Investigation of the thermal hydraulic characteristics of the natural circulation SMR under the rolling and inclined condition using MARS-KS code

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1. Introduction

As the global community confronts the global climate crisis, the International Maritime Organization (IMO) is advancing its carbon neutrality strategy in the maritime sector. As a result, the demand for ships using eco-friendly fuels is expected to rise rapidly. Among the various alternatives, nuclear-powered ships stand out as a promising solution for the future maritime industry due to their constant power output, zero carbon emission, and potential economic advantages.

Nuclear-powered ships were initially used for military applications, such as in nuclear submarines and aircraft carriers. More recently, nuclear-powered ships have been employed in high-power-demand vessels like icebreakers. Additionally, there has been active research on maritime nuclear systems represented as Floating Nuclear Power Plant (FNPP), with a focus on the development of Small Modular Reactors (SMRs) based on light-water reactor technology [1].

Especially, SMRs utilizing natural circulation, called Natural Circulation SMRs (NCSMRs), offer several advantages, including structural flexibility and enhanced passive safety, due to the absence of Reactor Coolant Pumps (RCPs). Furthermore, NCSMRs reduce the possibility of mechanical failures and extend maintenance intervals. Through these advantages, this study emphasizes the necessity of NCSMRs that are specifically suited for maritime ships.

However, the irregular and harsh condition at sea can significantly affect natural circulation flow on primary system of NCSMRs. Therefore, before adopting NCSMRs for ships, it is crucial to study the thermal hydraulic characteristics of natural circulation under dynamic conditions. In this study, a target NCSMR design was developed for initial study and analyzed with MARS-KS code, a recognized safety analysis tool.

For the analysis, ship's inclination and rolling motion within 6 DOF were considered. Therefore, the objective of this study is to analyze the thermal hydraulic characteristics of the NCSMRs under the maritime environment based on the conceptual design of the target NCSMR.

2. Methodology

2.1 Design of target NCSMR

Fig. 1 shows the nodalization of the target NCSMR. It is designed to produce 180 MWt, an attractive output level for maritime vessels. The primary system includes four core sections, a riser, a bidirectional downcomer, a pressurizer, and helical steam generators. The target NCSMR has a height of approximately 20 meters and a diameter of 6 meters. To maintain the focus on the primary system, the secondary system was simplified as a time-dependent volume and junction, allowing for faster simulations and reduced computational costs [2].

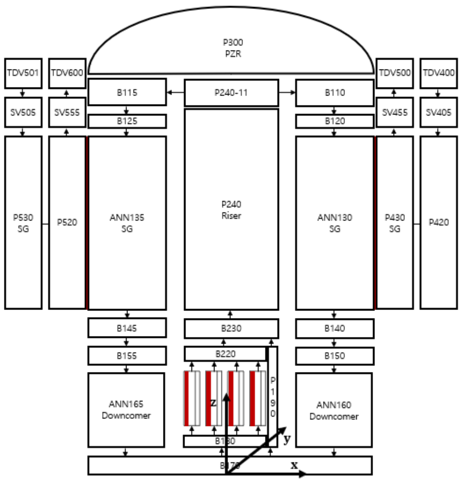

Fig. 1. Nodalization of the target NCSMR

2.2 Simulation of maritime conditions

The MARS-KS code is capable of accurately simulating maritime conditions using the 6 DOF and the reliability of this simulation was validated through the work of Beom, et al (2021).

. The 6 DOF consists of three transitional motions: surge, heave, and sway and three rotational motions: roll, yaw, and pitch as shown in Fig. 2. In the MARS-KS code, these motions are represented by sinusoidal functions, and an advanced momentum conservation equation is employed to account for additional accelerations [3].

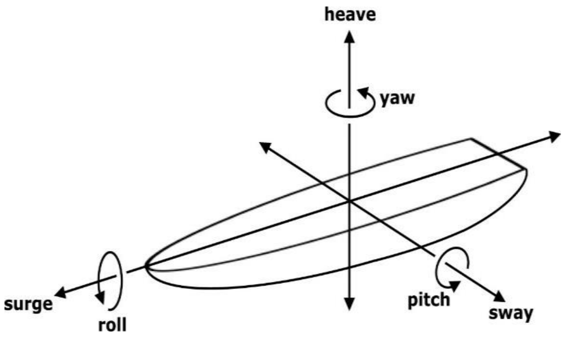

Fig. 2. Application 6 DOF to ship

2.3 Motion selection

Unlike previous research, this study reflected the inclined ship conditions and rolling motion among the 6DOF. When a ship experiences inclination and rolling at sea, the distance between the core and steam generator, known as thermal center, changes. The thermal center length significantly impacts the natural circulation flow as shown in Fig. 3. Therefore, this study focused on changes in the thermal center affecting the thermal hydraulic natural circulation characteristics under inclined and rolling conditions [4].

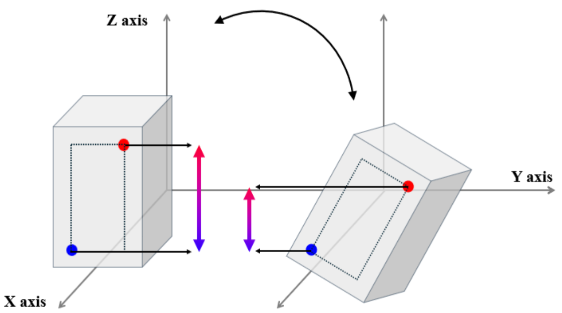

Fig. 3. Change of distance between thermal centers

2.4 Configuration of test matrix

A test matrix was configurated to evaluate the thermal hydraulic sensitivity and characteristics of natural circulation under maritime conditions. The variables considered in this simulation include the angle of inclination and amplitude of rolling with a constant period. The analysis focused on both single and combined effects of inclination and rolling motion. Therefore, total of 12 cases were considered as shown in Table I.

Table I: Test matrix for analysis

Case	Period [s]	Inclination [deg]	Rolling [deg]
01	0	0	0
02	0	10	0
03	0	20	0
04	0	30	0
05	10	0	10
06	10	0	30
07	10	10	10
08	10	10	30
09	10	20	10
10	10	20	30
11	10	30	10
12	10	30	30

3. Analysis and discussions

Under the given maritime conditions, major thermal hydraulic parameters such as core temperature, mass flow rate, and cladding temperature were analyzed and compared with the base case (stationary state) to assess the stability of the target NCSMR. Additionally, the trends about major parameters were observed in relation to variation in inclination and rolling motion.

Fig. 4. shows the core temperature difference between the core inlet and outlet under various conditions of inclination and rolling motions. In the base case, the temperature difference between the core inlet and outlet temperature was 57.9 K. In all cases, the core temperature difference increased by slightly less than 2% at the most intensified motion compared to the base case.

Notably, in case 07-08 and 11-12, which include combined motion, the oscillations of core temperature were more pronounced than in case 02-06 include single motion as presented in Figs. 4.

However, there were no significant differences from the base case.

* I: inclination, R: rolling

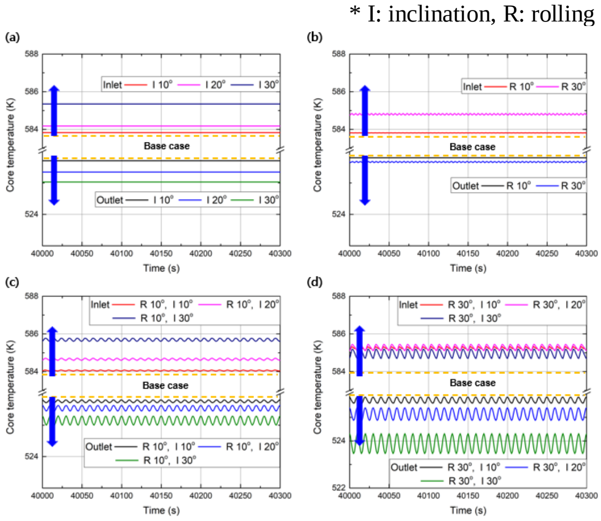

Fig. 4. Core temperatures under the motion condition of (a) inclination (b) rolling (c) and (d) inclination and rolling

Fig. 5 shows the mass flow rate of the primary system under various conditions. In the base case, the total mass flow rate was 602.4 kg/s. In Case 02-04, which include inclination, the difference in mass flow rates between the left and right sides of the primary system becomes more pronounced due to the bidirectional flow characteristics, as inclination increases as presented in Figs. 5 (a). It is predicted that gravitational acceleration differs between the left and right sides of primary system. This results in a reduction in total mass flow rate of the primary system compared to the base case.

In Case 05-06, which includes rolling motion, the mass flow rate exhibited symmetric and periodic oscillations, as presented in Fig. 5 (b). It was initially expected that an increased core temperature difference would enhance the natural circulation performance and thus increase the total mass flow rate. However, similar to Case 02-04, which include inclination, the total mass flow rate decreased in Case 05-06. This reduction is attributed to the shortened thermal center length compared to Case 01 as shown in Fig. 2.

In Case 07-08, 11-12, which include combined motion, changes of mass flow rate were observed excessively rather than single cases as presented in Figs. 5 (c) and (d).

The quantitative reduction in mass flow rate observed in the combined cases (Case 07-12) was similar to the sum of the reductions in mass flow rate at the corresponding single cases (Case 02-06), which involved either rolling motion or inclination. For instance, the sum of the reductions in mass flow rate between Case 02 (10 degree inclination) and Case 05 (10 degree rolling motion) showed similar values to the reduction in mass flow rate at Case 07 (both 10-degree inclination and rolling motion), as shown in Table II.

Although overall mass flow rate decreased, the operation of the target NCSMR is predicted to remain stable with respect to other major parameters.

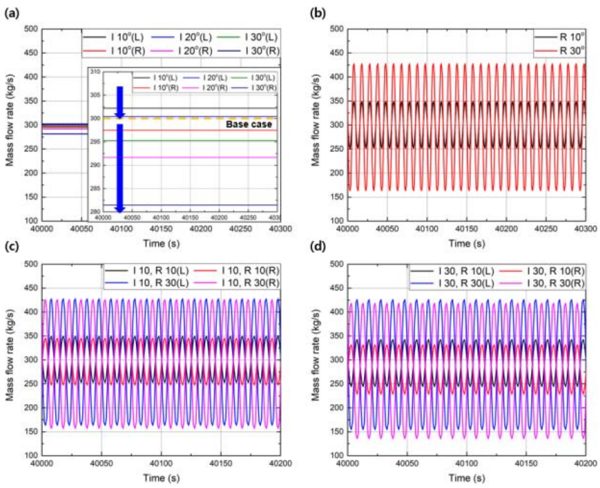

Fig. 5. Mass flow rate of primary system under the motion condition of (a) inclination (b) rolling (c) and (d) inclination and rolling

Table II: comparison of mass flow rate

Mass Flow Rate (kg/s)	① Stationary state: 602.4 kg/s											
	②	I 10°	*599.7 (-2.9)*	④	I 10°	*599.7 (-2.9)*	⑥	I 30°	*576.7 (-25.9)*	⑧	I 30°	*576.7 (-25.9)*
		R 10°	*600.7 (-1.8)*		R 30°	*588.4 (-14.2)*		R 10°	*600.7 (-1.8)*		R 30°	*588.4 (-14.2)*
	③	I 10° R 10°	*597.8 (-4.7)*	⑤	I 10° R 30°	*584.6 (-17.9)*	⑦	I 30° R 10°	*574.4 (-28.2)*	⑨	I 30° R 30°	*564.0 (-38.5)*
Erorrs (%)	② - ③ : 0.0			④ - ⑤ : 4.4			⑥ - ⑦ : 1.7			⑧ - ⑨ : 4.1		
	① - ③ : 0.8			① - ⑤ : 3.0			① - ⑦ : 4.7			① - ⑨ : 6.4		

Fig. 6 shows the cladding temperature under various conditions of inclination and rolling motions. The core is divided into four sections with sections 2 and 4 positioned identically along the y-axis, and sections 1 and 3 arranged symmetrically about the y-axis. In the base case, the highest point of cladding temperature was 616.2 K.

In Case 04, which includes inclination case as presented in Figs. 6 (a), cladding temperature was changed by slightly less than 1% as the mass flow rate in core region varied due to the inclination. In Case 06, which includes rolling case as presented in Figs. 6 (b), oscillations in cladding temperature occurred as the core moved away from the center axis. In Case 07 and 12, which include combined cases as presented in Fig. 6 (c) and (d), the cladding temperature in core sections near the center remained relatively stable. Also, as the motion intensified, oscillations in cladding temperature became more pronounced. Although changes in cladding temperature affected the mass flow rate, operation of the target NCSMR remained stable.

* HFA: Hot Fuel Assembly

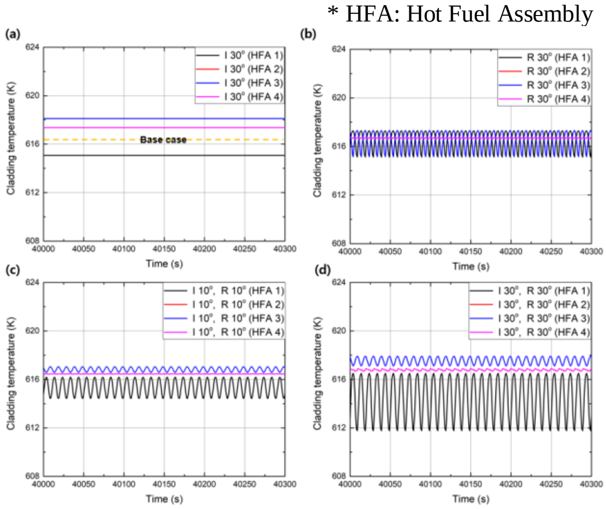

Fig. 6. Cladding temperature under the motion condition of (a) inclination (b) rolling (c) and (d) inclination and rolling

4. Conclusion

In this study, thermal hydraulic natural circulation characteristics under the inclined and rolling motion were observed with a target NCSMR. Through the three major parameters were analyzed and compared to the stationary state to certify safety. The major findings of this study can be summarized as follows:

- ✓ The core temperature was almost maintained under the given maritime condition compared to stationary state.
- ✓ The mass flow rate of the primary system decreased, and cladding temperature oscillated under the given maritime condition compared to stationary state. However, thermal output and natural circulations remained stable, with no issue in heat transfer observed.
- ✓ Consequently, the major parameters of the target NCSMR under the given motion condition were found to be similar to those of the stationary state. This suggests that the safety characteristics of the target NCSMR in a stationary state can also be applied to the given motion condition.

For the future study, additional cases will be analyzed with different motions. Additionally, accident scenarios will be composed and simulated using a detailed reactor nodalization design to verify safety by assessing thermal hydraulic behavior.

ACKNOWLEDGEMENTS

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