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Vapor film collapse triggered by external pressure pulse and the fragmentation of melt droplet in FCIs

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Abstract The fragmentation process of high-temperature molten drop is a key factor to determine the ratio heat transferred to power in FCIs, which estimates the possible damage degree during the hypothetical severe accident in the nuclear reactors. In this paper, the fragmentation process of melt droplet in FCIs is investigated by theoretic analysis. The fragmentation mechanism is studied when an external pressure pulse applied to a melt droplet, which is surrounded by vapor film. The vapor film collapse which induces fragmentation of melt droplet is analyzed and modeled. And then the generated pressure is calculated. The vapor film collapse model is introduced to fragmentation correlation, and the predicted fragment size is calculated and compared with experimental data. The result shows that the developed model can predict the diameter of fragments and can be used to calculate the fragmentation process appreciatively.

Key words Severe accident, FCIs, Melt droplet, Fragmentation, Vapor film collapse

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1 Introduction

Fuel coolant interactions (FCIs), an important phenomenon in nuclear reactor severe accident analysis, have been extensively studied in recent years[1,2]. Energetic FCIs result in melt jet breakup, premixing, triggering, melt droplet fragmentation, propagation and, consequently, vapor explosion. The fragmentation of high-temperature melt droplet on contacting the low-temperature coolant is a key factor to determine the heat transfer ratio and estimate the degree of damage in the vapor explosion. Currently, hydrodynamic fragmentation models, such as Taylor type correlation, Pilch Erdman's correlation, etc[3], are employed for FCIs numerical studies. However, under some conditions, such as the triggering phase and at the very beginning of the fragmentation, thermal fragmentation mechanism may dominate the fragmentation process[4]. However, as the relative velocity is usually very low and the local Webber number is lower than the critical Webber number, the conventional hydrodynamic fragmentation models are not suitable for these conditions. New models based on local thermal conditions are required.

Studies[5] show that, when the hot melt droplet released into coolant, a vapor film is formed immediately because of the violent evaporation of coolant. It surrounds the melt droplet, preventing further contact of the melt droplet with coolant. But the vapor film may collapse, triggered by external force or local conditions, inducing fragmentation of the melt droplet. The vapor film collapse is thought to be the triggering mechanisms in FCIs, which initiate the fine fragmentation and vapor explosion[6].

In this paper, external pressure pulse is considered as the initiation event, which triggers the vapor film collapse and induces fragmentation of the melt droplet. The vapor film collapse is analyzed and

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modeled, and the generated pressure is calculated. The vapor film collapse model is introduced to fragmentation correlation. The predicted fragment size is calculated and compared with experimental data.

2 Description of fragmentation mechanism triggered by external pressure pulse

A number of triggering and fragmentation mechanisms were proposed in Ref.[2], but complete theory on the interaction mechanism has not been concluded, while it is accepted that the triggering of FCIs results from the collapse of the insulating vapor film around the melt droplet[1]. The speculation of fragmentation mechanism in this study is based on the above studies. In an FCI, after sufficient premixing, coolant and melt materials attain to an equilibrium mixture, the melt jet is broken into small droplets surrounded by vapor film, which prevents further contact of the melt droplet with coolant and retards the fragmentation process. It is approximately a transitory stable phase unless there are some initial events. We take external pressure pulse as the initial event, which is applied to the equilibrium system and has impact on the droplet with vapor film. The vapor film around the droplet collapses and generates a larger pressure than the initial pressure pulse in the local area. The generated pressure exerts on the droplet and induces the instability of the melt droplet surface[7,8]. Spikes and fragments are generated on the surface and the fine fragmentation is initiated. These fine fragments intensify the heat transfer between melt and coolant, and generate a large local pressure pulse, which initiates another fine fragmentation and spreads to the whole system. The propagation is rapid and powerful, and is also called as thermal detonation[9].

3 Analysis of vapor film collapse

The pressure generation during the vapor film collapse is related to duration and amplitude of the initial pressure pulse, properties of the droplet and coolant, temperature and ambient pressure. The analytical model is shown in Fig.1. The dynamic vapor film collapse process is modeled by writing a momentum equation for vapor film dynamics and an energy equation for each region: droplet, vapor film and coolant liquid, and linking each region by the appropriate boundary conditions. An equilibrium is assumed on the interface between the vapor and coolant liquid. The integral approach is used in each region for the energy equations where the differential equation is integrated over the region, and a temperature profile is assumed.

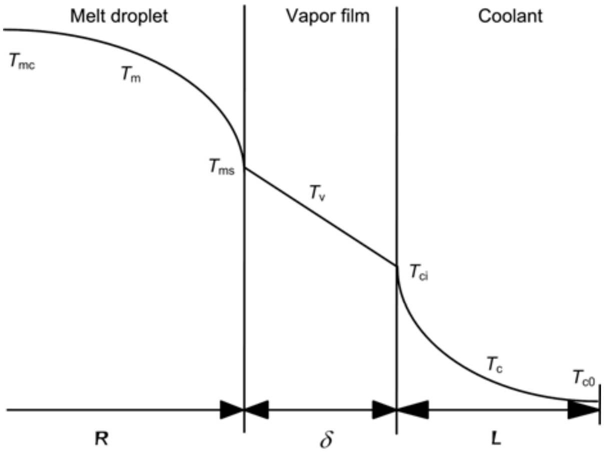

Fig.1 The analytical model for vapor film collapse.

The momentum equation for vapor film growth is modeled by the Rayleigh equation that neglects the effects of viscosity in a spherically symmetric system:

$$\frac{\mathrm{d}U}{\mathrm{d}t}+(\frac{3}{2})\frac{U^2}{(R+\delta)}=\frac{P_\mathrm{v}-P_\mathrm{c}}{\rho_\mathrm{c}(R+\delta)} \tag{1}$$

The ambient pressure during the vapor film growth is held constant.

Considering the evaporation of the coolant liquid on the interface, the velocity of the interface is given by

$$\frac{\mathrm{d}(R+\delta)}{\mathrm{d}t}=U+\frac{\mathrm{d}m_\mathrm{v}/\mathrm{d}t}{4\pi(R+\delta)^2\rho_\mathrm{c}} \tag{2}$$

where $\mathrm{d}m_\mathrm{v}/\mathrm{d}t$ is the evaporation (or condensation) rate on the interface, and can be calculated by the energy equation of the vapor:

$$\frac{\mathrm{d}m_\mathrm{v}e_\mathrm{v}}{\mathrm{d}t}=\frac{Q}{\mathrm{d}t}-P_\mathrm{v}\frac{\mathrm{d}V}{\mathrm{d}t}+\frac{m_\mathrm{v}}{\mathrm{d}t}h_\mathrm{v} \tag{3}$$

where the internal energy of the vapor is

$$e_\mathrm{v}=h_\mathrm{v}-P_\mathrm{v}/\rho_\mathrm{v} \tag{4}$$

and

$$Q=\frac{2k_\mathrm{v}}{\delta}(T_\mathrm{ci}-T_\mathrm{v})+\frac{2k_\mathrm{v}}{\delta}(T_\mathrm{ms}-T_\mathrm{v}) \tag{5}$$

The boundary conditions on the surface of the droplet and the interface of vapor and coolant can be written as

$$k_{\mathrm{m}} \frac{\partial T_{\mathrm{m}}}{\partial r}\Big|_{r=R} = k_{\mathrm{v}} \frac{\partial T_{\mathrm{v}}}{\partial r}\Big|_{r=R} + \varepsilon\sigma_{\mathrm{r}}(T_{\mathrm{ms}}^4 - T_{\mathrm{ci}}^4) \tag{6}$$

and

$$k_{\mathrm{c}} \frac{\partial T_{\mathrm{c}}}{\partial r}\Big|_{r=R+\delta} + \frac{dm_{\mathrm{v}}}{dt} h_{\mathrm{frag}} = k_{\mathrm{v}} \frac{\partial T_{\mathrm{v}}}{\partial r}\Big|_{r=R+\delta} + \varepsilon\sigma_{\mathrm{r}}(T_{\mathrm{ms}}^4 - T_{\mathrm{ci}}^4) \tag{7}$$

The temperature changes with time inside the droplet and coolant liquid near the vapor film can be written as

$$\frac{\partial T_{\mathrm{m}}}{\partial t} = (\frac{\alpha_{\mathrm{m}}}{r^2})\frac{\partial}{\partial r}(r^2\frac{\partial T_{\mathrm{m}}}{\partial r}) \tag{8}$$

and

$$\frac{\partial T_{\mathrm{c}}}{\partial t} + (\frac{\partial r}{\partial t})\frac{\partial T_{\mathrm{c}}}{\partial r} = (\frac{\alpha_{\mathrm{c}}}{r^2})\frac{\partial}{\partial r}(r^2\frac{\partial T_{\mathrm{c}}}{\partial r}) \tag{9}$$

where $\alpha_{\mathrm{m}} = k_{\mathrm{m}}/(\rho_{\mathrm{m}}C_{\mathrm{pm}})$ and $\alpha_{\mathrm{c}} = k_{\mathrm{c}}/(\rho_{\mathrm{c}}C_{\mathrm{pm}})$.

The pressure in the vapor film and the interfacial temperature are calculated by the equation of state of the coolant, $P_{\mathrm{v}} = P_{\mathrm{v}}(T_{\mathrm{v}},\rho_{\mathrm{v}})$ and $T_{\mathrm{ci}} = T_{\mathrm{sat}}(P_{\mathrm{v}})$.

The temperature distributions in the r direction in the droplet and the coolant liquid are required to solve these equations. Here a quadratic temperature distribution in the droplet is assumed:

$$T_{\mathrm{m}} = T_{\mathrm{mc}} + (T_{\mathrm{ms}} - T_{\mathrm{mc}})\left(1-\frac{x}{R}\right)^2 \tag{10}$$

where $x = R–r$, $x\in[0,R]$. The temperature distribution in the coolant liquid is assumed as

$$T_{\mathrm{c}} = T_{\mathrm{c0}} + (T_{\mathrm{ci}} - T_{\mathrm{c0}})\left(1-\frac{x}{L}\right)^2 \tag{11}$$

where $x = r–(R+\delta)$, $x\in[0,L]$.

4 Calculation of generated pressure

Based on the above equations by the Runge-Kutta-Gill method, as an example, the vapor film collapse induced by an external pressure pulse was calculated. The initial conditions were based on the conditions of Nelson's experiments[5]. Applying an external pressure pulse of 0.7 MPa to the system, the peak pressure in the vapor film during the collapse was 2.6 MPa (Fig.2), which is several times higher than the input pulse. As shown in Fig.3, thickness of the vapor film during the collapse is reduced to about 5 μm in a very short time. The minimal thickness indicates a collapse of vapor film at 0.032 ms. It is easy to find that the film thickness in Fig.3 is consistent with the pressure generation in Fig.2. This means that the pressure is generated by the collapse of vapor film.

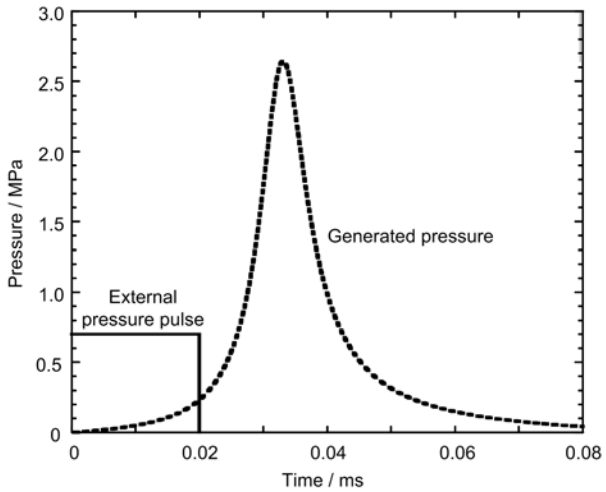

Fig.2 Generated pressure in the vapor film during the collapse induced by external pressure pulse.

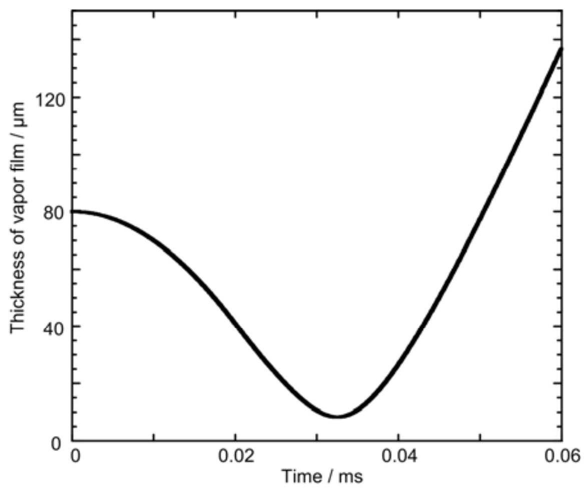

Fig.3 Thickness of vapor film during collapse induced by external pressure pulse.

Influence of the parameters on the pressure generation in the vapor film was investigated. The initial pressure pulse effect on the generated pressure is plotted in Fig.4. It shows that small amplitude increase of the initial pressure generated very high pressure. Higher droplet temperature caused lower pressure in the vapor film, as shown in Fig.5. This can be explained that, higher droplet temperature will induce more evaporation of coolant and then larger pressure will be generated in the vapor film, which resists the inward movement of the interface. Finally the amplitude of the generated pressure pulse in the vapor film is reduced. The higher ambient pressure can suppress the pressure peak in the vapor film, which is shown in Fig.6.

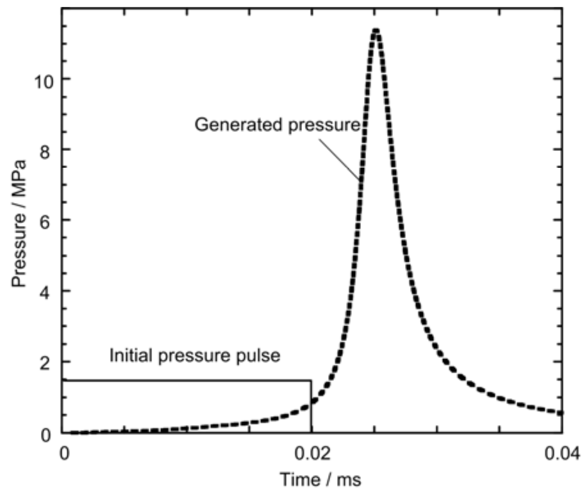

Fig.4 The initial pressure pulse effect on the generated pressure in the vapor film during the collapse.

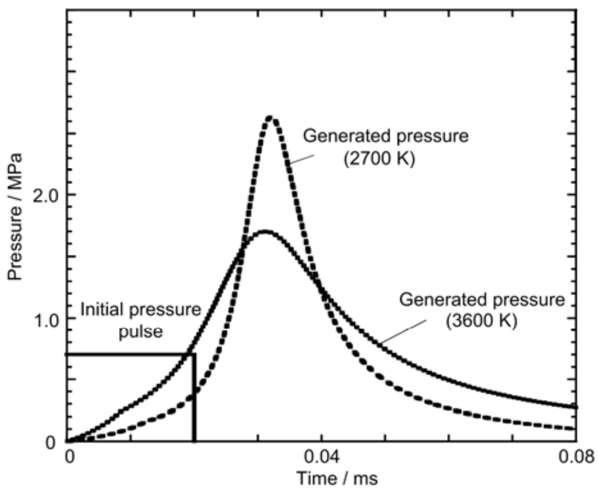

Fig.5 The droplet temperature effect on the generated pressure in the vapor film during the collapse.

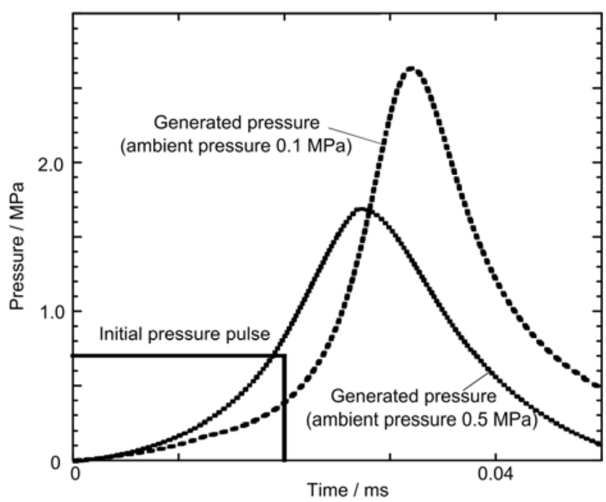

Fig.6 The ambient pressure effect on the generated pressure in the vapor film during the collapse.

5 Fragmentation of melt droplet

The generated pressure in the vapor film can induce the instability of the melt droplet surface and cause fragmentation of the melt droplet. A fragmentation correlation[10] based on melt droplet surface instability is introduced to calculate the fragmentation process of melt droplet, in which the size of the fragments can be written as

$$d_{\text{frag}} = \frac{d}{\left(\dfrac{\Delta P d}{2\sigma}\right)^{0.25}} \tag{12}$$

where d_{frag} is the fragment size, d is the diameter of the original droplet, and σ is the surface tension of the melt droplet. ΔP is the pressure exerted on the melt droplet surface, which is the generated pressure during vapor film collapse triggered by external pressure pulse, and can be calculated by the above equations.

The sizes of fragments in KROTOS-28[6], SIGMA-2000[11], Nelson's[5] and Mishima's[12] experiments are compared with calculation results. The predictions of fragment sizes by Eq.(12) and their experimental data are plotted in Fig.7. The experiment result and the calculated result both show that the diameter of the fragments are all less than 1mm, and the calculated results are a little larger than the experiment data or just at the upper range value of the experiment data. The deviation may be attributed to the fact that in this study only thermal fragmentation mechanism is considered. However, the hydrodynamic mechanism also affects the fragmentation process more or less. This model needs further development and verifications.

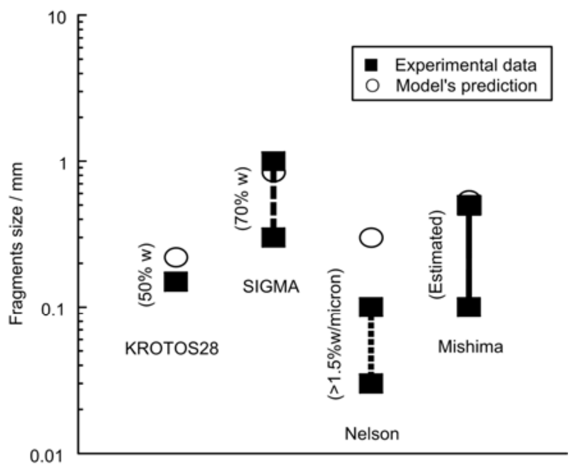

Fig.7 The comparison of fragment size with experimental data.

6 Conclusions

In this paper, the fragmentation process of melt droplet in FCIs is investigated by theoretic analysis. The acceleration mechanism is studied when an external pressure pulse is applied to a melt droplet, which is surrounded by vapor film. The vapor film collapse model triggered by external pressure pulse is developed, and fragmentation correlations for melt droplet are introduced to verify this model by comparing the predictions of fragments' size with experimental data. The result shows that the developed model can predict the diameter of fragments and can be used to calculate the fragmentation process appreciatively. The deviation of experiment with model's prediction suggests that combination of the hydrodynamic and thermal effects may be a better way to study the fragmentation process.

Nomenclatures

t Time (s)

T Temperature (K)

T_{mc} Center temperature of melt droplet (K)

T_{ms} Surface temperature of melt droplet (K)

T_{ci} Interfacial temperature of vapor and coolant (K)

T_{c0} Initial temperature of coolant (K)

T_{sat} Saturated temperature (K)

ΔP Generated pressure (Pa)

δ Thickness of vapor film (m)

σ_r Boltzmann constant ($W \cdot m^{-2} \cdot K^{-4}$)

V Volume (m^3)

m Mass (kg)

k Heat conductivity ($W \cdot m^{-1} \cdot K^{-1}$)

h Specific enthalpy ($J \cdot kg^{-1}$)

σ Surface tension ($N \cdot m^{-1}$)

U Velocity ($m \cdot s^{-1}$)

C_p Specific heat at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$)

e Specific internal energy ($J \cdot kg^{-1} \cdot K^{-1}$)

Q Thermal energy (J)

L Width of coolant area (m)

α Thermal expansion

ε Thermal emissivity

Subscript

c Coolant

v Vapor

m Melt

frag Fragment

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