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Influence of Improved Melt Breakup Model in Steam Explosion Simulation

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1. Introduction

During a severe accident of light water reactors (LWRs), the molten and relocated core is the primary heat source that governs the accident progression. Thus, the cooling of the molten core is the crucial factor for the accident mitigation and termination. In pressurized water reactors (PWRs), it is likely that water exists in the reactor cavity when the molten core drops there. So, the fuel-coolant interaction (FCI) is an important phenomenon due to its impact in both of the modes: a mild interaction facilitating melt breakup and cooling and an energetic steam explosion which may cause impulsive loads on the containment structure [1, 2].

In the previous works [3, 4] the authors examined influences of the model parameters and initial/boundary conditions on the steam explosion loads and also on the melt breakup/coolability in the plant scale condition. For those works, we used an FCI simulation code, JASMINE, developed at Japan Atomic Energy Agency (JAEA) [5].

The approaches for the steam explosion study and the coolability study differed in the way to handle the melt particle sizes during the premixing process. In the steam explosion study, the melt particle size during premixing was given as a constant and a parametric survey was included to cover the bounding (maximum) values for the load or to cover a reasonable range of the uncertainty. For the coolability study, however, an empirical particle size distribution model was introduced into the code since it has a direct impact on the melt cooling behavior. A model for non-local (beyond cell) radiation heat transfer, which can be significant with high temperature melt materials (~3000K) and in relatively long range of time, was also implemented for that purpose. [6]

In this work, we revisited the steam explosion analysis with the code with such additional models and examined the influence of those models in the steam explosion simulation. Experiments with alumina and corium (UO_2-ZrO_2 80:20wt% mixture) melt, namely KROTOS-44 and FARO-L33 [2] (hereafter K44 and L33) both performed at JRC-Ispra, EU, were referred to. Those data were also used for the validation of the original JASMINE [5].

2. Analytical Condition

The reference experiments are briefly described. KROTOS-44 was a medium scale steam explosion experiment with 1.5 kg of alumina melt at 2673K poured as a ϕ30mm jet into water at 363K, 0.1MPa. FARO-L33 was a large scale experiment with 100kg (~40kg at the time of trigger) of corium at 3070K poured as a ϕ50mm jet into subcooled water at 124K, 0.41MPa. In the former, a strong steam explosion with ~50MPa of pressure pulses and 160kJ of the kinetic energy was observed. In the latter, relatively weak explosion with ~10MPa of pressure pulses and ~180kJ of the kinetic energy was observed.

The analytical parameter settings for the base case and the parametric study are summarized in Table I. The base case was basically a re-run of the original validation calculation [5]. In the parametric study, modified melt droplet size (D1, D2), application of the droplet size distribution model (SD), application of the non-local radiation heat transfer model (NR) were examined. The case SD2 was a composite of SD with a larger fragmentation rate constant for tuning the result for K44; SD3 was a composite of SD2 with activation of non-local radiation model. The analytical grids are illustrated in Fig.1.

Calculations were performed in two steps. The

Table I: Analytical conditions

Base case condition

Analytical condition	KROTOS-44 (K44)	FARO-L33 (L33)
Melt flow-in condition	d=30mm,v=2.0m/s (~0.40s)	d=50mm,v~2.9m/s (2.6s)
Jet break-up factor, C_{ent}	1.5	1.0
Droplet diameter (mm)	10	3
Triggering (time)	14.8MPa-15cm^3 (0.9s[*1])	35MPa-29cm^3 (1.12s)
Fragmentation factor, C_{frg}	0.35	
Other explosion model parameters	Fragmentation period: 1 (ms), Heat partition for evaporation: 0.7	

Parameter study

Case	Modified parameter
D1	Droplet diameter -50%
D2	Droplet diameter +50%
SD	Droplet size distribution, Heat transfer (premix.) x2[*2]
NR	Non-local radiation HT
SD2	Same as **SD**, C_{frg} x2
SD3	Same as **SD2**, Non-local radiation HT

[*1] 1.7s in the experiment; shifted -0.8s due to actual delay in the melt leading edge progress by unknown reason. [*2] Usage of the size distribution model with doubled heat transfer coefficient is based on our model validation study (Moriyama et al. [6]).

premixing simulation was done first. The result at the time of triggering was extracted as a restart data set. Then, the explosion simulation was performed by using the restart data as the initial condition. The triggering time for K44 in the analysis, 0.9s, was different from the actual triggering time in the experiment, 1.7s. That was to compensate the delayed progress of the leading edge of the melt observed in the experiment probably by the not-well-controlled melt delivery process.

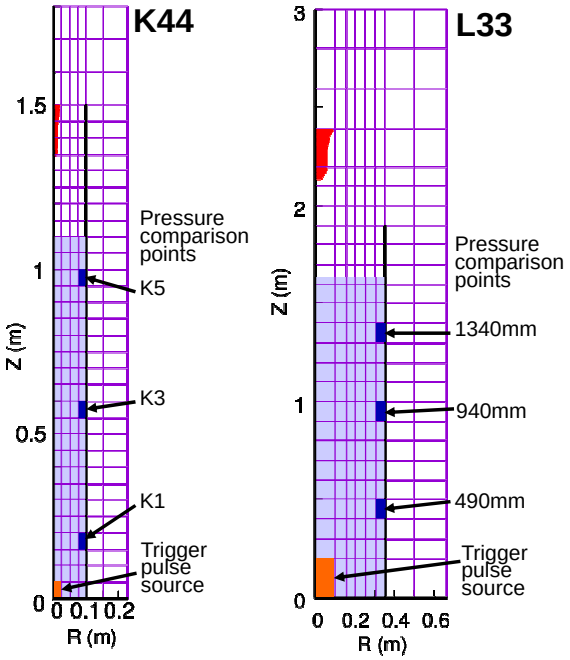

Fig. 1: Analytical grids.

3. Result

Figure 2 shows the evolution of the premixed mass of the melt, defined as the mass of melt at temperatures above the melting point and in the zones where the void fraction is less than 0.75. The premixed mass practically means the melt mass potentially participating in the following explosion process. The base case result for K44 (BA) showed a value in a plateau at the triggering time (0.9s). The plateau means that most of the melt delivered is underwater and premixed (kept in low void zones). The SD and SD3 cases showed lower premixed masses, meaning part of the melt with smaller particle diameters was solidified or in high void zones. Other cases were not significantly different from the base case.

The result for L33 showed significant solidification and void effect in all cases. The premixed mass in BA was about 1/4 of the total melt mass (~40kg) at the time of triggering (1.12s). The impact of the modified uniform particle diameters was strong; the cases D1 and D2 showed much less and more premixed masses, respectively. Results of other cases were close to each other.

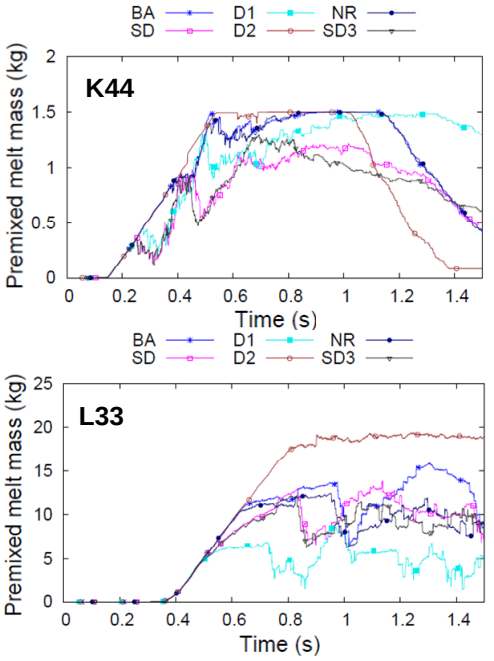

Fig. 2: Evolution of premixed mass of the melt.

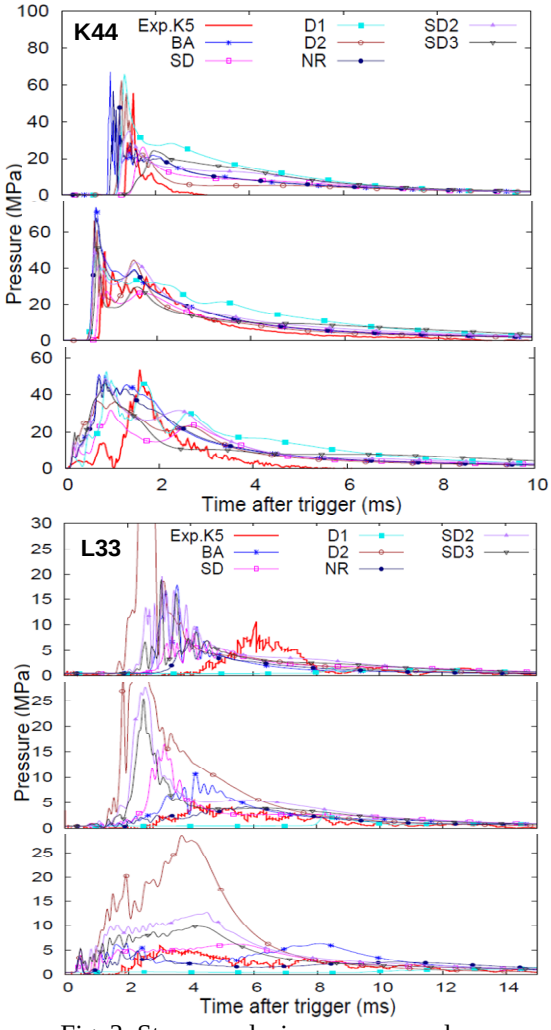

Fig. 3: Steam explosion pressure pulses.

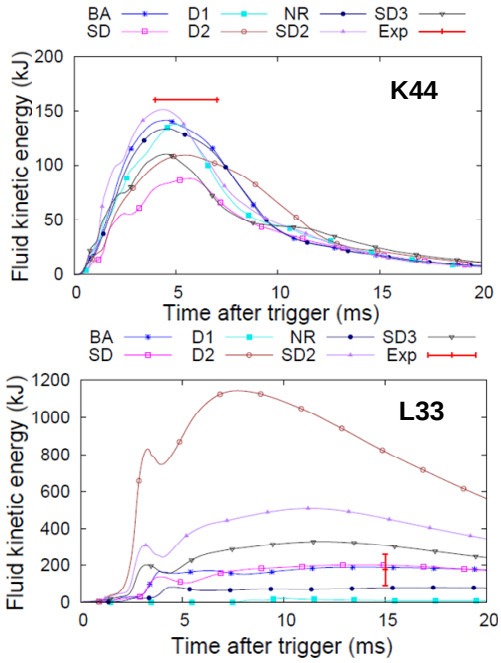

Fig. 4: Kinetic energy evolution during the explosion.

Figures 3 and 4 show the pressure pulses and the kinetic energy evolution during the steam explosion, respectively. The results reflected the different trends in the premixing simulation between K44 and L33 (Fig. 2). The base case results showed fair agreement with the experimental results in terms of the kinetic energy output in both of K44 and L33 (Fig. 4) as already demonstrated in the validation study [5].

In K44, the case SD showed less kinetic energy due to the less premixed mass than BA. The composite with the enlarged fragmentation factor, SD2, showed a good agreement with the experiment. The composite of the size distribution model, enlarged fragmentation rate and the non-local radiation model, SD3, the result turned back to an underestimation. Deviation from BA was not drastic in D1 and NR. However, the larger particle size, D2, lowered the kinetic energy. Larger particle diameters cause sower cooling and solidification and more premixed mass in the case the solidification is significant. However, this was the case that the smaller surface area reducing the fragmentation rate was more significant than the solidification effect during premixing.

In L33, those parametric effects appeared differently. The case SD showed a close result to BA. The superposed effect with an enlarged fragmentation, SD2, showed an overestimation. Modified uniform particle diameters, D1 and D2, showed drastic changes as expected by the strong influence on the premixed mass (Fig.2). The impact of the non-local radiation model, NR, was stronger than K44 because of the higher melt temperature at which radiation has much more contribution in the heat transfer. When this effect was combined with the size distribution model plus enlarged fragmentation rate, SD3, the overestimation was moderated to some extent.

4. Conclusions

The simulation of steam explosion experiments with alumina and corium melts was revisited with improved melt breakup model that were introduced for the necessity in relatively long term melt jet breakup and cooling simulation. The model improvement included an empirical melt particle size distribution model and a simplified non-local (beyond cell) radiation heat transfer model.

The influence of such models on the steam explosion simulation was not the same for two experiments with different melt materials, and we could not find one consistent set of model parameters with application of the newly introduced models to get satisfactory results on the simulation of both alumina and corium steam explosions.

So, it might be better to keep using the original simple and parametric method of handling the melt particle size for steam explosion simulations. The non-local radiation model that has a trend to increase the void fraction in the premixture might give non-conservative results in steam explosion simulations.

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