Experimental discussion on fragmentation mechanism of molten oxide discharged into a sodium pool


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Abstract
In a probable scenario for core disruptive accidents of Sodium-cooled Fast Reactors (SFRs), it is foreseen that molten core material would be discharged into lower sodium plenums through control rod guide tubes. Such material relocation might lead to a considerable thermal load on lower structures of the reactor vessels, while it has been suggested that in SFRs, as soon as the molten core material is discharged into coolant, it might be fragmented into smaller particles by fuel-coolant interactions and thus efficiently cooled in the reactor vessels. Hence, understanding of the fragmentation is crucial for achieving in-vessel retention of molten core material in SFRs. In this paper, based on the experimental results of a series of fragmentation tests, where around 10 kg of molten alumina (Al₂O₃) was discharged into a sodium pool (depth: 1.3 m, diameter: 0.4 m, temperature: 673 K) through a duct (inner diameter: 40mm to 63 mm) by using an experimental facility at National Nuclear Center of the Republic of Kazakhstan, dominant mechanisms for the fragmentation are discussed. In the present tests, mass median diameters of solidified Al₂O₃ particles were around 0.3 mm, which were comparable to the values predicted using conventional hydrodynamic-instability theories. However, even though the conventional theories predict that particle size becomes smaller with the increase of Weber number, such tendency was not observed in the present tests. Taking into account that in the present tests, the distances for fragmentation of molten Al₂O₃ were evaluated to be approximately 60 % to 70 % below the values predicted using an existing representative correlation which regards hydrodynamic instabilities as a dominant fragmentation mechanism, the observed independence on Weber number confirms a mechanism that before hydrodynamic instabilities sufficiently grow to induce fragmentation, thermal phenomena such as local coolant vaporization and resultant vapor expansion significantly accelerate fragmentation in SFRs.

Key words : Sodium-cooled fast reactors, Core disruptive accidents, In-vessel retention, Molten core material, Fragmentation

1. Introduction

Core Disruptive Accident (CDA) has been addressed as a major issue for the safety of Sodium-cooled Fast Reactors (SFRs) because due to the use of fast neutron and the nuclear characteristics of SFR core that the core material is not in its maximum reactivity configuration, coolant boiling and dynamic core-material relocation have potential for the insertion of positive reactivity. In a probable scenario for CDAs, it is considered that control rod guide tubes would become effective paths to discharge a large amount of molten core material into the lower sodium plenum of the reactor vessel (Suzuki et al., 2014). Although such discharge of core material would reduce the core reactivity substantially, it might also impose a significant thermal load on the lower structure in the reactor vessel, thus compromising the in-vessel retention (IVR) of molten core material. However, if the molten core material is fragmented into smaller particles well before it reaches the lower structure, the thermal load should be significantly reduced by enhanced quenching of the core
material. Hence, the fragmentation of molten core material is crucial for achieving IVR.

The purpose of this study is to develop a method to evaluate the fragmentation behavior of molten core material, including the distance for fragmentation (so-called jet-penetration length or jet-breakup length), under sodium-cooled conditions. As shown in Fig. 1, it is believed that a liquid-liquid direct contact mode would be maintained between the molten core material (oxide fuel) and sodium under the probable CDA condition because sodium has good thermal properties which inhibit the formation of stable vapor film (Kondo et al., 1995). Moreover, it has been pointed out that such the direct contact mode would lead to thermal interactions such as local coolant-vaporization that probably limit the jet-breakup length (Kondo et al., 1995). However, in the usual existing studies on the jet-breakup length, it has been assumed that the molten material penetrates into coolant with blanketed by the thick vapor of an ambient liquid and breaks up due to the fragmentation induced by hydrodynamic instabilities on the molten material, which means that such the hydrodynamic instabilities have been considered as a dominant mechanism to determine the jet-breakup length (Spencer et al., 1986), (Saito et al., 1988).

In this study, to obtain experimental knowledge on the fragmentation behavior of molten core material in the sodium-cooled conditions, a series of fragmentation tests (FR tests) has been conducted, where around 10 kg of molten oxide (namely, molten alumina) was discharged into a sodium pool using an out-pile experimental facility in National Nuclear Center of the Republic of Kazakhstan (Konishi et al., 2007), (Kamiyama et al., 2014). The previous paper of this study (Matsuba et al., 2012) reported that in the FR tests, the measured values of the distance for fragmentation were evaluated to be approximately 60% to 70% below the values predicted using an existing representative correlation (Saito et al., 1988) and such significant decrease might have been caused by the effect of thermal interactions. In this present paper, the particle size distribution of alumina debris obtained in the FR tests was analyzed and dominant mechanisms for the fragmentation of molten core material discharged into sodium are discussed.

![Fig. 1 Assumed fragmentation behavior of molten core material. It is believed that in LWR condition, molten core material penetrates into water with blanketed by a stable vapor film, while in SFR condition, a liquid-liquid direct contact mode would be maintained without such stable vapor film between molten core material and sodium.](image)

2. Experimental procedure and conditions

Figure 2 shows a schematic of the test section and an example of measurement layout in the FR tests. The test section consists of a discharge duct (inner diameter: 40 mm to 63 mm) and a sodium pool (depth: 1.3 m, inner diameter: 0.4 m). Molten core simulant is generated using an electromagnetic induction heating system and discharged into the sodium pool through the discharge duct. To avoid the entrainment of the cover gas (argon gas) into the sodium pool during the discharge, the vessel is fully filled with sodium. The free surface of sodium pool is established inside the sodium buffer tank connected to the lateral side of the vessel.

In the FR tests, molten alumina (Al₂O₃) was employed for the simulant for molten oxide fuel, in consideration of their similarity in the heat transfer characteristics. As mentioned in the introduction, it is believed that a liquid-liquid direct contact mode would be established between the molten core material and sodium under the probable CDA condition. The existing investigation showed that such the direct contact condition should be established with the combination of molten Al₂O₃ and sodium by adopting appropriate temperature conditions (Kamiyama et al., 2005).
Moreover, the heating ability of molten alumina is comparable to the molten oxide fuel even at a low degree of superheat around its melting point (approximately 2300 K), since molten Al₂O₃ has a higher heat capacity and latent heat of solidification than molten oxide fuel (Kamiyama et al., 2005). Therefore, it is believed that the employment of molten Al₂O₃ is reasonable.

The penetration of molten Al₂O₃ in the sodium was detected using fine steel wires installed at several different depths. To catch the stream of molten Al₂O₃, a pair of steel wires at each depth was crossed on the central axis of the discharge duct. If the stream of molten Al₂O₃ reaches the steel wires, it should rupture the wires by its heat. On the other hand, if the stream breaks up before it reaches the steel wires, the wires should remain intact. Thus, the installation of steel wires enables the measurement of the distance for fragmentation of molten Al₂O₃. A steel plate was also installed to check the erosion potential of molten Al₂O₃ at the position of the plate.

The experimental conditions are summarized in Table 1. Discharge of molten Al₂O₃ was started immediately after the reading of an infrared thermometer in the induction heating system reached 2473 K. The initial temperature and the initial pressure of sodium were 673 K and 0.35 MPa (abs.), respectively, which corresponded to the condition in lower sodium plenum of typical SFRs. In consideration of the limitation in the size of experimental facility, discharge diameter of molten Al₂O₃ was limited within from 40 mm to 63 mm, however, which was comparable to the diameter of the entrance nozzles of control rod guide tubes. The discharge pressure (back-pressure) of molten Al₂O₃ was pressurized at 0.47 MPa to 0.73 MPa. FR-1, FR-2 and FR-3 were low discharge-pressure cases, where the initial discharge velocity (i.e., initial penetration velocity into sodium) of molten Al₂O₃ was estimated at around 6 m/s. FR-4 and FR-5 were high discharge-pressure cases, where the initial discharge velocity was estimated at around 9 m/s. After the previous paper (Matsuba et al., 2012) was presented, to improve the reliability of the experimental results, FR-6 test was conducted as the retrial of FR-1. In these tests, approximately 10 kg of molten Al₂O₃ was discharged into the sodium. Post-test examinations of Al₂O₃ debris were conducted after the tests.

### Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Test number</th>
<th>FR-1</th>
<th>FR-2</th>
<th>FR-3</th>
<th>FR-4</th>
<th>FR-5</th>
<th>FR-6</th>
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<td>2473</td>
<td>2473</td>
<td>2473</td>
<td>2473</td>
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<tr>
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<tr>
<td>Inner diameter of discharge duct, mm</td>
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<td>50</td>
<td>50</td>
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<tr>
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<td>0.47</td>
<td>0.51</td>
<td>0.65</td>
<td>0.73</td>
<td>0.51</td>
</tr>
<tr>
<td>Sodium pressure, MPa (abs.)</td>
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<td>0.35</td>
<td>0.35</td>
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<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Fig. 2 Schematic of the test section and an example of measurement layout
3. Analyses of debris size distribution

In the FR tests, the molten Al2O3 formed porous debris in the sodium. Figure 3 shows a typical example of Al2O3 debris that accumulated in the melt catcher. Fine particles with a diameter less than 1 mm accounted for a large portion of the debris. Their shapes were sharp and spiky. In general, it is considered that formation of such porous debris would be caused by thermal interactions between the hot melt and coolant.

Figure 4 shows particle size distributions of Al2O3 debris that accumulated in the melt catcher. Except for FR-5, these particle size distributions were almost same in shape, and these curves could be closely related to Rosin-Rammler distribution. The curve of FR-5 test was quite different from the other tests in the range of particle size greater than about 1 mm. However, the curve in the range less than about 1 mm was similar to the other tests, and it was confirmed that Rosin-Rammler distribution could be applied to this range as well. A potential reason for this unique curve of FR-5 test might be attributed to the structural nature of the experimental device rather than the nature of fragmentation, which means that due to relatively high discharge-pressure, solidified Al2O3 adhering to the inner surface of upper structures (e.g., the crucible above the sodium pool) incidentally peeled away and dropped into the sodium pool.

Fig. 3 Typical example of Al2O3 debris accumulated in the melt catcher (FR-3 test). Fine particles with a diameter less than 1 mm accounted for a large portion of the debris. Their shapes were sharp and spiky.

Fig. 4 Particle size distribution of Al2O3 debris. Except for FR-5, these particle size distributions were almost same in shape.
Figure 5 shows a comparison of mass median diameter, which was determined from the particle size distributions of Al$_2$O$_3$ debris shown in Fig. 4. The values of mass median diameter were around 0.4 mm. These values are comparable to mass median diameters obtained in existing experimental studies such as THINA experiment (Huber et al., 1990) and FARO-TERMOS (Magallon et al., 1992) experiment, where about 5 kg of molten thermite mixture (namely, Al$_2$O$_3$ and iron) or about 100 kg of molten uranium oxide (UO$_2$) discharged into sodium, respectively. Thus, the size of Al$_2$O$_3$ debris obtained in the FR tests is not extraordinary compared to the results of the existing experimental studies using molten oxide. However, based on the principle of typical hydrodynamic instabilities such as Kelvin-Helmholtz instability and Rayleigh-Taylor instability, mass medium diameter should become smaller with the increase of the discharge velocity, while such tendency was not observed in the FR tests.

Figure 6 shows a comparison between the measured particle size and the predicted size using hydrodynamic instability theories. In this comparison, the Kelvin-Helmholtz instability model and the Rayleigh-Taylor instability model are used as typical hydrodynamic fragmentation models to predict the particle size. To make the comparison easier, the particle size is represented by the dimensionless mass median diameter, namely, mass median diameter normalized by the discharge diameter of molten Al$_2$O$_3$.

In the Kelvin-Helmholtz instability model, the minimum unstable wavelength is given by the following equation:

$$\lambda_{KH} = 2\pi D_j (1 + \frac{\rho_a}{\rho_w}) We^{-1.0}$$

$$We = \frac{\rho_w v^2 D_j}{\sigma_w}$$

Assuming the particle size ($D_m$) is equal to half of the minimum unstable-wavelength ($\lambda_{KH}/2$), the dimensionless mass median diameter is expressed as follows:

$$\frac{D_m}{D_j} = \pi (1 + \frac{\rho_a}{\rho_w}) We^{-1.0}$$

In the Rayleigh-Taylor instability model, the unstable wavelength with the fastest growth rate is given by the following equation:

$$\lambda_{RT} = \frac{4\pi}{\sqrt{3}} D_j (C We)^{-0.5}$$
Assuming $D_m = \lambda_{RT}/2$, the dimensionless mass median diameter is expressed as follows:

$$\frac{D_m}{D_j} = \frac{2\pi}{\sqrt[3]{3}}(C_d We)^{-1/3}$$

(5)

where the drag coefficient ($C_d$) was assumed to be 2.5 (Patel and Theofanous, 1981), (Nishimura et al., 2010).

As can be seen from Fig. 6, the measured mass median diameters of Al$_2$O$_3$ debris were comparable to the particle size predicted using typical hydrodynamic fragmentation models. However, even though the hydrodynamic fragmentation models predict that the particle size decreases with the increase of the Weber number, such the dependence of particle size on Weber number was not observed in the FR tests.

Fig. 6 Comparison between the measured particle sizes and the predicted size using hydrodynamic instability theories

4. Discussion on the fragmentation mechanism

According to existing studies where a molten copper jet or a molten stainless steel droplet was discharged into a sodium pool (Nishimura et al., 2010), (Zhang et al., 2010), it is considered that when the instantaneous contact interface temperature between the melt and coolant is below the freezing point of the melt, the fragmentation induced by the Rayleigh-Taylor instability at the jet leading edge is more dominant than the fragmentation by the Kelvin-Helmholtz instability at the lateral side of the jet under relatively high We number conditions ($We > 200$). It is suggested that such the fragmentation behavior is caused by a hydrodynamic mechanism where even though the surface layer of the jet is frozen, the following jet column with a large inertial force due to the high jet-velocity penetrates the downward decelerated leading edge and thereby successively supplies the hot melt that can suffer the fragmentation by the Rayleigh-Taylor instability (Nishimura et al., 2010), (Zhang et al., 2010). However, as shown in Fig. 6, the observed tendency in the FR tests was not consistent with the tendency predicted using the Rayleigh-Taylor instability model as well as the Kelvin-Helmholtz instability model. Therefore, it is believed that the current experimental results of the FR tests imply that in addition to the hydrodynamic mechanism related to the Rayleigh-Taylor instability, other mechanisms might have been involved in the fragmentation of molten Al$_2$O$_3$.

As reported in the previous paper of this study (Matsuba et al., 2012), in the FR test, the measured distances for fragmentation of molten Al$_2$O$_3$ were evaluated to be approximately 60% to 70% below the values predicted using an existing representative correlation which regards hydrodynamic instabilities as a dominant fragmentation mechanism (see Fig. 7). Here, the correlation used for this comparison is expressed as follows (Saito et al., 1988):

$$\frac{L}{D_j} = 2.1\left(\frac{\rho_m}{\rho_j}\right)^{0.5}\left(\frac{v^2}{gD_j}\right)^{0.5}$$

(6)

This correlation are assuming that the melt jet penetrates into coolant with blanketed by stable vapor film and breaks up due to hydrodynamic instabilities, which means that thermal fragmentation is not considered in this correlation. Therefore, it is believed that the significant reduction of the distance for fragmentation observed in the FR tests suggests
that as with a series of fundamental experiments (Matsuba et al., 2013), thermal fragmentation induced by local intensive coolant-vaporization enhanced the fragmentation of molten Al₂O₃ and thus reduced the distance for fragmentation. Taking into account such significant reduction of the distance for fragmentation, the observed tendency of mass median diameters shown in Fig. 6, namely, independence on the Weber number also confirms a mechanism that before hydrodynamic instabilities sufficiently grow to induce fragmentation, thermal phenomena such as local coolant vaporization and resultant vapor expansion significantly accelerate fragmentation. Through the current experiment, useful knowledge was obtained for the future development of an evaluation method of the distance for fragmentation of molten core material.

Fig. 7 Comparison between the measured distance for fragmentation and the predicted value using the existing representative correlation (Matsuba et al., 2012). The measured distances for fragmentation of molten Al₂O₃ were evaluated to be approximately 60% to 70% below the values predicted using an existing representative correlation (Saito et al., 1988) that regards hydrodynamic instabilities as a dominant fragmentation mechanism.

5. Conclusions

To develop a method for evaluating the distance for fragmentation of molten core material discharged into sodium, the particle size distribution of Al₂O₃ debris obtained in the FR tests was analyzed. The mass median diameters of solidified Al₂O₃ particles were around 0.3 mm, which was comparable to particle sizes predicted by hydrodynamic instability theories such as Kelvin-Helmholtz instability. However, even though hydrodynamic instability theories predict that particle size decreases with an increase of Weber number, such dependence of particle size on Weber number was not observed in the FR tests. Taking into account the fact that in the FR tests, the distances for fragmentation of molten alumina were evaluated to be approximately 60% to 70% below the values predicted using an existing representative correlation which regards hydrodynamic instabilities as a dominant fragmentation mechanism, the observed tendency of mass median diameters, namely, independence on Weber number confirms a mechanism that before hydrodynamic instabilities sufficiently grow to induce fragmentation, thermal phenomena such as local coolant vaporization and resultant vapor expansion significantly accelerate fragmentation.

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Nomenclature

\[ C_d \] draft coefficient [-]
\[ D_j \] discharge diameter of molten alumina [m]
\[ D_m \] mass median diameter [m]
\( g \) gravitational acceleration \([\text{m}^2/\text{s}^2]\)
\( L \) distance for fragmentation \([\text{m}]\)
\( v \) discharge velocity of molten alumina \([\text{m/s}]\)
\( We \) Weber number \([-\text{]}\)
\( \lambda_{KH} \) minimum unstable-wavelength in Kelvin-Helmholtz instability theory \([\text{m}]\)
\( \lambda_{RT} \) wavelength with the fastest growth rate \([\text{m}]\)
\( \rho_c \) density of coolant \([\text{kg/m}^3]\)
\( \rho_m \) density of melt \([\text{kg/m}^3]\)

References


