Influence of Spherical Particle Size Distribution on Pressure Gradients in Mixed Bed

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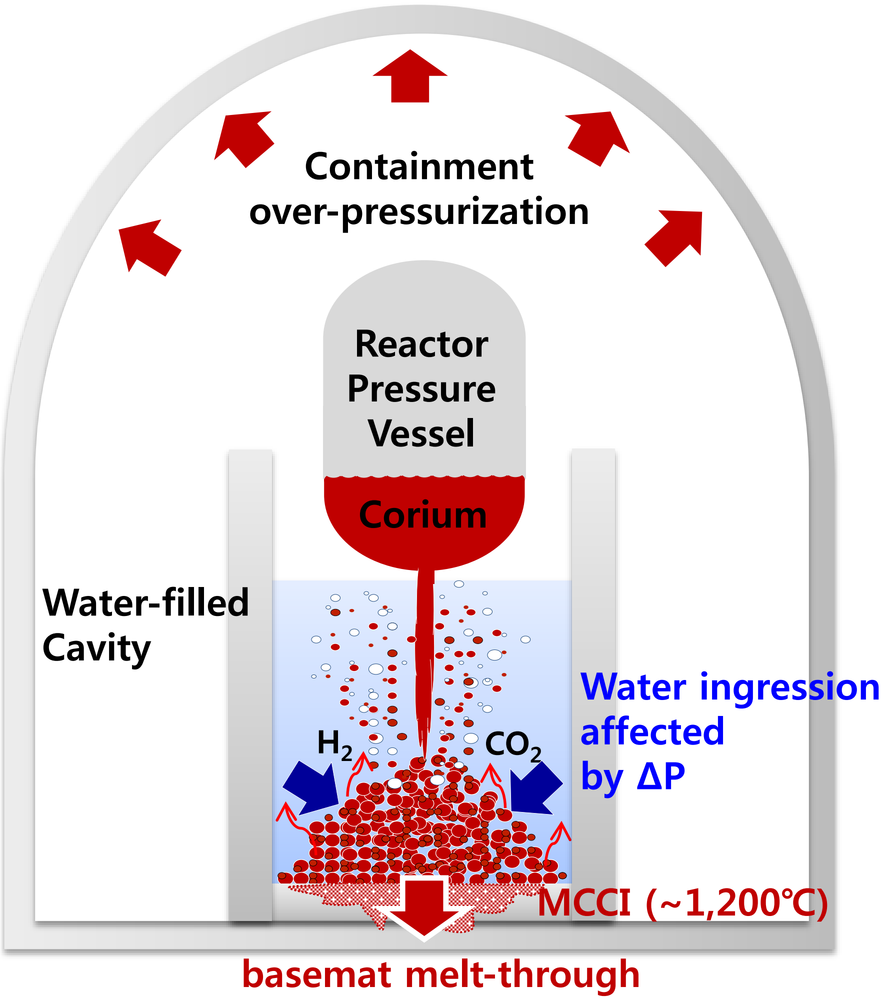
Contents

Topic : Particulate debris bed coolability on the ex-vessel containment floor

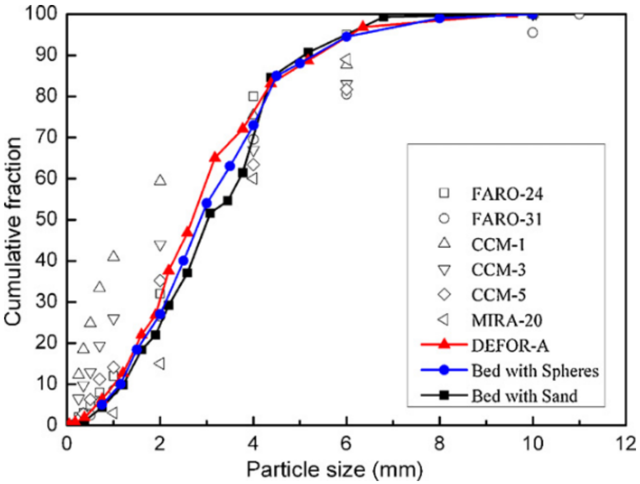


Necessary to understand **pressure drop mechanism** according to the characteristics of particulate bed **to assure the long-term coolability of debris bed** for containment integrity

Background

Characteristics of particulate debris bed at hypothetical SA situation

- **Debris Bed Layer Stratification (Axially / Radially)**
  - Crust region (Smaller particle, Lower porosity)
  - Inner region (Larger particle, Higher porosity)
  - Channeling in debris bed
- **Heterogeneous bed**
  - **Particle size distribution (~ 10 mm)**
  - Multi-grain composition
- **Irregular particle shape**



Particle size distribution from FCI tests *(Li et al., NED, 2012)*

Debris beds formed in DEFOR-E test *(Karbojian, A., et al., NED, 2009)*

Ergun equation : to predict the pressure drops of <u>single-phase flow</u> in porous media composed of <u>single-size</u> <u>spherical</u> particles

$$-\frac{dp}{dz}-\rho_f g=\underbrace{\frac{150\mu(1-\varepsilon)^2}{\varepsilon^3 d_p^{\ 2}}V_s}_{\text{Viscous}}+\underbrace{\frac{1.75\rho_f(1-\varepsilon)}{\varepsilon^3 d_p}V_s^{\ 2}}_{\text{Inertial}}$$

μ : dynamic viscosity [kg/m·s]
ρ_f : density of fluid [kg/m^3]
d_p : particle diameter [m]
ε : porosity
V_s : Superficial velocity of fluid [m/s]
x_i : particle size [mm]
f_i : fraction of # of particles [-]

(Mass mean diameter) $$d_m = \sum x_i m_i = \sum\left(x_i \frac{x_i^{\ 3} f_i}{\sum x_i^{\ 3} f_i}\right) = \frac{\sum x_i^{\ 4} f_i}{\sum x_i^{\ 3} f_i}$$

(Area mean diameter) $$d_a = \sum x_i a_i = \sum\left(x_i \frac{x_i^{\ 2} f_i}{\sum x_i^{\ 2} f_i}\right) = \frac{\sum x_i^{\ 3} f_i}{\sum x_i^{\ 2} f_i}$$

(Length mean diameter) $$d_l = \sum x_i l_i = \sum\left(x_i \frac{x_i\ f_i}{\sum x_i\ f_i}\right) = \frac{\sum x_i^{\ 2} f_i}{\sum x_i\ f_i}$$

(Number mean diameter) $$d_n = \sum x_i n_i = \sum\left(x_i \frac{f_i}{\sum f_i}\right)$$

Ergun equation

$$-\frac{dp}{dz}-\rho_f g=\frac{C_1\mu(1-\varepsilon)^2}{\varepsilon^3 d_p^{\ 2}}V_s+\frac{C_2\rho_f(1-\varepsilon)}{\varepsilon^3 d_p}V_s^{\ 2}$$

Relative permeabilities (K_{rl}, K_{rg}) / passabilities (η_{rl}, η_{rg})
Interfacial friction (F_i)

Momentum equation for 2∅

$$-\frac{dp_l}{dz}=\rho_l g+\frac{\mu_l}{K\cdot K_{rl}}V_{sl}+\frac{\rho_l}{\eta\cdot\eta_{rl}}\left|V_{sl}\right|\cdot V_{sl}-\frac{F_i}{s}$$

$$-\frac{dp_g}{dz}=\rho_g g+\frac{\mu_g}{K\cdot K_{rg}}V_{sg}+\frac{\rho_g}{\eta\cdot\eta_{rg}}\left|V_{sg}\right|\cdot V_{sg}+\frac{F_i}{\alpha}$$

1. Without consideration of interfacial friction

* α : void fraction, s (= 1 - α) : saturation

	K_{rg}	η_{rg}	K_{rl}	η_{rl}	F_i
Reed (R), 1982	α^3	α^5	s^3	s^5	-
Lipinski (L), 1982	α^3	α^3	s^3	s^3	-
Hu & Theofanous (HT), 1991	α^3	α^6	s^3	s^6	-

2. Consideration of interfacial friction

Schulenberg & Müller (SM), 1987

K_{rg}	η_{rg}	K_{rl}	η_{rl}	F_i
α^3	$0.1\alpha^4$ ($\alpha \le 0.3$) α^6 ($\alpha > 0.3$)	s^3	s^5	$350 s^7 \alpha \frac{\rho_l K}{\eta\sigma}(\rho_l - \rho_g) g (\frac{V_{sg}}{\alpha} - \frac{V_{sl}}{s})^2$

Tung & Dhir (TD), 1988

Void fraction	Flow regime	K_{rg}	η_{rg}	K_{rl}	η_{rl}
$\alpha_1 = \min(0.3, 0.6(1-\gamma)^2)$	Bubbly	$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{4/3}\alpha^4$	$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{2/3}\alpha^4$	s^4	s^4
$\alpha_2 \approx 0.52$	Transition	-	-		
$\alpha_3 = 0.6$	Slug	$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{4/3}\alpha^4$	$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{2/3}\alpha^4$		
	Transition	-	-		
$\alpha_4 \approx 0.74$	Annular	$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{4/3}\alpha^3$	$(\frac{1-\varepsilon}{1-\varepsilon\alpha})^{2/3}\alpha^3$		

$(0 < \alpha < \alpha_1)$ **Bubbly:** $C_1 = 18\alpha f, \quad C_2 = 0.34 s^3 \alpha f^2$	$F_i = C_1 \frac{\mu_l}{D_b^2} s V_r + C_2 \frac{((1-\alpha)\rho_l + \alpha\rho_g)}{D_b \varepsilon} s^2 \lvert V_r \rvert V_r$
$(\alpha_1 < \alpha < \alpha_2)$ **Transition**	
$(\alpha_2 < \alpha < \alpha_3)$ **Slug:** $C_1 = 5.21\alpha, \quad C_2 = 0.92 s^3 \alpha$	$F_i = C_1 \frac{\mu_l}{D_b^2} s V_r + C_2 \frac{((1-\alpha)\rho_l + \alpha\rho_g)}{D_b \varepsilon} s^2 \lvert V_r \rvert V_r$
$(\alpha_3 < \alpha < \alpha_4)$ **Transition**	
$(\alpha_4 < \alpha < 1)$ **Annular**	$F_i = \frac{\mu_g}{K \cdot K_{rg}} s V_r + s\alpha \frac{\rho_g}{\eta \cdot \eta_{rg}} \lvert V_r \rvert V_r$

Motivation

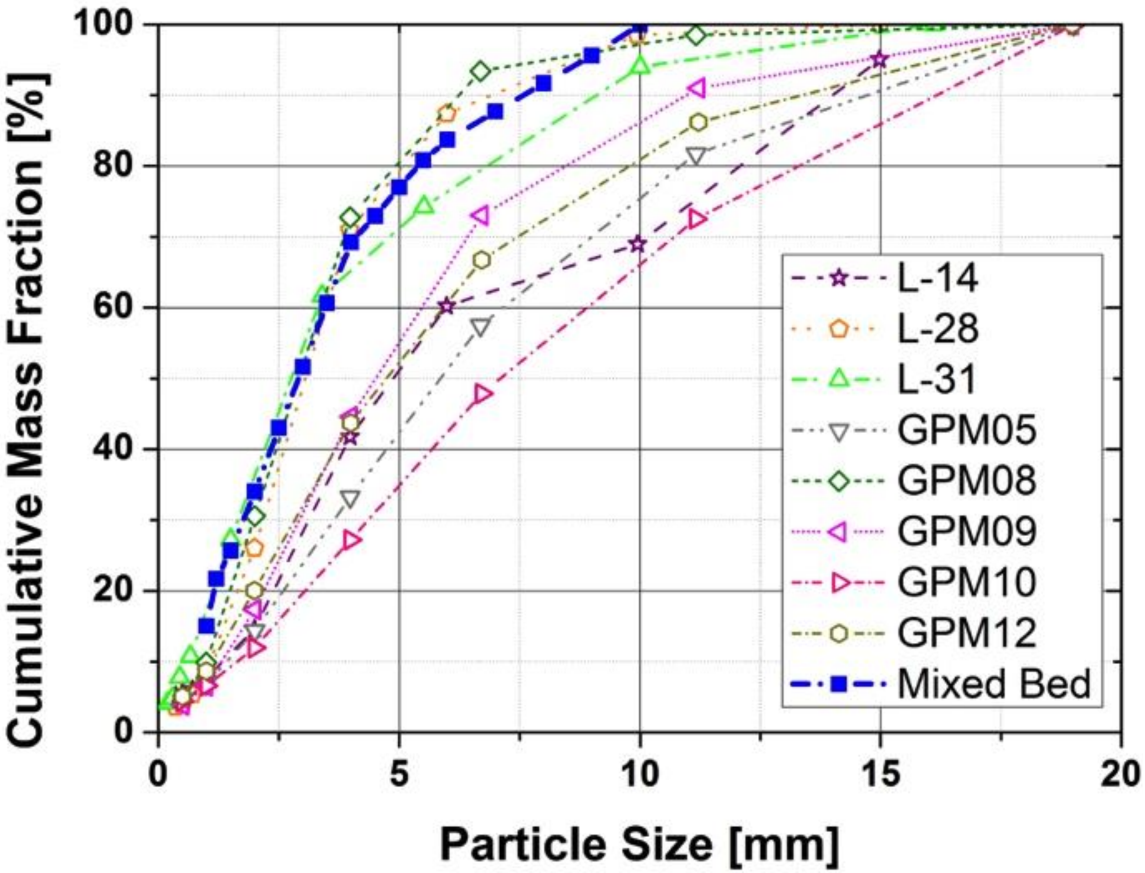
- **Which mean diameter is more suitable to predict frictional pressure drop in particulate debris bed composed of multi-size particles for safety analysis ?**

Objectives

- **To investigate the influence of particle size distribution on pressure gradients of both single-phase air flow and water/air two-phase flow in mixed bed, and the adequacy of suggested mean diameters as the effective particle diameter**

Experimental case

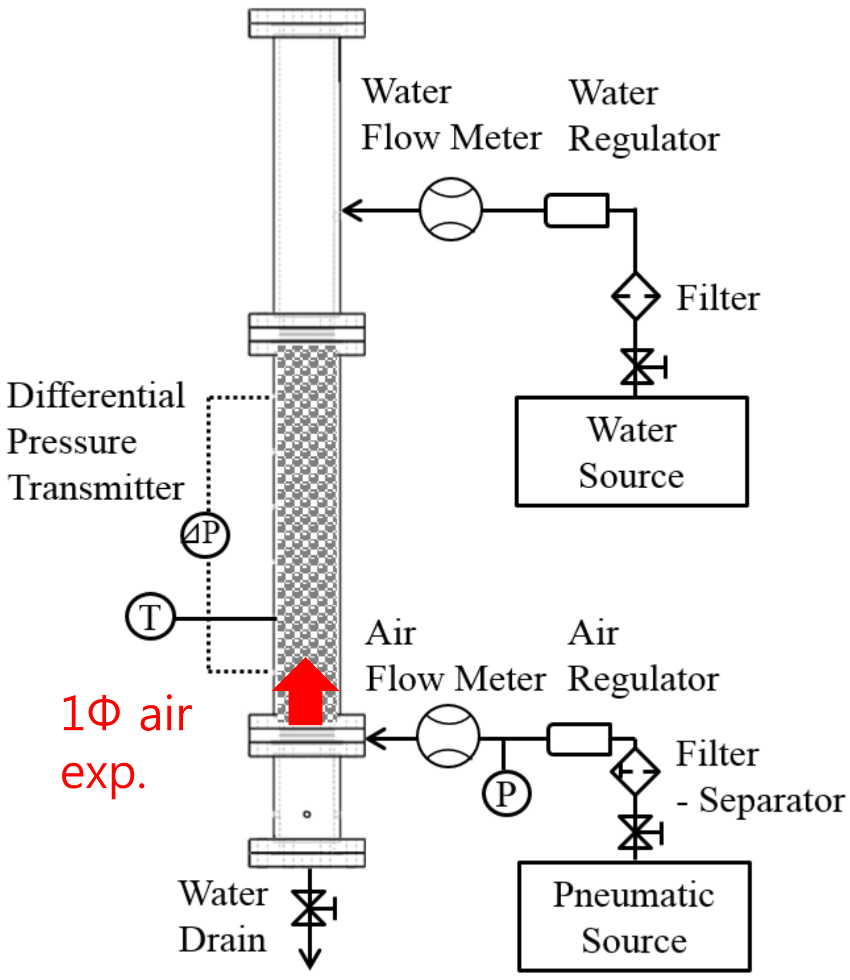
	Material	ε [-]	d_m [mm]	d_a [mm]	d_l [mm]	d_n [mm]
Mixed spherical particle bed	SUS 304	0.312	3.74	2.31	1.55	1.24



Particle Size [mm]	Mass Fraction [%]
1	15.0
1.2	6.7
1.5	4.0
2	8.3
2.5	9.0
3	8.6
3.5	9.0
4	8.6
4.5	3.7
5	4.1
5.5	3.8
6	2.9
7	4.0
8	4.0
9	3.9
10	4.4

Single-phase air flow

PICASSO (**P**ressure drop **I**nvestigation and **C**oolability **ASS**essment through **O**bservation)



[Experimental procedure]

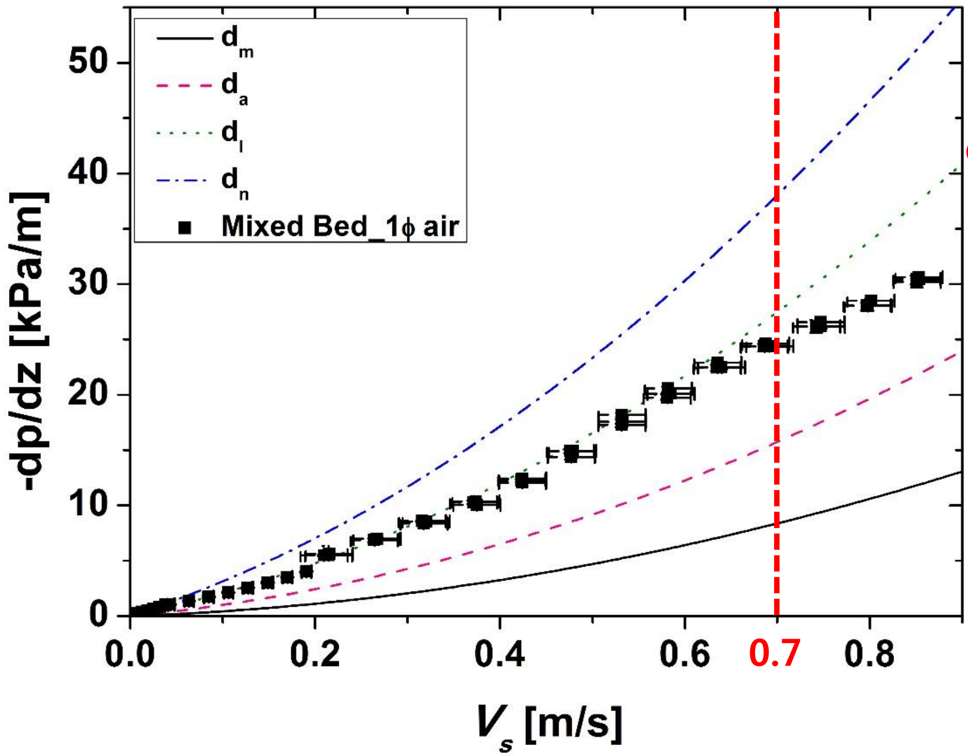
1) **Total mass of particles is measured** for the bed porosity and the mean particle diameter, and then it is **packed in test section**

2) **Upward air** is **injected into the bed**

3) The **flow rate and ΔP measured** (5 mins) when steady-state condition is established

4) The flow rate is changed to another value, and immediately above step (step 3) is **repeated** **(Air: 3 – 375 L/min)**

Comparison of the measured pressure gradients of single-phase air flow in mixed bed with the Ergun equation using various mean diameters



d_n: 1.24 mm

d_l: 1.55 mm

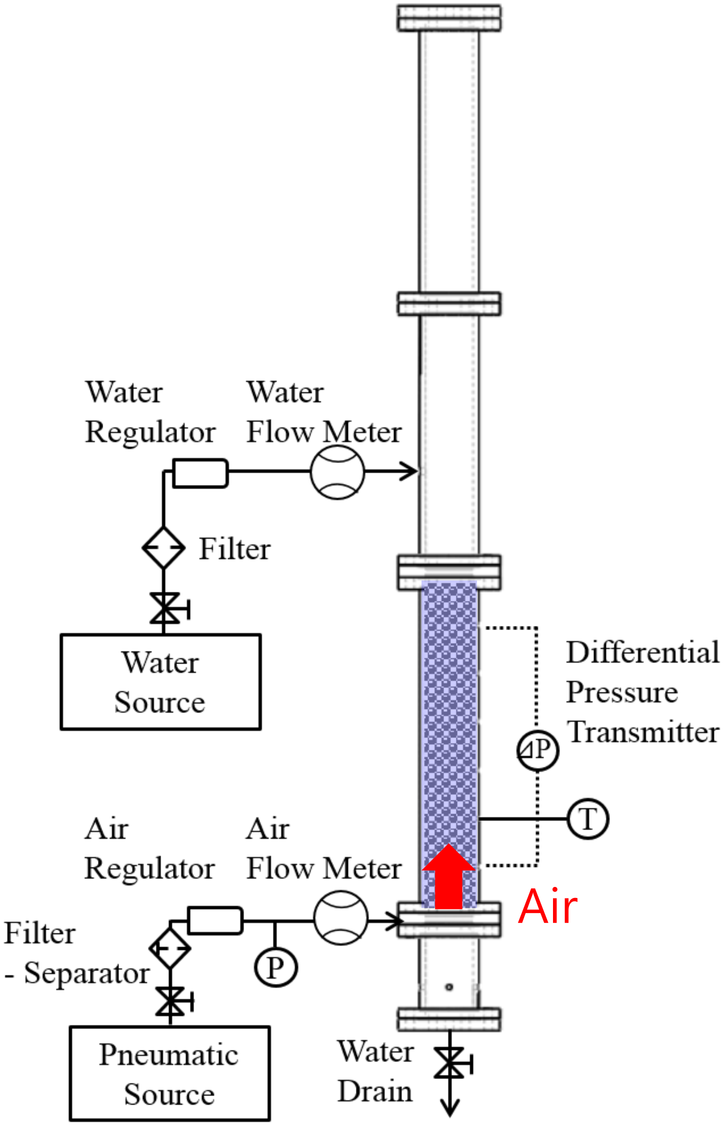
d_a: 2.31 mm

d_m: 3.74 mm

The experimental data is well predicted by the Ergun equation using the length mean diameter, d_l (1.55 mm) in the range of 0 – 0.7 m/s

Two-phase water/air flow

Experimental procedure (2Ø)



1) **Total mass of particles is measured** for the bed porosity and then it is **packed in test section**

2) **The bed and the pressure impulse lines are filled with single-phase water** **(different with 1Ø exp.)**

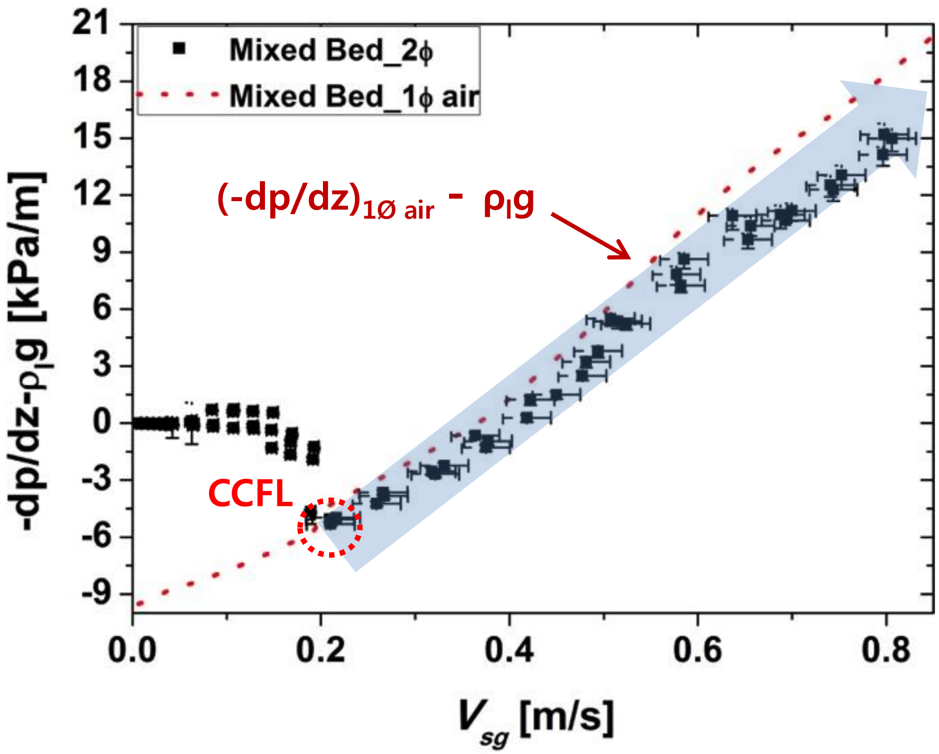
3) **The upward air is injected from the bottom of the bed (no additional water inflow condition)**

4) The **air flow rate** and **ΔP measured** when steady-state condition is established (5 mins)

5) The air flow rate is changed to another value, and immediately above step (step 4) is repeated (**Air: 3 – 375 L/min**)

Results (2Ø water/air flow in mixed bed)

Comparison of measured pressure gradients of water/air 2Φ flow in mixed bed to those of 1Φ air flow reduced by hydrostatic head of water column

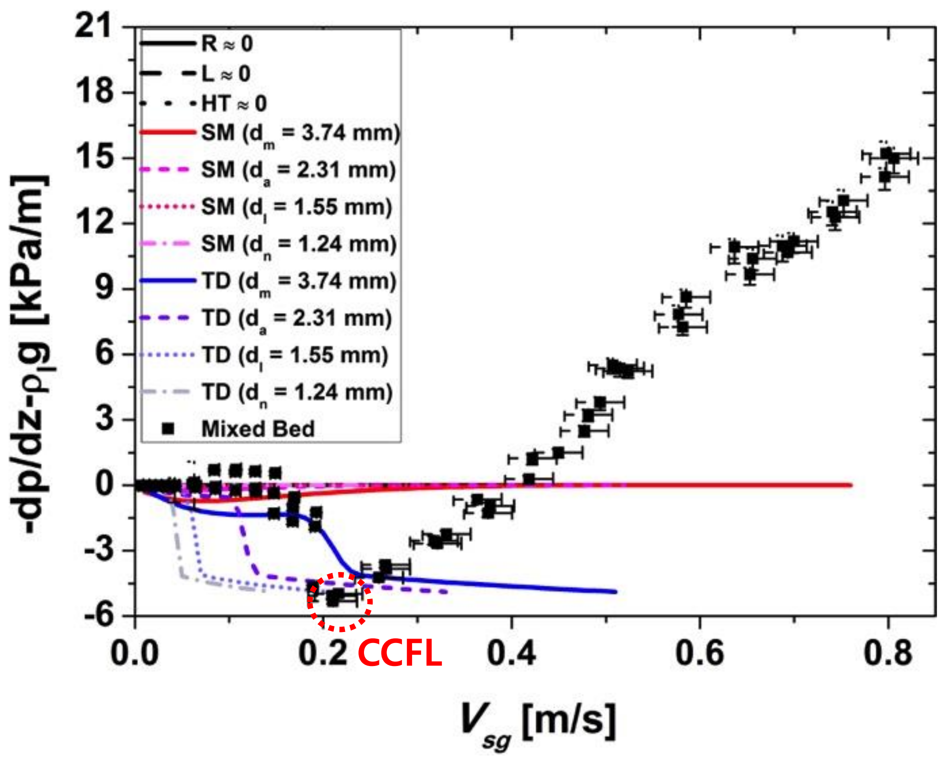


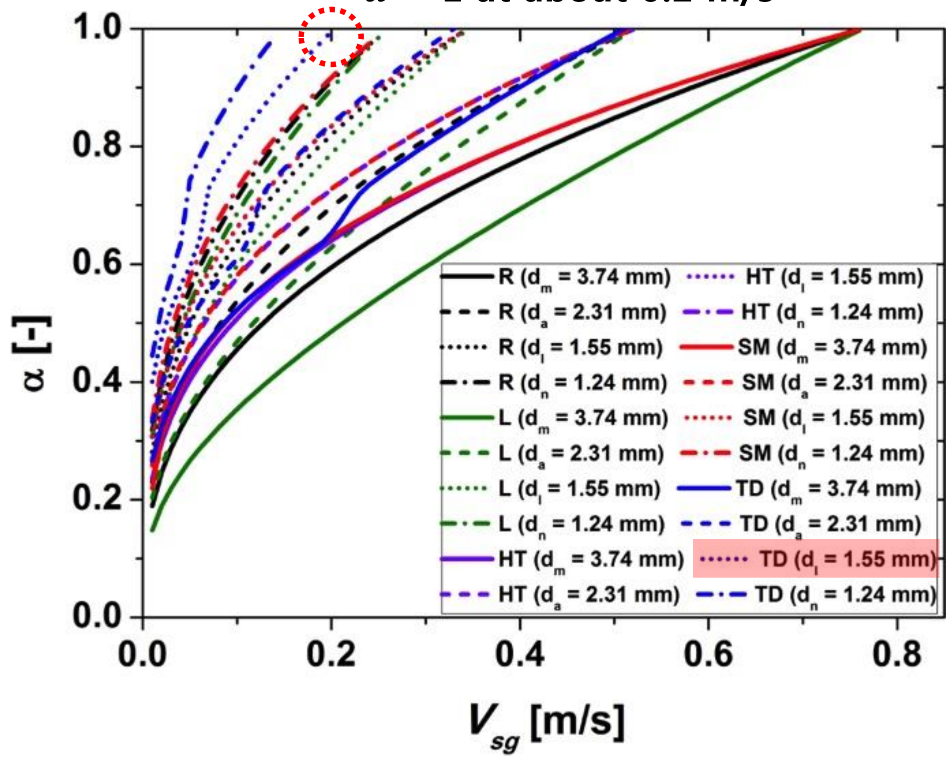
Steeply increasing after reaching the minimum value
: almost upward air flow only

It can be verified that it has **similar trend between them after reaching the minimum value**. It might be explained that there exists almost upward air flow only in the mixed bed though it may be considered that a small proportion of water remains at the surface of particles in the beds

Results (2∅ water/air flow in mixed bed)

Comparison of the measured pressure gradients of two-phase flow in mixed bed to analytical models





Tung & Dhir model with d_l (1.55 mm) can predict the **CCFL** (counter-current flow limitation) at about 0.21 m/s, although it does not match well with the experimental data in the whole range of the superficial air velocity

Conclusion

- **For single-phase air flow through the mixed bed,**
  - **Ergun equation using the length mean diameter (d_l)** predicts the experimental data well at the range of 0 – 0.7 m/s

- **For two-phase water/air flow through the mixed bed,**
  - **Tung & Dhir model using the length mean diameter (d_l)** can predict the **counter-current flow limitation** although it does not predict the measured pressure gradients well for the whole range of the superficial air velocity

Thank you