Parametric Study on the Fine Fragmentation Modeling in Energetic Steam Explosions

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1. Introduction

Since the TMI-2 nuclear accident, prevention and mitigation of severe reactor accidents has been a challenging task in reactor safety study and the recent Fukushima-I accident alerted on expediting installation of advanced measures to secure public safety against radiation hazard. In light water reactors, hydrogen explosion, steam explosion, or molten core concrete interaction could lead to a failure of reactor containment.

When molten core contacts with coolant in-vessel or ex-vessel, a violent steam explosion could occur and the resulting mechanical loading could cause the failure of surrounding structures such as reactor vessel or reactor cavity. The process of a steam explosion can be divided into four phases: (i) fuel-coolant premixing, (ii) triggering, (iii) explosion propagation, and (iv) expansion. Despite of the fact that the rate of fine fragmentation of fuel drops during the explosion propagation phase is crucial to the energetics of steam explosion, experimental data or theoretical modeling on the fine fragmentation are scarce.

In this paper, a parametric calculation on the fine fragmentation model has been carried using TRACER-II code [1] and the adequacy of the models tested is discussed.

2. Fine Fragmentation Models

It is quite well acknowledged that there are two different models of fine fragmentation of molten fuel drops. One is called “thermal fragmentation,” and the other is “hydrodynamic fragmentation.” A brief description of each model is given below.

2.1 Thermal Fragmentation

The idea of thermal fragmentation of a fuel drop was maybe first introduced by Kim and Corradini [2] and a mathematical model was constructed and implemented into TEXAS code by Tang [3]. A conceptual description of the model is the following. The vapor film around a hot liquid drop can be destabilized when a small pressure wave arrives. During the destabilization of film boiling, micro-scale jets of liquid coolant form by the Rayleigh-Taylor instability and penetrate into the fuel drop. Vaporization of these liquid jets can disintegrate the fuel drop into finer size (~0.1 mm or smaller).

The rate of fragmentation for a single particle is given by [3]

$$\dot{m}_{fr} = 6C_{fr}m_f\left(\frac{P-P_{th}}{\rho_c D_f^2}\right)^{0.5}\mathrm{F} \tag{1}$$

F is a function allowing a cut-off of fragmentation when so-called fragmentation time (1~2 ms) has elapsed or too high void of coolant (30~50%). The parameter C_{fr} is around 0.001~0.002. An assessment of this model indicated that the fragmentation time is too long compared to experimental observation of single drop tests as well as to hydrodynamic fragmentation model. In Eulerian modeling, the fragmentation rate per unit volume can be expressed by

$$F_{fr} = 6C_{fr}\alpha_f\rho_f\left(\frac{P-P_{th}}{\rho_c D_f^2}\right)^{0.5}\mathrm{F} \tag{2}$$

2.2 Hydrodynamic Fragmentation

The concept of hydrodynamic fragmentation of fuel drop during the explosion propagation is same as drop breakup in premixing phase [4]. The rate of fragmentation for a single particle is given by

$$\dot{m}_{fr} = 6C_{fr}m_f\sqrt{\frac{\rho_c}{\rho_f}}\frac{\Delta V}{D_f} \tag{3}$$

The parameter C_{fr} is 0.245. In Eulerian modeling, the fragmentation rate per unit volume is given by

$$F_{fr} = 6C_{fr}\alpha_f\sqrt{\rho_c\rho_f}\Delta V/D_f \tag{4}$$

The characteristic time for fragmentation is the order of

$$T^+ = \sqrt{\frac{\rho_f}{\rho_c}}\frac{D_f}{\Delta V} \tag{5}$$

For a small relative velocity of 10 m/s, T^+ is of the order of a few millisecond, and for 100 m/s, T^+ is a few tens of millisecond, which is quite consistent with experimental observation. Eq. (3) is widely used for fragmentation time in many FCI codes such as TRACER-II and MC3D and some codes use a variable expression for the dimensionless fragmentation time.

3. Parametric Calculations

The past FCI experiments that used real corium melt are limited to a few which include FARO, KROTOS, and TROI experiments. The recent OECD/NEA SERENA project financed the new KROTOS tests conducted by CEA and the TROI tests conducted by KAERI. Parametric calculations to assess the two types of fragmentation model were performed for one test from each experiment; KROTOS KS-4 and TROI TS-4 tests. The major test conditions are given in Table 1.

Table 1. Experimental conditions of KS-4 and TS-4

Parameter	KROTOS KS-4	TROI TS-4
Melt comp.	UO_2(80):ZrO_2(20)	UO_2(80):ZrO_2(20)
Melt mass, kg	3.21	14.3
Melt temp., K	2963	3011
Jet dia., cm	3.0 (2.16)*	5.0
Free fall, m	0.5	0.6
Water depth, m	1.1	1.0
Water temp., K	332	333
Pool dia., m	0.2	0.6
Pressure, bar	2.1	2.31
Jet speed, m/s	2.3 (1.6)*	2.8
Trigger time, s	1.04	0.715

*( ): Adjusted input values for simulation

For KS-4 simulation, the initial jet speed was adjusted to 1.6 m/s to match the free-fall trajectory in air space and the jet diameter was also corrected to give the same melt mass. The explosion pressure at different elevation is compared between hydrodynamic and thermal fragmentation model. It is noted that the hydrodynamic fragmentation model shows reasonable pressure compared to the data, but the thermal model shows lower pressure. This trend can be also explained by Fig. 2, the amount of fragmented melt mass.

In TS-4 simulation as shown in Fig. 3 and 4, the hydrodynamic model also gives higher pressures than the thermal model. But in this case, the difference is smaller than KS-4.

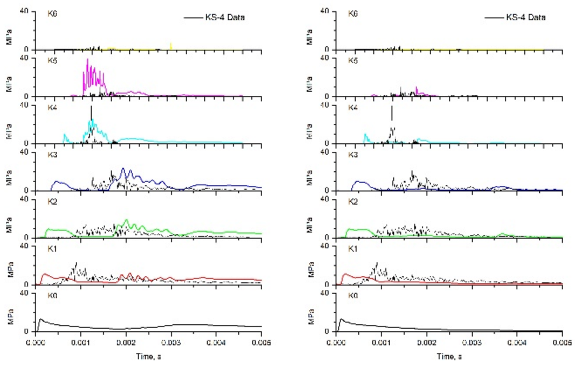

Fig. 1. Comparison of KROTOS KS-4 explosion pressure traces: (left) hydro, (right) thermal.

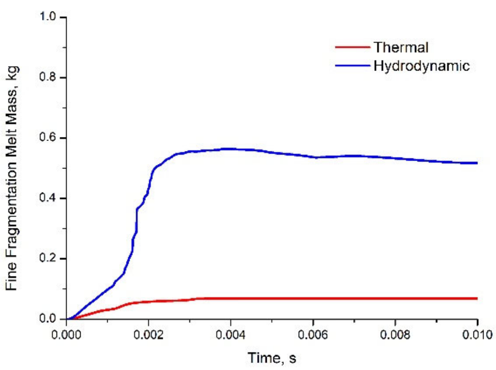

Fig. 2. Comparison of fine fragmentation melt mass in KROTOS KS-4 calculation.

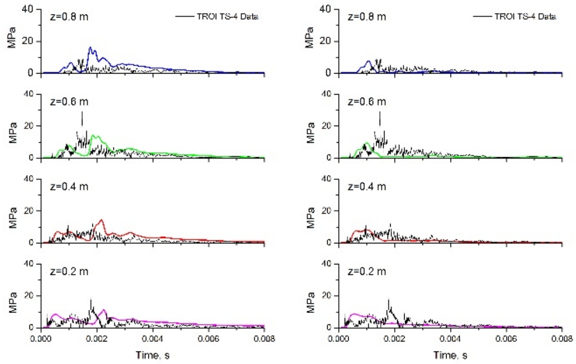

Fig. 3. Comparison of TROI TS-4 explosion pressure traces: (left) hydro, (right) thermal.

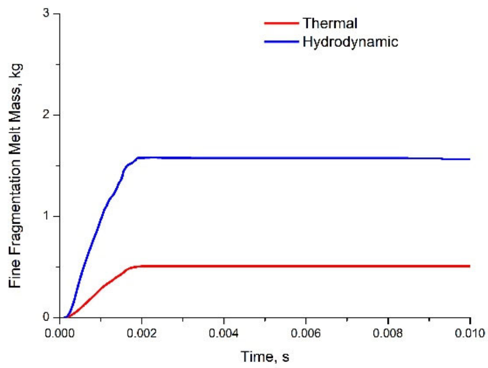

Fig. 4. Comparison of fine fragmentation melt mass in TROI TS-4 calculation.

4. Conclusions

Two types of fine fragmentation model, thermal fragmentation and hydrodynamic fragmentation, has been assessed by parametric calculations of some selected KROTOS and TROI tests. Thermal fragmentation model shows a long fragmentation time so that it could be suitable for triggering phase or mild explosion pressure. However, in a strong explosion where explosion propagation is fast, the hydrodynamic fragmentation model meets such a time scale.

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