Analysis of Steam Explosion for Material Effects

Luai Said Badghaish [a*], Sang Ho Kim [b], Rae-Joon Park[b]
[a]King Abdullah City for Atomic and Renewable Energy, Atomic Energy Sector, Al Olaya Rd., Riyadh, 12244, SA
[b]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, 34507, Korea*
[*]*Corresponding author: l.badghaish@energy.gov.sa*

1. Introduction

The interaction of the molten corium with coolant water in light water reactors known as molten fuel-coolant interaction (FCI), also FCI commonly known as steam explosion, is one of the most complex technical phenomena, involving a coupling between thermal-hydraulic and physic-chemical phenomena. It may represent potentially serious challenge to the reactor containment integrity and RPV structure.

There are going to be a new steam explosion program, even after OECD/SERENA-Phase 2 program. Providing exchanges among the experts and promoting access to some facilities in Europe. Korea finished their national FCI program early in 2017. Additional tests could be performed in TROI and KROTOS facilities, focusing on the impact of having more realistic corium material properties on steam explosion energetics and debris bed cooling [1].

The objective of this paper is to analyze the effects of the material properties in the molten metal melt to estimate the steam explosion load for various cases with different ratios of metal material properties. The material characters could play a fundamental role in steam explosion. Also, the analysis of the steam explosion for material effects is based on the geometric characteristics of SMART (System-integrated Modular Advanced ReacTor) as initial conditions.

TEXAS-V computer code is used to analyze the load of steam explosion in SMART as a tool to perform more detailed analysis on steam explosions and to perform simulations of FCI [2].

2. Methodology

The analysis is based on the base case of the SMART ex-vessel sensitivity analysis. The height of the RPV on the ground is 2.75 m and the pressure of lower containment area is 2 bar. In addition, there are assumed that the water elevation is 2.1 m from the bottom of the cavity and the molten metal melt discharge is on elevation of 3.55 m, which means a side failure. Also, the discharged diameter of the molten metal melt is 0.3 m with temperature of 2400 K while the water temperature in the cavity is 353 K and molten metal melt jet velocity is 5 m/sec. Also, there are constant values used for other variables.

By using TEXAS-V, the model of the grid structure is 34 vertical grids divided into 33 grids of height 0.3 m and last grid is 0.4 m, starting from the bottom of the cavity of total model height 10.3 m as shown in Fig. 1.

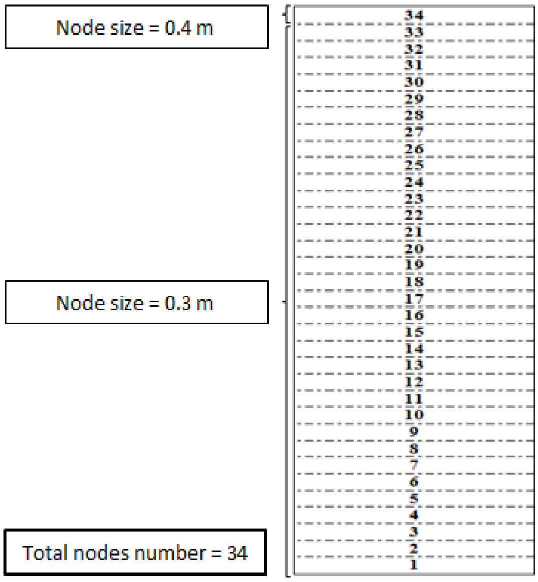

Fig. 1. Nodalization geometry with height of each part.

The analysis of steam explosion for the molten metal melt material effect is taken on Iron (Fe) and Zirconium (Zr). It is taken with different ratios of (Fe:Zr) which are "8:2, 7:3, 6:4, and 5:5". With the property of five material compositions for a fundamental role in the molten metal steam explosion, the loads of steam explosions are calculated in linearity regarding to the materials ratio as shown in Table I.

Table I: Material properties from various mass composition ratios.

Properties	*Units*	*Fe:Zr*			
Ratio	---	**8:2**	**7:3**	**6:4**	**5:5**
Melting temperature	*K*	1872	1904	1936	1968
Specific heat capacity	*J/kg/K*	415	398	381	364
Density	*kg/m3*	7601	7329	7193	7193
Thermal conductivity	*W/m/K*	68	62	57	51
Heat of fusion	*J/kg*	2.44E+05	2.42E+05	2.40E+05	3.39+E05

TEXAS-V computer code is divided into two step calculations for steam explosion phenomenon. The first step is the mixing calculation based on the initial corium discharge condition, and the second is the explosion calculation using the final state of the mixing calculation as an initial condition.

The output files of the explosion part in TEXAS-V represent lots of information that gives clarification to analyze the differences of the molten metal melt steam explosion ratios. The calculation of each case of the steam explosion for material effects analysis made for the maximum explosion pressure to calculate the impulse pressure which indicates the intensity of the steam explosion to analyze the differences of the molten metal melt steam explosion ratios.

3. Results

Steam explosion of molten metal melt is analyzed using TEXAS-V computer code under different ratios of metal composition.

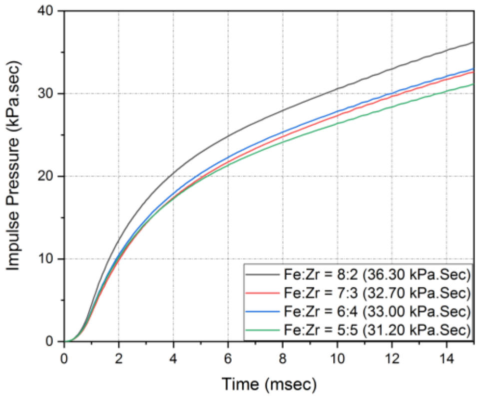

Fig. 2. Impulse pressure variations for different composition ratios.

As shown in Fig. 2, the maximum pressure in the case (Fe:Zr = 8:2) is 10.4 MPa and the impulse pressure is 36.3 kPa.s in node 3. Otherwise, the maximum pressure in the other cases is between 7.9 MPa and 10.4 MPa in node 3. Also, the impulses of the other are much smaller than the case of (Fe:Zr = 8:2). It is found that the particles are thermally fragmented more than the other cases.

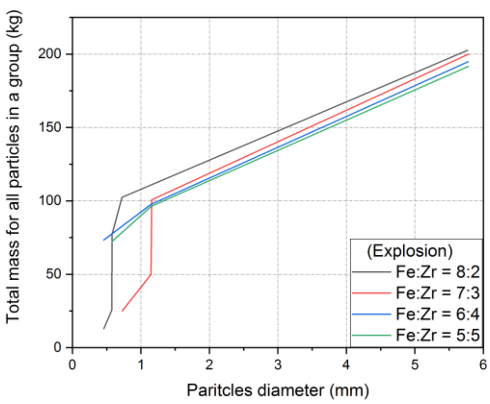

Fig. 3. Accumulated total mass distributions of particles with equivalent particle diameters after the explosion.

As shown in Fig. 3, in the explosion phase the accumulated total mass of particles is found much larger with the particles diameter below 1.0 mm in case (Fe:Zr = 8:2) than the other cases. The total mass of particles above the diameter of 1.0 mm in the case (Fe:Zr = 8:2) is a little higher than the other cases by approximately 20%.

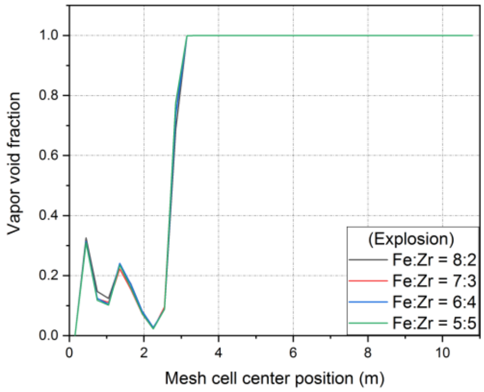

Fig. 4. Vapor void fraction of water after the explosion.

As shown in Fig. 4, in the region at 0.45 m of water level, slightly higher void fraction is found due to the continuous fragmentation of the corium jet in the case (Fe:Zr = 8:2) than the other cases. In addition, the particles in the region with the high void fractions are thermally fragmented.

4. Discussion

Even though the corium mixing area increased, there was no change on the tendency of the results. Otherwise, it shows that the case of (Fe:Zr = 8:2) have a much higher impulse than the other cases. In this kind of metal material properties, the relation of the Fe ratio is proportionally to the impulses of the steam explosion.

The current fragmentation model is based on previous experimental and theoretical research on fuel drop fragmentation. It was assumed that the fuel fragmentation was caused by a combination of hydrodynamic and thermal effects. It was proposed a semi-empirical model as the first approach to model the fuel fragmentation as shown in Eq. 1 [3].

$$\dot{m}_f \sim \rho_f \, 4\pi R_p^2 \, N_p \, V_{jet} \, F(\alpha) \, g(\tau) \qquad \text{(Eq. 1)}$$

ρ_f is the fuel density, R_p is the particle radius at any time, N_p is the number of particles in one fuel particle group, V_{jet} is the coolant jet velocity, $F(\alpha)$ is the compensation factor for coolant void fraction, and $g(\tau)$ is the factor for the available fragmentation time. The fragmentation rate is proportional to the fuel droplet surface area and the average jet velocity during the process [3].

5. Conclusions

TEXAS-V FCI integral code has been applied to this study. The selected premixing and explosion tests are calculated and the results are compered to identify the effect of material property ratios of the molten metal melt.

This study focused on the effects of the materials property ratios in the molten metal melt to analyze the ex-vessel steam explosion load in SMART. There are two metal materials identified in this study with five different ratios.

Based on the explosion phase simulation results on the effect of the molten metal melt can show the explosion strength for different composition. The maximum pressure is 10.4 MPa to the lower containment area of the reactor at 0.001 sec in the case (Fe:Zr = 8:2) and the pressure variation resulted in 36.6 kPa.s of impulse. The material property ratio of the case (Fe:Zr = 8:2) shows much higher impulse of a shock wave from the steam explosion than the other material properties ratios due to thermal of fine fragmentation and high void fraction. In premixing phase, all the metal material property ratios show approximately similar results. There is no a huge difference between them.

Even though the TEXAS-V code can model the oxidation of metal material and calculate the hydrogen production, it does not have a capability to simulate the hydrogen explosion. The additional hydrogen explosion reaction will be included in the further studies.

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