Fundamental experiment on the distance for fragmentation of molten core material during core disruptive accidents in sodium-cooled fast reactors

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Abstract: In a probable scenario for core disruptive accidents (CDAs) of sodium-cooled fast reactors, massive molten core material will be discharged into the lower sodium plenum through the control rod guide tubes and might impose a considerable thermal burden on the lower structures. Nevertheless, such thermal burden will be reduced, provided that the discharged molten core material is fragmented into small particles well before reaching the lower structures. In the present study, in order to develop an evaluation method of the distance for fragmentation of molten core material discharged into the sodium plenum, fundamental experiments were carried out using a high-density melt (an alloy with low-melting temperature) and water as simulants for the molten fuel and coolant, respectively. In the experiments, the melt was discharged into a water pool through a nozzle (inner diameter: from 30 mm to 150 mm) under a simulated CDA condition in which formation of a stable vapor film is inhibited around the melt surface and thus a liquid-liquid direct contact is maintained between the melt and water. The present experimental results showed that measured distances for fragmentation of the injected melt were limited to approximately 10 percent of predictions by the existing representative correlation, and that vapor expansion with pressure buildup in the vicinity of the melt could facilitate the reduction of the distance for fragmentation. Through the fundamental experiments, useful knowledge were obtained for the future development of an evaluation method of the distance for fragmentation of molten core material.

Keyword: sodium-cooled fast reactor; core disruptive accident; molten core material; fragmentation

1 Introduction

Sodium-cooled Fast Reactors (SFRs) have an advantage in the high thermal efficiency and the large safety margin with the high coolant-boiling temperature, which does not necessitate significant pressurization to prevent coolant boiling under the operating condition. However, once an occurrence of Core Disruptive Accident (CDA) is assumed, it may cause significant mechanical and thermal impacts which may degrade the integrity of the reactor vessel. In order to enhance the safety characteristics of SFRs, it is important to prevent the occurrence of CDAs and, in case one does occur, to mitigate any consequences and thus contain the impacts within the reactor vessel.

In a probable scenario for CDAs, massive molten core material can be discharged into the lower sodium plenum through the control rod guide tubes[1].

Figure 1 shows a schematic of core material relocation during CDAs.
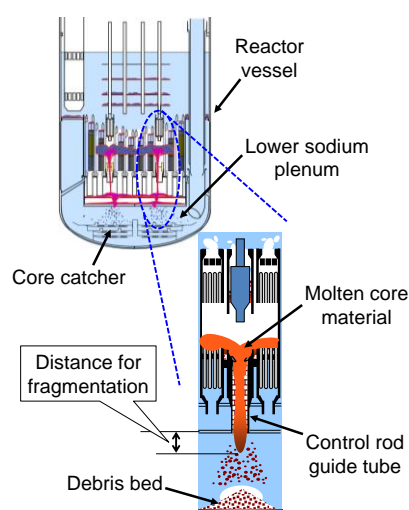

Fig. 1 Schematic of core material relocation during CDAs.

One of the most important mitigation measures against CDAs is to cool the discharged molten core material stably and thus retain the core material

within the reactor vessel. This concept is called "In-Vessel Retention" (IVR). The discharged molten core material may seem to impose a considerable thermal burden on the lower structures such as a core catcher. Nevertheless, if the discharged molten core is fragmented into small particles well before reaching the lower structures, it will be easier to attain IVR by efficient quenching of molten core material and decay heat removal from the quenched core material. Thus, it is essential to evaluate the distance for fragmentation of molten core material discharged into the lower sodium plenum.

The objective of the present study is to develop an evaluation method for the distance for fragmentation of molten core material discharged into the sodium plenum. In general, the distance for fragmentation is referred to as "breakup length". It is considered as a length in which an initially coherent stream of molten material disappears due to the breakup of the stream. In the past, some semi-empirical correlations have been developed to evaluate breakup length of molten materials in liquids such as water, based on experimental data and theoretical considerations on the breakup of a molten material blanketed by the thick vapor of an ambient liquid [2-[3]]. These existing correlations have assumed fragmentation induced by hydrodynamic instabilities as a dominant mechanism that determines the breakup length. In contrast, as shown in Fig. 2, it is unlikely that the molten core material can be blanketed by sodium vapor under CDA conditions, since sodium has good thermal properties which inhibit the formation of stable vapor film and thus a liquid-liquid direct contact will be maintained between molten material and sodium. [4]Besides, it has been noted that deep penetration of molten core material will be limited in a sodium environment due to thermal interactions resulting from the liquid-liquid direct contact [4]. Actually, several experiments and theoretical models on the fragmentation behavior of molten material in sodium have been reported [5-8]. Nevertheless, it is believed that there are few quantitative and well-organized experimental knowledge on the distance for fragmentation under the conditions where a liquid-liquid direct contact is maintained between molten material and coolant. In particular, effects of thermal interactions resulting from the liquid-liquid

direct contact have been less studied in terms of evaluation of the distance for fragmentation.
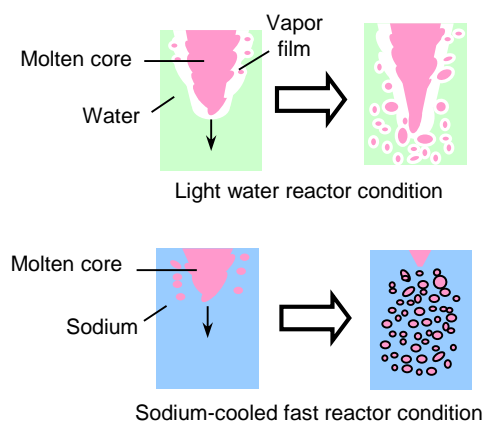

Fig. 2 Schematics of fragmentation behaviors.

In light of the background mentioned above, fundamental experiments using a high-density melt and water as simulants for the molten core material and coolant (sodium), respectively, were conducted to obtain experimental knowledge on the distance for fragmentation under a simulated CDA condition where formation of a stable vapor film is inhibited around the melt surface and thus a liquid-liquid direct contact is maintained between the melt and water.

2 Experimental procedure and experimental conditions

It is assumed that the density ratio between molten material and coolant is one of dominant parameters that affect the distance for fragmentation [3]. In the fundamental experiments, an alloy with low-melting temperature (melting point: 352 K, density: approximately 8 g/cm^3) was employed as a simulant for molten core material, since the density ratio between the alloy and water is similar to that between molten oxide fuel and sodium. The material combination of the alloy and water is also intended to enable visual observation, which is beneficial to understanding of the mechanism for fragmentation. Liquid-liquid direct contact was achieved by controlling temperature combination between the molten alloy (melt) and water within an appropriate range, based on the existing knowledge on molten fuel-coolant thermal interaction[4]. Specifically, temperatures of the melt and water were 623 K and 303 K, respectively, in the fundamental experiments.

As shown in Fig. 3, the experimental apparatus mainly consists of a crucible, a nozzle (inner diameter: from 30 mm to 150 mm) and a water pool (depth: 1.4 m, width: 1.0 m, length: 1.0 m). The melt (maximum mass: 400 kg) was generated in the crucible by using sheathed heaters wrapped around the crucible and then discharged into the water pool through the nozzle by withdrawing the plug. Flow rate of the discharged melt was measured by a flow meter (recording rate: 24 kHz) installed on the nozzle. Thermocouples (recording rate: 1 kHz) were installed on the central axis of the nozzle to measure temperature distribution along a column of melt in the water pool. Pressure sensors (recording rate: 24 kHz) were installed in the water pool to measure pressure changes associated with fragmentation of the melt. A high-speed camera (frame rate: 10,000 frames per second) was used to observe fragmentation behavior of the melt.
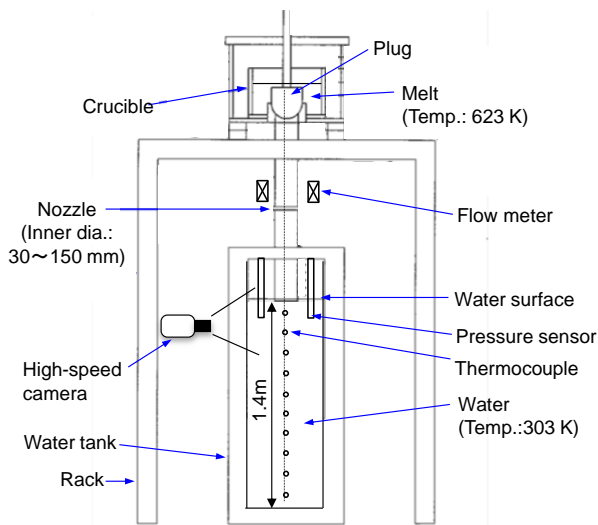

Fig. 3 Schematic of the experimental apparatus for fundamental experiments.

3 Experimental results and discussion

Figure 4 shows an example of fragmentation behavior observed in the fundamental experiments. As shown in Fig. 4, formation of vapor film that blankets the melt column was not observed in the fundamental experiments. Nevertheless, pictures from 0.0 ms to 8.0 ms display expansion of a vapor bubble generated in the vicinity of a lateral surface of the melt column. The following pictures display condensation of the vapor bubble (12.0, 14.0, 16.0 ms) and generation of fine fragment (18.0, 20.0 ms).

The observed behavior suggests that initially vapor expansion with pressure buildup fragmented a part of the melt column and then the fragmented melt particles quickly spread into the ambient water. It is believed that the vapor expansion resulted from thermal interaction in a liquid-liquid direct contact between the melt and water.
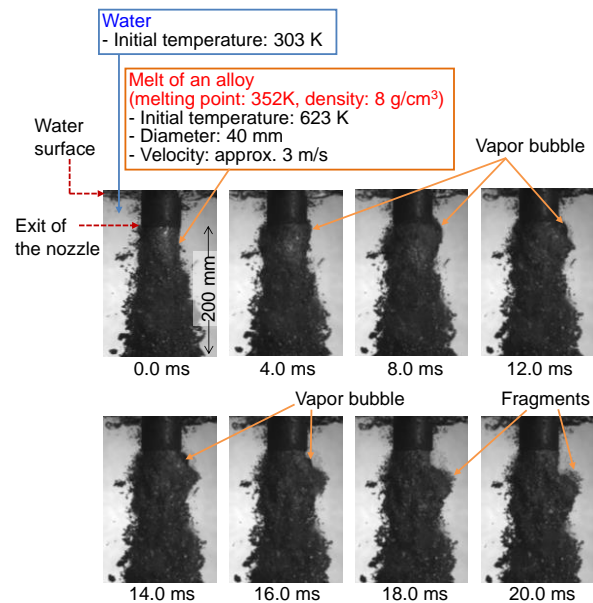

Fig. 4 Example of fragmentation behavior observed in the fundamental experiments.

Figure 5 shows an example of temperature and pressure in the water pool. It is believed that a lot of pressure spikes were associated with the growth and condensation of vapor bubbles. The measured temperatures shows that the temperatures at deeper positions (150, 250, 350, 850 mm) were rather lower than the initial melt temperature, while the temperature near the exit of the nozzle (50 mm) increased sharply immediately after the start of melt discharge and reached the initial melt temperature through most of the discharge duration. These temperature responses suggest that the melt column broke up due to intensive fragmentation at the early stage of the penetration and thus could not reach deeper positions.

Figure 6 shows examples of axial temperature distribution on the central axis of the melt column. These temperature distributions were obtained by plotting the maximum reached temperature at a depth against the distance from the exit of the nozzle. As can be seen clearly from Fig. 6, the temperature distributions reveal a sharp temperature decrease at a

certain distance. It is believed that the sharp temperature decrease resulted from a rapid increase of cooling area due to intensive fragmentation of the melt, while the temperature plateau near the exit of the nozzle indicates that a coherent molten column still sustains. Based on such translation, a distance for fragmentation was estimated from a cooling curve shown in Fig. 6. Actually, a distance up to a depth at which a rapid temperature decrease is initiated was defined as a distance for fragmentation.
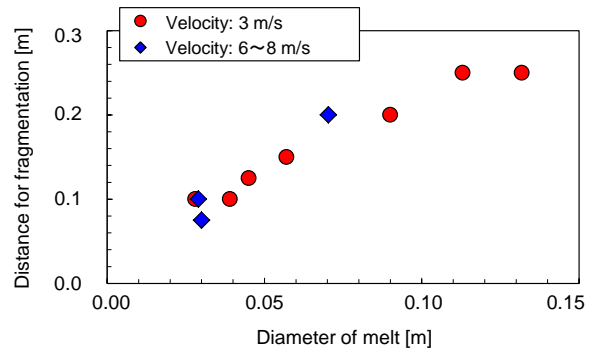
Fig. 7 Measurement results of distance for fragmentation.

Figure 7 shows measurement results of distance for fragmentation. Distance for fragmentation increased with the increase of the discharge diameter of melt. It is assumed that the increase of the discharge diameter and/or velocity enhances the inertial force of the melt against the resistance forces such as the buoyancy force and thus makes possible for the melt to penetrate more deeply [3]. The diameter dependency observed in the fundamental experiments is consistent with the existing assumption. In contrast, obvious velocity-dependency was not observed in the fundamental experiments. These results suggest that more intensive fragmentation might occur in the higher velocity conditions and thereby cancel out the enhanced inertial-force of the melt. The intensive fragmentation may be associated with hydrodynamic instabilities between the melt and ambient fluid in a liquid-liquid direct contact. Epstein *et al*. have proposed a theoretical model to describe fragmentation behavior in liquid-liquid system [8]. This model is assuming that entrainment rate of melt droplets into an ambient fluid is proportional to the velocity difference between the melt and ambient fluid, thereby canceling out the influence of the melt velocity on the distance for fragmentation. Nevertheless, based on the fragmentation behavior shown in Fig. 4, thermodynamics such as vapor expansion with pressure buildup resulting from thermal interaction might contribute to the intensive fragmentation that cancels out the influence of the melt velocity. Sugiyama et al. have proposed thermal fragmentation induced by the boiling of liquid coolant locally entrapped inside the melt column [9]. The proposed fragmentation mechanism is assuming that liquid coolant is entrapped inside the melt column as hydrodynamic instabilities grow at the contact interface between the melt and ambient liquid
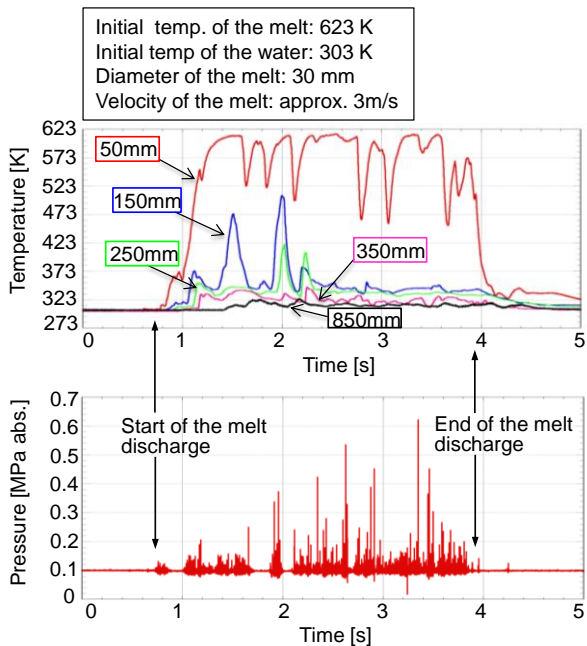

Fig. 5 Example of temperature and pressure in the water pool (The distances in the upper graph denote the distance from the exit of the nozzle to a temperature measuring junction.).
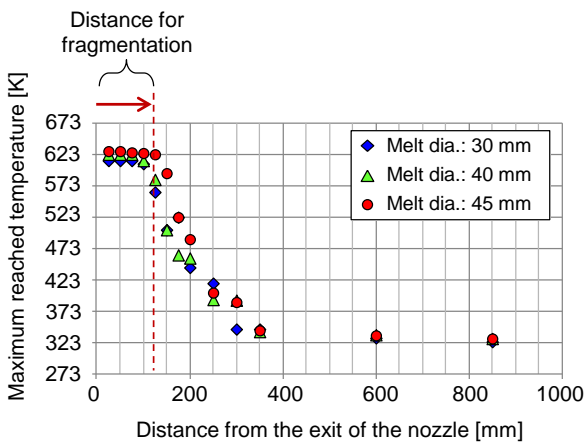

Fig. 6 Examples of axial temperature distributions on the central axis of the melt column.

coolant. In light of the proposed mechanism, it is possible that vigorous growth of hydrodynamic instabilities could enhance the local entrapment of coolant inside the melt in higher velocity conditions and thereby cause more intensive fragmentation that cancels out the influence of the melt velocity on the distance for fragmentation. The above discussion includes a hypothesis for now. Further studies should be conducted to describe the diameter and velocity dependency of the distance for fragmentation observed in the fundamental experiments.

Finally, in order to clarify effects of fragmentation resulting from the liquid-liquid direct contact on the distance for fragmentation, a comparison was conducted between measured distances for fragmentation and the predictions by the existing representative correlation. The correlation used for this comparison is expressed as [3]:

$$\frac{L}{D} = 2.1 \left(\frac{\rho_m}{\rho_c} \right)^{0.5} Fr^{0.5} \qquad (1)$$

Equation (1) was derived based on the model in which the balance between the inertial force and the resistance forces such as the buoyancy force dominates the breakup length (distance for fragmentation) of the column of molten material. The coefficient of the right side of Eq. (1) was determined by the experiments where water jets were injected into a freon-11 pool or a liquid nitrogen pool. Equation (1) has been often quoted, since it well predicts the breakup lengths of very heavy jets penetrating a light fluid. As shown in Fig. 8, the experimental values of L/D were limited to approximately 10 percent of the predicted values. In other words, the melt was fragmented within a quite shorter distance than the predicted distance by the existing correlation. As shown in Fig. 4, pressure buildup in the vicinity of the melt might facilitate the fragmentation, while the existing correlation is assuming that the melt penetrates coolant with blanketed by stable vapor film that inhibits the liquid-liquid direct contact. Therefore, it is believed that the large difference between the measured values and predictions is attributed to the fact that the existing correlation does not take into account thermal fragmentation resulting from the liquid-liquid direct contact. Based on the present experimental

results, it is concluded that distance for fragmentation can be facilitated due to vapor pressure buildup associated with thermal interaction and thus considerably limited against the increase of discharge diameter and velocity under the conditions where a liquid-liquid direct contact is maintained between the melt and coolant.
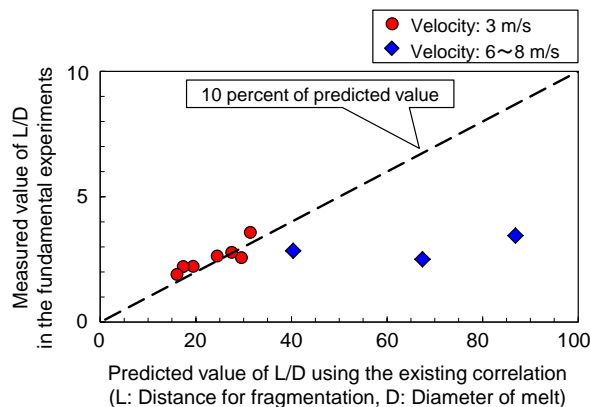

Fig. 8 Comparison between measured distances for fragmentation and the predictions by the existing representative correlation.

4 Conclusion

In order to develop an evaluation method of the distance for fragmentation of molten core material discharged into the sodium plenum, fundamental experiments were carried out using a high-density melt (an alloy with low-melting temperature) and water as simulants for the molten fuel and coolant, respectively. In the experiments, the melt was discharged into a water pool through a nozzle (inner diameter: from 30 mm to 150 mm) under a simulated CDA condition in which formation of a stable vapor film is inhibited around the melt surface and thus a liquid-liquid direct contact is maintained between the melt and water. The present experimental results showed that measured distances for fragmentation of the injected melt were limited to approximately 10 percent of predictions by the existing representative correlation, and that vapor expansion with pressure buildup in the vicinity of the melt could facilitate the reduction of the distance for fragmentation. Through the fundamental experiments, useful knowledge was obtained for the future development of an evaluation method of the distance for fragmentation of molten core material.

Nomenclature

L — Distance for fragmentation [m]

D — Diameter of melt [m]

Fr — Froude number [-]

(Greek symbols)

ρ — Density [kg/m^3]

(Subscripts)

m — Melt

c — Coolant

Acknowledgement

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