Experimental study on the ex-vessel corium debris bed development under two-phase natural convection flow in flooded cavity pool

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Eunho Kim Mooneon Lee, Hyun Sun Park*, and Jin Ho Park

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Contents

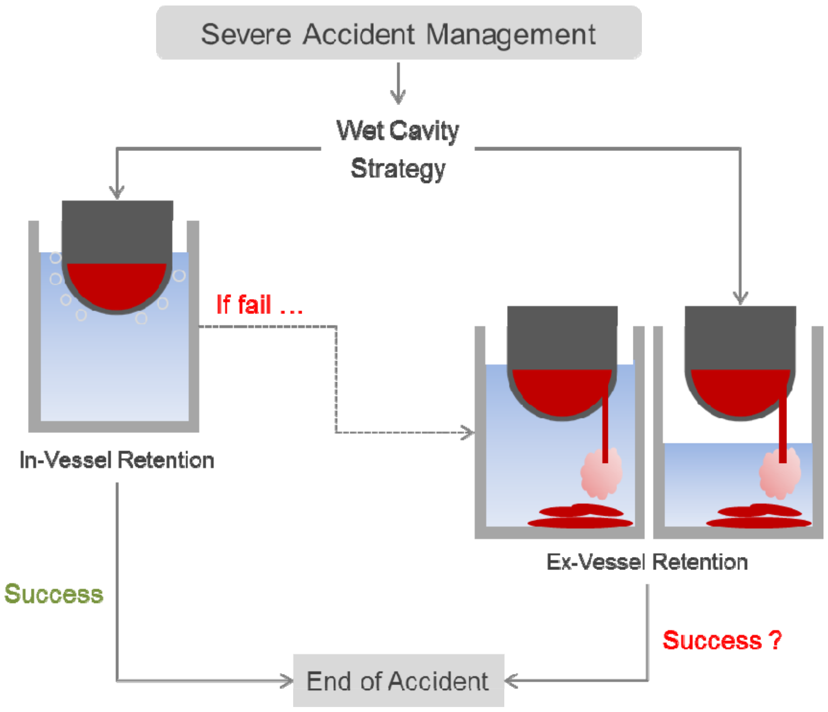
A. Introduction

- When RV failure occurs… (Decreased safety margin in the large power NPP/ Common cause failure by natural phenomena or other event)

- The relocated corium should be cooled before MCCI brings containment failure.

- In the wet cavity strategy, direct contact cooling of corium melt with coolant water is possible.

- Jet break-up, fragmentation, and particle bed formation can be expected in the cavity pool.

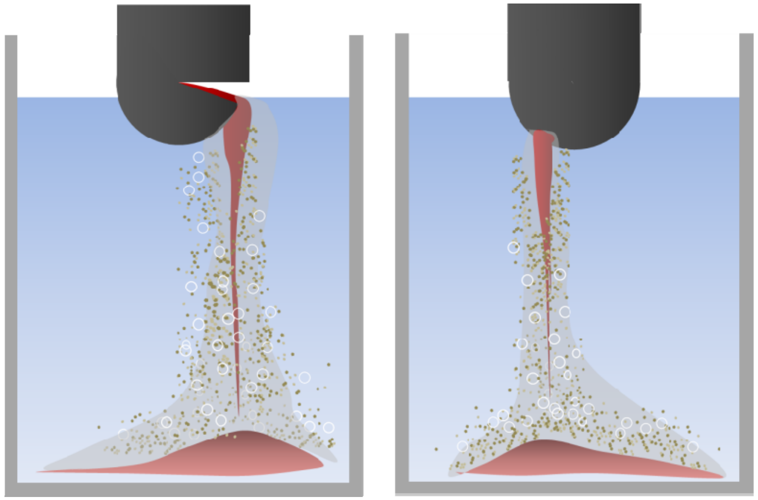


In the 'Wet Cavity Strategy' of LWR, the cavity pool is flooded before the melt comes out. Porous debris bed formation can be expected by direct contact cooling with coolant.

A. Introduction

- The fragmented corium particles can form the porous debris bed with the melt release in the deep pool.

- The porous characteristic of the debris bed can facilitate cooling, as long as the particles maintain their solid shape without remelting.



- Coolability of the relocated corium is dependent on its geometrical configuration and particles' physical status (solidification, remelting or continuous cooling).

- In the long term, the particle status also largely depends on **the bed configuration**.

In the deep pool, the porous corium debris bed can be developed.
Coolability of debris bed depends on its geometrical configuration and particle status.

A.1 Debris bed development & Two-phase flow

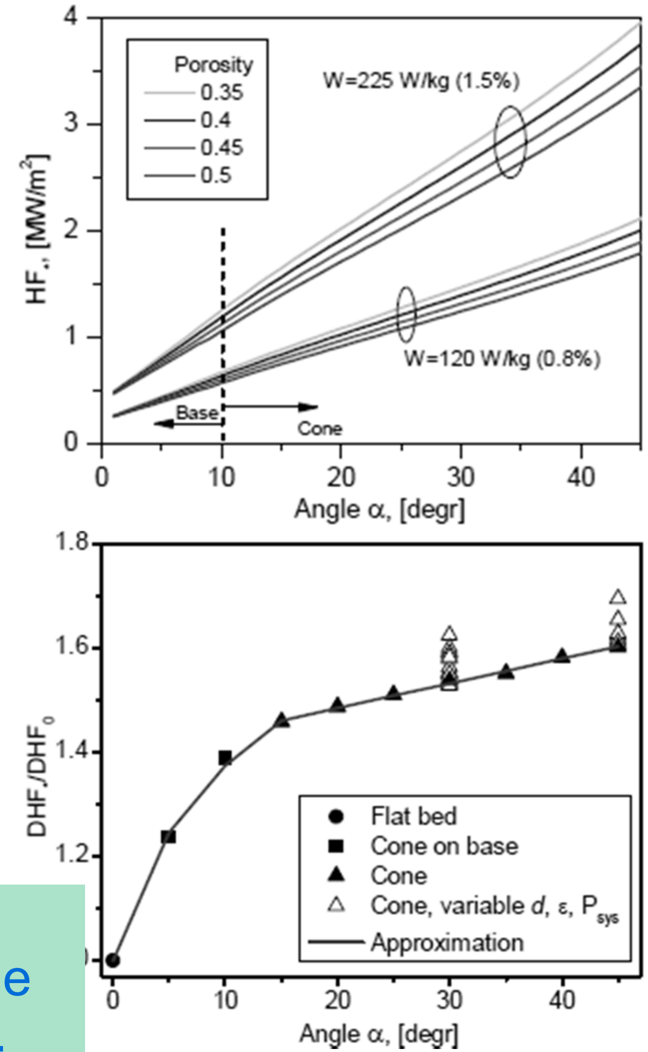
Some proofs…

- Depending on the bed shapes, the heat flux concentration and the cooling capacity show large difference.

Previous studies…

- Previous FCI tests give a lot of information on the jet breakup and fragmentation. But, they couldn't make a concrete conclusion. (L-24, flat bed, L-28 mound shape bed in FARO)

- Recent integral tests (DEFOR) showed the mound shape particle beds. (E4, E7 in DEFOR)



S. Yakush et al., ICONE20, 2012

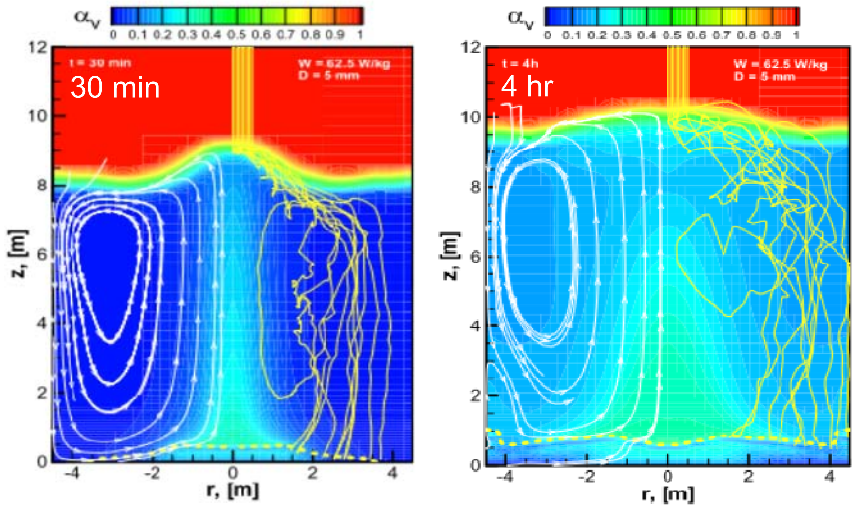
It is certain that bed shape affects on coolability.
However, not much things have been revealed yet to predict the prototypic debris bed configuration for coolability assessment.

A.1 Debris bed development & Two-phase flow

About bed formation process…

- The recent simulation study emphasized the effect of the large natural convection on the fragmented corium particles' settling in the cavity pool.

- The two-phase flow was induced by the decay heat of the debris bed, and the falling particles were spread away from the bed.



S. Yakush et al., ISAMM2009, 2009
'Dripping mode' of melt release

- As the corium particle is a heat source itself which makes counter-current flow, it has self-restrictive characteristic on the concentrated sedimentation.

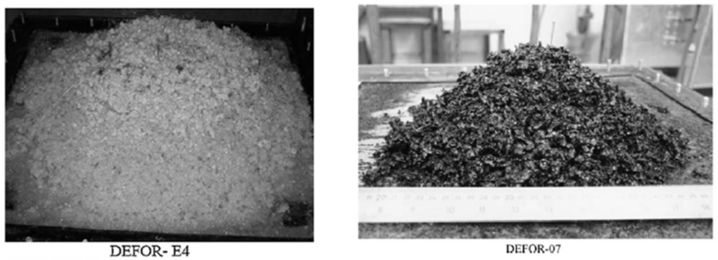
- The debris bed develops into well-spreaded flat shape.

The bubble driven large natural convection flow might affect the debris bed formation process by distorting the particles' falling trajectories with its counter-current flow.

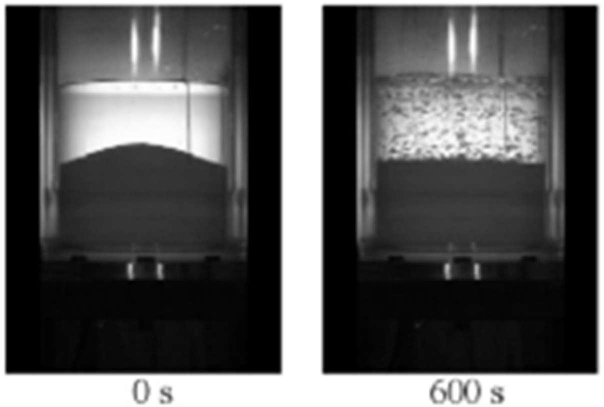
A.1 Debris bed development & Two-phase flow

But, there are more..

- Previous FCI tests couldn't reflect the decay heat, but naturally has two-phase flow effect by large initial heat .
- On the simulation, flow-particle interaction is one way. Particle swarm motion under higher melt release rate may cancel out this effect.
- 'Self-leveling' effect by the escaping bubbles also can contribute to the bed flattening, and it occurs at the same time.



Karbojian et al., NED, 2009

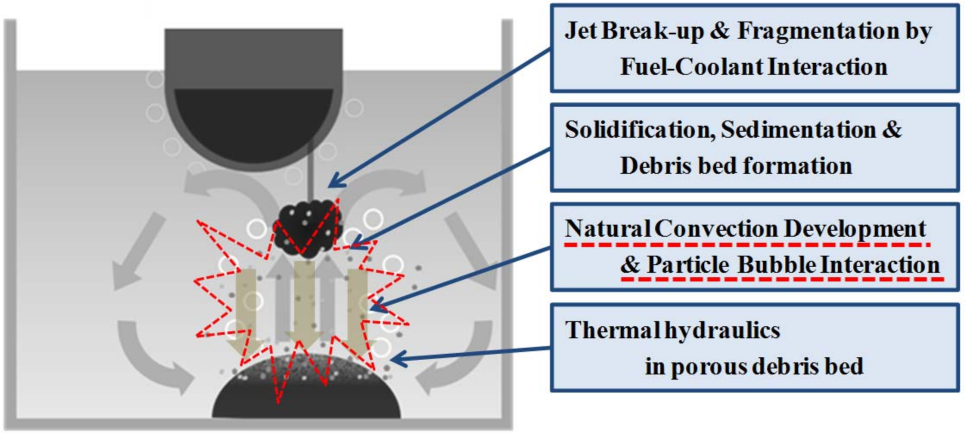


B. Zhang et al., NED, 2011

Dominance between the initial heat and decay heat, efficacy with the large amount of particles, and contribution of 'self-leveling' effect should be considered together.

A.2 Total scope and Objective

- The development and sustainability of the coolable porous debris bed is critical in the success of the wet-cavity strategy.
- The information of the geometrical configuration is essential to predict the coolability of the relocated corium.
- We paid our attention to the bubble generation by the particle heat and its influence on the bed formation process by inducing the large natural convection flow.



Conceptual figure of the corium debris bed development process

How will the geometrical configuration change of the debris bed with the two-phase flow by the particle heat?

A.2 Total scope and Objective

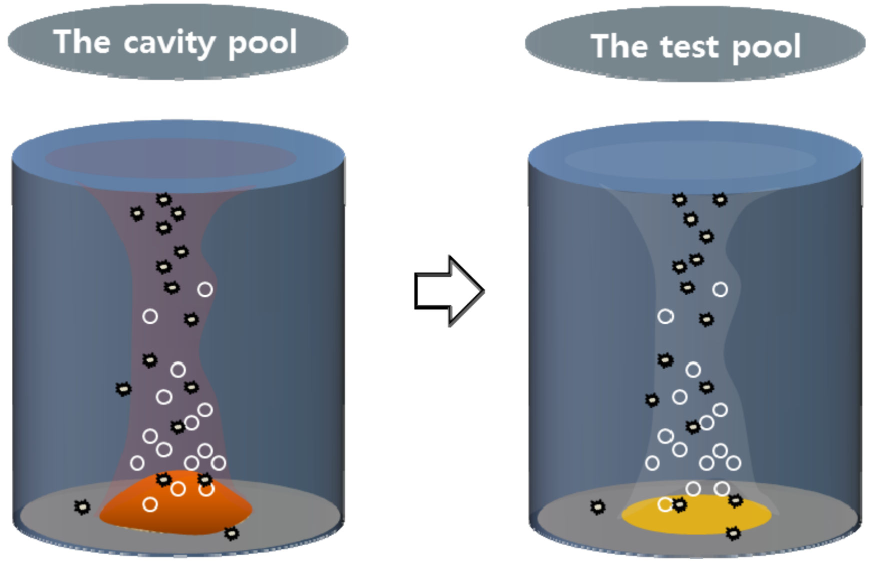
- The scope of this study is obtaining the supportive data and a phenomenological model for numerical code validation, which will extend to the reactor scale estimation on the ex-vessel debris bed formation.
- In this study, we limited the test conditions only with the natural convection flow induced by the bubbles generated from the debris bed.

Obtaining the supportive data and developing the phenomenological model for the code validation and scaling study

A.3 Approach and Assumptions

- Experimental study in a small scale pool

	Prototypic condition	In this study
Particle	Various sizes	Single size
	Irregular shape	Cylindrical shape
	• Fully fragmented (no melt jet) • Limited particle release rate	
Bubble	Steam vapor	Air bubble
	volume generation	Bottom injection
Pool	From subcooled	Saturation Temp.
	Deep & large	Short & narrow
Other effect	• Self-leveling is not prevalent • Initial heat of falling particles is negligible	

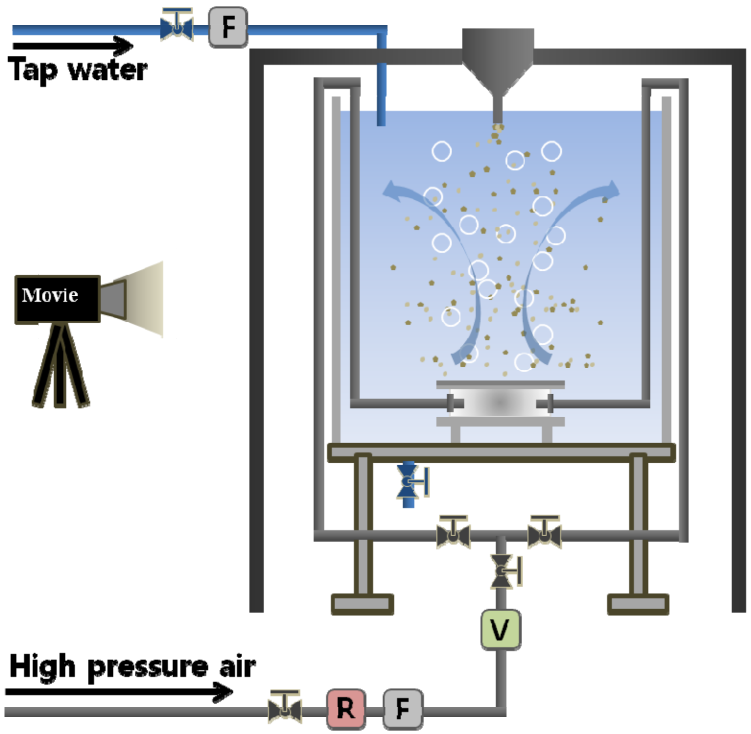


Boiling with decay heat

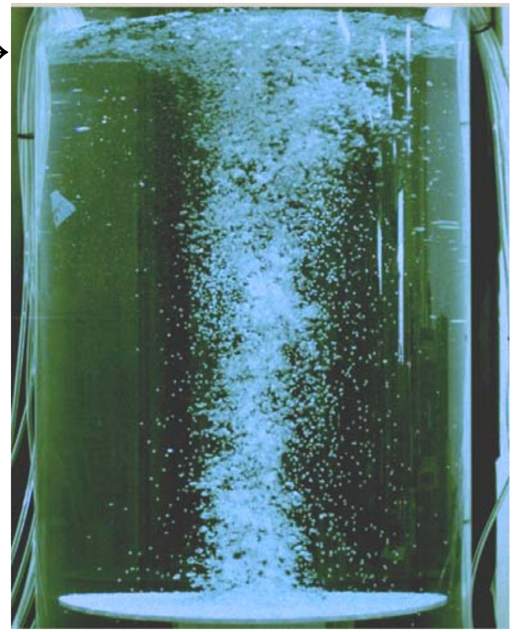
air bubble generation

B. Experimental Facility

- Test facility (DAVINCI)



Bubble: 30.5 LPM →

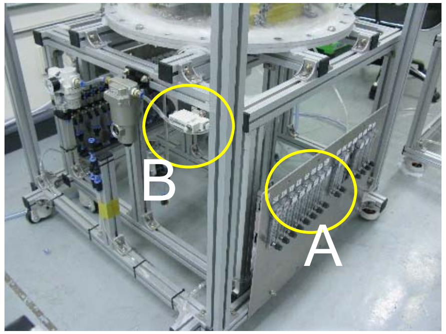


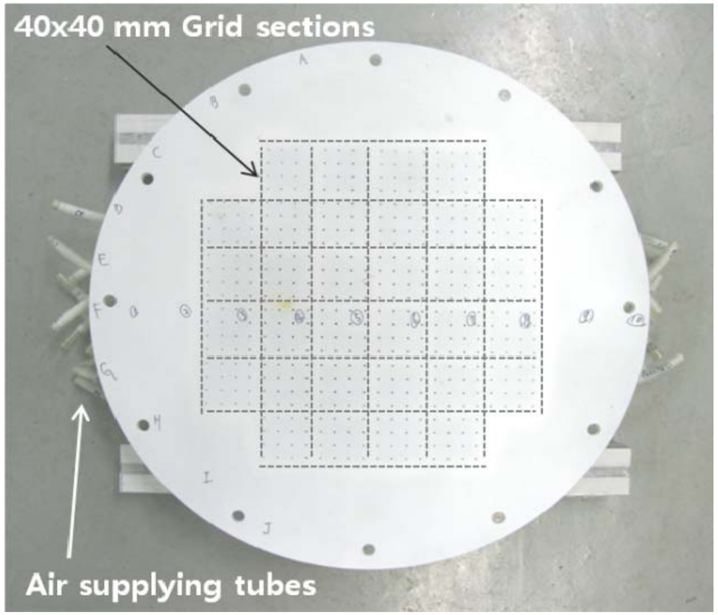
Acryl pool
- Height : 1.0 m
- Falling height : **0.76 m**
- Diameter : 0.6 m

Bubble generation
- 10~120 Liters/min

B. Experimental Facility

- Particle catcher plate module (PCP)





The catcher plate of PCP module #03
- 32 cell sections
- 16 holes (Φ1.5 mm) for each cell

Bubble generation rate of each cell is control by analogue flowmeters (rotameter, Dwyer RMA series)

Total flowrate is measured with digital flowmeter (SMC, PFM series)

B.1. Simulant Particles

- Simulant particles

Stainless steel 304 rods
- Matte white sprayed
- Cylindrical shape
- Density : ~8,000 kg/m^3
- Size : Φ 2 mm x H 2 mm (single size)
- 1.0 kg for each test
- Nozzle size : 14.5 mm (inner diameter)

- Water

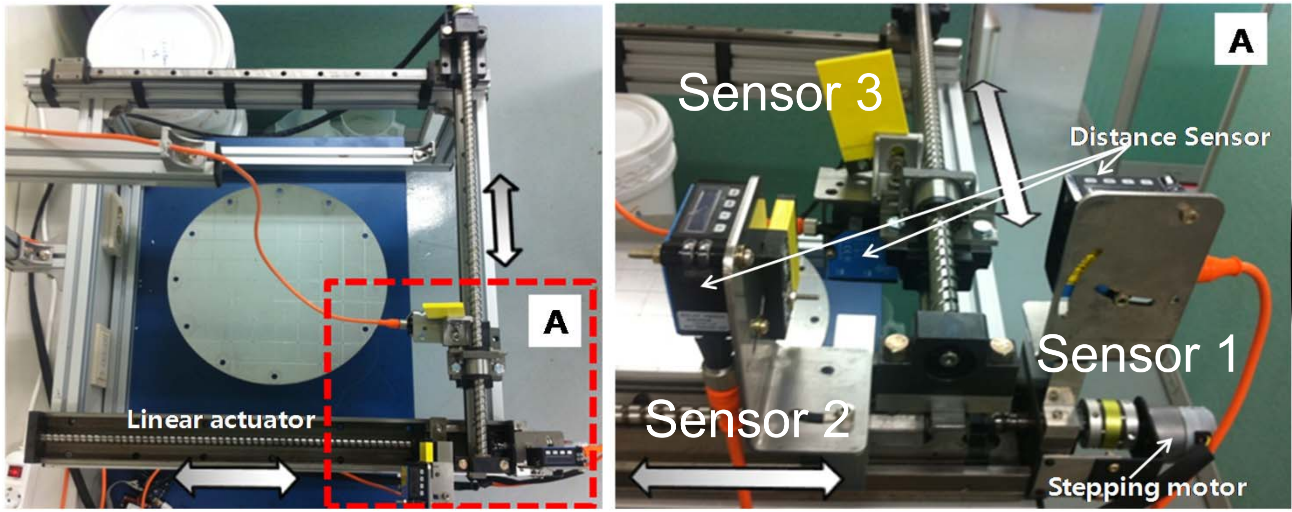
Tap water in room temperature
- Filtration : 5 μm (polypropylene filter)
- No temperature control

- Air

Utility compressor air
- Mist, particle filtration : 0.01 μm
- No temperature control

B.2 Measurement & Post-Process

- Particle bed scanning facility (ref. from KTH)

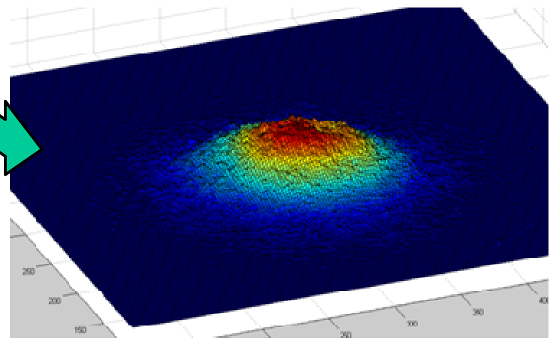


- Three distance sensors (SICK, DT20Hi Series)
- Motorized linear actuators (X, Y axis)
- “Sensor 3” measures height (Z axis) of the particle bed
- (X, Y, Z) data is used for reconstruction of bed in MATLAB S/W

Object particle bed

#04-04	1	2	3	4	5	6	7	8	9	10
a	0.00	0.00	0.06	0.36	0.51	0.59	0.58	0.17	0.00	0.00
b	0.00	0.18	0.84	1.16	1.91	2.04	1.42	1.05	0.21	0.00
c	0.03	0.59	1.24	4.82	11.99	14.05	7.24	1.54	0.78	0.08
d	0.29	0.99	2.40	15.11	32.70	33.93	20.96	5.03	0.82	0.39
e	0.60	1.21	3.79	19.98	39.22	41.74	26.12	6.70	0.61	0.32
f	0.65	1.30	3.43	17.19	30.88	32.62	20.79	4.91	0.69	0.37
g	0.39	1.28	2.36	7.36	15.33	14.13	7.86	1.00	0.47	0.18
h	0.13	1.02	1.79	2.91	3.28	2.27	0.94	0.41	0.31	0.11
i	0.00	0.40	0.91	1.32	1.23	0.95	0.52	0.25	0.22	0.00
j	0.00	0.00	0.18	0.34	0.43	0.40	0.36	0.17	0.01	0.00

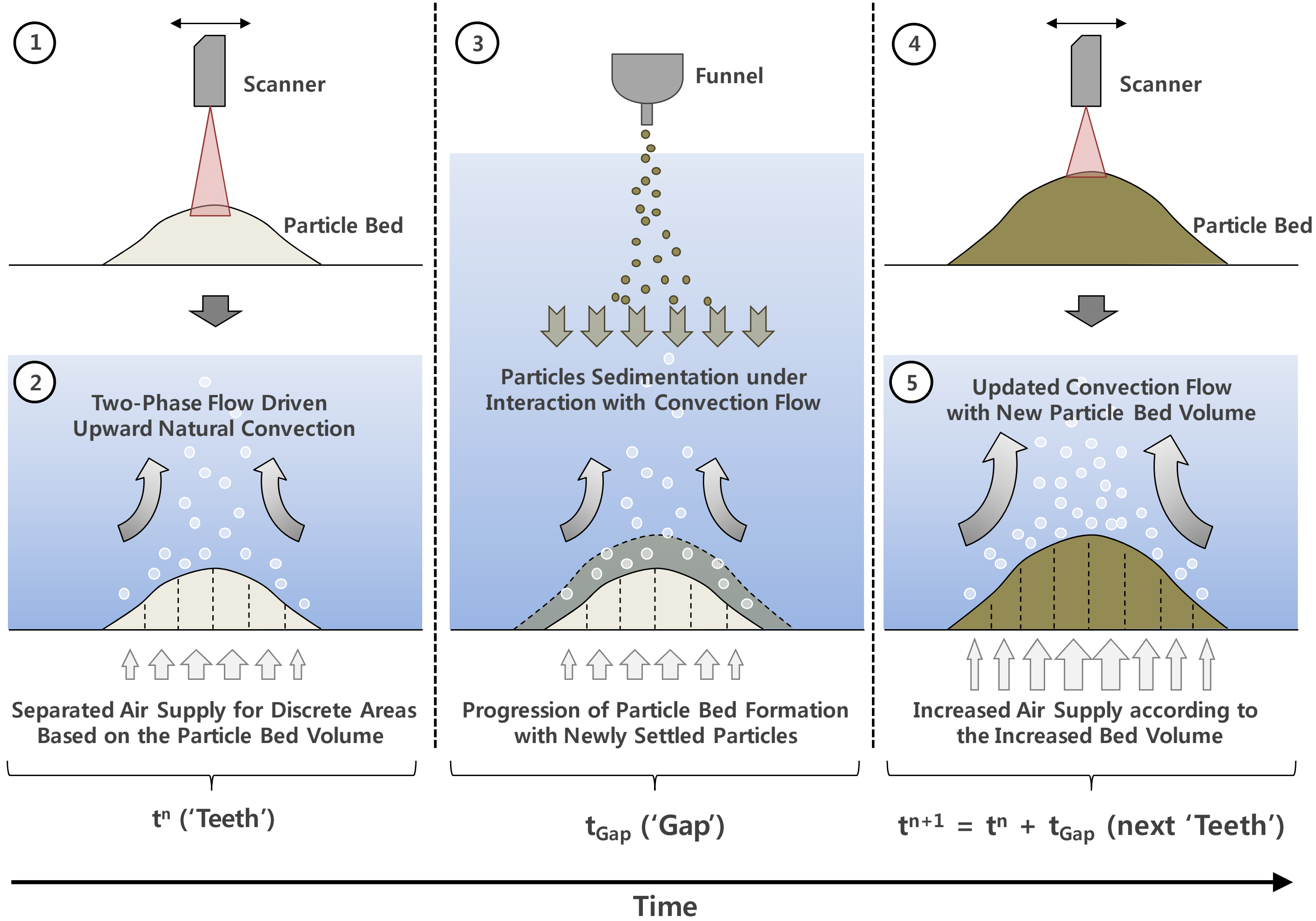
Calculated volume info.



Reconstructed particle bed

B.3 Test Procedure & Time Sequential Test Approach

- Gap-tooth approach



For reflecting the flow intensity change of the natural convection as the particle bed is developing

B.4. Test Matrix

- Test matrix

Test cases and total air flowrate for each case [liters/min]

Case	Time Sequence				
	t_1	t_2	t_3	t_4	t_5
Quiescent Pool Condition	0	0	0	0	0
Two-Phase Condition		36.0	67.0	94.8	118.8

***Volumetric heat generation rate : ~4MW/m^3**

- For comparative study
- Almost 10 seconds for each test case
- Equivalent to the total 50 seconds of particle bed development scenario

C. Result & Analysis

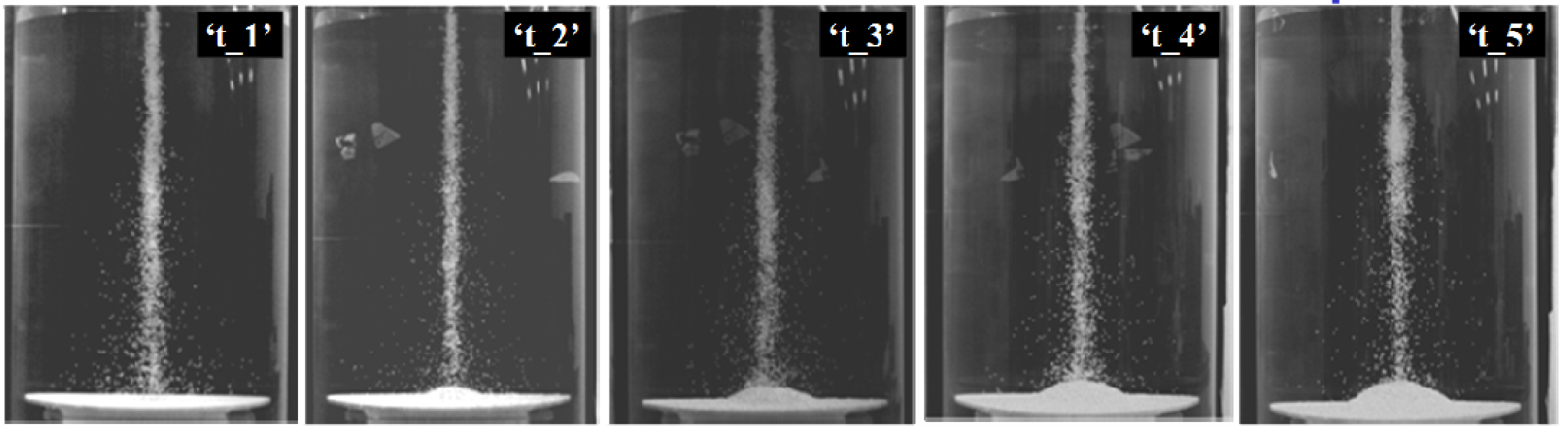
- Repeatability

	Top height [mm]		Total volum`e [ml]	
	Average	Std. Dev.	Average	Std. Dev.
‘t_1’ for both conditions	25.4	1.6 (6.3%)	195.5	32.5 (16.6%)
‘t_2’ quiescent pool condition	38.6	0.7 (1.8%)	395.7	14.1 (3.6%)
‘t_2’ two-phase condition	29.7	0.7 (2.4%)	357.9	16.0 (4.5%)

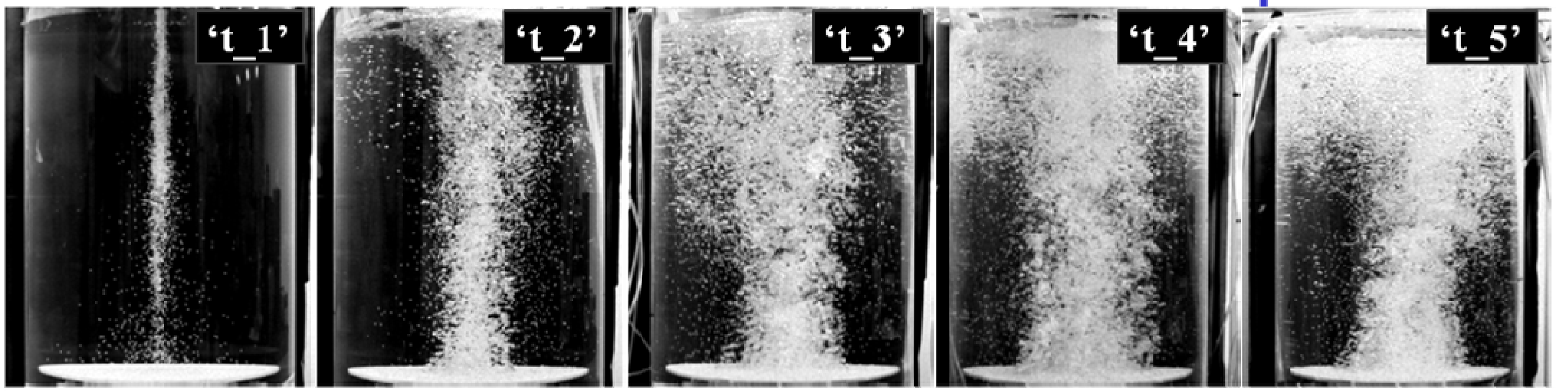
- For ‘t_1’ case for both condition : 7 tests
- For ‘t_2’ quiescent pool condition : 3 tests
- For ‘t_2’ two-phase condition : 3 tests

C.1 Snapshots of each test cases

Quiescent pool condition



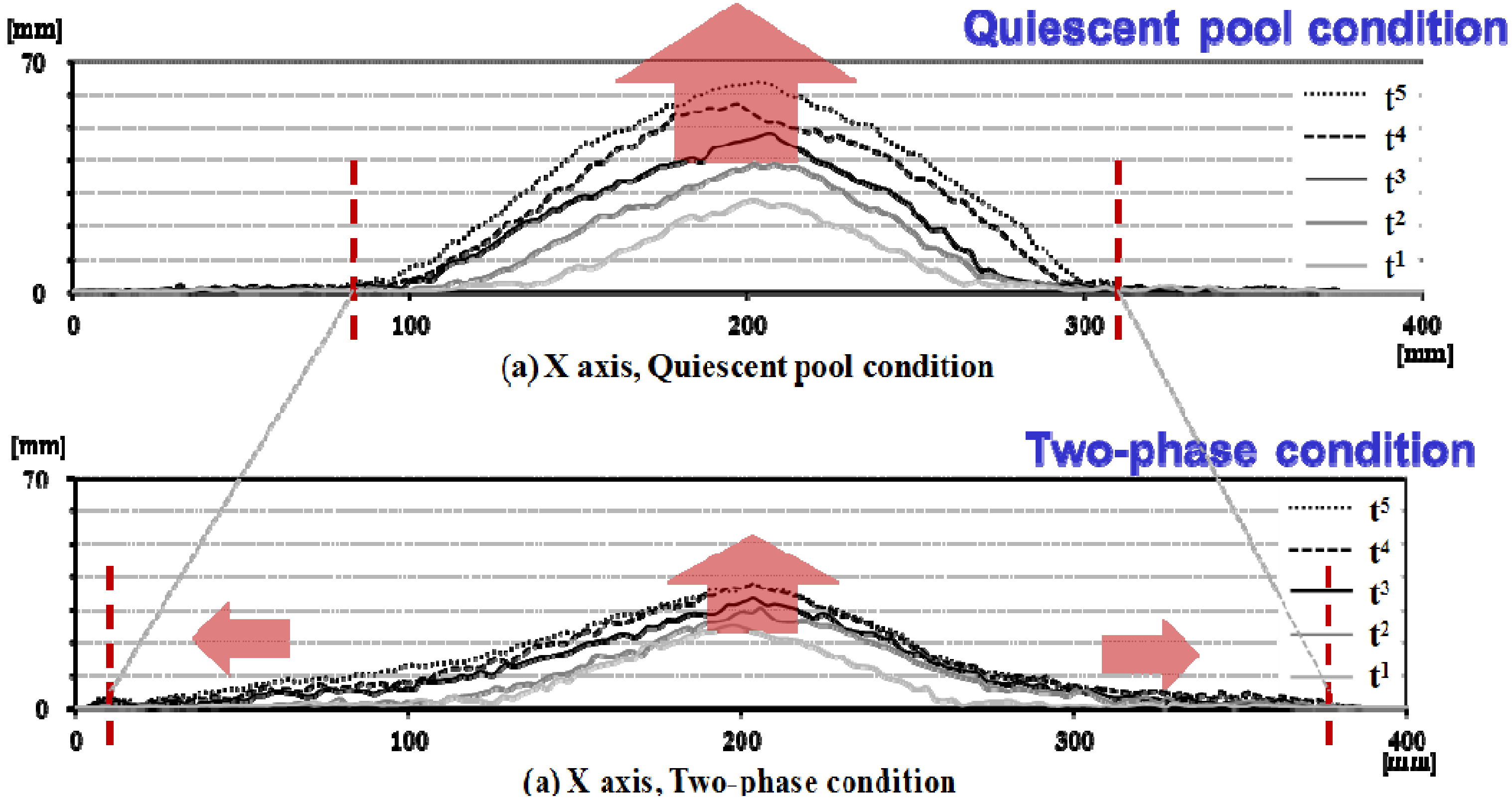
Two-phase condition



Bubble driven upward flow distorts the settling of simulant particles.
As the bubble generation increases, the two-phase flow intensity also enhances.

C.2 Outline view by time sequence

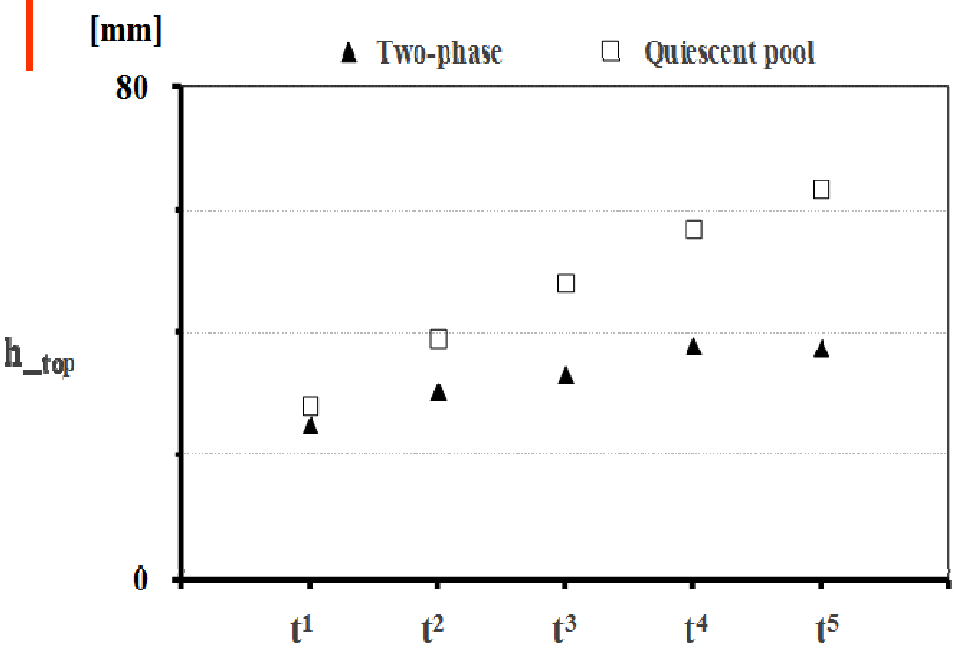
- Development of outline of particle bed

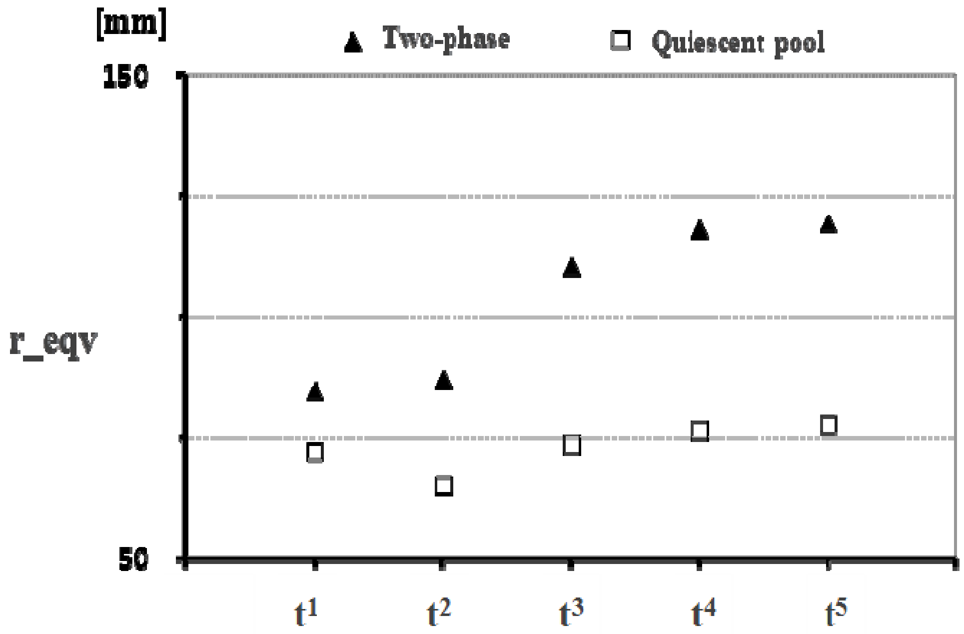


Quiescent pool condition shows consistent growth in axial direction & almost fixed bottom area.
Two-phase condition shows wide-spread growth & definite extension of periphery region.

C.3 Top Height & Overall Bed Shape

- Top height growth by time sequence/ Change of 'r_eqv' for 75% volume





⇨ **Delay of Dryout Occurrence**

⇨ **Higher Overall Debris Bed Coolability**

Bed height growth accompanies spreading which is advantageous in long-term bed cooling.

Thank you for attention.