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Numerical Analysis of Molten Corium Dispersion during Hypothetical High-Pressure Accidents in APR1400 Nuclear Power Plant

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1. Introduction

During a hypothetical high-pressure accident in a nuclear power plant (NPP), molten corium can be ejected through a breach of a reactor pressure vessel (RPV) and dispersed by the following jet of a high-pressure steam in the RPV. The dispersed corium is fragmented into smaller droplets in a reactor cavity of the NPP by the steam jet with very high velocity and is released into the upper compartment of the NPP by an overpressure in the cavity. The heat-carrying fragments of the corium transfer the thermal energy to the ambient air in the containment and react chemically with steam and generate hydrogen which may be burnt in the containment. The thermal loads from the ejected molten corium on the containment which is called direct containment heating (DCH) [1] can threaten the integrity of the containment.

New generation NPPs such as APR1400 and EPR have been designed in consideration of reducing the possibility of the containment failure from the DCH. In order for that, APR1400 has a convolute-type corium chamber connected to the reactor cavity. In the case of EPR, severe-accident dedicated depressurization valves are installed to preclude a high pressure melt ejection (HPME).

DCH in a NPP containment is related to many physical phenomena such as multi-phase hydrodynamics, thermodynamics and chemical reaction. In the evaluation of the DCH load, the melt dispersion rates depending on the RPV pressure are the most important parameter. Mostly, DCH was evaluated by using lumped-analysis codes with some correlations obtained from experiments for the dispersion rates.

The corium dispersion rates for many types of the NPP containments had been obtained by experiments in 90s. And some correlations from the experimental data were developed. As mentioned above, APR1400 has a corium chamber to reduce the corium dispersion rate. But there is no experimental data for the dispersion rate specific to the APR1400 cavity geometry. So its performance for capturing of the dispersed corium is not clearly known. During the evaluation of containment integrity by DCH in KNGR (synonym of APR1400) [2], the dispersion correlation [3] developed from experiments for Young-Gang 3&4 and Kori-1 cavity geometries was applied in a two-cell equilibrium (TCE) modeling.

As can be expected, the benefit of the convolute cavity geometry of APR1400 could not be resolved once the correlation is used.

In order to verify that using the correlation for APR1400 is conservative in view of the evaluation of the containment integrity by DCH, corium dispersion in the APR1400 containment was simulated by using MC3D code [3]. The MC3D code is a two-phase analysis code based on Eulerian four-fields for melt jet, melt droplets, water and gas mixture of vapor and non-condensable gas. The dispersion rates of the corium melt depending on the RPV pressure were obtained from the MC3D analyses and the values specific to the APR1400 cavity geometry were compared to the correlation.

2. Validation of MC3D with the High Pressure Melt Ejection Test for YGN 3&4

In the previous researches, DCH analyses for European NPPs such as P'4 and EPR were conducted by axi-symmetric or cylindrical modeling with MC3D code.

On the contrary, the cavity shapes of the Korean NPPs are not easily modeled with cylindrical coordinates because they look like two horizontal and vertical rectangular channels joined at their ends. A feasibility study was conducted for validity of the axi-symmetric approximation of Yung-Gwang 3&4 (YGN 3&4) test facility. It was found from the study that the axi-symmetric approximation for the YGN 3&4 test facility is impractical to get qualitative results of the melt dispersion. The purpose of the MC3D simulation of DCH for the YGN 3&4 tests is to find a way to model the channel-type cavity.

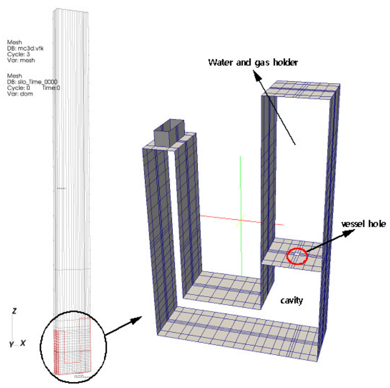

Fig. 1. Mesh of the simplified YGN 3&4 cavity

A Cartesian mesh was used for the geometry modeling, and the number of nodes in the mesh was 19 x 7 x 28 (=3724).

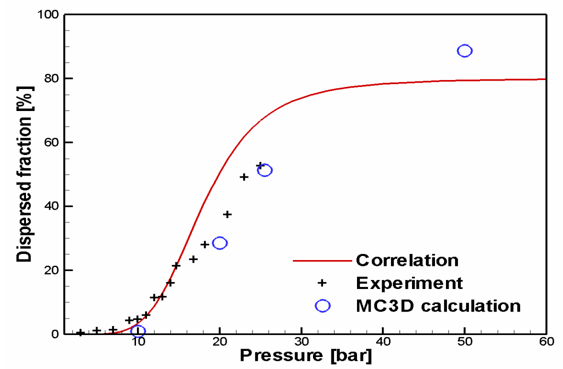

Fig. 2. Dispersion fraction depending on vessel pressure

The dispersion rates for the YGN 3&4 tests have been obtained by using the MC3D code at the vessel pressures of 10, 20, 25.5, 50 bar. The dispersion rate increased very rapidly as the initial pressure of the vessel increased. The dispersion rates from the MC3D analyses were compared to the experimental data and Kim' s correlation. It was found in this study that the Cartesian mesh for modeling of the channel-type cavity can produce reasonable results for melt dispersion.

3. Dispersion Fraction of the APR1400 Cavity

Similar to the YGN 3&4 NPP, APR1400 cavity is not axi-symmetric. It is a horizontally long rectangular channel. It is connected to a vertical ICI chase and has a corium chamber to capture dispersed corium. There are three flow paths in the APR1400 cavity.

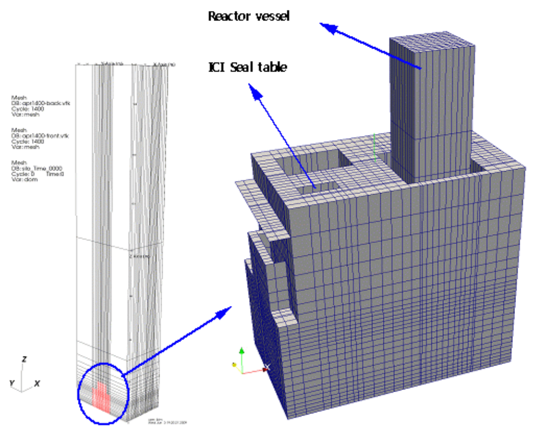

Fig. 3. 3-D mesh generated for MC3D analysis of APR1400

- Annulus around the reactor vessel and primary shield wall: This flow path connects the reactor cavity with upper dome and steam generator compartment.
- ICI seal table: During a normal operation, the ICI chase is not a flow path, but after its rupture by a pressure developed in the cavity, the ICI chase becomes a primary flow path for the dispersed corium.
- A damper on top of the entrance of the corium chamber. It is automatically opened when a pressure is build up in the cavity.

Because the corium dispersion occurs only in the cavity region, the cavity was modeled in detail, but the other region outside the primary shield wall was simplified only with the conservation of the containment volume. The left figure of Fig. 3 shows the simplified containment of APR1400 for the MC3D analysis and the right figure shows surface mesh of the primary shield wall and reactor vessel.

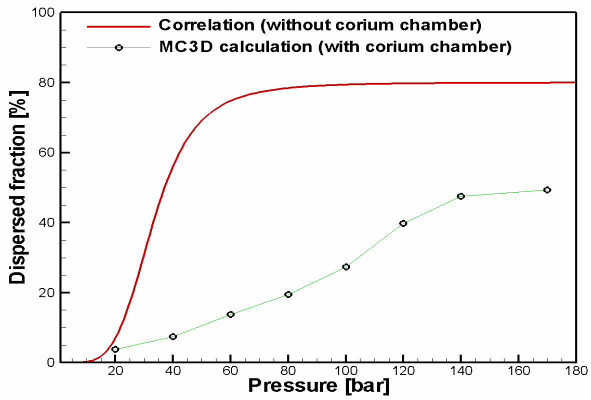

Fig. 4. Dispersion fraction depending on vessel pressure for APR1400

Dispersion fractions dependent on the initial vessel pressure obtained by MC3D calculation was compared to the Kim's dispersion correlation in Fig. 4. It depicts that the amount of the dispersed corium ejected from the APR1400 cavity is lower than the value expected by the correlation.

3. Conclusion

In this study, the 3-dimensional simulation of the corium dispersion in the APR1400 cavity was conducted by using MC3D code. It was found from the study that the correlation used for the DCH analysis of APR1400 can give conservative results for the containment integrity of APR1400.

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