Relevance Between Mixing Zone Size and Debris Bed Geometry in Fuel Coolant Interaction

Seong-Wan HONG [a*], Sang Mo AN[a],
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejon, 34057*
[*]Corresponding author: swhong@kaeri.re.kr

1. Introduction

It is known that the properties of the particulate debris bed such as particle size and distribution, bed porosity, and bed geometry which are caused by molten corium water interaction, affect the coolability of the bed accumulated on the floor of reactor cavity [1]. The particle size distribution and porosity were proposed by experimental data using available corium–water interaction [2].

FzK carried out the QUEOS experiments of which objective is to mainly investigate the premixing phase using hot spheres, not molten corium jet, in saturated water [3]. They provided the information on the particle bed geometry on the floor of the interaction chamber as well as the mixing zone size depending on the experimental conditions. KAERI carried out TROI fuel coolant interaction experiments using prototypic corium. In some TROI experiments, they investigated the mixing zone size for the cases without steam explosion [4]. In FARO L-28 test, the mixing zone and particle accumulation shape were observed [5].

From QUEOS, TROI and FARO tests, authors analyzed the relevance of mixing zone size and the particle bed geometry because the mixing zone size is the area where particles and voids in the water are distributed.

2. Methods and Results

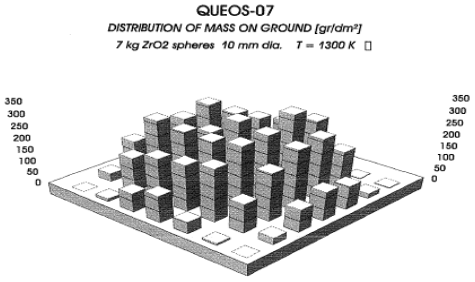
2.1 Debris Bed Geometry in QUEOS Experiments

Table 1 shows the initial conditions of the QUEOS base tests [3]. In these tests, hot spheres of two kinds of materials with different sizes and temperatures are released into the saturated water at atmosphere pressure with the drop release diameter of 180 mm. More details for the experiments can be found in the reference [3].

Table 1: Test Conditions in QUEOS Experiments

Test No	Material	Sphere Drop Diameter [mm]	Total Mass [Kg]	Single Drop Mass [g]	Sphere Drop Temp[K]	Weter level[m]/ Temp [K]	Drop Release Diameter [mm]	Drops Free Fall Distance [m]
7	ZrO2	10	7	3	1300	1/372.7	180	1.3
10	ZrO2	10	6.3	3	1800	1/372.7	180	1.3
3	Mo	4.2	10	0.4	920	1/372.7	180	1.3
4	Mo	4.2	10	0.4	1300	1/372.7	180	1.3
12	Mo	4.2	6.9	0.4	2300	1/372.7	180	1.3

The mass distribution of the accumulated particles in 49 (a matrix of 7×7) square boxes (10×10×5 cm) located at the bottom of the test section were provided, as exemplified in Fig. 1. For comparison between the tests, the mass distributions of the tests are converted into the mass fraction and given in Table 2.



0	35.7	137.9	125.5	145.3	27	0
12.10	146.2	264.2	235.4	259.6	156.2	8.9
81.1	184.7	255.2	214.1	255.3	197.4	53.5
116.3	199.7	253.8	295.3	186.2	220.4	72.3
51	227.4	274.6	277.3	321.5	257.2	47.6
8.9	126	206.1	257.2	259.8	163.7	3
0	29.8	98.9	124.8	102.6	21.1	3.2

Fig. 1. Mass distribution of accumulated particles (Test No. 7)

Table 2: Mass Fraction of Accumulated Particles and Particle Jet Characteristics

	Mass Fraction in Cells						
Test No	Ceneter	Avg. in 8 Cell	Ave. in. 16 Cell	Avg. in 24 Cell	Average Vel. Of Leading Edge [m/s]	Max. Mixing Zone Width [cm]	Mixing Zone/Release Daimeter
7	4.2	3.6	3	0.8	2.75	~ 50	~ 2.78
10	5.1	4.7	2.8	0.6	2.75	>50	> 2.78
3	19.5	6.4	1.6	0.2	4.44	~ 35	~ 1.94
4	16.7	6	1.9	0.2	4.44	> 50	> 2.78
12	11.9	5.7	2.2	0.3	3.21	~ 45	~ 2.5

They also provided the images of the leading edge location of a particle jet in the water with time as shown in Fig. 2. The average velocities were estimated using the images for the test.

In the fuel coolant interaction, the pre-mixing area where happening fuel coolant interaction before triggering is the first phase of the steam explosion four phases. The mixing zone size have used to define the interaction zone between the fragmented particle of molten material and water. Here, the same concept is used for data analysis. The diameter of the mixing zone is assumed under axisymmetric in the interaction zone. The maximum diameter is defined as the maximum mixing zone width in this paper. The maximum mixing zone width is also estimated using the image at the time the leading edge arrives at the bottom of the test section. The average velocity of the leading edge in the water

and the maximum mixing zone width are also provided in the Table 2.

For Test No. 7 and 10 using ZrO_2, the particles with high temperature in Test No. 10 are accumulated more closely to the center, even though they spread more widely as shown in Fig. 2.

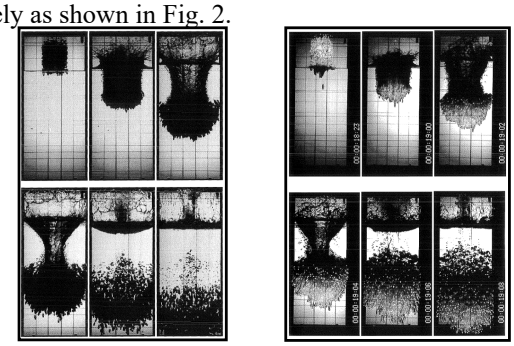


Fig. 2. Images in Test No. 7(Left) and 10(Right)

Meanwhile, much higher fraction of Mo particles (Test No. 3, 4 and 12) with larger density than ZrO_2 was accumulated near the center. However, the particle accumulation near the center becomes less with higher particle temperature (Test No. 3 vs. 12). The major reason seems that Mo drops are smaller and lighter than ZrO_2 so that they may spread widely by re-lifting force induced by vigorous steam production due to high particle temperature. Nevertheless, the maximum mixing zone size clearly increases with the increase of the particle temperature.

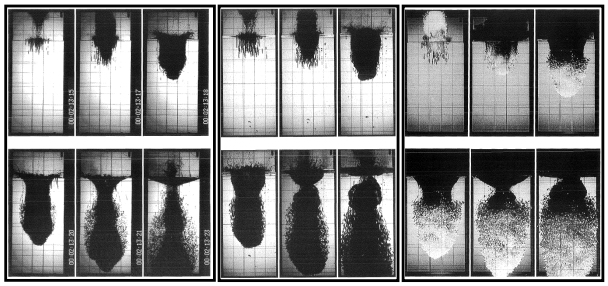


Fig. 3. Images in Test No. 3(Left), 4(Center) and 12(Right)

From the test results, the increase of maximum mixing zone size which increases with the increase of the drop temperature causes generally more accumulation of particles at the center of interaction chamber. However, this results seems to be not maintained for the small particle over certain temperature. The temperature and size of the particle are closely related to the accumulation of particle in the center of the test section.

2.2 Mixing Zone in TROI and FARO Experiments

KAERI did many fuel coolant interaction tests in the TROI facility using several prototypical corium melts and they observed mixing zone size in some tests without external triggering [3]. Fig. 4 shows the picture at the time the front of melt jet reached to the bottom of interaction vessel in the test No. TROI-VISU2 [4]. The maximum mixing zone size is about 30 cm.

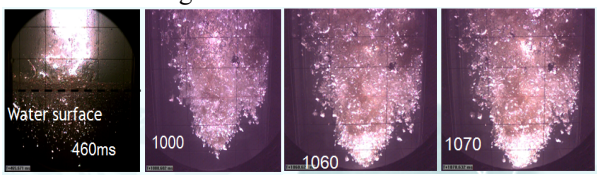


Fig. 4. Images in TROI-VISU2 test

The initial conditions and information on the mixing zone are shown in the Table 3. In the TROI-28, 29, 47 and 48 tests, the molten corium is injected into the water with high free fall over 3 m in the air. Meanwhile, TROI-VISU2 test, the free fall is about 1 m. The mixing zone sizes for several TROI tests is about 20 to 30 cm when the jet diameter of molten material is about 5 to 7.5 cm.

Table 3: Initial Conditions and Mixing Zone in TROI and FARO Experiments

Test No	Material (UO2:ZrO2:Fe)	Total Mass [Kg]	Interaction Vessel Size (cm)	Melt Temp [K]	Weter level [m]/ Temp [K]	Release Diameter [cm]	Mass Mean Diameter [mm]	Average Vel. Of Leading Edge [m/s]	Max. Mixing Zone Width [cm]	Mixing Zone /Release Diameter	Melt jet Free Fall Distance [m]
TROI-29	50:50	11	60x60	3450	0.67/287	5	2.91	2-2.5	~ 20	~ 4	3.8
TROI-47	63:27:10	11	60x60	3030	130/294	6.5	2.31	4.18	~ 20	~ 3.1	3.2
TROI-48	70:30	13	60x60	3620	1.2/335	7.5	2.13	6.3	~ 25	~ 3.3	3.3
TROI-VISU2	80:20	19	D=30	2990	1/341	5	3.3	1.7	~ 30	~ 6.0	1.0
FARO-28	80:20	161	D=71	2825	1.5/373	4.4	3	2.4	~ 40	~ 9.1	1.0

The ratio of mixing zone to release diameter is about 3 to 6, which increases with the longer free fall. This means the longer free fall may accumulate the particles in the smaller area of the bottom of interaction vessel because the debris distributes in the area of mixing zone. However, the data on debris accumulation on the bottom of interaction vessel in TROI experiments are not available. The ratio of mixing zone to release diameter in TROI is a litter larger than QUEOS experiments. The major reason seems that the melt temperature of the corium is much higher than the spheres used in QUEOS.

Meanwhile, JRC-ISPRA also did several tests using prototypical molten corium in FARO facility. In the FARO-28 test, they used 15 times more amount of molten corium than TROI. This test is the only test available of visualization image for mixing zone, as shown in Fig. 5. The free fall is about 1 m which is similar to the TROI-VISU2. The mixing zone was estimated about 40 cm when the melt front is contact with the bottom of interaction vessel. The ratio of maximum mixing zone size to release diameter is 1.5 times larger than TROI-VISU2. In other words, the mixing zone in the FARO test is a little bigger size than TROI-VISU2 even though the lots of molten corium was used. The reason is expected that the molten corium which is released later is not much contributed

to expand the mixing zone. Fortunately, the debris accumulation shape on the interaction vessel are also available in FARO L-28 test. It was found that the most of corium particles is accumulated almost symmetrically at the center of interaction vessel. From FAROL-28 test which is much closer to the reactor condition, we can imagine it is highly possible for the molten corium to accumulate near the center of the melt release. This is confirmed from the height of the debris in the catcher, as shown in Fig. 6.

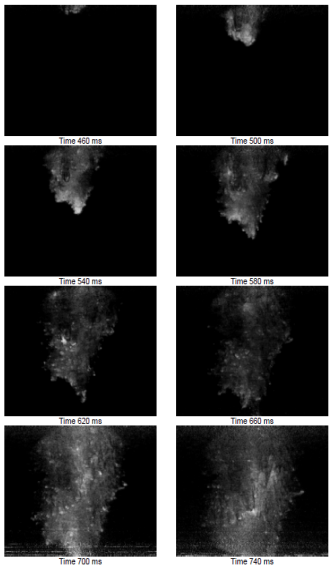


Fig. 5. Images of mixing zone in FARO L-28 test

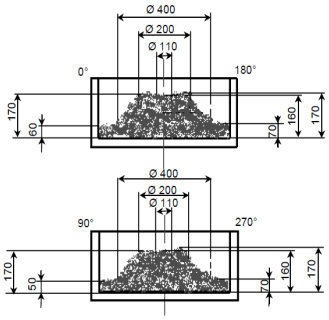


Fig. 6. Height of the debris in the catcher as measured along two radial positions after the test

3. Conclusions

From the QUEOS experiments, the particles is generally accumulated more closely to the center of the interaction vessel with higher particle temperature. However, the much more increase of temperature causes the scatter of particles because the particles re-lifting by vigorous interaction. Accordingly, the mixing zone size was not directly related to the accumulation of particles.

In TROI experiments using high temperature prototypic corium melt, the ratio of the maximum mixing zone to the melt release diameter is slightly larger than QUEOS using low temperature particles. Considering the higher melt temperature in TROI experiment, this result seems to be reasonable. In addition, the higher free fall causes the smaller mixing zone, and accordingly the debris accumulation in the small area of the bottom of the interaction vessel.

The mixing zone in the FARO test is a little bigger than TROI-VISU2 with similar free fall even though the lots of molten corium was used. The reason is expected that the molten corium released in later time of the melt jet is not much contributed to expand the mixing zone.

In conclusion, there closely exists the relevance between mixing zone size and debris bed geometry in fuel coolant interaction. This relevance may be validated from the debris formation model in the water.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT; Grant No. 2017M2A8A4015274).

REFERENCES

[1] Konovalenko, A. et al.. “Experimental investigation of particulate debris spreading in a pool,” Nuclear Engineering and Design, 297, pp. 208–219, 2016.
[2] Seong-Wan HONG and Sang-Mo AN, “Observation of Corium Debris Chacacteristics by Fuel-Coolant Interaction in the TROI Facility”, NTHAS11: The Eleventh Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, Busan, Korea, November 18-21, 2018.
[3] L. Meyer, G. Schumacher, “QUEOS, a Simulation-Experiment of the Premixing Phase of a Steam Explosion with Hot Spheres in Water-Base Case Experiments, Technical Report, April 1996
[4] S.W Hong, et al., “TROI TS-VISU test data report”, OECD/SERENA-2010-TR06, May, 2010
[5] R. Silverii and D. Magallon, “FARO LWR Programme Test L-28 Data Report”, Technical Note No. I.99.76, 1999