Analysis of Steam Explosion in Advanced SMRs

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1. Introduction

The evaluation of the alpha-mode failure which is designated as the containment failure by the failed reactor upper head as a result of an in-vessel steam explosion was done [1] and the the ex-vessel fuel coolant interaction analysis [2] was also carried out by regulation guides [3,4].

In this paper, the possibility of steam explosion (SE) occurrence in typical pressurized water-cooled small modular reactors (SMRs) where the reactor pressure vessel is enclosed by containment vessel is reviewed based on fundamental characteristics of steam explosion. The methods to evaluate the explosion strengths by in-vessel and ex-vessel steam explosions are also introduced and applied to the sample calculation.

2. Steam Explosion

2.1 In-Vessel Steam Explosion

The small size of reactor pressure vessel (RPV) in SMRs than traditional PWRs and BWRs will reduce the strength (load) from in-vessel steam explosion if the assumption that the larger pour jet causes the more energetic explosion as NUREG-1150 is applied. It was also concluded that the probability of the alpha-mode failure of the containment by an in-vessel steam explosion is very low [5] as 10^{-3}~10^{-5}. This conclusion will be maintained in SMRs because there is no any factor to increase the strength of in-vessel steam explosion in phenomenological. SERG-2 in the report [5] insists that the work required to fail the upper head of the reactor vessel is generally calculated to be of the order of 1,000MJ in traditional reactors. Nevertheless, the probability of alpha mode failure in NuScale was evaluated [6], and the independent analysis by USNRC was performed [7].

The below is the conservative and simple method based on thermodynamics to evaluate in-vessel steam explosion. The total thermal energy of melt (E_{ther}, J/kg) is given by

$$E_{ther} = m_{melt}(C_p \Delta T + h_{fg}) \qquad (1)$$

where m_{melt} (kg) , C_p(J/kg/K) ΔT (K) and h_{fg} (J/kg) denote the melt mass, the specific heat of melt, the temperature difference between initial melt and coolant, and the heat of fusion, respectively.

The steam explosion efficiency (η), so called the CR (conversion ratio), is defined as

$$\eta = \frac{E_{kin}}{E_{ther}} \qquad (2)$$

The kinetic energy (E_{kin}, J/kg) by the melt-water interaction can be estimated by assuming a one-dimensional acceleration of an inertial mass (water slug, m_{water}), as

$$E_{kin} = \frac{I_{tot}}{2m_{water}} \qquad (3)$$

where total impulse I_{tot} is in N·s, and m_{water} is the water slug mass in kg.

This method has applied to evaluate the conversion ratio from the measured explosion strength in several experiments [8,9]. Meanwhile, if the CR is properly assumed, the explosion strength in typical advanced SMRs can be predicted.

2.2 Ex-Vessel Steam Explosion

Because the distance between the bottom of the lower head of the RPV and CV (containment vessel) in advanced SMRs is small, not resulting in enough jet breakup, it is difficult to happen an explosive steam explosion. This small space also will limit the release of much of molten corium to cause an energetic steam explosion. The below is the TNT equivalent method for an ex-vessel steam explosion based on the impulse in the shock wave of explosion [10],

$$I = 5760\, W^{\frac{1}{3}} (W^{\frac{1}{3}}/R)^{0.891} \qquad (4)$$

where I is N·s/m^2, W is TNT the equivalent mass(kg), R (m) is the distance from explosion point to the structure affected by explosion.

This method is the simple and useful method in the case that the CR is properly assumed from the experiments because the TNT equivalent mass of Eq. (4) is determined by the conversion ratio to the kinetic energy of the thermal energy of melt.

3. Sample Analysis in typical SMRs

The melt mass of Eq. (1) is determined from the method which is used to estimate the containment failure probability by the alpha mode in the NUREG-5030 report as below

$$m_{melt} = 2\rho_f \delta L \sqrt{\pi A} \quad (5)$$

where m_{melt} (kg) is the melt density, L and δ is the vertical distance and the thickness assumed to participate in explosion, respectively.

The melt mass to predict the steam explosion strength TNT equivalent method of Eq. (4) is determined

$$m_{melt} = \pi\left(\frac{d_{jet}}{2}\right)^2 * H_{water} * \rho_{melt} \quad (6)$$

where d_{jet} is the melt jet diameter (m), H_{water} is the water height (m) and ρ_{melt} is the density of melt(kg/m^3).

Table 1 and 2 shows the calculation cases based on the material property of the reports [11, 12]. S.S stands for stainless steel.

Table 1. Calculation Cases

Case 1	80:20 (UO_2:ZrO_2)
Case 2	70:30 (UO_2:ZrO_2)
Case 3	UO_2/ZrO_2/Zr/S.S
Case 4	Oxide (UO_2+ZrO_2), Metal (Zr+S.S)

Table 2, Material properties of the compositions

	80% wt UO2/ 20% wt ZrO2	70 wt UO2/ 30% wt ZrO2
Melt Temperature [K]	3228	2950
Melt Superheat [K]	300	80
Temperature, Solidus-liquidus [K]	2882/2928	2840/2870
Density [kg/m³]	7300	8000
Specipic Heat, Cp, Solid-liquid [J/kg/K]	450/510	450/510
Latent Heat, Hfg [kJ/kg]	280	320

	UO2	ZrO2	Zr	Fe
Melt Temperature	3220	3073	2198	2011
Melting temperature	3120	2973	2098	1911
Density(kg/m³)	8740	5990	6130	7020
Specific heat(J/(kg-K))	485	815	458	835
Heat of fusion (kJ/kg)	288.9	731.7	251	261

	Oxide Pool (UO2 90%+ZrO 10%)	Metallic Pool (Fe90%+Zr10)
Melt Temperature [K]	3073	1700
Melting temperature [K]	2973	1600
Density [kg/m³]	8450	6890
Specific heat [J/(kg-K)]	510	778
Heat of fusion [kJ/kg]	320	260

The impulse to the upper head of the RPV is estimated under the assumption that the melt temperature is divided into the melting temperature of compositions and the mixture of oxide and metal. The dissipation of the explosion strength to the structures located above steam explosion point is also considered from the referring in USNRC independent review in NuScale. The maximum CR, 20%, for the calculation is conservatively selected from HICKS MENZIES steam explosion efficiencies [13] applied in NuScale.

Figs. 1~3 show the impulse applied to the RPV upper head by an in-vessel steam explosion. The effect of composition and melt temperature is relatively minor and the dissipation effect of the explosion strength to the structures located above steam explosion point is relatively great. The maximum impulse of the slug impacted to the upper head of RPV by an in-vessel steam explosion is about 8 to 10 psi·s with the dissipation effect. 10 psi.s of this analysis is equivalent to about the 800MJ.

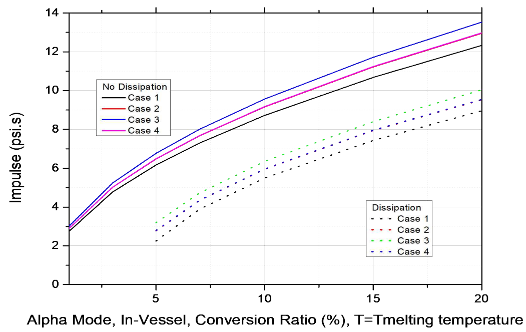

Fig. 1 Impulse by In-Vessel SE (T_{melt} =Tm.p)

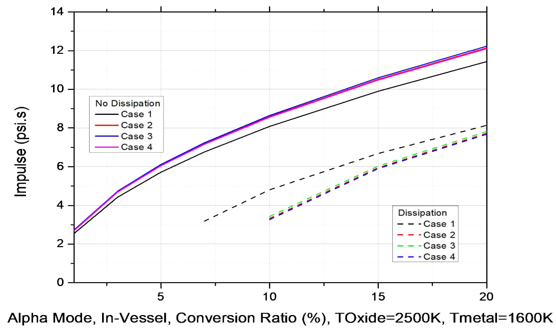

Fig.2 Impulse by In-Vessel SE (T_{melt}=T_{oxide},T_{metal})

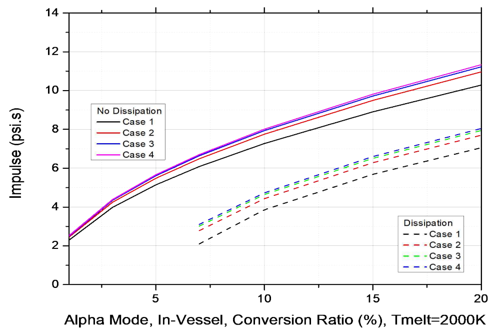

Fig. 3 Impulse by In-Vessel SE (T_{melt} =2000K)

Figs. 4 and 5 show the impulse applied to the CV by an ex-vessel steam explosion The maximum explosion strength is below 6 psi·s in 3% CR which is very conservatively assumed from the steam explosion experiments using corium melt jet.

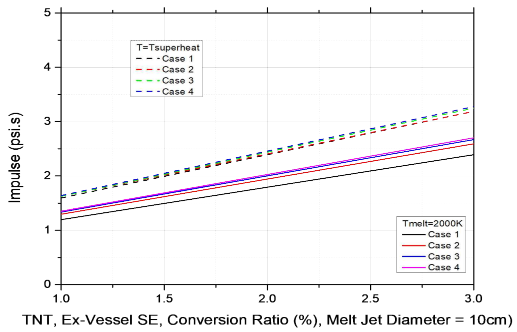

Fig. 4 Impulse by Ex-vessel SE(d_{jet} =10cm)

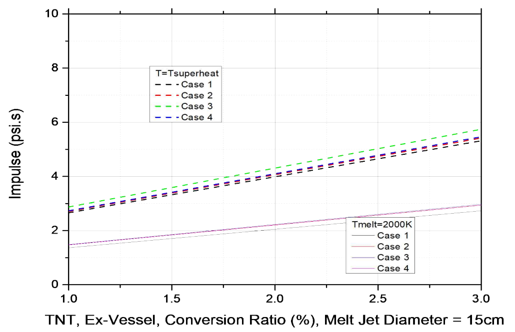

Fig. 5 Impulse by Ex-vessel SE(d_{jet} =15cm)

4. Conclusions

Considering geometric features in SMRs based on fundamental characteristics of steam explosion, it is analyzed that the probability of the alpha mode failure by an in-vessel steam explosion is lower than the traditional PWRs and BWRs and the possibility of energetic ex-vessel steam explosion is also very low.

From the analysis using the similar method to applied in the NuScale for the alpha mode failure probability of RPV by an in-vessel steam explosion, the dissipation effect of the explosion strength to the structures located above steam explosion point is important factor to influence the impulse strength. From the ex-vessel steam explosion analysis using the TNT equivalent method where is assumed the conversions from steam explosion experiments of the molten corium, the selection of the melt temperature of molten is important factor to influence the impulse strength.

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