Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Two-Phase Flow Effect on the Ex-Vessel Corium Debris Bed Formation in Severe Accident

Eunho Kim [a], Jin Ho Park [a], Moo Hwan Kim [a], Hyun Sun Park [a*], Weimin Ma [b], Sevostian V. Bechta [b]
[a] *Division of Advanced Nuclear Engineering, Pohang university of science and technology (POSTECH)*
77 Chuongam-Ro, Nam-gu, Pohang, Gyungbuk, Republic of KOREA, 790-784
[b] *Division of Nuclear Power Safety, Royal Institute of Technology (KTH)*
Roslagstullsbacken 21, SE-106 91, Stockholm, Sweden
[*] *Corresponding author: hejsunny@postech.ac.kr*

1. Introduction

Korean PWRs have SAMG (Severe Accident Management Guideline) with IVR-ERVC (In-Vessel Retention of molten corium through External Reactor Vessel Cooling) with wet cavity strategy, which uses the flooded coolant water in the cavity pool. IVR approach is a kind of verified method and also has been adapted to many reactors with confidence[1]. Though, in view of the severe accidents so far occurred, including Fukushima case, it is true that unfortunate situations are used to come with unsuspected causes and coincidental multiple failures. Therefore, it is worthy of studying and preparing the ex-vessel core melt release accident situation even for the reactors with IVR-ERVC.

In order to predict the risk of the ex-vessel severe accident, it is necessary to understand the characteristics of the relocated corium in the cavity for its long term coolability assessment. In Korean IVR strategy, if the situation degenerates into insufficient external vessel cooling, the molten core mixture can directly erupt into the flooded cavity pool from the weakest point of the vessel. Then, FCI (molten Fuel Coolant Interaction) will fragment the corium jet into small particulates settling down to make porous debris bed on the cavity basemat. To secure the containment integrity against the MCCI (Molten Core - Concrete Interaction), cooling of the heat generating porous corium debris bed is essential and it depends on the characteristics of the bed itself.

For the characteristics of corium debris bed, many previous experimental studies with simulant melts reported the heap-like shape mostly[2]. There were also following experiments to develop the correlation for the heap-like shaped debris bed[3]. However, recent studies started to consider the effect of the decay heat and reported some noticeable results with the two-phase flow effect on the debris bed formation. The Kyushu University & JAEA group[4] reported the experimental studies on the ‘self-leveling’ effect which is the flattening effect of the particulate bed by the inside gas generation. The DECOSIM simulation study of RIT (Royal Institute of Technology, Sweden) with Russian researchers[5, 6] showed the ‘large cavity pool convection’ effect, which is driven by the up-rising gas bubble flow from the pre-settled debris bed, on the particle settling trajectories and ultimately final bed shape.

The objective of this study is verification of the two-phase flow effect on the ex-vessel corium debris bed formation in the severe accident. For this study, a simulation test facility, named DAVINCI, was constructed and pebble stone particles in three sizes were used as the simulant particle. From the comparative experiments with air flow, it was shown that two-phase flow creates widely spreaded flat particle bed shape, which is more favorable for cooling in the same volume, rather than the typically accepted heap-like shape. It was also observed that the ‘large cavity pool convection’ effect is more dominant in the two-phase flow effect on the debris bed formation process than the ‘self-leveling’ effect. Moreover, it was also found that the two-phase flow condition results in the better debris bed composition against the concern of the coolability degeneration with late settling fine particles.

2. Methods and Results

2.1 Test facility

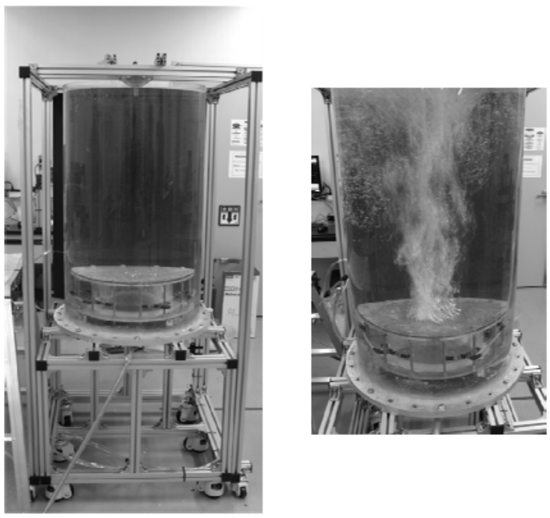

Fig. 1. The whole view of DAVINCI test facility (left), the view at the moment of bubble generation (right)

Figure 1 shows the DAVINCI test facility which is developed for simulating the reactor cavity pool. This facility consists of three parts including the test pool part, the particle injection part, and the bubble generator. The test pool is a transparent acrylic cylinder with 1.0 m height and 600 mm diameter. The simulant particles are injected into the pool by gravity through the funnels on the top of the pool. The bubble generator is composed with an air chamber and a particle catcher plate (Figure 2). It has 308 bubble generation holes at the center, which have 1.5 mm diameter. Grid lines were drawn by 40 mm x 40 mm, and the inner & outer zones were defined for sampling and analyzing. The particle settling distance is around 750 mm from the nozzle bottom to the particle catcher plate. Filtered tap water and high pressure air from utility line were used.

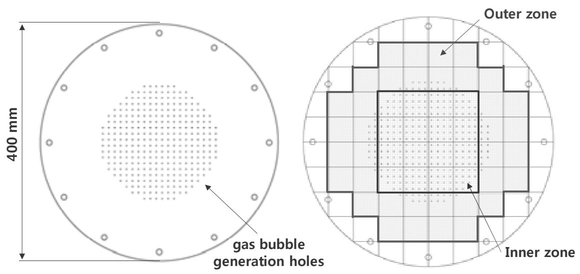

Fig. 2. The particle catcher plate, (left) 308 holes on the center of the plate for bubble generation, (right) partitioning of inner and outer zones on the catcher plate

2.2 Experiments

Stone pebble particles in three kinds of size, 1.0~2.0 mm, 2.8~4.0 mm, and 5.0~6.35 mm were used as simulant particles. Particle shape is irregular and its density is about 2,780 kg/m^3. Because the density of the corium debris particle is about 7,500 kg/m^3, the equivalent particle size for the same terminal velocity are 0.4~0.7 mm, 1.0~1.4 mm, and 1.6~1.9 mm in diameter. For all test cases, same amount (1.6 kg) of the simulant particles was used.

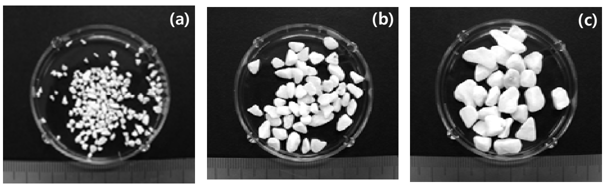

Fig. 3. Stone pebble simulant particles in the size range of (a) 1.0~2.0 mm, (b) 2.8~4.0 mm, (c) 5.0~6.35 mm

With the condition of two-phase flow and two kinds of nozzle size, eight test cases were conducted. The two-phase flow condition of experiments simulates the steam bubble generation from the pre-settled corium debris bed in real situation. The pre-settled debris bed was assumed to have cone-shape with 200 mm diameter and 26°of side slope angle. The air supply rate for bubble generation was calculated with the specific decay heat rate of 2 MW/m^3 under the saturated pool assumption. The nozzle sizes were 15 mm and 30 mm.

Table 1. Experimental condition for the test cases with the 15 mm nozzle diameter

Case	Particle Size [mm]	Two-phase flow condition [liter/min]
Uni.#01	1.0~2.0	0
Uni.#02		46.7
Uni.#03	2.8~4.0	0
Uni.#04		53.2

Table 2. Experimental condition for the test cases with the 30 mm nozzle diameter

Case	Particle Size [mm]	Two-phase flow condition [liter/min]
Uni.#05	2.8~4.0	0
Uni.#06		50.7
Uni.#07	5.0~6.35	0
Uni.#08		53.6

2.3 Result A –Two-phase flow effect on the bed shape

The shape of the debris bed is very important for its coolability. The heap-like shape is more unfavorable for the cooling compared with the well distributed flat bed in same volume, because it has larger depth at the center for coolant to penetrate into. Although there might be additional chance for coolant ingress from side wall, it was also shown as not enough[5].

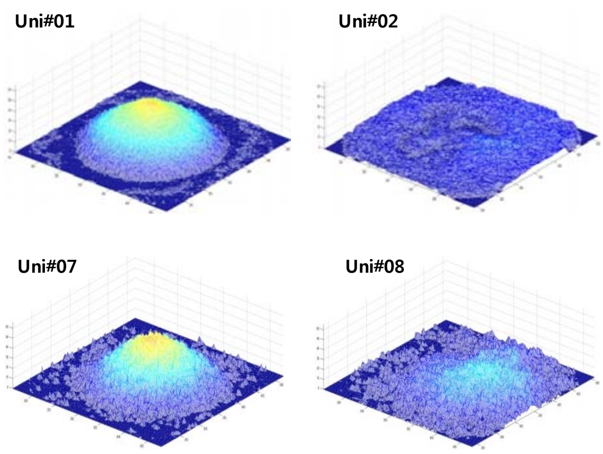

Fig. 4. 3D reconstructed images of the resultant particle bed for each test case (1.0~2.0 mm particle was used for Uni#01 & #02, and 5.0~6.35 mm particle was used for Uni#07 & #08)

As we employed two-phase flow condition with pre-settled debris bed assumption, there was vigorous bubble generation from the center region and induced large convection in the test pool. In the figure 4, the images on the left (Uni#01, Uni#07) are the resultant bed shapes of the test cases in quiescent pool, and the images on the right (Uni#02, Uni#08) are those with two-phase flow condition. All the quiescent pool test cases have heap-like shapes, but the two-phase condition test cases have fairly flattened bed shape than its comparison test cases, respectively. This shows the optimistic side of the two-phase condition by spreading the debris particles and making shallow bed to be easily cooled. These observations clearly support the previous studies [3, 5, 6] on the two-phase flow effects.

2.4 Result B –Dominance of the large cavity convection

Recently, there have been two approaches for investigating the two-phase flow effect on the debris bed formation, the 'self-leveling' of Kyushu University & JAEA group and 'large cavity pool convection' of RIT group with Russian researchers. Because the 'self-leveling' tests were conducted after the heap-like particle bed preparation, it is only related to the movement of the already deposited particles in the debris bed. On the other hand, the 'large cavity pool convection' effect was investigated on the falling particle's trajectory with transient simulation. As both studies showed their own effect, there was no comparison between the two effects on the bed formation.

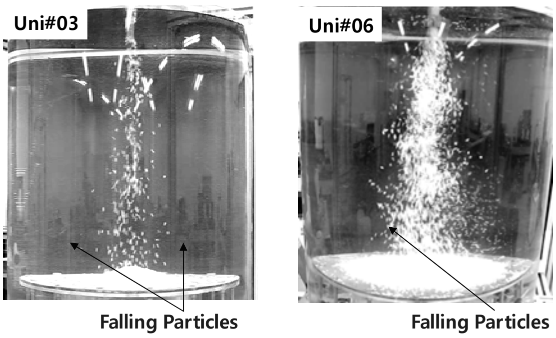

Fig. 5. The captured images of the test cases in quiescent pool (left) Uni#03, (right) Uni#05

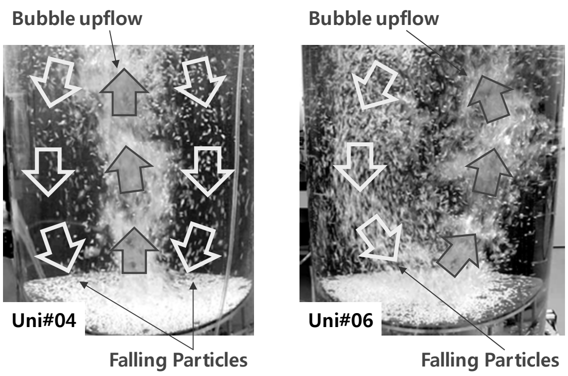

Fig. 6. The captured images for the test cases with large pool convection, (left) the symmetric convection flow in Uni#04, (right) the biased convection flow in Uni#06

Figure 5 shows the captured images for the test cases in quiescent pool and figure 6 shows those with two-phase flow condition. By comparing the Uni#03 & Uni#04, and also Uni#05 & Uni#06, the effect of 'large cavity pool convection' can be easily understood. The falling particles in the test cases with two-phase condition were scattered and swept away by the large convection flow with faster velocity, while those in the quiescent pool only settled straight down with some oscillation. On the other hand, the particle movement was rarely observed after once it arrived on the catcher plate even when there was still violent large convection flow above it. This might be interpreted as an insufficient initial condition for 'self-leveling' effect to show its effectiveness, because the particles were already well spreaded by the 'large cavity pool convection' effect.

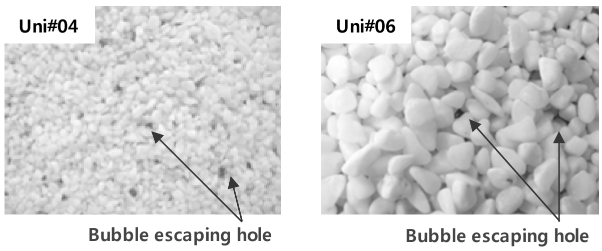

Fig. 7. The images of the bubble escaping holes on the resultant particle bed (All the sparsely distributed & relatively large dark spots are the bubble escaping holes but only two were pointed for each.)

Figure 7 shows the many bubble escaping holes on the bubble generating region in the resultant particle bed. It shows the way how the escaping bubbles make the 'self-leveling' effect on the particle bed. From the gentle slope around the bubble escaping holes, it is not hard to conjecture that the bubble up-rising flow does not give much effect on the bed structure after its own escaping path is developed. It seems that the 'self-leveling' effect by the escaping bubbles is inherently passive and localized by its operating characteristic. On the other hand, the 'large cavity pool convection' effect is active and far-reaching by the characteristics of dynamic counter flow and large scale natural circulation.

On the basis of the sequential process of the debris bed formation and the operating characteristics of each effect, it seems that the 'large cavity pool convection' effect will work dominantly during the debris bed formation process than the 'self-leveling' effect.

2.5Result C –Reduction of the fine particle related risk

In general, when the various sizes of particles fall down, the smaller size particles fall down later than the larger particles. There has been a concern about the fine particle related risk which includes the formation of a top crust layer or the reduction of the bed porosity by mixing with larger size particles[7].

Table 3 shows the total mass quantity of the three regions; the inner zone, the outer zone, and the out of plate. The inner zone has sixteen sections in the center of the catcher plate. It was considered as the region where the pre-settled corium debris develops the two-phase flow condition. The outer zone includes thirty six sections around the inner zone. This region was regarded as the periphery where is the potential location of following debris bed expansion. The out of plate zone consists of the remained sections on the plate and the outside of the catcher plate. It was considered as a relatively far place.

Table 3. Total particle mass quantity of each zone on the catcher plate, [gram]

Case	Inner zone	Outer zone	Out of plate
Uni.#01	1,141	431	28
Uni.#02	118	538	945
Uni.#03	1,329	270	0
Uni.#04	376	557	668
Uni.#05	812	735	53
Uni.#06	440	637	523
Uni.#07	1,089	452	59
Uni.#08	664	640	297

Figure 8 and figure 9 shows the mass composition of Uni#01~#04. For Uni#01 & Uni#02, small sized particles in 1~2 mm were used and for Uni#03 & Uni#04 large sized particle, 2.8~4 mm. Any other conditions were same, including nozzle size and total loading mass of particles, 1.6 kg.

On the basis of the figure 8 and 9, it was clearly shown that the smaller particles get more effect by two-phase flow condition in sedimentation. By comparing the Uni#01 and Uni#02 in figure 8, it shows that small particles in 1~2 mm size cannot settle down on the inner zone and mostly pushed away when there is two-phase flow condition. This tendency is also valid for the Uni#03 and Uni#04 in figure 9, but the degree of change is less than the smaller sized particles' case.

Also, by comparing the reduction ratio of the decreased quantity, it can be deduced that the two-phase flow condition make the composition with less fine particle fraction. For the smaller particles of figure 8, the inner zone mass fraction decreased under one tenth (71%→7%), but the larger particles of figure 9 showed around one fourth (83%→23%).

In this respect, it is certain that the two-phase flow condition gives the positive change of the debris bed composition in the respect of the coolability degeneration with fine particles.

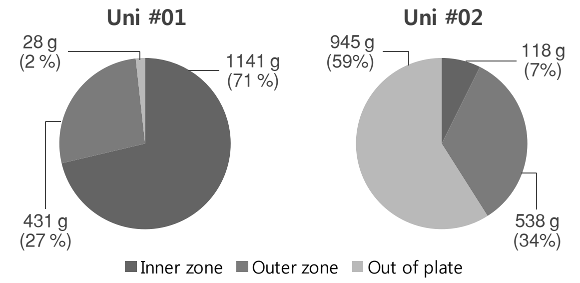

Fig. 8. Mass composition of Uni#01 & #02, which used particle size 1~2 mm

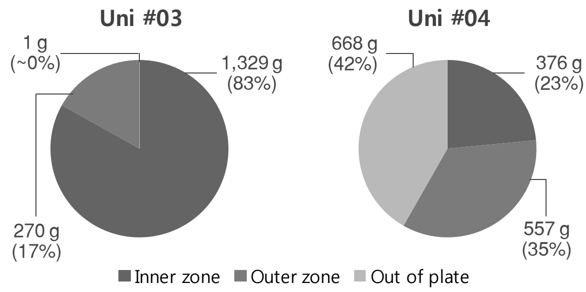

Fig. 9. Mass composition of Uni#03 & #04, which used particle size 2.8~4 mm

3. Conclusions

To investigate the influence of the two-phase flow effect on the ex-vessel corium debris bed formation in the severe accident, experimental study was conducted with simulant particles with newly constructed test facility, DAVINCI. Comparative eight tests were designed with two-phase flow condition with bubble generation, particle size, and nozzle size. From the analysis on the test movie and resultant particle beds, the two-phase flow effect on the debris bed formation, which has been reported in the previous studies[5, 6], was verified and the additional findings were also suggested.

For the first, in quiescent pool the particles settled to form a heap-like particle bed, while in two-phase flow condition the particles were spreaded over the particle catcher plate to form a fairly flat bed shape which is more favorable bed shape for cooling. This experimental result proved the two-phase flow effect of the previous simulation studies on the debris bed formation process. Secondly, it was observed that the 'large cavity pool convection' is the dominant effect than the 'self-leveling' effect during the debris bed formation with two-phase flow condition. For the last, it was found that the two-phase flow condition gives the positive change for the debris bed composition against the fine particle related risks such as the formation of a top crust layer or the reduction of the bed porosity.

ACKNOWLEDGEMENTS

This research was supported by National Research Foundation of Korea (NRF) grants funded by Korean government (MSIP) (NRF-2013M2A8A1040987) and (NRF-2012K1A2B4A01033432). This work was also co-sponsored by the Nuclear Safety Research Program of the Korea Radiation Safety Foundation grants funded by Korean government (NSSC) (Grant Code: 1305008-0113-HD140)

REFERENCES

[1] Theofanous, T., Liu, C., Additon, S., Angelini, S., Kymäläinen, O., and Salmassi, T., 1997, "In-vessel coolability and retention of a core melt," Nucl Eng Des, 169(1), pp. 1-48.

[2] Karbojian, A., Ma, W. M., Kudinov, P., and Dinh, T. N., 2009, "A scoping study of debris bed formation in the DEFOR test facility," Nucl Eng Des, 239(9), pp. 1653-1659.

[3] Shamsuzzaman, M. H., T.; Fuke. F.; Kai, T.; Zhang, B.; Matsumoto, T.; Morita, K.; Tagami, H.; Suzuki, T.; Tobita, Y., "Experimental Evaluation of Debris Bed Characteristics in Particulate Debris Sedimentation Behaviour," Proc. ICONE21: The 21st International Conference on Nuclear Engineering.

[4] Cheng, S., Yamano, H., Suzuki, T., Tobita, Y., Nakamura, Y., Zhang, B., Matsumoto, T., and Morita, K., 2013, "Characteristics of Self-Leveling Behavior of Debris Beds in a Series of Experiments," Nuclear Engineering and Technology, 45(3), pp. 323-334.

[5] Yakush, S., and Kudinov, P., "Simulation of ex-vessel debris bed formation and coolability in a LWR severe accident," Proc. ISAMM-2009, Böttstein, Switzerland, pp. 26-28.

[6] Yakush, S., Kudinov, P., and Dinh, T.-N., "Modeling of Two-Phase Natural Convection Flows in a Water Pool with a Decay-Heated Debris Bed," Proc. Proceedings of International Congress on Advances in Nuclear Power Plants (ICAPP 2008).

[7] Sehgal, B. R., 2006, "Stabilization and termination of severe accidents in LWRs," Nucl Eng Des, 236(19), pp. 1941-1952.