Investigation of Natural Circulation Instability for Inclined One-loop with Single-phase in MARS-KS

Ju Hun Jeong, Ji Yong Kim, In Cheol Bang*
Department of Nuclear Engineering., Ulsan National Institute of Science and Technology (UNIST).,
50 UNIST-gil., Ulju-gun., Ulsan., Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

Recently, interest in offshore nuclear power plants has been increasing, and several floating nuclear power plants have been being developed around the world [1]. Experimental and numerical studies on hydrodynamics, heat transfer and natural circulation in ocean conditions have been being conducted for facilitating the development of maritime reactors [2]. Furthermore, interpretation of the thermal hydraulic behavior of nuclear reactors as well as safety features in ocean conditions is necessary.

The typical ship motions are shown in Fig. 1. The external forces caused by the ocean conditions affect the natural circulation of the nuclear reactor system in a ship. Therefore, the operating condition of the offshore reactors in the ocean is not similar to that of onshore, including rolling, pitching, and heaving. The modification of the MARS-KS code was made to simulate the thermal-hydraulics phenomena under the ocean motion by Beom et al. [1].

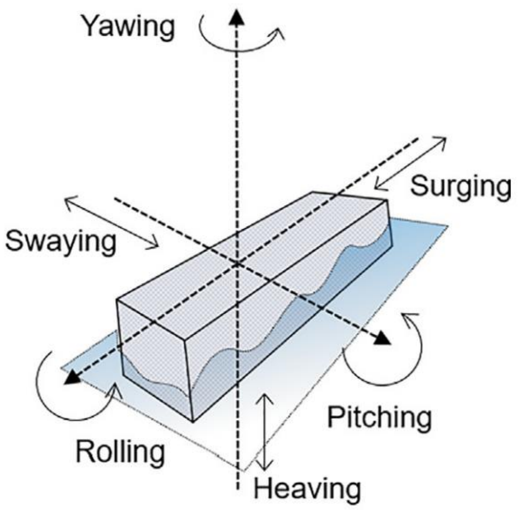

Fig. 1. Six degrees of freedom under dynamic motion [1].

Hence, an analysis of the natural circulation behavior under the inclined condition is additionally required. The inclination condition occurs when loading or unloading cargos or the normal operating and an accidental condition of the ship. Therefore, in this study, the natural circulation performance under the inclined conditions was analyzed with MARS-KS code.

2. MARS-KS Modeling

The MARS-KS code was utilized in the current study to analyze the natural circulation capability of the single-phase loop under inclined conditions. MARS-KS is a safety analysis code developed by the Korea Atomic Energy Research Institute (KAERI) [2] to analyze the transient thermal-hydraulic phenomena of nuclear power plants under postulated accident conditions.

2.1 Theoretical models

Three-dimensional movements in the ocean by the motion of tides, waves, and ships are expressed as six degrees of freedom, consisting of three translational motions (surging, swaying, and heaving) and three rotational motions (rolling, pitching, and yawing). Six degrees of freedom, in addition to gravity, appear in the form of acceleration. Acceleration consists of linear acceleration and rotational acceleration, and these accelerations can be described as the mathematical form in the momentum equation as [2],

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=-\nabla p+\mu\nabla^2\boldsymbol{u}+\rho\boldsymbol{g}$$
$$-\rho\left[\frac{d^2\boldsymbol{R}}{dt^2}+\Omega\times(\Omega\times\boldsymbol{r})+2\Omega\times\boldsymbol{u}+\frac{d\Omega}{dt}\times\boldsymbol{r}\right] \quad (1)$$

Where, p is the pressure, μ is the viscosity of the fluid, $\boldsymbol{g}$ is the gravitational acceleration, $\boldsymbol{R}$ is the position vector of the non-inertial frame as viewed from an inertial one, Ω is the angular velocity, and $\boldsymbol{r}$ is the position vector relative to the non-inertial frame. Compared with those under stationary conditions, the terms modified or added under dynamic conditions are as follows. The gravitational acceleration is expressed as $\boldsymbol{g}=-g\cos\theta\,\hat{\boldsymbol{z}}$, where θ is the angle of inclination or rotation, $d^2\boldsymbol{R}/dt^2$ is the acceleration of the non-inertial frame, $\Omega\times(\Omega\times\boldsymbol{r})$ is the centrifugal acceleration, $2\Omega\times\boldsymbol{u}$ is the Coriolis acceleration, and $d\Omega/dt\times\boldsymbol{r}$ is the tangential acceleration. The terms marked in bold represent vectors. Under the rolling motions and inclined condition, not only additional force but also the spatial coordinate of control volume need to be modified [2].

Zvirin et al. proposed the correlations for the flow rate and the temperature difference of the primary fluid according to the height difference between the heat source and sink [3]. As the height difference increases, the flow rate increases. However, the temperature difference of the fluid decreases as shown eq. (2) and eq. (3).

$$Q = \left[\frac{2\beta g \Delta z P}{\rho c R}\right]^{1/3} \quad (2)$$

$$\Delta T_R = \left(\frac{P}{\rho c}\right)^{2/3}\left(\frac{R}{2g\beta\Delta z}\right)^{1/3} \quad (3)$$

Where, Q is the flow rate, ΔT_R is the temperature difference between the hot and cold leg outlet, β is the thermal expansion coefficient, Δz is the elevation of the thermal center between the heat source and sink, c is the specific heat, and R is the flow resistance.

2.2 MARS-KS Modeling of Closed Single Phase Loop

In this study, a single-phase closed natural circulation loop was modeled. The inclined angle of the natural circulation loop was varied to analyze the effect of the inclination on the natural circulation performance. Even if the magnitude of the inclination angle is the same, there is the elevation difference between the heat source and sink changes according to the direction. The geometrical information for the analytical models is given below,

Where, the height of the heated and cooled sections is 5.0m. Each pipe node of the heated and cooled sections consists of twenty components of 0.25m. The length of the upper and lower pipe nodes is 1.0m and each pipe node consists of ten components of 0.1m. The hydraulic diameter of the entire pipe components is 0.1m. The cylindrical heat source is in contact with the 3rd through 6th pipe components of the heated section, consisting of four components of 0.25m. The elevation of the heat source is 1.0m. The cylindrical heat sink is in contact with the 3rd through 18th pipe components of the cooled section, consisting of six-teen components of 0.25m. The elevation of the heat sink is 2.5m. Hence, the elevation difference in the thermal center between the heat source and sink is 1.5m. The thickness of the heat source and sink is 0.02m. The time-dependent volume is located above the outlet of the heated section to maintain the operating pressure of 10.5bar. The closed loop is entirely filled with water as the primary fluid.

Three different inclined angle conditions were considered in the current study. The analysis conditions are summarized in Table 1.

Table. 1. Analysis conditions of each model.

	Model 1	Model 2	Model 3
Angle [°]	0	30	-30
Initial flow rate [kg/s]	1.2	1.2	1.2
Pressure [bar]	10.5	10.5	10.5
Power [kW]	50	50	50

3. Results and Discussion

3.1 Model 1 without inclination

The closed loop system with the inclination angle of 0° is described in Fig. 2. The system consists of a loop of the primary and secondary sides. In other words, the system consists of the heat source and sink structure. The primary fluid is heated by the heat source and flows upward due to the driving force caused by the density difference. Afterward, the fluid of the primary is cooled by the heat sink along the loop.

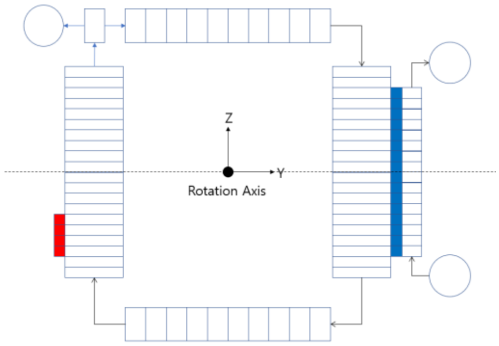

Fig. 2. Nodalization with no inclination condition.

The primary fluid temperature in the outlet region of the heated section is 433.03 K, which is lower than the boiling point of the operating pressure (10.5 bar) of the closed loop. Therefore, the primary flow condition is considered to be a single-phase flow.

3.2 Model 2 under 30° inclination condition

The nodalization of the closed loop with 30° inclined condition is shown in Fig. 3. When the inclination angle is 30°, the driving force for the natural circulation increases because of the increase of the elevation difference between the heat source and sink. This increases the mass flow rate in the cold leg. The temperature difference between hot and cold legs decreased due to the increased mass flow rate. The enhancement of the natural circulation was observed in the cause with 30° inclined condition.

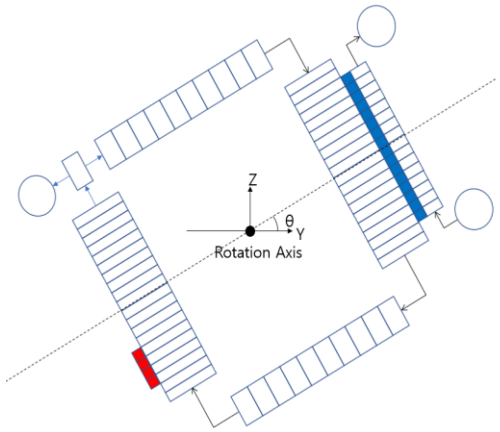

Fig. 3. Nodalization of model 2, 30° inclination condition.

3.3 Model 3 under -30° inclination condition

The closed loop system with -30° inclined condition is described in Fig. 4. When the inclination angle is -30°, the mass flow rate decreases unlike model 1. Since the elevation between the heat source and sink is the smallest, the flow rate is the smallest among all three models in steady state. Therefore, the temperature difference between the inlet and outlet at the cold leg is relatively large as known in the formula for the specific heat or eq. (2) and (3). Consequently, the driving force for the natural circulation decreases.

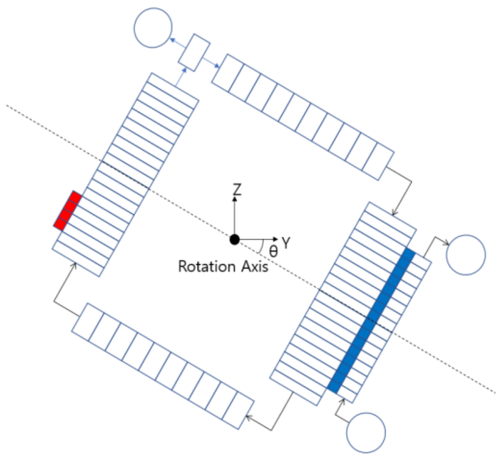

Fig. 4. Nodalization of model 3, -30° inclination condition.

3.4 Comparison with the parameters varying the inclination angle

The models according to the magnitude of the inclination angle were simulated with -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, and 60° inclination conditions, respectively. The natural circulation flow rate and the temperature difference under the various inclined conditions are depicted in Fig. 5 and Fig. 6 respectively. When the system is inclined toward the heat source with 15° inclination, where the inclination angle is positive, the elevation between the heat source and sink becomes maximum. Hence, the flow rate and natural circulation performance increase as shown in Fig. 5. And the temperature difference at the inlet and the outlet of the cold leg tends to decrease as shown in Fig. 6. In this section, it is figured that when the angle has a positive value, the natural circulation performance tends to be slightly increasing.

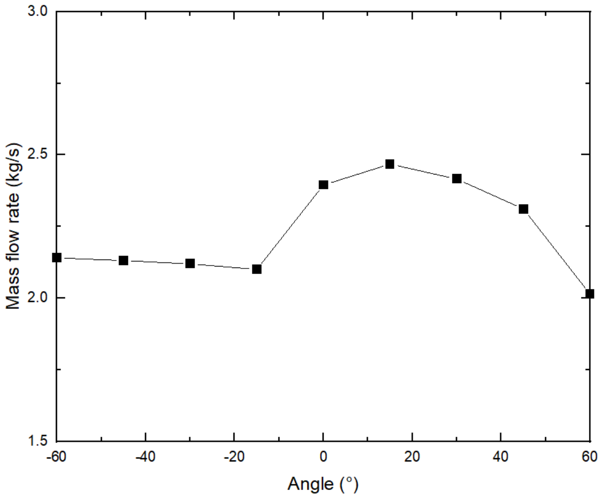

Fig. 5. Comparison with the mass flow rate in the cold leg according to the magnitude of the inclination angle.

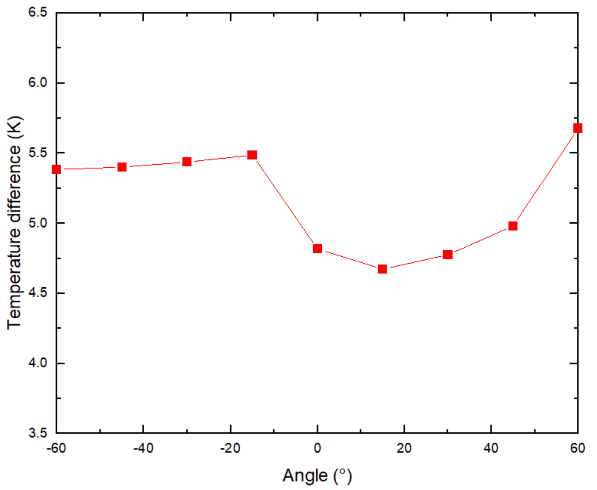

Fig. 6. Comparison with the temperature difference between the inlet and outlet at the cold leg according to the magnitude of the inclination angle.

However, when the magnitude of the inclination angle is larger than a specified value, ~15°, the flow rate decreases and resulting in a decrease in natural circulation performance. The oscillation of the mass flow rate is observed at the magnitude of angle, 60°. And the flow rate sharply decreases as the inclination angle exceeds 45°. Furthermore, if the inclination angle is getting larger, this will be a situation that should be avoided due to safety issues related to a ship.

On the other hand, when the system is inclined toward the heat sink, the inclination angle is negative and the elevation of decreases, the flow rate decreases and the temperature difference between the cold leg inlet and outlet increases. This eventually leads to a reduction in the natural circulation performance as expected from the previous experimental results. As the increase in the magnitude of the angle, there is a slight increase in the mass flow rate, but it can be negligible.

3. Conclusion

The natural circulation behavior under several inclination conditions was observed by using the MARS-KS code. Based on the results of each simulation, it is figured that the change in elevation according to the inclination condition affects the mass flow rate of the system and the cold leg inlet and outlet temperatures, and consequently changes the natural circulation performance. Brief summaries of the current MARS-KS code simulations are given below,

i When the system is inclined to a positive angle, the performance of the single-phase natural circulation tends to increase. However, it decreases with the angle being larger than the specified value.

ii Conversely, when inclined to a negative angle, the performance of natural circulation decreases.

In the future, an application and analysis to ocean motions with periodicity such as rolling, pitching, and heaving will be conducted. In addition, consideration to the instability that occurs within the system under the dynamic motions are applied will be required.

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