MARS-KS Helical Coil Steam Generator Tubes Node Sensitivity Analysis for i-SMR

Nihat Erdem Berber [a], Hae-Yong Jeong[a], Jae-Yong Lee [a*]
[a]*Department of Quantum and Nuclear Engineering, Sejong University, 209 Neungdong-ro, Gwangjin-ju, Seoul, 05066, Republic of Korea*
[*]*Corresponding author: jylee002@sejong.ac.kr*

1. Introduction

The helical coil steam generator (HCSG) is a critical component in advanced nuclear reactor designs, such as the innovative Small Modular Reactor (i-SMR), valued for its compact structure and high heat transfer efficiency. The major nuclear industry organizations in Korea (Korean Nuclear Society) are currently active in the development of i-SMR. For the design, licensing, and comprehensive safety analysis of these reactors, it is imperative that the simulation tools used provide highly accurate and dependable predictions of the system's thermal-hydraulic behavior. The reliability of these simulations is fundamental to ensuring reactor safety, and therefore, the underlying computational models must undergo a thorough validation process.

The Multi-dimensional Analysis of Reactor Safety-KS (MARS-KS) code is a thermal-hydraulic system code widely employed for such safety analyses. However, the accuracy and stability of system code predictions are highly dependent on the user-defined nodalization of the components. For components with complex geometries like the HCSG, determining the optimal number of nodes is crucial. An insufficient number of nodes may fail to capture important local phenomena, leading to inaccurate results, while an excessive number can lead to a significant increase in computational time without a proportional gain in accuracy. This balance is key to achieving a robust and efficient model.

This paper presents a nodalization sensitivity study for an i-SMR HCSG model using MARS-KS. The primary objective is to systematically investigate the impact of nodal resolution on key thermal-hydraulic parameters. By comparing results from coarse and fine-node models, this work aims to demonstrate how an appropriate nodalization scheme enhances the model's stability by reducing numerical oscillations and improves its predictive reliability. This study serves as a foundational step towards the development of a validated and trustworthy simulation model for the i-SMR HCSG.

2. Methods and Results

The HCSG model was developed based on a reference design for a small modular reactor (i-SMR). The model includes the primary side (reactor vessel and HCSG shell side) and the secondary side (HCSG tubes side). In the analysis, all of the components of i-SMR is modelled, however HCSG tubes and shell sides are focused for this paper.

A steady-state calculation was first performed to ensure the model's initial conditions were consistent with the i-SMR's design specifications. The key thermal-hydraulic parameters from the simulation were normalized against the design data and showed excellent agreement. This successful convergence was achieved with the 28-node HCSG configuration. Therefore, the 28-node model was selected as the final, reference model for the sensitivity analyses presented in this paper.

2.1 MARS-KS Nodalization and System Model

In the study conducted for this article, i-SMR was modeled with MARS-KS and a 10000-second simulation was performed for steady-state analysis.

To investigate the effect of nodalization, two different models with varying numbers of axial nodes for the helical tubes side were created:

- **Coarse-node model:** Less than 20 axial nodes for the secondary side of helical coil steam generator (tubes side).
- **Fine-node model:** More than 20 axial nodes for the secondary side of helical coil steam generator (tubes side).

Table 1: MARS-KS steady-state result of i-SMR with 28 nodes HCSG.

Parameters (at 10000 seconds)	Normalized MARS-KS Result Values
Mass Flow Rate (kg/s)	
Core Average	1.000
Core Hot Assembly	1.002
Core Bypass	0.998
IBA	1.001
RCS	1.000
RCPs	1.000
HCSG Bypass	1.000
Temperature (˚C)	
Core Inlet	1.000
Core Outlet	1.000
ΔT (Core)	0.997
Superheat (HCSG)	1.014
Pressure (MPa)	
Pressurizer	1.000
HCSG Outlet	1.006
Power (MW)	
HCSG Heat Transfer	1.000
Core	1.000

Figure 1 shows nodalization diagram of the i-SMR HCSG node sensitivity analysis including shell and tube sides, basically. The heat structures representing the heat transfer across the helical tubes were modeled accordingly for each nodalization scheme. The boundary and initial conditions, such as primary inlet temperature and flow rate, and secondary feedwater temperature and pressure, were kept constants for all simulations to ensure a consistent comparison.

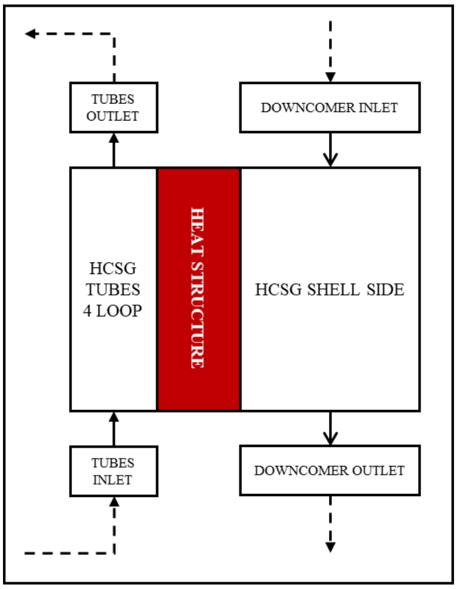


Fig. 1. MARS-KS basic nodalization for input model HCSG node sensitivity analysis for i-SMR.

2.2 Results of Helical Coil Steam Generator Tube Side

The simulations were performed to achieve a stable steady-state condition. The results from the different nodalization schemes were compared against each other to assess performance. Under steady-state conditions, a key parameter of HCSG tubes side analyzed were the void fraction and the normalized superheat temperature at the exit of the HCSG tubes.

As shown in Figure 2, the 14-node model (coarse-node) exhibits significant oscillations in the tube side exit temperature over time. In contrast, the 28-node model (fine-node) predicts a much more stable temperature that closely aligns with the target value. This indicates that the finer nodalization better resolves the complex two-phase heat transfer phenomena occurring in the tubes, leading to a more stable and reliable prediction of the outlet superheat.

Figure 3 illustrates the void fraction distribution along the secondary side tubes for the 14-node and 28-node models at 10,000 seconds. The fine-node model (Figure 3b) is capable of capturing the onset of boiling more accurately, showing zero void fraction in the initial nodes before boiling begins. The coarse-node model (Figure 3a) averages this effect over larger volumes, showing an immediate void fraction from the start. This detailed profile in the fine-node model leads to a more realistic prediction of the overall steam quality at the outlet.

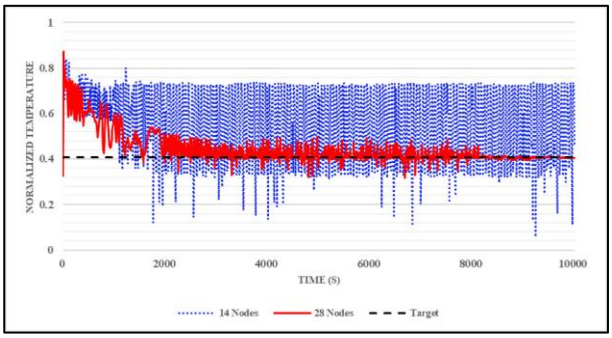
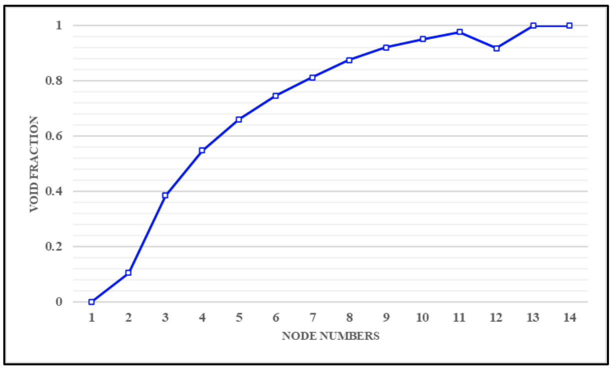
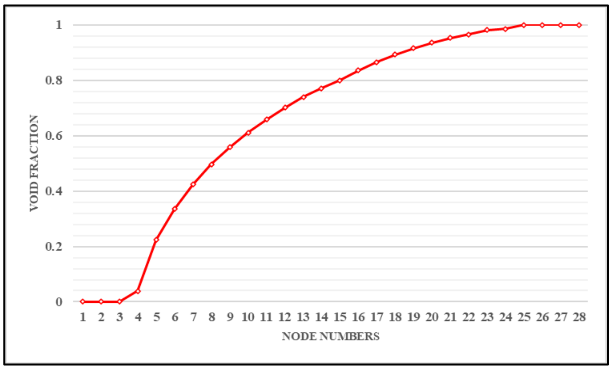


Fig. 2. i-SMR HCSG tubes side exit normalized superheat temperature.



(a)



(b)

Fig. 3. Void fractions along i-SMR HCSG tube at 10000 seconds. ((a) shows result of 14 nodes analysis, and (b) shows result of 28 nodes analysis.)

2.3 Results of Helical Coil Steam Generator Shell Side

The analysis of the primary (shell) side focused on the stability of heat transfer and the core temperatures at steady state operation.

Figure 4 shows the normalized heat transfer between the HCSG shell side and the tube side. Similar to the temperature results, the 14-node model results in a highly oscillatory heat transfer rate. The 28-node model, however, achieves a stable heat transfer rate that converges with the target value. This demonstrates that a finer nodalization on the secondary side also contributes to a more stable and accurate energy balance calculation for the entire system.

This stability is also reflected in the core temperatures, as seen in Figure 5. During the simulation to reach steady-state, the fine-node (28 nodes) model predicts stable core inlet and outlet temperatures that match the target values accurately. The coarse-node (14 nodes) model, while approaching the target, shows more pronounced oscillations and less stable behavior for both inlet and outlet temperatures. The finer nodalization allows the MARS-KS code to better resolve the thermal gradients, which is crucial for accurate predictions of the primary circuit's performance. While the fine-node model offers higher fidelity, the computational cost also increases. Therefore, a balance must be struck based on the specific requirements of the analysis.

While the fine-node model offers higher fidelity, the computational cost also increases. The CPU time for the 10,000-second simulation was 2222.3 seconds for the 14-node model and 2484.7 seconds for the 28-node model, representing a modest increase for the significant improvement in stability. Therefore, a balance must be struck based on the specific requirements of the analysis.

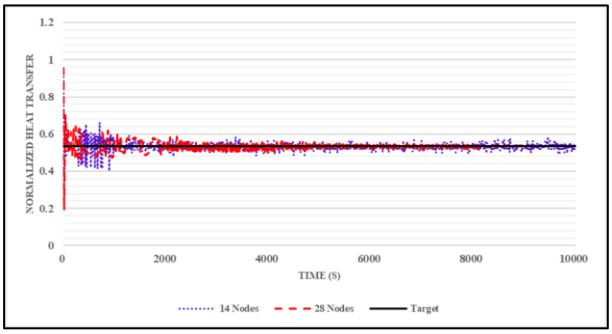


Fig. 4. Normalized heat transfer between i-SMR HCSG shell side and tubes side.

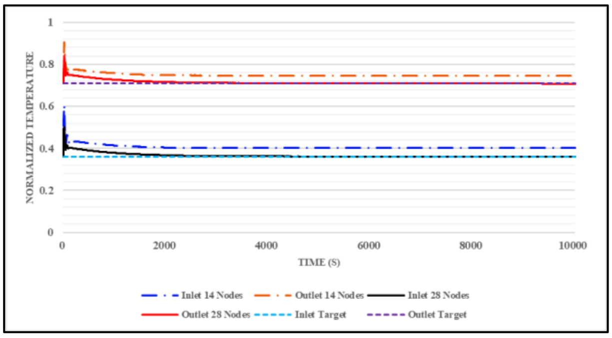


Fig. 5. i-SMR Core Normalized Inlet and Outlet Temperatures.

3. Conclusions

A nodalization sensitivity study for a helical coil steam generator of i-SMR was conducted using the MARS-KS code. The results demonstrate that increasing the number of nodes significantly improves the stability and accuracy of the predictions for steady-state conditions on both the primary and secondary sides.

The key findings are:

- A finer nodalization provides a more detailed and realistic profile of temperature and void fraction along the complex geometry of the HCSG.
- The 28-node model demonstrated excellent agreement with the normalized design data under steady-state conditions and was therefore selected as the reliable reference model for the i-SMR HCSG.
- A higher number of nodes is critical for achieving a stable and accurate solution by minimizing the numerical oscillations observed in coarser models.
- This study suggests that for reliable safety analysis of systems with HCSGs, a careful nodalization sensitivity study should be performed to ensure that the chosen nodal scheme is adequate to capture the important physical phenomena.

Future work will involve validating these models against experimental data from a scaled HCSG node sensitivity analysis facility to further refine the optimal nodalization strategy.

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