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Flow transition criteria of a liquid jet into a liquid pool

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HIGHLIGHTS

- Jet breakup and droplet formation in immiscible liquid-liquid systems was studied experimentally.
- The observed jet breakup behavior was classified into characteristic regimes.
- The droplet size distribution was analyzed using image processing.
- The variation of droplet size was compared with available melt-jet experiments.
- Extrapolation to the expected SFR conditions implied that most of the hydrodynamic conditions would be the atomization regime.

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ABSTRACT

To better understand the fundamental interactions between melt jet and coolant during a core-disruptive accident at a sodium-cooled fast reactor, the jet breakup and droplet formation in immiscible liquid-liquid systems were studied experimentally. Experiments using two different pairs of test fluids were carried out at isothermal conditions. The observed jet breakup behavior was classified into characteristic regimes based on the classical Ohnesorge classification in liquid-gas systems. The variation in breakup length obtained in the present liquid-liquid system was similar to that in a liquid-gas system. The droplet size distribution in each breakup regime was analyzed using image processing and droplet formation via pinch-off, satellite formation, and entrainment was observed. The measured droplet size was compared with those available from melt jet experiments. Based on the observation and analysis results, the breakup regimes were organized on a dimensionless operating diagram, with the derived correlations representing the criteria for regime boundaries of a liquid-liquid system. Finally, the experimental data were extrapolated to the expected conditions of a sodium-cooled fast reactor. From this, it was implied that most of the hydrodynamic conditions during an accident would be close to the atomization regime, in which entrainment is the dominant process for droplet formation.

1. Introduction

The next generation of nuclear reactors is likely to include sodium-cooled fast reactors (SFRs), which are designed to shut down passively and non-energetically in the event of a core-disruptive accident (CDA) (Suzuki et al., 2014a). Even if the event is non-energetic, a considerable amount of the fuel may melt in the core region. Therefore, it is essential that this core material can be held in the reactor vessel for a long time after it has solidified and cooled sufficiently. In other words, post-accident heat removal (PAHR) must be part of the safety assessment. Fig. 1 depicts a possible CDA scenario in which the molten core material enters the coolant as melt jets. It is therefore particularly important in PAHR to be able to estimate and evaluate the behavior known as jet breakup or fragmentation in the coolant. A fair amount of coolant (liquid sodium) could remain during a CDA in an SFR, unlike a loss-of-coolant accident in a light-water reactor. Qualitatively, the melt jets in an SFR accident are considered to fragment, of which would prevent the reactor structure from being attacked by concentrated jets, as well as helping the generated debris to cool down more quickly.

However, it would be very difficult to investigate the breakup of a melt jet directly in an SFR using actual materials. Instead, a scoping study of the fundamental process is an effective approach to understanding the actual situation. To date, there have been many experimental efforts under various conditions that have been aimed at clarifying the melt-coolant interaction, including UO_2 into

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Nomenclature

d	droplet diameter
D_{j0}	nozzle diameter
Fr	Froude number
L	breakup length
n	number of droplets
Oh	Ohnesorge number
Re	Reynolds number
u_{j0}	jet velocity
u_s	settling velocity
We	Weber number

Greek symbol

γ	density ratio
η	viscosity ratio
μ	dynamic viscosity
ρ	density
σ	interfacial tension or surface tension

Subscript

a	ambient
c	continuous phase (ambient)
cr	critical state
j	dispersed phase (jet)
m	mass median

sodium (Magallon et al., 1992; Schins and Gunnerson, 1986), molten oxide into sodium (Kaiser et al., 1998; Matsuba et al., 2015; Schins and Gunnerson, 1986), molten metal into sodium (Kaiser et al., 1998; Matsuba et al., 2016a; Nishimura et al., 2010; Schins and Gunnerson, 1986), corium into water (Huhtiniemi and Magallon, 2001; Magallon, 2006; Magallon and Huhtiniemi, 2001; Spencer et al., 1994), molten oxide into water (Kaiser et al., 2001; Karbojian et al., 2009; Kudinov et al., 2013; Manickam et al., 2014, 2016; Moriyama et al., 2005) and molten metal into water (Abe et al., 2006; Bang et al., 2003; Bang and Kim, 2014; Bürger et al., 1995; Cho et al., 1991; Dinh et al., 1999; Iwasawa et al., 2015b, 2015c; Kondo et al., 1995; Mathai et al., 2015; Matsuo et al., 2008; Pillai et al., 2016; Spencer et al., 1986; Wei et al., 2016). The aim of all these experiments and tests was not limited to understanding a CDA in an SFR; a severe accident in a light-water reactor was also included as a possible scenario.

In the context of FARO/TERMOS, Magallon et al. (1992) performed two experiments that involved pouring 100 kg-scale molten UO_2 into sodium. These experiments are often referenced as T1 and T2. Part of the debris was collected to analyze the size distribution of particles that settled in the test section. The evaluated particle sizes were in the range of 10^1–10^3 μm. The penetration distance of the melt was estimated to be as much 1 m, whereas the released diameters were 50 mm (T1) and 80 mm (T2). Suzuki et al. (2014a) pointed out that the distance was much smaller than that predicted by the Saito correlation (Saito et al., 1988) [see Fig. 22 in Suzuki et al. (2014a)]. Recently, Matsuba et al., carried out experiments involving molten aluminum (Al) into sodium (Matsuba et al., 2016a) and molten alumina (Al_2O_3) into sodium (Matsuba et al., 2016b). Although the debris that settled onto the bottom of the test section could be collected after the experiments, it was difficult to visualize and observe the jet breakup process in detail.

During the interactions between melt jet and coolant, thermal interactions (e.g., surface freezing or coolant-vaporization) and hydrodynamic interactions (e.g., interfacial instability between two fluids, such as Kelvin–Helmholtz/Rayleigh–Taylor instabilities, and liquid entrainment or stripping from the interface) are considered to occur simultaneously. In an SFR accident, there may be no significant vapor film on the jet surface (Kondo et al., 1995; Suzuki et al., 2014a), thus it is important to investigate the jet breakup behavior under the condition of liquid-liquid direct contact. Separate investigations of these thermal and hydrodynamic interactions would help to further understand the fundamental processes of jet breakup. Hence, a number of experimental studies have focused on the hydrodynamic interactions by using various test fluids in immiscible liquid-liquid systems (Abe et al., 2007; Dinh et al., 1999; Kuroda et al., 2012; Saito et al., 2014a,b, 2016a,c). Recently, the literature has been supplemented by numerical studies on jet breakup in immiscible liquid-liquid systems by using the volume-of-fluid method (Thakre et al., 2015), the advanced interface tracking method (Suzuki et al., 2014b), and the lattice Boltzmann method (Iwasawa et al., 2015a; Matsuo et al., 2015; Saito et al., 2016b).

As mentioned above, the hydrodynamic interaction is considered to be an important factor in melt-jet breakup. Nishimura et al. (2010) suggested a hydrodynamic fragmentation model that agreed well with their copper/sodium experiments at high ambient Weber numbers (>200). The ambient Weber number,

$$We_a = \frac{\rho_c u_{j0}^2 D_{j0}}{\sigma}, \tag{1}$$

is often used to characterize the jet breakup length (Bürger et al., 1995; Ginsberg, 1985; Thakre et al., 2015) and the diameters of the resulting fragments (Matsuba et al., 2016b; Nishimura et al., 2010). Matsuo et al. (2008) concluded from their melt-water experimental data that the dominant effect on jet breakup was the shear force that acted on the interface. They further concluded that, in such shear-force-dominated conditions, the Epstein–Fauske correlation (Epstein and Fauske, 2001) could be used to predict the jet breakup length. The key aspect of the Epstein–Fauske correlation is the assumption of entrainment on the basis of the Kelvin-Helmholtz instability. Epstein and Fauske (2001) indicates that their correlation agreed well with the previous data on breakup length, which are considered to be in the atomized state. The conditions for the appearance of atomized breakup in liquid-liquid systems is an issue that is yet to be clarified. Identifying those conditions would enables us to use a simplified physical model to predict breakup length and fragment diameter and hence be able to evaluate melt coolability (e.g., Abe et al., 2005, 2006).

The breakup of a liquid jet into droplets is itself an important phenomenon in natural and industrial processes, so the instability of liquid jets has been studied extensively [see the comprehensive reviews by Eggers and Villermaux (2008), Lin and Reitz (1998), and McCarthy and Molloy (1974)]. Based on his experimental observation, Ohnesorge (1936) showed that liquid jets generally falling into one of four regimes (Kolev, 2005; McKinley and Renardy, 2011):

(0) Slow dripping from the nozzle under gravity with no formation of a jet (dripping regime),
(I) Breakup of a cylindrical jet by axisymmetric perturbations of the surface (varicose regime),
(II) Breakup by screw-like perturbations of the jet (sinuous regime),
(III) Atomization of the jet (atomization regime).