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Experiment and modeling of jet breakup in fuel-coolant interactions

Kwang-Hyun Bang *, Hyoung-Tak Kim, Vo Duy Tan

Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-gu, Pusan 49112, South Korea

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ABSTRACT

In light water reactor core melt accidents, the potential risk of energetic molten fuel coolant interaction (FCI, steam explosions) in a partially-flooded reactor cavity has drawn substantial attention. However, when the cavity is completely filled with coolant and the reactor vessel lower head is submerged for the purpose of external reactor vessel cooling, the jet breakup behavior in this case could not only be quite different from the case of partially-flooded reactor cavity, but also affect the risk of fuel coolant interactions. In this study, the jet breakup in liquid-liquid system was experimentally investigated for a fully-flooded and a partially-flooded cavity, and the existing jet breakup models were evaluated against the experimental data. The jet breakup experiment, named as COLDJET, was carried out using the Woods metal whose melting point was 72 °C. The melt jet temperature was lower than the boiling point of coolant so that only the hydrodynamic aspect of jet breakup was investigated. The jet diameter was 50 mm and the coolant depth was 1 m. To investigate the effect of air space of free-falling jet, the experiment was conducted for both fully-flooded and partially-flooded cavities. In the latter case, the free-fall distance in air space was 1 m. A high-speed video camera (typically 4000 fps) was used to visualize the jet breakup and there was an obvious difference in jet breakup behavior between the fully-flooded and the partially-flooded cavities. The jet breakup lengths which were identified in the jet front falling speed were compared with existing models and found that the agreement with the Epstein and Fauske's model was remarkable. The solidified debris were collected, dried, and sieved to obtain the debris size distribution. It was observed that the average debris size in case of the fully-flooded condition was much smaller than that of the partially-flooded condition at the same jet injection velocity. This is because the entrained air layer between the melt and water acted as like vapor film in boiling condition. The prediction of most probable debris size by the model based on Kelvin-Helmholtz instability showed a good agreement with the experimental data. The jet breakup tests were also simulated using the TRACER-II code, which is a two-dimensional, transient, four-fluid code that can calculate the mixing and propagation of energetic fuel-coolant interactions. The test results were used to improve the jet breakup models of the code as well as to validate the code.

1. Introduction

In light water reactor core melt accidents, the molten fuel can be brought into contact with coolant water in the course of the melt relocation in-vessel and ex-vessel as well as in an accident mitigation action of water addition. For the last several decades, 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 the melt droplet sizes are, therefore, the key physical parameters in the analysis of FCIs (OECD, 2007).

An ex-vessel steam explosion may occur when the core melt is released from the failed reactor vessel lower head into the water-filled reactor cavity. The water level in the cavity can be either below or above the reactor vessel lower head depending on the severe accident management strategy. The former, a partially-filled cavity with free-fall air space for the melt jet, has been the major condition for the steam explosion studies in the past. The In-Vessel Retention by External Vessel Cooling (IVR-ERVC) strategy, however, requires the water level in the cavity be above the reactor vessel lower head so that the vessel lower head is completely submerged in coolant water. In this case, if the IVR-ERVC strategy fails the melt jet falls in liquid water without free fall in

* Corresponding author.
E-mail address: khbang@hhu.ac.kr (K.-H. Bang).

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Nomenclature

D	Diameter [m]
Fr	Froude number, $V/(gd)^{0.5}$
H	pool depth [m]
h	heat transfer coefficient [W/m^2 K]
i_{fus}	latent heat of fusion [J/kg]
k	wave number [m^{-1}]
g	gravitational constant [m/s^2]
V	velocity [m/s]
We	Weber number, $V^2 d\Delta\rho/\sigma$
Greek letters	
λ	wave length [m]
ρ	density [kg/m^3]
σ	surface tension [N/m]
Subscripts	
c	critical
D	fastest growing
in	inlet
j	jet
l	liquid
P	prototypic material
S	simulant material

air space. The jet breakup behavior in such a condition has been rarely studied, nor well identified.

The subject of liquid jet breakup has been widely studied in various engineering fields such as chemical reactors, spray, and liquid fuel injectors. In chemical engineering, for example, production of liquid drops from liquid issued from a nozzle has been largely investigated since the breakup of liquid column enlarges surface area for mass transfer. In general, drop formation or breakup of liquid issued from a nozzle can be divided into three regimes: (1) drop formation at the nozzle, (2) jet breakup, and (3) atomization at the nozzle (Sadhal et al., 1997). The primary parameter that controls the breakup regime is known as the liquid velocity at the nozzle. Scheele and Meister (1968) reported experimental data and prediction models for drop size and jetting velocity, below which the liquid disintegrates into droplets at the nozzle. Skelland and Johnson (1974) studied jet breakup in liquid-liquid systems and presented empirical correlations for drop size and jet breakup length. Most of the data and models obtained in these work are limited to small-diameter jets, less than 10 mm.

In ex-vessel fuel-coolant interactions of nuclear reactor severe accident, the corium jet issues from a breach of reactor vessel lower head and the diameter of a breach, if assumed circular, can be as large as 500 mm. This implies that the jet breakup information obtained in small-diameter jets may not be applicable to large-diameter jets of nuclear reactor cases. The length scale that can be used to divide small and large diameter jets is the capillary length scale, or more specifically, the critical wave length of Rayleigh-Taylor instability given by Eq. (1). Applying the corium properties given in Table 1, this length scale is near 20 mm.

$$\lambda_c = 2\pi\sqrt{\frac{\sigma}{(\rho_j + \rho_l)g}} \tag{1}$$

For corium jet breakup, analytical as well as empirical models have been proposed. Saito et al. (1988) proposed a correlation for jet breakup length based on their experimental data of simulant jet and coolant materials. Kondo et al. (1995) also performed an experiment of jet breakup using Woods metal for LMFBR safety study. Recently, Manickam et al. (2014) conducted a jet breakup experiment using Woods metal under no film boiling and their high-resolution visualization data was compared with their numerical simulation of jet breakup using a CFD code (Thakre et al., 2015). There were also analytical model developments that have been incorporated into a computer code for fuel-coolant interactions (Moriyama et al., 2006, 2016; Pohlner et al., 2006).

Epstein and Fauske (1985) presented a linear Kelvin-Helmholtz Instability (KHI) analysis for the mixing of core melt jet and water. They derived the dispersion equation for the growth constant for the disturbed motion of the core melt, steam and liquid water. In the general case, this equation is complex and cannot be solved analytically. They presented analysis on the two limiting cases of thin steam layer and thick steam layer. Bang et al. (2014) obtained numerical solutions of the complex-variable dispersion equations proposed by Epstein and Fauske and they proposed correlations for the fastest growing wave number and growth rate that can be used in FCI computer codes.

In the present study, the breakup of the melt jet released from the submerged vessel as well as free-fall geometry has been experimentally investigated using simulant melt of Woods metal. The preliminary results have been reported in earlier conferences (Bang and Kim, 2014; Kim and Bang, 2016). The initial melt temperature was set below the boiling point of water so that only the hydrodynamic mechanism of jet breakup can be identified. High-speed videos were taken to visualize the jet breakup behavior and the post-test debris were collected and sieved to obtain debris size distributions for two conditions.

2. Experiment

An experimental facility, called COLDJET, has been constructed in order to investigate the hydrodynamic mechanisms of jet

Table 1
Physical properties of corium and Woods metal.

Properties	Corium (OECD, 2007)	Woods metal (Bang et al., 2003a)
Composition	UO_2 80% + ZrO_2 20%	Bi 50% + Pb 27% + Sn 13% + Cd 10%
Melting temperature, °C	2609	72
Density, kg/m^3	7300	9383
Specific heat, J/kg K	510	168
Thermal conductivity, W/m K	3.0	18.8
Dynamic viscosity, Pa/s	0.005	0.002
Surface tension, N/m	0.573	~1.0
Latent heat of fusion, J/kg	280,000	33,500