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Numerical simulation of fragmentation of melt drop triggered by external pressure pulse in vapor explosions

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ABSTRACT

The fragmentation of molten drops is the key process in the fuel–coolant interaction (FCIs) which may occur during the course of a severe accident in a light water reactor (LWR). However, the mechanisms of this complicated process cannot be clarified sufficiently by experimental studies due to the rapid reaction. In this paper, a multi-phase thermal hydraulic code with the volume of fluid method (VOF) is developed and the fragmentation process of melt drops triggered by external pressure pulse is numerically analyzed to investigate the mechanism of fragmentation in vapor explosions. The simulation results show that the fragmentation process can be divided into several stages, including vapor film collapse, melt drop-coolant direct contact, formation of high pressure spots, rapid growth of a filament around the molten metal drop, rapid fuel coolant interaction area expansion, breaking up of the filament, and mixing of fragments with water. The calculation results are similar to Ciccarelli and Frost's (Nucl. Eng. Des., 146, 109–132) experiment data. The simulation results suggest that growth and breaking up of a filament are the essential mechanism of melt tin drop fragmentation. Penetration and evaporation of the water jets, which are assumed as fragmentation mechanism in Kim's model (Nucl. Sci. Eng., 98, 16–28, 1988), are not observed. In the calculation case, when molten metal density is hypothetically smaller, the water penetration is observed. Besides, the effects of external pressure pulse and molten metal temperature on the growth of filament and the explosion bubble are discussed.

1. Introduction

Fuel–coolant interaction (FCI) could occur as the molten fuel relocates and eventually interacts with the coolant during a severe core melting accident in a nuclear power plant. In this process the rapid heat transfer from the high temperature molten metal to the cold coolant and the phase transition of the coolant can induce a vapor explosion which may threaten the containment integrity and cause the release of radioactive to the environment. Therefore vapor explosion is an important issue for safety design and assessment of risk of a severe core melting accident in a nuclear power plant (Theofanous, 1995).

The molten melt falls into the cold liquid and then the hydrodynamic instabilities break up the molten jet and disperse it into the coolant to form a coarse mixture (on the scale of 1 cm in the case of molten corium and water). After that, Film boiling occurs around the molten drops due to the large temperature difference and the vapor film separates the molten drops from coolant liquid. Under some conditions such as external pressure pulse, the vapor film can collapse, which allows the direct contact of molten metal with coolant and further causes the fragmentation of molten metal drops. The fragmentation of molten drops leads to a sharp increasing of the heat transfer area which evaporates the ambient liquid in a short time and generates high pressure pulse. Single drop triggered by a pressure pulse is important as a local simulation of large scale explosion in the coarse mixture.

Many experimental studies for vapor explosion of single drop have been done to obtain the visual information and investigate the mechanism of fragmentation (Nelson and Duda, 1981; Ciccarelli and Frost, 1994; Park, 2005; Takashima, 2008; Rongyuan, 2011). Based on the visual experimental results, a number of thermal fragmentation models have been proposed. Kim and Corradini (1988) postulated that the trigger pulse induced a collapse of the vapor film surrounding the drop until it became unstable by the Raleighe Taylor (RT) instability. The RT instability makes the water micro jet penetrate into drop and subsequent vaporization of the penetrated water led to the fragmentation of the drop. This kind of vapor bubble collapse and jet formation was observed in the cavitation phenomena. For this model, some results are raised on the forming of the micro jet and penetrating of micro jet into the hot drop. Yabe et al. (1995) and Koshizuka and Oka (1995) showed

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Nomenclature

A	amplitude of perturbation wave
e	energy per unit mass
h_{lg}	latent heat
k	curvature
L	filament length
m	mass
n	unit normal vector
P	pressure
r	melt drop semidiameter
R	interaction semidiameter
t	time
T	temperature
u	velocity in the x direction
v	velocity in the y direction

Greek symbols

α	fractional volume
Γ	volume expansion or contraction
δ	Dirac distribution; vapor film thickness

Vapor film thickness

μ	dynamic viscosity
ρ	density
σ	surface tension
λ	thermal conductivity; wave length
$\phi\varphi$	heat transfer rate
Ψ	heat transfer based on the spontaneous nucleation theory

Subscripts

0	initial value
i	phase index
l	liquid
v	vapor
m	molten metal
max	maximum
x	x direction
y	y direction

that jet penetration did not occur because the melt density is relatively larger than the jet fluid density. Ciccarelli and Frost (1994) provided a different mechanism where the RT instability of the vapor film induced a local contact between water and drop surface without penetration of water into the drop. The contact of water with the hot molten drop led to a local pressurization that caused drop surface instability and formed the interface unstable like a filament. Since the fragmentation occurs in a very short time, many of the details of the above models are highly speculative and cannot be supported by conclusive experimental evidence.

Thus, some researches tried to analysis the fragmentation process by using numerical tool. Koshizuka and Oka (1995); Koshizuka (1999) has numerically analyzed the fragmentation using the moving particle semi-implicit (MPS) method in which grids are not necessary. Incompressible flows with fragmentation on free surfaces have been calculated in his study. Two types of boiling processer, normal boiling and rapid boiling based on the spontaneous nucleation theory were examined. The result showed that the spontaneous nucleation temperature played an important role in vapor explosion. Xuewu et al. (2000) analyzed the interaction of molten metal drop and coolant numerically. The numerical results showed that the quick growth of spikes is the essential mechanism of fragmentation.

In the present study, a muti-phase thermal hydraulic code is developed and applied to simulate the thermal fragmentation processes of melt drops triggered by external pressure pulse. The volume of fluid (VOF) method based on piecewise linear interface construction (PLIC) is used to track liquid–vapor interface in the code. Vapor film collapse, melt drop-coolant contact and filament growth and breakup in the fragmentation process are simulated to investigate the mechanism of fragmentation. The effects of external pressure pulse, and molten metal temperature on the filament growth and the explosion bubble growth are examined.

2. Mathematical model

There are three fluids in the vapor explosion system, consisting of liquid coolant, vapor, and melt drops. For each fluid, continuity, momentum, and energy equations are presented:

Continuity equation:

$$\frac{\partial \rho_i \alpha_i}{\partial t} + \frac{\partial \rho_i \alpha_i u_i}{\partial x} + \frac{\partial \rho_i \alpha_i v_i}{\partial y} = \Gamma_i \tag{1}$$

Momentum equation:

$$\begin{aligned}\frac{\partial \rho_i \alpha_i u_i}{\partial t} + \frac{\partial \rho_i \alpha_i u_i u_i}{\partial x} + \frac{\partial \rho_i \alpha_i u_i v_i}{\partial y} &= \frac{\partial}{\partial x}\left(\mu_i \alpha_i \frac{\partial u_i}{\partial x}\right) \\ &+ \frac{\partial}{\partial y}\left(\mu_i \alpha_i \frac{\partial u_i}{\partial y}\right) - \alpha_i \frac{\partial p}{\partial x} \\ &+ \sigma_i k_i \delta_s n_x\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial \rho_i \alpha_i v_i}{\partial t} + \frac{\partial \rho_i \alpha_i u_i u_i}{\partial x} + \frac{\partial \rho_i \alpha_i u_i v_i}{\partial y} &= \frac{\partial}{\partial x}\left(\mu_i \alpha_i \frac{\partial v_i}{\partial x}\right) \\ &+ \frac{\partial}{\partial y}\left(\mu_i \alpha_i \frac{\partial v_i}{\partial y}\right) - \alpha_i \frac{\partial p}{\partial y} \\ &+ \sigma_i k_i \delta_s n_y\end{aligned} \tag{3}$$

Energy equation:

$$\begin{aligned}&\frac{\partial \rho_i \alpha_i e_i}{\partial t} + \frac{\partial \rho_i \alpha_i u_i.e._i}{\partial x} + \frac{\partial \rho_i \alpha_i v_i.e._i}{\partial y} \\ &= \frac{\partial}{\partial x}\left(\lambda_i \alpha_i \frac{\partial T_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_i \alpha_i \frac{\partial T_i}{\partial y}\right) + \phi_i\end{aligned} \tag{4}$$

where $i = l, v, m$, represent coolant liquid, vapor and liquid metal respectively. Surface tension in the above equations is treated with Continuum Surface Force (CSF) model (Brackbill et al., 1992). φ is a source for the latent heat due to phase change at the interface.

When evaporation or condensation occurs at the interface, Γ is related to the interfacial mass flux m.

$$mh_{lg} = (\vec{q_l} - \vec{q_v})\,\vec{n} + \Psi = \left(\lambda_l \frac{\partial T}{\partial n}|_l - \lambda_v \frac{\partial T}{\partial n}|_v\right) + \Psi \tag{5}$$

where $\vec{q_l}$ and $\vec{q_v}$ are heat flux vectors in liquid side and vapor side of the interface, $\vec{n}$ is the unit normal vector to the interface and Ψ is heat transfer based on the spontaneous nucleation theory (Iida and Okuyama, 1994).

The spontaneous nucleation occurs in the order of μs and much higher than other energy source (Inoue et al., 1992). Thus kinetic energy and viscous work are neglected in Eq. (5).

The properties in the cell are determined as below: