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Multiple Boundary Layer Stripping Model by Plateau-Rayleigh Instability for Fuel-Coolant Interactions

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1. Introduction

As the severe accident analysis and prediction become important after several nuclear power plant accidents, many researchers tried to predict whole severe accident progression investigating various phenomena during a severe accident. One of them is FCI (Fuel-Coolant Interaction) phenomenon which is resulted from RPV (Reactor Pressure Vessel) failure at high pressure and high temperature condition of molten fuel. If RPV fails, the melt is ejected to the cavity which is flooded by water as a jet form. Then, the ejected melt jet interacts with water causing massive steam generation and resulting in particulate debris bed on the basemat. As a result of FCI, the initial boundary conditions of steam explosion and debris bed coolability are determined and that is the reason why understanding exact mechanism of melt jet breakup is important in this field. That is, FCI can be said as a starting phenomenon in the ex-vessel severe accident scenario.

Until now, numerous previous researchers conducted FCI experiments and numerical analysis in small scale and plant scale. Usually, if the possibility of the steam explosion at the early stage of FCI is excluded, then researchers focused on ‘jet breakup length’, ‘particle size distribution’ and ‘debris bed configuration’. Regarding the jet breakup length, while the experimental data for the jet breakup length are sufficient, there are no consistent correlations or models estimating proper jet breakup length including most of the experimental results [1].

To investigate the reason of inconsistent experimental results of the jet breakup length and the particle size distribution, new experimental facility, called the MATE (Melt jet breakup Analysis with Thermal Effect) facility, was constructed in the POSTECH and the experiment is conducted [2]. Currently two cases are conducted with same condition for repeatability test. However, results show a very large discrepancy between two results for the jet breakup length with the similar condition. In this paper, the reason why the large difference between repeatability tests is occurred is investigated. From the visualization images, the reason is understood, also the new jet breakup model, considering the Plateau-Rayleigh instability of melt jets before entering the water pool, is proposed.

2. Methods and Results

In this section, experimental conditions and results about jet breakup length data are introduced. Problem in the results is raised and the cause is also discovered.

2.1 Experimental facility and conditions

The MATE facility is a new melt jet breakup experiment facility constructed at POSTECH in 2015. The purpose of the MATE facility is the investigation of the melt jet breakup phenomenon with the thermal effect (the vapor film effect and the solidification effect) along the various Bond numbers by changing the nozzle diameter. The MATE facility is composed of two parts; the water pool and the crucible. The water pool has a dimension of 0.55 X 0.55 X 2 m (length X width X height) and can heat up to the saturated temperature. The crucible can load melt up to 3.5 liters and can heat up to 350℃. The melt temperature is usually under 300℃ to easily visualize the melt jet breakup phenomenon because the very high temperature (~2700K of real corium temperature) emit the strong light and generate massive steam disturbing the visualization. Since the melt temperature is too low to sustain the vapor film around the melt jet like real FCI situation, water pool is in saturated condition to generate the vapor film in all tests. The main measurement method is visualization using high speed cameras; one observes the entire pool with 200 fps to measure the jet breakup length, and another observes the small region of the water surface with 1000 fps for the observation of the behavior of the melt jet surface in detail. Thermocouple is hard to measure the jet breakup length because the melt jet breakup is highly complex phenomenon with multi-fluids and multi-phases.

Using the MATE facility, two tests with the same experimental conditions are conducted for a repeatability test. The Bi-Sn alloy and the water is used as a simulant of the melt and the coolant. Since a density is one of the basic parameter governing jet breakup phenomenon, the Bi-Sn alloy is chosen which has a similar density with the real corium and the low melting temperature. The density of Bi-Sn alloy is assumed as 8770 kg/m^3. Table I shows the experimental conditions.

Table I: Experimental conditions of MATE 00, 00-2

Parameters	MATE 00	MATE 00-2
Melt	Bi-Sn alloy (58% + 42%)*	
Melt mass	2.42 kg	2.488 kg
Free fall height	0.8 m	0.5 m
Melt temperature	310℃	300℃
Water temperature	95℃	99℃
Water depth	1.25 m	1.5 m
Nozzle diameter	14 mm	14 mm

*The melting point of Bi-Sn alloy is 411K

Different conditions are free fall height and water depth which is related each other. MATE 00 is expected to have small jet breakup length by small jet inlet diameter at water surface because of the large free fall height.

2.2 Jet breakup length

To investigate the jet breakup length behavior in terms of the various parameters such as the jet diameter, the jet velocity, and the melt density, melt jet breakup experiments are conducted and the jet breakup length is measured from the visualization data. The method to obtain a jet breakup length from the images is locating the point where the jet leading edge velocity changes. The definition of the jet breakup length is the length where the continuous jet is totally broken into the discontinuous droplets. That is, before the jet breakup length, the momentum boundary layer within the jet could not reach the center of the jet, and then the following center of jet penetrates water with higher speed than the affected jet by the normal and the shear force. After the jet breakup length, the jet leading edge velocity suddenly decreases because there is no mass supply to the leading edge. However, this method has disadvantages that the subsequent jet breakup following the initial jet breakup is not measureable. The subsequent jet breakup is important for the real plant scale analysis because the releasing time of the melt is very long and the contribution of the initial jet breakup to the total result is very small. In order to measure it, we may need other types of measurement techniques such as the X-ray radiography that allows to visualize the melt breakup in the chaotic vapor films and clouds.

According to the post-processing of images, the jet breakup length is calculated for each experiment. The jet breakup lengths are 0.63 m and 0.35 m for the MATE 00 and MATE 00-2, respectively.

2.3 Visual observation on P-R instability based jet breakup

Even though two experiments have similar conditions, the jet breakup length shows large difference. Moreover, according to the prediction in section 2.1, MATE 00 should have a smaller jet breakup length because of the smaller jet diameter due to the long free fall height.

The reason of large difference between two test results comes from the unstable jet before entering the water surface that results in the larger melt jet erosion rate.

Figure 1 shows the post-processed images that evidences the existence of the boundary layer stripping (BLS) mechanism on the middle of jet in MATE 00-2. On the top side of Figure 1, the melt jet shows the Plateau-Rayleigh instability (PRI) derived by the surface tension to minimize the surface area of the jet. PRI would be induced in this experiment by the turbulent mixing when the plug in the crucible is removed from the nozzle to release the melt.

The visual images indicates that the initial disturbance induced PRI on the jet column before entering the water surface and PRI triggered additional boundary layer stripping mechanism that forms multiple mushroom-like shapes on the middle of the jet surface enlarging the melt jet erosion rate. This is the reason why the jet breakup length of MATE 00-2 is much shorter than that of MATE 00.

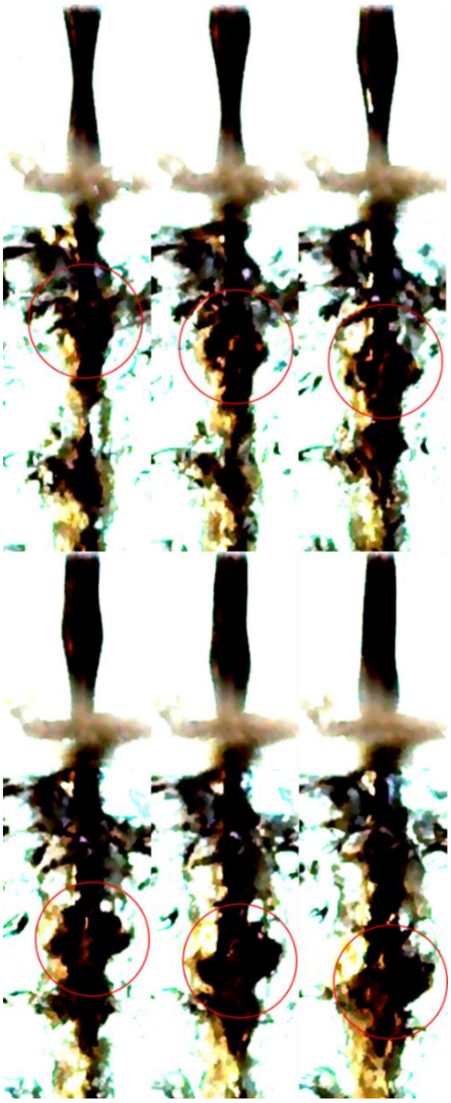

Fig. 1. Post-processed images for formation of mushroom-like shape on the middle of jets by unstable jet injection in MATE 00-2; red circle: boundary layer stripping region

3. New Jet breakup model

3.1 Suggestion of new jet breakup model

In order to confirm the discussion in the section 2.3, a new simplified jet breakup model to analyze the jet breakup with instabilities combined with KTI with multiple BLS based on PRI is proposed. Figure 2 shows the schematic that illustrates the existing models from previous research and the new model. Moriyama et al. [3] developed a simplified jet breakup model assuming a linear cone shape jet shown in Figure 2 (a). The melt jet erosion flux equation of Eq. 1 was developed using the mass balance and with the assumption of the linear decrease of the jet diameter.

$$m_e = \frac{1}{2}\rho_m \frac{D_{Ji}V_{Ji}}{L_{brk}} \tag{1}$$

Where m_e is an erosion mass flux, ρ_m is the melt density, D_{Ji} is the jet inlet diameter, V_{Ji} is the jet inlet velocity, L_{brk} is the jet breakup length

Chu et al. [4] developed a more complex model containing a leading edge configuration which is eroded by the boundary layer stripping mechanism. The melt jet erosion rate by the boundary layer stripping mechanism can be expressed as Eq. 2 [5].

$$M_{input} = M_{KHI} + M_{BLS} \tag{2}$$

Where M_{input} is the input mass rate by jet, M_{KHI} is the erosion mass rate by the K-H instability, M_{BLS} is the erosion mass rate by BLS

Previous researchers usually assumed melt jet erosion model like Fig 2 (a) or (b). However, from the observation of the MATE 00-2 result, it shows that additional boundary layer stripping effect also exists.

In this paper, Eq. 3 is a newly proposed model with the simple mass balance between the mass inlet rate and the mass erosion rate by the K-H instability mechanism and the BLS mechanism, assuming the jet configuration including multiple mushroom-like shape (Figure 2. (c)).

$$M_{input} = M'_{KHI} + (a-1)M_{BLS,2} + M_{BLS,1} \tag{3}$$

$$a = \frac{L_{brk}}{\lambda_{PRI}} \tag{4}$$

Where, M'_{KHI} is the erosion mass rate by the K-H instability in multiple BLS model and λ_{PRI} is the wave length of the P-R instability.

The situation shown in Figure 2. (c) is occurred when the jet is unstable or undergo long free falling before entering the water pool. Due to PRI, the melt jet becomes sinuous, and water applies a normal pressure on the point of abrupt increase of diameter generating a mushroom-like shape as same as the leading edge.

In the new model, there is the additional erosion mass rate through $M_{BLS,2}$ smaller than $M_{BLS,1}$ because the center of the jet still keeps moving downward. The procedure to calculate each term is as follows.

(1) Calculate $M_{BLS,1}$ using Eq. 2 and Eq. 5 with measured parameters

$$m_e A = \frac{1}{2}\rho_m \frac{D_{Ji}V_J}{L_{brk}} \frac{\pi D_{Ji}}{2} L_{brk} = M_{KHI} \tag{5}$$

$$m_e A = \frac{1}{2}\rho_m \frac{D_{Ji}V_J}{L_{brk}} \frac{\pi D_{Ji}}{2} L'_{brk} = M'_{KHI} \tag{6}$$

Where V_J is the leading edge velocity, and L'_{brk} is the measured jet breakup length in the multiple BLS model (Figure 2. (c) and L_{brk} is the ideal jet breakup length with only the KHI model).

(2) Calculate $M_{BLS,2}$ using Eq. 3 and modified Eq. 6 with calculated parameters.

In this analysis, PRI wave length and each term are needed to be adjust to meet the general cases.

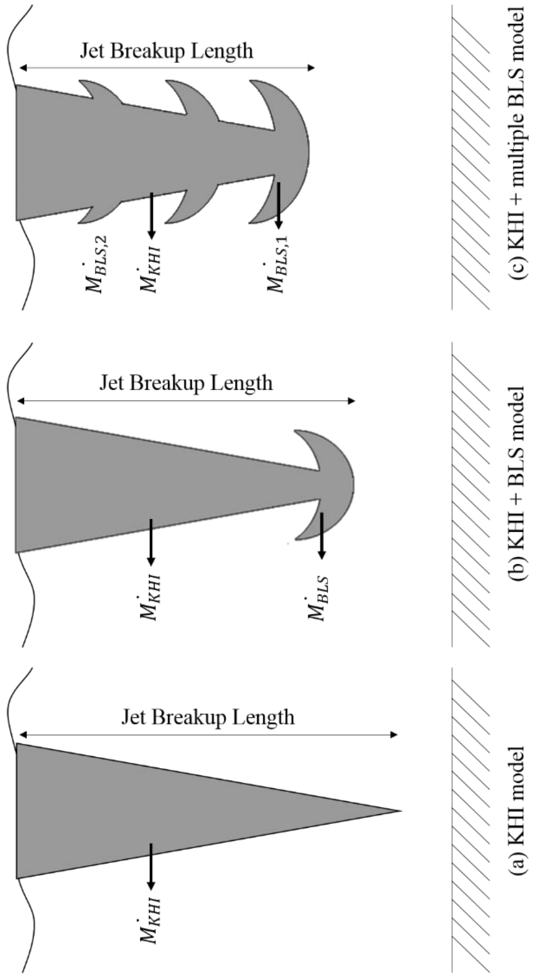

Fig. 2. Simplified jet breakup models; (a) Kelvin-Helmholtz instability model, (b) K-H instability + Boundary Layer Stripping model, (c) K-H instability + multiple BLS model

3.2 The MATE result analysis using the new model

The new model is applied to the MATE 00-2 experiment to compare $M_{BLS,1}$ and $M_{BLS,2}$, to investigate the fraction of each mechanism for evaluating total melt jet erosion rate.

According to the measured and calculated parameters, results from Eq. 2 and Eq. 5 are M_{input} = 1.78 kg/s, M_{KHI} = 1.06 kg/s, $M_{BLS,1}$ = 0.72 kg/s with the jet breakup length of 0.63 m. To obtain $M_{BLS,2}$, Eq.3 and Eq.6 are used with a = 3~7 (wave length = 50 ~ 120 mm), and the jet breakup length = 0.35 m. Thus results are M'_{KHI} = 0.59 kg/s, $M_{BLS,2}$ = 0.12 kg/s with a = 5 as the median value.

As a result, the fractions of each term for MATE 00-2 are 33%, 40%, 27% for M'_{KHI} , $M_{BLS,1}$, $M_{BLS,2}$, respectively.

The results indicates that multiple BLS has significant effect on the melt jet breakup in MATE 00-2 and result in the shorter jet breakup length.

4. Conclusions

In two MATE experiments, the jet breakup lengths are compared and analyzed with the visualization data. From the observation, the new jet breakup model is proposed including the multiple boundary layer stripping mechanism. Combining the existing and new models, the erosion rate fraction for total melt mass rate was obtained. The new model showed that multiple BLS mechanisms contribute approximately 30% of the total melt jet breakup resulting in the short jet breakup length observed in the MATE 00-2 experiment.

The new model needs more experiments for validation and the sensitivity analysis in terms of the jet diameter, the initial disturbance degree on the jet breakup length.

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