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

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1. Introduction

In progression of severe accident in nuclear power plants, it is important to assure the coolability of the relocated corium in the reactor cavity due to vessel failure. Since under this circumstance, concrete ablation and over-pressurization caused by molten corium concrete interaction (MCCI) may threaten the integrity of containment, the final barrier of the defense-in-depth, to prevent the release of radioactive material to environment. To ensure the long-term cooling of corium in the reactor cavity, it is important to ensure the coolant ingression into the internally heat generated corium debris bed which is governed by pressure drop in porous media. For this reason, it is necessary to understand pressure drop mechanisms in porous bed to verify the feasibility of water penetration into particulate debris bed.

According to the previous investigations on molten fuel-coolant interaction (FCI) experiments, it was found that quenched particulate debris bed was composed of irregular shape particles (Karbojian et al., 2009 [1]; Magallon, 2006 [2]). Therefore, empirical or semi-empirical models based on the Ergun equation (Ergun, 1952 [3]) for single-phase flow in porous media composed of single sized spherical particle were developed to consider the effect of particle shape on frictional pressure drop by means of adding a shape factor (Eq. 7) (Li and Ma, 2011 [4]) or modifying the Ergun constants etc. (Leva, 1959 [5], Handley and Heggs, 1968 [6], Macdonald, 1979 [7], Foumeny et al., 1996 [8]).

However, many models may have limitation to predict pressure drop in porous media consisted of irregular shape particles although the Sauter mean diameter (SMD) or the Equivalent diameter (ED) is applied as the effective diameter using a shape factor to express non-sphericity. Because flow path may be changed by particle shape although the porosity of bed composed of the same mean diameter is equal to that of bed composed of spherical particles. Therefore, the plausibility of using the mean diameter for non-spherical particles as the effective particle diameter would be verified.

2. Model

Above mentioned the Ergun equation (Eq. 1) which is the momentum conservation equation presented pressure loss of flow in porous media is expressed by

$$-\frac{dp}{dz}=\frac{150\mu(1-\varepsilon)^2}{\varepsilon^3 d_p{}^2}V_s+\frac{1.75(1-\varepsilon)\rho_f}{\varepsilon^3 d_p}V_s{}^2 \qquad (1)$$

In here, 150 and 1.75 are the empirical Ergun constants and μ and ρ_f are the dynamic viscosity and the density of the fluid respectively and $-dp/dz$ represents pressure loss in porous media which has the porosity of ε (Eq. 2) and composed of spherical particle diameter of d_p when the superficial velocity is V_s . In the case of porosity, it can be calculated by measuring the total mass of particles ($\sum m_p$) in the test section and the density of particle (ρ_p) since the volume of the test section (V_t) is already known.

$$\varepsilon = 1 - \frac{\sum m_p/\rho_p}{V_t} \qquad (2)$$

According to the Ergun equation, permeability (Eq. 3) which is the measure of the flow conductance of the matrix and passability (Eq. 4) which is the quality of being passable respectively, are calculated by

$$K=\frac{\varepsilon^3(d_p)^2}{150(1-\varepsilon)^2} \qquad (3)$$

$$\eta=\frac{\varepsilon^3 d_p}{1.75(1-\varepsilon)} \qquad (4)$$

Based on this Ergun equation, the equation to predict pressure drop in particulate bed which is composed of irregular shape particles is expressed by Eq. 5. The equation is that the mean diameter of irregular shape particle considered the shape factor (SMD or ED) is substituted into the Ergun equation as the effective diameter (d_{eff}) instead of the spherical particle diameter.

$$-\frac{dp}{dz}=\frac{150\mu(1-\varepsilon)^2}{\varepsilon^3 d_{eff}{}^2}V_s+\frac{1.75(1-\varepsilon)\rho_f}{\varepsilon^3 d_{eff}}V_s{}^2 \qquad (5)$$

SMD of particle (Eq. 6) is calculated by multiplying a shape factor (Eq. 7) to the volume-surface mean diameter, d_{vs} (Eq. 8), where V_p is the volume of particle and A_p is the surface area of particle, and ED (Eq. 9) is calculated by multiplying a shape factor to SMD.

$$\varphi d_{vs} = \varphi \frac{6V_p}{\varphi A_p} = \frac{6V_p}{A_p} = \frac{6}{S_v} = d_{sd} \quad (6)$$

$$\varphi = \frac{A_{sp}}{A_p} = \frac{\pi^{\frac{1}{3}}(6V_p)^{\frac{2}{3}}}{A_p} \quad (7)$$

$$d_{vs} = \frac{6V_p}{A_{sp}} = \frac{6V_p}{\varphi A_p} \quad (8)$$

$$d_{eq} = \varphi d_{sd} \quad (9)$$

In the case of modified Ergun constants, Table I. lists the constants suggested by previous researchers.

Table I: Modified Ergun Constants

Model	C_1	C_2
Ergun, 1952	150	1.75
Leva, 1959	200	1.75
Handley and Heggs, 1968	368	1.24
Macdonald et al., 1979	180	1.8
Foumeny et al., 1996	130	$\frac{d_t / d_{sd}}{0.335 d_t / d_{sd} + 2.28}$

3. Experimental Facility Setup and Procedure

3.1 The Experimental Facility Setup: PICASSO

To study the effect of particle shape on frictional pressure drop in particulate debris bed, an experimental investigation on single-phase frictional pressure drop of water was conducted at the PICASSO (Pressure drop Investigation and Coolability ASSessment through Observation) facility, POSTECH in Korea.

Fig. 1 shows the schematic diagram of experimental facility. The experimental facility consists of regulators, water and air flow meter, differential pressure transducer and the test section.

The cylindrical test section made by Plexiglas with the inner diameter of 100 mm and the height of 700 mm has 6 holes on the side wall to measure pressure drop in packed bed. It has a 100 mm difference of level between them. To hold particle bed, the Plexiglas mesh which have the diameter of 2 mm and the pitch of 3 mm is located in the bottom of the test section, and there are two cylindrical Plexiglas tubes to supply water into the test section at the upper part of the test section and to inject air into the test section at the lower part of the test section respectively. However, it is mentioned that air is not used in this study.

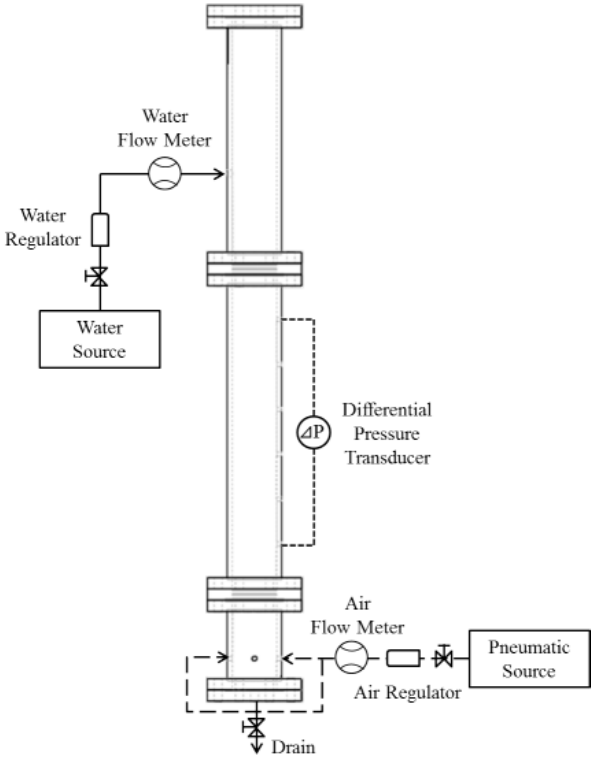

Fig. 1. Schematic diagram of the experimental facility.

3.2 The Experimental Procedure

With the experimental facility, the single phase flow experiment using water was performed to investigate the effect of particle shape on frictional pressure drop in particulate bed.

Table II: Test Cases

Bed	Shape	Particle Size (mm)		φ	ε	d_{sd} (mm)	d_{eq} (mm)
		D	L				
1	Sphere	2	-	1	0.400	2	2
2	Cylinder	1.98	4.95	0.805	0.400	2.48	2
3	Sphere	5	-	1	0.393	5	5
4	Cylinder	4.98	13.9	0.789	0.393	6.34	5

Table II. lists the test cases, total 4 cases. All of particles are SUS304 stainless steel with the density of 7,900 kg/m^3 and the particle size of spherical particles for Bed 1 and 3 are 2 mm and 5 mm respectively. In the case of irregular shape particles (Bed 2 and 4), cylindrical shape is chosen and its sizes (diameter, D and length, L) are deduced to have the same ED with that of spherical particle. Fig. 2 shows the sample of particles in each bed.

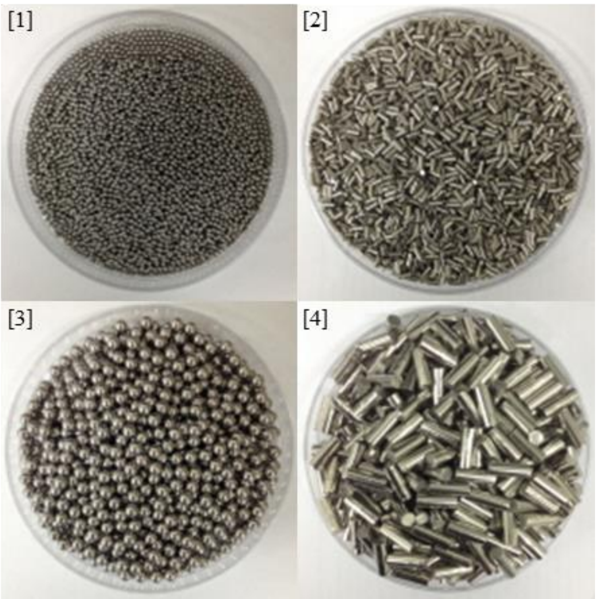

Fig. 2. The sample of particles in each bed.

The experimental procedure is as in the following. At the beginning of the test, the total mass of particles is measured and then particles are packed in the water-filled test section. In here, it is mentioned that the total mass of cylindrical shape particles is equal to that of spherical particles (Bed 1 and 2: 26.08 kg, Bed 3 and 4: 26.37 kg) and the cylindrical particles (Bed 2 and 4) are packed in different manner compared with spherical particles (Bed 1 and 3) to obtain the same bed porosity with that of spherical particles. In this study, spherical particles are packed by slowly pouring small amounts of particles and cylindrical particles are packed by slowly pouring small amounts of particles, stirring particles in the test section and shaking the vertical test section repeatedly with reference to random close packing (RCP) and random loose packing (RLP) methods (Nemec and Levec, 2005 [9]). Secondly, downward water is injected at the top of the test section (top-flooding) in ambient condition. Thirdly, the water flow rate and the pressure drop are measured when steady-state condition is established. Finally, the water flow rate is changed to another value, and immediately above step are repeated.

Before conducting the experiment, all of measurement devices are calibrated. The water flow rate is measured by PF3W Series manufactured by SMC Korea with the range of 2~16 LPM and its accuracy of ±3% and the pressure drop was measured by Model 230 manufactured by SETRA with the range of 0~2 PSID and the accuracy of ±0.25%. In the case of differential pressure transducer, it is manually installed to eliminate gravity effect and valve manifolds are used to equalize pressure between high and low pressure ports.

4. The Experimental Results and Discussion

4.1 Comparison between SMD and ED

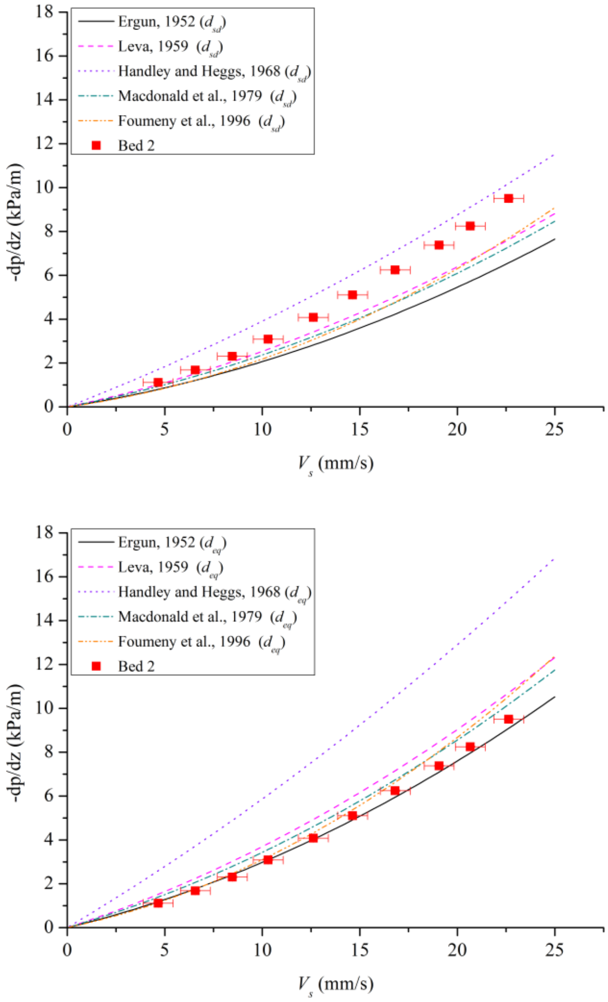

Fig. 3. Comparisons of the experimental data for Bed 2 with the models (Upper: SMD, Lower: ED).

Fig. 3 shows the comparisons of the experimental data for Bed 2 with the models which is listed in Table I. Upper one shows that the experimental data is compared with the models applied with SMD (2.48 mm) of cylindrical particles in Bed 2. On the other hand, lower one shows that the experimental data is compared with the models applied with ED (2 mm) of cylindrical particles in Bed 2.

Table III: Mean deviation between the experimental data for Bed 2 and the models

Model	Mean diameter	
	d_{sd}	d_{eq}
Ergun, 1952	30.15 %	3.81 %
Leva, 1959	15.54 %	22.11 %
Handley and Heggs, 1968	25.94 %	88.16 %
Macdonald et al., 1979	20.64 %	14.05 %
Foumeny et al., 1996	24.03 %	6.86 %

Table III. lists the mean deviation the experimental data for Bed 2 with the models when SMD or ED is applied. As a result of this, most of the models predict the experimental data for Bed 2 within 22.11 % except the Handley and Heggs model when ED is applied rather than SMD. Besides the Ergun equation using ED of the cylindrical particle with 1.98 mm in diameter and 4.95 mm in length predicts well the experimental data for Bed 2 (3.81 %).

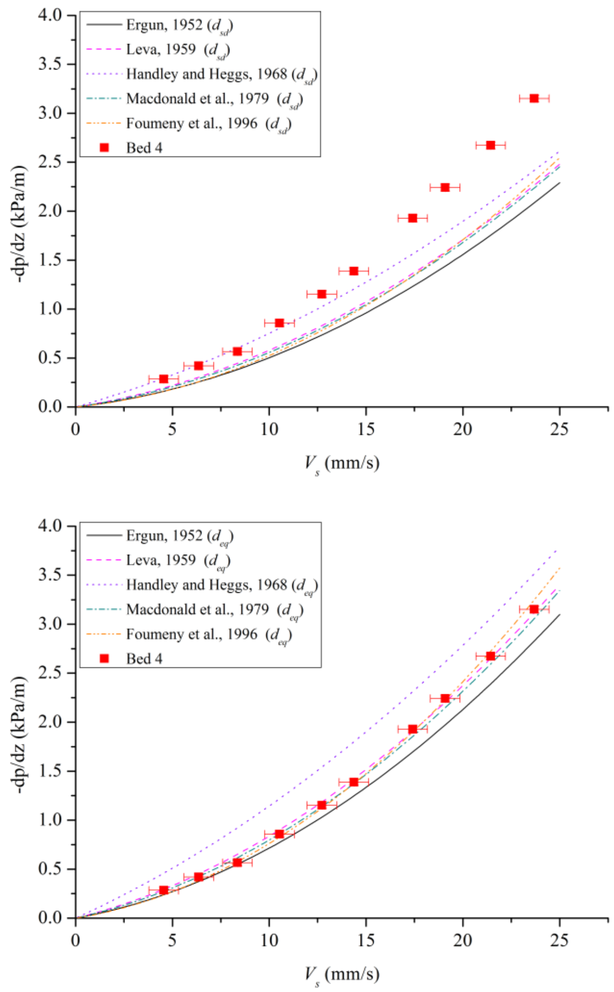

Fig. 4. Comparisons of the experimental data for Bed 4 with the models (Upper: SMD, Lower: ED).

Fig. 4 shows comparisons of the experimental data for Bed 4 with the models. Upper one shows that the experimental data is compared with the models applied with SMD (6.34 mm) of cylindrical particles in Bed 2 and lower one shows that experimental data is compared with the models applied with ED (5 mm).

Table IV. lists the mean deviation between the experimental data for Bed 4 and the models when SMD or ED is applied to the models. As a result of this, most of the models predict the experimental data within 10.48 % except the Handley and Heggs model when ED is applied rather than SMD. Besides the Macdonald et al. model using ED of the cylindrical particle with 4.98 mm in diameter and 13.9 mm in length predicts well the experimental data for Bed 4 (3.08 %).

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

Model	Mean diameter	
	d_{sd}	d_{eq}
Ergun, 1952	36.27 %	10.48 %
Leva, 1959	27.73 %	4.14 %
Handley and Heggs, 1968	12.84 %	35.30 %
Macdonald et al., 1979	30.05 %	3.08 %
Foumeny et al., 1996	32.38 %	4.17 %

Thus, most of the models applied ED than SMD are predicted frictional pressure drop in particulate bed composed of non-spherical particles well with the water flow range of 2~10 LPM. Because ED of non-spherical particles which is multiplying a shape factor to SMD may be more representing the complex geometry in packed bed composed of non-spherical particles than SMD.

As conclusion for cylindrical particle beds in this study, it is similar with the result of KTH (Li and Ma, 2011 [4]). The result of KTH is that the models predict the frictional pressure drop well when ED is adopted at high flow rate (V_s > 7mm). However, there is a difference between the experimental data in our study and that of KTH. The experimental data of KTH using the cylindrical particles with the diameter of 3 mm and the length of 6 mm is well predicted by the LEVA model. In comparison, the Ergun equation and Macdonald et al model predict the experimental data well for Bed 2 and Bed 4 respectively. Therefore, it would be needed to analyze more in the future.

4.2 Plausibility of ED

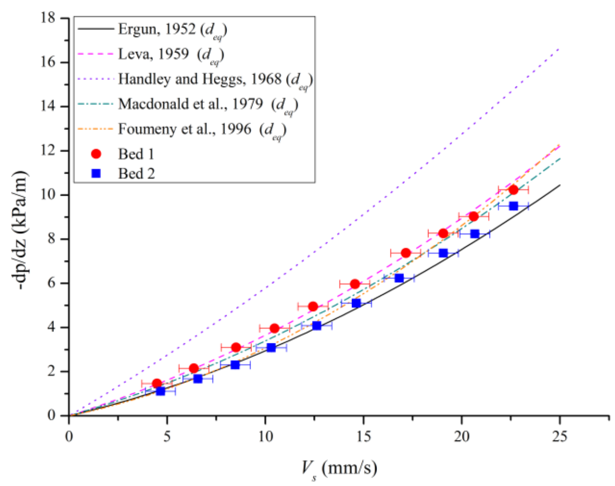

Fig. 5. Comparisons of the experimental data for Bed 1 and 2 (porosity: 0.4) with the models.

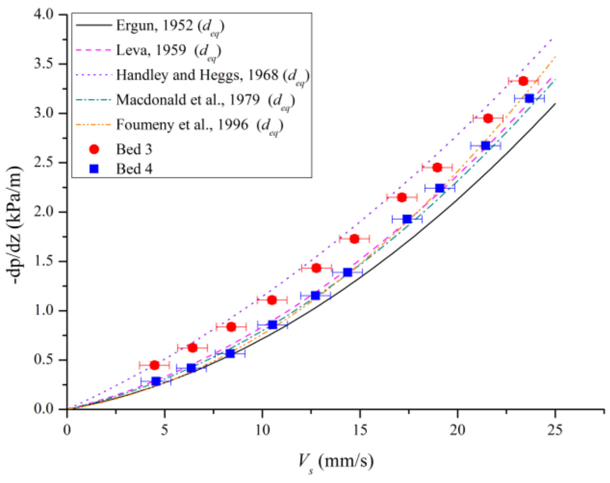

Fig. 6. Comparisons of the experimental data for Bed 3 and 4 (porosity: 0.393) with the models.

Fig. 5 and Fig. 6 show the comparisons of the experimental data for Bed 1 and Bed 2 (Fig. 5), Bed 3 and 4 (Fig. 6) with the models respectively.

With the reference to Eq. 5, the experimental data must have the same value of frictional pressure drop when the bed parameters (porosity, mean diameter) and the fluid parameters (dynamic viscosity, density and superficial velocity) are equal. However, the value of frictional pressure drop in the bed composed of cylindrical particles (Bed 2 and Bed 4) is lower than that of spherical particles (Bed 1 and Bed 3). Since it may have lower frictional drag in bed composed of cylindrical particles than spherical particles structurally.

5. Conclusion

An experimental investigate on single-phase frictional pressure drop of water in packed bed was conducted in the transparent cylindrical test section with the inner diameter of 100 mm and the height of 700 mm to study the effect of particle shape on frictional pressure drop in porous media. This paper reports the experimental data for spherical particles with the diameter of 2 mm and 5 mm and cylindrical particles with ED of 2 mm and 5 mm. And also, the experimental data compared with the models to predict frictional pressure drop in particulate bed. The conclusions are summarized as follows.

(1) As a result of the experiment to measure frictional pressure drop in particulate bed composed of cylindrical particles (Bed 2 and Bed 4), the models predict the experimental data well within 22.11 % 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 (3.81 %) in comparison, the measured pressure drops in Bed 4 are well predicted by the Macdonald et al. model (3.08 %)

(2) According to the existing models, the experimental data must have the same value of frictional pressure drop when porosity, mean diameter of bed and fluid parameters (dynamic viscosity, density and superficial velocity) are equal. However, the value of frictional pressure drop in bed composed of cylindrical particles (Bed 2 and 4) is lower than that of spherical particles (Bed 1 and 3).

6. Acknowledge

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