Experimental Investigation of the Effect of Particle Shape on Frictional Pressure drop in Particulate Debris Bed

Jin Ho Park, Eunho Kim, Hyun Sun Park *

Division of Advanced Nuclear Engineering, POSTECH, Pohang, Republic of Korea

**Corresponding author : hejsunny@postech.ac.kr*

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Background (1)

Ex-vessel corium coolability

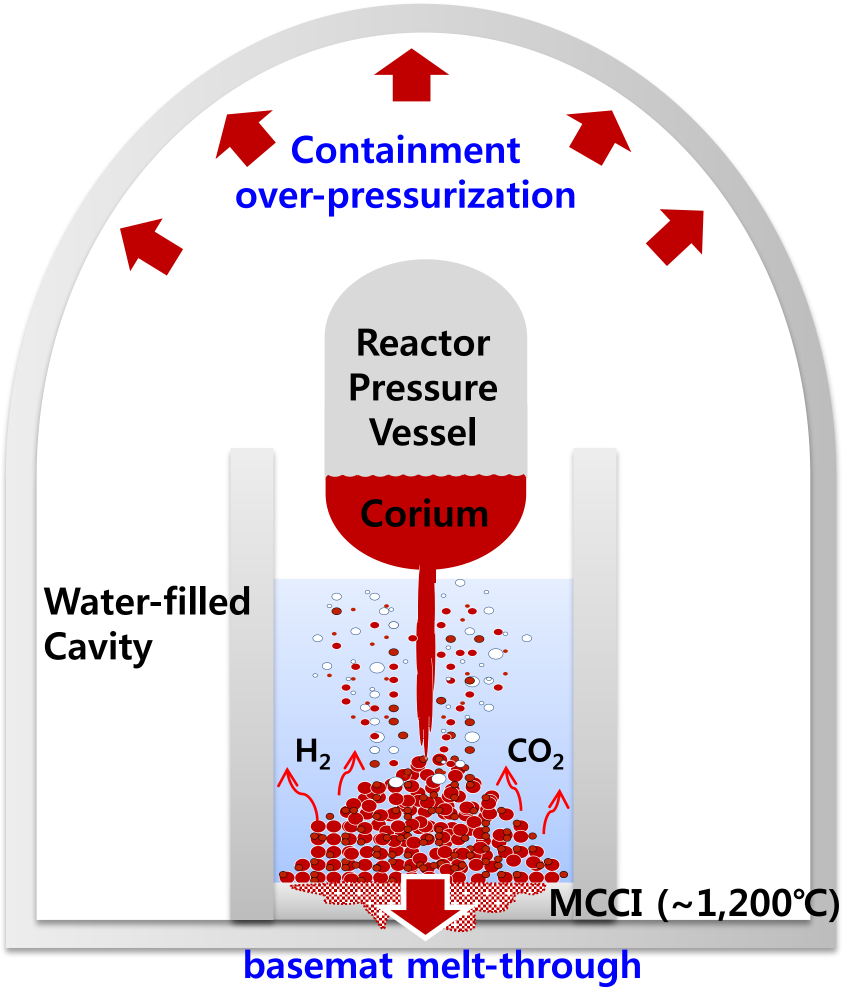


Fig 1. The effect of MCCI on containment integrity

Pending Issue: Assurance of Long-Term Coolability of Internally Heat Generated Bed

Background (2)

Necessary to supply the water into the bed continuously

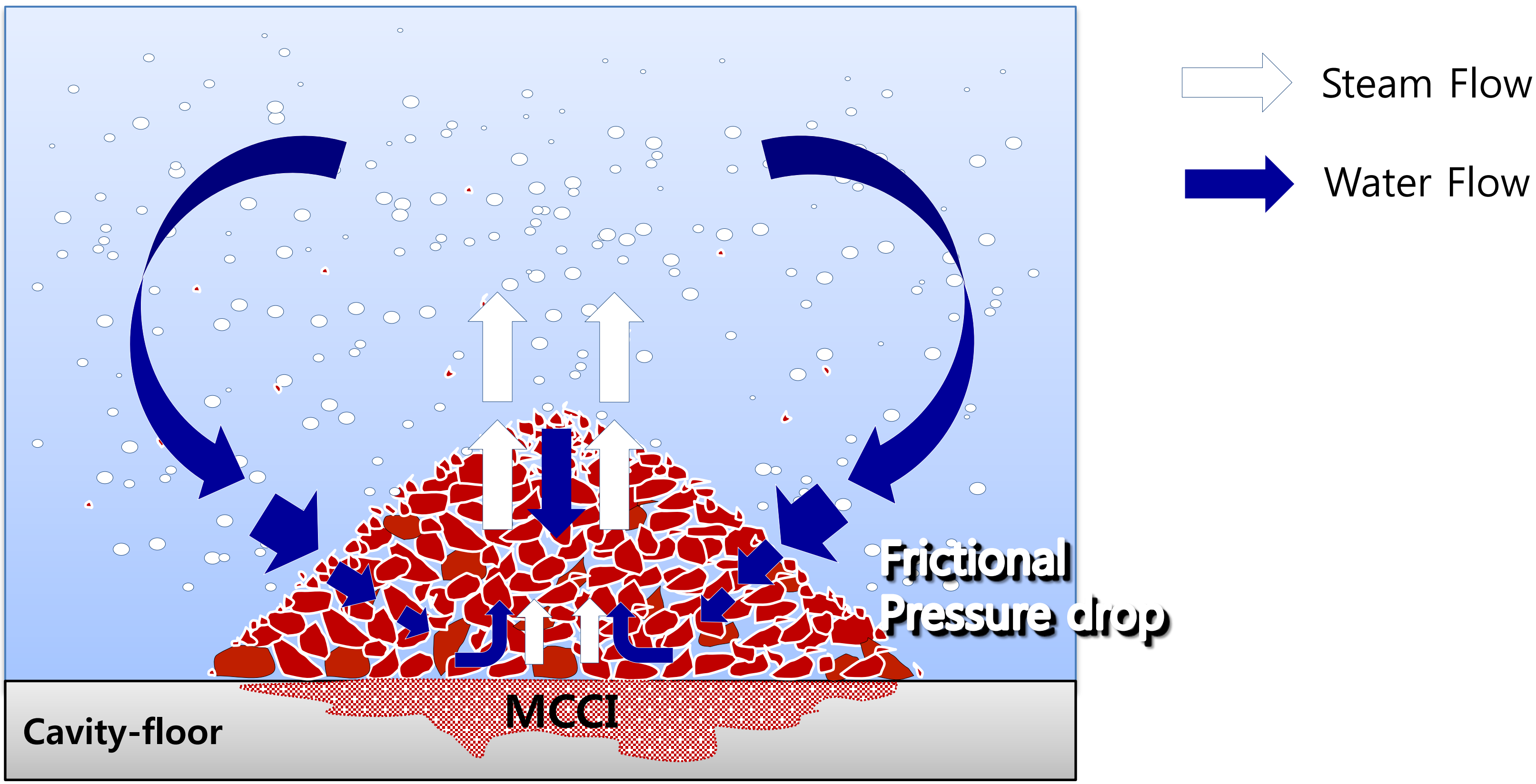


Fig 2. Schematic of ex-vessel melt coolability

Need to understand pressure drop mechanism according to the characteristics of particulate bed and its effects on coolability

Background (3)

Characteristics of Particulate Debris Bed at hypothetical real situation

- **Debris Bed Layer Stratification (Axially / Radially)**
  - Inner region (Large particle, High porosity)
  - Crust region (Small particle, Low porosity)
  - Channeling in bed

- **Heterogeneous bed**
  - Particle size distribution
  - Multi-grain composition

- **Irregular shape**

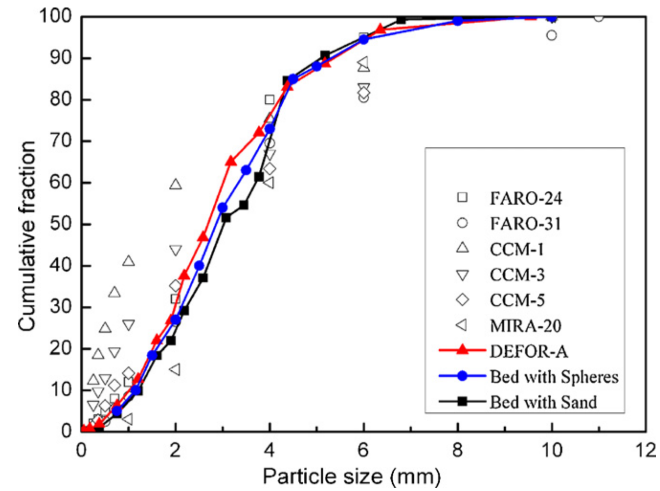


Fig 3. Particle size distribution from FCI tests [1]

Fig 4. Debris beds formed in DEFOR-E test [2]

Models

Ergun equation, 1952 : to predict the pressure loss of single-phase flow in porous media composed of single sized spherical particles

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

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]
C_1 : 150 C_2 : 1.75 (Ergun Constants)

(1) Mean diameter for non-spherical particle

(Sauter mean diameter)

$$d_{sd}=\frac{6V_p}{A_p}$$

(Shape factor)

$$\varphi=\frac{Surface\ of\ sphere\ of\ equal\ volume\ of\ the\ particle}{Surface\ area\ of\ the\ particle}$$

(Equivalent diameter)

$$d_{eq}=\varphi d_{sd}$$

(2) Ergun constants modified

Table 1. Modified Ergun Constants

	C_1	C_2
Ergun, 1952 [3]	150	1.75
Leva, 1959 [4]	200	1.75
Handley and Heggs, 1968 [5]	368	1.24
Macdonald et al., 1979 [6]	180	1.8
Foumeny et al., 1996 [7]	130	$\frac{d_t/d_m}{0.335d_t/d_m+2.28}$

Objectives

To study the effect of particle shape on frictional pressure drop in particulate debris bed

- Which mean diameter is more useful to predict frictional pressure drop in particulate debris bed composed of non-spherical particles ?

Sauter mean diameter (d_{sd}) or Equivalent diameter (d_{eq}) ?

To investigate the adequacy of using the mean diameter for non-spherical particles as the effective particle diameter

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

Test case

Table 2. Test case

Bed	Material	Particle Shape	Particle Size [mm]		Total mass of particles	Porosity	Shape Factor	d_{sd} [mm]	d_{eq} [mm]
			Diameter	Length					
1	SUS304	Sphere	**2**	-	26.08 kg	0.400	1	2	2
2		Cylinder	1.98	4.95			0.805	2.48	**2**
3		Sphere	**5**	-	26.37 kg	0.393	1	5	5
4		Cylinder	4.98	13.9			0.789	6.34	**5**

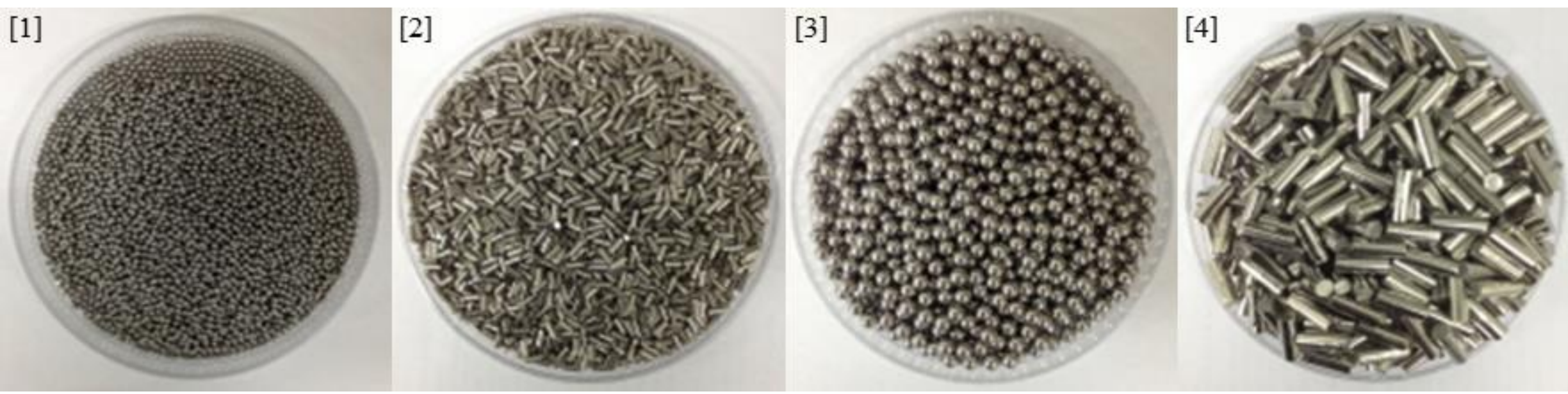


Fig 5. The sample of particles in each bed

Experimental Facility (PICASSO)

Pressure drop Investigation and Coolability ASSessment through Observation

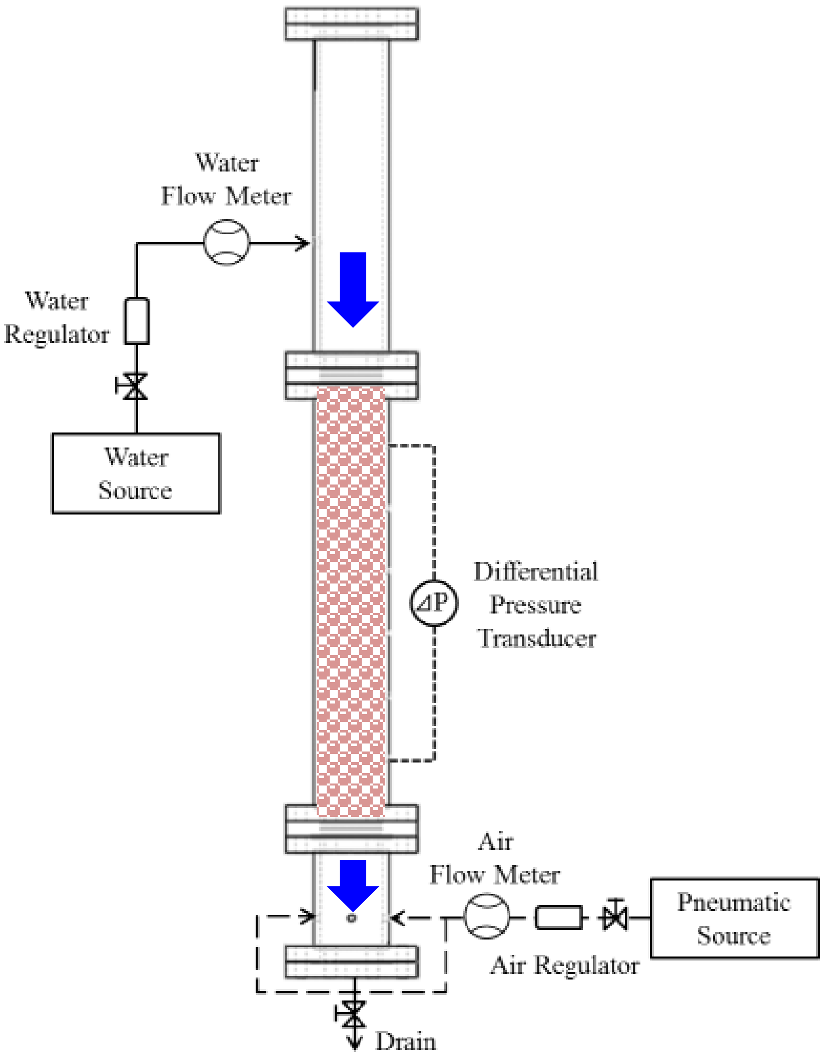


Fig 6. Schematic diagram of the experimental facility

[Test section]

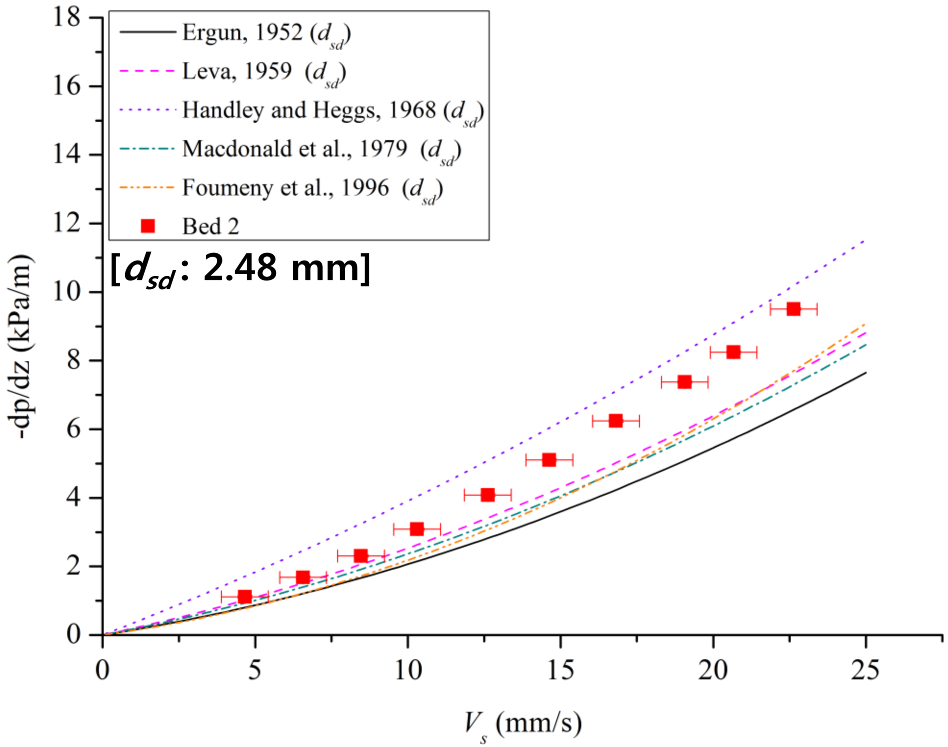
Inner Diameter : 0.1 m / Length : 0.7 m

Distance between pressure tap: 0.5 m

[Experimental procedure]

1) Total mass of particles is measured
2) Particles packed in water-filled test section
3) Downward water is injected at the top of the test section (top-flooding)
4) The water flow rate and the pressure drop are measured when steady-state condition is established
5) The water flow rate is changed to another value, and immediately above step are repeated

Results (Bed 2: Cylinder, D:1.98 mm, L:4.95 mm)



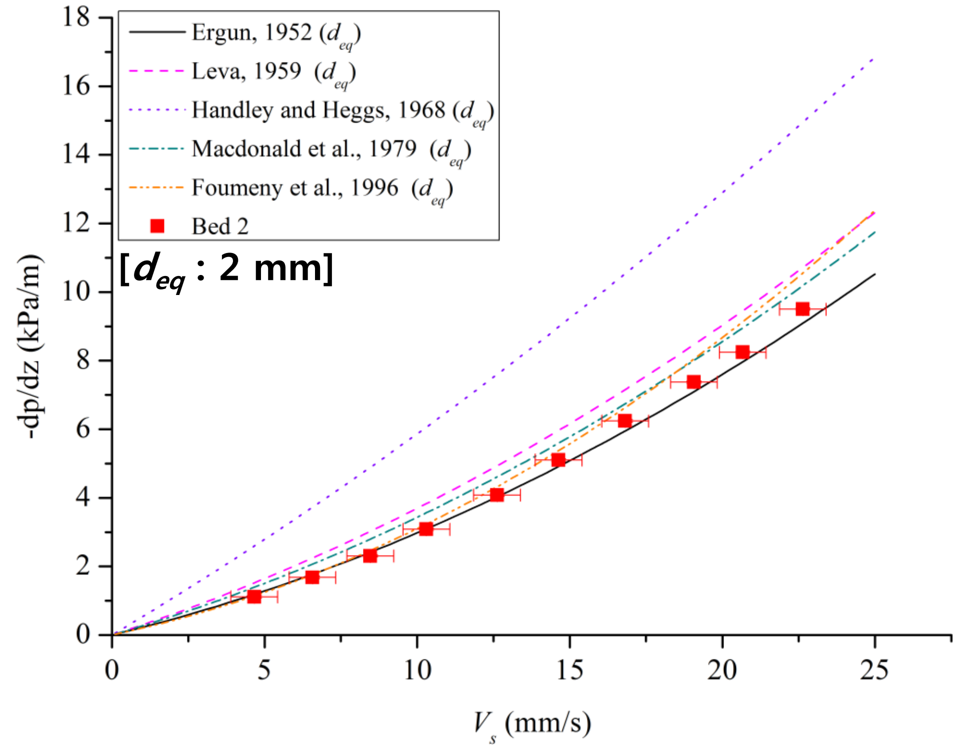
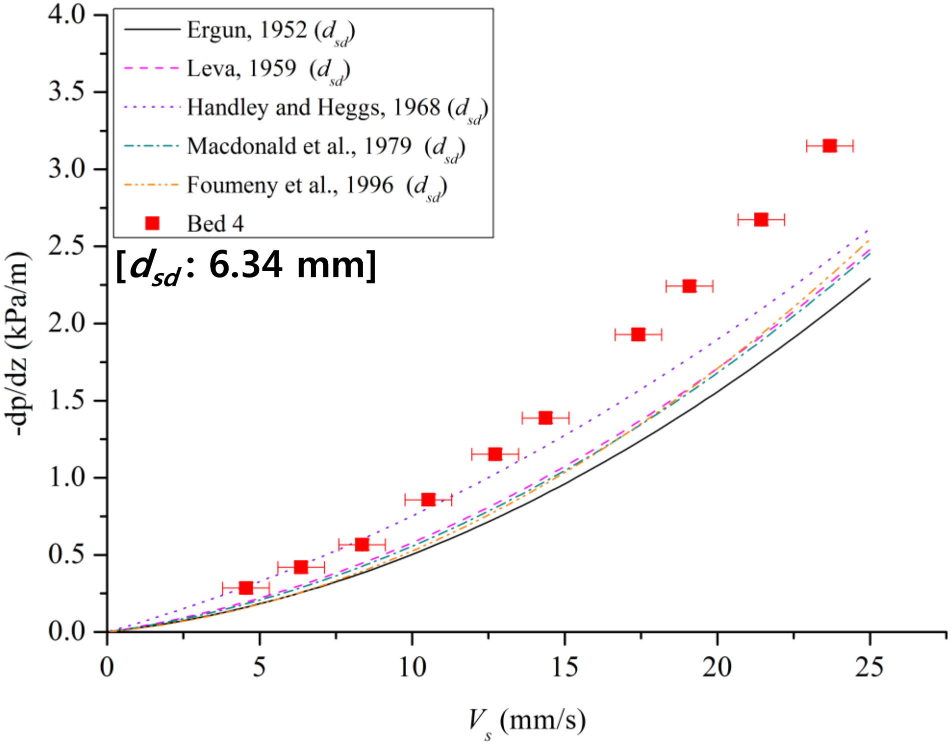


Table 3. Mean deviation between the experimental data for Bed 2 and the models

Model	Mean diameter	
	d_{sd}	d_{eq}
Ergun, 1952	30 %	**3.8 %**
Leva, 1959	16 %	22 %
Handley and Heggs, 1968	26 %	88 %
Macdonald et al., 1979	21 %	14 %
Foumeny et al., 1996	24 %	**6.9 %**

Most models predict the experimental data for Bed 2 within 22 % except the Handley and Heggs model when ED is applied rather than SMD

Results (Bed 4: Cylinder, D:4.98 mm, L:13.9 mm)



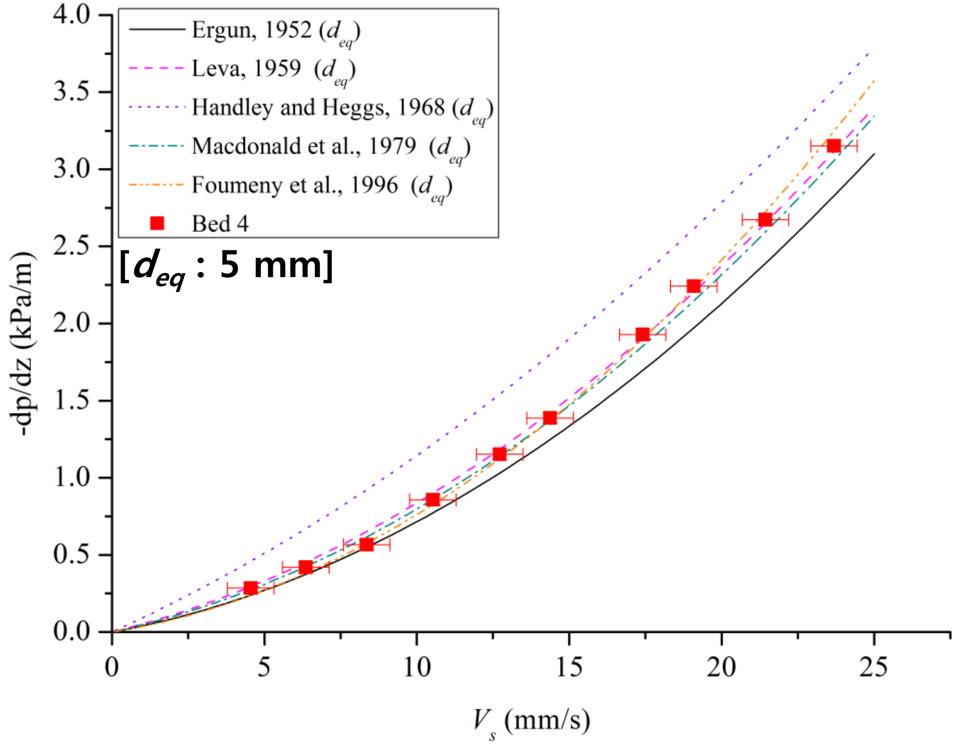
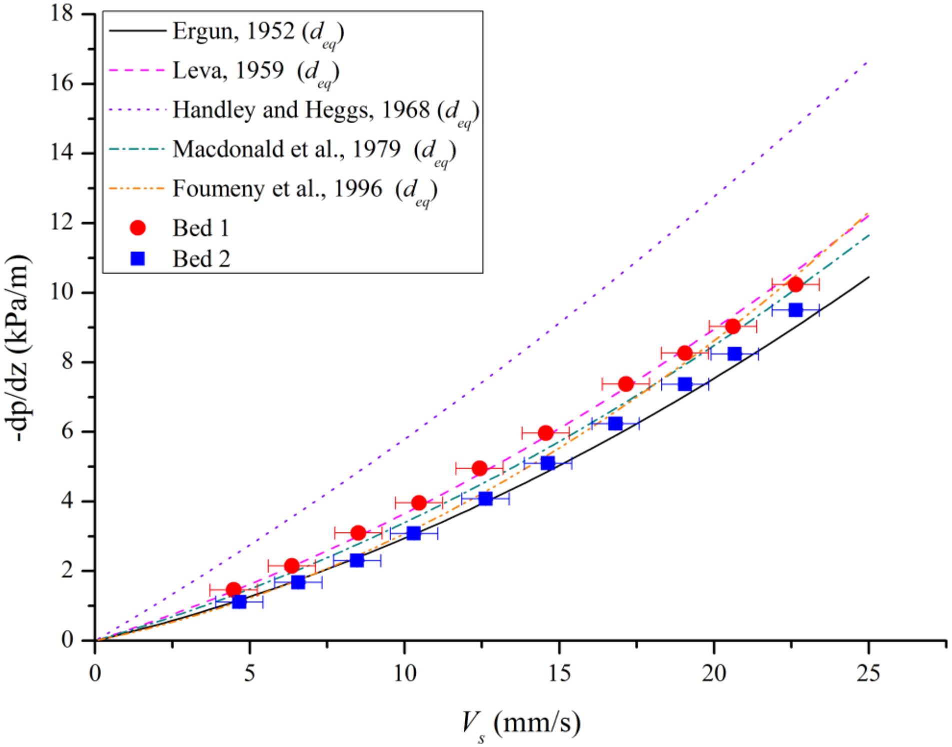


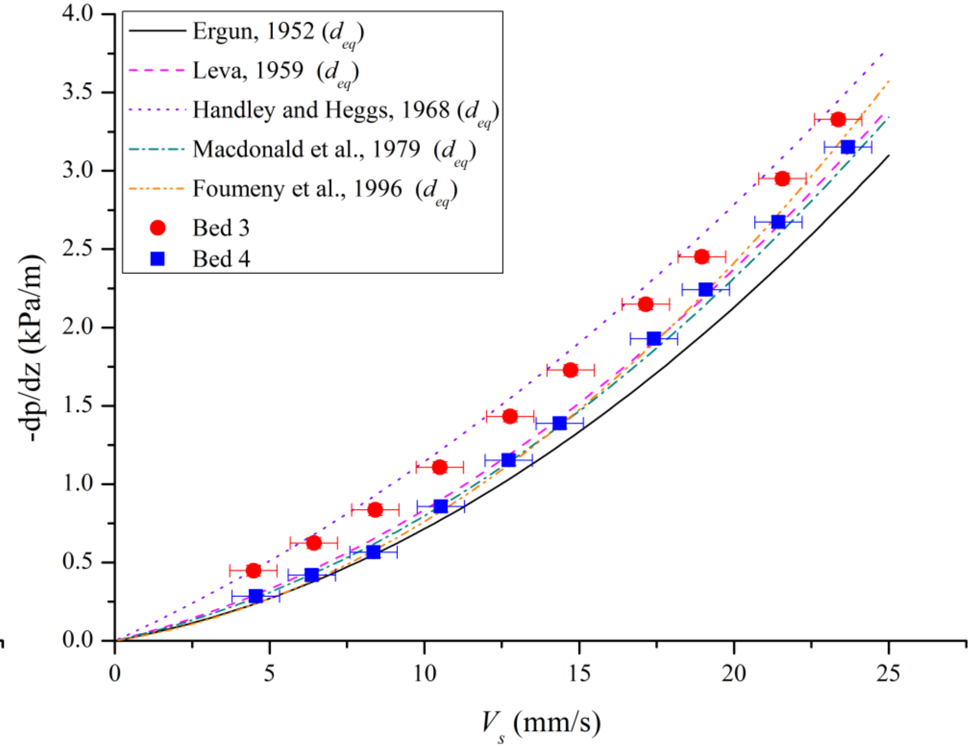
Table 4. Mean deviation between the experimental data for Bed 4 and the models

Model	Mean diameter	
	d_{sd}	d_{eq}
Ergun, 1952	36 %	**10 %**
Leva, 1959	28 %	**4.1 %**
Handley and Heggs, 1968	13 %	35 %
Macdonald et al., 1979	30 %	**3.1 %**
Foumeny et al., 1996	32 %	**4.2 %**

Most models predict the experimental data for Bed 4 within 10 % except the Handley and Heggs model when ED is applied rather than SMD

Results (Adequacy of mean diameter)





[Bed 1 & 2] d_{eq} : 2 mm, ε : 0.4

[Bed 3 & 4] d_{eq} : 5 mm, ε : 0.393

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

Mean deviation **0.78 kPa/m (17 %)** **0.24 kPa/m (20 %)**

Pressure drop in non-spherical particle bed is lower than that of spherical particle bed, but its deviation are within accuracy of models

Summary

Cylindrical particles (Bed 2 and Bed 4), the models predict the experimental data well within 22 % except the Handley and Heggs model when ED is applied to the models

- However, the well matched model may differ slightly depending on the beds. The measured pressure drops in Bed 2 are well predicted by the Ergun equation (3.8 %) in comparison, the measured pressure drops in Bed 4 are well predicted by the Macdonald et al. model (3.1 %)

Pressure drop in non-spherical particle bed is lower than that of spherical particle bed, but its deviation are within accuracy of models

Reference

[1] Li, Liangxing, Weimin Ma, and Sachin Thakre. "An experimental study on pressure drop and dryout heat flux of two-phase flow in packed beds of multi-sized and irregular particles." Nuclear Engineering and Design 242 (2012): 369-378.

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[4] LEVA, Max. Fluidization. McGraw-Hill, 1959.

[5] Handley, D., and P. J. Heggs. "Momentum and heat transfer mechanisms in regular shaped packings." ***Transactions of the Institution of Chemical Engineers and the Chemical Engineer*** **46.9 (1968): T251.**

[6] Macdonald, I. F., et al. "Flow through porous media-the Ergun equation revisited." ***Industrial & Engineering Chemistry Fundamentals*** **18.3 (1979): 199-208.**

[7] Foumeny, E. A., et al. "Elucidation of pressure drop in packed-bed systems." Applied Thermal Engineering 16.3 (1996): 195-202.

Thank you