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Pressure drops of single/two-phase flows through porous beds with multi-sizes spheres and sands particles

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ABSTRACT

This paper reports an experimental research of single and two-phase gas/liquid flow in packed porous beds composed of multi-sizes spheres and irregular particles. A test facility named DEBECO-LT is designed and constructed to investigate the friction laws of adiabatic single and two-phase flows in a porous bed. The results show that the effective diameter of multi-sizes non-spherical or irregular particles bed can be derived on the basis of bed consisted of spheres as long as they have a wide range of grain sizes and the similar size distribution. Given the effective particle diameter obtained from single-phase flow through the packed bed with multi-size spheres or irregular particles, the pressure drop of two-phase flow through the bed can be predicted by the Reed model. The experimental data provide insights for the flow characteristic of porous bed, as well as high-quality data for validation of the coolability analysis models and codes.

1. Introduction

Characterization of single and two-phase gas/liquid flow in porous media composed of stationary granular particles is of importance to many engineering applications, ranging from agricultural, biomedical, mechanical, chemical and petroleum engineering to food industry (Jamialahmadi et al., 2005). A special interest comes from the quantification of corium coolability in nuclear power safety analysis, where two-phase flow and heat transfer in a debris bed may occur due to fragmentation of molten corium in coolant, and the coolability of the porous bed is crucial to the stabilization and termination of a severe accident in a light water reactor (LWR), since it is more coolable than a molten pool due to the formation of internal porous structure. Towards quantitative understanding of debris bed coolability, lots of experimental and analytical studies have been performed, and a good number of empirical models or semi-empirical models have been developed for the assessment of debris bed coolability in a severe accident. The models are related to the knowledge and treatment of two-phase flow and heat transfer in porous media. Summaries and reviews of the previous studies can be found in the works of Bürger et al. (2010), Nemec and Levec (2005), Schmidt (2004), Lindholm (2002) and Dullien (1975).

The central point in modeling is to provide the formulation of the friction laws for momentum equations of single and two-phase flow in particulate beds. The pressure drop of single-phase flow through porous media can be expressed by the Ergun equation (Ergun, 1952) as:

$$-\frac{dp}{dz} = \frac{\mu}{K}J + \frac{\rho}{\eta}J^2 \tag{1}$$

where dp/dz is the pressure gradient along the bed, μ is the dynamic viscosity of fluid, ρ is the density of the fluid and J is the superficial velocity of fluid. The parameters K and η are called permeability and passability, respectively. For uniform spherical particles bed, they are usually expressed as:

$$K = \frac{\varepsilon^3 d^2}{150(1-\varepsilon)^2} \qquad \eta = \frac{\varepsilon^3 d}{1.75(1-\varepsilon)} \tag{2}$$

where 150 and 1.75 are called Ergun constants derived from the experiments, d and ε are particle diameter and porosity of the debris bed, respectively.

The Ergun equation was extended to the case of two-phase flow through particulate beds via the inclusion of relative permeability and relative passability for assessment of debris bed coolability. Such approach was adopted in the Lipinski model (Lipinski, 1982) and its variations (Reed, 1982; Schulenberg and Műller, 1987; Tung and Dhir, 1988; Hu and Theofanous, 1991), as shown in Eq. (3) and Table 1.

$$-\frac{dp_l}{dz} = \rho_l g + \frac{\mu_l}{K \cdot K_{r,l}} J_l + \frac{\rho_l}{\eta \cdot \eta_{r,l}} J_l \cdot |J_l| - \frac{F_i}{1-\alpha} \tag{3a}$$

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Nomenclature

d	bubble diameter (m)
F_i	Interfacial friction (N)
J	superficial velocity (ms^{-1})
K	permeability (m^2)
M	mass (kg)
P	pressure (Pa)
s	saturation
V	volume (m^3)

Greek letters

α	void fraction
ε	porosity
η	passability (m)
μ	dynamic viscosity (Pas)
ρ	density (kg m^{-3})

Subscripts

g	gas
l	liquid

$$-\frac{dp_g}{dz} = \rho_g g + \frac{\mu_g}{K \cdot K_{r,g}} J_g + \frac{\rho_g}{\eta \cdot \eta_{r,g}} J_g \cdot |J_g| + \frac{F_i}{\alpha} \tag{3b}$$

where J_l and J_g are the superficial velocities of fluids; and K_r and η_r are relative permeability and relative passability that are listed in Table 1, together with the interfacial friction F_i. α is the void fraction and s is saturation which is equal to $(1 - \alpha)$.

For the above models, one can see the particle diameter is a key parameter in the determination of frictional terms. However, the selection of the diameter is not straightforward in debris beds, since the debris beds formed from FCI consist of various particles with different sizes and irregular shapes, as illustrated in Fig. 1. Such prototypical characteristics play an important role in quantification of debris coolability (Ma and Dinh, 2010). Only a few experiments and limited data are available for the particulate beds packed with irregular-shape and multi-size particles. There is a clear need on more experimental data for particulate beds packed with multi-size and irregular particles.

The first step of the present study was to quantify the effective particle diameter of a particulate bed packed with multi-diameter spheres or irregular particles. Glass spheres and sand particles with similar size distributions were employed to represent the two types of particles, respectively. The experiments were carried out on the DEBECO-LT (Debris Bed Coolability-Low Temperature) test facility which was designed to investigate the friction laws of air/water single or two-phase flow in porous media. Pressure drops were measured for single-phase flow through the particle bed, and the effective particle diameter was obtained based on the pressure gradient and the Ergun equation. After that, an experiment on the frictional drags of two-phase flow through the particulate bed was also carried out, and the data were used to validate the models.

2. Description of experiments

To obtain the effective diameter of multi-size particles and examine the flow characteristics of single and two phase flow in the packed porous bed, the test facilities of DEBECO-LT (Debris Bed Coolability – Low Temperature) were designed and constructed at State Key Laboratory of Multiphase Flow in Power Engineering (MPFL) to perform adiabatic single/two-phase flow tests in porous media.

2.1. DEBECO-LT test facility

Fig. 2 illustrates the schematic diagram of DEBECO-LT facility, with most parts made of transparent plexiglas to facilitate visual observation. The test section accommodating the packed bed is made of a plexiglas pipe of 120 mm in inside diameter and 600 mm in height. At both inlet and outlet of the test section, two pieces of stainless steel wire meshes are applied between flanges to support the bed from below and prevent the particles from leaving the bed. Air is supplied from the bottom and flows up through the packed bed, and the deionized water can be supplied from either bottom or top for bottom-fed (co-current flow) or top-flooding (counter-current flow) tests. All tests are operated under atmospheric pressure.

The flowrates of air and water are measured by OMEGA flowmeters (rotameter, FL-2000 series). The temperatures are monitored by using OMEGA K-type thermocouples. Two Rosement-3051 differential pressure transmitters with an uncertainty of ±0.25% of the full scale value (10 kPa and 20 kPa respectively) are installed to measure pressure drops. The differential pressure transmitters are connected to the test section through valve manifolds and pressure tapping of 5 mm diameter. A small chamber with a net serving as a steam/water separator is provided at each pressure tap to prevent steam from entering the pressure lines. The valve manifolds are used with the differential pressure transmitters to perform the block, equalizing and vent requirements of the transmitters. For ΔP_1 illustrates in Fig. 2, the distance of two pressure measurement points is about 500 mm. While ΔP_2 locates in the middle of the bed and the measuring distance is about 300 mm. The recorded pressure gradients from the two

Table 1
Parameters of the two phase flow models.

Model	Parameter		
	K_r	η_r	F_i
Lipinski (1982)	$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^3$ $\eta_{r,g} = \alpha^3$	0
Reed (1982)	$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^5$ $\eta_{r,g} = \alpha^5$	0
Hu and Theofanous (1991)	$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^6$ $\eta_{r,g} = \alpha^6$	0
Schulenberg and Műller (1987)	$K_{r,l} = s^3$ $K_{r,g} = \alpha^3$	$\eta_{r,l} = s^5$ $\eta_{r,g} = \alpha^6$, $\alpha > 0.3$ $\eta_{r,g} = 0.1\alpha^4$, $\alpha \leqslant 0.3$	$F_i = 350 \quad s^7 \alpha \frac{\rho_l K}{\eta \sigma}(\rho_l - \rho_g) g \left(\frac{J_g}{\alpha} - \frac{J_l}{s}\right)^2$