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Validation of analysis models on relocation behavior of molten core materials in sodium-cooled fast reactors based on the melt discharge experiment

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Abstract

In order to improve the safety of nuclear power plants, it is necessary to make sure measures against their severe accidents. Especially, in the case of a sodium-cooled fast reactor, there is a possibility that molten core material would be discharged through control rod guide tubes into the inlet coolant plenums beneath the reactor cores in the event of a core disruptive accident (CDA). It is important to ensure in-vessel retention that keeps and confines damaged core material in the reactor vessel even if the CDA occurs. In this study, effective cooling of the melt in coolant was confirmed by comparing the experiment and analysis. CDA scenario initiated by a unprotected loss of flow condition-, which is a typical cause of core damage, is generally categorized into four phases according to the progression of core-disruptive status, which are the initiating, early-discharge, material-relocation and heat-removal phases for the latest design in Japan. During the material-relocation phase, the molten core material flows down mainly through the control rod guide tube and is discharged into the inlet coolant plenum below the bottom of the core. The discharged molten core material collides with the bottom plate of the inlet plenum. Clarification of the accumulation behavior of molten core material with such a collision on the bottom plate is important to reduce uncertainties in the safety assessment of CDA. In present study, in order to make clear behavior of core melt materials during the CDAs of sodium-cooled fast reactors, analysis was conducted using the SIMMER-III code for melt discharge simulation experiments by Imaizumi et al. in which low-melting-point alloy was discharged into a shallow water pool. As the result, temperature and pressure behaviors during the discharge almost coincided between the analysis and the experiment. Therefore, it can be concluded that the validity of the analysis cell system model was confirmed.

Keywords : Sodium-cooled fast reactor, Core disruptive accident, Relocation of molten core material, SIMMER-III

1. Introduction

In case of a core disruptive accident (CDA) in a sodium-cooled fast reactor (SFR), it is important to ensure in-vessel retention which maintains and confines the damaged core material in the reactor vessel. Recently, molten jet impingements were discussed for the capability of a SFR's in vessel core catcher (Lecoanet, et al., 2021). However, such researches are limited to the sodium coolant system. When the molten core material is formed as the core melts which is composed of the fuel and other structures, it flows down mainly through the control rod guide tube and flows into the lower inlet coolant plenum at the bottom of the core support structure. Then, the molten core material shows

fragmentation behavior with solidification of the materials because of contact with a large amount of low-temperature sodium coolant in the plenum. However, if the space height of the inlet coolant plenum is not sufficient, the discharged molten jet impinges directly with the bottom plate of the inlet plenum as shown in Fig. 1. It is possible to provide a large thermal load to the plate structure. In order to clarify the dominant mechanism for the thermal interaction during the jet impingement in the inlet coolant plenum, a fundamental experiment was performed by using a low-melting-point alloy with a shallow water pool which enabled detailed observations of the phenomena (Imaizumi, et al., 2017). In the experiments, detailed temperature behavior on the bottom plate and pressure measurements during the discharge process were conducted to evaluate the thermal interaction behavior. In addition, complex interface phenomena during the discharge process such as the dispersion of the molten alloy, instability of the contact interface, mixing with peripheral coolant, break-up, occurrence of dryout and the growth of vapor region were observed by the high-speed video camera. The objective of this study is to validate the evaluation method for the material-relocation phase of CDA in SFR (Fig.1) by SIMMER code. Especially, the mechanism of the transient behavior associated with the impinging jet melt at the bottom plate in the inlet plenum is important. This report shows the result for confirming the validity of the analysis cell system model in Fig.3 by comparison with the experimental data by the experimental apparatus in Fig.2.

Fig. 1 Material-relocation phase in CDA

2. SIMMER code development

SIMMER-III is a two-dimensional multi-velocity-field, multiphase, multi-component, Eulerian fluid dynamics code coupled with a fuel-pin model and a space-time and energy-dependent neutron kinetics model. Since SIMMER-III is expected to become a standard tool for fast reactor safety analysis, the development and assessment of this code have been carried out in cooperation with European partners (Tobita et. al., 2002). One of recent issues for the code development is an evaluation for the in-vessel retention (IVR) against CDA. During the material-relocation phase, the molten core material flows down mainly through the control rod guide tube and is discharged into the inlet coolant plenum below the bottom of the core. Coolability of the molten core material in the inlet coolant plenum affects the material relocation behavior during CDA. Therefore, the evaluation capability of coolability for the molten core materials in the inlet plenum is one of key issue for the code development. The objective of this study for the SIMMER code development is to validate the analysis cell system model for the discharge process by the water experiment.

3. Experiment and analysis conditions

Figure 2 shows the schematic diagram of the experimental apparatuses by Imaizumi, et al., 2017. Molten alloy (Bi: 58wt%, Sn: 42wt%) with a low melting point of 138 °C and a density of $8 \times 10^3 \text{ kg/m}^3$ in a crucible above a water pool was discharged through a nozzle into a shallow water pool. The nozzle diameter is 28 mm, and the amount of the molten alloy (afterwards: melt) is approx. 50 kg. Scale of the experimental apparatuses was determined from a design

example of core inlet plenum heights. To investigate the effect to the melt fragmentation by the bottom plate, the distance between the nozzle exit and the bottom plate was set 100 mm which was insufficient height to fragment of the impinging melt jet (Matsuba, et al., 2013). In case of a sodium coolant, during the core melt falling, stable vapor film in the interface is not formed and the melt jet impinges directly to bottom plate. The phenomena can be simulated by the water and low melting point molten alloy experiments. The melt dispersion behavior was recorded by a high-speed video camera. The temperature distribution during the jet impingement was obtained by thermocouples which were attached on and upper part of the bottom plate in the radial distances of 0, 25, 50, and 100 mm, and heights of 3, 8, 50, and 100 mm. Pressure gauges also were attached upper part of the bottom plate. The jet speed of 4 m/s was measured by experimental video. Initial temperatures of the melt and water were set 500°C and 30 °C, respectively, to simulate the typical accident conditions in SFRs where the molten fuel and coolant contact directly rather than generate stable vapor films. In addition, the experiment with plenum wall was performed to confirm the melt behavior when coolant volume might be limited. The result for experiment with plenum wall is considered in section 4-3. Figure 3 shows analysis cell system model for the SIMMER-III code. The experiment apparatus has a cylindrical shape. Therefore, cylindrical coordinates system of SIMMER-III can be applied directly without any approximation for the configuration. The central axis of the cylindrical coordinates corresponds to the center of the melt injection nozzle. The vertical axis and the horizontal axis were divided into 62 cells and 11 cells, respectively. The melt level height in the model is the same with the experimental apparatus. The horizontal radius of the melt crucible, however, was fitted to match the melt liquid volume to discharge. The initial pressure of air and coolant was set to 0.1 MPa, and boundary conditions were set at the top of system to be opened atmosphere condition. At the zero second of the calculation, the melt was started to discharge by the natural gravity force. The calculation was continued approx. 10 seconds until to finish the melt discharge into the water. Figure 4 shows details of analysis cell system model. The number of mesh above the plate is set finely in analysis model because of that the melt and coolant in the experiment make contact and, violently.

Fig. 2 Experimental apparatuses
(Imaizumi, et al., 2017)

Fig. 3 Analysis cell system model

Fig. 4 Details of Analysis cell system model

4.Result

4.1 Experiment result

Figure 5 shows the state during the melt injection in the experiment. When the melt is injected into the water, it impinges with the bottom plate and disperse along the bottom plate. Thereafter, generation of vapor due to contact between the coolant and the melt was confirmed. As a result, the melt was rapidly cooled during the dispersion process on the bottom plate, suggesting that the fragmentation was greatly enhanced by the bottom plate.

Figure 6 shows the measured temperature on the bottom plate. The central position ($r=0$ mm) temperature indicates the highest temperature more than 400°C , it decreased rapidly to approx. saturation temperature at the $r=100$ mm radius. This fragmentation can be attributed to the deformation of the melt by the bottom plate into a ring shape which has extended area of melt-water interface. Figure 5 suggests that the temperature greatly fluctuates by the contraction of the coolant due to the generation of vapor.

Fig. 5 State of molten alloy dispersion
(Imaizumi, et al., 2017)

Fig. 6 Temperature on bottom plate in the experiment
(Imaizumi, et al., 2017)

4.2 Analysis result

4.2.1 Temperature

Figure 7 shows the temperature comparison on the bottom plate center ($r=0$ mm) below the nozzle between the experiment and analysis. Each phase of all the components is evaluated by the multiphase and multicomponent flows model in SIMMER code, in order to compare the experimental and analysis result in similar conditions, the analysis temperature is evaluated by volume averaged value of water and melt in the cell in Fig. 7. The molten material is able to be treated as solidified one when temperature of the melt below 138°C because of that the melting point of the melt is 138°C . The analysis temperature shows a liquid phase melt temperature. If the temperature decreases lower than melting point of 138°C , the melt becomes solid, so the melt temperature is not indicated below 138°C . Calculated melt temperature in Fig. 6 shows fluctuating behavior during the injection because of the thermal interaction with water. The melt amount in the analysis was determined to have finished because of that injection almost of the melt as of 4.5s. Also in the experiment, melt injection time was determined because of that the measured temperature shows constant saturation temperature after approx 4.5 s. The analysis velocity showed that the water coolant didn't

flow into the lower area of the bottom plate and fluids mixing during fragmentation mainly occurs at the upper part of the plate (Fig. 8). In order to confirm overall heat balance in experiments, the measured temperature at the upper part of the plate (indicated “comparison point” in Fig. 8) is compared with analysis (Fig. 9). As shown in Fig. 9, the measured temperature initiate fluctuation at 1s and rise up to 45°C in the maximum at around 5s. The measured temperature gradually decrease and reached 35°C at 10s. The analysis temperature start to rise at 3s and reached the maximum value of 44°C around 6s, then decreasing in the same manner with experimental data. As the possible reason for the discrepancy of the timing, it is noteworthy that the analysis cell at the temperature measurement point has a rather large size with the cylindrical coordinates. However, general tendency of the temperature behavior shows reasonable agreements for the jet impingement transient.

In observation of the state of the solidified material remaining on the bottom plate in the experiment, the solidified material in the vicinity of 100 mm from the center of bottom plate wasn't ingot states but fragmented states. Further, comparing the temperatures at the points of $r=50$ mm and 100 mm on the bottom plate in experiment, the melt temperature was higher than the melting point at $r=50$ mm, but lower at the $r=100$ mm point as shown in Fig. 10. It means that the melt solidification by the fragmentation occurred the region between $r=50$ mm to 100 mm in radius. Figure 11 shows the analysis result which indicates the position of molten alloy's phases on the bottom plate at 2.0s. The blue colored region shows liquid phase of the molten metal, and the red colored region shows the solidified molten metal in analysis. The phase change position from liquid to solid corresponds between $r=50$ mm and 100mm. It means that the analysis has the capability for the prediction of the solidification position of the molten metal jet impingement to the pool bottom plate.

Fig. 7 Temperature behavior of melt

Fig. 8 Velocity vector of coolant in analysis

Fig. 9 Comparison of overall temperature in coolant

Fig. 10 Thermocouple of two points and melting point in the experiment

Fig. 11 Liquid and the solid components of the melt in the analysis

4.2.2 Pressure

Figure 12 shows the pressure fluctuation in the experiment and analysis without the plenum condition. Comparing these results, the tendency of the behavior such as the range of the maximum value/minimum value of the pressure pulse and the generation frequency of the pressure pulse almost coincided. As shown in Fig.12, since the pressure was measured in the horizontal direction with respect to the bottom plate, the pressure might be a moving force of the solidified particles to the radial direction.

Fig. 12 Comparison of pressure behavior

4.3 Experiment with plenum volume restriction

4.3.1 Experiment result

Depending on a SFR design, coolant volume in a lower inlet plenum might be limited by the plenum wall structures. Therefore, the experiment was performed with limited coolant region by installing a plenum volume restriction wall. Emura, et. al. 2017 conducted the melt discharge experiment in which a plenum volume restriction wall was installed. It was observed that vapor bubble development resulting from thermal interaction with water tends to be suppressed by installing a restriction wall (Emura, et. al. 2017). Figure 13 shows the high-speed camera photo for the state of the melt injection during the experiment and the measured dispersion velocity from the photo. As shown in Fig. 13 (1), if there are no plenum wall, the water pool surface level is strongly fluctuated by the intense vapor generation. In the case of the system with plenum wall in Fig. 13 (2), the liquid level fluctuation is rather suppressed.

Figure 14 shows the pressure behavior during the melt injection in the experiment. the peak values of the pressure pulses in the system with the plenum wall were rather higher than the pressure without a plenum wall cases. The reason

might be the constraint effect of the coolant on the bottom plate. The pressure pulse should be increased in a small room.

Fig. 13 Status of the molten alloy dispersion

Fig.14 Pressure during the melt injection in the experiments

4.3.2 Analysis result of temperature

Figure 15 shows the temperature comparison on the bottom plate center ($r=0$ mm) below the nozzle in the experiment and analysis. From the analysis result, injection start time and injection end time of the melt almost coincided in comparison with the experiment. The integrated melt injection mass reached approx. 48 kg at 10 seconds. Calculated melt temperature in Fig. 15 shows fluctuating behavior during the injection because of the thermal interaction with water. On the other hand, in the experimental result, fluctuating behavior of temperature was not indicated because the interaction between melt-coolant was suppressed on the bottom plate central by limiting coolant volume by the plenum wall. In the analysis, the temperature inside the cell was calculated, against in the experiment, the temperature of material that contact with the thermocouple was measured. There in the experiment, the temperature fluctuation was not confirmed because of that the thermocouple was covered with the melt during the melt injection.

In order to confirm overall heat balance in experiments, the measured temperature at the upper part of the plate (indicated “comparison point” in Fig. 8) is compared with analysis (Fig. 16). As shown in Fig. 16, the experimental and analysis results indicated almost the same behavior. In addition, temperature at the system with plenum wall during the melt injection was higher than temperature at the system without plenum wall.

Fig. 15 Temperature behavior of melt

Fig. 16 Comparison of overall temperature during the melt injection in coolant

4.3.3 Analysis result of pressure

Figure 17 shows pressure fluctuation during the melt injection in experiment and analysis. Comparing these results, the tendency of the behavior such as the pressure range and the generation frequency of the pressure pulse between 1~2 seconds almost coincided. In the experiment, the pressure increased gradually after 2 seconds. This phenomenon was probably caused by variation in output signal of the pressure gauge due to change in its ambient temperature, so called temperature drift.

Fig.17 Comparison of pressure behavior

5. Conclusions

In this study, in order to make clear behavior of core melt materials during the material-relocation phase of CDA of SFRs, analysis was conducted using the SIMMER-III code for a melt discharge simulation experiment in which low-melting-point alloy was discharged into a shallow water pool.

Comparison was made for the experimental data to validate the analysis model for the melt fragmentation phenomena enhanced by the melt jet impingement to the bottom plate of the inlet coolant plenum below the core. As a result, followings are obtained as conclusion.

- The analysis cell model which prepared for the discharge experiment was successfully able to simulate the melt injection by gravity to the shallow water pool.

- The analysis temperature shows a similar fluctuating behavior with experiment during the fragmentation because of the thermal interaction with water.

- The integrated melt injection mass in calculation reached approx. the same value with the experiment value.

- The overall heat balance was confirmed by the transient temperature comparison at the upper part of the plenum. It showed reasonably good agreement with experiment.

- The melt solidification by the fragmentation occurred the region between $r=50$ mm to 100 mm in radius in experiment. Analysis results for the phase change from liquid to solid showed the same tendency with the experiment.

- The measured peak values and the frequency of pressure pulses by thermal-interaction caused of the fragmentation could be predicted with reasonably good agreements.

- In case for the limited plenum volume, the intense liquid level fluctuation with the vapor generation was suppressed by the wall, but the dispersion velocity seems to be increased because of the acceleration by a narrow cross section area to flow out from the plenum restriction wall.

As mentioned above, the overall temperature behavior and the pressure behavior almost coincided between the analysis and the experiment. Therefore, it can be concluded that the validity of the analysis system model was confirmed. In the future study, the behavior of molten core material during relocation process will be clarified through the analysis using the validated analysis model.

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