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Technical Note

Direct simulation of flashing liquid jets using the MPS method

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1. Introduction

Flashing jets are formed as pressurized liquid with temperature exceeding the saturation temperature at atmospheric pressure is discharged into low-pressure environment through a nozzle. Some hypothetical severe accidents in nuclear reactors are closely relevant with flashing jets triggered by rapid depressurization, e.g. the LOCA severe accidents for the pressurized water reactors (PWR) and the sodium–water reaction (SWR) accident for the sodium-cooled fast breeder reactors.

As for the mechanism of flashing jets, it was discovered from the optical observations [1–3] that an inner intact core surrounded by the diverging fine spray exists outside of a nozzle, which infers that flashing jets are actually atomized outside of the nozzle and liquid has entered deeply into metastable state at the nozzle exit. However, the effect of light scattering limits the optical experimental techniques to obtain detailed quantitative visualization of flashing jet topology.

In this paper, the moving particle semi-implicit method (MPS) [4] is applied to simulate flashing jets. Flashing jets are assumed as issuing from a short nozzle with high depressurization, which is corresponding to the actual scenarios for the above severe accidents in nuclear reactors. The structure and behaviors of flashing jets and the effect of superheat degree on them will be addressed in this paper.

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2. Identification of evaporation mode for flashing

Evaporation mode is not only a key issue for numerical simulation of flashing jets, but also is the hinge for understanding the phenomena. The experimental observations [5] had identified four different boiling modes for superheated jets, namely, homogeneous boiling, wall boiling, particle boiling and surface boiling. The former three modes should be excluded subject to the assumption of jets from a short nozzle and with high depressurization: The range of superheat degree for our concerned applications is not enough to activate homogeneous boiling; wall boiling can also be avoided due to the short-nozzle assumption; and particle boiling comes to standstill when the injection pressure p_A exceed the saturation pressure p_s by the overexpansion, i.e. $p_A - p_s > p_s - p_\infty$ (p_∞ is the atmosphere pressure), which is almost satisfied for high depressurization.

Thus surface boiling is dominant in jet flashing, this is to say, it should be postulated that evaporation occur merely on the jet surface while its core remains in the superheated metastable liquid state. This postulation has been confirmed by some experiments for short-nozzle flashing jets [2,3]. However, the origin of the surface boiling mechanism is as yet not completed understood [5]. Jones [6] attributed it to turbulent pressure fluctuations on the jet surface. Wildgen and Straub [5] thought that surface nuclei are generated from the entrained gas and vapor by vortices. There is no evidence yet to verify the above two explanations. Herein, we will present another explanation from the viewpoint of pressure relaxation.

When pressurized liquid suddenly issues from a nozzle, it could be thought subjectively that the column

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of liquid consists of two regions before flashing initiates, viz. slim interface layer exposed to atmosphere and core region. The conservation of mass and normal momentum across the interface layer are expressed as

$$J = \rho_l(\mathbf{u}_l - \mathbf{v}) \cdot \mathbf{n} = -\rho_g(\mathbf{u}_g - \mathbf{v}) \cdot \mathbf{n} \tag{1}$$

$$J(\mathbf{u}_g - \mathbf{u}_l) \cdot \mathbf{n} + p_g - p_l = -\zeta\nabla \cdot \mathbf{n} \tag{2}$$

where J is the mass flux across the interface, $\mathbf{u}$, p and ρ represent respectively velocity, pressure and density of fluid, $\mathbf{v}$ is the displacement velocity of the interface, $\mathbf{n}$ is the unit normal to the interface pointed to the vapor side, ζ is interfacial tension coefficient, and the subscripts g and l represent respectively vapor and liquid. It is observed from Eqs. (1) and (2) that the pressure acting on the interfacial liquid side is not completely relaxed to vapor pressure (here p_g), as shown in Eq. (3) at neglecting interfacial tension.

$$p_l = p_g + J^2\left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right) \tag{3}$$

Such effect is caused by the expansion of fluid particles undergoing the transition from liquid to vapor, wherein liquid seems to be impelled inward and prevented from collapse.

3. Mathematical formulation

3.1. Mathematical formulation

The hydrodynamic governing equations for flashing jets can be expressed as

$$\frac{\mathrm{D}\rho\mathbf{u}}{\mathrm{D}t} = -\nabla p + \nabla \cdot \mu(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}}) + \zeta\kappa\delta\mathbf{n} \tag{4}$$

$$\nabla \cdot \mathbf{u} = 0 \tag{5}$$

A two-dimensional Cartesian coordinate is built up in the calculation configuration, as shown in Fig. 1. The boundary condition along the chamber wall, except the nozzle exit, is set as non-slip wall condition. The

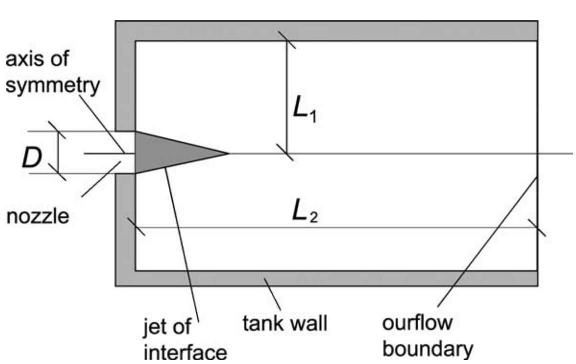

Fig. 1. Schematic configuration of flashing jets.

inflow boundary condition is assigned to uniform profile along the nozzle exit. Flashing is assumed as complete adiabatic, that is to say, no heat transfer between fluid particles. And interfacial tension force is just imposed on the jet surface, which means that it is ignored as liquid particles are entrained away from the interfacial layer. The modeling of surface tension for the MPS methods is based on the continuum surface force model (CSF), which is described in detail in Ref. [7].

3.2. Flashing model

Non-equilibrium vapor generation is one of the most important features of liquid flashing as pressure suddenly decays. As a consequence, flashing starts with some delay and thus the real vapor quality pattern may essentially differ from the equilibrium one. Jones [8] pointed out that the relaxation models is a suitable model in describing the effects of thermal non-equilibrium from the phenomenological viewpoint. In this paper, the homogeneous non-equilibrium relaxation model (HRM) is adopted to model the flashing process. The brief description of this model is shown in the following.

In the HRM model, the vapor generation rate Γ is approximated by extracting the first term from a Taylor series expansion of the vapor generation rate, as shown

$$\Gamma = \rho_m\frac{\mathrm{D}x}{\mathrm{D}t} = \rho_m\frac{x_e - x}{\tau} \tag{6}$$

wherein

(a) ρ_m is the mixture density.

$$\rho_m = \frac{\rho_g\rho_l}{x\rho_l + (1-x)\rho_g} \tag{7}$$

(b) x_e is the equilibrium vapor quality, which is chosen as equilibrium isenthalpic quality, not as often postulated equilibrium isentropic quality [9].

$$x_e = \frac{s - s_{sl}(p_\infty)}{s_{sg}(p_\infty) - s_{sl}(p_\infty)} \tag{8}$$

where the subscripts sg and sl are respectively for saturation state of gas and liquid. As well known, the definition of the equilibrium isenthalpic quality assumes that the vapor/liquid mixture be at rest after vaporization; this results in the highest possible quality since no latent heat is converted to kinetic energy. Thus, the initial velocity of vapor particles generating from flashing should be set to zero.

(c) Vapor quality x is calculated based on its equivalent dependence on local void fraction α.

(d) τ is the relaxation time, which is fitted as a power function of void fraction and pressure decay amount [10] as

$$\tau = \tau_0 \alpha^{-0.54} \varphi^{-1.76} \quad (9)$$

where $\tau_0 = 7.57546 \times 10^{-3}$s, φ is the non-dimensional pressure decay amount, $\varphi = (p_s - p_\infty)/(p_{cr} - p_A)$, where p_{cr} is the critical pressure of fluid.

The strategy in incorporating the HRM flashing model with the MPS method is presented as follows. Firstly, interfacial liquid particles are identified [4]. Then the vapor generation rates of these interfacial liquid particles are calculated using Eq. (6). Each liquid particle is associated with its generated vapor mass accumulation. A new child vapor particle is released as the mass accumulation exceeds that of one vapor particle, which is displaced outwards for l_0 distance oriented to the normal direction of its parent flashing particle. Flashing is terminated for a liquid particle as its local vapor quality x reaches the equilibrium vapor quality x_e,

4. Results and discussion

Concerning with our potential applications, water is chosen as the working medium for numerical simulations. In all the computational cases, the injection pressure and the backpressure are kept constant respectively at 17 MPa (its saturated vapor pressure is 352 °C for water) and 0.2 MPa. The injection velocity is approximately taken as the critical flow velocity of equilibrium two-phase flow isenthalpically corresponding to the metastable liquid state after liquid is suddenly depressurized. The present study is concentrated on the effect of superheat degree on the behaviors of flashing jets. The range of superheat degree was investigated about from 77 °C to 231 °C, the corresponding injection temperatures of which are from 200 °C to 352 °C.

The particle size is uniformly taken as $l_0 = 0.5$ mm (nozzle diameter D taken as 4 mm) for water, vapor and the ambient liquid. The sensitivity of the computational dimensions L_1 and L_2 were investigated. It was found that the use of $L_1/D = 12$ and $L_2/D = 4$ were large enough to establish insensitivity of jet behaviors. Fig. 2 presents some numerical simulation results of flashing jet structure at different superheat degrees, wherein liquid water and flashing-generated vapor are marked respectively by black-color particles and light gray-color particles and ambient liquid particles are not shown for visual clarity.

Examination of the numerical simulation results allows one to conclude that: Flashing jet is torn away into a conic-shaped liquid core under surface boiling, and extinguishes for some distance (defined as extinction length) downstream of the nozzle exit; the central region of flashing jets remains intact for the extinction length. At low superheat degree (e.g. seen in Fig. 2-1), it can be seen that relatively large drops are pinched off from jet tip besides fine droplets expelling from the jet surface. However, at high superheat degree (e.g. seen in Fig. 2-4), it is not clearly evident that large drops pinch off from jet tip. The above jet structure and behaviors are consistent

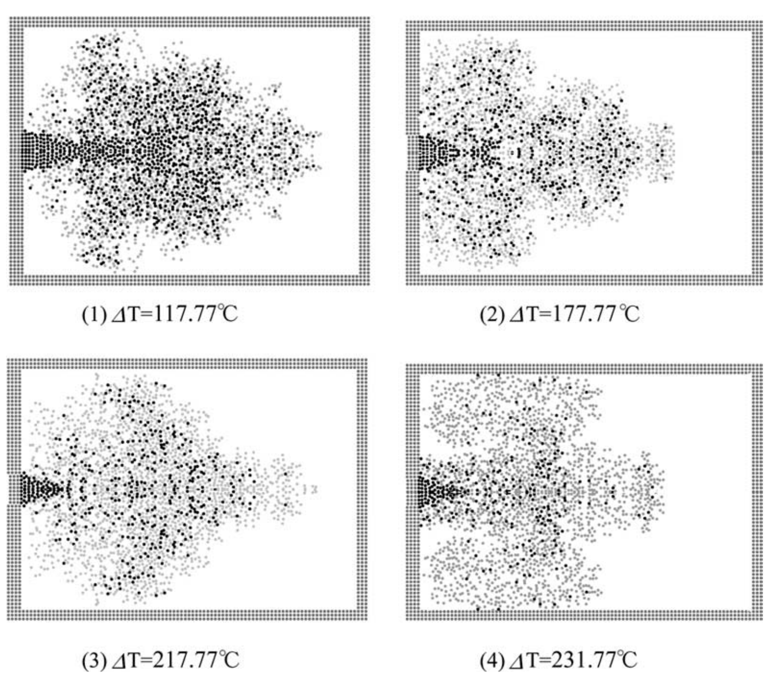

Fig. 2. Flashing water jets at different superheat degrees.

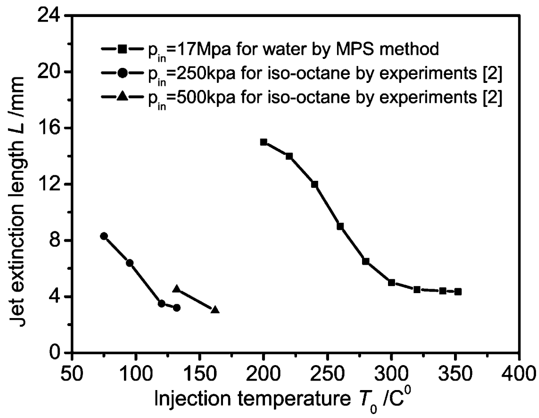

Fig. 3. Extinction lengths of flashing jets for different injection temperatures.

with the experimental observation results of Simoes-Moreira et al. [3]. Fig. 3 shows the extinction lengths at different injection temperatures for both our numerical simulation results and the experiment results using liquid *iso*-octane [3]. The two features on the extinction length can be condensed: The first one is that the extinction length decreases with increase of superheat degree, which would be ascribed to higher evaporation rate at high superheat degree; the second one is that the extinction length is becoming weakly dependent on superheat degree as injection temperature is approaching to the saturated vapor temperature corresponding to injection pressure. The latter can be explained as: the vapor generation rate is in reality a power function of vapor quality in that the relaxation time is a power function of void fraction, in spite of the assumed local linear dependence on vapor quality.

5. Conclusions

Flashing jets subjected to high depressurization are successfully simulated under surface boiling in this study. The revealed structure and geometry of flashing jets from the numerical simulation results are comparable with the existing optical observations. Jet central region consists of a conic-shaped liquid core embraced by two-phase fine droplet flow. The extinction length of flashing jets decreases with increase of superheat degree, and moreover is becoming weakly dependent on superheat degree as injection temperature is approaching to the saturated vapor temperature corresponding to the injection pressure.

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