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Validation of the motion model in MARS-KS for gravity driven injection

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1. Introduction

Recently, international efforts to reduce greenhouse gases have increased due to severe climate change, and accordingly, many studies have been conducted on using nuclear energy as a power source for propulsion of ships and marine power plants. Some countries are already actively developing and using marine nuclear technology [1] and several research for marine nuclear power plants have also started in Korea, for example, a design project on the small nuclear reactor BANDI-60s (KEPCO-ENC) [2], a conceptual design research for lead-bismuth cooling high speed reactor MicroUranus (UNIST) [3], and a conceptual design research of floating type nuclear power plant using SMART (KAIST) [4].

Unlike land-based nuclear power plants, marine nuclear power plants operate under ocean conditions and the conventional safety analysis should be changed since the plants can incline and fluctuate due to ocean waves and wind. Therefore, development studies of MARS-KS code for a moving reactor have conducted [5,6], which is the code for multi-dimensional and multi-purpose thermal-hydraulic system analysis of nuclear reactor transients developed by KAERI. In these previous studies, the motion model and the new user-supplied input motion option for the simulation of irregular motions were implemented in MARS-KS and quantitative verification was completed by solving basic conceptual problems.

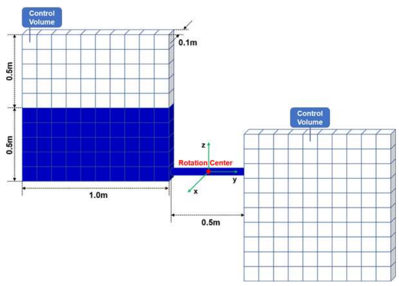
Following the process, this study was carried out to validate whether the motion model can be properly applied in real situations. First, we evaluated the code capability for passive safety system analysis by modeling a simplified gravity injection system. In this case, the multi-dimensional modeling effect was analyzed using two different models, 1D PIPE and MULTID. In addition, the code ability for a realistic accident was evaluated through the calculation of the progressive ship flooding experiments by Ruponen [7]. In this calculation, the experimental data and the MARS-KS results were compared during flooding process inside the ship due to external damage.

2. Results

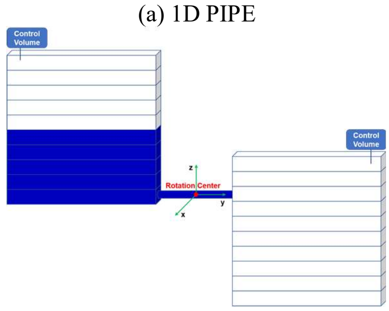
2.1 Analysis of Simplified Gravity Injection System

A number of recent nuclear reactors under development adopt a passive safety system that can maintain safety of a nuclear power plant without operator action or emergency power during an accident condition. A typical passive safety system principle is a gravity-driven coolant injection system. When a ship is tilted in marine condition, the pressure head becomes different from that in the land, affecting the cooling water injection capacity. To evaluate the effect, we simulated the simplified gravity injection system and compared the flow rate change under three different motion conditions, the vertical stationary condition, 30° inclination, and ±30° rolling, with a 10 seconds period. Also, two different models, 1D PIPE and MULTID, were used to evaluate the effect of multi-dimensional modeling.

In the calculation, two square slabs located at different elevations were simulated as shown in Figure 1. Initially, the left slab was half-filled with water and the right slab was empty. Two slabs were connected with a pipe and the flow rate in the pipe was monitored during the calculation. The detailed dimensions, nodalization and motion conditions for the calculation are presented in Figure 1 and 2.

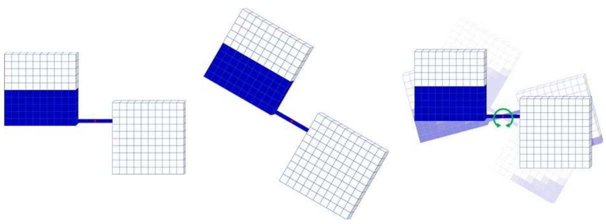


(a) 1D PIPE



(b) MULTID

Figure 1. MARS-KS nodalization of simplified gravity injection system



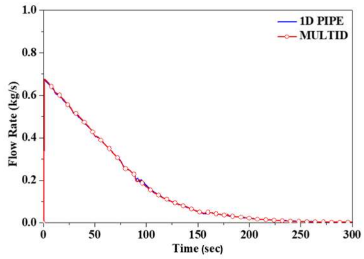
(a) Vertical (b) 30° inclined (c) ±30° rolling

Figure 2. Three motion conditions of simplified gravity injection system

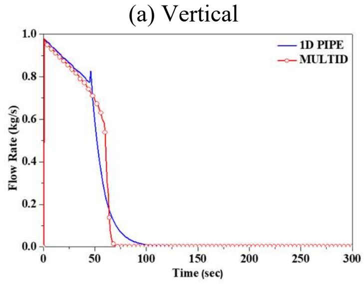
Under the vertical stationary condition, it is observed that the water in the left slab at the higher position gradually moves to the right slab as time goes, but there is no difference between the results from the 1D PIPE model and MULTID model as shown in Figure 3-(a).

When the initial inclination of 30° was given, the water inside the left slab moved faster to the right slab than the previous calculation since two slabs were inclined to the right resulting in a higher gravitational head. It should be noted that there was a difference between the results of 1D PIPE and MULTID as shown in Figure 3-(b). The reason for the difference is that vertical stratification cannot be properly calculated when the 1D PIPE model is used. As shown in Figure 4, when the water level reaches one large cell at the bottom, the fluid in the cell becomes a two-phase mixture resulting increase of the pressure drop between two slabs and the flow rate in the connected pipe begins to decrease sharply. However, with the MULTID model, stratification is calculated relatively accurate and the rapid decrease of flow begins later.

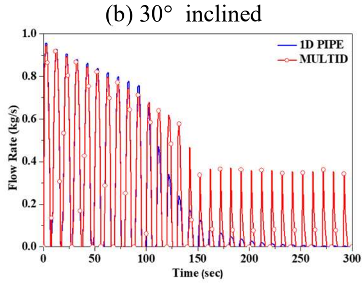
The different results between two models were also observed in the fluctuation condition. Figure 3-(c) shows the flow rate in the connected pipe under the ±30° rolling condition. In the case of the MULTID, the oscillation of flow rate due to the reverse flow is observed longer and larger than that of 1D PIPE because the phase separation is calculated more accurately and spill over occurs when MULTID is used as shown in Figure 5.



(a) Vertical

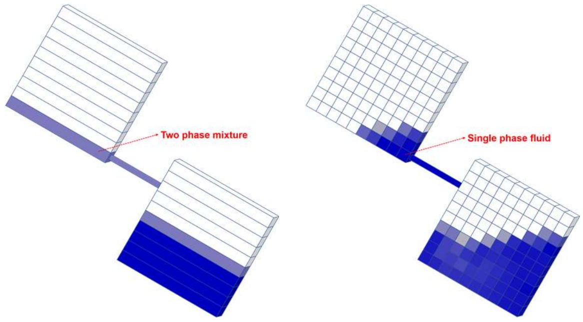


(b) 30° inclined



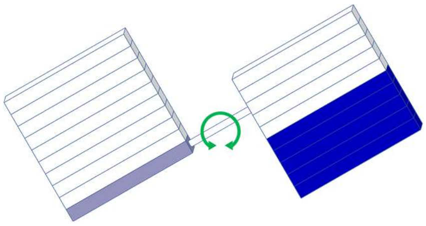
(c) ±30° rolling

Figure 3. Comparison of flow rate in the connected pipe under three motion conditions

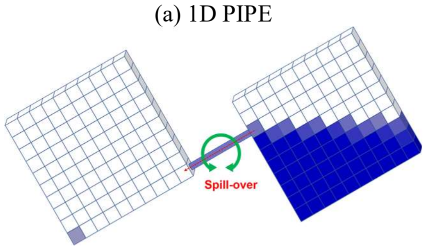


(a) 1D PIPE (b) MULTID

Figure 4. Comparison of calculation results between 1D PIPE and MULTID under 30° inclined condition



(a) 1D PIPE



(b) MULTID

Figure 5. Comparison of calculation results between 1D PIPE and MULTID under ±30° rolling condition

The effect of such a multi-dimensional modeling can be increased when the inclination of the ship becomes larger or the length of the calculated cell becomes longer. Therefore, it is necessary to consider the suitability of multi-dimensional modeling when analyzing the passive safety system incorporating the gravity driven injection in actual marine nuclear power plants, especially the cooling water level is very low or the inclination of the ship is large.

2.3 Analysis of Ship Flooding Experiment

In this section, a ship flooding experiment analysis was performed to evaluate prediction ability in a realistic accident using the motion model implemented in MARS-KS. For this purpose, the Ruponen experiment was calculated, which observed the progressive flooding of a box-shaped ship due to the external damage of the ship. Ruponen performed several experiments to provide detailed measurement data for the validation of numerical simulation methods for progressive flooding of passenger ships. In the experiment, the box-shaped ship was used which have eight flooded compartments located slightly forward from the midsection of the ship in order to ensure sufficient trim in the flooded condition. (Figure 6) Also, two artificial holes located at the side and the bottom were made to simulate external damages of the ship. In order to obtain high-accuracy data, the water level, pressure, and floating position of each compartment were recorded and measured simultaneously using sensors and the discharge coefficients of the openings between the compartments including the damaged holes were directly measured and calculated.

Based on Ruponen's data, Kim et al. [8] simulated the progressive flooding using their own in-house code SyFAP and showed good agreement between the experiment data and their numerical analysis results. In this study, we used inlet flow rate into the damage holes and trim angle boundary conditions of two experiments by Ruponen derived from SyFAP. Figure 6 shows the two different damage locations in the experiment and the detailed dimensions and nodalization used in MARS-KS validation are shown in Figure 7 and Table 1.

Figure 8 shows the water level in each compartment over time in two experiments. As shown in Figure 8-(a), it was confirmed that the prediction of MARS-KS motion model is consistent with Ruponen's experimental data of Case A. However, in the Case B (Figure 8-(b)), the difference of water level was observed in some compartments. This is clearly observed in the DB1 compartment and it is because that the water level in the DB1 is decided by the balance between the water and the air pocket formed in the DB1 and MARS-KS uses the coarse grids in the simulation due to the characteristic of system analysis code.

However, despite the limitations of the coarse grids, the overall water level trends in all compartments by MARS-KS shows similar behaviors of the experimental data, so that the motion model is implemented appropriately in MARS-KS.

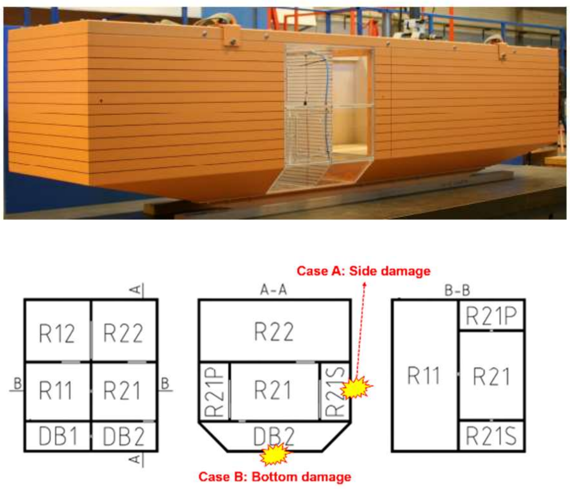


Figure 6. The box-shaped model ship used in Ruponen's experiment(upper), targeted 8 compartments and two damage hole locations (lower)

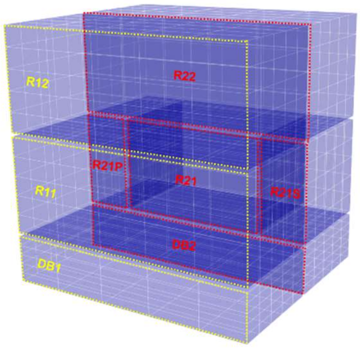
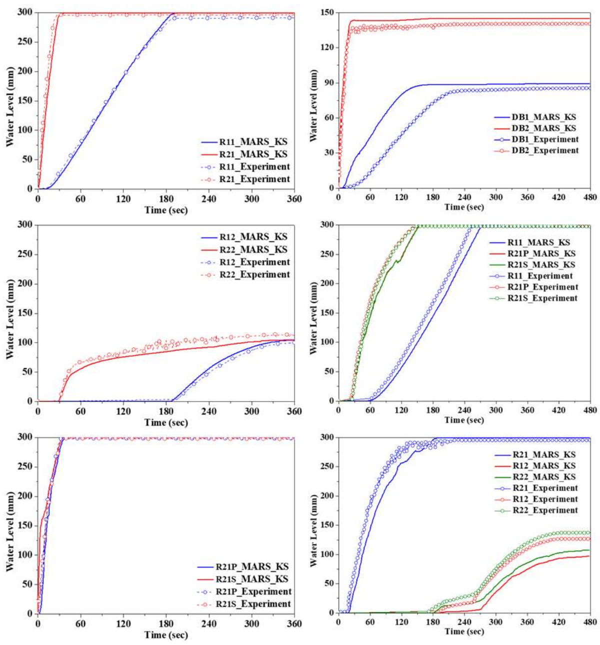


Figure 7. MARS-KS nodalization of ship flooding experiment

Table 1. Dimensions of compartments in Ruponen's experiment

Room	X (mm)	Y (mm)	Z (mm)
R12 & R22	780	335	315
R11	780	335	300
R21	460	335	300
R21P & R21S	150	335	300
DB1 & DB2	490	335	145



(a) Case A (b) Case B

Figure 8. Comparison of experimental data and MARS-KS results

3. Conclusions

In this study, the analysis ability of the MARS-KS motion model was evaluated by calculating simplified gravity injection system and ship flooding experiment. As a result of the simulation, it was found that the motion model in MARS-KS is suitable for prediction of the flow behavior and the water level in the ship when inclination and fluctuations occur in the ocean.

However, it is necessary to consider the effect of the multi-dimensional modeling when the water level is low or the inclination of the ship is large. In addition, MARS-KS can predict the overall water level trends well, but the highly accurate prediction is limited due to the characteristic of the system code. In the future, users need to fully consider these limitations and reflect them in the analysis process.

ACKNOWLEDGEMENT

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