A Single-Sphere Film-Boiling Model for Triggerability and Explosion Potential

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1. Introduction

The main causes for the controversy about the corium explosiveness are the hydrogen effect, large voided mixture, material property, poor triggering event (wrong position, weak triggering, wrong time), and low superheat due to a high melting temperature. It has been suggested that a steam explosion of the corium/water system must be suppressed due to the physical properties of corium such as high temperature, high density, multi-component oxide melt, and low thermal conductivity [1]. It was also claimed that the magnitude of the effect on the FCI results of corium/water systems is on the order of higher density, higher temperature, and non-eutectic composition [2]. This concept of a material effect is supported to some degree by parametric experimental results. However, the parametric results between the steam explosion pressure and the material compositions do not directly provide an understanding of the mechanism for the material difference affecting a steam explosion process, even though the sensitivity results can reveal the trends of some parameters affecting the FCI results. This concept of a material effect is supported to some degree by parametric experimental results. The parametric tests themselves also provide us with information on the effect of each initial parameter on a steam explosion. However, sensitivity studies between the steam explosion pressure and the initial value of a parameter do not directly provide an understanding of the steam explosion process. Handling the explosion pressure and initial condition without a mixing could not contribute to a code development process. We need a certain parameter for representing mixing, but we cannot measure it during the FCI tests. The particle size distribution collected after the FCI tests can be a good indicator for explaining a mixing process.

In this paper, TROI tests[3] were analyzed in view of a particle size response for various types of fuel coolant explosions. The heat losses and remnants were calculated using a single-particle film boiling model, and this model was then adapted to various-sized particles to evaluate the triggerability and explosion potential more realistically.

2. A Single-Sphere Film-Boiling Model

The heat loss from a melt particle is a measure of the explosiveness of a melt/water system because the heat loss determines the vapor fraction of the melt/water mixture and the heat content of the particles, which is a resource of a steam explosion. The heat loss is also a function of the melt particle size and thermal conductivity. The specific and latent heats are also related to the heat remnant and heat loss. The heat remnant (=initial heat-heat loss) is the remaining heat of the particles after mixing.

Figure 1 shows the configuration of a single particle heat transfer model based upon the heat conduction.

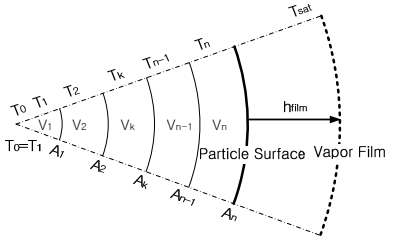

Fig. 1 Concept for a single-sphere, film-boiling model

The integral form of the energy balance equation of a single spherical particle without a heat source term can be described as Equation (1). Equation (2) can be obtained by the Green-Gauss theorem. Then, the discretized energy equations are derived into Equations (3) − (6) using the 1-dimensional FVM method. This equation is solved by TDMA and the time-dependent temperatures, and the heat losses are obtained as follows:

$$\int \rho C_p \frac{\partial T}{\partial t} dV = \int \nabla \cdot k(\nabla T) dV \tag{1}$$

$$\rho C_p V_k \frac{\partial T}{\partial t} = \int k(\nabla T) d\underline{A} = \sum_f k(\nabla T)_f A_f \tag{2}$$

$$\rho V_1 C_p \frac{T_1^* - T_1}{\delta t} = kA_1 \frac{T_2^* - T_1^*}{\delta r} + kA_0 \frac{T_0^* - T_1^*}{\delta r}, \quad T_1^* = T_0^* \tag{3}$$

$$\rho V_k C_p \frac{T_k^* - T_k}{\delta t} = kA_k \frac{T_{k+1}^* - T_k^*}{\delta r} + kA_{k-1} \frac{T_{k-1}^* - T_k^*}{\delta r} \tag{4}$$

$$\rho V_n C_p \frac{T_n^* - T_n}{\delta t} = kA_n \frac{T_s - T_n^*}{\delta r} + kA_{n-1} \frac{T_{n-1}^* - T_n^*}{\delta r} \tag{5}$$

$$kA_n \frac{T_s - T_n^*}{\delta r} = -h_{film} A_n (T_s - T_{sat}) \tag{6}$$

where r, V, A, ρ, C_p, k, h_{film}, T^*, T, T_{sat}, T_s, and t are the radius, finite volume, finite volume surface, density, specific heat, thermal conductivity, film-boiling heat transfer coefficient, new time step temperature, old time step temperature, saturation temperature of the coolant, surface temperature of the particle, and time, respectively. All other variables except for the diameter can be determined without consideration.

Some assumptions are needed for determining the fuel diameter. An area mean diameter should be used for this calculation, but the mass mean diameter can only be

measured from the experiments. Furthermore, the mass mean diameter includes an error owing to coarse sieving steps and maximum and minimum sieve sizes.

3. Analyses with a Representative Diameter

Past work shows that the particle size is highly dependent on the material type: a large particle size of alumina, zirconia, 70:30 corium, and 80:20 corium seems to be 10 − 30 mm, ~ 10 mm, ~ 7 mm, and ~ 6 mm, respectively. Thus, their particle sizes are defined as 12 mm, 6 mm, 3.75 mm, and 3.5 mm, respectively, by considering an experimental mass mean diameter and a large particle size distribution.

For a heat loss from 0.5-liter melt particles, the initial condition and the calculation results are presented in Table I. The 0.5-liter melt particles of 80:20 corium, 70:30 corium, zirconia, and alumina are assumed to be in water with the given diameter and temperature shown in Table I. The initial heat contents of each 0.5-liter melt are 7.54 MJ, 7.19 MJ, 5.13 MJ, and 4.35 MJ for 80:20 corium, 70:30 corium, zirconia, and alumina, respectively.

The heat losses after 0.5-s mixing are 4.97 MJ, 4.35 MJ, 2.08 MJ, and 1.68 MJ for 80:20 corium, 70:30 corium, zirconia, and alumina, respectively. The descending order of the calculated heat loss is 80:20 corium, 70:30 corium, zirconia, and alumina, and this is consistent with the ascending order of the triggerability: 80:20 corium, 70:30 corium, zirconia, and alumina. The order of heat loss during mixing, the order of vapor fraction, and the order of triggerability maintain this consistency.

The heat remnant in Table I might be an indicator of the explosion potential during a triggered explosion because the steam explosion is a process of converting heat energy into mechanical energy. The heat remnants after 0.5-s mixing are 2.57 MJ, 2.84 MJ, 3.05 MJ, and 2.67 MJ for 80:20 corium, 70:30 corium, zirconia, and alumina, respectively. This indicates that the descending order of the steam explosion potential, if the mixture was triggered, is zirconia, 70:30 corium, alumina, and 80:20 corium. But this order of explosion potential seems to not be exactly concurrent with the experimental observations, in which the zirconia and alumina are more explosive than corium.

The participant melt seemed to be limited to large-sized particles, and therefore, the heat remnant evaluated with a single representative diameter could not be an exactly correct indicator of the explosion potential during a triggered explosion. All the heat loss turns into the overall void fraction, but not all of the heat remnant can be converted into explosion energy in reality though the thermal energy remaining in the mixture at an explosion trigger is obviously the maximum potential of the steam explosion. It should be considered that solidified small particles cannot participate in the explosion. In the next study, the heat analyses for the profiled-sized particles will be conducted.

Table I. Calculated heat losses and remnants

Property	Unit	Corium (80:20)	Corium (70:30)	Zirconia (100)	Alumina (100)
Thermal Conductivity	W/m·K	2.85	2.322	1.296	7.5
Diameter	mm	3.5	3.75	6	12
Temperature	K	3100	3100	3100	2600
Density	kg/m^3	7625	7263	5096	3800
Total Heat	MJ/0.5L*	7.54	7.19	5.13	4.35
Heat loss (0.5s)	MJ/0.5L	4.97	4.35	2.08	1.68
Heat remnant (0.5s)	MJ/0.5L	2.57	2.84	3.05	2.67

*0.5L = 0.5 liters **Debris Data of 90:10 Al_2O_3:ZrO_2 Melt

4. Conclusions

This paper indicates that particle size distributions can be a parameter to distinguish the difference between explosive FCI and non-explosive FCI and to determine the void fraction of the mixture through the interfacial heat transfer area. For the triggerability, a system having a small particle size and large thermal conductivity induces a larger heat loss and a more voided mixture, which means a less triggered system. The explosion potentials are dependent not upon the triggerability but upon the heat contents of the particle group, which can participate in a steam explosion. Heat content to be converted into explosion energy is more important than the void fraction or the heat loss during mixing. It may depend on the conductivity how small-sized particles can participate in the explosion fragmentation, because a particle below a certain size is solidified and not fragmentated into a fine size.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Research and Development Program of National Research Foundation of Korea (NRF) with a grant funded by the MEST (Ministry of Education, Science and Technology) of the Korean government.

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