Integral Test of Ex-vessel Debris Bed Formation in a Pre-flooded Reactor Cavity

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1. Introduction

When molten corium is released into a pre-flooded reactor cavity during a severe accident, corium jet is broken up and fragmented into small particles by fuel-coolant interaction and then a debris bed is formed at the bottom of the cavity. Thus the ex-vessel debris bed coolability is important in terms of the containment integrity, and it can be enhanced by the multidimensional infiltration of water into the bed, which depends on the thermohydrodynamic characteristics through the bed according to the bed's geometrical configuration. The objectives of this paper are to observe the final debris bed shape formed under a deep water pool using simulant debris particles and investigate the integral effects of steam spike induced by hot particle jet entering the pool, convective flow in the pool and self-leveling of the bed.

2. Experimental method

A large-scale ex-vessel debris bed formation test facility, called DEFCON (DEbris bed Formation and COolability experimeNt) was constructed as shown in Fig. 1. The details of the facility specifications, test procedure, method and image processing of two dimensional debris bed can be found in previous papers [1-2]. Total 300 kg of a few mm-sized stainless steel particles were used as the simulants of corium debris. The particles coming out of a nozzle with 50 mm in inner diameter is poured into the water pool after 1.4 m free-fall. The amount of steam proportional to the accumulated mass and the decay heat of the bed was simulated and controlled by air injection from the bottom of the water tank, as shown in Fig. 2.

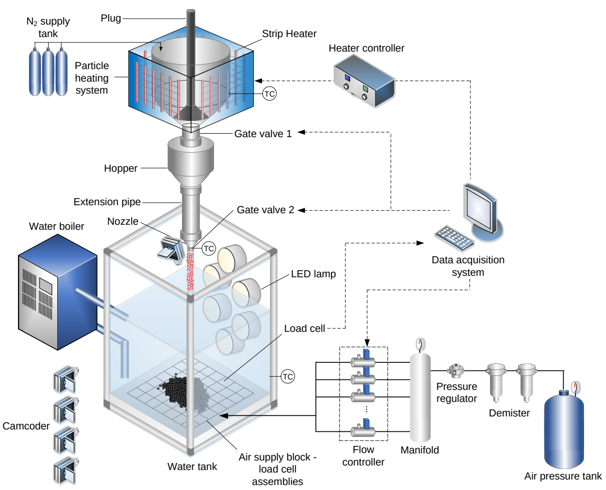


Fig. 1. DEFCON test facility.

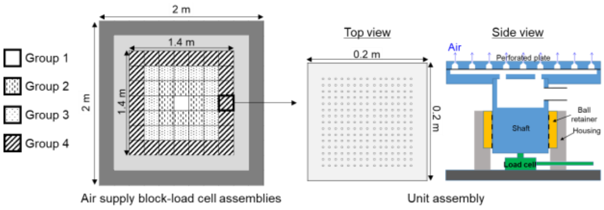


Fig. 2. Measurement of accumulated particle mass and air injection method for simulating steam generation.

Based on the similarity analysis [3] and test limitations, the experimental variables were determined as follows: particle shape (sphere, cylinder), particle size distribution (1-7 mm), particle temperature (20-700°C), decay heat (0-2.2 MW/m^3), water pool depth (1.3-2.6 m) and water temperature (20-100°C). The test matrix is given in Table 1, where the poly-sized distributions are based on the mean distribution of TROI particles [4].

Table I: Test Matrix

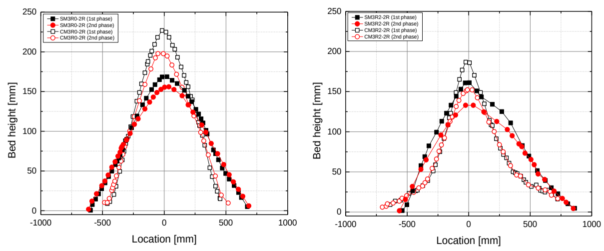
Test ID	Particle characteristics								Water pool		Porosity (-)
	Shape	Distribution (wt.%)					Temp. (°C)	Decay heat (MW/m^3)	Depth (m)	Temp. (°C)	
		1 mm	2 mm	3 mm	5 mm	7 mm					
SM1R0-2R	Sphere	100					20	0	2.6	20	0.370
SM1R2-2R	Sphere	100					20	2.2	2.6	20	0.370
SM170-21	Sphere	100					700	0	2.6	100	0.370
SM3R0-2R	Sphere			100			20	0	2.6	20	0.385
SM3R2-2R	Sphere			100			20	2.2	2.6	20	0.385
SM3R0-1R	Sphere			100			20	0	1.3	20	0.385
SM3R2-1R	Sphere			100			20	2.2	1.3	20	0.385
SM350-2R	Sphere			100			500	0	2.6	20	0.385
SM370-2R	Sphere			100			700	0	2.6	20	0.385
SM372-2R	Sphere			100			700	2.2	2.6	20	0.385
SP3R0-2R	Sphere	13		46	26	15	20	2.2	2.6	20	0.365
CM3R0-2R	Cylinder			100			20	0	2.6	20	0.353
CM3R2-2R	Cylinder			100			20	2.2	2.6	20	0.353
CM3R0-1R	Cylinder			100			20	0	1.3	20	0.353
CM3R2-1R	Cylinder			100			20	2.2	1.3	20	0.353
CM370-21	Cylinder			100			700	0	2.6	100	0.353
CM372-21	Cylinder			100			700	2.2	2.6	100	0.353
CP3R0-2R	Cylinder		35	24	26	15	20	0	2.6	20	0.348
CP3R2-2R	Cylinder		35	24	26	15	20	2.2	2.6	20	0.348
CP370-21	Cylinder		35	24	26	15	700	0	2.6	100	0.348
CP372-21	Cylinder		35	24	26	15	700	2.2	2.6	100	0.348

All the tests are carried out through two phases. The first phase is a 'particle sedimentation and initial bed formation', where the particles fall down for around 80 seconds and form an initial bed without any air injection in no decay heat cases or with air injection proportional to the accumulated bed mass in the non-zero decay heat (i.e., 2.2 MW/m^3) cases. As soon as the particle sedimentation is finished, the air injection in the non-zero decay heat cases is terminated immediately. The effect of steam spike on the initial bed shape can be found by comparing the tests using cold and hot particles. In addition, the effect of convective flow can be investigated by comparing the bed shapes between the cases with and without air injection in the first phase. The second phase is a 'bed flattening by self-leveling', where the initial bed at the first phase is flattened by air injection for around 30 minutes and then the final bed shape is obtained. As the bed shape being deformed, the air flow rate at every group in Fig. 2 varies with the change of particle mass. The independent effect of self-leveling can be investigated by comparing the bed shapes in the first and second phases for each test.

3. Results and discussions

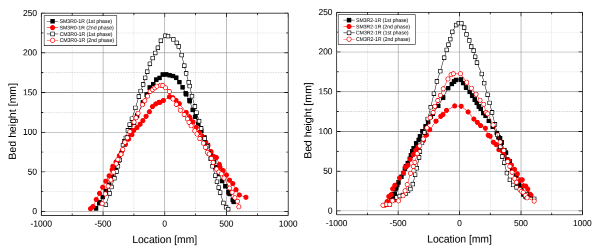
3.1. Effect of particle shape

The bed shapes of 3 mm cold spherical and cylindrical particles under cold water pool with 2.6 m and 1.3 m in depth without or with 2.2 MW/m^3 decay heat conditions are compared in Figs. 3 and 4, respectively. The cylindrical particles formed a higher bed at the center than the spherical particles, and also the self-leveling phenomenon in the second phase was observed more apparently. In the first phase of initial bed formation, the spherical particles rolled down and moved sideways more easily, thus a stable initial bed was formed already in the first phase and further self-leveling was not significant. On the other hand, the cylindrical particles formed a high and relatively unstable initial bed in the first phase due to high friction between the particles. However, a larger surface area of a cylinder than a sphere even with the same particle size made more significant influence of air injection on the particle movement and consequently led to a clear self-leveling.



(a) (b)

Fig. 3. Bed shapes of 3 mm cold spherical and cylindrical particles under cold water pool with 2.6 m in depth and (a) without or (b) with 2.2 MW/m^3 decay heat.

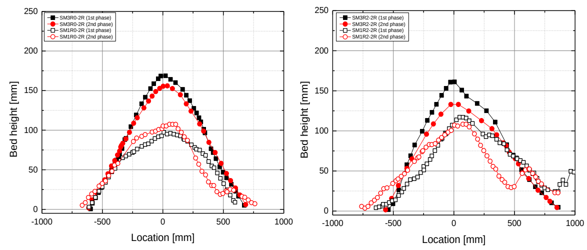


(a) (b)

Fig. 4. Bed shapes of 3 mm cold spherical and cylindrical particles under cold water pool with 1.3 m in depth and (a) without or (b) with 2.2 MW/m^3 decay heat.

3.2. Effect of particle size

The bed shapes of 1 mm and 3 mm cold spherical particles under cold water pool with 2.6 m in depth and without or with 2.2 MW/m^3 decay heat conditions are shown in Fig. 5. At the particle jet entrance into the water pool, the 1 mm particles were dispersed more easily than 3 mm particles by the flow motion created during the jet entrance and/or air injection. In addition, as the top of the bed being collapsed easily by the impact of following particle jet, 1 mm particles spread more widely along the flow motion. As a result, a flat debris bed was remained during the first phase of initial particle bed formation and the bed shapes showed a bit asymmetric compared to the beds of 3 mm particles. Moreover, because of the flat and stable bed formation of 1 mm particles in the first phase, the air injection in the second phase led to not further bed flattening but more asymmetric bed shape.



(a) (b)

Fig. 5. Bed shapes of 1 mm and 3 mm cold spherical particles under cold water pool with 2.6 m in depth and (a) without or (b) with 2.2 MW/m^3 decay heat.

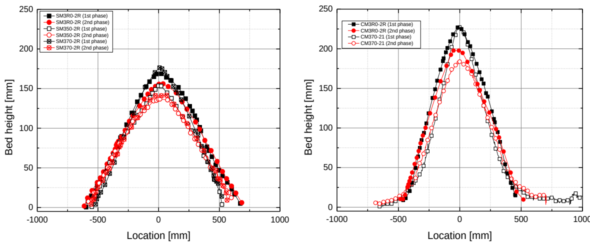
3.3. Effects of decay heat and water pool depth

The convective flow created in the water pool mainly by air injection affects the particle sedimentation and consequently the initial particle bed shape. The higher decay heat is, the more significantly the convective flow motion should affect the initial debris bed formation with a larger amount of air injection. Thus, the effect of convective flow on the initial bed shape can be investigated by comparing the bed shapes with and without air injection in the first phase according to the decay heat.

As shown in Figs. 3 and 4 for 3 mm particles, the initial beds of spherical particles in the first phase do not exhibit big differences between 1.3 m and 2.6 m water pool depths regardless of air injection during the particle sedimentation. However, the bed of cylindrical particles is flattened significantly by air injection in a large 2.6 m water pool (Fig. 3(b)), which is not shown clearly in 1.3 m water pool (Fig. 4(b)). As described previously, this is because the cylindrical particles is influenced more significantly by convective flow motion in the pool due to relatively large surface area. However, this effect should become weaker in the lower water pool because the region of the pool affected by the convective flow motion and particle sedimentation times are reduced simultaneously. Thus, the deeper the water pool and the larger particle surface area, the more widely the particles spread during the particle sedimentation to form a flatter initial bed.

3.4. Effects of particle and water pool temperatures

The steam spike induced by the interaction between hot particles and water can enhance particle dispersion at the particle entrance into the water pool, which can be found by comparing the cases using cold and hot particles. The bed shapes of 3 mm cold and hot spherical and cylindrical particles entering cold and hot water pool are compared in Fig. 6. The steam spike was not observed clearly for both 3 mm spherical and cylindrical particles, and accordingly the effect on the initial bed shape in the first phase was negligible. On the other hand, in the tests using 1 mm hot spherical particles (Fig. 7), a large amount of steam with strong convective motion was observed near the pool surface, which resulting in wide spread of particles over the whole water tank. That is, the steam spike effect was not significant for 3 mm particles due to relatively high falling load, whereas it becomes effective for small particles due to low falling load and significant increase of heat transfer area.



(a) (b)

Fig. 6. Bed shapes of 3 mm cold and hot spherical particles under cold water pool with 2.6 m in depth and (a) without or (b) with 2.2 MW/m^3 decay heat.

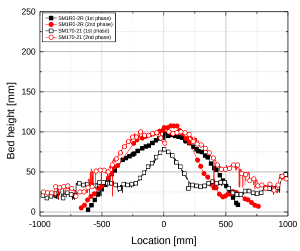
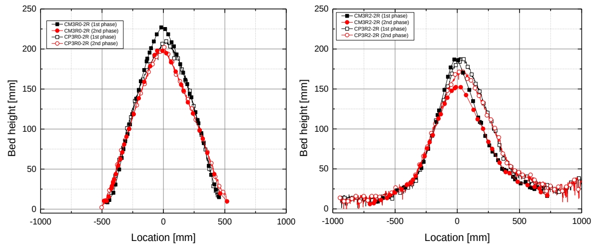


Fig. 7. Bed shapes of 1 mm cold and hot spherical particles entering cold and hot water pool with 2.6 m in depth without decay heat.

3.5. Effects of particle size distribution

The bed shapes of 3 mm mono- and poly-dispersed cold cylindrical particles under the same water pool depth and decay conditions are compared in Fig. 8. Except that more small particles of the poly-dispersed particles spread far from the center of the bed for 2.2 MW/m^3 decay heat case, a clear difference between the bed shapes according to the particle size distribution was not seen. This result was the same with the case using hot particles without decay heat, as shown in Fig. 9. Therefore, considering the finding in the previous research of the irregular shape of real debris particles and their mean particle size of 3 mm [4], it can be concluded that the mono-dispersed 3 mm represent approximately the typical debris bed shape formed in the pre-flooded reactor cavity.



(a) (b)

Fig. 8. Bed shapes of 3 mm mono- and poly-dispersed cold cylindrical particles under cold water pool with 2.6 m in depth and (a) without or (b) with 2.2 MW/m^3 decay heat.

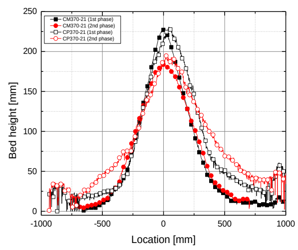


Fig. 9. Bed shapes of 3 mm mono- and poly-dispersed hot cylindrical particles under hot water pool with 2.6 m in depth without decay heat.

4. Conclusions

In this paper, a comprehensive test results of ex-vessel debris bed formation using simulant debris particles were described and the integral effects of steam spike during the hot particle falling into a water pool, convective flow in the pool and self-leveling of the bed were investigated considering various scenarios of ex-vessel melt release and fragmentation in the pre-flooded reactor cavity.

It was found that the mean particle size and shape have a great influence on the debris bed formation. The final bed shape of spherical particles is mainly determined by the particle behavior in the early phase of bed formation, and thus the effects of convective flow and self-leveling on the debris bed formation are relatively minor. On the other hand, the cylindrical particles forms a relatively higher bed which is unfavorable for long term cooling. However, it is affected more significantly by thermohydraulic characteristics in the pool by decay heat and water pool depth, thus the effects of convective flow and self-leveling on the debris bed formation appears more dominantly.

Based on the experimental results in this paper and the particle characteristics of real debris such as irregular shape and mean particle size, it is estimated that the bed formed by mono-dispersed 3 mm cylindrical particles represents reasonably the real ex-vessel debris bed shape.

ACKNOWLEDGMENTS

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