Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Ex-vessel Debris Bed Formation Experiments in the Pre-Flooded Reactor Cavity Using 3 mm Stainless Steel Particles

Sang Mo An [a*], Keun Sang Choi [a], Ki Han park [a], Chang Wan Kang [a],
[a]*Korea Atomic Energy Research Institute (KAERI), 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: sangmoan@kaeri.re.kr*

1. Introduction

A postulated severe accident scenario of RPV (reactor pressure vessel) lower head failure and ex-vessel corium release into a pre-flooded reactor cavity is depicted in Fig. 1 [1]. Under the pre-flooding reactor cavity adopted as the mitigation strategy for Korean PWRs (pressurized water reactors) [2], it is estimated that the molten corium jet is broken into lots of particles by the interaction with water to finally form a porous debris bed on the cavity floor. In order to retain the containment integrity by minimizing or preventing MCCI (molten corium-coolant interaction), the long-term debris bed coolability should be secured. The bed coolability in the pre-flooded reactor cavity is generally represented by DHF (dryout heat flux), the minimum power at which local dryout is reached. It is enhanced significantly by the infiltration of water into the bed, which depends on not only the two-phase pressure drop characteristics in the bed [3, 4] but also its geometrical configuration [4-9].

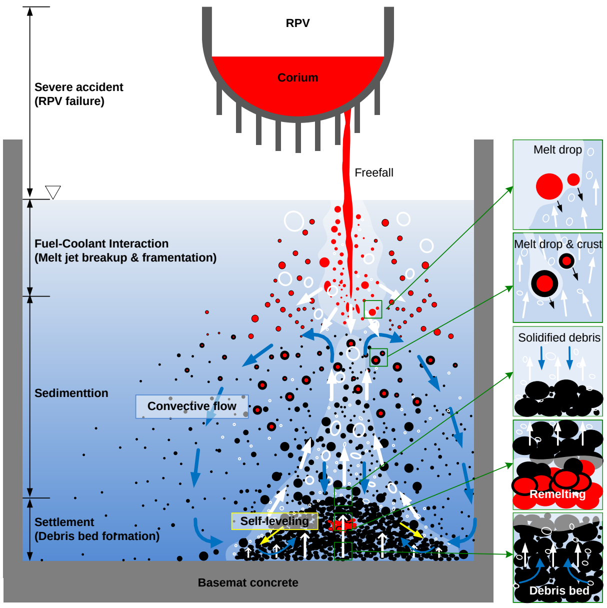


Fig. 1. A schematic of ex-vessel corium release into a pre-flooded reactor cavity

Two major factors influencing the debris bed shape under the pre-flooded cavity condition have been investigated [7-21]. One is the two-phase 'convective flow' created in a pool in the early phase of jet breakup and particle sedimentation, and the other is long-term spreading or flattening of the bed in the late phase, so called 'self-leveling'. Both of them are induced mainly by steam generation from the debris bed with the sustained decay heat. In the previous researches, a coherent jet of cold metallic particles has been typically used to simulate the fragmented corium particles in the pre-flooded cavity. In reality, however, a huge amount of steam should be produced by the interaction between lots of hot particles with water, which could disperse the falling particles in the pool far away. Therefore, vigorous steam generation, so called 'steam spike' in the early phase of jet breakup and particle sedimentation is needed to be considered as another potential factor affecting the bed shape.

A large-scale ex-vessel debris bed formation test facility was constructed to investigate the comprehensive effects of 'convective flow', 'self-leveling' and 'steam spike' on the debris bed shape. STS (stainless steel) particles were selected as the simulants of the fragmented corium particles because of the similar density of 8000 kg/m^3. In this paper, the effect of 'steam spike' caused by hot particles was not considered yet, which will be investigated in the near future. Instead, 300 kg of non-heated 3 mm STS particles were used, and the combined effects of 'convective flow' and 'self-leveling' on the debris bed shape were investigated according to the particle shape (sphere and cylinder) and decay heat of the bed (0-2.4 MW/m^3).

2. Experimental Method

2.1 Experimental Setup

A schematic of the experimental facility, called DEFCON (DEbris bed Formation and COolability experimeNt) is shown in Fig. 2. It consists of a particle heating & delivery system, water tank, air supply system, data acquisition and visualization systems. Recently, the particle heating system was constructed to simulate hot corium debris, which has the capability to heat 1000 kg particles up to nearly 1000°C using the electrical heating. The heated (or non-heated) particles are delivered into a hopper, and then released through a nozzle down into the pre-flooded water tank (2 m×2 m×4 m), which has several polycarbonate visualization windows at the sidewalls. 49 assemblies of air supply block-load cell are installed at the bottom of the water tank for simulating the steam generation from the debris bed proportional to the mass of accumulated particles (bed). Each assembly consists of an air-supply block connected with a gas flow controller by a tube and a load cell at the bottom for the bed mass measurement. The surface area of an air supply block is 0.2 m×0.2 m, so total area of particle mass measurement covered by 49 assemblies is 1.4 m×1.4 m.

Six 480 W LED lights are installed at the backside of the water tank for backlighting. Four camcorders are installed for visualization of particle sedimentation and bed formation in the water tank; one near the nozzle hole for top view, and the others in the front of the water tank for side views.

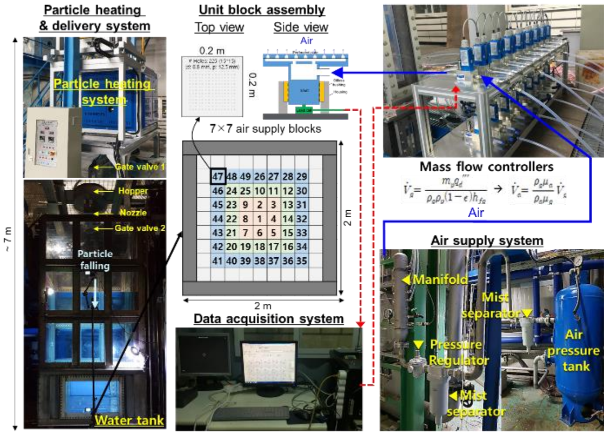


Fig. 2. DEFCON test facility

2.2 Experimental Methods

The experimental conditions are listed in Table I. Total 300 kg of non-heated 3 mm spherical or cylindrical STS particles are released through a 50 mm nozzle, fall 1.4 m freely in the air, and then enter the 2.6 m water pool. The test variables are the particle shape and the amount of steam generated from the debris bed depending on its decay heat. The volumetric decay heat of a corium debris bed for typical LWRs (light water reactors) ranges from 1 to 4 MW/m^3 [21].

Table I: Experimental Conditions

Test ID	Particle characteristics			Pool Depth [m]
	Shape	Equivalent diameter [mm]	Decay heat [MW/m^3]	
S1	Sphere	3	0	2.6
S2		3	2.4	
C1	Cylinder	3	0	
C2		3	2.4	

Based on the similarity of Reynolds numbers between air and steam at a saturation condition, the volumetric air flow rate for the beds of 3 mm sized-spherical and cylindrical STS particles according to the mass of accumulated particle within the volumetric decay heat range of 0.5-4 MW/m^3 was evaluated, which is represented in Fig. 3. The maximum uniform air flow rate by the air supply system was estimated around 5000 lpm, which corresponds to the steam generation at 2.4 MW/m^3 decay heat condition. In other words, the maximum decay heat of the bed simulated in the experiment is 2.4 MW/m^3.

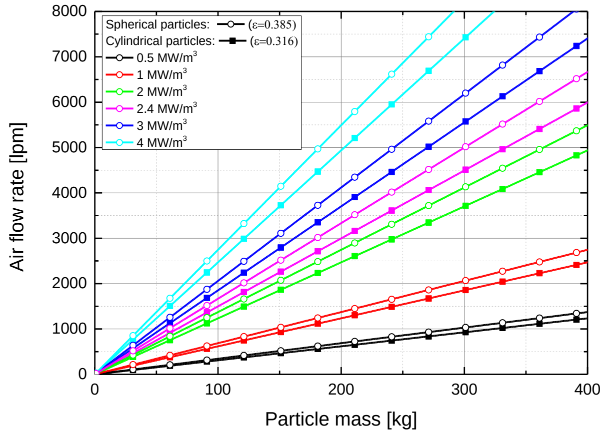


Fig. 3. Air flow rate for simulation of the steam generation according to decay heat and accumulated particle mass

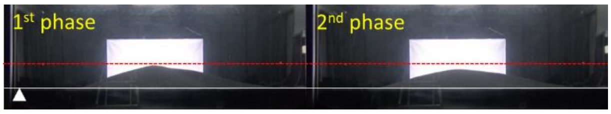
All the tests are performed in two or three phases. The first phase is a ‘particle sedimentation and initial bed formation’, where the particles fall down and form an initial bed without any air injection for non-decay heat cases (S1 and C1) or with air injection according to the accumulated bed mass and decay heat condition (S2 and C2). If the particle sedimentation is completed, the air injection from the bottom is terminated. The independent effect of ‘convective flow’ on the initial bed shape can be investigated by comparing the bed shapes with or without air injection. The second phase is a ‘bed flattening by self-leveling’, where the initial bed formed at the first stage is flattened by continuous air injection. As the bed shape is deformed, the air flow rate at each assembly of air-supply-load cell varies in real time with the measured bed mass. The final bed is formed after the second phase. Thus, the independent effect of ‘self-leveling’ on the final bed shape can be investigated by comparing the bed shapes after the first and second phases. In addition, as the third phase, the maximum air flow rate is supplied regardless of the decay heat condition to investigate the most flattened bed shape. This is only for the non-decay heat cases (S1 and C1).

3. Results and Discussions

The side-view images of the debris bed at the end of three phases are shown in Fig. 4. A red line is a guide drawn horizontally at the top of the highest bed to compare the degree of self-leveling. In all the tests, nearly axisymmetric Gaussian shape of debris beds were formed and the self-leveling through three phases was observed. The self-leveling effect were observed more clearly for the bed of cylindrical particles.

Compared to the beds of cylindrical particles, those of spherical particles were more flattened at every phase under the same decay heat and corresponding air injection condition. This is because the spherical particles can easily roll down from the top of the bed center to spread more widely. In other words, the cylindrical particles form a higher bed at the center, which is unfavorable for the effective bed cooling.

(a) Test S1



(b) Test S2

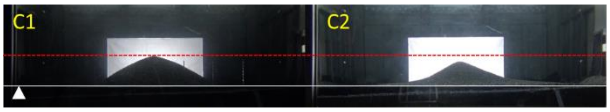
(c) Test C1

(d) Test C2

Fig. 4. Debris bed shapes at different phases

The bed shapes at the end of the first and second phases are compared in Figs. 5 and 6, respectively. The bed shapes of spherical particles between S1 and S2 in Fig. 5(a) do not show big difference between each other, while those of cylindrical particles with the air injection (C2 in Fig. 5(b)) shows more significantly flattened shape than the bed without the air injection (C1 in Fig. 5(b)). This implies that the bed of cylindrical particles is influenced more significantly by convective flow in the early phase of particle sedimentation. This might be due to larger surface area of the cylindrical particles, which leads to higher flow resistance even in the same of convective flow field. Moreover, as shown in Fig. 6, the bed having flatter initial bed at the first phase shows more flattened final bed shape in the end by the self-leveling effect.

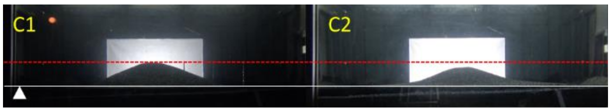
(a) Test S1 and S2



(b) Test C1 and C2

Fig. 5. Debris bed shapes at the end of the first phase

(a) Test S1 and S2



(b) Test C1 and C2

Fig. 6. Debris bed shapes at the end of the second phase

In summary, the spherical particles form a more flattened bed and creates a more favorable geometric configuration in terms of bed cooling than the non-spherical particles. This is because the spherical particles can be more widely spread by low friction between the particles, which predominates over the steam generation from the bed. Thus, if once the spherical particles form a bed, the bed shape is hardly changed even in large amount of steam. That is, the effects of the convective flow in the early phase of particle sedimentation and self-leveling in the late phase do not make a significant influence on the debris bed formation of spherical particles. On the other hand, even though the non-spherical particles form a higher bed unfavorable for effective bed cooling, its shape can be flattened effectively by steam during the whole process of bed formation. The corium debris are highly irregular and non-spherical shapes, thus the debris bed shape and the corresponding bed coolability should strongly depend on the flow field induced by steam generation.

4. Conclusions

The experiments of ex-vessel debris bed formation in the pre-flooded reactor cavity were performed using 300 kg of 3 mm spherical and cylindrical STS particles as the simulant particles of ex-vessel corium debris. The effects of steam generation by different bed decay heat conditions on the final bed shape were investigated. In all the test cases, axisymmetric Gaussian shape of debris beds were formed. The bed of spherical particles showed more flattened debris bed at every phase that that of cylindrical particles. However, the bed of cylindrical particles was influenced more significantly by the convective flow in the early phase of particle sedimentation process and self-leveling in late phase of continuous bed cooling, both of which are induced steam generation from the debris bed with sustained decay heat. Both the effects of convective flow and self-leveling should be more significant for smaller particles, and thus the tests using particles smaller than 3 mm will be performed in the near future.

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] S.M. An, S.H. Kim, J.H. Park, Experimental Investigation on Ex-vessel Debris Bed Formation Using Simulant Particles, Transactions of American Nuclear Society, Vol. 120, p.1142, Jun. 9-13, 2019, Minneapolis, USA.

[2] Y. Jin and K. Ahn, Improvement of Diagnostic Flow Chart in Severe Accident Management Guidance of OPR1000 Reflecting Fukushima Accident Experience, Proceedings of

Korean Nuclear Society Spring Meeting, May 29-30, 2014, Jeju, Korea.
[3] J.H. Park, Modeling of Two-Phase Flow Pressure Drop for Predicting Ex-Vessel Debris Bed Coolability in Nuclear Reactor Severe Accident, Doctoral Thesis, Pohang University of Science and Technology, 2018.
[4] L. Li, W. Ma, S. Thakre, An Experimental Study on Pressure Drop and Dryout Heat Flux of Two-phase Flow in Packed Beds of Multi-sized and Irregular Particles, Nuclear Engineering and Design, Vol.242, p.369, 2012.
[5] P. Kudinov, A. Konovalenko, D. Grishchenko et al., Investigation of Debris Bed Formation, Spreading and Coolability, NKS-287, KTH Royal Institute of Technology, Sweden, 2013.
[6] S. Basso, Particulate Debris Spreading and Coolability, Doctoral Thesis, KTH Royal Institute of Technology, 2017.
[7] A. Konovalenko, S. Basso, P. Kudinov, S.E. Yakush, Experimental Investigation of Particulate Debris Spreading in a Pool, Nuclear Engineering and Design, Vol.297, p.208, 2016.
[8] W. Ma and T.N. Dinh, The Effects of Debris Bed's Prototypical Characteristics on Corium Coolability in a LWR Severe Accident, Nuclear Engineering and Design, Vol.240, p.598, 2010.
[9] L. Li, S. Thakre, W. Ma, An Experimental Study on Two-phase Flow and Coolability of Particulate Beds Packed with Multi-sized Particles, Proceedings of International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14), Sep. 25-29, 2011, Toronto, Canada.
[10] S. Thakre and W. Ma, An Experimental Study on the Coolability of Stratified Debris Beds, Proceedings of International Congress on the Advances in Nuclear Power Plants (ICAPP-2014), April 6-9, 2014, Charlotte, USA.
[11] S. Thakre, On Fuel Coolant Interactions and Debris Coolability in Light Water Reactors, Doctoral Thesis, KTH Royal Institute of Technology, 2015.
[12] E. Takasuo, A Summary of Studies on Debris Bed Coolability and Multi-dimensional Flooding, NKS-374, VTT Technical Research Centre of Finland Ltd, 2016.
[13] S. Basso, A. Konovalenko, P. Kudinov, Empirical Closures for Particle Debris Spreading Induced by Gas-Liquid Flow, Nuclear Engineering and Design, Vol.297, p.19, 2016.
[14] S. Basso, A. Konovalenko, P. Kudinov, Effectiveness of the Debris Bed Self-Leveling under Severe Accident, Annals of Nuclear Energy, Vol.95, p.75, 2016.
[15] S. Basso, A. Konovalenko, S.E. Yakush, P. Kudinov, The Effect of Self-leveling on Debris Bed Coolability under Severe Accident Conditions, Nuclear Engineering and Design, Vol.305, p.246, 2016.
[16] A. Konovalenko, S. Basso, A. Karbojian, P. Kudinov, Experimental and Analytical Study of the Particulate Debris Bed Self-leveling, Proceedings of International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Sep. 9-13, 2012, Kaohsiung, Taiwan.
[17] B. Zhang, T. Harada, D. Hirahara et al., Self-Leveling Onset Criteria in Debris Beds, Journal of Nuclear Science and Technology, Vol.47, p.384, 2010.
[18] S. Cheng, H. Yamano, T. Suzuki et al., Characteristics of Self-Leveling Behavior of Debris Beds in a Series of Experiments, Nuclear Engineering and Technology, Vol.45, p.323, 2013.
[19] A. Konovalenko, S. Basso, P. Kudinov, Experiments and Characterization of the Two-phase Flow Driven Particulate Debris Spreading in the Pool, Proceedings of International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10), Dec. 14-18, 2014, Okinawa, Japan.
[20] E. Kim, J.H. Park, M.H. Kim, H.S. Park, The Influence of Two-phase Flow on Pore Clogging by Fine Particle Settlement during Ex-vessel Debris Bed Formation in Severe Accident, Proceedings of International Conference on Nuclear Engineering (ICONE-22), July 7-11, 2014, Prague, Czech Republic.
[21] E. Kim, M. Lee, H.S. Park et al., Development of an Ex-Vessel Corium Debris Bed with Two-phase Natural Convection in a Flooded Cavity, Nuclear Engineering and Design, Vol.298, p.240, 2016.