Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

An Experimental Study on the Breakup of Simulant Melt Jet Released from the Submerged Reactor Vessel Lower Head

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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 [1].

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 space for the melt jet, has been the major condition for the steam explosion studies in the past. An In-Vessel Retention by External Vessel Cooling (IVR-ERVC), however, requires the water level in the cavity be above the reactor vessel lower head so that the vessel can be completely submerged in coolant water. In this case, the melt jet falls in liquid water without free fall. The jet breakup behavior in such a condition has been rarely studied, nor well identified.

In this work, jet breakup of the melt released from the submerged vessel has been experimentally investigated using stimulant melt of Woods metal. 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.

2. Experimental Apparatus

The experimental apparatus consisted mainly of melt generator, intermediate melt catcher with quick-opening slide valve, and water pool tank. A schematic diagram and a picture of the experimental apparatus are shown in Fig. 1.

The melt generator has a stainless steel crucible placed inside a cylindrical radiant heater of 2.7 kW rating and it is placed inside a sealed steel container for pressurization purpose to vary the initial melt jet speed. A set of temperature controller and K-type thermocouple was used to control the melt temperature. It was designed to produce and deliver up to 15 kg of molten Woods metal.

To deliver melt jet directly into the water pool without passing in air space, an intermediate melt catcher was designed and coupled with the melt generator. It has a pneumatically-operated quick opening valve with circular hole of 50 mm at the bottom. This valve pack was submerged in water pool.

The water tank was an open-topped rectangular box, made of transparent glass wall for the visualization purpose. The tank dimension is 0.6 m in each side, 1.0 m of pool depth. A high-speed video camera was set to visualize the jet breakup process. The water temperature in the tank was controlled using an electric water heater.

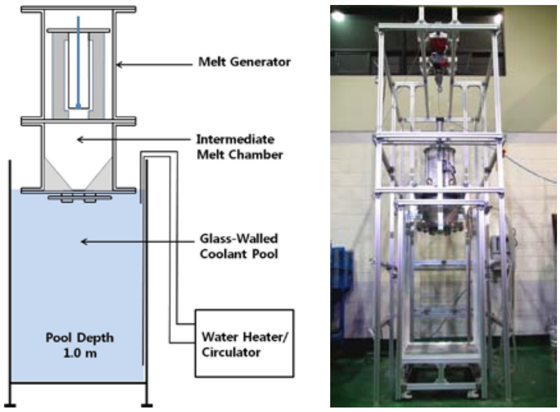

Fig. 1. Jet Breakup Experimental Apparatus

3. Experimental Results and Analysis

The jet breakup experiments were conducted using 50 mm-diameter Woods metal jet. The melt mass was 15 kg and the melt temperature was 85^{o}C to prevent water from boiling. The water temperature was set at 50^{o}C. The initial jet velocity was ~1.5 m/s, obtained from the video image analysis. Some selected physical properties of Woods metal are given in Table 1.

Table 1: Physical properties of Woods metal [2]

Melting temperature	72^{o}C
Density	9383 kg/m^3
Specific heat	168 J/kgK
Thermal conductivity	18.8 W/mK
Kinematic viscosity	2x10^{-7} m^2/s
Surface tension	~1.0 N/m

The breakup of Woods metal liquid jet released directly into water pool was visualized and the images of 0.1 second apart are shown in Fig. 2. 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. It is well known that the jet breakup at the leading edge is due to boundary layer stripping at the jet leading edge and the lateral breakup is due to the Kelvin-Helmholtz instability at the melt-water interface. These jet breakup mechanisms were well visualized in the present experiments.

Fig. 2. Jet breakup snap shot every 0.1 s (D_{jet} = 50 mm, V_{jet} = ~1.5 m/s)

The debris were collected, dried, and sieved. The six levels of sieve size were 0.5, 1.0, 2.8, 4.75, 9.5, and 15.9 mm. The debris size distributions of three tests at the identical conditions are shown in Fig. 3. The nearly identical size distributions confirmed good repeatability of the experiments. Some of the jet was remained as a cake in the water tank and the mass of this cake was indicated as the sieve size of 20 mm in Fig. 3. The sieve size of the largest mass was 4.75 mm.

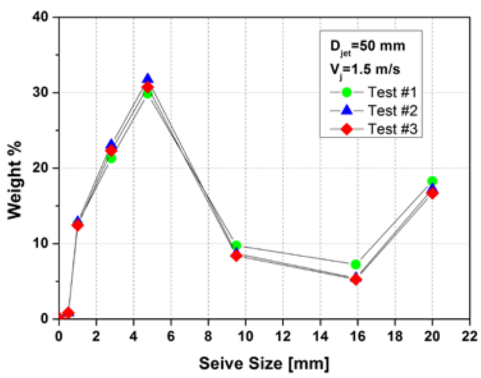

Fig. 3. Debris size distribution (D_{jet} = 50 mm, V_{jet} = ~1.5 m/s)

A linear Kelvin-Helmholtz instability analysis was presented by Epstein and Fauske [3] 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. In the present experimental condition, however, only the melt and liquid water interface is relevant since the jet was released directly into the liquid water. In this case, the fastest growing wave number, $k_{D,}$ is

$$k_D = \frac{2\rho_j \rho_l (V_l - V_j)^2}{3(\rho_j + \rho_l)(\sigma_j + \sigma_l)} \qquad (1)$$

The k_D can be used in calculating the drop size from jet breakup by assuming the drop size to be the corresponding wave length. When applying Eq. (1) to the Woods metal-water interface, the $k_{D,}$ = 1280 and the λ_D = 4.9 mm. This length scale of debris size fairly agrees with the sieve size of the largest mass of debris as seen in Fig. 3.

4. Conclusions

Non-boiling liquid jet breakup experiment was conducted using 50 mm-diameter Woods metal jet released from a vessel submerged in water pool. The post-test debris was sieved and the debris size distributions were obtained. The size of the largest mass of the debris shows a fair agreement with the debris size prediction of Kelvin-Helmholtz instability model.

REFERENCES

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