Effect of Froude number on melt jet breakup length with low melting point metal alloy in free falling condition

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1. Introduction

Investigation of the safety of the Nuclear Power Plants (NPPs) with the severe accident should include various scenarios to ensure the effectiveness of accident management strategies. For the wet cavity strategy adapted to some of NPPs in Korea, the water pool exists under the Reactor Pressure Vessel (RPV) to cool down the molten core materials (corium) effectively.

If the RPV fails due to the thermo-mechanical stress, the molten core can be ejected in the form of a jet interacting with the coolant in the cavity. Through undergoing the Fuel-Coolant Interaction (FCI), the molten corium becomes particulate debris and it settles down on the basemat of the reactor cavity in the form of a porous debris bed[1,2]. The debris bed coolability has an influence on the occurrence of the molten core concrete interaction (MCCI), which may threaten the containment integrity. The relation between the melt jet breakup and the coolability was studied by Moriyama et al.[3,4] reporting a relationship between the jet breakup length and the liquid melt fraction in the debris bed by a numerical simulation using JASMINE code. The importance of the jet breakup length on the overall debris bed coolability was confirmed again by Hwang et al. (2018) by the numerical simulation with COOLAP-I code. Thus, the estimation of the jet breakup length in the reactor scale is the critical issue.

Since 1970s, a large number of research were conducted to investigate the jet breakup length. As a result, the two types of widely used jet breakup length correlations were developed by Saito et al. (1988)[5] (called the Saito correlation in this paper) and Epstein and Fauske (2001)[6] (called the Epstein correlation in this paper), as expressed as follows:

$$L_{brk} = 2.1 D_J \left(\frac{\rho_m}{\rho_c}\right)^{0.5} (Fr)^{0.5}, Fr = \frac{V_J^2}{gD_J} \qquad (1)$$

$$L_{brk} = \frac{D_J}{2E_0}\left(\frac{\rho_m}{\rho_c}\right)^{0.5};\ E_0\ is\ 0.05 - 0.1 \qquad (2)$$

where L_{brk} is the jet breakup length, D_J is the jet diameter at the water surface, V_J is the jet velocity at the water surface, ρ_m is the melt density, ρ_c is the coolant density, Fr is the Froude number, and E_0 is the entrainment coefficient which has a range from 0.05 to 0.1 [6].

However, the consistent conclusion about the jet breakup length correlation was not obtained, even though there were a lot of experiments. Thus, we focused on the low temperature experiments using low melting point melt, in this paper. The effect of Froude number was investigated by changing the free fall height of the melt jet. The separation of the jet breakup length correlation was confirmed in our experiments.

2. Melt Jet Breakup Experiments

2.1 Previous low melting point melt experiments

Figure 1 shows the non-dimensional jet breakup length data of previous experiments using low melting point melt such as Wood's metal[7,8]. The experiments were categorized by the water temperature condition into the saturated water condition (red symbols) and the subcooled water condition (blue symbols). Distinct trend is shown that experiments with saturated water follow the tendency of Saito's correlation and experiments with subcooled water follow the tendency of Epstein's correlation. It is assumed that the phase of the coolant which interacts with the melt jet is the key point; melt-water interaction occurs in the subcooled water condition and melt-steam interaction occurs in the saturated water condition. It is more probable to be fragmented in the melt-water interaction due to the high density than steam. In other words, the important factor is not a water temperature, but a vapor generation intensity. Thus, the behavior vapor zone should be investigated in order to estimate the real accident conditions (very high melt temperature).

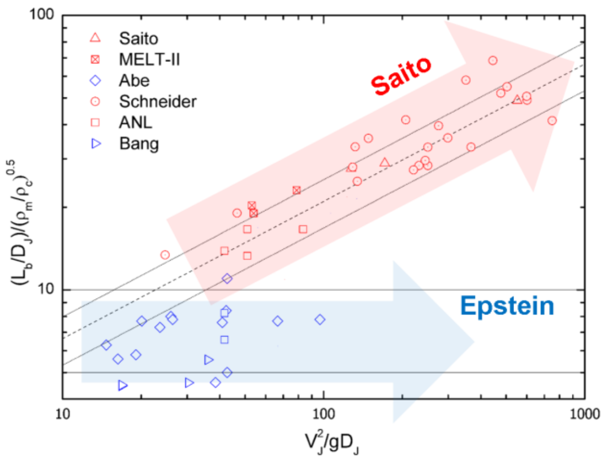

Fig. 1. Separation of jet breakup length correlation by water temperature condition in low melting point melt experiments

2.2 MATE Facility

The melt jet breakup experimental facility, named MATE (Melt jet breakup Analysis with Thermal Effect) was constructed in POSTECH, Korea in order to investigate the jet breakup length[9]. The Bi-Sn alloy at the eutectic composition (58:42 wt%, melting temperature: 138 °C) is used as a simulant of corium having similar density of 8750 kg/m^3 and surface tension of approximately 0.4 N/m. The main measuring method is visualization with two high-speed camera. One observes the entire area of water pool with 500 fps for the purpose of the measurement of the jet breakup length, and another observes the smaller area at water surface with 2000 fps to measure the jet diameter and velocity before penetration into the water surface. Detailed investigation of the melt jet characteristic was performed in the previous work[9].

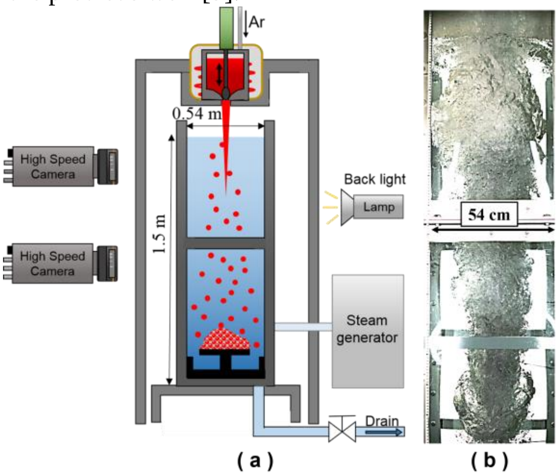

Fig. 2. MATE facility: (a) Schematic design, (b) Processed image from high-speed camera, MATE13

2.3 Nozzle Geometry

For the ejection of the melt jet, two nozzle opening systems were utilized in MATE experiments. First, the plug was pulled and then the slide gate opened after few moments in order to stabilize the melt movement inside the crucible.

The nozzle geometry is described in Fig. 3. (b) for two types of nozzle; Bell-mouth and tapered nozzle. Three types of nozzle (bell-mouth, tapered, toothed) were examined to observe the nozzle influence. The toothed nozzle is the nozzle that the turbulence generating structure (toothed structure) is attached inside the nozzle at the outlet on tapered nozzle in order to generate more unstable melt jet.

2.4 Test Conditions

To investigate the theory that was mentioned in Section 2.1, 20 experiments were conducted in various Froude number, the melt temperature, and the water temperature (Table 1.). MATE20 ~ 24 were nozzle effect tests with tapered and toothed nozzle. Especially, MATE23 was conducted with very low melt mass. The Froude number was controlled by changing the free fall height of the melt jet from 0.56 m to 1.22 m. The temperature condition was divided into the saturated water condition (melt Temp.: 300 °C & water Temp.: 100 °C) and the subcooled water condition (Melt Temp.: 250 °C & water Temp.: 60 °C). The boiling regimes of each conditions were film boiling regime for the saturated condition and non-film boiling regime for the subcooled condition[9].

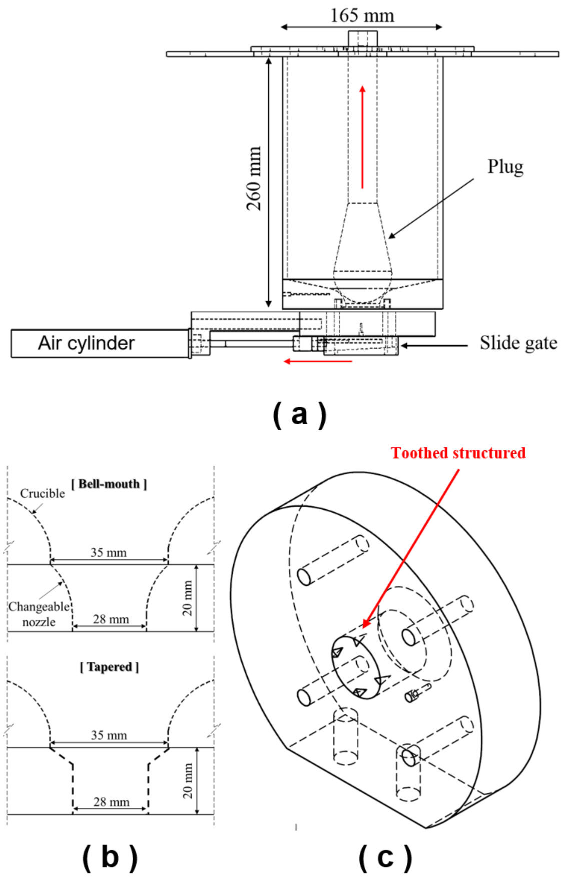

Fig. 3. Schematic design for three types of nozzle geometry; (a) nozzle opening system with plug and slide gate system, (b) Bell mouth nozzle and tapered nozzle, and (c) Toothed structure for toothed nozzle

3. Data Analysis and Results

3.1 Effect of free fall height on Froude number

The relation between the free fall height and the Froude number was investigated by changing free fall height with same nozzle diameter (22 mm diameter nozzle; MATE14, 18 – 24). Three different free fall heights were examined and the following Froude number was obtained by analyzing the jet diameter and velocity from the high-speed camera images. The Froude number increases as the free fall height increases as shown in Fig. 4. The discrepancy of data in same free fall height was resulted from different melt mass.

Table 1. Experimental conditions of the MATE experiments (MATE10-MATE29)

Case	Nozzle diameter [mm]	Melt Mass [kg]	Melt temperature [˚C]	Pool temperature [˚C]	Free fall height [m]	Boiling regime*	Nozzle Geometry
MATE10	14	2.6	300	99	0.56	FB	Bell-Mouth
MATE11	14	2.5	250	60	0.56	NFB	Bell-Mouth
MATE12	35	19.0	248	61	0.56	NFB	Bell-Mouth
MATE13	35	19.1	300	99	0.56	FB	Bell-Mouth
MATE14	22	7.3	250	60	0.88	NFB	Bell-Mouth
MATE15	28	10.2	250	60	0.88	NFB	Bell-Mouth
MATE16	22	7.6	300	99	0.88	FB	Bell-Mouth
MATE17	28	10.1	301	99	0.88	FB	Bell-Mouth
MATE18	22	7.1	300	99	0.88	FB	Bell-Mouth
MATE19	22	10.5	300	99	0.88	FB	Bell-Mouth
MATE20	22	7.5	250	60	0.88	NFB	Tapered
MATE21	22	6.6	250	60	0.88	NFB	Tapered
MATE22	22	7.5	90	40	0.88	NFB	Tapered
MATE23	22	1.0	245	60	0.88	NFB	Tapered
MATE24	22	7.5	250	60	0.88	NFB	Toothed
MATE25	22	7.6	300	99	1.22	FB	Bell-Mouth
MATE26	22	7.5	250	60	1.22	NFB	Bell-Mouth
MATE27	22	7.4	250	60	0.56	NFB	Bell-Mouth
MATE28	22	7.4	250	60	1.22	NFB	Bell-Mouth
MATE29	22	7.2	300	99	0.56	FB	Bell-Mouth

* FB: Film boiling regime, NFB: Non-film boiling regime

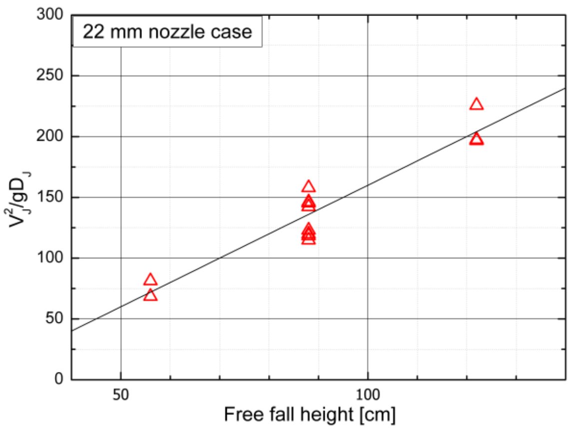

Fig. 4. Effect of free fall height on Froude number with the same nozzle (22 mm diameter nozzle)

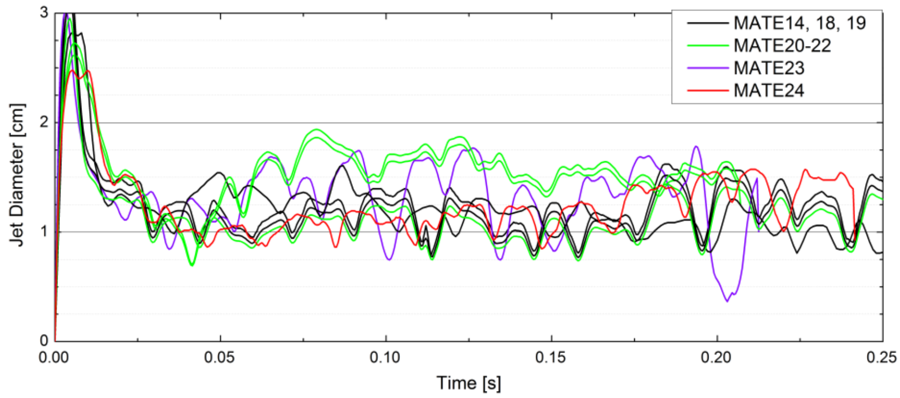

Fig. 5. Measured metal alloy jet diameter at water surface with different nozzle shape; Black: Bell-mouth nozzle, Green: Tapered nozzle, Red: Toothed nozzle, Violet: Low melt mass case

3.2 Effect of nozzle geometry

The effect of nozzle geometry was investigated by tracking the jet diameter history before entering the water surface and it is shown in Fig. 5. The base cases with bell-mouth nozzle are expressed as the black line (MATE14, 18, 19), the tapered nozzle cases are expressed as the green line (MATE20 – 22), and the toothed nozzle case is expressed as the red line (MATE24). In conclusion, there were no big difference between the nozzle types on the jet diameter. The jet breakup length data was also similar each other. Besides, the violet line (Fig. 5) is the low melt mass case showing large fluctuation than other cases.

3.3 Jet breakup length

The jet breakup length data were analyzed and were plotted in Fig. 6. The saturated condition cases were red circle and the subcooled condition cases were blue circle. Similar trend is confirmed as the theory in Section 2.1.; the saturated condition cases were dependent on the Froude number and the subcooled condition cases were independent on the Froude number. Currently, the additional experiments in the high Froude number range are being conducted to assure this trends. Due to the limitation of the space (height) of the laboratory, the pressurization of the crucible will be adapted in order to increase the Froude number range.

The reason why our subcooled cases show larger non-dimensional jet breakup length (near 20) than other subcooled condition experiments in previous works (5 – 10, Fig. 1) is that we used the reduced jet diameter due to the free falling for the non-dimensionalization, the jet diameter reduces almost to half than the initial diameter. On the other hand, the previous research usually utilized the nozzle diameter for the non-dimensionalization even in the free fall experiments.

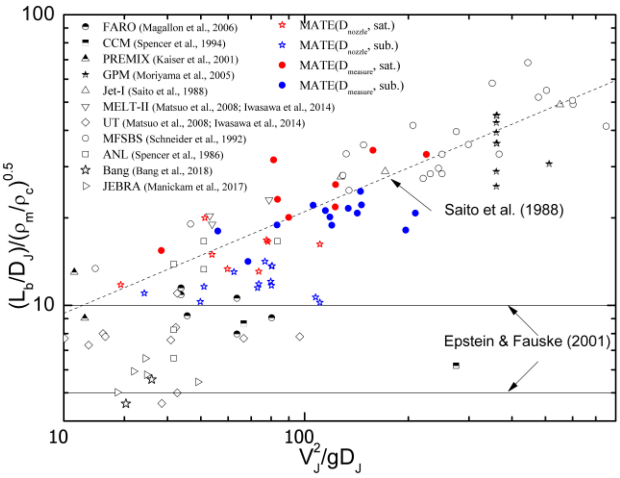

Fig. 6. Non-dimensional jet breakup length data of MATE experiments according to the Froude number

4. Conclusions

Twenty melt jet breakup experiments with low melting point metal alloy (Bi-Sn alloy) were conducted to investigate the Froude number effect on the jet breakup length in free fall condition. Froude number increases as the free fall height becomes longer.

The effect of nozzle shape was also investigate by applying three types of nozzles; bell-mouth nozzle, tapered nozzle, and toothed nozzle (promoting turbulence of melt jet). However, no difference between three nozzles was observed in terms of the jet diameter history.

By analyzing the non-dimensional jet breakup length of MATE experiments, the separation of the jet breakup length correlation was confirmed according to the water subcooling condition. Further study will be conducted in high Froude number range to assure the jet breakup length behavior in low temperature experiments.

ACKNOWLEDMENTS

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