

Microarticle

Studies on hydrodynamic deformation and fragmentation of melt jet injected into water pool using level set method

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ABSTRACT

The molten core material (corium) that can be formed during severe accident scenarios in light water reactors (LWRs) can drop in the water pool and form a “melt jet” (hereafter referred to as “jet”) flow. We presented a numerical model to study the hydrodynamic deformation and fragmentation of a jet in the water pool using the Level Set (LS) method, despite that previous investigations had employed the widely used Volume-Of-Fluid (VOF) method. The effects of jet inlet speed, diameter and surface tension on the jet breakup length were studied and the results were in good agreement with previously performed experiments and with results obtained using the VOF method. The dimensionless jet breakup length was found to generally decrease with increasing jet inlet speed and increase with increasing jet diameter. In conclusion, the present model could successfully simulate the jet breakup in melt coolant interactions, and the results demonstrated a promising use of the LS method.

Introduction

Molten core material (corium) can be produced during a severe reactor accident as a result of inefficient core cooling and/or during loss of coolant accident (LOCA). The presence of water during the corium displacement in both in-vessel or ex-vessel release would lead to energetic fuel-coolant interactions (FCIs) [1–3]. During the interaction between molten corium with water, steam explosion would occur, which is mainly due to the large temperature difference between the corium and water. The FCI could be divided into premixing and explosion phases [4]. In the premixing phase, the “melt jet” (hereafter referred to as “jet”) flow of the corium into the water pool produced “molten fragments” (hereafter referred to as “fragments”) with varying sizes due to hydrodynamic fragmentation as a result of the relative velocity between the corium and water. The exposed surface area of the corium determined its heat transfer rate to its surrounding environment. Therefore, fragmentation of the jet as it propagated through water pool in the reactor should be precisely evaluated to reveal the underlying mechanisms of FCI. Various fragmentation models were reviewed by Fletcher and Anderson [3], and were categorized into two classes with focus on thermal and hydrodynamic effects. The leading edge of the jet would be deformed into a mushroom-like geometry due to the drag force during the premixing phase. The modes of jet breakup as well as breakup length were studied both theoretically and experimentally [5–10]. The jet breakup occurred as a result of two types of

instabilities, namely, (i) Rayleigh-Taylor (RT) and (ii) Kelvin-Helmholtz (KH) instabilities. The leading edge was more susceptible to RT instability due to deceleration of the jet in the medium (coolant or water) [5]. Moreover, due to the difference between the densities of corium and water, the leading edge of the jet broke up as a result of RT instability. For higher jet inlet speeds, the jet flow would become thinner due to the KH instability induced when the shear stress overcame the jet surface tension to cause the so-called “stripping” from the jet surface. The modes of jet breakup as well as breakup length were studied both theoretically and experimentally [5]. Thakre et al. [11] pointed out the complexity associated with the intermixing of the jet with water due to the simultaneous actions of many mechanisms. The authors performed 2-dimensional (2D) numerical simulation using Volume-Of-Fluid (VOF) method to study jet fragmentation at lower temperatures, which separately studied the hydrodynamic fragmentation under non-boiling conditions. In addition to the VOF method, the Level Set (LS) method was also a powerful approach in simulating two fluid problems [12–16]. As such, it would be worthwhile to examine jet fragmentation using the LS method to compare with the results obtained from the VOF method. In a previous paper, Rudman [17] remarked that “...the level set methodology does not guarantee volume conservation in highly distorted flows and this can give rise to unacceptable errors in the method...”. However, this remark might only be valid for the initially developed LS methods that were somehow oversimplified. Recent developments made the LS method more exhaustive and robust. In fact, the LS method

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was used in a variety of applications such as shape recognition [18], crystal growth, dendrite solidification [19], propagation of cold plasma in cell buffer medium [20], cold plasma mixing with blood [21] and study of the water droplet behavior during its impact on an isothermal solid surface [22]. The present model successfully simulated the jet breakup in jet-coolant interactions and the results demonstrated another promising use of the LS method.

Materials and methods

The LS method was used to track the evolution of the jet flow in the water pool. The interface was initialized at the contact between the water pool and the inlet at which the melt was injected into the water pool. The standard LS function which contained the LS variable ϕ would take different signs at different sides of the interface. In other words, the LS function detected the transition between the two phases using the Heaviside function. However, the abrupt changes between the two phases arising from the sign function would lead to numerical instabilities. To reduce these instabilities, particularly when the shape of the melt in the water pool significantly changed as a result of the jet breakup, the smeared-out Heaviside function was used:

$$H_s = \begin{cases} 0 & \phi < \epsilon \\ \frac{1}{2} + \frac{\phi}{2\epsilon} + \frac{1}{2\pi} \sin\left(\frac{\pi\phi}{\epsilon}\right) & -\epsilon \leq \phi \leq \epsilon \\ 1 & \phi > \epsilon \end{cases} \quad (1)$$

where ϵ was the mesh-dependent half thickness of the interface between the moving fluids in which the LS function varied mainly from 0 to 1. The final LS function was

$$\frac{\partial\phi}{\partial t} + \mathbf{u} \cdot \nabla\phi = \gamma \nabla \cdot \left(\epsilon \nabla\phi - \phi(1-\phi) \frac{\nabla\phi}{|\nabla\phi|} \right) \quad (2)$$

where γ was introduced for better numerical stability by reducing the oscillations in the LS function and at the same time keeping the interface thickness constant. The Navier-Stokes momentum and continuity equations were also used. As such, the 2D model was used in the present work, with dimensions of $100 \times 500 \text{ mm}^2$, which also made comparisons with previously reported results [11] possible. Fig. 1 schematically shows the 2D setup with the employed boundary conditions (BCs). The structure of the jet at different time intervals were obtained for three different jet inlet speeds, namely, 1, 5 and 10 ms^{-1} .

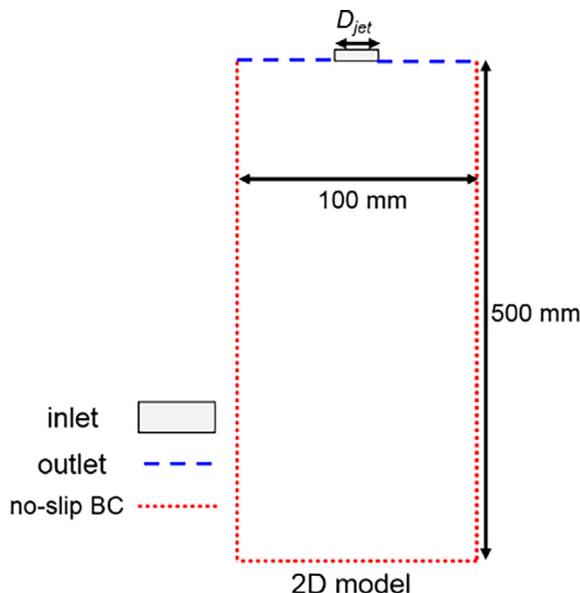


Fig. 1. Schematic diagram showing the 2D setup with boundary conditions (BCs) used in the present work.

The Wood’s metal (also known as Lipowitz’s alloy) is a eutectic alloy consists of 50% bismuth (Bi), 26.7% lead (Pb), 13.3% tin (Sn), and 10% cadmium (Cd) by weight, and is widely used to study the interaction between melt and water. The Wood’s metal has a low melting point of $\sim 70^\circ\text{C}$. Its properties used in the present model included: surface tension = 1 N/m ; density = 9700 kg/m^3 ; viscosity = $0.00194 \text{ Pa}\cdot\text{s}$. A grid sensitivity study was performed by considering three different grid resolutions with average sizes of ~ 0.66 , ~ 1.42 and $\sim 1.80 \text{ mm}$ and the number of element domains in each of the considered grids were 80,183, 15,996 and 10,400, respectively. All computations were performed in parallel on a supercomputer consisting of dual Intel Xeon E5-2630 v3 2.40 GHz using 32 physical cores and hyper-threaded to 64 and the average computational time was $\sim 363 \text{ min}$.

Results and discussion

Graphical representation

Hydrodynamic deformation of jets with different jet inlet speeds of 1, 5 and 10 ms^{-1} are shown in Fig. 2, with different time intervals. The jet diameter (D_{jet}) was set at 10 mm. The hydrodynamic deformation of the jet strongly depended on the jet inlet speed, which was governed by the instabilities in the jet flow. In Fig. 2(a), propagation of the jet in the water pool was less distorted and less stripping from the jet flow was observed. In contrast, severe stripping from the jet flow was observed for jet inlet speeds of 5 and 10 ms^{-1} as shown in Fig. 2(b) and (c). The severe distortion and stripping at higher jet inlet speeds were due to the dominance of Kelvin-Helmholtz (KH) instability. The leading edge of the jet was more susceptible to Rayleigh-Taylor (RT) instability due to deceleration of the jet in the surrounding medium (i.e., coolant/water) and therefore a mushroom-shaped leading edge was clearly displayed in the first time interval shown in Fig. 2(b) and (c). The jet breakup variations versus the jet inlet speed were due to formation of different breakup regimes, namely, (1) laminar, (2) transition, (3) turbulent and (4) atomization [5].

Grid sensitivity study

The results for three different grid resolutions with average sizes of ~ 0.66 , ~ 1.42 and $\sim 1.80 \text{ mm}$ are shown in Fig. 3. As the present study focused on the hydrodynamic deformation and fragmentation of a jet in the water pool, accurate capture of the interface between the jet and water was essential. Fig. 3 shows that the captured interface did not significantly vary for different grid resolutions. The results shown in later sections of the present paper were obtained using the average grid size of $\sim 1.42 \text{ mm}$ which corresponded to 15,996 element domains.

Jet breakup length versus jet inlet speed

The effect of jet inlet speed on the dimensionless jet breakup length is shown in Fig. 4. The results from our model were compared to those previously obtained from experiments and from the VOF method. The decreasing trend was explained by the variations in the breakup regime (i.e., laminar, transition, turbulent and atomization) and also the dominance of instabilities developed as a result of the jet flow in the water pool. At higher jet inlet speeds, the KH instability severely deformed the jet and led to its early breakup, which would not occur at lower speeds. In particular, KH instability would cause severe stripping from the jets and decreased the jet breakup lengths. Fig. 4 also showed that the distortion in the breakup regime intensified as the jet inlet speed increased, which agreed with the dominated deformation of the jet flow in the water pool by KH instability. Formation of fragments from the injected jet was also noticed in Fig. 4.

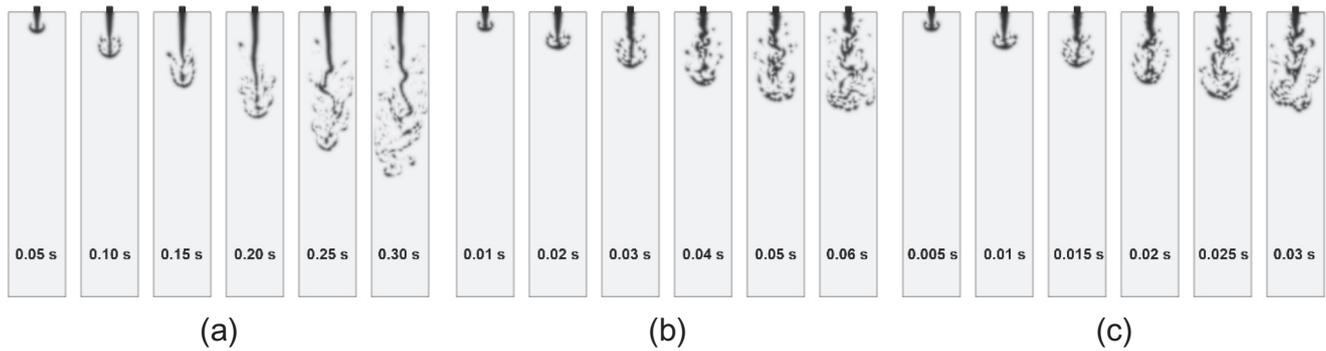


Fig. 2. Hydrodynamic deformation of jet injected into the water pool with jet inlet speed of (a) 1, (b) 5, (c) 10 ms⁻¹.

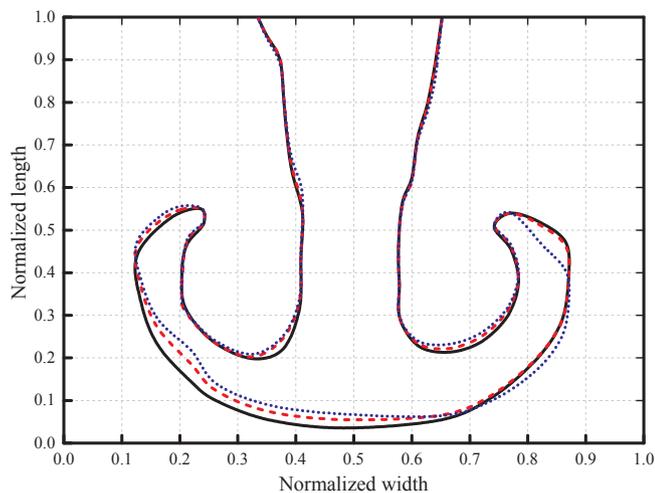


Fig. 3. Captured interface between the jet and water with jet inlet speed of 1 ms⁻¹. Solid black line: results for average grid size of 0.66 mm; dashed red line: results for average grid size of 1.42 mm; dotted blue line: results for average grid size of 1.80 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

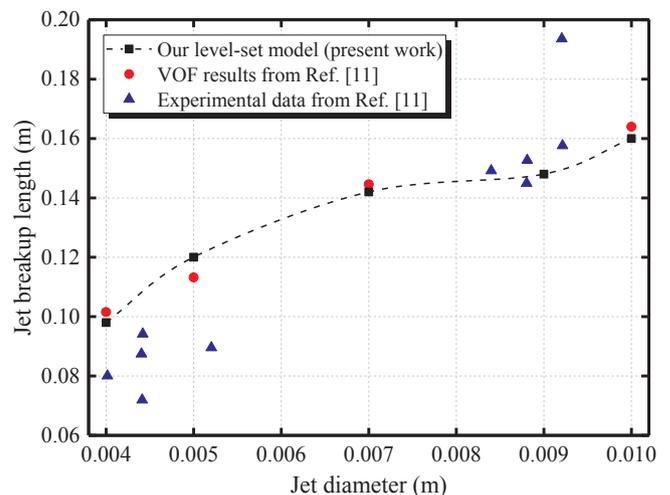


Fig. 5. Variation in the jet breakup length versus jet diameter for jet inlet speed of 1.5 ms⁻¹ obtained from experiments and from the VOF method [11], and obtained using our LS method.

Jet breakup length versus jet diameter

Bürger et al. [5] remarked that variations in the jet breakup regime and mechanism could be strongly related to the jet diameter. Fig. 5 showed that the jet breakup length increased with the jet diameter, and the results were close to those obtained using the VOF method. Deviations from the experimental values were likely due to employment of the 2D model that disregarded the occurrence of coarse breakup and sideways stripping which were the two main mechanisms in jet fragmentation. The coarse breakup in the jet showed its effect at the leading edge and was related to RT instability, while the sideways stripping led to formation of a large number of smaller fragments around the jet. For thicker jets, a larger surface area was present, which favored sideways stripping. As such, the results obtained using the 2D model were overestimated.

Jet breakup length versus surface tension

Surface tension was an important parameter which affected the RT instability. At lower surface tension values, the jet was less intact, so an early jet breakup was expected. Variations in the dimensionless jet breakup length for different surface tension values are shown in Fig. 6. The jet breakup length in general increased with the surface tension. However, there was a critical surface tension which led to the highest dimensionless jet breakup length of ~0.8 N/m [23]. At lower surface tensions, particularly < 1 N/m, our estimated dimensionless jet breakup lengths were smaller than those obtained from VOF simulations, which was due to the different interface capturing techniques.

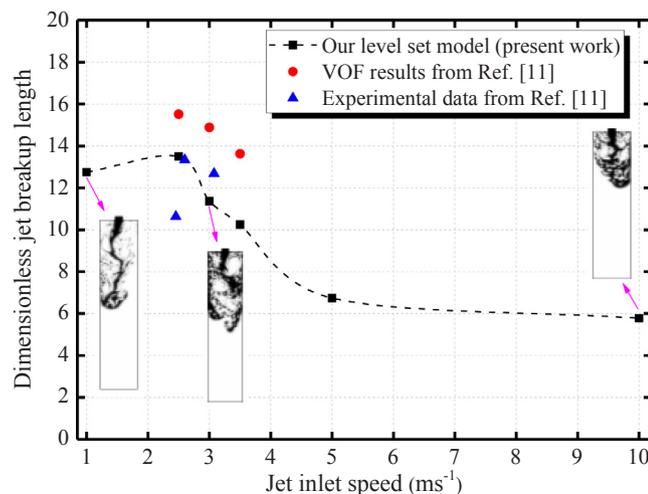


Fig. 4. Variation in the dimensionless jet breakup length with the jet inlet speed for jet diameter of 20 mm, obtained from previous experiments and from the VOF method [11], and obtained using our LS method. The graphical presentations from our model are shown as insets in the plot.

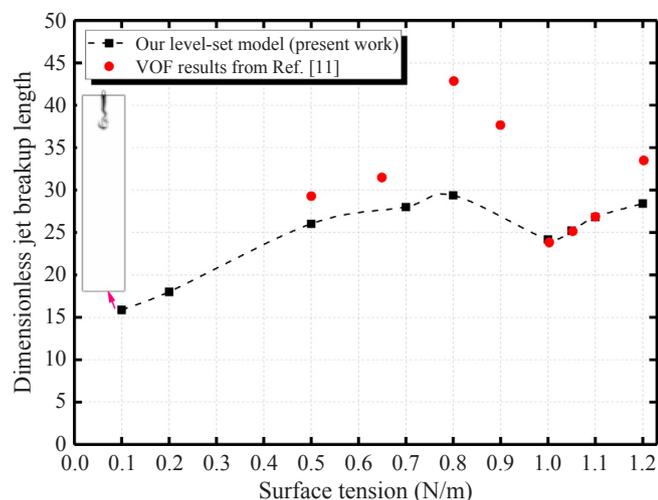


Fig. 6. Variation in the dimensionless jet breakup length versus surface tension for jet diameter of 5 mm at jet inlet speed of 1.5 ms^{-1} obtained using the VOF method [11] and our LS method. A graphical representation from our model is shown in the figure.

The obtained results proved that the surface tension affected the jet breakup length and led to early jet breakup at lower surface tensions.

Conclusions

In situations where melt jet is produced (i.e., in partial or complete loss of coolant), the present results would be useful in studies related to the hydrodynamic deformation and fragmentation of the melt jet. Our present model was found capable of simulating the jet injection in the water pool and the predicted results were in good agreement with those previously obtained from experiments and the VOF method. The hydrodynamic deformation and fragmentation of the jet were analyzed. The effects of jet inlet speed, jet diameter and surface tension on the jet breakup length were also studied, and good agreements with those previously obtained from experiments and from the VOF method were also achieved. The main source of uncertainties in the present system mainly arises from the severe deformation and fragmentation of the melt jet in the water column.

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