Experimental Investigation of the Effect of Spherical Particle Size Distribution 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. 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. Therefore, it is important to ensure the coolant ingression into the internally heat generated debris bed which is governed by pressure drop in debris bed to assure the long-term cooling of debris bed on the cavity floor. For this reason, it is necessary to understand the pressure drop mechanism in porous bed that can be characterized by physical parameters that include porosity, particle morphology, particle size distribution etc.

According to previous investigations on molten fuel-coolant interaction (FCI) experiment, the settled particulate debris bed after fuel-coolant interaction were stratified and it was composed of multi-sized particles with irregular shape. (Karbojian et al., 2009 [1]; Magallon, 2006 [2]). Among these characteristics of debris bed, this study focused on the effect of particle size distribution on frictional pressure drop in bed.

2. Model

The Ergun equation [3], a momentum conservation equation for single-phase flow in porous media composed of single-sized spherical particles is

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

where 150 and 1.75 are empirical Ergun constants, μ [Pa·s] and ρ_f [kg/m^3] are the dynamic viscosity and the density of the fluid, respectively and *-dp/dz* [Pa/m] represents pressure loss in porous media according to the superficial velocity V_s [m/s]. In the case of porous media, it is characterized by the bed porosity, ε (Eq. 2) and the particle diameter, d_p [m]. The porosity is calculated by the total mass of particles in a test section, $\sum m_p$ [kg]; the density of particles, ρ_p [kg/m^3] and the known volume of a test section, V_t [m^3].

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

Based on the Ergun equation, the frictional pressure drop in multi-sized particles bed is predicted by using various mean particle diameters as the effective diameter instead of single-sized spherical particle diameter in Eq. 1. Those are such as mass mean diameter, d_m; area mean diameter, d_a; length mean diameter, d_l, and number mean diameter, d_n. These mean diameters for multi-sized particles are defined as Eq. 3 – Eq. 6

$$d_m = \sum x_i m_i = \sum(x_i\frac{x_i^{\,3} f_i}{\sum x_i^{\,3} f_i}) = \frac{\sum x_i^{\,4} f_i}{\sum x_i^{\,3} f_i} \quad (3)$$

$$d_a = \sum x_i a_i = \sum(x_i\frac{x_i^{\,2} f_i}{\sum x_i^{\,2} f_i}) = \frac{\sum x_i^{\,3} f_i}{\sum x_i^{\,2} f_i} \quad (4)$$

$$d_l = \sum x_i l_i = \sum(x_i\frac{x_i\ f_i}{\sum x_i\ f_i}) = \frac{\sum x_i^{\,2} f_i}{\sum x_i\ f_i} \quad (5)$$

$$d_n = \sum x_i n_i = \sum(x_i\frac{f_i}{\sum f_i}) \quad (6)$$

where x_i is the particle size, and the f_i is the fraction of number of particles in mixed bed, and the parameters m_i, a_i, l_i and n_i are size distribution functions by mass, area, chord length, and number of the particles, respectively [4].

The frictional pressure drop in bed can be plotted against the particle Reynolds number, Re_p (Eq. 7) which is for single-phase flow in the bed. In here, area mean diameter, d_a is used to calculate particle Reynolds number.

$$\mathrm{Re}_p = \frac{\rho_f V_s d_a}{\mu(1-\varepsilon)} \quad (7)$$

3. Experiment

3.1 Experimental Facility

To study the effect of the size distribution of spherical particles on frictional pressure drop in mixed bed, an experiment using single-phase water was conducted at the PICASSO (Pressure drop Investigation and Coolability ASSessment through Observation) facility, POSTECH in Korea.

Fig. 1 shows the schematic of the experimental facility. It consists of regulators, flow meters, a differential pressure transmitter and the test section for holding a particle bed. The cylindrical test section made of Acrylic with the inner diameter of 100 mm and the height of 700 mm has 6 pressure ports on the side wall with 100 mm intervals. To hold particle bed, the Acrylic meshes with the diameter of 2 mm and the pitch of 3 mm are located at the top and the bottom of the test section respectively, and there are two cylindrical Acrylic tubes to supply water into the upper part of the test section and to inject air into the lower part of the test section. It is mentioned that air is not used in this study.

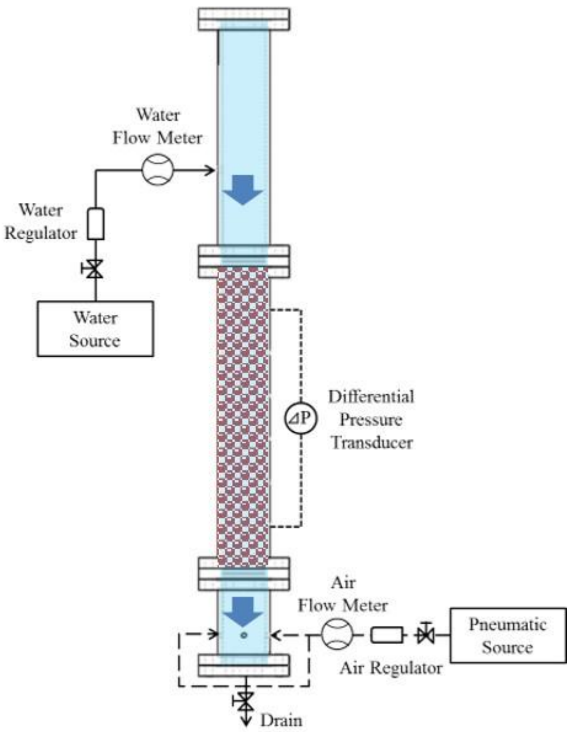

Fig. 1. Schematic of the experimental facility.

3.2 Experimental Condition

The experiment using single-phase water was performed to investigate the effect of particle size distribution on frictional pressure drop in mixed bed.

Fig. 2 shows the particle size distributions of previous studies from FCIs experiment [5], Bed 5 of KTH [4], and this study. The spherical particle sized distribution in mixed bed (POSTECH) is similar to that of Bed 5 (KTH) published in 2011 [4]. Mixed bed is composed of multi-sized spheres whose sizes are varied from 1 mm to 10 mm and its particle size distribution is as listed in Table I and its sample is in Fig. 3.

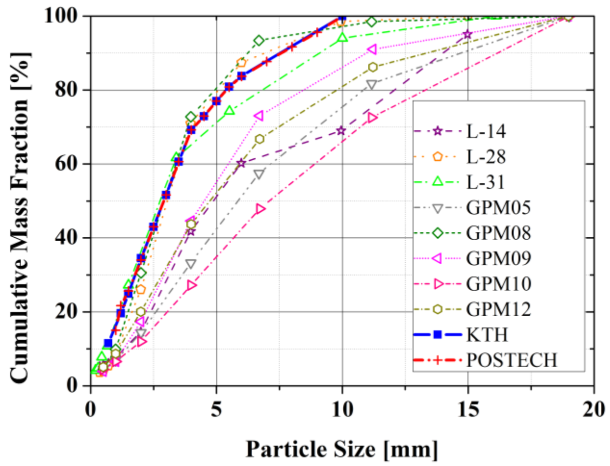

Fig. 2. Particle size distributions of previous studies [4, 5] and this study.

Table I: Particle size distributions in Bed 5 of KTH [4] and this study

KTH		POSTECH	
Particle Size [mm]	Cumulative Mass Fraction [%]	Particle Size [mm]	Cumulative Mass Fraction [%]
0.7	11.5	1	15.0
1.2	19.6	1.2	21.7
1.5	24.9	1.5	25.7
2	34.5	2	34.0
2.5	43.0	2.5	43.0
3	51.6	3	51.6
3.5	60.6	3.5	60.6
4	69.2	4	69.2
4.5	72.9	4.5	72.9
5	77	5	77.0
5.5	80.9	5.5	80.8
6	83.8	6	83.7
7	83.8	7	87.7
8	83.8	8	91.7
9	83.8	9	95.6
10	100	10	100

Table II. lists data of Bed 5 of KTH [4] and mixed bed. In this study, the material of all of spherical particles is stainless steel (SUS304) with the density of 7,930 kg/m^3 and bed porosity is 0.312. Various mean particle diameters for mixed bed are calculated by using Eq. 3 – Eq. 6, and the effective mean diameter of mixed bed, d_e is deduced by using measured frictional pressure drops and the Ergun equation.

Table II: Data of Bed 5 of KTH [4] and mixed bed

	KTH	POSTECH
ε	0.34	0.312
d_m [mm]	3.97	3.74
d_a [mm]	2.12	2.31
d_l [mm]	1.18	1.55
d_n [mm]	0.9	1.24
d_e [mm]	1.82 ($Re_p < 7$) 1.22 ($Re_p > 7$)	1.69 ($Re_p < 7$) 1.85 ($Re_p > 7$)
Re_p	0 – 35	0 – 70

Fig. 3. Sample of multi-sized spherical particles in mixed bed.

3.3 Experimental Procedure

The experimental procedure is as in the following. At the beginning of the test, the total mass of particles in each size is measured to obtain the cumulative mass fraction and the bed porosity, and then the particles are packed in the test section and water is filled in the test section from below the bed to eliminate accumulated void in bed with about 16 L/min. Second, water is injected downward at the top of the test section (top-flooding). Third, the water flow rate and the pressure drop in bed are measured for 3 minutes after steady-state condition is established. Finally, the water flow rate is changed to another value, and immediately above step is repeated from 0.15 to 9.5 L/min. In this study, the experiment was conducted 3 times.

Before conducting the experiment, all of measurement devices were calibrated. The water flow rate is measured by turbine type flow meters, FLR1000 series by OMEGA and its accuracy of ±1% full span, and the pressure drop in bed is measured by Rosemount 3051S series with the range of -62l to 623 mbar and its accuracy of ±0.025% full span. In the case of pressure transmitter, its range is changed from -300 to 300 mbar by using HART protocol.

4. Experimental Results and Discussion

4.1 Experimental Results

The frictional pressure drops of water flow in Bed 5 of KTH according to particle Reynolds number are as plotted in Figs. 4(a) and 5(a) with predicted data by the Ergun equation, using the mean particle diameters. Bed 5 of KTH is composed of multi-sized sphere (0.7 mm – 10 mm) and its porosity is 0.34. The cumulative mass fraction and its mean diameters are listed in Table I and Table II.

As shown in Figs. 4(a), the prediction of the Ergun equation using the area mean diameter (2.12 mm) is comparable with the experimental data of the frictional pressure drops when the particle Reynolds number is less than 7. In Fig. 5(a), measured frictional pressure drops are well predicted by the Ergun equation applying the length mean diameter (1.18 mm) at a $Re_p > 7$.

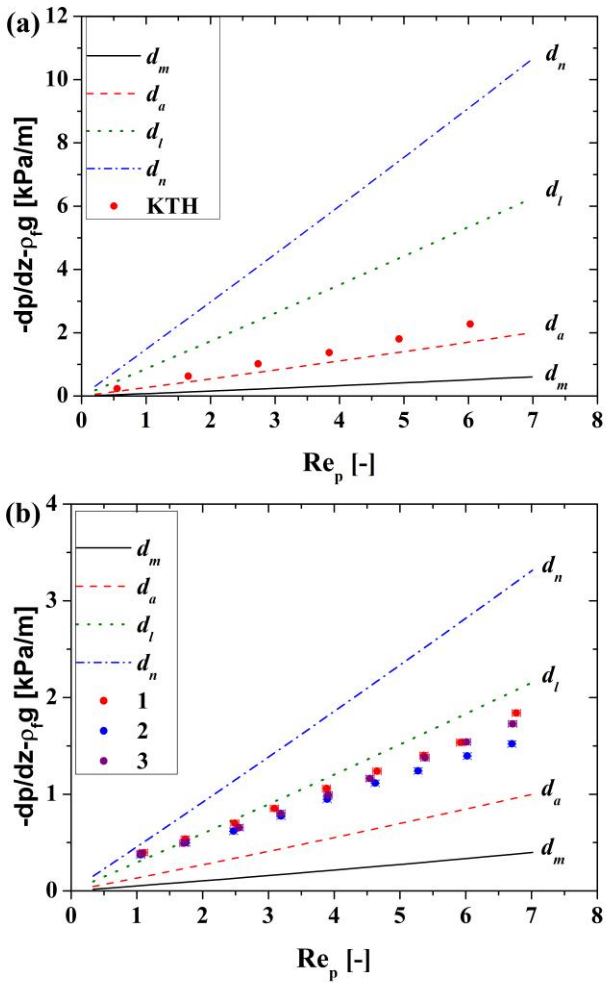

Fig. 4. Frictional pressure drops of water flow at $Re_p < 7$: (a) Bed 5 of KTH, (b) mixed bed in this study.

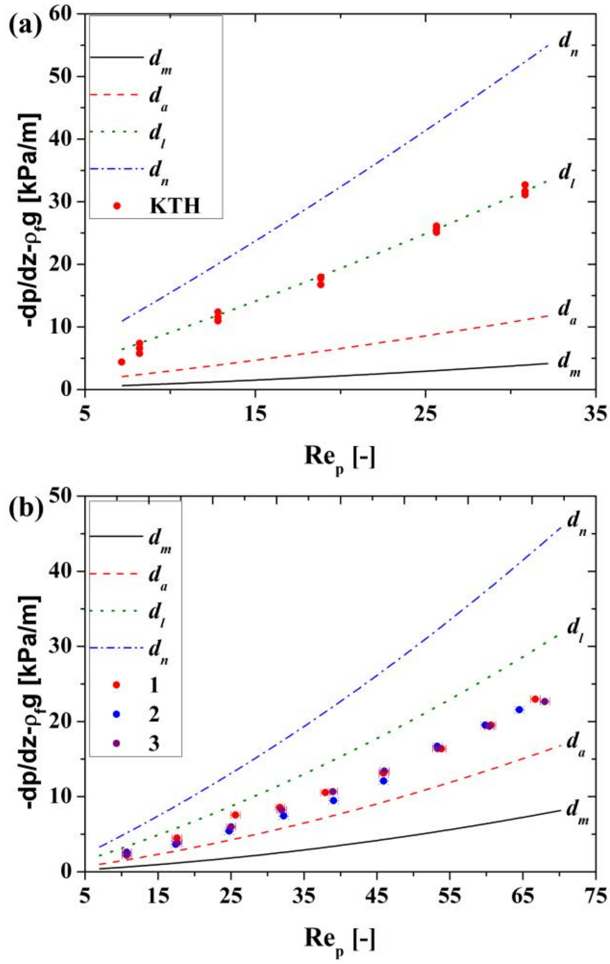

Fig. 5. Frictional pressure drops of water flow at $Re_p > 7$: (a) Bed 5 of KTH, (b) mixed bed in this study.

Figs. 4(b) and 5(b) show the comparison of the measured frictional pressure drops in mixed bed to the Ergun equation applying each mean diameter. When the particle Reynolds number is less than 7 as illustrated in Fig. 4(a), measured frictional pressure drops in mixed bed with the effective diameter of 1.69 mm is close to the prediction of the Ergun equation using the length mean diameter (1.55 mm). In contrast, it is predicted by the value (1.85 mm) between the length mean diameter (1.55 mm) and the area mean diameter (2.31 mm) after the particle Reynolds number is higher than 7.

4.2 Discussion

As shown in Fig. 2, the cumulative mass fraction in mixed bed has approximately similar trend to that of Bed 5 of KTH. However, as listed in Table II, the bed porosity and the mean particle diameters (d_m, d_a, d_l, d_n) are different because of the difference of chosen spherical particle sizes and those mass fractions (Fig. 6). Specifically, the mass fractions of particle sizes whose size ranges from 3 mm to 6 mm are approximately same between Bed 5 of KTH and mixed bed in this study. On the contrary to this, the mass fractions of particle sizes with the range from 0.7 mm to 2.5 mm, and from 7 mm to 10 mm are different although the cumulative mass fractions correspond closely (d_p < 2.5 mm : 43%; and 7 mm < d_p < 10 mm : 16.2 – 16.3% as shown in Table I). Therefore, mean particle diameters calculated by Eq. 3 – Eq. 6 are different, even though the cumulative mass fractions are almost similar trend.

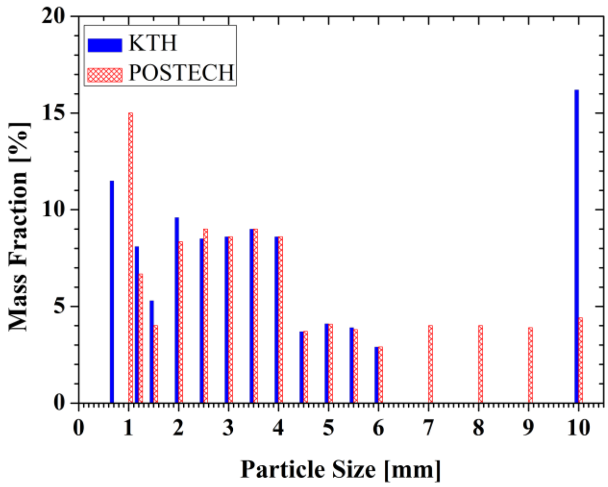

Fig. 6. Mass fractions of each particle size in Bed 5 of KTH and mixed bed of POSTECH.

The results of comparisons between measured frictional pressure drops in mixed bed and predictions by the Ergun equation with the mean particle diameters, the measured frictional pressure drops in mixed bed are well predicted when the length mean diameter (1.55 mm) is adopted before the particle Reynolds number is lower than 7 as illustrated in Fig. 4(b), contrast to the result of KTH which is the area mean diameter is more suitable. Besides, it also has different trend when the particle Reynolds number is higher than 7 that the effective diameter in mixed bed is 1.85 mm which is the value between the length mean diameter (1.55 mm) and the area mean diameter (2.31 mm). On the other hand, the effective diameter in Bed 5 of KTH is 1.22 mm and it is close to the length mean diameter (1.18 mm). It may be that the fractions of number of each particle size in mixed bed and the bed porosity are changed if chosen particle sizes and its mass fractions are different, nevertheless, the same cumulative mass fraction is introduced because flow paths may be changed by the fraction of number of particles and the porosity in bed affecting to hydrodynamic resistance.

5. Conclusions

The experiment using single-phase water was conducted to investigate the effect of spherical particle size distribution on frictional pressure drop in mixed bed. This study reports the experimental data for measured frictional pressure drops in bed according to the particle Reynolds number. It is composed of multi-sized spherical particles whose sizes are varied from 1 mm to 10 mm. Besides, the experimental data is compared to the Ergun equation with the mean particle diameters (mass, area, length, and number mean diameters). The results of this study are also compared to those of KTH published in 2011 [4]. The conclusions are summarized as follows.

The calculated mean particle diameters can be changed according to chosen particle sizes and those mass fractions even though the cumulative mass fractions are almost similar trend. As results of obtaining the effective diameter in mixed using measured frictional pressure drops and the Ergun equation, it is close to the length mean diameter when the particle Reynolds number is lower than 7, however, it has the value between the length mean diameter and the area mean diameter when the particle Reynolds number is higher than 7. It is contrast to the results of KTH that the area mean diameter is more suitable at the lower particle Reynolds number and the length mean diameter is well predict frictional pressure drops after the particle Reynolds number is higher than 7.

In conclusion, there exists no mean diameter to predict frictional pressure drops well in the whole flow rate range. It may be that the fraction of number of particles and the porosity in mixed bed are changed if chosen particle sizes and its mass fractions are different although the same cumulative mass fraction is introduced because flow paths may be changed by the fraction of number of particles and the porosity in bed affecting to hydrodynamic resistance. In this respect, more analysis is needed as further work.

6. Acknowledge

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