Improvements of evaporation drag model

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Abstract A special visible experiment facility has been designed and built, and an observable experiment is performed by pouring one or several high-temperature particles into a water pool in the facility. The experiment result has verified Yang's evaporation drag model, which holds that the non-symmetric profile of the local evaporation rate and the local density of vapor would bring about a resultant force on the hot particle so as to resist its motion. However, in Yang's evaporation drag model, radiation heat transfer is taken as the only way to transfer heat from hot particle to the vapor-liquid interface, and all of the radiation energy is deposited on the vapor-liquid interface and contributed to the vaporization rate and mass balance of the vapor film. In improved model heat conduction and heat convection are taken into account. This paper presents calculations of the improved model, putting emphasis on the effect of hot particle's temperature on the radiation absorption behavior of water.

Keywords Improved evaporation drag model, Fuel-coolant interactions (FCI), Heat convection, Radiation heat transfer

CLC number TK12

1 Introduction

Fuel-coolant interactions (FCI) may occur in the course of a severe accident in a light water reactor.[1] During the last 15~20 years, much research has been performed, including both experimental and numerical investigations, to study the interaction of molten fuel/ high-temperature particles with water. The extent of FCIs can range from benign film boiling to explosive interactions. Four distinct phases are considered to occur during an explosive FCI: pre-mixing, triggering, propagation, and expansion phases. Although remarkable progress in description of the pre-mixing and expansion phase of the steam explosion has been achieved in recent years,[2] the fundamental phase of the FCI process has not been well understood yet. This includes the coupling effect between film boiling heat transfer and evaporation drag around melt/ high- temperature particles in cold liquid during pre- mixing stage of steam explosion. Several large- scale experimental programs and efforts on analysis are underway, but small-scale molten or single high-temperature particles poured into the cold liquid pool has seldom been done. For verifying the theory of evaporation drag model, a visible experiment facility has been designed and built, in which a stove for heating the particles was set up to produce a temperature above 2500K. A series of experiments included pouring a single and six high-temperature particles into a low saturated temperature liquid pool. The particle's falling-down speeds were recorded by a high-speed camera,[3] so the special resistant, which is induced by the high-speed evaporation surrounding the particles and acting on the moving high- temperature particles, can be measured. Results of the visible experiment manifest that the film thickness profile around the hot sphere is very different from the cold sphere, and a vapor film surrounded the hot sphere with different thickness circumferentially. The experiment and theoretical analysis show that there is a resultant force on the hot sphere, which resists its motion.[4] From Yang's evaporation drag model,[5] if a hot particle is surrounded by a vapor film with different thickness circumferentially, both local evaporation rate and local

Partially financed by National Natural Science Fund of China (No. 50046026 & No. 50376036) and 985 Engineering Fund of Shanghai Jiaotong University.

Received date: 2003-09-10

density of the vapor may have a non- spherically-symmetric distribution, which could induce a non-spherically-symmetric profile for pressure and form a flow around the particle. This non-symmetric profile would bring about a resultant force on the hot particle so as to resist its motion.

Radiation heat transfer plays a significant role in the behavior of elevated hot particles in contact with water. In Yang's evaporation drag model, radiation heat transfer is the exclusive mechanism to transfer heat from the hot particle to the vapor-liquid interface. The predicting results show that this assumption is reasonable for FCI (Fuel and Coolant Interaction) conditions. The experiment data and the calculation are nearly identical. In fact, the literature survey indicates that a significant part of the radiation energy deeply penetrates the body of the liquid. Specifically, for the core melt jet with surface temperature about 3000 K, only 25%, 50% and 70% of the radiated energy are deposited within the first millimeter (0.001m), first centimeter (0.01m) and first decimeter (0.1m) of the water behind the vapor-liquid interface, respectively [6]. The vapor film thickness and vapor velocity are determined from the vaporization rate, which is proportional to the heat absorbed by the interface between the particle and water.

However, as the temperature is dropping down, heat conduction and heat convection have to be taken into consideration. This paper describes an improved evaporation drag model, in which, besides the radiation heat transfer, both heat conduction and heat convection are taken into account. At the same time, calculations relating to the effect of hot particle's temperature on the radiation absorption behavior of water are presented.

2 The modified model

In old evaporation drag model, the evaporated mass is

$$\Gamma_{\mathrm{h}} = \frac{q_{\mathrm{h}}^{\mathrm{r}}}{h_{\mathrm{fg}}} \qquad (1)$$

where h_{fg} is the latent heat of vaporization (J·kg $^{-1}$); $q_{\mathrm{h}}^{\mathrm{r}}$ is heat flux of hot sphere (W·m $^{-2}$), and can be written as

$$q_{\mathrm{h}}^{\mathrm{r}} = \varepsilon_{\mathrm{l}}\varepsilon_{\mathrm{h}}\sigma\left(T_{\mathrm{h}}^{4} - T_{\mathrm{l}}^{4}\right) \qquad (2)$$

where ε_{l} is absorption coefficient of the liquid; ε_{h} is emissivity coefficient of the particle; T_{h} and T_{l} are temperatures(K) of the particle and the liquid, respectively; σ is radiation heat transfer constant of the black body, which equals 5. 67×10^{-8} W·K^{-4}·m^{-2}.

In improved evaporation drag mode,

$$\Gamma_{\mathrm{h}} = \frac{q_{\mathrm{vl}}^{\mathrm{r}} + q_{\mathrm{FB}}^{\mathrm{c}} - q_{\mathrm{sl}}^{\mathrm{c}}}{h_{\mathrm{fg}}} \qquad (3)$$

where $q_{\mathrm{vl}}^{\mathrm{r}}$ is radiation heat flux absorbed from the vapor-liquid interface (W·m^{-2}); $q_{\mathrm{FB}}^{\mathrm{c}}$ is heat flux due to conduction through the vapor film (W·m^{-2}); $q_{\mathrm{sl}}^{\mathrm{c}}$ is heat flux from the liquid interface into the liquid due to convection (W·m^{-2}).

Analysis of heat transfer for a high-temperature particle dropping in liquid coolant is illustrated in Fig.1.

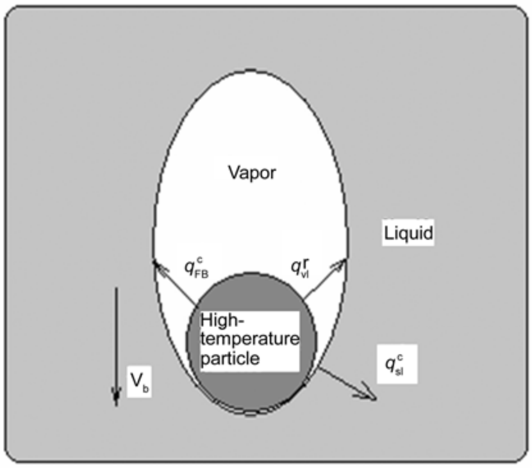

Fig.1 Analysis of heat transfer for a high-temperature particle dropping in liquid.

2.1 Radiation absorption

The knowledge of where the radiation is deposited is important for the following reasons. (1) If the water is saturated, all the heat transferred to the water generates steam. At the same time, it is important to be able to determine how much radiation from melts in a given volume is absorbed in that volume and how much is absorbed elsewhere. (2) If the water is locally and strongly subcooled, the above is still a concern but more importantly there is a need to know how much radiation is absorbed at the steam/water interface, and where steam generates, how much radiation is absorbed in the bulk of the liquid, and only removes subcooling. The scaling of radiation heat flux with temperature is complicated because of the variation of the spectral absorption of water. Therefore, it is necessary to take into account the detailed radiation properties of water. The amount of radiation absorbed by a layer of water depends on both thickness of the layer and the spectral content of the incident radiation. Fletcher [7] once presented calculations of the effect of melt temperature on radiation absorption behavior of water. But at the recent specialist meeting in Japan there was a viewpoint that this formulation was wrong and that the absorption data used were incorrect. So we will present formulations based on the corrected data in this paper. We assume that the steam/water interface covers the first decimeter (0.1m) of the water behind the vapor-liquid interface where steam generates under FCI condition. Radiation heat flux absorbed from the vapor-liquid interface is

$$q_{\mathrm{vl}}^{\mathrm{r}} = C_{\mathrm{T}} \cdot q_{\mathrm{h}}^{\mathrm{r}} \quad (4)$$

where C_T is multiplier, which takes into account the temperature of hot sphere:

$$C_{\mathrm{T}} = 1 - k(0.001T_{\mathrm{h}} - 1) \quad (5)$$

where k is an empirical constant. When $T_{\mathrm{h}} \geqslant 1000\mathrm{K}$, k=0.25335; when $T_{\mathrm{h}} < 1000\mathrm{K}$, k=0.

The vapor generation speed of the high-temperature particle is

$$\phi = \frac{\Gamma_{\mathrm{h}}}{\rho_{\mathrm{l}}}, \quad \Gamma_{\mathrm{h}} = \frac{q_{\mathrm{vl}}^{\mathrm{r}}}{h_{\mathrm{fg}}}, \quad \phi = \frac{q_{\mathrm{vl}}^{\mathrm{r}}}{\rho_{\mathrm{l}} h_{\mathrm{fg}}} \quad (6)$$

where ϕ is vapor generation speed ($\mathrm{m \cdot s^{-1}}$); ρ_{l} is density of the coolant ($\mathrm{kg \cdot m^{-3}}$); h_{fg} is the latent heat of vaporization ($\mathrm{J \cdot kg^{-1}}$).

Fig.2 shows a comparison of the vapor generation speed of the high-temperature sphere versus its temperature between new and old models. When temperature of the sphere is greater than 1800K, the difference between the calculated data according to new model and those according to old model is found to be distinct. It indicates the radiation energy partially penetrates the body of the liquid, as temperature of the particle is high enough. So the amount of vapor generated by radiation drops greatly.

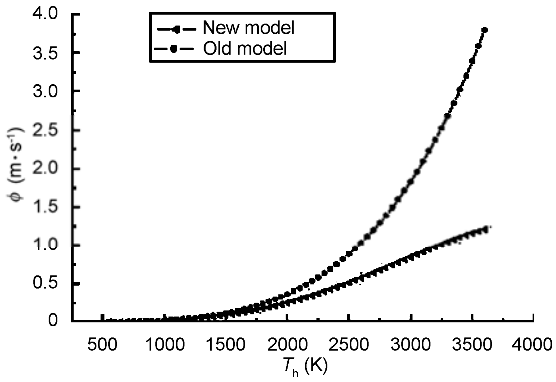

Fig.2 The vapor generation speed of the high-temperature sphere versus its temperature — a comparison between new and old models.

2.2 Heat flux from the liquid interface into liquid

Heat flux from liquid interface into liquid due to convection is

$$q_{\mathrm{sl}}^{\mathrm{c}} = \alpha \cdot (T_{\mathrm{sat}} - T_{\mathrm{l}}) \quad (7)$$

Heat transfer coefficient is

$$\alpha = C_{\mathrm{g}} \frac{\lambda_{\mathrm{l}}}{D_{\mathrm{h}}} Nu_{\mathrm{sl}} \quad (8)$$

where λ_{l} is thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$); D_{h} is diameter of the hot sphere (m).

According to Liu's paper, [8]

$$C_{\mathrm{g}} = \left(\frac{\alpha_{\mathrm{l}}}{\alpha_{\mathrm{g}} + \alpha_{\mathrm{l}}} \right)^{1/4} \quad (9)$$

where α_{g} is gas volume fraction in three phase flow; α_{l} is water volume fraction in three phase flow.

The Nusselt number at liquid/vapor interface for natural convection or for forced convection is

$$\begin{aligned} Nu_{\mathrm{sl}} &= Nu_{\mathrm{sl,n}}, \quad \text{for} \quad Re < 0.001 \\ Nu_{\mathrm{sl}} &= \max\left(Nu_{\mathrm{sl,f}}, Nu_{\mathrm{sl,n}}\right), \quad \text{for} \quad Re > 0.001 \end{aligned} \quad (10)$$

where $Nu_{\mathrm{sl,n}}$ is the Nusselt number at liquid/vapor interface for natural convection, $Nu_{\mathrm{sl,f}}$ is the Nusselt number at liquid/vapor interface for forced convection.

In case of subcooling there is a heat flux transferred from liquid/vapor interface into bulk of the liquid. We compute the Nusselt number for natural convection only using the Achenbach correlation[9] verified for $0 < Gr_{\mathrm{l}} Pr_{\mathrm{l}} < 5 \times 10^6$:

$$Nu_{\mathrm{sl,n}} = 2.1\cdot(1+15S_{\mathrm{p}}^{*3})\left[3.71+0.402\left(Gr_{\mathrm{l}}Pr_{\mathrm{l}}\right)^{1/2}\right] \quad (11)$$

where $2.1\cdot(1+15S_{\mathrm{p}}^{*3})$ is empirical multiplier depending on the superheating; Gr_{l} is Grashoff number for liquid, which equals $g\cdot D_{\mathrm{h}}^{3}\left[\left(T_{\mathrm{sat}}-T_{\mathrm{l}}\right)/T_{\mathrm{l}}\right]\cdot(\rho_{\mathrm{l}}/\mu_{\mathrm{l}})^{2}$; Pr_{l} is liquid Prandtl number; S_{P}^{*} is modified superheat number:

$$S_{\mathrm{p}}^{*} = c_{\mathrm{pv}}(T_{\mathrm{hs}}-T_{\mathrm{sat}})/h_{\mathrm{fg}} * Pr_{\mathrm{v}} \quad (12)$$

where c_{pv} is vapor specific heat at constant pressure, ($\mathrm{J\cdot kg^{-1}\cdot K^{-1}}$); $(T_{\mathrm{hs}}-T_{\mathrm{sat}})$ is wall superheat (K); Pr_{v} is vapor Prandtl number.

The forced-convection Nusselt number is defined by Kolev [10]:

$Nu_{\mathrm{sl,fc}} = \max(Nu_{\mathrm{sl,fcl}}, Nu_{\mathrm{sl,fct}})$, for $Re_{\mathrm{l}}<7.7\times10^{5}$ and $0.7<Pr_{\mathrm{l}}<10^{4}$,

where

$$Nu_{\mathrm{sl,fcl}} = 1.5\times(1+5S_{\mathrm{p}}^{*3})\left[\frac{0.037Re_{\mathrm{l}}^{0.8}Pr_{\mathrm{l}}}{1+\dfrac{2.443}{Re_{\mathrm{l}}^{0.1}}(Pr_{\mathrm{l}}^{2/3}-1)}\right] \quad (13)$$

$$Nu_{\mathrm{sl,fct}} = 1.5\times(1+5S_{\mathrm{p}}^{*3})\left[0.664Re_{\mathrm{l}}^{1/2}Pr_{\mathrm{l}}^{1/3}\right] \quad (14)$$

where Re_{l} is liquid Reynolds number, Pr_{l} is liquid Prandtl number.

2.3 Film boiling in saturated liquid

Here we consider film boiling predominant forced convection in saturated liquid. The heat flux due to conduction through the vapor film is

$$q_{\mathrm{FB}}^{\mathrm{c}} = \alpha_{\mathrm{fc,v}}\left(T_{\mathrm{hs}}-T_{\mathrm{sat}}\right) \quad (15)$$

According to the model of Epstain－Hauser,[11] heat transfer coefficient for forced convection of vapor is

$$\alpha_{\mathrm{fc,v}} = \frac{\lambda_{\mathrm{v}}}{D_{\mathrm{h}}}0.60\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{v}}}\right)^{1/4}Re_{\mathrm{V}}^{1/2}/Sp^{*\frac{1}{4}} \quad (16)$$

where λ_{v} is thermal conductivity ($\mathrm{W\cdot m^{-1}\cdot K^{-1}}$), Re_{v} is vapor Reynolds number.

3 Conclusion

Yang's evaporation drag model is suitable for a hot-particle moving in liquid during premixing stage of vapor explosion. By combining Yang's model with the results of comprehensive modern experimental and theoretical studies, an improved model has been developed. This new model adds elements of radiation absorption behavior of water, heat conduction and heat convection to Yang's model to better predict behaviors of high-temperature particles in contact with low-temperature liquid. The detailed improvement of evaporation drag model is described. Some errors in the Yang's model have been corrected. The modified model now gives a consistent result for a wide range of hot sphere's temperature. Based on the verified model, we try to provide a computer code of a hot-particle moving in liquid during premixing stage.

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