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Simulation of the mixing process in FCIs with hydrodynamic fragmentation model

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Abstract Fuel Coolant Interactions (FCIs) are important issues in nuclear reactor severe accident analysis. In FCIs, fragmentation model of molten droplets is a key factor to estimate degree of possible damage. In this paper, the mixing process in FCIs is studied by the simulation of MIXA experiment with hydrodynamic fragmentation model. The result shows that hydrodynamic fragmentation model underestimates the fragmentation rate of high temperature molten droplets under the condition of low Weber numbers. It is concluded that models based on thermal fragmentation mechanism should be adopted to analyze the FCI process and its consequence.

Key words Severe accident, FCI, Molten fuel droplet, Fragmentation, MIXA

CLC number TL364+.4

1 Introduction

Fuel Coolant Interactions (FCIs), numerically studied in recent years, are important issues in nuclear reactor severe accident analysis. In FCIs, the fragmentation of high-temperature molten droplets contacting with low-temperature coolant in the mixing process is used to estimate degree of possible damage, and is a key factor to determine the ratio of heat transferred to power. The development and verification of models for fundamental processes in FCIs request a multi-phase, multi-component, and fluid-dynamics computer code. Currently, hydrodynamic fragmentation models (such as Taylor type correlation, Pilch and Erdman's correlation, etc.)[1,2] are employed for FCIs numerical studies. They are developed based on relative velocity of droplets to coolant liquid. Studies[3,4] show that, in high Weber number cases, hydrodynamic mechanism dominates the fragmentation process. With low Weber numbers, however, thermal fragmentation mechanism may dominate the fragmentation process,[5] which is caused by vapor film collapse or surface solidification of the melt droplets.

In this study, validity of the hydrodynamic fragmentation model under the condition of low Weber numbers is tested and evaluated through the simulation of the MIXA-06 experiment.[6] The mixing process in FCIs is investigated.

2 Description of experiment

MIXA are simulated experiments of the mixing study of FCIs, which were performed at Winfrith Technology Centre in conjunction with the CHYMES code development and validation effort.[6,7] The process involves pouring kilograms of thermitically generated UO_2 melts (81% uranium dioxide and 19% molybdenum metal at 3600 K) into a near-saturated water pool of square section of 0.37m (side)×0.6 m (depth). A droplet former is employed to produce a stream of droplets with diameter of 6 mm, and a cylindrical skirt is used to control the stream to a diameter of 0.12 m.

In the MIXA-06 experiment, 3 kg of molten urania were released. The melt droplets pour lasts for a total time of 1.0 s. The vessel is left open to the at-

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mosphere via a venting line. The initial pressure is 0.1 MPa in the experiment and the water is initially heated to around the saturated temperature.

3 Geometry and initial conditions

In this simulation, the geometry and initial conditions are mostly consistent with the experiment parameters, but a few differences were made to optimize the computer calculation.

The experimental vessel with square-section is modeled as an axis-symmetric cylindrical volume with the same cross sectional area as the real vessel in a radius of 0.21 m. The total height of calculation region is 1.5 m with 0.6 m of water, and rest of the volume is just air, left open to outside, as shown in Fig.1.

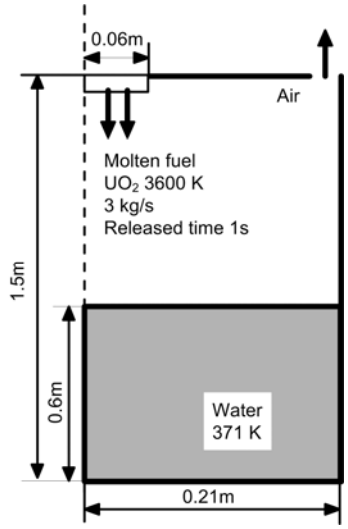

Fig.1 Geometric model.

For all calculations, an initial melt droplet diameter of 6 mm is specified. The material of melt droplets is simulated by 100% UO_2. A stream of the melt droplets, with a volume fraction of 0.05, flows into the vessel at a rate of 3 kg/s in a time interval of 1.0 s.

4 Calculation and discussion

The calculated result mainly contains the falling of melt droplet stream in water, namely, the front advancement of melt droplets stream, which is a perfect expression of the mixing region in FCIs. The front advancement of the droplet stream is dominated by the drag coefficient between the droplets and liquid coolant, the heat transfer coefficient and the surface area of the droplets. Because the former two coefficients were estimated in previous studies,[8,9] the surface area model becomes the main factor. The surface area is a function of the radius of droplets and fragments, which is related to the fragmentation of droplets, so in this paper the front advancement of droplet stream is indirectly dominated by the fragmentation model employed in the calculation.

4.1 Base case

Basically, Taylor correlation (hydrodynamic fragmentation model) is employed to model the fragmentation of the droplets. In this model, the equilibrium radius of droplets is calculated as:

$$r_{\mathrm{d}}^{\mathrm{e}} = \frac{We_{\mathrm{Cr}}\sigma}{2\rho_{\mathrm{c}}\Delta v^2} \tag{1}$$

where Δv is the relative velocity difference between droplet and coolant, σ is the surface tension, ρ_{c} is the density of coolant and We_{Cr} is the critical Weber number, a dimensionless number to describe when the melt droplet starts to fragmentize. The default value of critical Weber number are fixed to 12 previously.[1]

In calculating the Base case, the initial radius of the melt droplets is set to 0.003 m, radius of the droplets during their falling and fragmentation in water is calculated by Eq.(1), and the minimum radius of the melt droplets is set to 0.001 m, which is corresponding to the average value estimated from experiment data.

By the calculation, the front advancements of the stream of melt droplets in water from the simulation and experiment are plotted in Fig.2, which shows that the calculated penetration rate of the droplet stream is

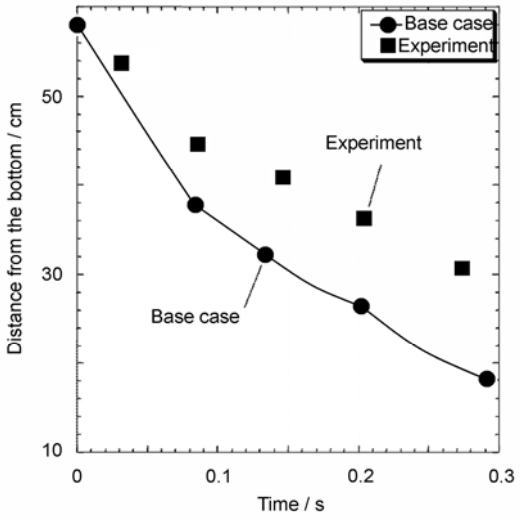

Fig.2 Simulated front advancements of the stream of melt droplets in water in Base case.

faster than that from the experiment. This means that the surface area of the droplets, and fragmentation rate of the droplets, are underestimated.

4.2 Parametric cases

Several parametric cases were carried out based on the Base case to investigate the influence of the fragmentation model on the mixing region related to the fragmentation model.

Case 1: Because size distribution of the droplet could not be obtained from the calculation and in Base case the radius of the fragments was set to 0.001 m, one did not know that during the penetration whether or not the fragment size reaches the value. Therefore, the minimum radius of the fragments was set to 0.0005 m instead of 0.001 m in Case 1, and Taylor correlation was also employed. The front advancements of the stream of melt droplets in water in Case 1 and Base case are plotted in Fig.3, which suggests that the calculated penetration rates of the stream of droplets are almost the same in both cases. The calculated results suggest that during the penetration, the radius of most fragments does not reach the average value of 0.001 m as estimated from the experiment. This means that the Taylor correlation fragmentation model underestimates the fragmentation rate in the simulated experiment.

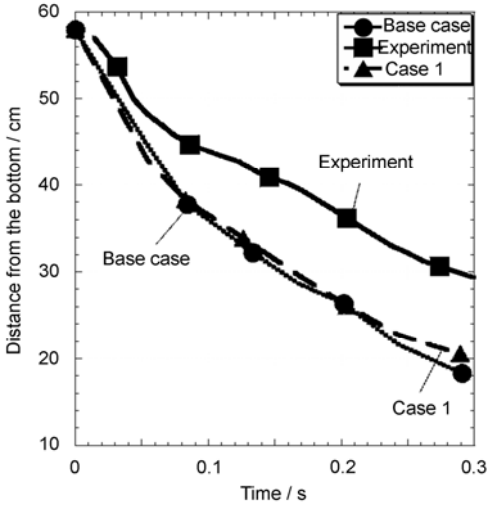

Fig.3 Simulated front advancements of the stream of melt droplets in water in Case 1 and Base case.

Case 2: The difference between Case 2 and Base case is that a time constant multiplier of 0.001 for the Weber breakup of the melt droplets was added to investigate influence of the fragmentation time in Taylor correlation on the mixing region. The front advancements of the stream of melt droplets in Case 2 and Base case are shown in Fig.4. Although the fragmentation time is very short, the front advancement does not change too much in these two cases, which shows that this parameter does not work in the calculation of these cases.

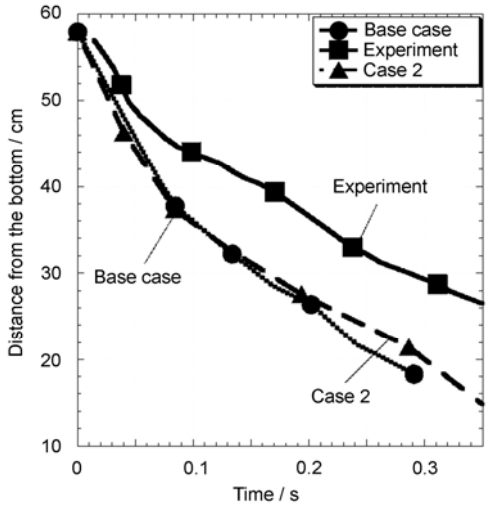

Fig.4 Simulated front advancements of the stream of melt droplets in water in Case 2 and Base case.

Cases 3 and 4: The critical Weber number was set to 0.12. The time constant multiplier for the Weber breakup of the melt droplets was set to 1.0 and 0.001, respectively, to see which parameter in the Taylor type correlation for the fragmentation of droplets affects the fragmentation rate. The front advancement of the droplets is plotted in Fig.5. It was found that when the critical Weber number was 12, with a short fragmentation time, the front advancement of melt droplets did not change; but when the critical Weber number is 0.12 and fragmentation time was reduced 1000 times, the penetration rate reduced greatly. These can be seen in the results of Case 4.

The simulated results suggest that the critical Weber number and the fragmentation time may be the factors affecting the fragmentation rate in the simulation of the experiment. The calculation shows that in the experiment, the Weber number of the droplets in the system is around or less than 12. This means that part of the fragmentation process of the droplets during the penetration was cut off, hence a reduction of the fragmentation rate. These results suggest that under the condition of low Weber numbers the hydrodynamic fragmentation model could not describe the fragmentation rate of the melt droplets.

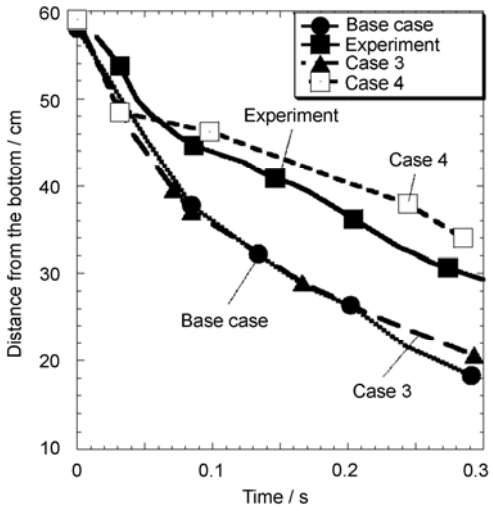

Fig.5 Simulated front advancements of the stream of melt droplets in water in Case 3 and Case 4..

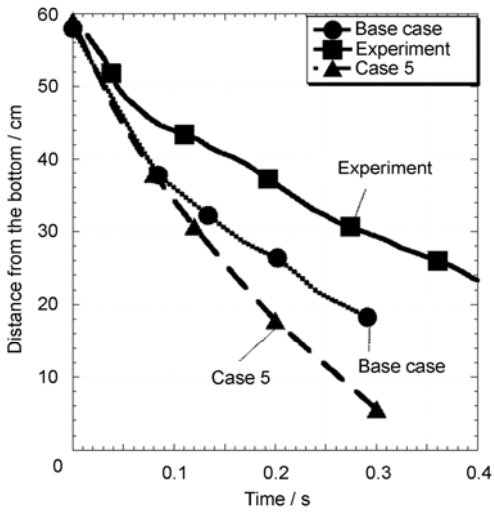

Fig.6 Simulated front advancements of the stream of melt droplets in water in Case 5.

Case 5: This is designed to understand influence of the current fragmentation model on the mixing region by obtaining different front advancements of the droplet stream induced by the current fragmentation model. Both the initial and final radii of the melt droplets were 0.003 m in the mixing region, i.e. without fragmentation of the droplets. The front advancements of the melt droplet stream are plotted in Fig.6. It shows that the front advancement of the melt droplets in Case 5 was faster than that of the experiment and Base case. The calculated results indicate that the Taylor correlation fragmentation model works in the simulation of the experiment, but the fragmentation rate is underestimated.

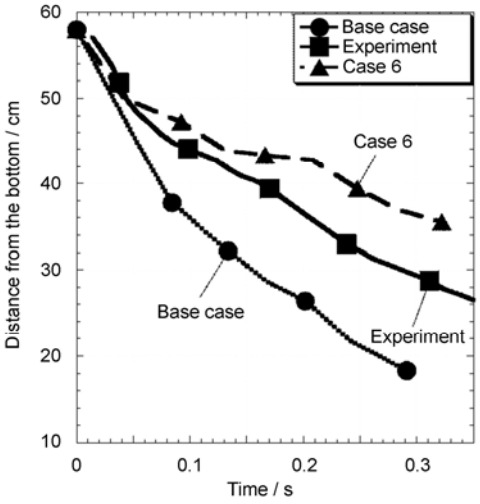

Fig.7 Simulated front advancements of the stream of melt droplets in water in Case 6.

Case 6: The fragmentation of the droplets in Case 6 was modeled by setting the minimum and maximum radii of the melt droplets to 0.001 m in the mixing region. This means that the droplets entering into the water region would be fragmented immediately into small parts of 0.002 m in diameter. The front advancements of the melt droplet stream in water in the simulation and the experiment are plotted in Fig.7. It shows that calculated penetration rate of the droplet stream is slower than that of the experiment and Base case. The results indicate that the fragmentation rate of the droplets is overestimated by the fragmentation model. The real fragmentation rate of the droplets in the experiment is between Base case and Case 6.

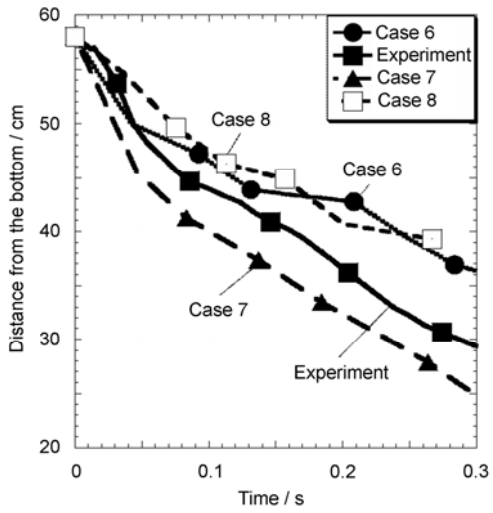

Fig.8 Simulated front advancements of the stream of melt droplets in water in Case 7 & Case 8.

Cases 7 and 8: The fragmentation model of melt droplets in both cases had the same minimum and maximum radii of melt droplets in the mixing region.

The minimum radius of droplets was set to 0.0015 m and 0.0007m respectively in the two cases to calculate size effect of the fragmented droplets on the mixing region. The front advancements of melt droplets are plotted in Fig.8. It shows that the front advancement is sensitive to minimum radius of the melt droplets.

Case 9: This is designed to understand the difference between the Pilch and Erdman's correlation [10] for the droplet fragmentation and the Taylor correlation in Base case. The front advancements of the droplet stream are plotted in Fig.9, in which no difference can be found between the two hydrodynamic fragmentation models.

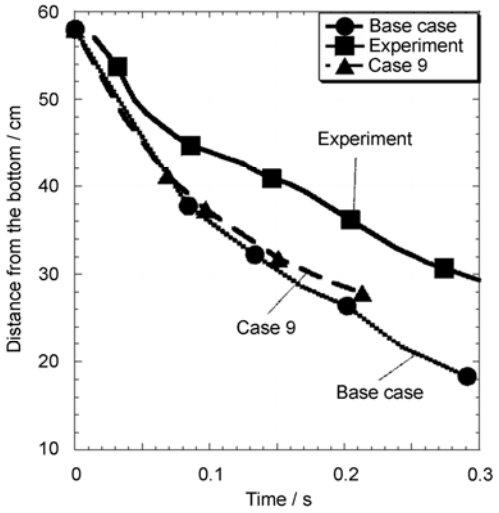

Fig.9 Simulated front advancements of the stream of melt droplets in water in Case 9.

By simulating the Base case and parametric cases, we found that the front advancement of the melt droplet stream in experiment was underestimated by Taylor type fragmentation model. Parametric investigation also shows that hydrodynamic fragmentation model underestimate the fragmentation rate and the radius of fragments. These may be related to the fact that hydrodynamic fragmentation models were developed based on relative velocity of droplets to coolant liquid. Under low Weber numbers and high temperatures, the relative velocity will not be the main factor.

5 Conclusions

In this paper, the hydrodynamic fragmentation model is estimated under condition of low Weber numbers through the simulation of the MIXA-06 experiments. The calculated results show that the hydrodynamic fragmentation model underestimates the surface area of the droplets in the simulation of the experiment with low Weber numbers.

Since the fragmentation model affects the mixing region in FCIs and the estimation of energy conversion as well, a good fragmentation model is needed to the simulation codes to study the molten material interaction with coolant.

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