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Accident analysis of a floating nuclear reactor under inclination using MARS-KS moving reactor model

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1. Introduction

With the increasing demand for carbon emission reduction, marine nuclear reactors are in the spotlight recently as a zero-emission energy source for ship propulsion or offshore plants [1]. For the deployment of the marine reactors, their safety should be ensured and they should meet the safety standards of both maritime and nuclear engineering fields. Thus, the safety analysis of a marine nuclear reactor needs to be extended to ocean conditions. A marine reactor operates in the sea and it can be placed in an inclined state by grounding, stranding, flooding, etc. This requires the accident analysis capability of a safety analysis code for the reactor under inclination to confirm the satisfaction of the acceptance criteria of the reactor.

For this purpose, Seoul National University has been improving the moving reactor model of MARS-KS [2]. MARS-KS is a code for thermal-hydraulic system analysis of light water reactor transients and employs a moving reactor model that can calculate dynamic motion effects on the reactor system. To demonstrate the improved capability of the MARS-KS moving reactor model, accident analyses of a marine nuclear reactor were conducted in the present study.

A floating nuclear reactor, BANDI-60 [3], which was developed at KEPCO-E&C, was analyzed using MARS-KS when it is tilted. This paper presents the simulation results of BANDI-60 when the DVI break SBLOCA occurs with two inclination conditions.

2. BANDI-60 modeling

The details of BANDI-60 is introduced in Kim et al. [4] and its passive safety system features are presented in Fig. 1. The reactor adopts fully passive safety systems that use natural forces and battery power. Among various accident scenarios, Small Break Loss of Coolant Accident (SBLOCA) with DVI line break was analyzed. Fig. 2 shows the nodalization of the reactor coolant system, containment, and the reactor core [4], where the core was modeled with divided four sections. The simulation results of the normal operation and the accident condition were introduced in Ref [4]. The design features of the reactor and its signal logic are also presented in the reference. Thus, this paper covers only the accident analysis results under inclinations.

Two accident cases of inclination were analyzed; one is +30° inclination in the same direction as the angle of the broken DVI nozzle and the −30° inclination in the opposite direction as shown in Fig. 3.

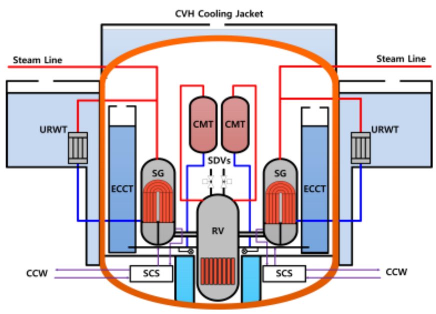
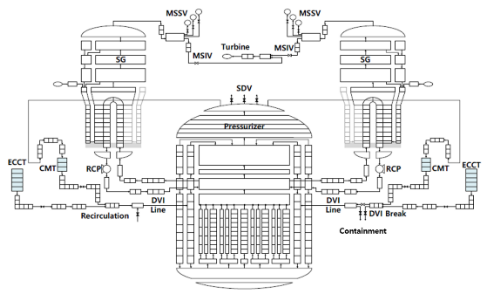


Fig. 1 Schematics of BANDI-60 Safety System [4]



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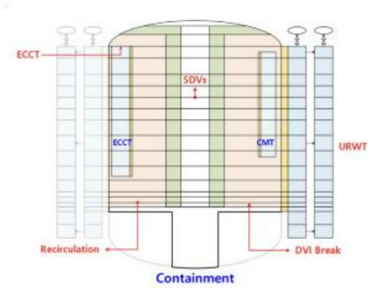

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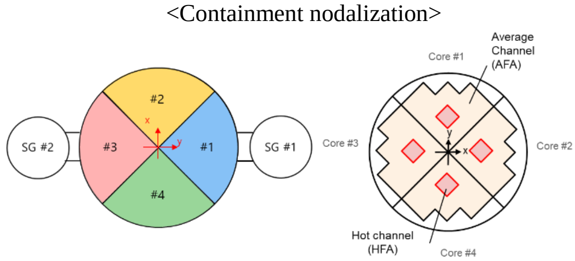

<Reactor core sections>
Fig. 2 Modelling of BANDI-60 for MARS-KS [4]

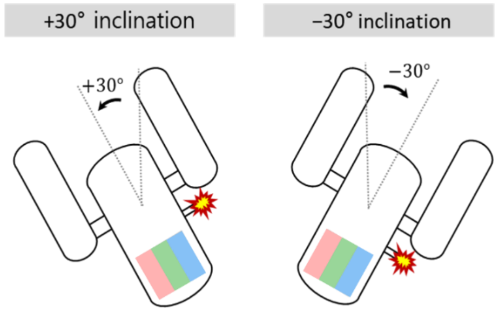

Fig. 3 Inclination conditions of the present accident analyses

3. Analysis results

<u>+30° inclination</u>

Fig. 4 shows the mass flow rates in each reactor core section and the core inlet and exit temperatures during the normal operation when the reactors are in the vertical and inclined states. Compared to the vertical state that showed identical flow rates and temperatures at each section, the inclination generated the core flow rate and exit temperature deviations concerning the relative locations of the core sections to the break. The farthest core section to the break (Section-3, red-colored) was located at a lower elevation than the other, and a slightly higher flow rate and lower temperature were observed. The larger elevation difference between the core exit and the highest steam generator U-tube applied additional circulation force. This might cause a relatively larger flow rate through Section-3. The deviations, however, were not significant with the circulation being forced by the reactor coolant pumps.

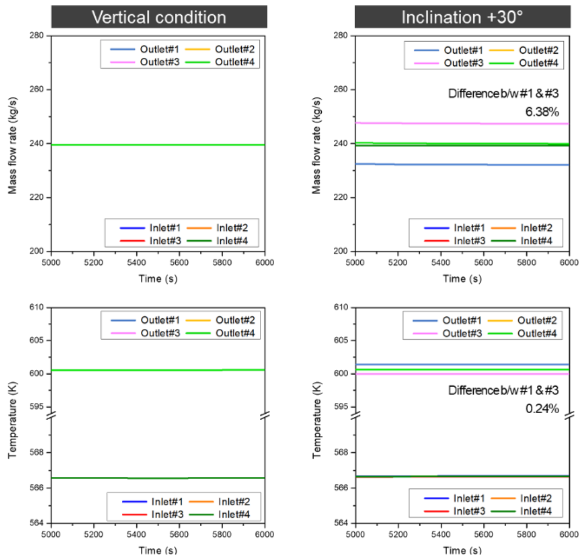

Fig. 4 Normal operation results: vertical and inclined states

Fig. 5 shows the simulation results of the core collapsed water levels and the maximum cladding temperatures at each core section under the SBLOCA condition. The total simulated problem time was 72 hours after the break but the initial 2000 seconds was displayed to magnify early transient behaviors.

The water levels under the inclination showed clear deviations from each other as two-phase flows were generated in the core. In particular, Section-1 (blue colored) has the lowest water level with the phase separation and void clustering in the upper part of the core. However, the location of the break was higher than the exit of the highest core section, and then a sudden rise in the cladding temperature was not observed and a comparable trend to the vertical condition appeared even with the inclination.

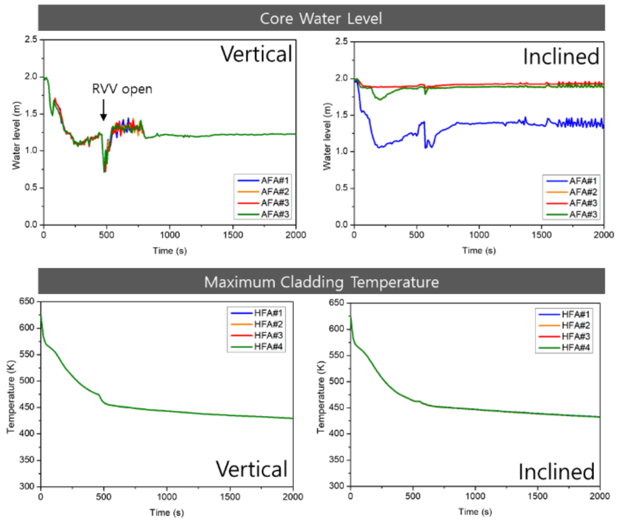

Fig. 5 Accident results: vertical and +30° inclined states

<u>-30° inclination</u>

The same analyses of the normal operation and DVI line break accident were repeated with -30° inclination. The normal operation analysis showed very similar results with the +30° inclination case with a flip in the horizontal direction. On the other hand, the accident analysis presented remarkable differences.

As illustrated in Fig. 3, the broken DVI became located in the downward-facing part of the inclined reactor vessel. In this case, faster and more discharge of the coolant inventory was expected. Fig. 6 shows the core water level and maximum cladding temperature transients under -30° inclination. As expected, the core water level showed a fast and significant decrease after the break. Especially, the water level in the farthest core section (Section-3, red-colored) dropped more than the others as it is located at the highest elevation.

The large decrease in the water level resulted in the core uncover temporarily. Thus, the cladding temperatures increased rapidly different from the vertical and +30° inclination cases. The peak cladding temperatures at each core section showed obvious relation with the core elevation created by the inclination. The higher the core exit is located, the higher the peak cladding temperature appears.

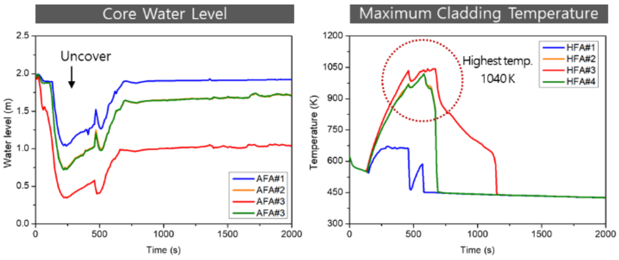

Fig. 6 Accident results: -30° inclined states

Despite the core uncover and sudden rise of the cladding temperature were observed in the analyses with -30° inclination, the peak value satisfied the acceptance criteria of the accident (below 1204°C) and the heated fuels were quenched immediately by the activation of the emergency core cooling tank and the reactor vent valve. Furthermore, the long-term cooling continued successfully by the passive containment cooling system and the activation of the passive recirculation system. Fig. 7 shows the long-term transient results along 72 hours, which shows the gradual make-up of the core collapsed water level maintaining the core cooling capability after the quenching.

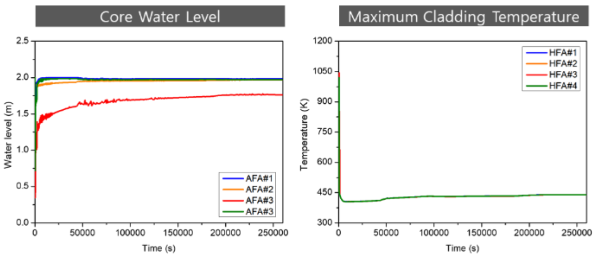

Fig. 7 Long-term cooling analysis results: -30° inclined states

4. Conclusions

In this study, a floating nuclear reactor, BANDI-60, was analyzed using MARS-KS postulating the DVI line break SBLOCA under ±30° inclinations. The results clearly showed that the thermal-hydraulic behaviors of the reactor system vary significantly with the combination of the break location and the inclination direction. In the worst situation, when the break was located on the downward facing side, the sudden rise of the cladding temperature appeared. But the peak temperature did not exceed the acceptance criteria of the accident even in the worst case.

The code and its physical models require further improvements. For instance, the heat transfer models need to be extended and validated for inclinations and motions. Their transient prediction capability needs to be validated under motions and inclination. In terms of the reactor modeling, the containment should be analyzed with multiple pipes considering the multi-dimensional effect in the long-term cooling.

Nevertheless, the present work demonstrated the capability of the moving reactor model of MARS-KS successfully. The expected transients were well reproduced by the model such as the core uncover under the inclination. Thus, it will be able to contribute to the safety analysis of a marine nuclear reactor and to the quantification of the ocean motion effects if the improvements mentions above are completed.

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