Numerical Analysis on the Multi-phase Thermal-hydraulic Phenomena in the Passive Cooling System of i-SMR

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1. Introduction

In a nuclear power plant, the reactor core generates heat through fission. Unlike other power plants, even after reactor shutdown, the residual heat continues to be generated due to the radioactive decay of unstable fission products in the core, which decay over a long period into stable isotopes. Therefore, it is essential to ensure sufficient heat removal capacity for decay heat even after shutdown.

Recently, Korea has developed the innovative-Small Modular Reactor (i-SMR). It adopts a passive cooling system to prevent severe accident situations caused by power-off accidents, such as the Fukushima Daiichi NPP accident..

In this study, the multi-dimensional and multi-phase flow behavior and cooling performance in the ultimate heat sink, the Emergency Cooling Tank (ECT), were numerically analyzed using the three-dimension thermal hydraulics code, CUPID.

2. Methods and Results

2.1 Passive Cooling System of i-SMR

The i-SMR adopts a passive cooling system to remove residual heat. The passive cooling system includes the Passive Auxiliary Feedwater System (PAFS) and the Passive Containment Cooling System (PCCS). Fig. 1 shows a layout diagram of the i-SMR reactor building, illustrating the passive cooling system in a simplified manner.

In the PAFS, superheated steam of the steam generator during an accident is supplied to a submerged passive condenser in the ECT through steam supply pipes. Condensation occurs within this heat exchanger, transferring heat to the ECT.

In the PCCS, steam released from the top of the pressurizer transfers heat to the outer wall of a heat exchanger located at the top of the containment vessel. The heated coolant inside the heat exchanger then flows to the ECT .

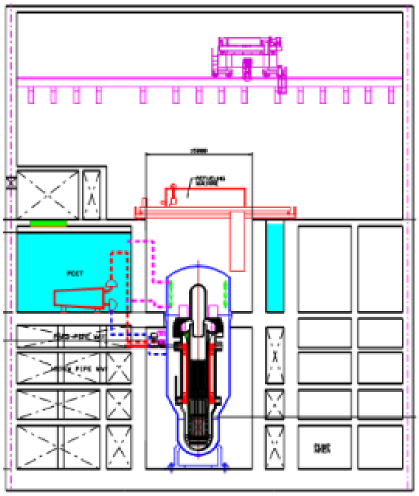

Fig. 1. i-SMR structure layout

2.2 Thermal-Hydraulics Code CUPID

As described above, the i-SMR adopts a passive cooling system in which two-phase flow occurs. Previously, two-phase flow was predicted using one-dimensional (1D) system thermal hydraulics codes.

The conventional one-dimensional code such as RELAP5-3D, CATHARE-3D, MARS-3D, SPACE codes analyzed thermal-hydraulic phenomena with conservative model approaches. However, these codes have challenges in handling complex geometries or accurately evaluating three-dimensional natural circulation phenomena[1,2].

CUPID was developed to overcome these limitations and to accurately simulate two-phase flow phenomena. CUPID adopts a three-dimensional two-fluid and three-field (gas, continuous liquid, droplet) model. The governing equations are formulated by the Finite Volume Method (FVM), and an energy-decoupled scheme is adopted to ensure high computational speed and numerical stability[3].

2.3 CUPID calculation model

Instead of the flow regime maps used in the system codes, the flow regime in CUPID was classified into three regions: bubble, mist, and sharp surface. The simple topology map , as shown in Fig. 2, was used in this study.

Ishii's interfacial drag force model and the Ranz–Marshall interfacial heat transfer model [4] were applied to account for interfacial interactions. the Interfacial Area Concentration (IAC) model was used. More detailed information about the calculation models was summarized in Table 1.

For numerical stability, steam was set instead of air in the upper part of the ECT, a large drag force was applied at the free surface between steam and water. Also, to prevent liquid leakage through drag without evaporation, a small drag force was assigned to region with void fraction exceeding 0.99.

Table 1. Specific calculation information

Contents	Model
Topology map	Simple topology
Interfacial area	IAC
Interfacial drag	Ishii
Interfacial heat transfer	Ranz and Marshall

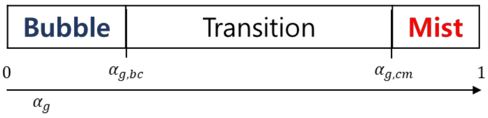

Fig. 2. Simple topology map in CUPID

2.4 Mesh information

The ECT geometry was referenced from the IAEA Advanced Reactor Information System (ARIS) i-SMR status report [5]. The mesh was generated using the open-source software SALOME developed by EDF. Fig. 3 shows the schematic diagram on i-SMR passive cooling system. The ECT consisted of an internal heat exchanger connected to the PAFS and an external heat exchanger connected to the PCCS.

Fig. 4 shows the specific ECT mesh. The total number of mesh cells was 13,392, with a representative cell size of 0.5m. The heat exchanger regions were modeled using a porous medium approach. For calculation convenience, the heat flux in the heat exchanger region was treated as a boundary condition.

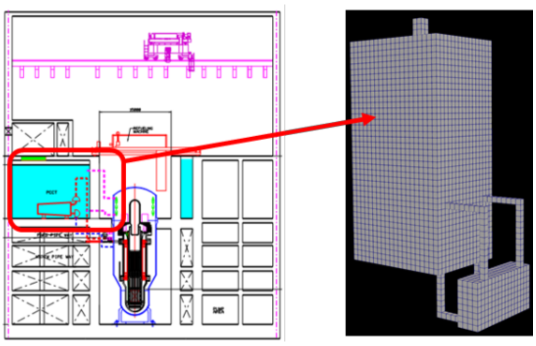

Fig. 3. General arrangement for reactor building

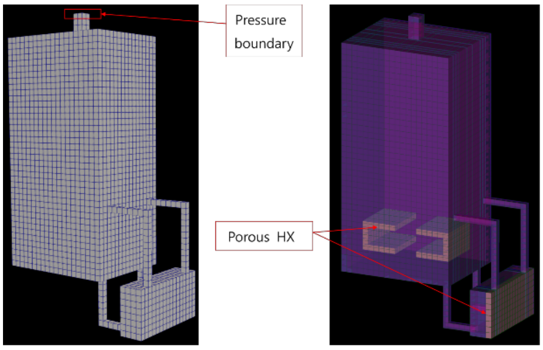

Fig. 4. Specific information of the ECT mesh.

2.5 Result and discussion

When heat was provided initially, single-phase natural convection occurred. This phenomenon had continued until the temperature of the water in the tank and the heat exchanger reaches the saturation temperature.

Once the saturation temperature was reached, flashing occurred at the top of the tank. Following flashing, a relatively high void fraction was observed in the pipe section connecting the PCCS to the ECT. Fig. 5 shows the normalized temperature distribution before flashing and void fraction distribution during flashing.

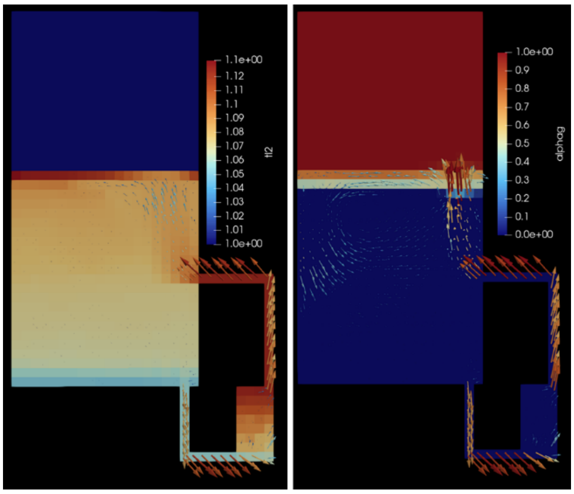

Fig. 5. Temperature distribution before flashing (left) void fraction distribution at flashing (right).

As steam generated in the PCCS entered the ECT tank, it condensed immediately, and flashing occurred again at the top of the tank, repeating this cycle. During this cycle, two-phase natural circulation was observed dominantly.

After the pipe connected with PCCS was exposed to steam, the natural circulation was diminished, and natural circulation caused by PAFS became dominant within the ECT. Fig. 6 shows he void fraction distribution for two-phase natural circulation and diminished natural circulation.

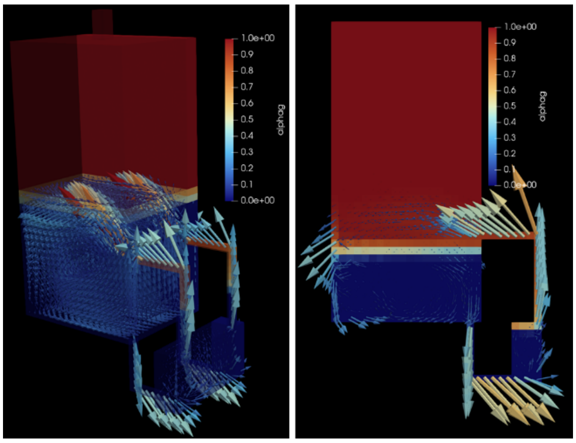

Fig. 6. Void fraction during 2-phase natural circulation (left)
Void fraction during diminished natural circulation (right)

3. Conclusions

In this study, a thermal-hydraulic analysis on the passive cooling system of the Korean i-SMR was performed using the CUPID code.

It was observed that after the heat source was applied, single-phase natural convection initially occurred, and after flashing began, two-phase natural convection became dominant. The entire process from boiling to flashing was successfully simulated using CUPID.

The discharge of steam through the pressure boundary from the tank containing water and steam was also successfully calculated.

Future work will focus on simulating the entire heat removal process of the passive cooling system under more realistic boundary conditions, which includes the multi-scale heat transfer modeling of PCCS..

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