Breakup Behavior of Molten Wood's Metal Jet in Subcooled Water

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1. Introduction

There are safety characteristics of the metal fueled sodium fast-cooled reactor (SFR), by identifying the possibility of early termination of severe accidents. If the molten fuel is ejected from the cladding, the ejected molten fuel can interact with the coolant in the reactor vessel. This phenomenon is called as fuel-coolant interaction (FCI). The FCI occurs at the initial phase leading to severe accidents like core disruptive accident (CDA) in the SFR. A part of the corium energy is intensively transferred to the coolant in a very short time during the FCI. The coolant vaporizes at high pressure and expands so results in steam explosion that can threat to the integrity of nuclear reactor. The intensity of steam explosion is determined by jet breakup and the fragmentation behavior. Therefore, it is necessary to understand the jet breakup between the molten fuel jet and the coolant in order to evaluate whether the steam explosion occurs or not [1, 2].

The liquid jet breakup has been studied in various areas, such as aerosols, spray and combustion. In early studies, small diameter jets of low density liquids were studied [3]. The jet breakup for large density liquids has been studied in nuclear reactor field with respect to safety. The existence of vapor film layer between the melt and liquid fluid is only in case of large density breakup [2].

This paper deals with the jet breakup experiment in non-boiling conditions in order to analyze hydraulic effect on the jet behavior. In the present study, the wood's metal was used as the jet material. It has similar properties to the metal fuel. The physical properties of molten materials and coolants are listed in Table I, respectively. It is easy to conduct the experiment due to low melting point of the wood's metal.

Table I. Physical properties of molten materials and coolants

	Metal fuel	Wood's metal	Sodium	Water
Density [kg/m^3]	14100	9383	966	998
Surface tension [N/m]	0.573	~ 1.0	0.200	0.073
Viscosity [mPa·s]	$5 \cdot 10^{-3}$	$1.877 \cdot 10^{-3}$	1.125	1.002
Melting / Boiling point [℃]	1077 / (-)	72 / (-)	(-) / 881	(-) / 100

2. Experiment

2.1 Experimental apparatus

A schematic diagram of the experimental apparatus to test jet breakup in subcooled water is shown in Fig. 1. The experimental apparatus is composed of crucible for molten wood's metal and a water pool tank. The water tank has rectangular geometry made of acryl with 0.07 m width and 0.4 m height. The acryl enables to visualize the behavior of the jet breakup in the subcooled condition. The jet nozzle installed at the bottom of the crucible is wrapped with heating cable to keep the wood's metal melting during the injection.

The behavior of the molten wood's metal jet in the water pool was observed by a high-speed video camera(Phantom, v9.1). The time resolution of the video images is 0.01s. The velocity fields of the jet breakup was measured by the PIV(Particle Image Velocimetry) technique. A CCD camera and ND:YAG laser which is double-oscillator laser($\lambda = 532$nm) were used for the measurement instrument.

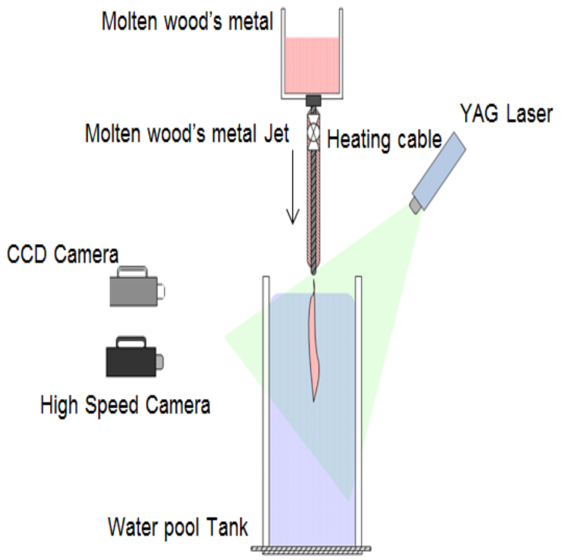

Fig. 1 Schematic diagram of experimental apparatus

Table II. Experimental conditions

Molten Wood's Metal Jet			Water
Diameter (mm)	Impinging Velocity(m/s)	Temperature (℃)	Temperature (℃)
6.95	2.80	90	21.5
6.95	3.10	90	21.5
9.30	2.80	90	21.5
9.30	3.10	90	21.5

2.2 Experimental procedure

The experimental conditions of the present study are listed in Table II. For the phenomenological observation of the jet breakup, the experimental conditions were set up to get visibility for the result. The jet velocity could be controlled by the static falling method and ejection method. The static falling method uses the gravitational force. The method is as follows. The molten material in the crucible is statistically put into the water pool. On the other hand, the ejection method pressurizes the molten material by the nitrogen gas. Then, the stop plug in the crucible is drawn out to eject the molten material into the water pool. The latter has efficient space placement to the experimental setup, but the turbulence is generated around the nozzle when the molten material is ejected by the pressure. The turbulence can affect the behavior of the jet breakup, so static falling method was adopted for the experiment [4].

After each experiment, the debris of the jet was collected, dried and sieved to analyze characteristics of the jet breakup. Then the debris was distributed according to the debris size.

3. Experimental results

3.1 Behavior of molten wood's metal jet

A time-series of the behavior of molten wood's metal jet under each experimental condition is shown in Fig.2 to 5. Figure 2 and 3 showed the behaviors of the jet with different velocities of 2.8 m/s and 3.1 m/s when the nozzle inner diameter is 6.95 mm. In the case of nozzle with inner diameter of 9.30 mm, the behaviors are shown in Fig. 4 and 5 for the two velocities. All experiments showed that the breakup occurred instantly

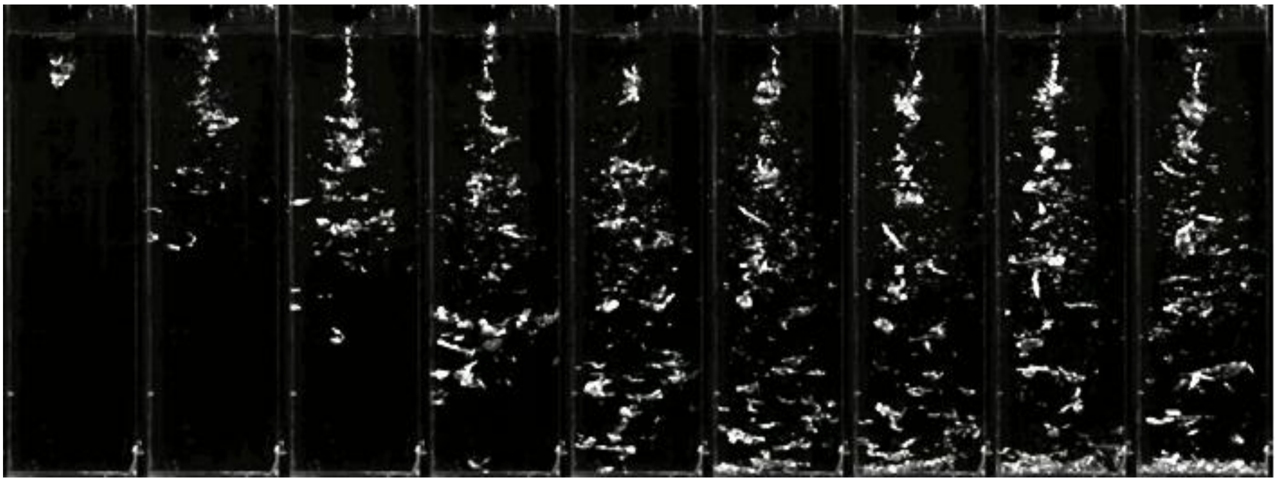

Fig. 2 Breakup behavior of molten wood's metal for the jet diameter of 6.95 mm and the jet velocity of 2.8 m/s

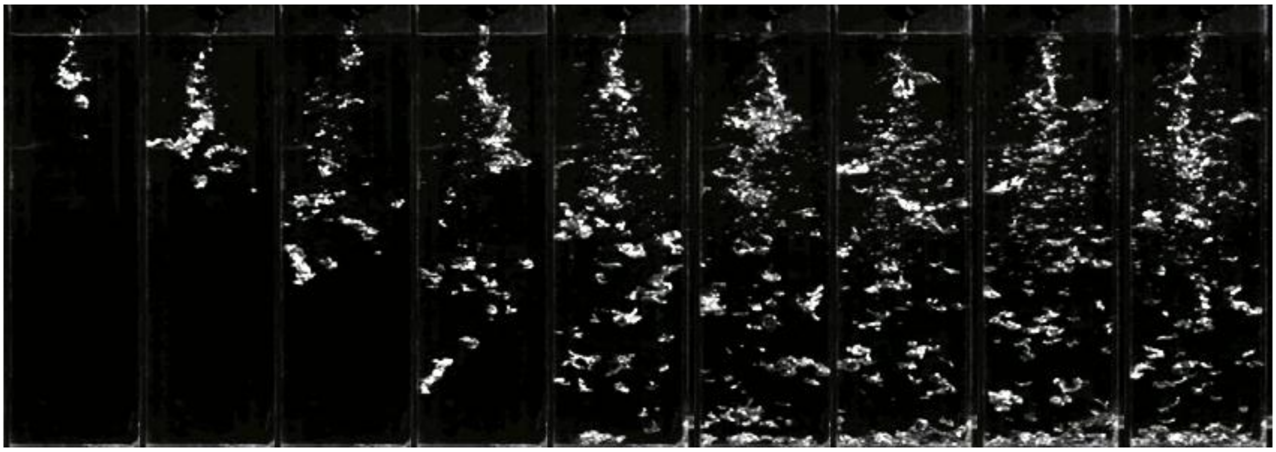

Fig. 3 Breakup behavior of molten wood's metal for the jet diameter of 6.95 mm and the jet velocity of 3.1 m/s

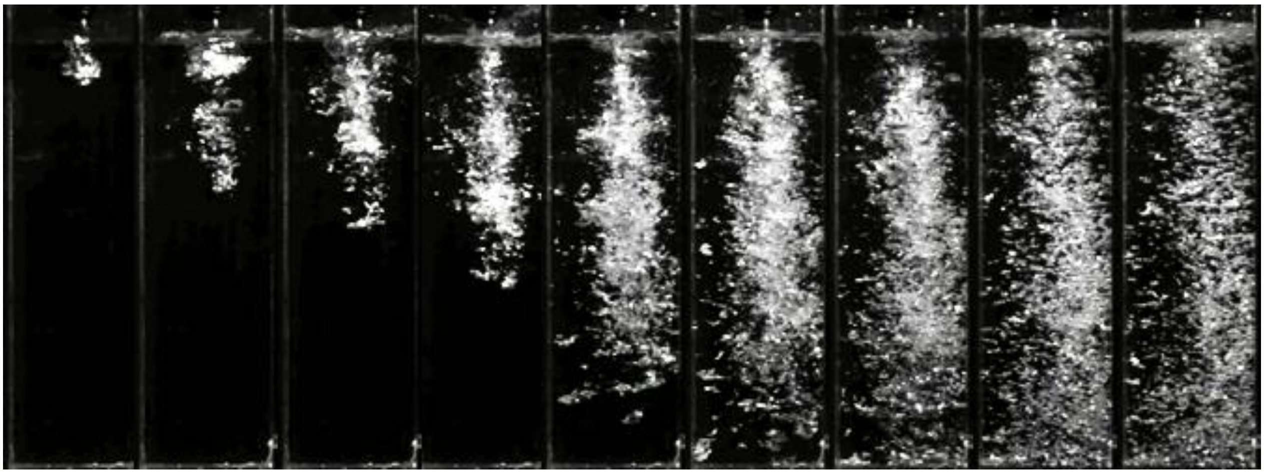

Fig. 4 Breakup behavior of molten wood’s metal for the jet diameter of 9.30 mm and the jet velocity of 2.8 m/s

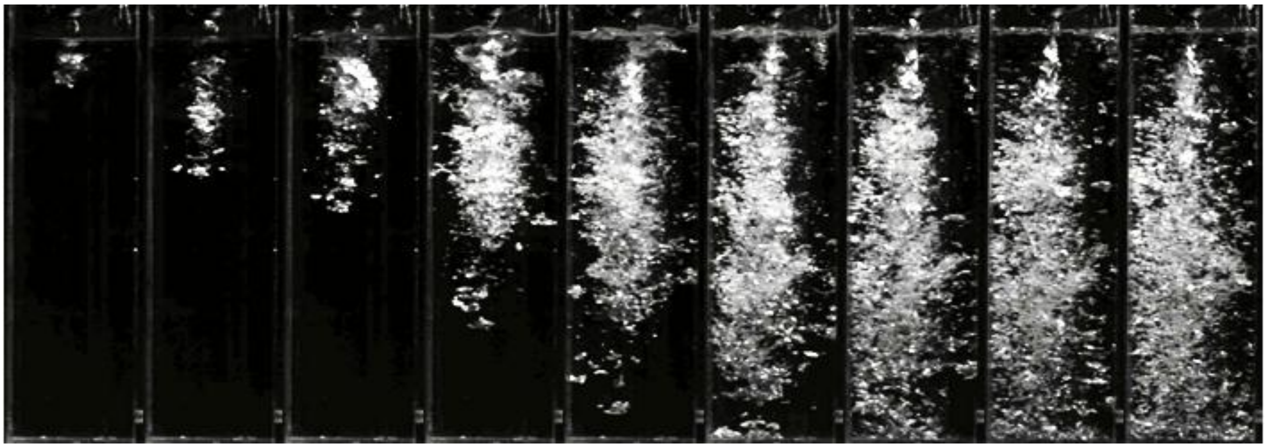

Fig. 5 Breakup behavior of molten wood’s metal for the jet diameter of 9.30 mm and the jet velocity of 3.1 m/s

as the jet contacted with the water and the fragmented debris moved in radial direction. However, there were some differences between experimental conditions. As shown in Fig. 2 and 3, there was no significant difference according to changes in the jet velocity. Generally the breakup rate strongly depends on the jet velocity but the density ratio affects the breakup behavior most significantly at low jet velocity(< 4.5 m/s) [5].

For the nozzle with diameter of 9.30 mm, extensive breakup occurred as the jet entered the water pool. It was observed that the more molten wood’s metal is ejected, the debris moved strongly in radial direction. During the ejection, the entrained air and non-condensable gases in the water were released as shown in Fig. 4 and 5. This made the jet breakup shown more vigorously.

3.2 Debris shapes and sizes

After the jet breakup, the debris was stacked on the bottom of the tank. The debris was gathered to be sieved using different apertures. The gathered debris in the experiment is shown in Fig. 6. The fragmented debris was observed in a various shape from sphere-like to flat sheet-like. The debris shapes were determined surface solidification and contact conditions between two fluids [6].

The debris size distributions for the different diameters are shown in Fig. 7 and 8. For the condition of the inner diameter of 6.95 mm and the jet velocity of 2.8 m/s, the debris size of 22 mm gave the largest mass fraction, 39%. For higher jet velocity of 3.1 m/s, the debris size of 14 mm gave the largest mass fraction, 36%. For the nozzle with the diameter of 9.30 mm, the size distribution was different. For jet velocity of 2.8 m/s, the debris size of 14 mm gave the largest mass fraction, 36%. For higher jet velocity of 3.1 m/s, the debris size of 14 mm gave the largest mass fraction, 50%. It means that the debris size decreases as either the diameter or the jet velocity increases [2, 7].

Fig. 6 Debris of molten wood’s metal

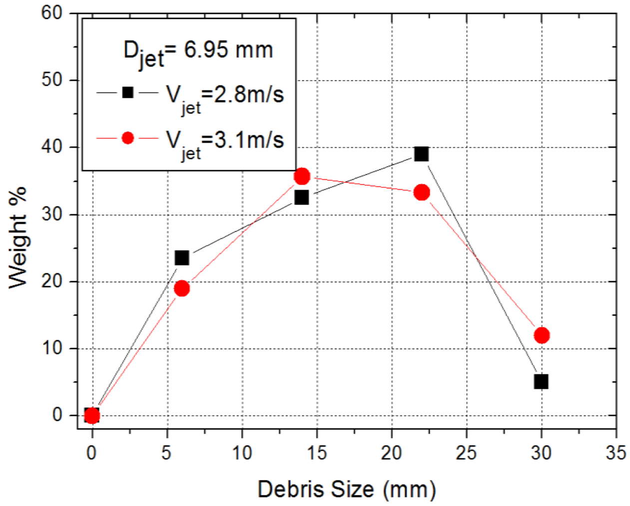

Fig. 7 Debris size distribution of 6.95 mm jet diameter

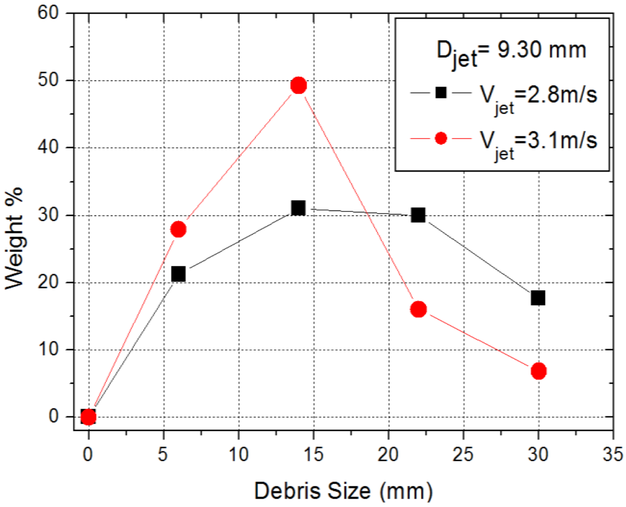

Fig. 8 Debris size distribution of 9.30 mm jet diameter

3.3 Velocity fields during jet breakup

The extensive jet breakup was observed depending on the nozzle diameter. The present study measured the velocity field using PIV technique to analyze the jet behaviors. Figure 9 and 10 show the velocity fields for the different diameters of 6.95 mm and the 9.30 mm when the jet velocity is 2.8 m/s.

The velocity of the water flow was about 0.18 m/s regardless of the pool height and the directions was irregular. Based on the results, the jet breakup occurred in the various directions including the vertical direction following ejected jet. As shown in Fig. 9 and 10, an error region caused by exceptional velocities was measured in the bottom of the pool. Also, the boundary region between the molten wood's metal and the water

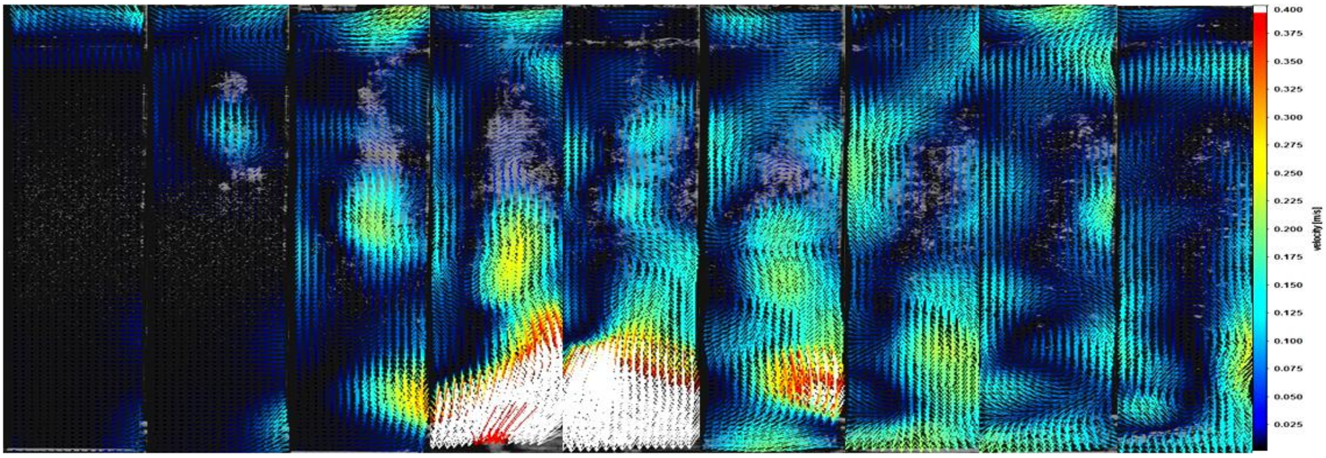

Fig. 9 Velocity fields for the jet diameter of 9.30 mm and the jet velocity of 2.8 m/s

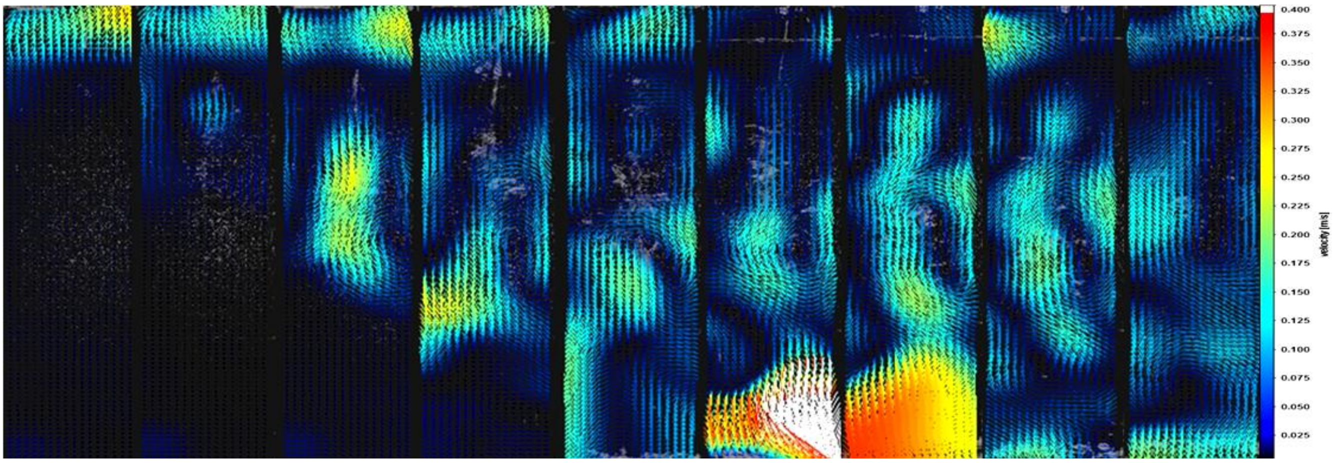

Fig. 10 Velocity fields for the jet diameter of 9.30 mm and the jet velocity of 3.1 m/s

was not measured. The reason for the errors is that the wood's metal is metal. The light reflectance of the wood's metal is so high that it acts as a disturbance in the PIV measurements.

4. Conclusions

In order to clarify the dominant factors determining jet breakup and size distribution of the debris, the experiment that the molten wood's metal was injected into the subcooled condition was conducted. The behaviors of the jet breakup were visually compared between each experimental condition. The behaviors were observed by using a high-speed video camera and PIV technique. Conclusions of the study are as follows:

1. The inner nozzle diameter affects the jet breakup. The breakup occurred extensively when the diameter increased. Consequently, that the jet breakup rate increased as the diameter increased through the analysis of the debris size distribution.
2. It turned out that the behavior of the jet breakup was quite different according to the jet velocity. In case of low jet velocity like the present experiment, the density ratio of the jet and the coolant affected jet breakup dominantly. It was observed phenomenologically that the jet breakup rate increased as the jet velocity increased. The tendency meets the hydrodynamic instability theory.
3. From the visual data using a high-speed camera and PIV technique, the jet was broken at the front, side part of the jet. If the PIV measurement technique is improved regarding the light reflectance between jet and seeding particle, quantitative analysis of the jet breakup can be possible.

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