# Experiments on sedimentation of particles in a water pool with bottom surface inclination under quiescent pool conditions

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## 1. Introduction

In a scenario of severe accident in Light Water Reactors (LWRs) leads to major core damage and its subsequent melting. This molten core will eventually flow into the lower plenum of the reactor vessel. In case of insufficient cooling, the vessel wall will be damaged causing breach by high temperature melt which will be released into the reactor cavity. In the wet cavity strategy, the discharged high temperature corium can be adequately cooled by low-temperature coolant water. This fuel-coolant interaction (FCI) will allow the corium to break and settle on the bottom of the reactor cavity forming a porous debris bed. For adequate assessment of coolability of relocated corium, it is necessary to thoroughly understand the relevant processes of debris bed formation, including melt jet breakup and particle sedimentation, and the structural characteristics of the resulting debris bed. The geometrical configuration of the debris bed including both internal and external structure is important for the coolability assessment because it provides the boundary conditions for simulations.

Previous studies concerning ex-vessel severe accident mainly dedicated on studies of FCI [1-3] and the molten corium–concrete interaction (MCCI) [4] influence to structural integrity. Earlier, studies [2, 5] have described the particle size distribution of the fragmented melt and the geometry of the result particle bed. In addition, some investigations [6, 7] were made on the study of the thermo-hydraulic phenomena inside a porous particle bed. However, relatively little efforts has been made to study the development of the debris bed or proposing any debris particle dispersion technique.

Various studies [8-10] considered the heat generating characteristics of corium particles on the development of large natural convection flow and particle sedimentation in the flooded cavity. Yakush et al. [8, 9] using simulations demonstrated that the two-phase natural convection changes the trajectory of the falling particles resulting in a more flattened debris bed formation. The findings of the Yakush et al. [8] were supported by the experimental studies using simulant particles and air bubble injection [11, 12]. Earlier [13-14] an effort has been made to study the particle sedimentation under the bubble-induced natural convection flow condition to examine the spreading of the settled debris using the DAVINCI (Debris bed research Apparatus for Validation of the bubble-Induced Natural Convection effect Issue) test facility at Pohang University of Science and Technology, Pohang, Korea. The tests results showed that the simulated falling particle under two-phase condition using bubble flow forms a debris bed with larger radius. In addition an analytical model for the growth of the debris bed and its external geometry was presented by considering the kinetic interactions between the debris particles and the bubble-induced coolant flow. The final form of the model of the conical debris bed presented for predicting characteristic length of the debris bed ($R_{75\%}$) and side slope angle ($\theta_s$) is as follows:

$$R_{75\%} = 0.414\left\{\left(\frac{(\rho_l-\rho_g)^2}{\rho_p\rho_g h_{lg}}\right)\left(\frac{q_d^{''}H_s^2\tau}{\dot{m}}\right)\left(\frac{\alpha u_b D_{pc}^4}{(1-\varepsilon)u_p^4}\right)\right\}^{1/3} \quad (1)$$

$$\tan\theta_s = 4.127\left\{\left(\frac{\rho_g h_{lg}}{(\rho_l-\rho_g)^2}\right)\left(\frac{\dot{m}^2}{q_d^{''}H_s^2}\right)\left(\frac{u_p^4}{\alpha u_b D_{pc}^4}\right)\right\} \quad (2)$$

Good agreement between the measured and calculated datasets was made in the investigation. While in the quiescent pool condition (QPC), large fraction of the particles fall in a narrow cylindrical column and small fraction were scattered laterally due to turbulence and collisions. The particles arrived in a narrow area at the center of the particle catcher, and the particle bed grew rapidly as particles accumulated. In the TPC tests, the rising stream of bubbles induced an upward flow of the liquid, which intersected with the downward particle flow. The trajectory of the particles was affected, and the particle flow broadened. The resulting particle bed covered a larger area, with a smaller proportion of the particles accumulated at the center. Taking the clue from these results, it was postulated that a containment bottom with a certain slope can enhance the spread of the debris particle sedimentation by channeling the momentum of the falling particles laterally outward. In this view, a bottom surface mounting with a certain slope was designed and tested using the DAVINCI facility. This study investigated the sedimentation of particles in a water pool with bottom surface inclination under quiescent pool conditions (QPC). Later tests are planned to perform under two-phase conditions (TPC) with bottom inclination. The results from the analysis will be utilized to modify the existing model describing the debris bed geometry developed using energy flux model. Fig. 1 depicts the scope of the present study using DAVINCI tests with bottom inclination under QPC and TPC.

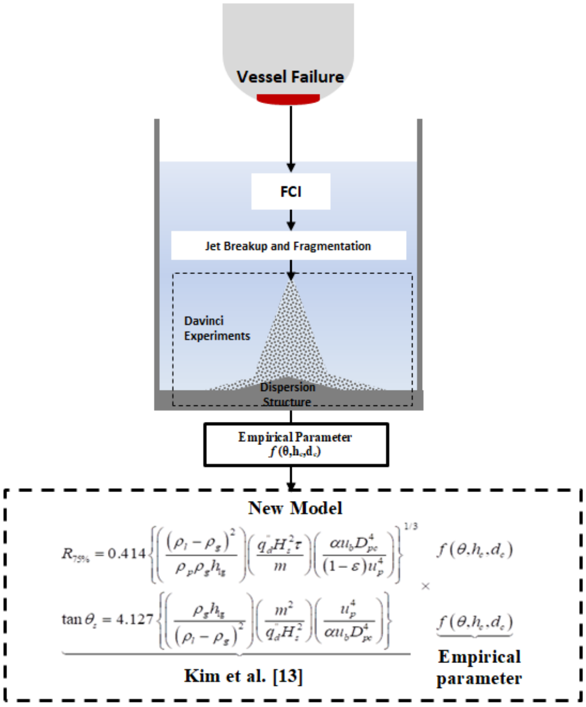


**Fig. 1:** Scope of the present study using DAVINCI tests with bottom inclination

## 2. Test facility and instrumentation

Figs. 2 show schematic of the DAVINCI test facility designed to simulate particulate debris sedimentation behavior in a flooded reactor cavity together with two-phase natural convection by a heat-generating debris bed.

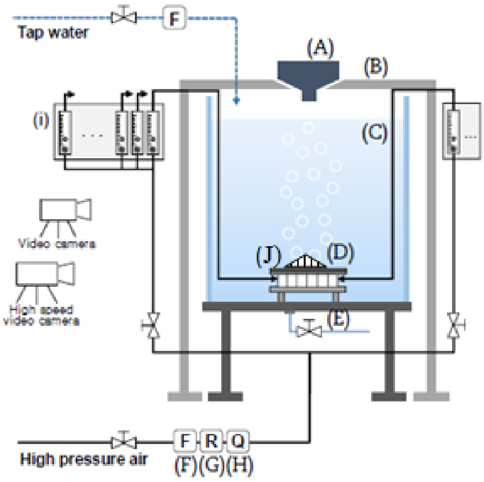


**Fig. 2:** Schematic diagram of DAVINCI test facility. (A) Funnel (B) Funnel rack (C) Test pool (D) Particle catcher plate (PCP) module (E) Water drain valve (F) Filter (G) Pressure regulator (H) Flowmeter (I) Rotameters with needle valves (J) bottom inclination mounting.

DAVICI test facility consists of four major constituents: a particle injection system, a test pool, a PCP module that equips an air injection system and a bottom inclination structure to drive the particle dispersion process. The particles injection system consists of funnel and funnel rack. The particles were released by gravity after removing a rubber plug from the nozzle. Test pool is made from transparent acrylic to facilitate visualization. A perforated PCP was placed at the bottom of the pool. The PCP was connected to air chambers beneath the catcher plate. Vapor generation from the hot debris bed was simulated with 32 air chambers in a predetermined air flow rate distribution.

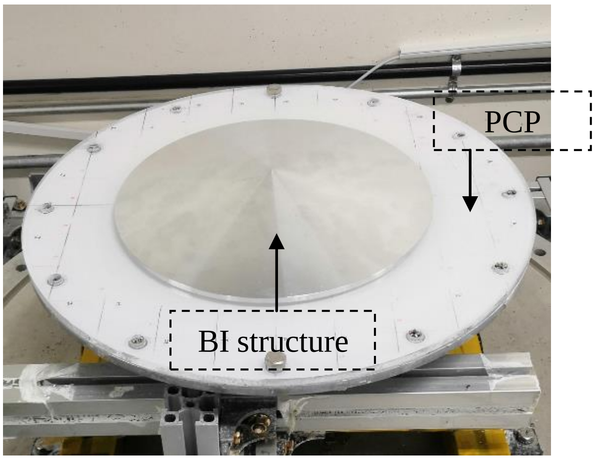


**Fig. 3:** Photographic view of bottom inclination mounting (BI) for QPC tests

In case QPC tests, for the purpose of dispersion of falling simulated debris particles, a conical structure as depicted in Fig. 3, with a diameter of $d_{cone}$ = 25 cm and $h_{cone}$ = 3.5 cm height is machined from aluminum with a cone angle of $\theta_c$ = 13.5°. The bottom inclination (BI) mounting is placed precisely at the center of PCP. The particles were made of stainless steel 304 have cylindrical shape, and the density was measured to be about 8,000 kg/m$^3$, which is similar to the prototypic condition [15]. Table 1 provides the details of particles with various sizes for each test condition.

**Table 1:** Test cases for QPC tests

| Test case | Particle dia. (mm) | Particle mass (Kg) |
|---|---|---|
| QPC-BI-1 | 2 & 5 | 5 |
| QPC-FS-1 | 2 & 5 | 5 |
| QPC-BI-2 | 5 | 5 |
| QPC-FS-2 | 5 | 5 |

To measure the particle size distribution along the axial and radial locations of the debris bed, particles are separated by size using standard tests sieves and weighed with an electronics scale (EK-4100i, A&D Weighing, USA) with a measuring uncertainty of ± 50 mg. For planned TPC tests, the total air flow rate will be measured by a mass flow controller (PFM511S, SMC, Japan), and air flow rates for the 32 air chambers will be adjusted using rotameters with needle valves (RMA14-

26; Dwyer Instruments, USA). All tests were recorded using a digital camcorder (30 frames/s; HDRPJ790; Sony, Japan) and the shot are taken using digital camera (lens: f/2.0; STYLUS TG-4; Olympus).

### 3. Results for the formation of debris beds under quiescent pool conditions (QPC).

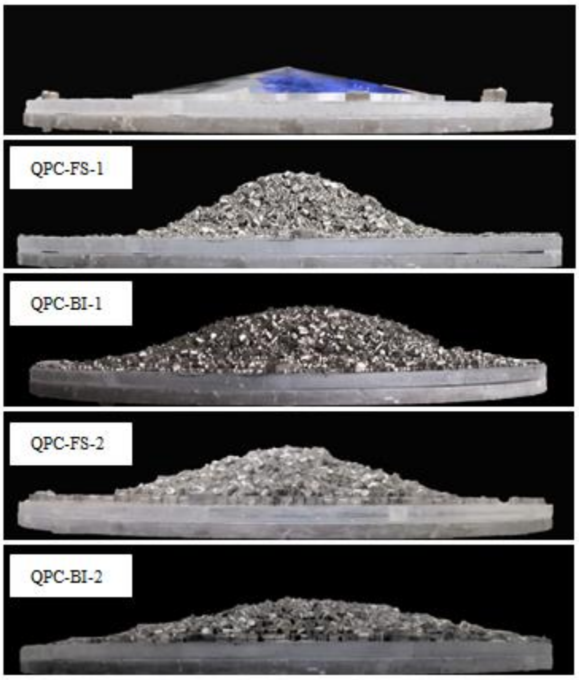


**Fig. 4:** Snapshot of debris bed for different QPC tests cases

Fig. 4 shows snapshots of debris bed formation for test with bottom inclination (QPC-BI-1 & 2) and without flat bottom surface (QPC-FS-1 & 2) under quiescent pool conditions (QPC). In the QPC-FS tests, the results follow the earlier findings [11-13] where most of the particles fell vertically in a narrow cylindrical column, and a small fraction were scattered laterally due to turbulence and collisions. Thus the particle bed exhibited distinct growth in the vertical direction, but little growth in the lateral direction. In case of QPC-BI tests, the scattering of the particles is driven by the inclined bottom surface. The momentum of falling particles after striking the inclined bottom surface is diverted radially outward. Thus the growth of the particle bed is higher in the lateral direction compared to the vertical direction. The resulting particle bed covered a larger area, with a smaller proportion of the particles accumulated at the center compared to QPC-FS tests.

Fig. 5 shows the spread pattern of the debris bed along the length of PCP. In case of QPC-FS-1 and 2, it can be observed that the simulated debris particles get accumulated at the center region which led to the distinct growth of debris bed in the vertical direction.

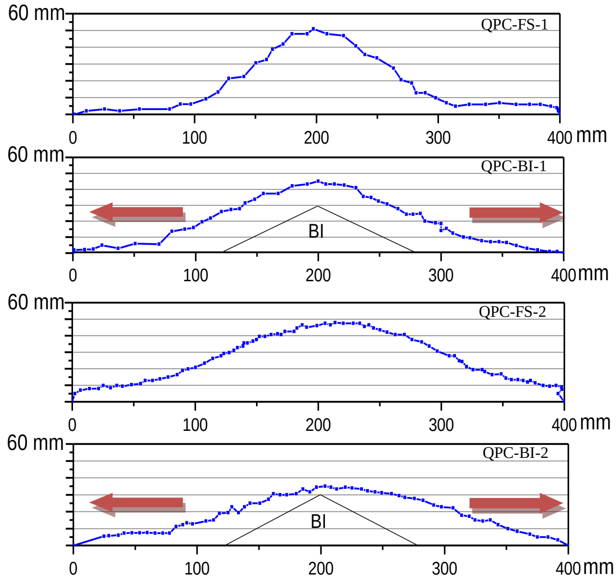


**Fig. 5:** Measured height of debris bed for test different cases

While, in case of QPC-BI-1 and 2, it is evident that the inclined surface is effective in scattering the simulated debris particle in the peripheral region thus increasing the growth of the debris bed in the lateral direction and reducing the growth in vertical direction. From the view point of cooling of the debris bed, such debris bed formation with higher lateral growth can delay the dry-out significantly [15]. Table 2 summarizes the results of the debris bed geometry from present test cases.

**Table 2:** Findings of debris bed geometry for different case

| Case | Bed Height* (mm) | Bed Radius** (mm) |
|---|---|---|
| QPC-FS-1 | 51.2 | 21.5 |
| QPC-BI-1 | 48.5 | 33.7 |
| QPC-FS-2 | 45.3 | 24.2 |
| QPC-BI-2 | 34.7 | 32.9 |

*Measured from top of bottom inclination structure
**Measured from center of PCP to outside

### 4. Plan of the experiments under TPC

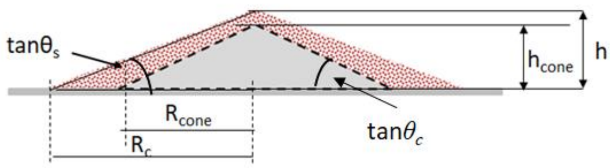


**Fig. 6.** A schematic diagram showing the side slope angle ($\theta_s$) and characteristic length ($R_c$) for a conical debris bed using bottom inclination structure ($\theta_c$)

Fig. 6 shows a schematic diagram illustrating conical debris bed using bottom inclination structure. The formation of debris beds under the influence of a two-phase flow induced by steam generation due to the decay heat of the debris bed will be investigated post QPC tests. Table 3 shows the tests cases planned for the study on sedimentation of particles in a water pool with bottom inclination under TPC. For the tests, the particles sizes will be varied while the total particle weight will be kept constant. The results from the analysis will be utilized to modify the existing model (Eq. 3 and Eq. 4) describing the debris bed geometry developed using energy flux model. Here, $\tan\theta_c$ is the conical bottom inclination structure angle, $A_{cone}$ is the surface area of conical bottom inclination structure and $A_s$ is the area of PCP surface. Coefficient $C_1$ and $C_2$ will be deduced from regression analysis using the test data from planned test described in Table 3 and will be different for both equation.

Modified characteristics length model:

$$R^m_{75\%} = 0.414\left\{\left(\frac{(\rho_l-\rho_g)^2}{\rho_p\rho_g h_{lg}}\right)\left(\frac{q^{"}_d H_s^2\tau}{\dot{m}}\right)\left(\frac{\alpha u_b D_{pc}^4}{(1-\varepsilon)u_p^4}\right)\right\}^{1/3}\left(\tan(\theta_c)\right)^{C_1}\left(\frac{A_{Cone}}{A_{Bottom}}\right)^{C_2} \quad (3)$$

Modified side slope angle model:

$$\tan\theta_s^m = 4.127\left(\frac{\rho_g h_{lg}}{(\rho_l-\rho_g)^2}\right)\left(\frac{\dot{m}^2}{q^{"}_d H_s^2}\right)\left(\frac{u_p^4}{\alpha u_b D_{pc}^4}\right)\left(\tan(\theta_c)\right)^{C_1}\left(\frac{A_{Cone}}{A_{Bottom}}\right)^{C_2} \quad (4)$$

**Table 3:** Test cases for planned TPC tests

| Test case | Particle dia. (mm) | Particle mass (Kg) | Total air flow rate (lpm) |
|---|---|---|---|
| TPC-BI-1 | 2 & 5 | 5 | 0 - 120 |
| TPC-FS-1 | 2 & 5 | 5 | 0 - 120 |
| TPC-BI-2 | 5 | 5 | 0 - 120 |
| TPC-FS-2 | 5 | 5 | 0 - 120 |
| TPC-FS-3 | 2 | 5 | 0 - 120 |
| TPC-BI-3 | 2 | 5 | 0 - 120 |
| TPC-FS-4 | 3.5 | 5 | 0 - 120 |
| TPC-BI-4 | 3.5 | 5 | 0 - 120 |

## 5. Conclusion

In this study, we investigated experimentally the influence of the bottom inclination on the debris bed sedimentation process. The results of these experiments show that the bottom inclination (QPC-BI) redirects the momentum of the falling debris particles in lateral direction resulting in the formation of a debris bed with a larger radius than flat surface (QPC-FS), which is favorable for cooling by delaying the dry-out. Furthermore, a host of tests will be carried out under TPC conditions and empirical parameters will be deduced from these experiments. The model considering the kinetic interactions between debris particles and the bubble-induced coolant flow will be modified with the empirical parameter.

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