Debris Bed Formation Experiment under Pre-Flooded Cavity Conditions using Simulant Particles

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1. Introduction

In light water nuclear power plants, when severe accident occurs the molten core material (corium) is relocated into the water-filled reactor cavity as a severe accident management measure by reactor pressure vessel failure. In the situation, the melt jet is broke up, fragmented, and the melt droplets become solidified. After that, the solidified debris is sedimented and finally the debris bed is formed as illustrated in Fig. 1 [1]. To terminate severe accident progression, the assurance of the ex-vessel debris bed coolability is essential since it is the pre-conditions of molten corium concrete interaction resulting in concrete floor erosion, which threaten to the integrity of nuclear power plant containment. Therefore, it is important to assure long-term coolability of the relocated corium on the cavity floor by supplying sufficient coolant into the internally heat generating debris bed. Because effectiveness of such coolant supply into a debris bed is determined by the pressure gradient through porous debris bed according to debris bed shape, it is necessary to investigate the debris bed shape, which is affected by the sedimentation of simulant particles, spreading and self-leveling of particle beds.

Thus, the objective of research is for the experimental data acquisition including visualization to suggest a new improved model for the prediction of debris bed shape. In the research, there are non-heating and heating experiments using simulant particles (spherical and non-spherical stainless steel particles (SUS 304 with the density of 8,000 kg/m^3) with or without particle size distribution from the results of TROI experiments).

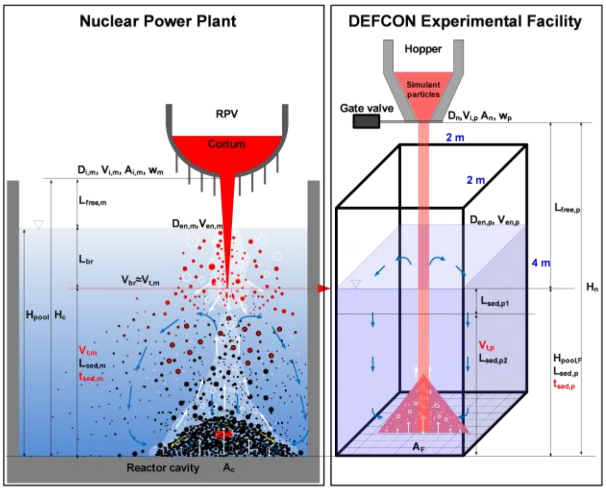

Fig. 1. Schematic of the phenomena under accident condition and DEFCON experimental facility [1].

2. Similarity Analysis

To establish the experimental case, the similarity analysis was performed. Through the results of MELCOR calculation [2] on four initiating events (SBLOCA and LBLOCA with the initial rupture diameter of 76 mm and 150 mm, respectively) until the rupture diameter reaches 0.3 m, the characteristics of melt ejection according to initiating events are listed in Table I. The average rupture diameter are from 0.15 to 0.23 m and the total mass of melt material are from 13,671 to 20,762 kg, and the average mass flux are from 16,956 to 62,653 kg/m^{2}s.

Table I: The characteristics of melt ejection according to initiating events [2]

Initiating event	Average rupture diameter (m)	Total mass of corium (kg)	Average mass flux (kg/m^{2}s)
SBLOCA-76	0.15	18,261	62,653
SBLOCA-150	0.20	20,762	52,562
LBLOCA-76	0.23	14,536	22,006
LBLOCA-150	0.20	13,671	16,956

The characteristics of phenomena under ex-vessel phase according to initiating events with the cavity pool height of 4 m are listed in Table II. The characteristics are calculated with the assumptions (continuous single jet, no occurrence of steam explosion, and the solidified particles are sedimented with the terminal velocity after jet breakup length) and the properties (the density of melt particle $\rho_{m,p}$ is 7,300 kg/m^3 and the diameter of melt particle $d_{m,p}$ is 3.5 mm).

Table II: The characteristics of phenomena under ex-vessel phase according to initiating events

	SBLOCA -76	SBLOCA -150	LBLOCA -76	LBLOCA -150
Melt ejection velocity (m/s)	8.583	7.200	3.015	2.323
Entry diameter of jet into the water (m)	0.130	0.166	0.139	0.108
Entry velocity of jet into the water (m/s)	11.510	10.520	8.242	8.015
Jet breakup length by Epstein model (m)	1.751	2.237	1.881	1.456
Terminal velocity of particles (m/s)	0.806			
Sedimentation length of particles (m)	2.249	1.763	2.119	3.405
Sedimentation time of particles (s)	2.791	2.188	2.630	4.226

The results is that the terminal velocity of melt particles $v_{t,mp}$ is 0.806 m/s, the sedimentation length of melt particles $L_{sed,mp}$ are from 1.763 to 3.405 m, and the sedimentation time of melt particles $T_{sed,mp}$ are from 2.188 to 4.226 s. Thus, to simulate the situation between the accident condition and the DEFCON experimental condition, the terminal velocity of melt particles $v_{t,mp}$ and the sedimentation time of melt particles $T_{sed,mp}$ are matched with the nozzle height of DEFCON $h_{nozzle,\,DEFCON}$ is 3.96 m. The resulting DEFCON pool depth to simulate the accident situation with the cavity pool height of 4 m according to initiating events are listed in Table III.

Table III: The DEFCON pool depth

Initiating event	DEFCON pool depth (m)
SBLOCA-76	3.039
SBLOCA-150	2.564
LBLOCA-76	2.912
LBLOCA-150	3.326

3. Experiment

3.1 Experimental Facility with Measurement System

The schematic of experimental facility named DEFCON (DEbris bed Formation and COolability experimeNt) is illustrated in Fig. 2. The DEFCON are composed of the particle delivery system, the water pool, the air supply system, the visualization system, and the data acquisition system.

The particle delivery system is to supply the simulant particles from the hopper to the water pool. The gate valve (M15 series manufactured by KANEKO SANGYO) is installed at the outlet of particle delivery system. The water pool (2 m × 2 m × 4 m) is to simulate the water-filled reactor cavity. There are the polycarbonate windows for visualization on the two side walls, and through taps for measuring the pressure (Series 35X HTC manufactured by KELLER) and the temperature (T-type manufactured by OMEGA) on the other side walls. At the bottom of water pool, there are 49 EA air injection plates (225 EA 0.8 mm holes, 10 mm pitch) on the load cells (25 EA MD100C and 24 EA MD400C manufactured by Line Tech) to simulate the steam, which is generated by the decay heat of fission products. The air supply system consists of the air tank, the mist separator (SAM850 manufactured by SKP), the water separator (SAMG850 manufactured by SKP), the pressure regulator (SAR925 manufactured by SKP), the manifold, and it is connected with mass flow controllers (MFC). The visualization system is composed of the six 480W LED lights (HLG-240H-48A manufactured by MEAN WELL) for back-light, and cameras (MIRO M110 manufactured by Phantom, LT225 manufactured by Lumenery, and HDR-CX450 manufactured by Sony). The data acquisition system is the NI PXIe-8840 manufactured by National Instrument.

Fig. 2. Schematic of the experimental facility.

3.2 Experimental Case

Through the similarity analysis, the experimental cases are established to investigate the effects of the water pool height, the decay heat power density (volumetric air flow rate), and the particle shape with or without particle size distribution on the resulting debris bed shape. Among them, the experimental case in this study is listed in Table IV as a base case.

Table IV: Experiment case in this study

Temperature of particles	Room temperature
Nozzle diameter	50 mm
Nozzle height	3.96 m
Total mass of particles	300 kg
Particle shape	Sphere
Particle size	3 mm
Water pool height	2.564 m
Water temperature	Room temperature
Volumetric air flow rate	By 1 MW/m^3

The experimental case is for a non-heating experiment, thus the temperature of particles and the water are a room temperature. The nozzle diameter and height are 50 mm and 3.96 m, respectively. The total mass of 3 mm spherical particles is 300 kg. The water pool height is 2.564 m from the result of similarity analysis of accident situation with the cavity pool height 4 m in SBLOCA-150 case. The volumetric air flow rate are deduce by Eqs. (1) and (2) with the decay heat power density of 1 MW/m^3. The volumetric air flow rate according to the particle mass and the decay heat power density is shown in Fig. 3.

$$\dot{V}_{\mathrm{g}} = \frac{m_{\mathrm{p}} q_{\mathrm{d}}'''}{\rho_{\mathrm{g}} \rho_{\mathrm{p}} \left(1-\varepsilon\right) h_{\mathrm{fg}}} \tag{1}$$

$$\dot{V}_{\mathrm{a}} = \frac{\rho_{\mathrm{g}} \mu_{\mathrm{a}}}{\rho_{\mathrm{a}} \mu_{\mathrm{g}}} \dot{V}_{g} \tag{2}$$

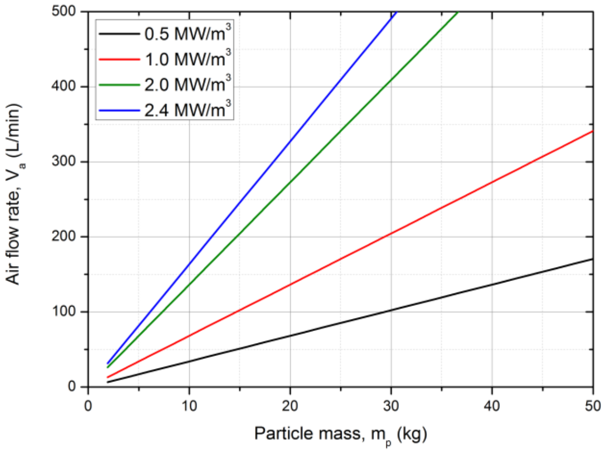

Fig. 3. The volumetric air flow rate according to the particle mass and the decay heat power density, respectively.

3.3 Experimental Procedure

The experimental procedure began with the preparation as follows. The total mass (m_p: 300 kg) of 3 mm spherical particles is measured using a balance (IE-300 manufactured by CAS), and the particles are loaded into the hopper. In the water pool, the water is filled up to the level of 2.564 m. In the air supply system, the air is filled in the air tank, and the air regulator is controlled to supply the air to the mass flow controllers. In the visualization system, the six LED lights are turned on for back-light, and cameras are installed to visualize the water level in the pool, the bottom of water pool, and the overall view of water pool. Finally, all analog output signals from measurement devices are collected using data acquisition system with the time resolution of 1 s.

In the experiment, after matching the load cell signals are the zero, the gate valve is opened to supply particles from the hopper to the water pool. After that the particles settle down through the water pool and finally, form a particle bed. Originally, the air is injected at the bottom of water pool according to the deposited particle mass during the deposition of particles. However, in this experiment, the air is injected after all particles are deposited to investigate the effect of air injection on the self-leveling of particle bed.

4. Results and Discussion

As illustrated in Fig. 4, the total mass of 3 mm spherical particles (m_p: 300 kg) are injected into the water pool at the saving time of 205 s, during 67 s (Fig. 6).

Fig. 4. The overview of water pool when the particles are injecting into the water pool.

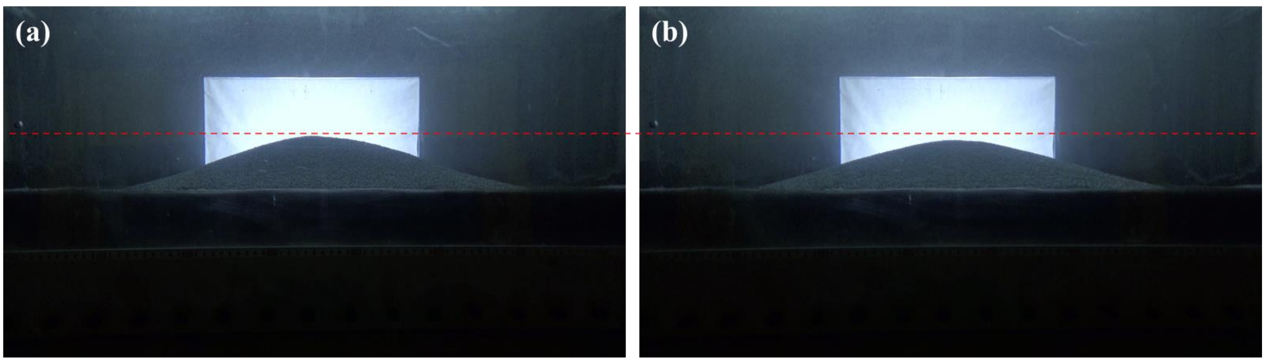

Fig. 5. The particle bed shapes: (a) a deposited particle bed without air injection, (b) a particle bed after air injection according to the mass of particles on each air injection plate.

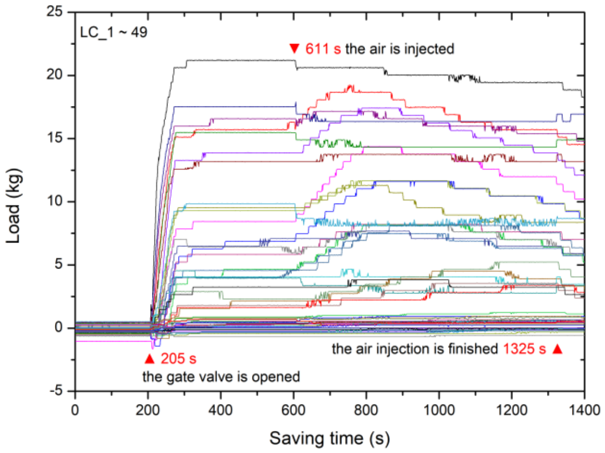

Fig. 6. The signals of load cells according to saving time under conducting an experiment.

The shape of deposited particle bed without air injection is illustrated in Fig. 5(a), it has a conical shape. After that, at the saving time of 611 s, the air is injected from the bottom of deposited particle bed according to the mass of particles on each air injection plate during 714 s in order to investigate the effect of air injection on the self-leveling of particle bed as illustrated in Fig. 7.

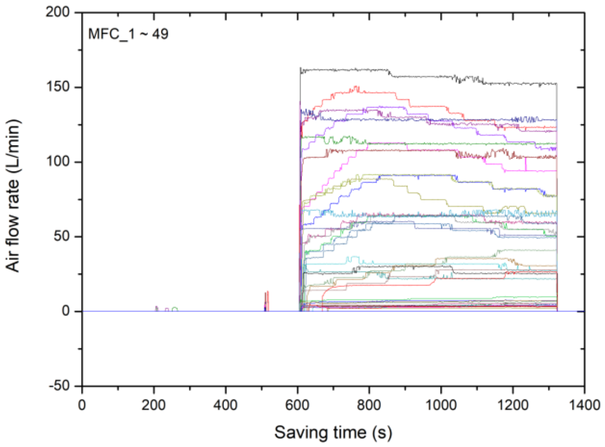

Fig. 7. The injected volumetric air flow rate from mass flow controllers according to saving time.

The resulting shape of particle bed after air injection is illustrated in Fig. 5(b) and it maintains its conical shape, however its spreadability can be confirmed by the height difference in the center of the particle bed in Fig. 5. This confirms that there is the self-leveling effect on the change of debris bed shape under the air injected conditions.

In the further work, it is scheduled to perform more specific analysis on the quantification of bed shape (the height, diameter, repose angle and so on), and the quantification of measured load cell signals in each air injection plate according to saving time. Because the load cell signals may be affected by the buoyancy, reaction, and resulting water convection by air injection as well as the particle transfer to the other air injection plates.

5. Conclusions

The similarity analysis was performed on four initiating events (SBLOCA and LBLOCA with the initial rupture diameter of 76 mm and 150 mm, respectively) until the rupture diameter reaches 0.3 m.

Through the similarity analysis, the experimental cases were established to investigate the effects of the water pool height, the decay heat power density (volumetric air flow rate), and the particle shape with or without particle size distribution on the resulting debris bed shape.

Among them, the experimental case in this study is for a non-heating experiment as a base case, thus the temperature of particles and the water are a room temperature. The nozzle diameter and height are 50 mm and 3.96 m, respectively. The total mass of 3 mm spherical particles (SUS304) is 300 kg. The water pool height is 2.564 m from the result of similarity analysis of accident situation with the cavity pool height 4 m in SBLOCA-150 case.

The result of experiment is that the shape of deposited particle bed without air injection has a conical shape, and the resulting shape of particle bed after air injection according to the mass of particles on each air injection plate maintains its conical shape, however its spreadability can be confirmed by the height difference in the center of the particle bed. This confirms that there is the self-leveling effect on the change of debris bed shape under the air injected conditions.

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