Explosion Strength of Prototypic Molten Corium by Steam Explosion

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1. Introduction

It was known that the explosivity of the corium would be very low and the conversion ratio would be almost zero [1]. The exlosivity, expressed as the strength of an explosion, can be evaluated the dynamic pressure and/or force measured in the experiment or sometimes by the conversion ratio. The dynamic pressure and/or force measured in the experiment can be used for a qualitative evaluation of the explosivity by simply comparing them among the experiments. More generally, the explosivity of the molten material is expressed through the conversion ratio. The explosivity by using the conversion ratio is evaluated. This method is called the quantitative method because several experimental factors are well considered. In this paper, the explosivity of the prototypic from the TROI steam explosion experiment is investigated by using qualitative and quantitative methods.

2. Methods and Results

The typical TROI facility used to simulate the interaction of molten prototypic material with water under partially flooded reactor cavity conditions. In this test, there is a free fall from the exit of the intermediate melt catcher to the water surface. More detail explanation of the facility in the reference [2]. For reactor submerged conditions, the molten material is released into the water surface without a free fall, which is the distance from the exit of the intermediate melt catcher to the water surface. More detail explanation of the facility in the reference [3].

2.1 Explosivity by Experimental Parameters

For the qualitative evaluation of explosivity, the effects of experimental parameters are investigated from the experiments with similar initial and boundary conditions, not exact conditions, except for the parameter to be investigated.

Effect of Depth of Coolant: From the experiments performed in cases in which the water heights are 67cm and 130 cm, expressed by TS water H in the Table I, the effect of depth of coolant to the explositivity is investigated. For ZrO_2 and Corium of $70\%UO_2/30\%ZrO_2$, explosive strength is increased with the increase of the coolant depth. For Corium of $80\%UO_2/20\%ZrO_2$, water depth dependence was not observed. Accordingly, explosive strength increases with an increase of water depth because melt jet has more chance to break-up. However, this result will be limited to the water depth used in the experiment.

Table I: Effect of Depth of Coolant

Material	Weight %	Sub-cool, K	TS water H, cm	TS area m2	Init. P. MPa	Released mass, kg	Free fall, m	Trigger	SE	Dynamic P., MPa	Dynamic load,kN
ZrO2	100	85	67	0.283	0.11	5.43	3.8	No	SE	5.5	>500
		84	130	0.283	0.11	5.479	3.2	ET	SE	8.5	810
UO2/ZrO2	70/30	88	67	0.283	0.105	6.545	3.8	No	SE	0.8	210
		86	130	0.283	0.105	11.734	3.2	ET	SE	5.7	235
UO2/ZrO2	=77-78 /22-23	85	67	0.283	0.102	7.21	3.8	No	No	-	-
		85	67	0.283	0.116	9.055	3.8	No	No	-	-
		78	130	0.283	0.118	21.065	3.2	No	No	-	-
		80	130	0.283	0.11	10.385	3.2	No	No	-	-

TS : Test Section, ET : External Trigger, SE : Steam Explosion

Effect of Interaction Chamber Shape: From the experiments performed for the cases that the interaction chamber size is 0.283 cm^2 (diameter 60cm) and 0.36 cm^2 (60cmx60cm), expressed by TS water area in the Table II, the effect of the interaction chamber shape to the explosivity is investigated. For ZrO_2, the higher explosivity in the cylinder shape is appeared. For the Corium of $70\%UO_2/30\%ZrO_2$, there is not much difference in the dynamic pressure. But, the dynamic load is measured at the in the cylinder shape. For the corium of $80\%UO_2/20\%ZrO_2$, the dependence of interaction chamber was not observed. Accordingly, the cylindrical shape shows slightly higher explosivity.

Table II: Effect of Interaction Chamber Size

Material	Weight %	Sub-cool, K	TS water H, cm	TS area m2	Init. P. MPa	Released mass, kg	Free fall, m	Trigger	SE	Dynamic P., MPa	Dynamic load,kN
ZrO2	100	83	67	0.283	0.104	2.28	3.8	No	SE	11.5	>250
		85	67	0.283	0.11	5.43	3.8	No	SE	5.5	>500
		81	67	0.36	0.1	4.256	3.8	No	SE	2.2	-
		89	67	0.36	0.114	2.98	3.8	No	SE	5.5	-
UO2/ZrO2	70/30	81	67	0.283	0.108	7.735	3.8	No	SE	7	250
		77	67	0.36	0.116	12.23	3.8	No	SE	9	-
UO2/ZrO2	77-78 /22-23	87	67	0.283	0.11	7.855	3.8	No	No	-	-
		89	67	0.36	0.105	12.105	3.8	No	No	-	-
		85	130	0.071	0.105	5.325	3.1	No	No	-	-
		80	130	0.283	0.11	10.385	3.2	No	No	-	-

TS : Test Section, SE : Steam Explosion

Effect of Free Fall Distance: From the experiments with 1 m and ~ 3 m of the free fall in Table III, the effect of the free fall distance to the explosivity is investigated. For ZrO_2, the bigger dynamic load is measured at the longer free fall distance. However, the dynamic pressure shows opposite trend. In the test with 1.0m free fall, the external trigger device was properly working in the time the melt jet arrived at the bottom of the interaction chamber. But, in the test with 3.2m free fall, but the spontaneous explosion happened.

Accordingly, there was a limitation of the direct comparison. For the corium of 70%UO_2/30%ZrO_2, the longer free fall distance shows the bigger dynamic load and pressure. It seems that the longer free fall makes a higher injection velocity of the melt jet, causing a higher break-up rate of the melt jet.

Table III: Effect of Free Fall Distance

Material	Weight %	Sub-cool, K	TS water H, cm	TS area m2	Init. P. MPa	Released mass, kg	Free fall, m	Trigger	SE	Dynamic P., Mpa	Dynamic load,kN
ZrO2	100	78	100	0.283	0.109	9.437	1	ET	SE	20	480
		84	130	0.283	0.11	5.479	3.2	ET	SE	8.5	810
UO2/ZrO2	70/30	75	100	0.283	0.117	12.506	1	ET	SE	12	280
		68	95	0.283	0.11	5.26	3.55	ET	SE	17	360

TS : Test Section, ET : External Trigger, SE : Steam Explosion

2.2 Conversion Ratios

The conversion ratio under partially flooded condition of reactor cavity is calculated for experiments performed under SERENA Project [4]. The largest value of calculated values from dynamic pressures and force is selected. The conversion ratio, as seen in the Table IV, is spanning a range between 0.1% and 0.7%. TS6 including 4 kinds FP materials based on the oxidic material shows maximum explosivity because this composition has large difference between the liquids temperature and solidus temperature. We have to keep in mind that this composition closes to the reactor accident conditions. This maximum value is much larger than the conversion ratio, 0.15% from KROTOS experiments. Nevertheless, it was turned out the conversion ratio of the corium is smaller than it of Al_2O_3, 1.5 to 3%.

Table IV: Conversion Ratio by FCI under the Partially Flooded Condition of Reactor Cavity

Test ID	TS-1	TS-2	TS-3	TS-4	TS-5	TS-6
Delivered Melt Mass (kg)	15.4	12.5	15.9	14.3	17.9	9.3
Melt Composition (wt%) UO_2/ZrO2 Zr U Fe_2O_3 FP	73.4/ 26.6	68.0/ 32.0	71.0/ 29.0	81.0/ 19.0	76.0/ 18.3 5.0 0.7	73.3/ 18.5 4.9 3.3
Water Depth (m)	1.0	1.0	1.0	1.0	1.0	1.0
Water Temperature (K)	301	334	331	333	337	338
Sub-cooling (K)	115.9	61.7	65.1	64.0	57.7	56. 9
System Pressure (MPa)	0.4	0.2	0.2	0.2	0.2	0.2
Fall Distance (m)	1.0	1.0	1.0	1.0	1.0	1.0
Jet Diameter (mm)	50	50	50	50	50	50
Conversion Ratio (%)	0.12	0.28	0.22	0.35	0.06	0.66

The conversion ratio of reactor vessel flooded condition, Test ID W8 with the same water temperature as SERENA project in the Table V, is 0.005%. This is much smaller than the SERENA test cases. The conversion ratio in the Test ID W10 test case with high subcooling is 0.46%. Compared with W8, the result seems reasonable because it is known that the lower water temperature shows higher explosivity.

Accordingly, the maximum conversion ratio of prototypic corium by steam explosion is about 1.0% because the collected debris after experiments, not mass contributing steam explosion which can be exactly estimated, is considered for the calculation of the conversion ratio.

Table V. Conversion Ratios by FCI under the Reactor Flooded Condition

Test ID	W8	W9	W10
Delivered Melt Mass (kg)	23.949	20.2	13.484
Melt Composition (wt%) UO_2/ZrO2	76.77/23.23	75.74/24.26	74.33/25.67
Water Depth (m)	0.99	0.99	0.99
Water Temperature (K)	341	340	298
Sub-cooling (K)	32	33	75
System Pressure (MPa)	0.116	0.12	0.126
Fall Distance (m)	~0	~0	~0
Jet Diameter (mm)	50	50	50
Conversion Ratio (%)	0.005	N/A	0.46

3. Conclusions

From the qualitative method, it is estimated the explosivity from the experimental parameters such as the coolant depth, the shape of the interaction chamber, the free fall height of the melt jet. The results agree with the general trends to the level that can be explained reasonably. It is not sufficient for explosivity estimation because the explosive location and mass are not considered. The quantitative method where the amount of molten mass and the location effect appearing the maximum pressure is considered. Conversion ratios of experimental data produced by partially flooded condition are rather low, spanning a range between 0.1% and 0.7%. Conversion ratio under the reactor submerged condition is smaller that of reactor cavity partially conditions. This method is more adaptable to compare the explosivity among experiments using the different facilities each other. Finally, it is recommended that conversion of 1.0% is used for reactor safety evaluation by steam explosion.

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REFERENCES

[1] I. Huhtiniemi, D. Magallon, Insight into steam explosions with corium melts in KROTOS, Nuclear Engineering and Design, Vol.204, p. 391, 2001.
[2] Seong-Wan Hong1, Pascal Piluso2 and Matjazu Leskovar, Status of the OECD-SERENA Project for the Resolution of Ex-vessel Steam Explosion Risks, Journal of Energy and Power Engineering, Vol.7, p. 423, 2013.
[3] S. W. Hong, Y. S. Na, S. H. Hong & J. H. Song, Fuel-Coolant Interaction Test Results Under Different Cavity Conditions, Nuclear Technology, Vol.196, p. 538, 2016,
[4] OECD/NEA, Agreement on the OECD/NEA SERENA Project; to address remaining issues on fuel-coolant interaction mechanisms and their effect on Ex-vessel steam explosion energetics, 2008.