analyses.

Table I: MARS-KS steady-state results with N1 and N5

Parameters	Normalized MARS-KS Results	
	N1	N5
Temperature (°C)		
Core Inlet	1.027	1.027
Core Outlet	0.995	0.995
Riser	0.995	0.995
Pressure (MPa)		
Core	1.006	1.006
Riser average	1.005	1.005
Mass Flow Rate (kg/s)		
Primary coolant	1.311	1.286
Feed water	1.015	1.015
Power (MW)		
Core	1.000	1.000

2.3 Results of sensitivity analysis in transient-state

The SBO event is initiated by the loss of AC power, resulting in a turbine trip and a rapid decrease in the feedwater flow rate. Consequently, the heat removal capability of the steam generator is reduced, leading to an increase in the primary system pressure and coolant temperature. When the pressurizer pressure reaches the high-pressure trip setpoint, the reactor is automatically tripped. After the pressurizer pressure reaches its maximum value, the RHRS valves are opened to remove the decay heat through natural circulation.

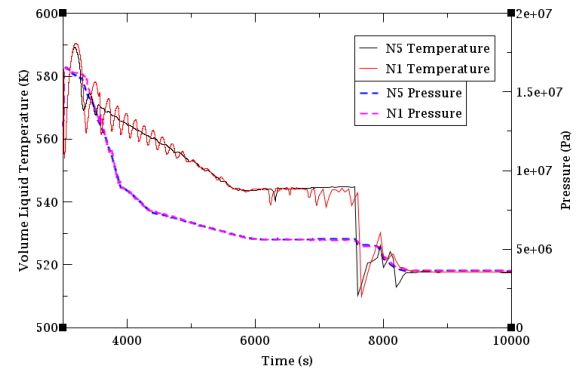


Fig. 3. Comparison of core temperature and pressure during SBO.

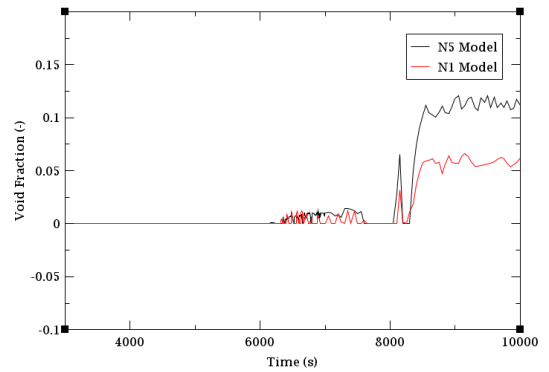


Fig. 4. Comparison of core void fraction during SBO.

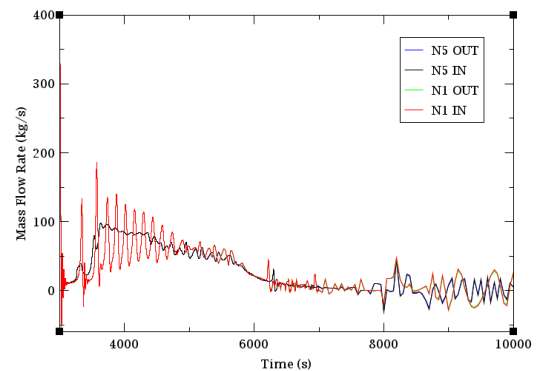


Fig. 5. Comparison of core mass flow rate during SBO.

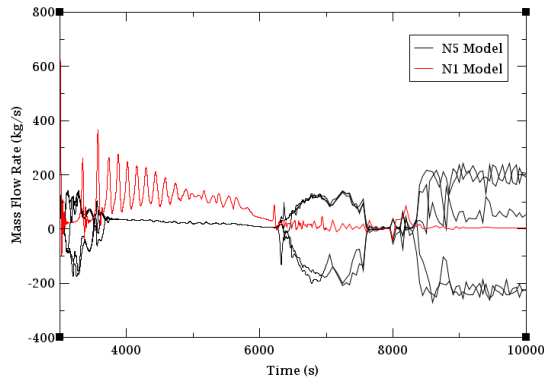


Fig. 6. Comparison of riser mass flow rate during SBO.

Figure 3 compares the transient responses of the core temperature and pressure predicted by the N1 and N5 models during the SBO transient. Following the reactor trip and RHRS actuation, both the core temperature and the pressure gradually decrease as decay heat is removed by natural circulation. The overall transient responses predicted by the two models exhibit similar trends, although the N1 model exhibited larger temperature oscillations during the natural circulation phase.

Figure 4 and 5 compare the transient responses of the core void fraction and mass flow rate. No vapor generation is observed during the early stage of the transient because the primary coolant remains in a subcooled liquid state. The void fraction begins to increase at about 6,000 s in both models as the coolant approaches saturation during the natural circulation phase. The presence of vapor in certain regions of the RCS does not necessarily indicate a loss of core cooling capability, as adequate core heat removal may still be maintained through two-phase natural circulation. After approximately 8,000 s, the void fraction increases rapidly, and the N5 model predicts consistently higher values than the N1 model. At the end of the transient, the maximum core void fraction predicted by the N5 model reaches approximately 0.12, whereas the N1 model predicts 0.06. This result indicates that the radial nodalization of the riser influences the prediction of natural circulation flow behavior in the primary system. The mass flow rates in volumes 110 and 120 were predicted to be identical. In addition, the inlet and outlet mass flow rates of each volume were found to be the same.

Figure 6 compares the transient responses of the riser mass flow rate predicted by the N1 and N5 Models. For the N5 Model, the individual mass flow rates in each of the five radially divided riser channels are presented. Following the reactor trip, the N1 model exhibits noticeable oscillations in the riser mass flow rate. In contrast, after the onset of boiling, the N5 model predicts both positive and negative mass flow rates in the individual radial channels. This behavior indicates the development of non-uniform flow distribution and local flow reversal within the riser during the two-phase natural circulation period. Unlike the single-channel N1

model, the five-channel N5 model is capable of representing channel-wise flow redistribution and local hydraulic behavior, providing a more detailed prediction of the natural circulation characteristics.

3. Conclusions

This study investigated the influence of radial nodalization on the prediction of natural circulation behavior in the SMR under steady-state and station blackout (SBO) conditions using the MARS-KS code. The major findings of this study are summarized as follows.

- During the SBO transient, the single column N1 model predicted larger temperature oscillations.
- The multi-column N5 Model predicted a higher void fraction during the later stage of the transient.
- The multi-column N5 Model predicted both positive and negative mass flow rates in individual riser channels.

Overall, the global thermal-hydraulic responses, such as the core temperature and pressure, exhibited similar trends for both radial nodalization schemes, whereas notable differences were observed in the prediction of local natural circulation characteristics, particularly in void distribution and channel-wise flow behavior.

Future work will investigate the detailed flow mechanisms responsible for the observed differences between the N1 and N5 models by analyzing channel-wise flow redistribution, crossflow, and void transport in the RCS. In addition, various radial nodalization schemes will be investigated to establish an optimized nodalization methodology for SMR analysis.

Acknowledgment

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