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Revisit of Melt Jet Breakup Length Correlations for Fuel-Coolant Interactions: Preliminary Experiment Results in the MATE Facility

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1. Introduction

After Fukushima-Daiichi nuclear power plant (NPP) accident, the severe accident of light water reactor is drawing attention again, though, before that, the world wide severe accident research activities were in the reducing or closing phase.

Nowadays, most countries having NPPs are trying to establish regulation considering beyond design based accidents (DBAs) or preparation for severe accidents. Therefore, technical need on the prediction capability for key phenomena in the severe accident scenario is becoming more and more important.

Thought severe accident scenarios are in a vast spectrum, the key factor of the accident progression or termination is the behavior of the molten and relocated core material. In the late phase, after a large amount of the core melt is accumulated in the lower head of the reactor vessel, the scenario becomes rather simple and the cooling of the melt in the vessel or in the reactor cavity is the primary issue. Unless so called dry-cavity strategy is taken, the reactor cavity is likely to have water, and the molten core drops into a water pool in the reactor cavity.

After ejection from the reactor vessel, the melt jet penetrates water and the fuel-coolant interaction (FCI) occurs. The FCI can be in two specific modes, energetic steam explosions or mild interactions. In this work, we focus on the latter. The melt breaks up into droplets during the penetration and those droplets undergo cooling and solidification, sedimentation and formation of a debris bed on the containment floor. Depending on the cooling behavior during the sedimentation and after settlement as a debris bed, stable cooling of the debris or re-melting due to the decay heat may occur. In the case of hindered cooling and re-melting, ablation of the concrete base mat, so called molten core-concrete interaction (MCCI) is concerned.

This paper will focus on the melt jet breakup and sedimentation process that determine the characteristic of the debris bed. Microscopically, as a result of the melt jet breakup, debris size distribution and particle shape are determined and which affect the pore size, porosity of the debris bed and pressure drop characteristics inside the debris bed. Macroscopically, jet breakup length, which means the length required for a jet to be totally fragmented into droplets, determines the amount of melt reaching the base mat as a continuous jet without fragmentation, that should have a significant influence for the possibility of MCCI. In other words, melt jet breakup phenomena is preceding phenomena of debris bed cooling and MCCI, so it should be thoroughly understood.

Melt jet phenomena can be analyzed in two concept. First concept is hydrodynamic analysis and the other concept is thermal analysis considering vapor film and solidification effect.

From the 1900s, a lot of engineers are interested in analyzing jet breakup phenomena hydrodynamically, because jet breakup phenomena is appeared in many physical situation such as spray and coating system, diesel engine fuel injection system, melt atomization in manufacturing metal particle [1][2]. As a result, many researchers studied about hydrodynamic behavior of jet [3].

However, in severe accident situation, melt jet is in very high temperature (over 2700K) which triggers drastic generation of vapor film. Thick vapor film makes the situation as a liquid-vapor-liquid interaction not a liquid-liquid interaction. Some researchers tried to investigate the effect of vapor film or solidification of melt droplet [4][5]. Also, there were many experiment for melt jet breakup and those can be divided to two groups. Some researchers conducting experiment with very high temperature similar with real melt and other researchers conducted low temperature under the boiling temperature of water. In high temperature experiment, visualization of jet breakup phenomena was hard and in low temperature experiment, there was no film boiling, so vapor film effect was not considered.

Still, there are some uncertainties analyzing the melt jet phenomena in real situation especially about jet breakup length.

To investigate melt jet breakup phenomena more accurately, POSTECH constructed a new test facility, called MATE (Melt jet breakup Analysis with Thermal Effect) and tried the preliminary test. Test was conducted with Bismuth-Tin alloy which has melting point as 138℃. Coolant is saturated water to generate vigorous vapor film and melt temperature is ~310℃. Main data is achieved through High Speed Camera with image processing technique.

The purpose of this test facility is investigating the Bond number effect to the jet breakup length in film boiling regime by altering nozzle diameter.

2. Methods and Results

In this section, the test facility and experimental condition is introduced. Also, images from high speed camera is shown. Using image processing technique, jet breakup length is obtained.

2.1 Experimental condition

The experimental condition is determined through considering previous experiments and research. According to the previous researcher, there are two jet breakup correlations, one is Saito's correlation which is expressed by

$$\frac{L_b}{D_{Ji}} = 2.1 N_\rho^{\frac{1}{2}} Fr^{\frac{1}{2}} \qquad (1)$$

$$N_\rho = \frac{\rho_m}{\rho_l} \qquad (2)$$

$$\mathrm{Fr} = \frac{V_{Ji}^2}{g D_{Ji}} \qquad (3)$$

where the symbols denote L_b is jet breakup length, D_{ji} and V_{ji} are melt jet diameter and velocity at water surface, ρ_m and ρ_l are density of jet and coolant, g is gravitational acceleration, and Fr is Froude number.

Another is Epstein's correlation which is expressed by

$$\frac{L_b}{D_{Ji}} = \frac{1}{2E_0}(N_\rho)^2 \qquad (4)$$

where the E_0 is entrainment coefficient with the value of the order 0.05-0.1. Two correlations are mainly used currently, and they show totally different behavior, Saito's correlation is linearly proportional to the jet velocity, but Epstein's correlation dose not. Important thing is that some experimental results follow Saito's correlation and other experimental results follow Epstein's correlation. Thus, previous researcher plot the all experimental results along the Bond number and he found that it seems like there is some criteria dividing Epstein's regime and Saito's regime. However, current experimental data was too limited to figure out the jet breakup length correlation along the Bond number because there is some range that experiment dose not conducted [6].

Therefore, experimental condition is set up to fill the vacant Bond number range (Bond number : 10 ~ 100).

Bond number is expressed by

$$\mathrm{Bo} = \frac{\Delta\rho g D_{Ji}^2}{\sigma} \qquad (5)$$

where $\Delta\rho$ is difference of density between melt and coolant, and σ is surface tension.

To control the Bond number, jet diameter at water surface is chosen as a variable. Therefore, various nozzle size is manufactured according to the appropriate Bond number including consideration of diameter decrease by free fall of jet from nozzle to water surface.

Calculated nozzle diameter is 14mm (Bond number, 10) ~ 35mm (Bond number, 100). Material to simulate molten fuel is bismuth-tin alloy. It has similar density with molten fuel and low melting temperature (138℃) which can be used in medium temperature condition. To make vigorous vapor film, a saturated water is used as a coolant. In preliminary test, melt mass is ~2.5kg.

All the detailed experimental condition is summarized in Table. 1.

Table I: Experimental condition of preliminary test

Conditions	Value
Melt temperature	310℃
Melt mass	2.42kg
Nozzle diameter	14mm
Free fall height	80cm
Pool temperature	95℃
Water depth	135cm

2.2 Experimental Test Facility

TPFL laboratory in POSTECH constructed a test facility for melt jet breakup experiment with small single – story building. Inside the building, there is closed room for highly dangerous experiment such as melt jet breakup and steam explosion. All the controls are conducted outside of the room using remote control system.

The test facility is consists of three parts, pool and crucible and measurement system. Schematic diagram of the test facility is shown in figure. 1.

Both pool and crucible is made of SUS304. A size of pool is 55 × 55 × 200 cm (length × width × height) and a size of crucible is 155 × 230 mm (diameter × height). Pool has three visualization window made of polycarbonate and one aluminium plate for inserting thermocouples. Inside a crucible, it has smoothly curved nozzle to minimize the turbulence effect at the nozzle when melt is ejected (fig. 2). The overall view of test facility is shown in figure. 3.

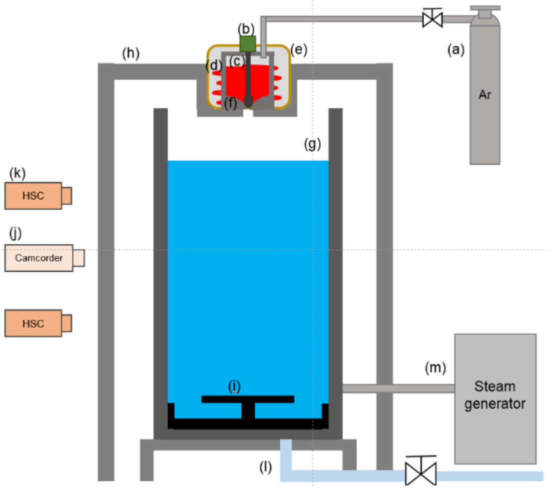

Fig. 1. . Schematic diagram of the MATE facility for melt jet breakup experiment: (a) argon bombe, (b) air cylinder, (c) plug, (d) heater, (e) insulator, (f) crucible, (g) pool, (h) support, (i) debris catcher, (j) camcorder, (k) high speed camera, (l) drain, (m) steam generator

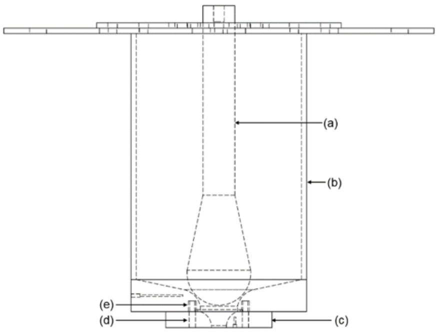

Fig. 2. Crucible: (a) plug, (b) SUS304 pipe, (c) SUS nozzle, (d) bolt for nozzle, (e) metal wire

Fig. 3. Overall view of the MATE facility

2.3 Preliminary Test result with High Speed camera

To gather the information about the melt jet fragmentation behavior, High speed camera is used. Using high speed camera, whole melt jet breakup process is captured at 200fps(frame per second) and 1000μs of exposure time. The test is also captured by camcorder. The images of preliminary test are shown in figure. 4.

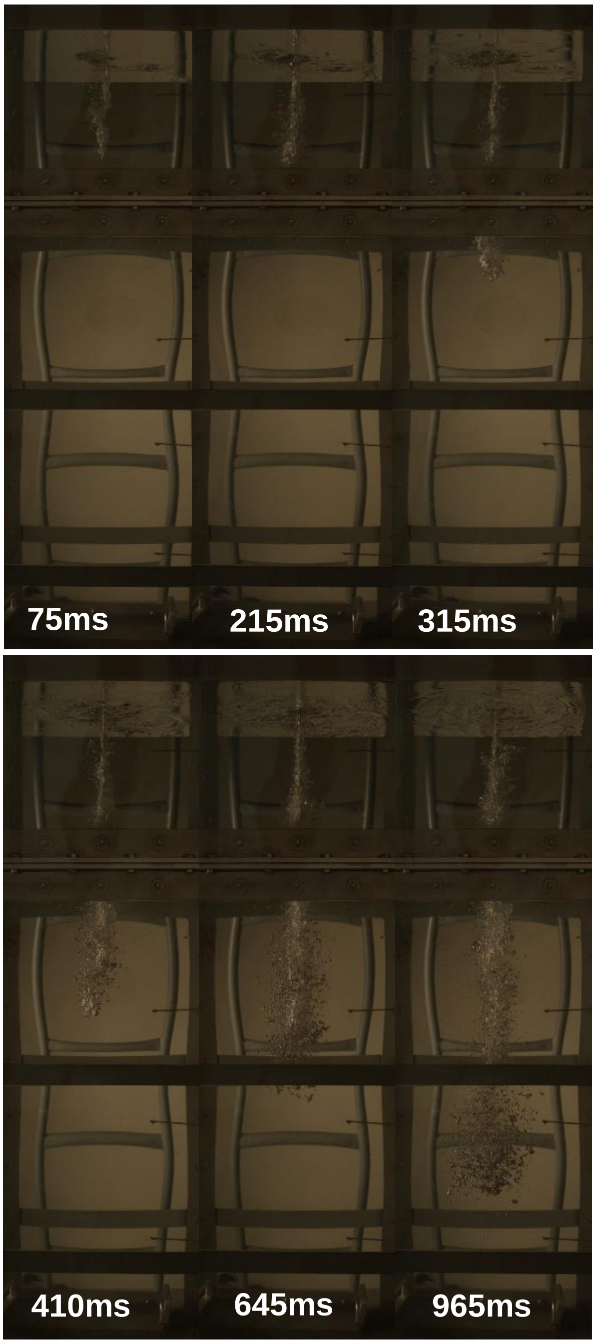

Fig. 4. High speed camera images (1920 × 600, 1000μs) with 14mm nozzle diameter

In figure. 4, fragmentation process and sedimentation process are observed. However, jet does not show any lateral axis breakup of leading edge by boundary layer stripping [7]. The reason is considered as a small diameter of jet resulting more dominant Kelvin-Helmholtz instability effect than Rayleigh-Taylor instability effect. In this test, Rayleigh-Taylor instability wavelength is ~25mm and Kelvin-Helmholtz instability wavelength is ~0.3mm. A jet diameter at water surface is expected approximately 7mm, so there are less possibility to be fragmented by Rayleigh-Taylor instability and it causes little lateral axis behavior in fragmentation regime.

To figure out leading edge position and velocity, post image processing technique is conducted using MATLAB. After remove background image, adjust the intensity of each pixel and binarize the image. The result is shown in figure. 5.

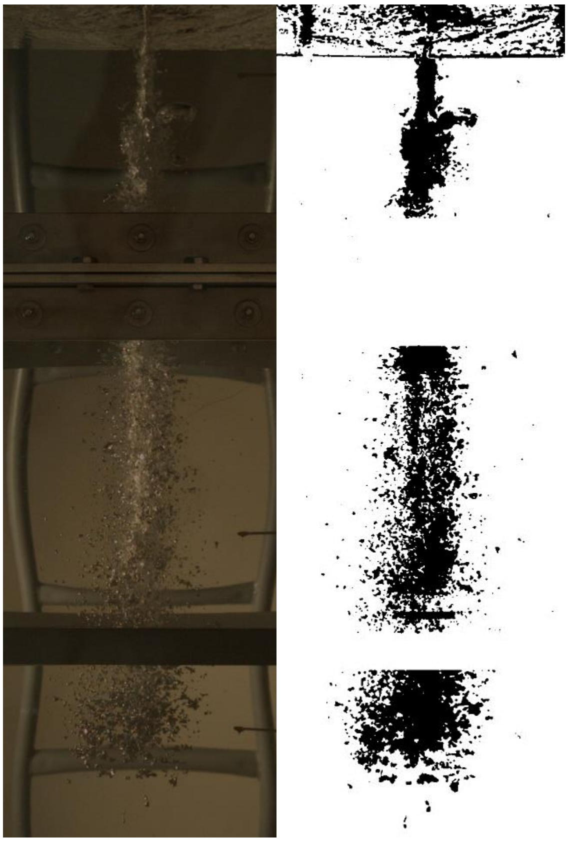

Fig. 5. Original image (left), binarized image (right)

As shown in figure. 5, binarized image can express the edge of the particles and the jet very clearly. From the binarized image we can get the position and velocity data of leading edge.

Figure. 6 show the leading edge position as indicated in figure. 6, gray dotted line is water surface. The jet breakup length can be obtained from the point where jet velocity decrease. On the graph, red line show the velocity of leading edge and three section exist which having different velocity. The intersecting point between second third red lines is jet breakup length. However, the reason why first and second red lines show different velocity is not clear, because there is missing data over 90 ~ 105 cm approximately due to the frame of experimental facility. Nevertheless, the intersection point between first and second red lines exist almost at water surface, and that is the reason why it is not a jet breakup length. More test is needed to explain the reason.

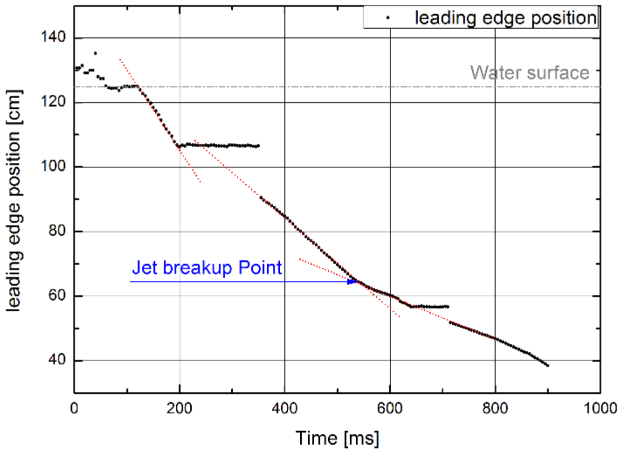

Fig. 6. Leading edge position along the time

The jet breakup length is pointed by blue arrow, and jet breakup length is 63.5 cm. The jet breakup length data follows Saito's correlation.

3. Conclusions

From the preliminary test, we got the image data and analyzed it. Through image processing technique, we can distinguish the melt jet and particles, and can get the jet breakup length data. The obtained jet breakup length follows Saito's correlation. Through the preliminary test, a lack of light was verified. Doing image processing, some difficulties occurred due to the trouble with distinguishing the jet and particles. Also, as a next task, distinguishing vapor film and liquid jet will be conducted. To do it, more powerful light is needed in order to make a distinction between vapor (permeable to light) and jet or particle (non-permeable to light).

Also, more test will be conducted with various nozzle size to figure out the tendency of jet breakup length along the Bond number.

ACKNOWLEDGEMENTS

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