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Influence of particle morphology on pressure gradients of single-phase air flow in the mono-size non-spherical particle beds

Jin Ho Park, Mooneon Lee, Kiyofumi Moriyama, Moo Hwan Kim, Hyun Sun Park *

Division of Advance Nuclear Engineering, POSTECH, Pohang, Gyeongbuk-do 37673, Republic of Korea

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A B S T R A C T

Adequate equivalent diameters for non-spherical particles in predicting the pressure drop of fluid flow through particle beds were pursued. A series of experiments to measure the pressure drop of single-phase air flow through particle beds were performed using three kinds of spherical particles (2, 3.5 and 5 mm diameter) and four kinds of cylindrical particles. The experimental data were utilized for evaluating previous models and for proposing a new model, a modified Wu et al. (2008) model with an alternative Ergun constant for the viscous energy loss term.

The proposed model agreed well with the pressure drop of single-phase flow through spherical particle beds within 10% in average. The experimental data for cylindrical particle beds also agreed well with the proposed model within 16% in average by applying the equivalent diameter proposed by Li and Ma (2011) as a characteristic size of non-spherical particles.

1. Introduction

A severe accident (SA) in a nuclear power plants is an accident condition more severe than a design basis accident (DBA), a very unlikely event involving an initiating event by external factors such as seismic, flooding or by internal factors such as loss of coolant accident (LOCA), transients together with multiple equipment failures, resulting crippled engineered safety feature (ESF). Consequently, the reactor core is unable to be cooled and melts due to decay heat from the fission products. When such a core damage accident occurs, molten core material (corium) can fall and relocate into the lower plenum of the reactor pressure vessel (RPV) and further release into the reactor cavity. In progression of corium release, molten fuel-coolant interactions (FCIs) can occur in the reactor cavity which is filled with water by cavity flooding system (CFS), containment spray and so on as the severe accident management (SAM) strategy. It results in fragmentation of melt jet. Thereafter, the split melt drops settle down, quench and finally form a debris bed with internal heat source by the decay heat.

In the late phase of severe accidents in nuclear power plants, it is crucial to assure coolability of the relocated corium on the reactor containment floor. Under this circumstance, concrete ablation and over-pressurization caused by molten corium concrete interaction (MCCI) may occur in case the corium cooling is not sufficient. It would threaten the integrity of the containment building which is the final barrier in the physical sense of the defense-in-depth to prevent the release of radioactive material to the environment. Thus, it is of key importance to ensure sustainable coolant ingression into the internally heat generating corium debris bed to provide the long-term stabilization and termination of the severe accident progression. Since the coolant ingression is governed by pressure drop of the flow in the debris bed affected by the debris bed characteristics, it is necessary to investigate the pressure drop mechanism in the porous debris bed that can be characterized by physical parameters that include bed porosity, particle morphology, particle size distributions etc. The characteristics of the debris bed on the reactor containment floor in hypothetical accident conditions can be found from previous investigations on FCI experiments. The quenched particulate debris bed is composed of irregular particle morphology and it has a particle size distribution from a few of micro-meters to about 10 mm (Karbojian, 2009; Magallon, 2006).

Among these characteristics of debris bed on the reactor containment floor, to consider the influence of particle morphology on pressure gradient of single-phase flow, many researchers were suggested empirical or semi-empirical models based on the Ergun equation Ergun (Ergun, 1952) in many ways by fitting experimental data: (i) the modification of the Ergun constants ($C_1 = 150$, $C_2 = 1.75$) adopting the Sauter mean diameter, d_{sd} as the effective particle diameter (Leva, 1959; Handley and Heggs, 1968; Ozahi et al., 2008; Macdonald et al., 1979; Foumeny et al., 1993, 1996),

* Corresponding author.
E-mail address: hejsunny@postech.ac.kr (H.S. Park).

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Nomenclature

A_p	surface area of the particle (m^2)
C_1, C_2	Ergun constants (–)
d_{eq}	equivalent diameter (m)
d_i	inner diameter of ring/hollow spheres (m)
d_p	particle diameter (m)
d_{sd}	sauter mean diameter (m)
d_t	inner diameter of test section (m)
g	acceleration due to gravity (m/s^2)
h_p	height of particle (m)
Ga_i	modified Galileo number (–), $Ga_i = (\rho_i/\mu_i)^2\, g(d_p\varepsilon/(1-\varepsilon))^3$
k_0	shape parameter of the cross-section of the channel (–)
K	permeability (m^2)
m_p	mass of particle (kg)
p	pressure (Pa)
Re_p	the particle Reynolds number (–), $Re_p = \rho_i V_{si} d_p/\ \mu_i(1-\varepsilon)$
V_p	volume of the particle (m^3)
V_{si}	superficial velocity of i-phase fluid (m/s)
V_t	volume of the test section (m^3)
Greek symbol	
β	the ratio of the pore diameter to the throat diameter (–)
ε	porosity (–)
η	passability (m)
μ	dynamic viscosity (Pa·s)
τ	tortuosity (–)
ρ_i	density of i-phase fluid (kg/m^3)
φ	shape factor of particle (–)
ψ_i	dimensionless pressure drop of i-phase fluid (–), $\psi_i = [(-dp/dz) - \rho_i g]/\rho_i g$
Subscript	
i	phase; l = liquid, g = gas
p	particle

(ii) the suggestion of the equivalent diameter, d_{eq} assuming that the Ergun equation is valid for non-spherical particle beds (Li and Ma, 2011), (iii) the adoption of d_{sd} for the viscous energy loss term and d_{eq} for the inertial energy loss term with the modified Ergun constants of $C_1 = 181$ and $C_2 = 1.63$ (Clavier, 2015) and (iv) the suggestion of the Ergun constants based on tortuosity τ research with the physical meaning (Carman, 1937; Wu et al., 2008).

Through these intensive previous researches, various modified Ergun constants and effective diameters were suggested for single-phase flow through porous media by using single-size spherical, non-spherical particles with known geometry (cylinder, prism, hollow sphere, hexagonal screw/bolts etc.) and irregular (gravel) particles.

Nevertheless, there still remain unsuccessful issues on pressure drop in porous media composed of non-spherical particles, i.e., adequate effective particle diameter for non-spherical particles or the Ergun constants suitable for the safety analysis of ex-vessel debris bed coolability in particular.

For this reason, it is obviously necessary to clarify the questions on the adequacy of the suggested effective diameters for a non-spherical particle and the modified Ergun constants by investigating the influence of particle morphology on pressure gradients in beds. Thus, in this study, the pressure gradients of single-phase air flow in well-packed mono-size spherical and cylindrical particle beds were obtained and a model is proposed to predict the pressure drop of single-phase flow in porous bed by modifying the Wu et al. model (Wu et al., 2008).

2. Pressure drop models for single-phase flow in porous bed

The Ergun equation (Ergun, 1952), a momentum conservation equation for single-phase flow in porous media composed of single-size spherical particles, is as follows:

$$-\frac{dp}{dz} - \rho_i g = \frac{C_1 \mu_i (1-\varepsilon)^2}{\varepsilon^3 d_p^2} V_{si} + \frac{C_2 \rho_i (1-\varepsilon)}{\varepsilon^3 d_p} V_{si}^2. \quad (1)$$

The first term of the right-hand side (RHS) is the viscous energy loss term derived from the Blake-Kozeny equation and the second term is the inertial energy loss term derived from the Burke-Plummer equation where C_1 (150) and C_2 (1.75) are the empirical Ergun constants, μ_i and ρ_i are the dynamic viscosity and the density of fluid (i: phase; l = liquid, g = gas), respectively; $-dp/dz$ represents pressure loss in porous media of the porosity ε and composed of the particle diameter d_p when the superficial velocity of fluid is V_{si}. The bed porosity is calculated by

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

where $\sum m_p$ is the total mass of particles in the test section, ρ_p is the density of particles, and V_t is the volume of the test section. According to the Ergun equation, the permeability K, a measure of the flow conductance of the matrix, and the passability η, a quality of being passable are defined as follows:

$$K = \frac{\varepsilon^3 d_p^2}{C_1 (1-\varepsilon)^2}, \quad (3)$$

$$\eta = \frac{\varepsilon^3 d_p}{C_2 (1-\varepsilon)}. \quad (4)$$

Based on the above mentioned Ergun equation, many researchers considered the influence of particle morphology on the pressure gradient by means of modifying the Ergun constants and substituting the particle diameter with the Sauter mean diameter d_{sd} as effective particle diameter as listed in Table 1 (Leva, 1959; Handley and Heggs, 1968; Ozahi et al., 2008; Macdonald, 1979; Foumeny et al., 1993, 1996) or by suggesting the equivalent

Table 1
Modified Ergun Constants with d_{sd}.

Model	C_1	C_2
Ergun (1952)	150	1.75
Leva (1959)	200	1.75
Handley and Heggs (1968)	368	1.24
Ozahi et al. (2008)	160	1.61
Macdonald (1979)	180	For smooth particles, 1.8 For rough particles, 4.0
Foumeny et al. (1993, 1996)	130	For spherical particles, $\frac{d_t/d_{sd}}{0.335 d_t/d_{sd} + 2.28}$
	211	For cylindrical particles, $3.81 - \frac{5.265}{d_t/d_{sd}} - \frac{7.047}{(d_t/d_{sd})^2}$