SBLOCA analysis of a floating nuclear reactor under combined heaving and inclination

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1. Introduction

The marine industry is considering nuclear power as a potential solution to reduce greenhouse gas emissions [1]. Research and development of marine nuclear reactors for ship propulsion and offshore floating power plants have increased due to their high mobility, which makes them useful for powering remote areas or supporting marine resource exploration [2]. However, external forces induced by ocean motions can affect the thermal-hydraulic behaviors of these reactors. To accurately predict their behavior, advanced features must be added to system analysis codes to consider motion effects.

MARS-KS is a thermal-hydraulic system analysis code for audit calculation in Korea which was developed by KAERI. Previous research [3,4] has improved the moving reactor model in MARS-KS for the safety analysis of floating reactors by adding external body force terms, and the present study applies this improved code to postulated accident simulations of the BANDI-60 floating reactor under development. However, other constitutive models such as heat transfer model were not modified and the original models were used as they are. BANDI-60 is a water-cooled Small Modular Reactor (SMR) designed by KEPCO-E&C, a block-type reactor incorporating a fully passive safety system [5]. However, this safety system operates with a gravity-driven injection system, which could be highly affected by ocean motions [6]. Therefore, it is necessary to analyze the performance of the passive safety system operating under ocean conditions.

A series of simulations were conducted for a Direct Vessel Injection (DVI) line break of Small Break Loss of Coolant Accident (SBLOCA) to quantify the impact of ocean conditions on accident analyses. Previous research was conducted under static inclined and rolling conditions and the heaving and combined motion conditions have not been investigated. In the present study, heaving motion and combined heaving and inclination were imposed for ocean conditions of the BANDI-60 accident simulation.

2. Offshore floating nuclear reactor BANDI-60

In this section, the target floating reactor, BANDI-60, is described. It can be constructed on a barge and has 60MW electric power [5,7]. Its overall configuration is presented in Fig.1.

2.1 Passive safety system of BANDI-60

The BANDI-60 reactor incorporates various passive safety features, including the Passive Safety Injection System (PSIS), the Passive Containment Cooling System (PCCS), and the Passive Residual Heat Removal System (PRHRS). The PSIS supplies water to the Reactor Coolant System (RCS) during a LOCA by drawing from the Core Makeup Tank (CMT) and Emergency Core Cooling Tanks (ECCT). The CMTs are pressurized with the same pressure as the Reactor Pressure Vessel (RPV), while the ECCTs are at atmospheric pressure within the Containment Vessel (CV). The injection lines are equipped with four Reactor Vent Valves (RVVs) connected to the RPV head and four Reactor Recirculation Valves (RRVs) at the same elevation as the DVI lines.

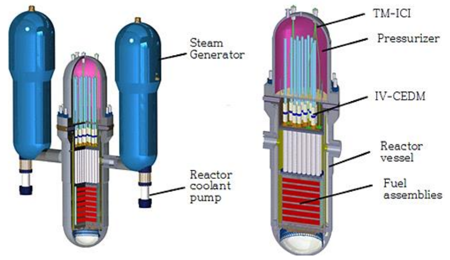


Fig. 1. BANDI-60 system diagram

2.2 MARS-KS normalization of BANDI-60 with PSIS

BANDI-60 with RCS and PSIS was nodalized with MARS-KS as shown in Fig.2. The reactor coolant system is bounded by the main feedwater lines and turbines, while the containment vessels are filled with air at room temperature and atmospheric pressure. To apply the asymmetry from inclination, the reactor core, and downcomer are divided into 4 parts as shown in Fig.3-(a). If the system inclines toward the left side, Section-1 is placed higher and in the opposite case, Section-3 is placed higher (Fig.3-(b)). The simple diagram of BANDI-60 with RCS and PSIS is shown in Fig.4. SGs, CMTs, and ECCTs are located symmetrically around the core. The DVI line break was simulated with an open valve.

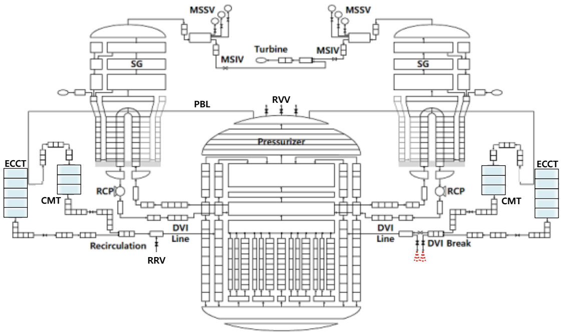
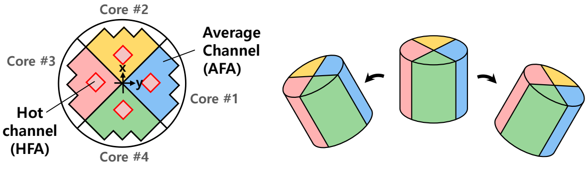


Fig. 2. Nodalization of BANDI-60 with DVI line break



(a) (b)

Fig. 3. Core division for motion conditions – (a) Core division in top view (b) Core status under the inclination

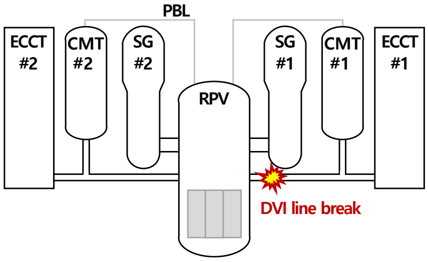
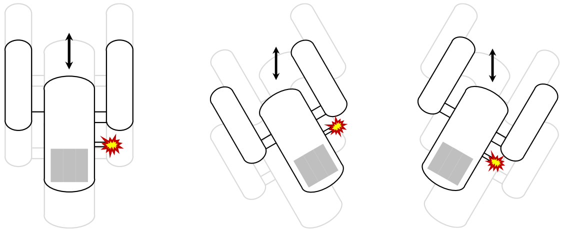


Fig. 4. Simple diagram of BANDI-60 with PSIS

3. BANDI-60 SBLOCA analysis

In BANDI-60, SBLOCA is the most serious design-basis accident. Therefore, SBLOCA analyses with the double-ended guillotine break of the DVI line were conducted. The conservative assumptions were applied: a single train DVI line was broken and a single reactor vent valve and reactor recirculation valve out of four were opened.

The simulated ocean conditions are heaving motion with 0.3g acceleration amplitude and 12s period, and combined motion of 0.3g - 12s heaving with ±20^o inclination. The motion conditions were selected by referring to the design criteria in IMO regulations for nuclear merchant ships [8] for inclination and the military standard handbook used within the US navy [9] for heaving conditions. To evaluate the heaving effect, the results under the heaving condition were compared to the vertical case, and results under combined inclination and heaving conditions were compared to the single static inclined condition.



(a) (b) (c)

Fig. 5. Motion conditions of analyses – (a) Heaving (b) Combined +20^o inclination and heaving (c) Combined -20^o inclination and heaving condition

3.1 Event sequence of SBLOCA under the vertical condition

During this event, the loss of offsite power occurs simultaneously with the break, which triggers the s-signal and leads to reactor and turbine trips. Following this, the PSIS begins to operate after secondary isolation and RCP trips, and recirculation is established for long-term cooling with the help of the gravitational head.

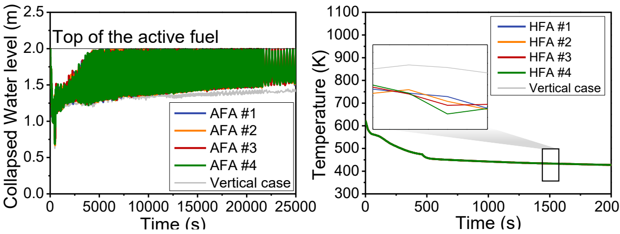
The passive safety injection system's performance is heavily reliant on gravity, making it highly sensitive to inclination. Hence, this study aims to determine the impact of combined motion with an inclination and heaving on this safety system during an SBLOCA event.

Table 1: SBLOCA signal logic

Event	Signal Logic
DVI line break	Initiating event
Loss of offsite power	Coincidence with initiation
Reactor trip/ Safety injection signal/ CMT open	2.0 delay from PZR lower pressure signal (<12.4795 MPa) (s-signal)
Turbine trip	Activate by reactor trip signal
Main steam line isolation	Activate by turbine trip signal
RCP trip	6.0s delay from safety injection signal
ECCT open	Vessel pressure<2MPa or CMT level<20%
RVV open	Every CMT level<30%
RRV open	Containment level>27.35% and Every ECCT level<66.7%

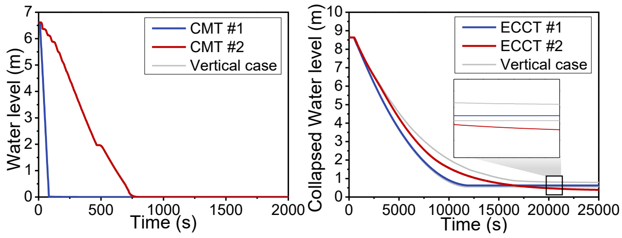
3.2 Transient analysis result under heaving condition

The SBLOCA analysis was performed under the heaving condition with 0.3g acceleration amplitude and a 12s period. Results were compared to the vertical condition to investigate the heaving effect. Under the heaving motion, the collapsed water levels in the core fluctuate as shown in Fig.6-(a). Compared to the vertical case, the collapsed water level remains higher and the peak cladding temperature shows a similar trend but has a slightly lower value (Fig.6-(b)). When LOCA occurs, the CV pressure gradually increased from atmospheric pressure by discharge through broken side, and after RVV opens, it reached the same pressure as the RV pressure within a few seconds. The pressure at the time it became the same is 9 bar and gradually decreased thereafter. Water injection from CMT which is pressurized as the RCS pressure shows a similar trend with the vertical case as shown in Fig.7-(a). However, the injection from ECCT on the opposite side of the break remains lower compared to the vertical case (Fig.7-(b)).



(a) (b)

Fig. 6. Core parameters under heaving conditions – (a) Core collapsed water level (b) Peak cladding temperature



(a) (b)

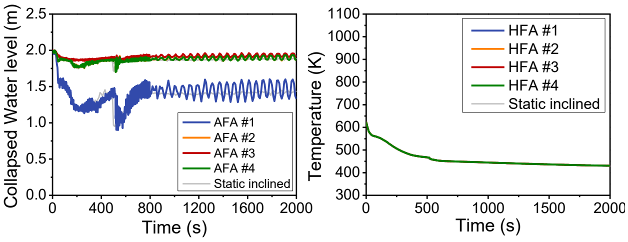
Fig. 7. PSIS parameters under heaving conditions – (a) CMT collapsed water level (b) ECCT collapsed water level

3.3 Transient analysis result under combined inclined and heaving condition

The accident analyses with combined motions were conducted under the 0.3g 12s heaving condition with ±20° inclination. To investigate the combined motion effect, the results were compared with the ±20° static inclination cases.

3.3.1 heaving with +20° inclination

Under +20° inclination, the collapsed water level along each core section shows asymmetric value in static inclined conditions. In particular, the core section which moved upward (Section-1) showed the lowest water level value. Under the combined inclined and heaving condition, the lowest level in Section-1 is maintained due to the relative height difference but it fluctuates significantly due to heaving, as shown in Fig.8-(a). However, Fig.8-(b) shows that the peak cladding temperature is not affected by the additional heaving motion.



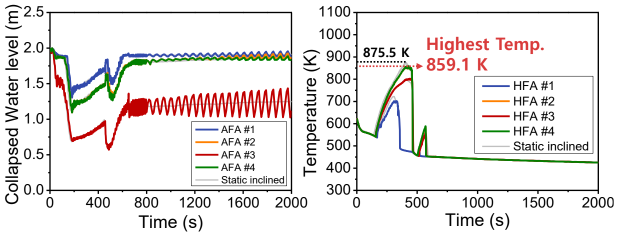
(a) (b)

Fig. 8. Core parameters under combined +20° inclined and heaving condition – (a) Core collapsed water level (b) Peak cladding temperature

3.3.2 heaving with -20° inclination

Under -20° inclination, the break in the DVI line was situated on the lower side, causing a fast discharge of coolant through the break. Consequently, a significant reduction in the water level in the core occurred, especially in the section above the break side (Section-3) as shown in Fig.9-(a). This led to a temporary core uncover, resulting in a sudden rise in the peak cladding temperature as Fig.9-(b). The highest temperature peak appeared in Section-3 which had the largest core uncovered area by inclination. Thanks to the additional heaving motion, the collapsed water level fluctuates, and the sudden rise in the peak cladding temperature also occurred but with a lower peak value (859.1K) than the static inclination case.

These simulation findings suggest that the inclination of the vessel can have a considerable impact on thermal hydraulic behavior under SBLOCA accidents, particularly when the break and the inclination are aligned in the same direction and the additional heaving can slightly mitigate the significance of the situation.



(a) (b)

Fig. 9. Core parameters under combined -20° inclined and heaving condition – (a) Core collapsed water level (b) Peak cladding temperature

3. Conclusions

This study utilized the moving reactor model of MARS-KS to conduct a series of accident analyses for a floating nuclear reactor, with a focus on analyzing the DVI line break SBLOCA for the BANDI-60 under various ocean conditions. Heaving and heaving with inclination were selected for the ocean conditions of the accident analyses. The results imply that heaving motion provokes the increase of gravitational injection, and does not worsen the accident. Still, static inclination in the same direction as the break remains a significant factor to consider in PCT analysis during the design and safety assessment of floating reactors.

Moving forward, further improvements in the containment model and analysis of additional ocean conditions are necessary, along with enhancements to the thermal-hydraulic and component models in the code to improve the accuracy and safety of marine nuclear reactors.

ACKNOWLEDGEMENTS

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