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A hydrodynamic fragmentation model based on boundary layer stripping

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ABSTRACT

Fuel Coolant Interactions (FCIs) are important issues in nuclear reactor severe accident analysis, which have drawn much attention by experts all over the world for many years. The boundary layer stripping is one of the mechanisms that result in hydrodynamic fragmentation during FCIs, and has been studied for many years. However, the results and trends predicted by the existing fragmentation rate models based on such a mechanism are still very different from the experimental data. In this study, in order to develop a fragmentation rate model of a liquid droplet, induced by boundary layer stripping, a new velocity distribution in boundary layer is proposed, which covers two very significant parameters. Then, based on theoretical modeling and experimental data, semi-empirical correlations which can predict the fragmentation rate and the average size of fragments are established, which are verified by typical experimental data and are compared with previous model predictions. The result shows that the fragmentation rate calculated by the present model and the certain range of average fragment size are in good agreement with the experimental data, which proves that the two new parameters involved can reflect the velocity distribution in boundary layers of both the melt and coolant more appropriately and reliably. With the help of the model from IFCI and CULDESAC codes, there is reason to believe the present hydrodynamic fragmentation model could be applied in FCI codes in the future.

1. Introduction

Fuel Coolant Interactions (FCIs) are important issues in nuclear reactor severe accident analysis, which contain melt jet breakup, premixing, triggering, melt droplet fragmentation, propagation and, consequently, vapor explosion (Lin et al., 2008), and need to be further studied, including fragmentation mechanisms. Based on experimental studies (Ciccarelli and Frost, 1993; Abe et al., 2006; Sa et al., 2011), some models (Kim and Corradini, 1988; Ciccarelli and Frost, 1994; Cao et al., 2002) are developed to describe the fragmentation process. Hydrodynamics effects are assumed to play an essential role especially during the propagation stage because of the relative velocity between melt and coolant caused by pressure transmission (Corradini, 1989).

Burger et al. (1986) considered that the effect of boundary layer and Kelvin–Helmholtz instability could result in the droplet-stripping process. Baines (1979) assumed that the boundary layer stripping would dominate when Weber number is at 200–2000. Fragmentation is induced by Rayleigh–Taylor instability when Weber number goes higher. Reinecke and Waldman (1970) proposed an empirical correlation based on experimental data. Ranger and Nicholls (1969) built a boundary layer stripping model based on droplet-stripping process in aerodynamic experiments. Burger (1984) gave an introduction to Rayleigh–Taylor instability model and capillary wave stripping model.

In boundary layer stripping, the tangential relative velocity of flow at the droplet surface exerts a shearing force, settling the boundary layer in motion (Corradini, 1989) and hydrodynamic fragmentation occurs when inertial force of the active melt overcomes its surface tension. There is still some difference between Ranger's predictions and the experimental data.

In addition, the risk of steam explosion in nuclear reactor can be evaluated with some codes, such as MC3D, SIMMER-III (Cao et al., 2002) which includes hydrodynamic models, but there still exists a broad gap between the calculated results and the experimental data. Therefore, it is worth to develop hydrodynamic fragmentation model for these codes.

2. The velocity distributions in boundary layers

A geometry model is established based on boundary layer stripping mechanism, as shown in Fig.1, where x represents the

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Nomenclature

A	dimensionless interface velocity
B	intermediate variable
C_D	drag coefficient
C_{frag}	fragmentation coefficient
D	droplet diameter
m	droplet mass
Oh	Ohnesorge number
P	pressure
R	droplet radius
r	x projection in vertical direction
T	dimensionless time
t	time
U	fluid velocity
u	Boundary layer velocity
V	droplet velocity
We	Weber number
x	coordinate or the arc length
Y	distance between coolant boundary layer and the interface
y	coordinate

Greek symbols

α	boundary layer shape factor
δ	thickness of boundary layer
ε	melt-to-coolant density ratio(ρ_p/ρ_c)
υ	kinematic viscosity
ρ	fluid density
σ	surface tension force

Subscripts

0	initial
∞	main flow
b	break-up
c	coolant
cr	critical value
$frag$	fragmentation
$frag,th$	theoretical calculation
p	melt drop
r	relative

curvilinear coordinate along with the interface separating the two phases and y represents the coordinate perpendicular to it (Ranger and Nicholls, 1969). The velocity distributions at the equator between the two boundings are denoted by u_c and u_p, respectively. The velocities of the main flow from the left to the right and the melt droplet are symbolized by U_∞ and V, respectively. Therefore, the relative velocity can be defined as $U_r = U_\infty - V$.

It is assumed that the initial velocity of the melt droplet is 0 and the kinematics equation determines the process of acceleration during hydrodynamic fragmentation. And it is also assumed that the boundary layer stripping occurs only at the equator of the melt droplet without taking the deformation of the initial spherical droplet into consideration. Besides, the velocity of stripping part is replaced with an apparent velocity based on velocity of area-weighted average.

The simplified boundary layer momentum integral equations for the coolant and the melt droplet are shown as Eqs. (1) and (2):

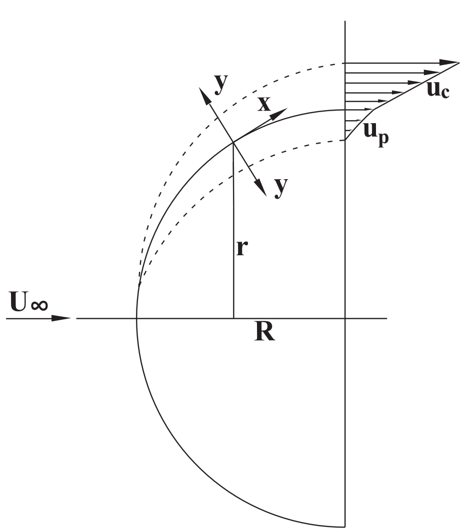

Fig. 1. Schematic of geometry model for the boundary layer stripping (Ranger and Nicholls, 1969).

$$\frac{\partial}{\partial x}\int_0^\infty u_c(U-u_c)dy+\frac{dU}{dx}\int_0^\infty (U-u_c)dy+\frac{1}{r}\frac{dr}{dx}\int_0^\infty u_c(U-u_c)dy=\upsilon_c\frac{\partial u_c}{\partial y}|_{y=0} \quad (1)$$

$$\frac{\partial}{\partial x}\int_0^\infty u_p^2dy+\frac{1}{r}\frac{dr}{dx}\int_0^\infty u_p^2dy=-\upsilon_p\frac{\partial u_p}{\partial y}|_{y=0}-\frac{1}{\rho_p}\frac{dP}{dx}\delta_p \quad (2)$$

The shearing force at the interface should satisfy the Eq. (3):

$$-\rho_p\upsilon_p\frac{\partial u_p}{\partial y}|_{y=0}=\rho_c\upsilon_c\frac{\partial u_c}{\partial y}|_{y=0} \quad (3)$$

The differential form of Bernoulli equation is shown as Eq. (4):

$$\frac{dP}{dx}=-\rho_cU\frac{dU}{dx} \quad (4)$$

As to the flow velocity U, it can be obtained from the formula of the uniform flow around a cylinder, shown as Eq. (5):

$$U=\frac{3}{2}U_r\sin\left(\frac{x}{R}\right) \quad (5)$$

For the melt droplet, the kinematics equation can be simplified because of the trivial amount of gravity as follows:

$$\frac{4}{3}\pi R^3\rho_p\frac{dV}{dt}=C_D\frac{\rho_c}{2}U_r^2\pi R^2 \quad (6)$$

Ranger and Nicholls (1969) introduced simplified expressions of velocity distributions in two phases from Taylor to his stripping model in aerodynamics. However, it's inconvenient for low Weber numbers which overestimate the velocity distributions of boundary layers especially when the region is near the interface. As shown in Fig.2, several significant differences occur between the experimental data and the predicted one and here the symbol Y means the distance between the coolant boundary layer and the interface. As a result, the notation of Y/R refers to the non-dimensional distance.

It is supposed that the velocity distributions of boundary layers are influenced by the shaping factor of both the melt and coolant materials. Therefore, a more suitable velocity profile of boundary layers is proposed based on Seeley's research (Seeley et al., 1975) on velocity distributions of boundary layer near a sphere. In the profile, both shaping factors are taken into account in the