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Conversion Ratio of Molten Corium in TROI Steam Explosion Experiment

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has run the TROI (Test for Real cOrium Interaction with water) program for a research on a fuel-coolant interaction (FCI) by using prototypical corium material since 2001. About 80 times experiments using several kinds of prototypic materials and experimental conditions have been carried out so far [1]. Some of them were conducted in the framework of the OECD/NEA SERENA project which was commonly operated by KAERI and CEA in France [2]. Under this project, experiments were conducted to simulate the FCI under condition in which a reactor cavity is partially flooded. In addition, KAERI more recently carried out the FCI experiments under condition in which the reactor vessel is flooded to the cold leg.

In this paper, the conversion ratio (CR) which is the scale of explosivity in the steam experiments are compared for experiments performed under different cavity conditions.

2. Methods and Results

2.1 Calculation Methodology of Conversion Ratio

From steam explosion experiments, the dynamic pressures and dynamic load, F, are generally obtained.

The impulse is defined by integrating the dynamic pressure, P(t).

$$I = A\int P(t)dt \quad (1)$$

where A is the cross-sectional area of the interaction vessel (and water column).

The impulse can be also obtained by integrating the dynamic force, F(t).

$$I = \int F(t)dt \quad (2)$$

For the calculation of conversion ratio, the maximum of values obtained by Eq. (1) and Eq. (2) is used for conservatism. The impulse accelerates the water column in the interaction chamber above the measuring position.

The velocity of the water column can be estimated from the momentum transport given as

$$V_{water} = \frac{I}{m_{water}} \quad (3)$$

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

$$E_{kin} = \frac{I^2}{2m_{water}} \quad (4)$$

Finally, the explosion efficiency (η), so called the conversion ratio, is defined as

$$\eta = \frac{E_{kin}}{E_{ther}} \quad (5)$$

where E_{ther} is the total thermal energy of the melt (E_{ther}) which is given by

$$E_{ther} = m_{melt}(c_p\Delta T + h_{fg}) \quad (6)$$

where m_{melt}, c_p, ΔT and h_{fg} denote the melt mass, the specific heat of the melt, the temperature difference between the initial melt and coolant, and the heat of fusion, respectively. The calculation of the kinetic energy is performed at each elevation to observe the dispersion on the results.

2.2 CR from tests under reactor cavity partially flooded conditions

The OECD/SERENA project (sometimes referred to as SERENA Phase II programme) was formulated to resolve the uncertainties on the issues by performing a limited number of well-designed tests with advanced instrumentation. The TROI test facility for this project is shown in Fig. 1. The more detail explanation of experimental facility was stated in the paper [3].

The geometric configurations and melt compositions in the OECD/SERENA project were selected so that they reflect the most relevant accident scenarios for an ex-vessel FCI. The tests were performed with standard ex-vessel conditions, i.e., a pressure of 0.2 MPa and a subcooling of 50 K except for the first test. Table I shows the material properties for the calculation of conversion ratio. The material properties generally depend on the material composition and melt temperature but the constant value of Table 1, which is applied for the OECD/SERENA project, is used.

Table I: Material Properties

Properties	Corium (70:30)	Corium (78:22)
specific heat (J/kg K)	639	638
density(kg/m3)	7263	7625
fusion heat(kJ/kg)	422	387

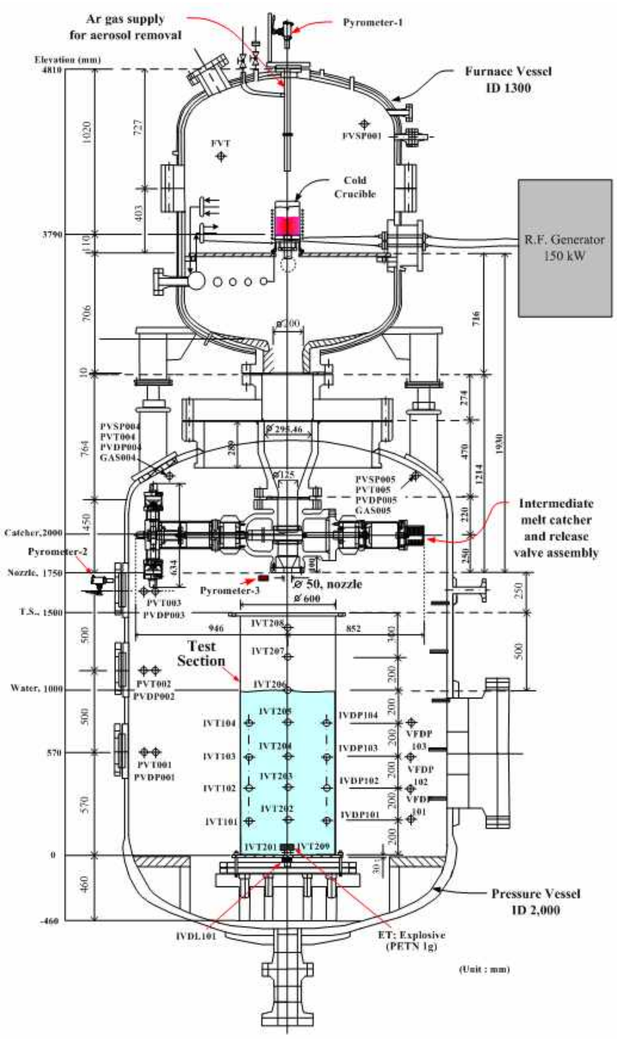

Fig.1. TROI test facilities with a free fall of molten material

Fig. 2 and 3 shows example of the dynamic pressures and impulse load measured in the TS-6 test. These data is used to estimate the conversion ratio mentioned in section 2.1[4].

Actual conditions used and/or achieved for experiments as well as main results are provided in the Table II and all values are rounded off to nearest decimal [5].

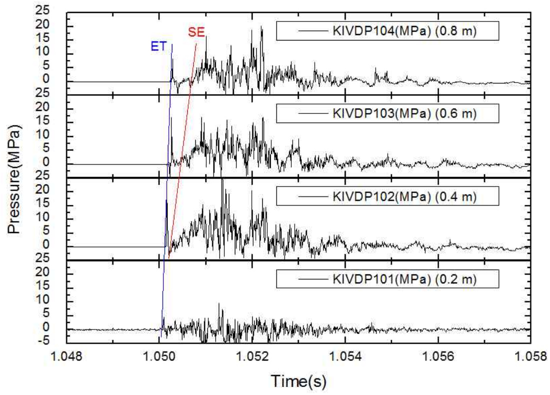

Fig. 2 Dynamic pressures measured in the TS-6 test

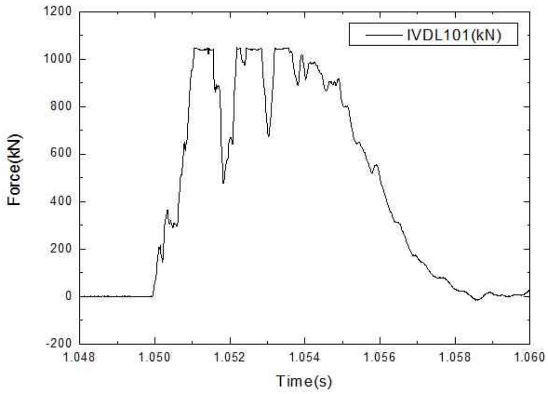

Fig. 3 Dynamic load in the TS-6 test

Table II Result of FCI tests under reactor cavity partially flooded conditions

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 Temperature (K)	~3000	3063	3107	3011	2940	2910
Melt Superheat (K)	145	228	272	171	140	239
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
Triggering Time After Release (ms)	939	875	.875	1 040	1 046	1 050
Location of Melt Leading Edge at Trigger Time (m)	~0.3	~0.4	~0.4	~0.4	~0.1	~0.4
Void at Triggering (vol %)	~4	~3	~2	14-24	12-34	4-10
Max. Pressure (MPa)	17	10	12	20	7	25
Impulse (N.s)	6640	>8000	~9000	>>9000	4680	>>9000
Steam Explosion	S/E	S/E	S/E	S/E	Steam Spike	S/E
Conversion Ratio (%)	0.12	0.28	0.22	0.35	0.06	0.66

The steam explosion efficiency (expressed in terms of sometime conversion ratio) in all tests is rather low, spanning a range between nominally 0.1% or less to no more than 0.7%. The maximum conversion ratio is estimated in the TS-6. It is confirmed that the conversion ratio of the corium is smaller than it of Al_2O_3. It is estimated that the conversion ratio of Al_2O_3 is about 1.5 in the KROTOS test [6].

2.3 CR from tests under Reactor Flooded Condition

For fuel coolant interaction experiments under the reactor submerged conditions, the TROI facility is modified so that molten material can release into the water surface without a free fall which is the distance from the exit of the intermediate melt catcher to the water surfaces, as shown in Fig. 4

The test condition is maintained with the same as SERENA project except for the free fall distance. In the W10 test of the table 2, the water temperature is room temperature, 25^{o}C [7].

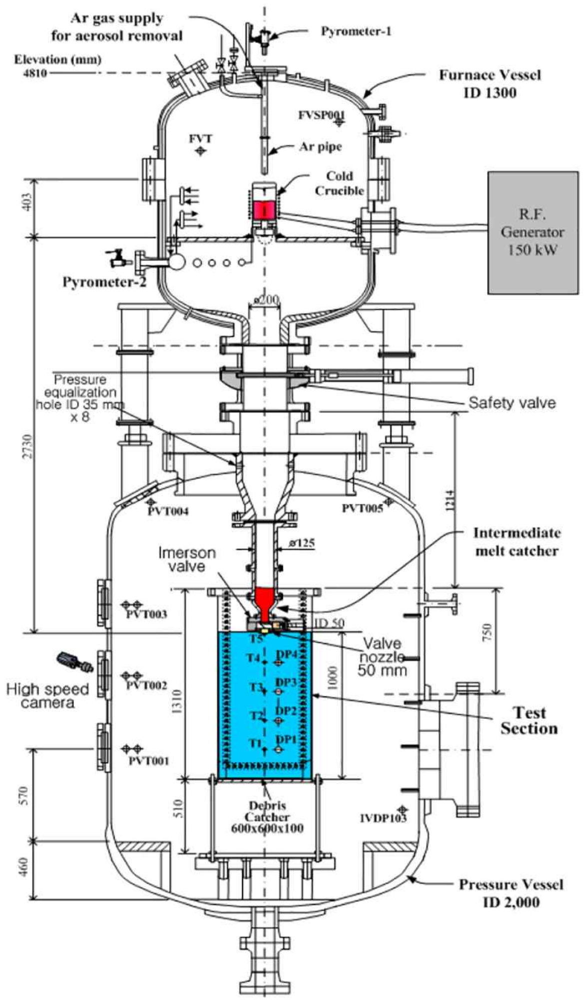

Fig. 4. TROI test facilities for reactor submerged conditions

Table III shows actual conditions used and/or achieved for experiments as well as main results under reactor submerged conditions. The conversion ratio is 0.006 with the same water temperature as SERENA project. This conversion ratio is much smaller the SERENA tests cases. The conversion ratio in the W10 test case where water temperature is relatively low is 0.46. It is estimated that this qualitative result is reasonable because it is known that the lower water shows higher explosivity[8].

Currently, the experimental data for reactor submerged case is not enough to draw the conclusion for the conversion ratio. However, it is appeared that the conversion ratio under reactor submerged condition is smaller them of under reactor cavity partially conditions.

Table III Results of FCI under reactor submerged conditions

Test ID	W8	W9	W10
Delivered Melt Mass (kg)	23.949	20.2	13.484
Melt Temperature (K)	3250	3311	3021
Melt Superheat (K)	400	500	250
Melt Composition (wt%) UO_2.ZrO2	76.8/23.2	75.7/24.3	74.3/25.7
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)	1.0	1.0	1.0
Jet Diameter (mm)	50	50	50
Triggering Time After Release (ms)	542	Fail to Trigger	560
Location of Melt Leading Edge at Trigger Time (m)	1.0 >	N/A	0.8-1.0
Max. Pressure (MPa)	18	N/A	12
Impulse (N.s)	740	N/A	5390
Steam Explosion	-	-	S/E
Conversion Ratio (%)	0.005	N/A	0.46

3. Conclusions

The calculation method of the conversion ratio in steam explosion tests is introduced. The conversion ratios for fuel coolant tests under reactor cavity partially flooded conditions and under reactor flooded condition are compared. It is estimated that the conversion ratio under reactor cavity partially flooded condition is relatively the larger value than it under reactor submerged condition. It was also observed that explosivity in the experiment using corium composition is relatively is weaker than it of Al_2O_3.

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