Sensitivity Assessment of Natural Circulation SMR Applicable to Maritime Ships Using MARS-KS code

Seung Gyu Hyeon[a], Jae Hyung Park[a], Hyo Jun An[a], JinHo Song[a] and Sung Joong Kim[a]*
[a]Department of Nuclear Engineering, Hanyang University
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
** Corresponding author: sungjkim@hanyang.ac.kr*

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1. Introduction

As confronting the global climate crisis, most of countries have planned out to eliminate fossil fuel or to replace it with low carbon emission energy based on diverse carbon neutral policies. Such dramatic change in energy policy is not limited on the ground application. Notably, maritime sector takes this trend more seriously. For example, the International Maritime Organization (IMO) has introduced a direct carbon-neutral policy to reduce carbon emissions to at least half of the 2008 levels by 2050. Utilizing nuclear energy for a ship propulsion can contribute significantly to achieving a carbon neutrality.

In this regard, the small modular reactors (SMRs) have been highlighted for their attractive characteristics such as enhanced safety, flexibility on site and power, and multi-purpose applicability. Moreover, the adoption of Natural Circulation SMRs (NCSMRs) further maximizes these advantages, and natural circulation SMR can be considered as the alternatives of conventional diesel propulsion systems [1].

Unlike the ground SMR, propulsion systems under maritime condition are exposed to 6 degrees of freedom (6 DOF), and also affected by irregular wind and geological condition. These factors should be considered to ensure the safe operation of NCSMRs [2].

As such, along the ship movement, understanding the hydrothermal behavior in the reactor system becomes essential, which needs to be evaluated by a proper experiment or simulation. An example is to utilize the MARS-KS code, which is safety analysis code that has the function to simulate the ocean conditions.

So, the objective of this study is to develop a conceptual design of NCSMRs suitable for ships first. To investigate the correlation between maritime condition and natural circulation, the thermal-hydraulic sensitivity of the natural circulation performance was initially evaluated in a stationary state assuming no moving motion. Based on the stationary analysis, a dynamic analysis was conducted under maritime conditions considering moving motion.

2. Methodology

2.1. Design of Natural Circulation SMR

Fig. 1 shows the nodalization of the target NCSMR. This nodalization was constructed to utilize the MARS-KS code for thermal-hydraulic safety analysis. The target NCSMR has dimensions of approximately 20 m in height and 6 m in diameter. Furthermore, it consists of 4 sections of core, a riser, an ambidirectional downcomer, a pressurizer and helical steam generators in a primary system. The secondary system was simplified as a time-dependent volume and junction to focus on the primary system. Such simplification allows for the faster simulation and saves the computational cost. The intended thermal power of the target NCSMR was designed to generate 180 MWt, which is deemed to be attractive power level for maritime ship.

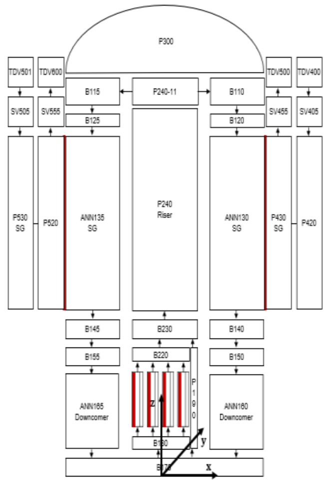

Fig. 1. Nodalization of the NCSMR

2.2. Effect of ocean motion

Typically ocean motions are generated by either wind or geological effects, which affect the movement of maritime ships. The reactors equipped in ships are also affected by ocean motions, which cause significant fluctuation or changes in the thermal-hydraulic behavior of the NCSMR [3].

The ocean motions are expressed as 6 degrees of freedom (6 DOF) as shown in Fig. 2. The 6 DOF includes 3 rotational motions of rolling, pitching, and yawing, and 3 translational motions of surging, swaying, and heaving. The effect of heeling is neglected as the situations of tilted ship are not assumed. Among the 6 DOF, rolling and heaving motion dominantly influence ship movement due to the structural characteristics of ships, which include their long length and short width.

As a result, the NCSMR is dominantly affected by rolling and heaving motion in the ocean. In this study, the variables of motion are selected as the extent of rolling and heaving motion.

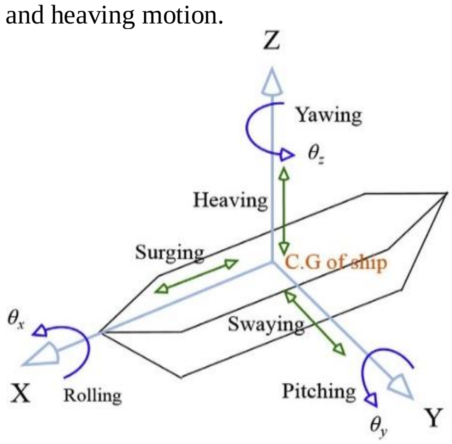

Fig. 2. Degrees of Freedom (6 DOF)

2.3. Test Matrix

A test matrix was constructed to conduct system analysis reflecting the rolling and heaving motions. The major parameters in the test matrix are degree of rolling motion, acceleration of heaving motion, and period of two motions. Each parameter was established as shown in Table I referred by experimental data of Tan Si-chao et al. and Hiroyuki MURATA et al. [4, 5].

The stationary analysis was initially conducted through Case 01 (C 01). Subsequently, based on the stationary analysis, each effect of rolling and heaving motions was confirmed in Cases 02~05 (C 02~05). The combined effect of rolling and heaving motions was investigated through Cases 06~07 (C 06~07).

Table I: Test matrix for MARS-KS code analysis

Case	Period [s]	Rolling [deg]	Heaving [m/s^2]
01	0	0	0
02	8	10	0
03	8	20	0
04	8	0	0.3
05	8	0	0.8
06	8	10	0.3
07	8	20	0.8

3. Analysis results

3.1. Stationary state (Base case)

The natural circulation analysis at the stationary state (C 01) was pertinently simulated using the MARS-KS code. According to the calculation, the coolant heated in the core moves upward through the riser. Heat transferred from the core to the coolant is effectively removed through the heat exchanger. Subsequently, the coolant flows down along the annular-shape downcomer. In this stationary state, the temperature difference between core inlet and outlet is 58.5 K, the mass flow rate of primary side (left or right) is 297.7 kg/s, the pressurizer pressure is 15 MPa, and the pressurizer water level is 3.2 m as shown fig. 3. All the parameters were established stably during the steady-state.

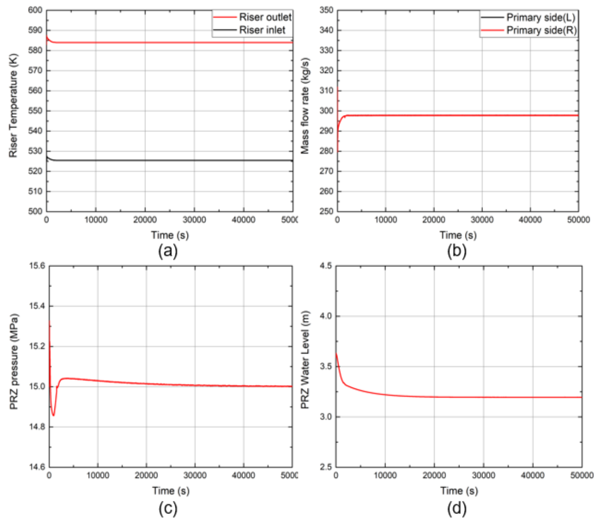

Fig. 3. Stationary state results (a) riser temperature (in/out) (b) primary side mass flow rate (c) pressurizer pressure (d) pressurizer water level

3.2. Moving state (each effect)

According to the test matrix, an analysis on the rolling and heaving motion was conducted. Fig. 3(a) and (b) show the mass flow rate of the primary side on rolling 10° and 20° respectively (C 02 and 03). Figs. 3 (c) and (d) show the mass flow rate of primary side on heaving 0.3 m/s^2 and 0.8 m/s^2 respectively (C 04 and 05). As the amplitudes of rolling and heaving increase, the oscillation of mass flow rates also increases. Although the amplitudes of rolling and heaving are not compared quantitatively, the sensitivity of rolling motion on the mass flow rate was larger than that of heaving motion under the conditions of this numerical calculation.

Furthermore, it was observed that the descending flows through the downcomer in both directions had symmetrical mass flow rate as the ship moves due to ocean motion.

Additionally, concerning the temperature difference between the inlet and outlet of the riser, it was observed that the greater the motion effect on the ship, the larger the temperature difference compared to stationary state.

At the riser outlet during heaving motion, a little fluctuation was observed as shown in Fig. 4. In all cases, the pressurizer pressure and water level are maintained similar to the condition of stationary state. Although the mass flow rate changes, subcooled boiling does not occur, and heat transfer remains stable. However, there are limitations in terms of correct analysis under motion conditions as the original heat transfer model were used without reflecting motion in the MARS-KS code.

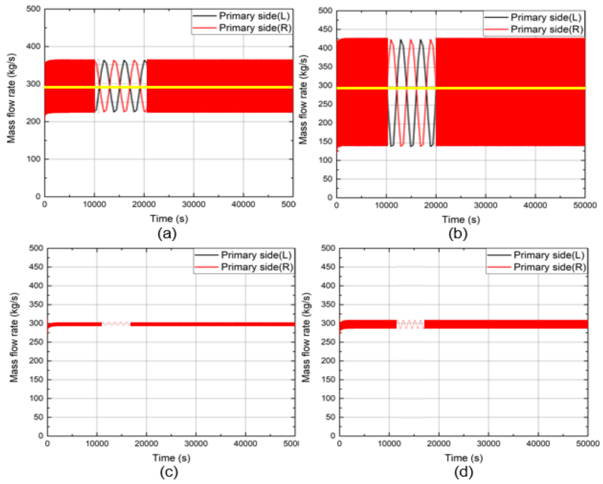

Fig. 4. Moving state results of mass flow rate (a) R10° (b) R 20° (c) H 0.3 m/s^2 (d) H 0.8 m/s^2

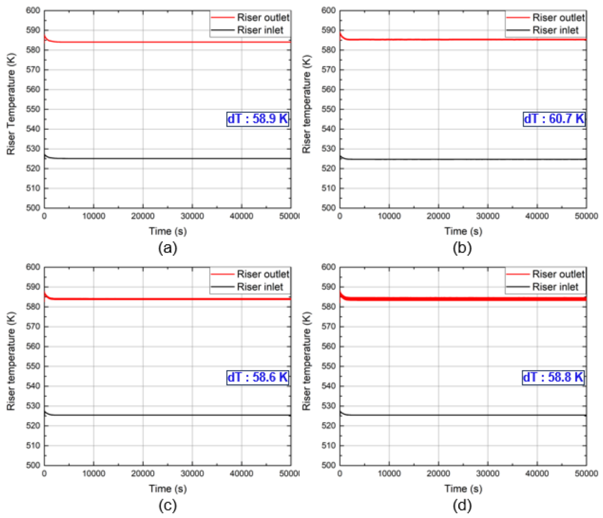

Fig. 5. Moving state result of riser temperature (a) R10° (b) R 20° (c) H 0.3m/s^2 (d) H 0.8m/s^2

3.3. Moving state (combined effect)

Considering the real maritime conditions with a coexistence of 6 DOF, the combined effects from rolling and heaving motion were examined. The Fig. 6 (a) and (b) show the mass flow rate of primary side on rolling 10° with heaving 0.3 m/s^2 (C 06) and rolling 20° with heaving 0.8 m/s^2 (C 07) respectively. The Figs. 6 (c) and (d) show the riser temperature on rolling 10°, with heaving 0.3 m/s^2 (C 06) and rolling 20° with heaving 0.8 m/s^2 (C 07) respectively. It was observed that the combined effects were close to the summation of each effect, and left side appeared to be slightly more fluctuated in mass flow rate compared to the right side as shown in Figs. 6 (a) and (b). Also, the riser temperature difference of combined effect is the same tendency of Fig. 5 as shown in Figs. 6 (a) and (b).

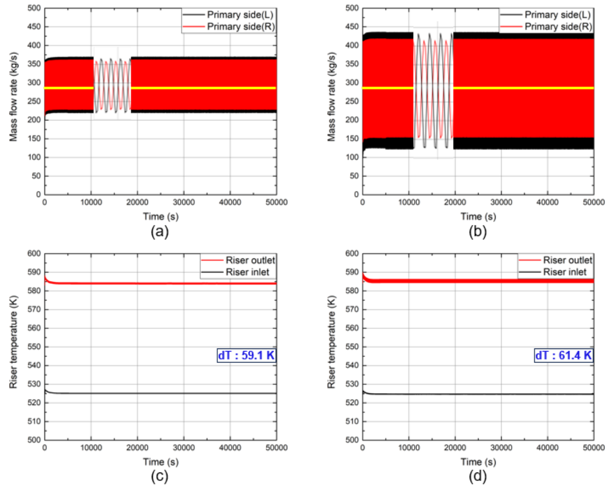

Fig. 6. (a) mass flow rate R10°, H0.3m/s^2 (b) R20°, H0.8m/s^2 (c) riser temperature R10°, H0.3m/s^2 (d) R20°, H0.8m/s^2

The results of sensitivity assessment for all cases exhibit a prominent tendency. In rolling (C 02 and 03) and heaving (C 04 and 05) motion cases the larger the amplitude, the greater the value of change. Rolling motion is more sensitive compared to heaving motion as shown in Table II.

Table II: Sensitivity assessment of various cases

Case	Core T_{Out} - T_{In} [K]	Relative rate [%]	Mass Flow Rate [kg/s]	Relative rate [%]
01	58.5	baseline	279.7	baseline
02	58.9	0.6	225.7/364.1	19.3/30.1
03	60.7	3.7	139.1/426.3	50.2/52.4
04	58.6	0.2	293.9/301.7	5.07/7.86
05	58.8	0.5	287.6/308.1	2.82/31.8
06	59.1	1.0	220.4/368.7	21.2/31.8
07	61.4	4.9	123.1/433.3	55.9/54.9

4. Conclusions

In this study, system analyses were performed to assess the sensitivity of NCSMR in maritime condition applicable to ships.

According to the calculations results, maritime conditions induced oscillations in thermal hydraulic parameters. Despite these oscillations affecting natural circulation, it remains maintained, and the major parameters of the target NCSMR remain steady in this test matrix. The major findings of this study can be summarized as follows:

- ✓ The rolling motion showed a larger sensitivity to the mass flow rate than heaving motion in this study.
- ✓ Additionally, it is observed that the results of sensitivity assessment for natural circulation exhibit a prominent tendency using MARS-KS code.
- ✓ According to MARS-KS analysis, although oscillations occur, overall thermal hydraulic performances of the target NCSMR are maintained.

For the future study, the secondary system of NCSMR is required to be concretized for accurate simulation. Additionally, thermal hydraulic design parameters will be determined through further analysis on target NCSMR. Moreover, analysis will be conducted by randomly sampling of 6 DOF to simulate irregular ocean motion.

ACKNOWLEDGEMENTS

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