An Investigation of Material Effects on Breakup Model of Steam Explosions

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1. Introduction

The purpose of this study is to evaluate several fragmentation models during the mixing of the steam explosions. First, several static fragmentation models based upon Rayleigh-Taylor instability, Weber number, and Kelvin-Helmholtz instability were considered. The dynamic fragmentation model considering the dependency of the breakup process on the dynamic velocity was then assessed.

2. Analyses of Breakup Particles

There are several fragmentation models to explain the jet breakup during the mixing: Rayleigh-Taylor instability, Weber number, and Kelvin-Helmholtz instability. The wave length at the fastest growth rate is expressed as follows based on the Rayleigh-Taylor instability [1].

$$\lambda = 2\pi\sqrt{3\sigma_j / \left[(\rho_j - \rho_s)g\right]}\,. \qquad (1)$$

When a droplet exists in a flow, the surface tension balances the shear force from the relative velocity of fluids. The critical Weber number We_c is derived as

$$We_c = \rho_s U^2 d / \sigma_j\,. \qquad (2)$$

The most stable droplet diameter in a flow is expressed by

$$d = We_c \sigma_j / \rho_s U^2 \qquad (3)$$

where We_c becomes 18 for the turbulent flow.

Epstein and Fauske [2] derived the following expressions for two extreme cases of thick vapor film and thin vapor film,

$$k_p = \frac{2\rho_{jet}\rho_i V_{rel,jet,i}^2}{3(\rho_{jet} + \rho_i)\sigma_{jet,i}}\quad , \qquad (4)$$

$$n_{\max}^2 = \frac{\rho_{jet}\rho_i k_p^2 V_{rel,jet,i}^2}{(\rho_{jet} + \rho_i)^2} - \frac{\sigma_{jet,i} k_p^3}{\rho_{jet} + \rho_i}\,, \qquad (5)$$

$$\lambda_p = \frac{2\pi}{k_p} = \frac{3\pi(\rho_{jet} + \rho_i)\sigma_{jet,i}}{\rho_{jet}\rho_i V_{rel,jet,i}^2} \qquad (6)$$

where k_p is the wave number corresponding to the fastest growing wave. The subscript i of ρ_i denotes vapor or water for the thick film or thin film case, respectively. The thick film correlation was applied when $k_p\delta \geq 2$; otherwise, the thin film correlation was used, where δ is the vapor film thickness.

The calculated fuel drop diameters for 80:20 corium, 70:30 corium, zirconia, and alumina, are presented in Figure 1. The calculations were done for some range of fuel drop velocity. The diameter based upon Rayleigh-Taylor instability only reflects the effect of the density difference and remains constant at 30~46 mm for the velocities. The calculated diameters based upon the critical Weber number and the Kelvin-Helmholtz instability reflect both the effects of density and velocity, but these diameters are not enough to explain the material effect because the velocities are all the same in the calculation. In Figure 1, the melt drop diameters are all the same even though the density is different.

Thus, dynamic information for the fuel velocity and the breakup rate is needed to effectively analyze the breakup process. The dynamic fuel velocity can be calculated using the simple force balance equation, in which the drag force and the gravitational force are the major forces. For a falling Lagrangian fuel particle through a water pool, the momentum balance equation is as follows:

$$\rho_f V_f \frac{dU}{dt} = -\frac{1}{2}\rho_f C_D A_f U^2 + V_f(\rho_f - \rho_l)g\ .(7)$$

The above differential equation can be solved by the time marching method as follows:

$$U^{n+1} = U + dt * \left[-\frac{1}{2}\rho_f C_D A_f U^2 + V_f(\rho_f - \rho_l)g\right] / (\rho_f V_f)\ .(8)$$

The breakup rate based on the relative velocity and the density ratio of the coolant and the melt are as follows [3]:

$$\frac{dL_m}{dt} = -C_0 |U_{rel}| \sqrt{\rho_c / \rho_f} \qquad (9)$$

where L_m is the melt length-scale, $U_{rel}(= U_f - U_m)$ is the velocity difference between the melt and the steam-water mixture.

The above differential equation can be used as follows:

$$L_m^{n+1} = L_m - C_0 |U_{rel}| \sqrt{\rho_c / \rho_f} * dt\ . \qquad (10)$$

The dynamic breakup process can be calculated using Eqs. (8) and (10) and the breakup process will be stopped when the Weber number by Eq. (2) exceeds the critical Weber number.

The calculated melt drop location and melt drop diameter are presented in Figures 2 and 3, in which the x-axis is the elapsed time after the melt drop starts to penetrate from the water surface into the water pool. The initial conditions are the melt drop diameter, water pool depth, and melt drop velocity, which are set to be 5 cm, 67 cm, and 8.63 m/s considering jet diameter of 5 cm, water pool of 67 cm, and free fall height of 3.8 m in typical TROI tests.

The ascending order of melt progression velocities are alumina, zirconia, 70:30 corium, and 80:20 corium, which is the result of the force balance in which the heaviest material has the largest gravitation force.

The ascending order of melt drop diameter is 80:20 corium, 70:30 corium, zirconia, and alumina in Figure 5. The largest velocity of the heaviest material, 80:20 corium, results in the smallest melt drop diameter by Eq. (10) in which the melt breakup rate is proportional to the relative velocity, and the Weber number theory, in which the melt breakup occurs at high density and high velocity.

Thus, the material effects on the melt breakup can be explained by the breakup model and Weber number theory in which the melt velocity and the melt diameter should be calculated dynamically.

3. Conclusions

In this study, several breakup models were considered to evaluate the breakup size for various materials. The material effects on the melt breakup can be explain by the breakup model and Weber number theory in which the melt velocity and the melt diameter should be calculated dynamically. The ascending order of melt drop diameter which is 80:20 corium, 70:30 corium, zirconia, and alumina, is exactly the same as that of TROI experimental results and previous experimental work. The largest velocity of the heaviest material, 80:20 corium, results in the smallest melt drop diameter in which the melt breakup rate is proportional to the relative velocity, and Weber number theory, in which the melt breakup occurs in high density and high velocity.

Acknowledgements

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References

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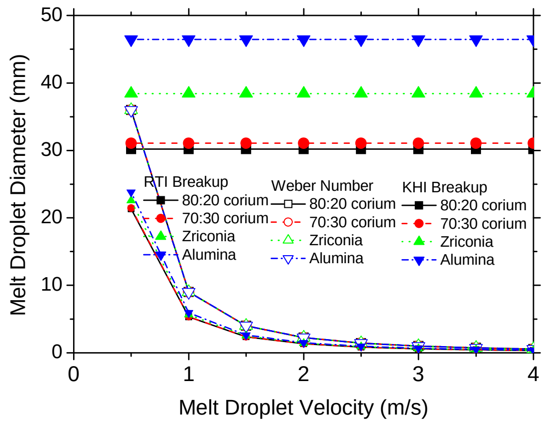

Fig. 1 Calculated Melt Droplet Diameter Using Static Rayleigh-Taylor Instability Model, Critical Weber number model, and Static Kelvin-Helmholtz Instability Model.

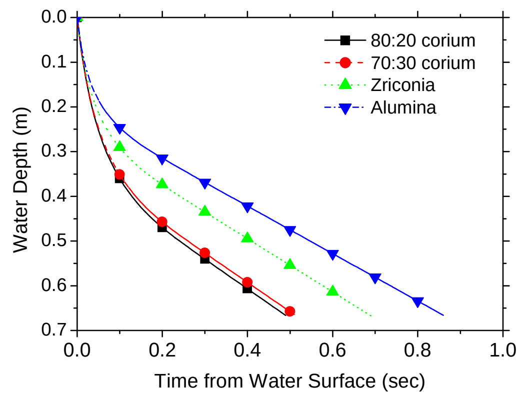

Fig. 2 Calculated Melt Drop Location Using Dynamic Jet Breakup Model.

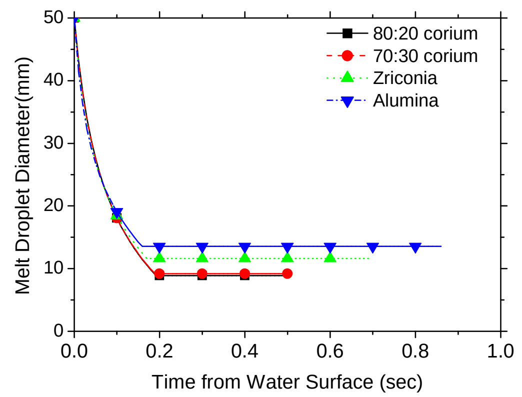

Fig. 3 Calculated Melt Droplet Diameter Using Dynamic Jet Breakup Model.