Sensitivity Analysis for Propagation Phase in Steam Explosion under Submerged Reactor Vessel Condition

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1. Introduction

Since nuclear safety act including severe accident enforcement was revised in 2015, the capability to manage accidents has been more important. The six issues which can threaten the integrity of containment after a remarkable damage of core were notified. One of those is a molten fuel-coolant interaction (FCI). An explosion can be caused by violent boiling when water is quickly heated by the corium during the FCI.

For the steam explosion issue, it has to be proven that the integrity of containment is protected. If it cannot meet the criteria of the safety margin, a system or procedure, which minimize the risk of the steam explosion, has to be equipped additionally.

The understanding and knowledge for the in-vessel and ex-vessel steam explosions are constantly being discussed and gathered in various perspectives due to its high importance. A recent report from an international joint research also summarized the status of the knowledge for main phenomenon parameters and properties having an impact on steam explosion [1].

The steam explosion consists of four phases, which are premixing, triggering, propagation, and expansion. In this paper, the results of a premixing experiment, which was performed at the experimental facility of TROI (Test for Real cOrium Interaction with water) in Korea, were utilized for analyzing the effects of the parameters on the load of the explosion.

The purpose of this paper is to analyze the effect of the parameters in the propagation phase on the impact load of a steam explosion.

2. Experiment for IVR-ERVC Condition

Korean advanced pressurized water reactors such as APR1400 (Advanced Power Reactor 1400 MWe) or SMART (System-integrated Modular Advanced ReacTor) adopted a strategy of an in-vessel corium retention by external reactor vessel cooling (IVR-ERVC). According to the purpose of the strategy, a cavity has to be filled with water and the water level in the cavity has to be maintained at the level of the cold leg bottom.

TROI-79 experiment was carried out for the analysis of molten fuel coolant interaction in this condition. To experimentally simulate the IVR-ERVC condition, a prototypic corium was released directly into the coolant water without a free fall in a gas phase before making contact with the coolant [2].

About 20 kg of corium was heated up to 3,000 K in the furnace vessel, and delivered to the intermediate catcher located above the water. Next, it discharged from the nozzle into the water. The diameter of the nozzle exit was 5.0 cm. The test section was filled with 360 kg of water. Water pool depth was 1.0 m. Spontaneous steam explosion was not observed in the test. More detailed information is described in the previous papers [2, 3].

3. Simulation of Propagation Phase in TEXAS-V

To simulate the steam explosion phenomenon, the TEXAS-V code developed in University of Wisconsin-Madison was used. TEXAS-V uses a transient, three fluid, and one-dimensional models capable of simulating fuel-coolant mixing interactions [4].

TEXAS-V code has two modes of calculations. In the first mode for the mixing of fuel in water, three hydraulic fragmentation models (Rayleigh-Taylor instabilities (RTI), Kelvin-Helmholtz instabilities (KHI) and boundary layer stripping (BLS)) can be calculated in the code.

The second mode includes the simulations of phases for triggering, propagation, and expansion. After the calculation for the mixing, a spontaneous or external triggering is assumed to occur at a specified location. The pressure pulse from the triggering initiates film collapse and subsequent coolant jet formation [5]. Next, the direct contact of the corium liquid and water causes rapid evaporation of water. It resulted in the sharp increase of the pressure and more fragmentation on the surface of the molten fuel. The fragmented fuel droplets are quenched by the water again. This process is repeated as the pressure wave is propagated to other parts.

In the propagation and expansion phase, the fragmentation rate is basically calculated as follows [5].

$$\dot{m}_f = C\,\rho_f\,A_f N_f\,\left(\frac{P-P_0}{\rho_c}\right)^{0.5} F(\alpha) g(\tau) \quad \text{Eq.(1)}$$

When this equation is rearranged, the fragmentation rate is proportional to the total mass of all fuel particles in one of the Lagrangian particle groups. The fragmentation in the propagation phase ceases in one of two conditions. The first is when the local pressure is lower than the threshold pressure for film collapse. Secondly, the factor $g(\tau)$ becomes zero after the characteristic time, τ. In addition, when the void fraction of a cell is larger than the specific value, the function of void fraction, F(α), significantly decreases. This fragmentation rate is used for calculating the heat from the fragmented melt to coolant. The vaporization in a short time results in the sharp increase of pressure.

4. Results of Sensitivity Analysis

The premixing phase was firstly simulated by the TEXAS-V code based on the initial condition and results of the TROI-79 experiment. The five thermo-couples at each height of test section were installed for melt front detection in the experiment facility. The movements of the melt jet leading front in the experiment and simulation are displayed in Fig. 1. The error bar means the start and end of the temperature increase. It takes about 0.51 sec for the corium jet to reach the bottom of the test section in both the experiment and simulation. Fig. 2 shows the pressure distributions in the experiments and simulations. Even though there was no steam explosion in the experiment, a spontaneous steam explosion was assumed to occur at the bottom in these simulations. Table I shows the list of the cases and parameters in the sensitivity analysis.

For the cases with different parameters, the explosion phases were calculated. The reference case was set to be the standard. The mass of the fragmented particles summed up at every time step in the cases. Fig. 3 shows the cumulative masses of the fragmented corium in the propagation phase. More mass of the melt was fragmented as the characteristic time increased. The increase of the number of independent leading particles caused more fragmentation in the premixing phase. It resulted in the increase of the interaction area and the number of small particles in a group. In the case of NB-5, the pressure wave was not propagated from the bottom to the middle of the melt jet.

The corium mass under water at the end of premixing has to be considered in the cases of the different initial particle size. Setting a lower void fraction in the F-function reduced the fragmentation time in the propagation phase.

The pressure from the steam explosion is also calculated during the propagation phase. From the pressure variations in a bottom cell, the impulse at the bottom is calculated. The impulse of the pressure wave is converted to the mechanical energy. The calculated mechanical energies from the steam explosions in the cases are shown in Fig. 4.

Table I: Simulation Cases with Parameters

Case	Descriptions for Parameters in Cases	Value in REF
REF	Reference case	-
CFR	Constant C in Eq.(1)	0.002
CHT	Characteristic time in propagation	0.001 s
NB	Number of leading particles	1
RAD	Initial particle radius	2.5 cm
VOF	Void fraction in F-function	0.3

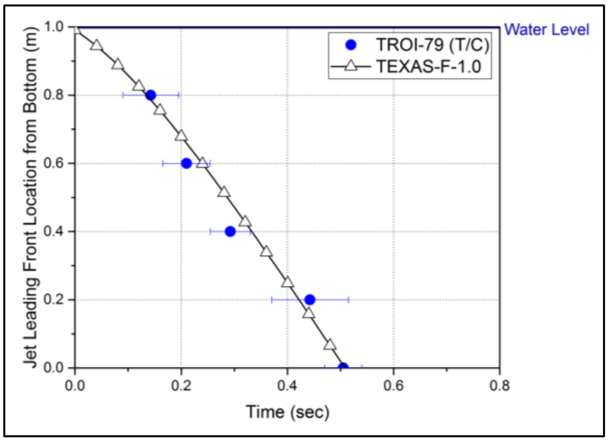

Fig. 1. Movement of Melt Jet Leading Front

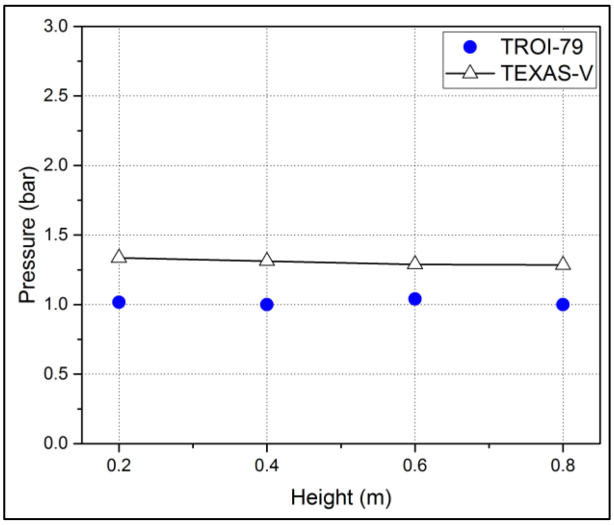

Fig. 2. Pressure Distribution at the End of Premixing Phase

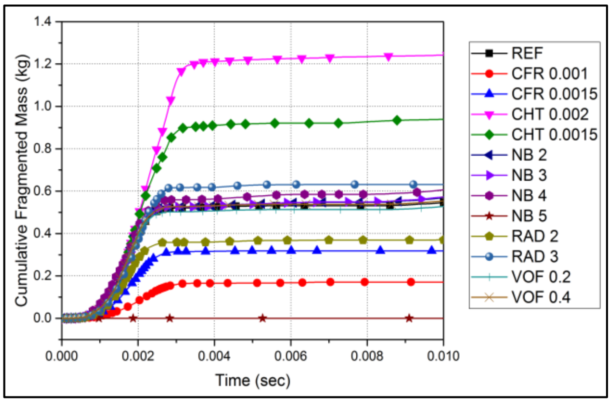

Fig. 3. Fragmented Melt Mass in Propagation

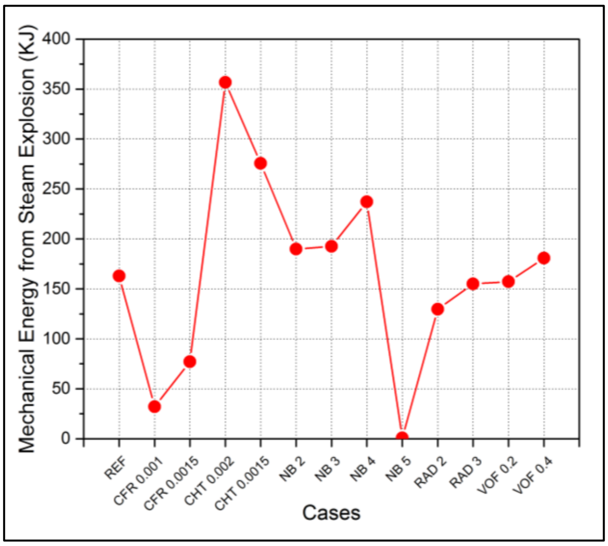

Fig. 4. Calculated Mechanical Energy from Steam Explosion

5. Conclusion

The parameters in the fragmentation rate during the propagation phase were analyzed for estimating the changes of the effects on the steam explosion. Most of the cases tended to be proportional to the mechanical energy of the steam explosion as presented in Eq. (1). However, the degree of change in the parameters was all different. The initial size of the melt jet affects several variables in the simulations.

Some sensitive parameters for sub-phenomena in the steam explosion have to be carefully set for more exact simulations. Accordingly, the risk of the steam explosion depending on the end state of the premixing phase has to be specified based on the results of more parametric analysis.

Acknowledgement

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