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Effect of Air Entrainment on Breakup of Plunging Liquid Jet into Water Pool

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1. Introduction

The potential risk of explosive molten fuel coolant interactions (FCI, steam explosion) has drawn substantial attention in the safety analysis of reactor severe accidents. The steam explosion intensity is largely dependent upon the degree of volumetric fractions of melt droplets and steam in the fuel-coolant mixture. The rate of melt jet breakup and droplet sizes are, therefore, the key physical parameters in the analysis of FCIs.

In a recent OECD/NEA international program SERENA [1], the areas where research may be needed to reduce the level of uncertainties in the code predictions have been identified. The predicted void fractions in the mixture were generally much higher than experimental data and a deficiency in melt jet breakup modeling would be one of the primary causes.

In this paper, an extended study of non-boiling liquid jet breakup from the previous jet breakup experiment [2] is reported with an emphasis on the role of air entrainment by plunging liquid jet into water pool. An improved jet breakup model is also presented with comparison to the experimental data.

2. Liquid Jet Breakup Experiment

2.1 Experimental Apparatus

The experimental apparatus consisted mainly of an electric furnace, melt crucible and water pool tank. The furnace was a cylindrical radiant heater of 1 kW rating and a set of temperature controller and K-type thermocouple was used to control the furnace temperature. Inside the furnace the melt crucible, made of stainless steel, was placed. It was designed to produce and deliver up to 2.5 kg of molten Woods metal.

At the bottom of the crucible a nozzle piece made of stainless steel was attached and a conical-shaped plug with a vertical rod attached was seated on the nozzle. The plug was raised by a pneumatic actuator at the time of melt delivery. The nozzle opening was 20 mm in the present study. In the previous experiment, the variation of jet velocity was provided by pressurizing the crucible, but this caused additional breakup due to turbulence produced in the nozzle. To remove this additional effect, the elevation of furnace and crucible was varied in the present experiment instead.

The water tank was an open-topped rectangular box, made of transparent glass wall for the visualization purpose and the side is 360 mm each and the height is 800 mm. A high-speed video camera was set visualize the jet breakup process.

To prevent water from boiling so that only hydrodynamic mechanism of jet breakup can be investigated, the melt temperature was 85-95°C and the water temperature was set at 50°C. The highest jet velocity at entering the pool was 5.5 m/s. After the test, the debris was collected, dried, and sieved. Some selected physical properties of Woods metal are given in Table 1.

Table 1: Physical properties of Woods metal

Parameters	Value
Melting temperature	72°C
Density	9383 kg/m^3
Specific heat	168 J/kgK
Vol. Expansion coefficient	2.2x10^{-5} /K
Thermal conductivity	18.8 W/mK
Kinematic viscosity	2x10^{-7} m^2/s
Surface tension	~1.0 N/m

2.2 Experimental Results

The breakup of Woods metal liquid jet was visualized and the images of 1/30 second apart are shown in Figure 1. The breakup was observed to occur first at the leading edge. As the jet continued to enter, breakup also occurred at lateral surface of the jet. A depression was formed in the water surface where the jet entered, referred to as the induction trumpet [3]. This is where air is entrained into the pool. The entrainment of air along the jet surface can affect the jet breakup and this will be discussed in the jet breakup model below.

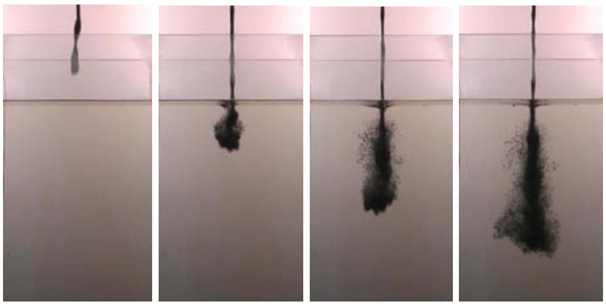

Fig. 1. Jet breakup snap shot every 1/30 s (D_{jet} = 20 mm, V_{jet} = ~5.5 m/s)

3. Jet Breakup Model and Analysis

A linear Kelvin-Helmholtz instability analysis was presented by Epstein and Fauske [4] in their study on the mixing of core melt jet and water. They derived the dispersion equation for the growth constant n for the disturbed motion of the core melt, steam and liquid water. The geometrical configuration of this condition is depicted in Fig. 2. For a non-boiling condition, entrained gas film plays a role of the vapor film.

$$\begin{aligned}&[\rho_g\left(n+ikV_g\right)^2+\left\{\rho_l\left(n+ikV_l\right)^2+\sigma_l k^3\right\}\\&\cdot\tanh\left(k\delta\right)]\cdot[\rho_j\left(n+ikV_j\right)^2+\sigma_j k^3]\\&+\rho_g^2(n+ikV_g)^4\tanh(k\delta)\\&+\rho_g\left(n+ikV_g\right)^2[\rho_l\left(n+ikV_l\right)^2+\sigma_l k^3]=0\end{aligned}\tag{1}$$

In the general case, this equation is complex and cannot be solved analytically. Epstein and Fauske presented analysis on the two limiting cases of thin steam layer and thick steam layer, in which Eq. (4) can be solved analytically. The fastest growing wave number, $k_{D,}$ is

For thin film: $$k_{D,o}=\frac{2\rho_j\rho_l(V_l-V_j)^2}{3(\rho_j+\rho_l)(\sigma_j+\sigma_l)}\tag{2}$$

For thick film: $$k_{D,\infty}=\frac{2\rho_j\rho_g(V_g-V_j)^2}{3(\rho_j+\rho_g)\sigma_j}\tag{3}$$

The k_D can be used in calculating the drop size from jet breakup by assuming the drop size to be a half of the wave length. When applying Eq. (2) and (3) to the analysis of jet breakup in fuel-coolant interaction, it is found that the drop size for thin film is in sub-millimeter range that is too small, and in contrast, the drop size is too big for thick film.

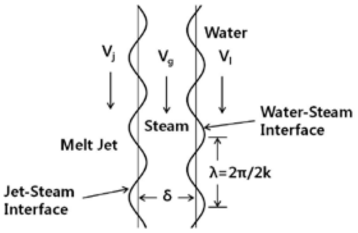

Fig. 2. Schematics of K-H instability model for melt jet-steam-water system

To overcome this limitation, the general dispersion equation for the K-H instability in melt jet-steam-water interfaces, Eq. (1), was solved numerically and the results were correlated for vapor film thickness and relative velocities.

$$\frac{k_D}{k_{D,\infty}}=1+\frac{1}{\frac{k_{D,\infty}}{k_{D,,o}}+25(V_g-V_j)^{1.5}\delta+(k_{D,\infty}\delta)^2}\tag{4}$$

For a case of non-boiling, the vapor film is replaced with air film entrained by the plunging jet. The amount of air entrainment by plunging jet was estimated by Evans et al model [3] and it was an order of 0.1 mm, very thin gas film on the jet surface.

The predictions of most probable debris size ($\lambda_D/2$) using three different models are listed in Table 2. These values are also plotted together with the debris size distribution data in Fig. 3. Without consideration of entrained gas, the predicted debris size, 0.18 mm, is too small compared to the debris size of largest mass in the experiment, 1.9 mm. It is shown that the inclusion of entrained air results in good agreement with the experimental data.

Table 2: Comparison of debris size models

	Eq. (2)	Eq. (3)	Eq. (4)
k_D	17100	24.2	1910
$\lambda_D/2$, mm	0.18	130	1.64

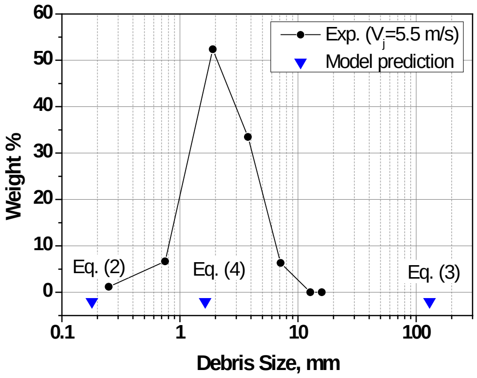

Fig. 3. Debris size distribution (D_{jet} = 20 mm, V_{jet} = ~5.5 m/s)

4. Conclusions

Non-boiling liquid jet breakup experiment was conducted and the debris size was analyzed with a new jet breakup model with an emphasis on the role of air entrainment. The predicted debris size with consideration of entrained air showed good agreement with the experimental data.

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