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Liquid permeability of packed bed with binary mixture of particles

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ABSTRACT

We investigate the effect of binary sized packing on the permeability of water flow through a column packed with binary mixture of spherical particles. The size ratios λ of large to small particles are chosen to be 1.4 and 2.5. Particle packing density for binary mixture of the particles is larger than that for equal sized particles and shows the maximum around the particle blending ratio at which large particles are densely packed and all the small particles fill the void among the large particles. This behavior is observed in both experimental results and theoretical estimation. The variation pattern of packing density with the blending ratio does not agree with that of permeability. The permeability increases with relative fraction of large particles at the maximum packing. Experimental results for the permeability are compared with three theoretical models. Variation pattern of the permeability with the blending ratio from these theoretical models agrees with that from the experiment. Theses theoretical models are in good agreement each other.

1. Introduction

Permeation of viscous flow through porous media is encountered in many natural as well as artificial situations. Typical examples in chemical engineering processes are packed bed tower and filter in which permeation of fluid plays an important role in overall performance of the equipment. For optimum design of these processes it is necessary to determine pressure drop over the bed as a function of average velocity of fluid. The pressure drop is caused by the drag force acting on packing particles by the viscous fluid. Calculation of the drag force by the viscous flow through arrays of fixed particles has also drawn academic interest as a fundamental problem in fluid mechanics. In particular, significant progress in the theoretical studies has been made by employing rigorous calculation of hydrodynamic interaction among fixed spherical particles placed in mean flow [1–5]. It has been reported that the numerical calculation results for closely packed particles are in good agreement with those from the well-known Kozeny–Carman's equation [6] which is based on modeling of pore space in fixed bed packed with uniformly sized spherical particles as a bunch of capillary tubes [1,2]. Recently, theoretical work has been extended to countercurrent gas–liquid flow through the packed bed with hard spheres [7]. In most of theoretical studies the packed bed is usually considered to be filled with uniformly sized packing materials.

In practice packed beds often contain particles with size distribution. Effect of packing size distribution on the fluid permeation can be understood by examining the case of binary packing. Binary packing gives additional process variables such as size ratio and blending ratio of the particle species, compared with that of equal sized packing. The packing density, i.e. total volume fraction of the particles depends on the size and the blending ratio of two species of particles. Binary packing enhances the particle packing density by filling two kinds of void. One is the void among the large particles and the other is the virtual void among the small particles to be actually replaced by large particles. This void filling effect increases fluid permeability in overall. However, the packing density variation with the blending ratio of particles does not agree with that of fluid permeability. It is necessary to obtain suitable model for predicting the fluid permeability for binary sized packing.

Studies on the case of binary packing are relatively few [8–10]. Thies-Weesie et al. [8] investigated liquid permeation through fixed bed of binary mixture of consolidated particles from a scaled relation of the Kozeny–Carman's equation. Their experimental results seem to be in poor agreement with the theoretical results. Mota et al. [9] proposed a semi-empirical relation for the fluid permeability from the experimental results for the case of large size ratios, i.e. more than 10, of large to small particles.

Present study is concerned with determining Darcy's permeability of liquid flow through fixed bed packed with binary mixture of hard spheres. First, packing density of the binary mixture of spherical particles is measured and the measured results are compared with theoretical estimations.

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Nomenclature

D	diameter of particles
D_L	diameter of large particles
D_S	diameter of small particles
$<F>$	average force exerted on the surface of particles by fluid
k_P	permeability
$K(\phi)$	dimensionless drag coefficient
n	number density of particles
$<-\nabla p>$	pressure gradient along the bed
U	average fluid velocity
x_L	relative volume fraction of large particles
x_S	relative volume fraction of small particles
$x_{L,\max}$	relative volume fraction of large particles at the maximum packing density

Greek letters

α	variation of packing density with λ
ϕ	packing density of particles
$\phi_{\max}$	maximum packing density of particles
ϕ_L	packing density of large particles
ϕ_S	packing density of small particles
ϕ_0	maximum volume fraction of particles for equal sized packing
λ	diameter ratio of large particle to small particle
μ	fluid viscosity

Then permeation experiment is carried out using a packed bed with spherical glass beads. The permeability are measured at various blending ratios for the size ratio of large to small particle $\lambda = 1.4$ and 2.5. The results are compared with those from theoretical models.

2. Experimental procedure

We set up a fixed bed packed with spherical glass beads. Nominal diameters of the glass beads are 0.2, 0.5, and 0.7 mm, respectively. The beads were screened with sieves to obtain uniform size distribution as shown in Fig. 1. The beads of each size were prepared to form a random mixture of the glass beads. The size ratios λ of large to small beads are chosen to be 1.4 (0.7/0.5) and 2.5 (0.5/0.2). At each size ratio, packing density of binary mixture of spherical particles is measured for several blending ratios of particles. The measurement has been carried out five times for each experimental condition.

Next, the bed is packed with the glass beads and is assembled for permeation of water. Water flows through the bed from the top to the bottom of the bed at room temperature. The packed bed consists of three parts, i.e. inlet, column, and drain part as shown in Fig. 2. A pressure gauge (Model: Tuffman pressure meter 655/655L) is implemented at the inlet and drain part to measure the pressure drop along the bed. The pressure drop was measured varying the average liquid velocity. Since liquid flow and pressure drop exhibit fluctuation at initial liquid flow, experimental data was taken when steady state is reached. Fig. 3 shows that the liquid flow is in steady state. It is seen that the liquid flow rate is constant over the measuring time. This permeation experiment for each condition was performed five times for each packed state that the packing density was measured and the experimental data were averaged. Air can form in the packed bed and cause pulsation of the pressure drop along the bed. In order to avoid air formation the beads are wetted with water and air is vented before reaching steady flow of water. The dimension of the bed which is 2.0 cm in diameter and 6.2 cm in height is selected to be sufficiently large compared with the size of glass beads. The measured data of pressure drop and average liquid velocity are used to calculate Darcy's permeability. The permeability results are given as a function of the volumetric mixing ratio of glass beads and the size ratio.

3. Results and discussion

3.1. Packing density

Pore space for packed bed is determined by packed state of particles. The maximum packing density for random arrays of particles is less predictable and has been obtained by many investigators [11–16]. For binary mixture of spherical particles the maximum packing density varies with size and blending ratio of small and large particles. For the infinite size ratio of the binary mixture, the maximum packing density $\phi_{\max}$ is given by

$$\phi_{\max} = \phi_L + (1 - \phi_L)\phi_S \quad (1)$$

where $\phi_L$and ϕ_S are the packing density for large and small particles each. Relative volume fraction of large particle at $\phi_{\max}$, i.e. $x_{L,\max} = \phi_L/\phi_{\max}$, is readily determined. Assuming that this $x_{L,\max}$ is valid over entire range of size ratios, the particle packing density is simply given as a function of size ratio and relative volume fraction of large particles. This assumption is based on the packed state in which large particles are densely packed and small particles are placed only in the void space among the large particles. Our experimental results show that this assumption is acceptable. In Fig. 4, it is seen that experimental results for the packing density at $\lambda = 1.4$ and 2.5 commonly show the maximum values at around $x_L$of 0.735 which is obtained from Eq. (1) when both ϕ_L and ϕ_S are

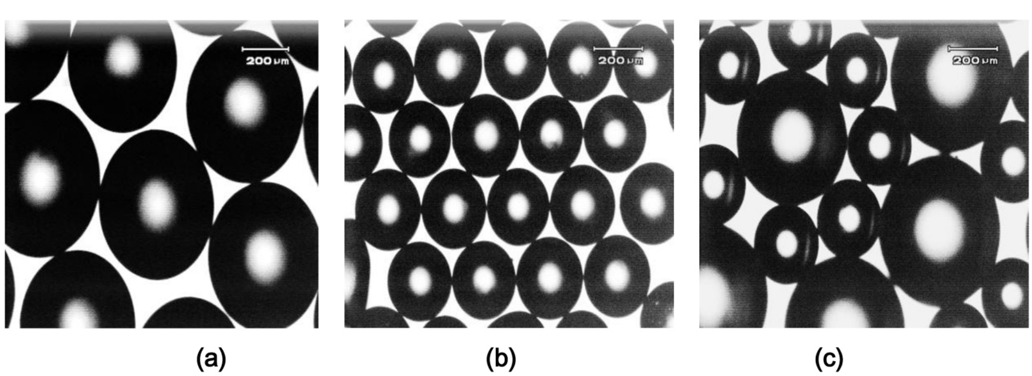

Fig. 1. Microscopic image of glass beads: (a) 0.5 mm glass beads (b) 0.2 mm glass beads (c) binary mixture of 0.2 mm and 0.5 mm glass beads.