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Parameter Dependence of Steam Explosion Load and Proposal of a Simple Model

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1. Introduction

The fuel coolant interaction (FCI) including steam explosion is one of the phenomena that may threat the integrity of containment vessel during severe accidents of light water reactors (LWRs). Presently the focus is on the ex-vessel (outside the reactor vessel) cases due to high possibility of having a deep subcooled water pool that is a condition favorable for a strong steam explosion.[1] One of the difficulties of handling this phenomenon in terms of risk assessment is that the scaling of its load between the laboratory (10^{-3}-10^{2}kg, simulant materials) and plant scales (10^{2}-10^{5}kg, UO_2 base oxides) is not straight forward, due to the complexity of the phenomenon. Then, knowledge and fundamental models on the mechanisms obtained through experiments have been integrated into computer codes that can be applied to the plant scale analysis.[2,3]

JASMINE is a steam explosion simulation code developed at Japan Atomic Energy Agency (JAEA)[4] and presently available from OECD/NEA Databank. A steam explosion is simulated by two steps, premixing and explosion stages. A triggering is assumed at a certain timing by the user.

A validation and application strategy of steam explosion codes in the risk assessment was proposed by Moriyama and Nakamura [5], i.e. (a) tuning of the explosion model parameters so that it simulates steam explosion experiments with alumina well, (b) consideration of possible difference between alumina and UO_2-ZrO_2 based prototypic material (corium) in solidification and void generation behavior during premixing, and (c) assumption of triggering at the time the "premixed mass" takes the maximum. The "premixed mass" was defined by them as the mass of the molten ($T>T_{melt}$) material in the zone (cells) where void fraction is less than 0.75. They showed dependence of the steam explosion loads on the jet breakup model parameters, jet inlet diameter and triggering time.

In this work, we used JASMINE code and extended their work by including more parameters in the initial condition with an emphasis on the water pool depth that is important from the view point of accident management with flooded cavity. Note that we follow the definition of premixed mass by Moriyama & Nakamura as representative index of the premixing condition. The calculations in this work used model parameter settings validated on FARO and KROTOS experimental data [3].

Also, we proposed a simple method for evaluation of the steam explosion load based on the observation of this parameter study and a simple evaluation method for premixing by Moriyama et al.[6]

2. Analysis condition assuming a typical PWR geometry with JASMINE code

The PWR reactor cavity geometry used in the cooperative analysis program OECD/SRENA Phase-I Task-4[4] was referred as in Fig.1. The conditions for the analyses are summarized in Table 1. The melt material was assumed to be UO_2-ZrO_2 (80:20wt%) mixture.

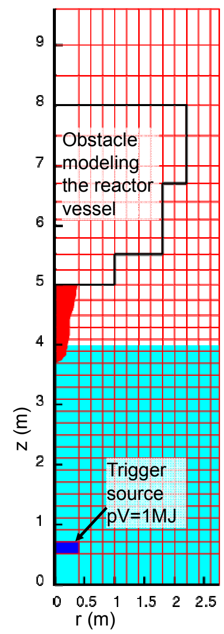


Fig.1: JASMINE analysis grid based on a typical PWR cavity geometry used in SERENA Phase I project.[4]

The parameters examined are as follows.

- Trigger timing (Tr#): assumed at the time of the 1st peak of "premixed mass" (PPM) in Base case; shifted -0.3s -- +0.5s in 3 cases; given at the melt-bottom contact (MBC) in 1 case
- Melt droplet diameter during premixing (Dd#): typical size of corium droplets observed in experiments is 2--3mm [3], larger droplets are kept molten longer and can make the explosion stronger [5]
- Melt jet inlet diameter (Dj#): 0.1--0.5m by considering partial creep failure of the lower head; related to the flow rate of the melt, i.e. larger jet makes more melt mass available in the premixture
- Melt jet inlet velocity (Vj#): 4--16m/s by considering gravitational discharge and remaining pressure up to

1MPa in the reactor vessel; related to the flow rate of the melt together with the jet diameter

- Melt jet inlet temperature (Tj#): given with 60--460K superheat above the melting point (2840K)
- Water pool depth (Hp#): 2--6m including the case the lower head is submerged for in-vessel melt retention
- Water temperature (Tw#): subcool 2--70K

Table 1: Parametric study on steam explosion loads in a typical PWR ex-vessel geometry

Case	Triggering time (shift from PPM,s)	Droplet diameter (mm)	Jet diameter (m)	Jet inlet velocity (m/s)	Jet inlet temperature (K)(superheat)	Pool depth (m)	Water temperature (K)(subcool)
Base	PPM[*1](0.91s)	5	0.3	4	2950 (110)	4	342 (50)
Tr1	PPM-0.3	=	=	=	=	=	=
Tr2	PPM+0.3	=	=	=	=	=	=
Tr3	PPM+0.5	=	=	=	=	=	=
Tr4	MBC[*2]	=	=	=	=	=	=
Dd1	=	3	=	=	=	=	=
Dd2	=	10	=	=	=	=	=
Dj1	=	=	0.1	=	=	=	=
Dj2	=	=	0.5	=	=	=	=
Vj1	=	=	=	8	=	=	=
Vj2	=	=	=	16	=	=	=
Tj1	=	=	=	=	2900 (60)	=	=
Tj2	=	=	=	=	3300 (460)	=	=
Hp1	=	=	=	=	=	2	=
Hp2	=	=	=	=	=	3	=
Hp3	=	=	=	=	=	5	=
Hp4	=	=	=	=	=	6	=
Tw1	=	=	=	=	=	=	322 (70)
Tw2	=	=	=	=	=	=	390 (2)

= : same as the base case; *1) PPM: time at the 1st peak of premixed mass
*2) MBC: time at melt bottom contact; Other conditions: System pressure 0.2MPa, Melt material=UO_2(80wt%)-ZrO_2(20wt%), Cavity geometry as in Fig.1

3. Analysis results

Figure 2 shows evolution of the premixed mass in the cases except Tr#. The premixed mass increases during the penetration of the melt jet into water, saturates when it balances with the mass reaching the bottom or solidifying. After the 1st peak, decrease of the premixed mass (1.1s in Base case) and following oscillation occur due to void generation and escape in the premixture. In the cases with different tiriggering timings (Tr#), different snapshots from the same premixing simulation for Base case was used as the initial conditions for the explosion simulation. The triggering time for Base case was 0.91s, and that for MBC (melt-bottom contact) was 0.57s.

Comparison between cases shows that the thick melt jet (Dj2) and the high inlet velocity (Vj1, 2) cases that make larger melt flow rate show larger premixed mass.

Figure 3 shows the kinetic energy in the explosion simulation. Significantly large kinetic energies are seen in the cases with high mass flow rates (Dj2, Vj1,2).

Figure 4 shows the energy conversion ratio by the conventional definition based on the thermal energy of the total melt mass. The results showed values linearly increasing with the increase of the kinetic energy up to 3%, indicating a systematic influence. Exceptions are the cases of small or large jets (Dj#) that may change the melt surface area to volume ratio in the premixture, or change the ratio of the jet and the center grid sizes that influences the void generation behavior in the calculation.

Figure 5 shows the relation of the premixed mass and the kinetic energy. Nearly linear dependence is seen between them, indicating that "the premixed mass" is a good index for the melt mass participating in the explosion process.

Figure 6 shows the energy conversion ratio redefined with the reference thermal energy limited to the premixed mass. The conversion ratio showed a flatter distribution than the conventional one mostly in the range 3--5% except the cases with small kinetic energy, namely Dj1 with a small jet, Tr2 and Tr3 with small premixed mass due to the trigger timing and Hp1 with a shallow pool.

Figure 7 (a)--(g) summarize the parameter dependence. The observation is as follows.

Trigger timing (a): the premixed mass changed significantly by the triggering time and the kinetic energy changed accordingly.

Melt droplet size (b): the larger droplet size made the larger molten and premixed mass due to slower

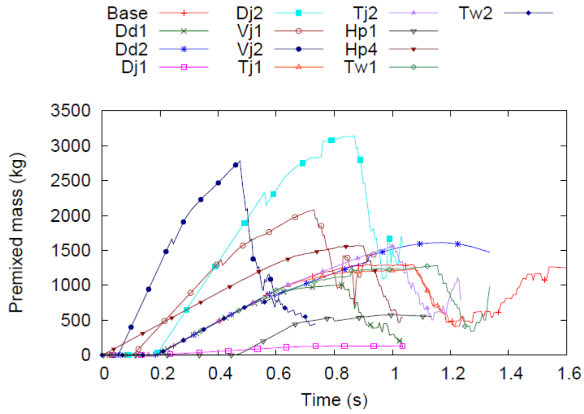


Fig. 2 Evolution of the premixed mass for various cases

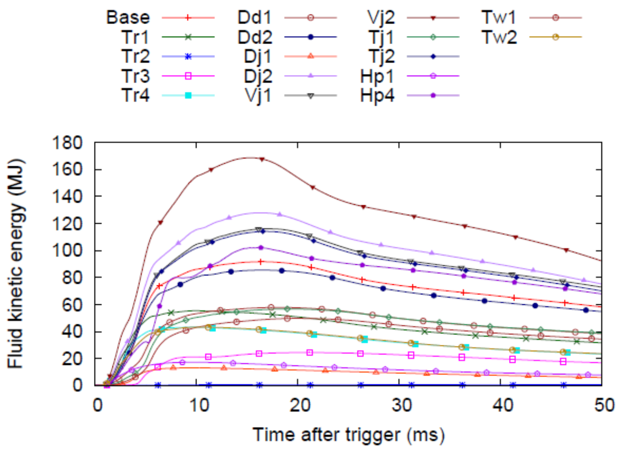


Fig. 3 Histories of the fluid total kinetic energy after the triggering.

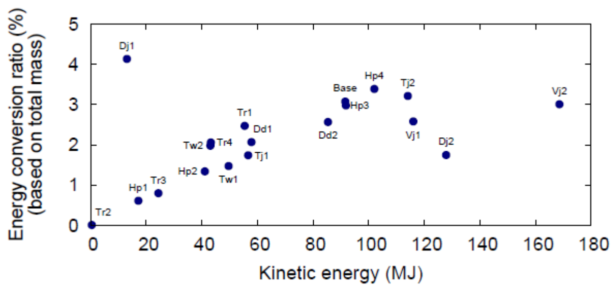


Fig. 4 Energy conversion ratio based on the total mass of the melt in the system.

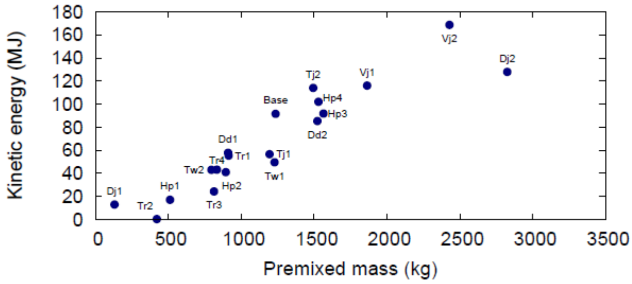


Fig. 5 The relation between the premixed mass and the kinetic energy.

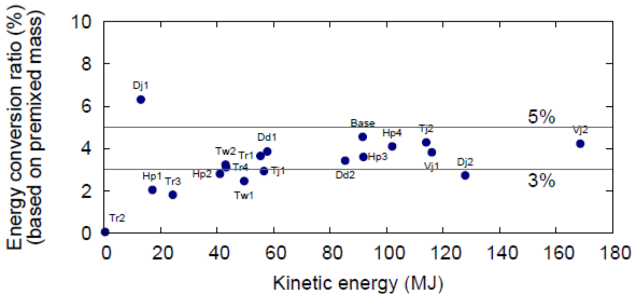


Fig. 6 Energy conversion ratio based on the premixed mass.

cooling; the kinetic energy had a broad peak in the middle range.

Melt jet size (c) & melt jet velocity (d): the size and velocity of the melt jet, i.e. the melt flow rate, had a major influence on the premixed mass and kinetic energy.

Melt jet temperature (e): the higher initial melt temperature (superheat) gave the longer duration before freezing of the melt droplets, then, the larger premixed mass.

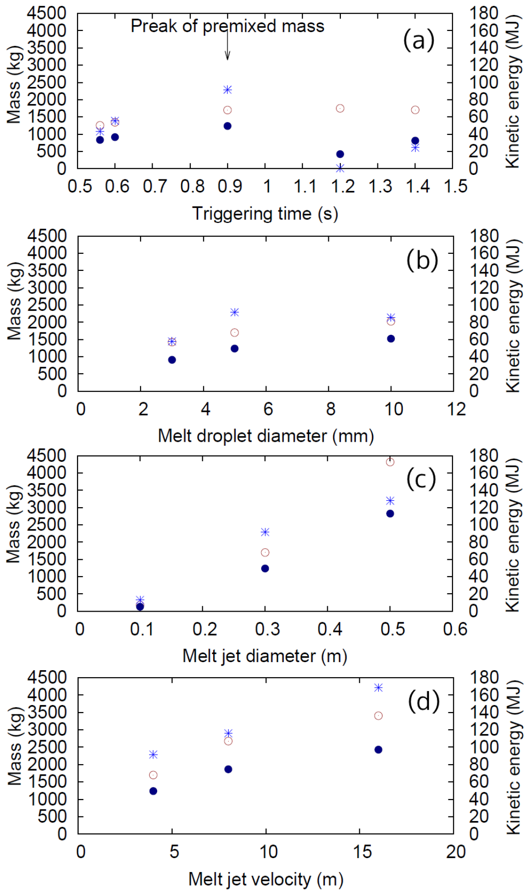
Water pool depth (f): the deeper water pool accommodates the more melt mass premixed and enable the stronger steam explosion.

Water temperature (g): either cold or hot (near saturation) water reduced the premixed mass due to solidification or void, respectively; the middle range subcool of water maximized the explosion load.

In summary, the melt jet diameter and initial velocity which determine the melt inlet flow rate, and the triggering time that significantly influences the premixed mass are the primary factors to determine the thermal energy available for the steam explosion. The water pool depth and the melt initial temperature (superheat) also have strong influence on the explosion load. In all the cases, the premixed mass is well correlated with the explosion load as shown in Fig.5, and can be used as a good intermediate index for the premixing result.

4. Simple modeling method

The analysis results described in the previous section suggest a possibility of a simplified method for evaluation of steam explosion loads. Because the energy conversion ratio based on the premixed mass was in a relatively narrow range, using a constant number and a simplified premixed mass evaluation would be feasible. For the



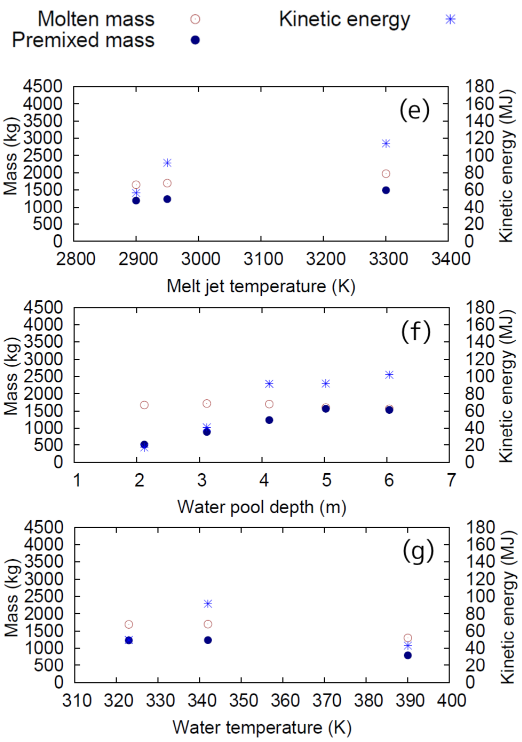


Fig.7 Parameter dependence: (a) Triggering time, (b) Melt droplet diameter in premixture, (c) Melt jet diameter at inlet, (d) Melt jet velocity at inlet, (e) Melt jet temperature at inlet (melting point=2840K), (f) Water pool depth (reactor vessel bottom height=5m), (g) Water temperature.

latter, Moriyama et al. [6] proposed a premixing model in which a pseudo-steady state melt jet breakup, time for settlement and solidification of the melt droplets were considered (Fig.8). The molten mass in the jet column and melt droplets are taken as the "premixed mass". A difference from JASMINE is that influence of the two-phase flow and void is not considered. A constant conversion ratio, 4%, is used with the internal energy for the premixed mass for the kinetic energy evaluation.

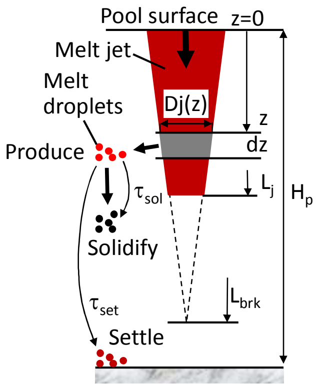


Fig. 8 Concept of the simple premixing model.

Figure 9 and 10 show comparison of the premixed mass and the kinetic energy evaluated by JASMINE and the simple method. The evaluation by the simple method is larger than that by JASMINE by the factor 1.5--2 for the premixed mass, and by the factor 1--3 for the kinetic energy.

5. Conclusions

We examined influence of model and initial/boundary condition parameters on the steam explosion loads by JASMINE code [4]. Parameters that showed strong influences were the melt jet diameter and initial velocity which determine the melt inlet flow rate, the triggering time that significantly influences the premixed mass, the water pool depth and the melt initial temperature (superheat). The premixed mass, defined as the mass of melt droplets and the jet column in the less voided zone ($\alpha<0.75$), is well correlated with the explosion load and confirmed to be a good index for the premixing. The energy conversion ratio based on this premixed mass was in a narrow range mostly 3--5%.

A simple method to evaluate the steam explosion loads was proposed based on a simplified premixing model [6] and usage of a constant energy conversion ratio. Comparison between JASMINE and the simple method showed that the simple method overestimates the premixed mass by the factor of 1.5--2, and the explosion load by the factor of 1--3.

ACKNOWLEDGEMENTS

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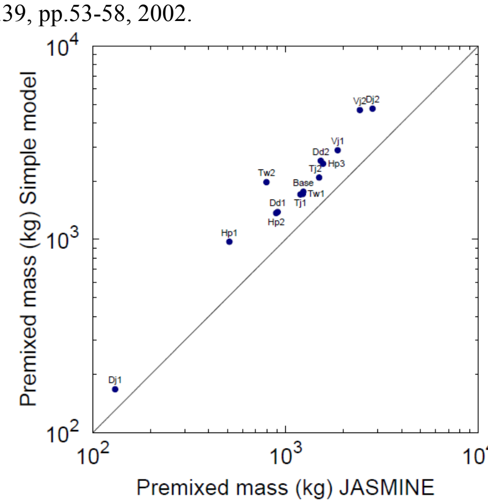

Fig. 9 Comparison of the results of JASMINE code and the simple method: Premixed mass.

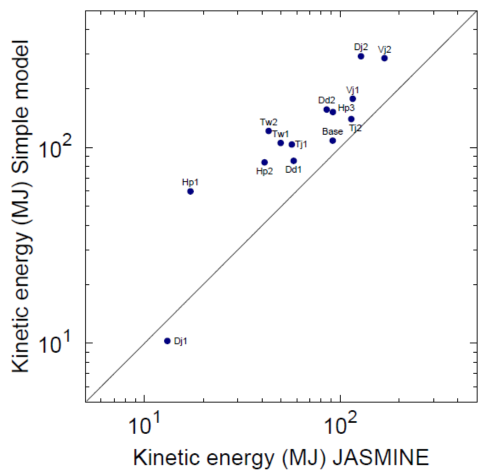

Fig. 10 Comparison of the results of JASMINE code and the simple method: Kinetic energy output.