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Review

Melt jet-breakup and fragmentation phenomena in nuclear reactors: A review of experimental works and solidification effects

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ABSTRACT

During severe accidents at Nuclear Power Plants (NPPs), fuel-coolant interaction (FCI) is a critical event in which the melt released from the core region comes into contact with the coolant. The melt may eject in the form of a melt jet and threaten the integrity of the NPP. Therefore, fragmentation of the melt jet and quenching of particulate fragments from the melt jet are invaluable from the viewpoint of safety assessment. To assess the integrity of an NPP, melt fragmentation phenomena that affects quenching and sustainable cooling of the debris bed are important factors that must be predicted and evaluated precisely. The present review summarizes experimental works on the FCI phenomenon, especially, fragmentation of a melt jet during a severe accident in an NPP. In addition, special attention is paid to solidification effects. Based on the literature survey, we discussed the dominant factors governing the fragmentation mechanisms. Furthermore, we discuss the applicability of various models for estimating these phenomena.

1. Introduction

For stabilization and termination of a severe accident in a Nuclear Power Plants (NPP), investigating the risks and the progression of the severe accident is important (Sehgal, 2006, 2012). During a severe accident in an NPPs, fuel-coolant interaction (FCI), critical event in which the melt released from the core region comes into contact with the coolant, needs to be assessed for ensuring NPP integrity. The melt may be injected in the form of a melt jet and threaten the integrity of NPPs such as Light Water Reactors (LWRs) (Ma et al., 2016; Sehgal and Bechta, 2016) and Sodium-cooled Fast Reactors (SFRs) (Suzuki et al., 2014; Tobita et al., 2016). Therefore, fragmentation of the melt jet (called as the jet-breakup), which means a coherent jet disappears in this paper, and quenching of the particulate fragments from the melt jet are invaluable from the viewpoint of safety assessment. For the safety assessment, it is important to predict and evaluate precisely the characteristic values of the jet-breakup and the fragmentation phenomena that affects the quenching and sustainable cooling of the debris bed (Dinh et al., 1999).

If a melt jet directly hits the internal structures without jet-breakup, it may threaten the integrity of a reactor vessel and, consequently, threaten the integrity of a containment vessel. Hence, *the jet-breakup length*, which refers to as the distance from the liquid (coolant) surface to the location where a coherent melt jet disappears (Chu et al., 1995; Matsuo et al., 2008; Iwasawa et al., 2015a; Li et al., 2017), is important. In addition, fine fragmentation of a melt jet may lead to vapor explosion, which threaten the integrity of the NPP. Even if vapor explosion does not occur, molten fragments may threaten the integrity of the NPP, when they directly hit the internal structures without quenching. In addition, fine fragmentation of a melt affects debris bed formation and decay heat removal. Therefore, it is important to estimate and evaluate *fragment size* from the viewpoint of safety assessment.

FCI phenomena of a melt jet, such as jet-breakup and fragmentation is known to be complex, mainly because of two interactions that occur simultaneously: hydrodynamic (e.g., interfacial instability at two-phase interface and liquid entrainment or stripping from interface), and thermal (e.g., coolant boiling and solidification of a melt surface) (Chu et al., 1995; Sugiyama et al., 1999; Nishimura et al., 2010; Manickam et al., 2017). Many experiments have been carried out using various combinations of melt and coolant. In addition to large-scale experiments using actual fuels, scoping experiments focusing on the fundamental processes of the FCI phenomena have also been carried out to investigate each interaction and the dominant factors governing the FCI phenomena.

The present review article summarizes experimental works on the FCI phenomena, especially, jet-breakup and fragmentation of a melt jet during a severe accident in NPPs. In addition, special attention is paid to solidification effects. Based on the literature survey, this article

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Nomenclature

d	characteristic length
D	bending stiffness
D_j	jet diameter
E	Young's modulus
E_0	entrainment coefficient
Fr	Froude number
g	gravitational acceleration
k	wave number
L_{brk}	jet-breakup length
P	pressure
t	time
T_i	initial interfacial temperature
ΔT_c	coolant subcooling
u	fluctuating velocity in horizontal direction
U	uniform velocity in horizontal direction
v	fluctuating velocity in vertical direction
V	uniform velocity in vertical direction
v_j	jet velocity
v_{rel}	relative velocity
x	horizontal direction
y	vertical direction

Greek symbol

δ	crust thickness
ε	Poisson's ratio
γ_t	temporal growth rate
γ_y	spatial growth rate
ϕ	velocity potential
η	displacement of interface
κ	thermal conductivity
λ	wavelength
λ_n	neutral-stable wavelength
λ_m	most-unstable wavelength
ρ	density
σ	interfacial tension or surface tension
ω	angular frequency

Subscript

0	initial
j, 1	melt jet
c, 2	coolant
s	sodium
w	water

discusses dominant the factors governing jet-breakup and fragmentation. Furthermore, this article discusses the applicability of various models for estimating these phenomena.

The remainder of this is organized as follows. In **Chapter 2**, previous experiments on FCI, including jet-breakup and fragmentation, are reviewed and summarized. These review and summary are presented in terms of melt and coolant composition. In **Chapter 3**, the dominant factors governing the jet-breakup of a melt jet are discussed based on the literature survey. In addition, existing models for estimating the jet-breakup length are presented based on their applicability. In **Chapter 4**, the dominant factors governing the fragmentation of a melt jet are discussed based on the literature survey. In addition, existing models for estimating the fragment size are presented based on their applicability. In **Chapter 5**, the solidification effects of the FCI phenomena are reviewed and summarized. A model for estimating the fragment size considering the solidification effects is presented. **Chapter 6** concludes this article.

2. Previous experiments on FCI phenomena

The following sections will summarize the previous experiments on the FCI phenomena in terms of melt and coolant composition. Given that the focus of this review article is on the jet-breakup and the fragmentation phenomena of a melt jet, the experiments considered herein are those involving injected melts weighing several hundred grams to several hundred kilograms (injected melt jets not melt droplets).

2.1. Oxide/sodium system

This section summarizes the previous experiments on the FCI phenomena involving oxide melt and sodium, which mainly target SFRs. They are summarized in Table 1.

In the M-Series experiments conducted in the Argonne National Laboratories (ANL) (Johnson et al., 1975; Sowa et al., 1979) and the FLAG experiments conducted in the Sandia National Laboratories (SNL) (Chu, 1982), uranium oxide melt was injected, with a focus on vapor explosion. Zagorul'ko et al. (2008) conducted the experiment using the

Table 1
Previous experiments on FCI phenomena conducted using oxide/sodium system.

Organization (Test facility or program)	Melt/Coolant	References
ANL (M-Series)	UO_2-Mo, UO_2-ZrO_2-SS/ Sodium	Johnson et al. (1975) Sowa et al. (1979)
SNL (FLAG)	Fe-Al_2O_3, UO_2-ZrO_2-SS/ Sodium	Chu (1982)
JRC (BETULLA)	UO_2, Al_2O_3/Sodium	Holtbecker et al. (1977) Schins (1984) Schins et al. (1984, 1986) Schins and Gunnerson (1986)
JRC (FARO/TERMOS)	UO_2/Sodium	Magallon et al. (1992)
JAEA (FR Tests)	Al_2O_3/Sodium	Matsuba et al. (2012, 2015a, 2015b, 2016)
IPPE (Pluton)	ZrO_2- Fe/Sodium	Zagorul'ko et al. (2008)