Similarity Experiment of Ex-vessel Debris Bed Formation in a Pre-flooded Reactor Cavity

Sang Mo An [a*], Jaehoon Jung [a], Jin Ho Park [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 cavity pre-flooding strategy is adopted as a mitigation measure for Korean PWRs (pressurized water reactors) [1]. Based on the recent inspections of the operating Korean PWRs as one of the follow-up actions after the Fukushima accident, a few meters of deep pool can be typically secured in the cavity. Even though deep pool is obviously favorable for ex-vessel corium cooling, debris agglomeration and cake formation may be formed due to incomplete jet fragmentation and non-coolable geometry of the debris bed with high decay heat, which deteriorate the long-term debris bed coolability [2-5]. It was found that the multi-dimensional infiltration of coolant into the bed enhances the long-term debris bed coolability, which depends on the two-phase pressure drop in the bed associated with its geometrical configuration [6-12]. Two-phase flow in the bulk pool ('convective flow') disperses the falling particles to affect the initial debris bed shape [13-16]. After the settlement at the cavity, the final bed shape is determined after spreading or flattening of the bed induced by steam escaping the bed, so called 'self-leveling' [2, 17-21]. This paper describes a test facility and introduces similarity analysis to perform the debris bed formation experiments using debris simulant particles, and represents some preliminary test results.

2. Experimental Setup

A schematic of the experimental facility, called DEFCON (DEbris bed Formation and COolability experimeNt) is shown in Fig. 1. It consists of a particle delivery system, water tank, air supply system, data acquisition system and visualization system. A hopper on the top can accommodate about 1000 kg of simulant particles of corium debris, which is connected with a particle delivery nozzle and gate valve. Once a gate valve is opened, the particles in the hopper fall down into the water pool by gravity and are accumulated at the bottom of the water tank (2 m×2 m×4 m). It has several pieces of polycarbonate windows at the sidewalls for visualization and 49 air-supply block assemblies at the bottom for simulating the steam generation from the debris bed. More air-supply block assemblies can be installed according to the test conditions and debris bed shape. Each assembly consists of an air-supply block and a load cell at the bottom for the particle mass measurement. The particle mass is recorded in real time by data acquisition system, and the volumetric steam generation rate ($\dot{V}_\mathrm{g}$) under the assumption of saturation condition is estimated by

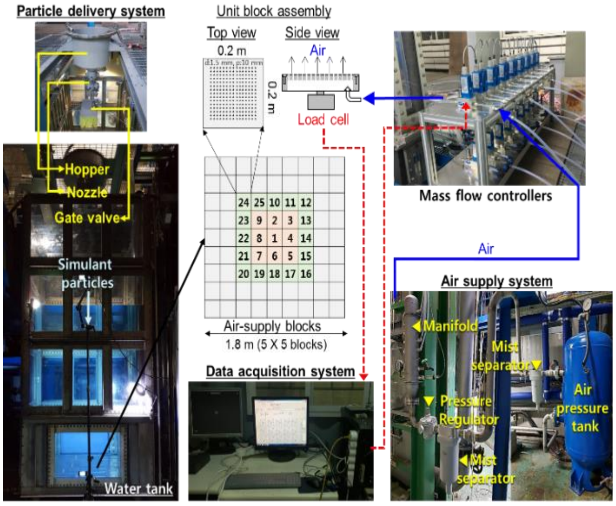

Fig. 1. A schematic of experimental setup (DEFCON).

$$\dot{V}_\mathrm{g} = \frac{m_\mathrm{p} q'''_\mathrm{d}}{\rho_\mathrm{g}\rho_\mathrm{p}(1-\varepsilon)h_\mathrm{fg}} \qquad (1)$$

where m_p is particle mass, q'''_d volumetric decay heat rate or decay heat power density of a debris bed, ρ_g steam density, ρ_p particle density, ε porosity of a debris bed, and h_fg latent heat of vaporization of water. The volumetric decay heat rate (q'''_d) of a debris bed for typical LWRs (light water reactors) ranges from 1 to 4 MW/m^3 [16]. Based on the same Reynolds numbers between steam and air, the volumetric air flosw rate for the corresponding steam flow rate ($\dot{V}_\mathrm{a}$) is evaluated by

$$\dot{V}_\mathrm{a} = \frac{\rho_\mathrm{g}\mu_\mathrm{a}}{\rho_\mathrm{a}\mu_\mathrm{g}}\dot{V}_\mathrm{g} \qquad (2)$$

where ρ_a air density, μ_a air viscosity, and μ_g steam viscosity. That is, if the particle mass (m_p) is measured by a load cell, the volumetric steam generation ($\dot{V}_\mathrm{g}$) according to the mass and air flow rate ($\dot{V}_\mathrm{a}$) to have same inertial force of the steam to spread of flatten the debris bed is calculated. Then, the air flow rate is controlled by a mass flow controller, and dry air is supplied to each air-supply block through the air-pressure tank, two mist separators and manifold, whose outlet pressure is set to 5 bar by a pressure regulator. The steam explosion and its effect on the debris bed formation are considered in this study.

Six LED lights and diffusion sheets are installed at the backside of the water tank for backlighting, and several camcorders and high-speed cameras are installed at the front side for visualization of the particle sedimentation and debris bed formation.

In the present preliminary experiments, 3 mm spherical STS (stainless steel) particles were used as simulant corium debris particles and the porosity of the STS bed was measured 0.385.

3. Similarity Analysis

In order to determine the experimental conditions of ex-vessel debris bed formation for typical Korean operating power plants, the initial and boundary conditions of RPV (reactor pressure vessel) failure and ex-vessel corium release into the reactor cavity for OPR1000 were evaluated by a severe accident scenario analysis using MELCOR 1.8.6 code. Six accident scenarios were considered in the MELCOR analysis; two SBOs (station black out), TLOFW (total loss of feed water), SGTR (steam generator tube rupture), SBLOCA (small break loss of coolant accident), LBLOCA (large break loss of coolant accident). In addition, we referred to the ex-vessel corium release conditions in the SERENA (Steam Explosion Resolution for Nuclear Applications) FCI (fuel-coolant interaction) research report [22] and some references [23, 24]. Based on the MELCOR code analysis and references for the RPV failure and ex-vessel corium release conditions, the ranges of main parameters were determined and summarized in Table 1, where m_m is released melt mass, T_m released melt temperature, T_c water pool temperature in a cavity, $D_{i,m}$ met jet diameter at the failed RPV hole, and P_c cavity ambient pressure.

Table I: Main Parameters during Ex-vessel Corium Release for OPR1000

Melt composition (mass fraction)	Oxide : Metal = 70-85 : 15-30 - Oxide: UO_2 : ZrO_2 = 80 : 20 - Metal: Zr : STS = <50 : >50
m_m [kg]	70000-130000
T_m [K]	- Oxide: 2700-3000 - Metal: >1700
$D_{i,m}$ [m]	0.076-0.3
V_m [m/s]	1-13
P_c [MPa]	0.1-0.3
T_c [K]	300-390

Figure 2 represents the similarity between the real accident and experimental conditions. A similarity analysis was performed based on the results of MELCOR analysis and the initial and boundary conditions shown in Table 1. Three similarity parameters were selected; released mass flux of melt (w_m), sedimentation time of a solidified melt particle from the melt jet breakup point to the cavity floor ($t_{sed,m}$), and Reynolds number of steam generated in the debris bed as shown in Eq. (2). Table II represents the ex-vessel corium release conditions in a nuclear power plant and corresponding experimental conditions based on the similarity analysis when 3 mm spherical STS particles are used: H_{pool} is pool depth in a reactor cavity, $v_{i,m}$ melt release velocity at the failed RPV hole, $L_{free,m}$ melt freefall height, D_n diameter of a particle delivery nozzle, H_n height from the bottom of a water tank to the outlet of a particle delivery nozzle, and $H_{pool,F}$ pool depth in a water tank. The eight experimental conditions in Table II were selected by considering the experimental limitations.

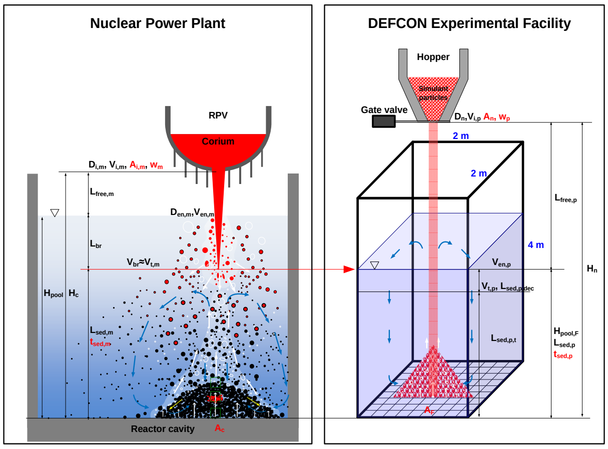

Fig. 2. Similarity of ex-vessel corium release phenomenon.

Table II: Results of Similarity Analysis for Ex-vessel Corium Release

	Plant conditions							
w_m [kg/m^{2}s]	20000		40000		20000		40000	
H_{pool} [m]	3.5	4.7	2.9	4.0	3.9	5.2	3.4	4.6
$D_{i,m}$ [m]	0.15				0.2			
$v_{i,m}$ [m]	2.7		5.4		2.7		5.4	
$L_{free,m}$ [m]	3.5	2.3	4.1	3.0	3.1	1.8	3.5	2.5
	Experimental conditions							
D_n [mm]	37.5				50			
H_n [m]	3	4.1	4.1	5	3	4.1	4.1	5
$H_{pool,F}$ [m]	2.4	3.4	1.5	2.5	2.4	3.4	1.5	2.5

4. Shakedown Test Results

A preliminary test was performed using 400 kg of 3 mm spherical STS particles. The experimental conditions were D_n=50 mm, H_n=4.1 m, $H_{pool,F}$=2.6 m, and q'''_d = 1 MW/m^3. Figure 3 shows the snapshots of particle entry into the pool (Fig. 3(a)), initial stage of a particle bed formation (Fig. 3(b)), and end stage after the particle delivery (Fig. 3(c)).

Even though large uncertainties of the particle mass measurement and accordingly the air supply control according to the particle mass was still not perfect, it was found that the debris bed has a widespread conical shape and hardly change once it forms a bed in spite of high airflow rate. Figure 4 compares the debris bed shapes when air was supplied in proportional to the measured particle mass (Fig. 4(a)) and then when the maximum air flow rate (~ 500 lpm) was supplied near the center of the bed (Fig. 4(b)). That means the ‘self-leveling’ was not clearly observed under the present experimental conditions.

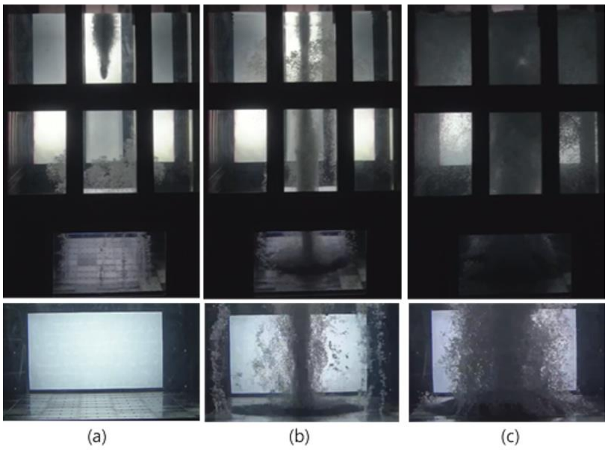

Fig. 3. Visualizations of particle falling and bed formation of STS particles.

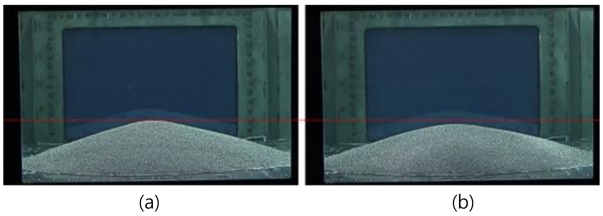

Fig. 4. Debris bed shapes; (a) after the experiments and (b) after the maximum air supply

5. Conclusions

A DEFCON facility was constructed to perform the experiments of debris bed formation using debris simulant particles. The experimental conditions based on a similarity analysis were established, and a preliminary test was performed using 400 kg of 3 mm spherical STS particles. Even though it is necessary to improve the particle mass measurement and air supply control systems, we observed the axisymmetric conical debris bed shape and confirmed the possibility of debris bed formation and coolability experiments. The effects of 'two-phase convective flow' and 'self-leveling' on the debris bed formation were not clearly observed under the preliminary test condition. Thus, a series of experiments based on the similarity analysis will be performed in the future using various sized non-heated and heated STS particles. The final goal of this study is to develop an empirical model of debris bed shape under the various conditions of corium release into the deep water pool.

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REFERENCES

[1] 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.

[2] 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.

[3] A. Karbojian, W.M. Ma, P. Kudinov, T.N. Dinh, A Scoping Study of Debris Bed Formation in the DEFOR Test Facility, Nuclear Engineering and Design, Vol.239, p.1653, 2009.

[4] P. Kudinov, A. Karbojian, C. Tran, W. Villanueva, Agglomeration and Size Distribution of Debris in DEFOR-A Experiments with Bi_2O_3-WO_3 Corium Simulant Melt, Nuclear Engineering and Design, Vol.263, p.284, 2013.

[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] W. Ma, 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.

[7] 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

[8] 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.

[9] S. Thakre, L. Li, W. Ma, An Experimental Study on Coolability of a Particulate Bed with Radial Stratification or Triangular Shape, Nuclear Engineering and Design, Vol.276, p.54, 2014.

[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] A. Konovalenko, S. Basso, P. Kudinov, S.E. Yakushi, Experimental Investigation of Particulate Debris Spreading in a Pool, Nuclear Engineering and Design., Vol. 297, p.208, 2016.

[14] 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.

[15] 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.

[16] 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.

[17] 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.

[18] 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.
[19] 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.
[20] 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.
[21] 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.
[22] OECD/NEA, OECD/SERENA Integrated Report-Steam Explosion Resolution for Nuclear Applications, 2014.
[23] Y.J. Cho et al., A Study on Evaluation Methodology for Steam Explosion in the Reactor Cavity during a Severe Accident, Nuclear Safety Technology Analysis (N-STAR), KINS, 2017.
[24] B.R. Sehgal, Nuclear Safety in Light Water Reactors - Severe Accident Phenomenology, Academic Press, Boston, 2012.