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Segregation in water fluidized beds of sand particles

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ABSTRACT

Fluidization experiments were conducted on four fractions of filtration (quartz) sand using columns of 144 and 64 mm i.d. The size distribution of the fractions obtained by sieving followed an approximately modified normal (Gaussian) particle size distribution with respect to the projected particle diameter, while the shape factor decreased linearly with increasing projected particle diameter. The expansion characteristics of the sand particles followed a Richardson–Zaki relationship. The intercept velocity, i.e., the extrapolated value of the fluid superficial velocity to $\varepsilon=1$ on the plot log (U) *vs.* log (ε), agreed quite well with the experimentally determined mean free settling velocity of the cloud of about 30 randomly selected particles. During fluidization, the beds were hydraulically separated into 10 sub-fractions, which are then analyzed. For the mixture $d_p=0.75$–1.25 mm during fluidization at an overall bed expansion of 35%, the bed partially segregated since, remarkably, the smallest particles were concentrated at the top, while the largest particles were concentrated in the bottom zone. In the remaining part of the bed (about 80% of total mass), the particles were well mixed. Similar experiments were performed with sand mixtures $d_p=1.60$–2.00 mm, $d_p=1.40$–2.00 mm and $d_p=1.166$–2.00 mm. By analyzing the particle size distribution at the bottom and at the top of the bed, it was concluded that the bed was well mixed if the sieving ratio of the largest to smallest sieve opening was less than about 1.5.

1. Introduction

Liquid–solid fluidized beds are used in several processes, such as solids separation and classification, adsorption, ion exchange, catalytic cracking, hydrometallurgical operations, wastewater treatment and biotechnological processes by Epstein [1]. Probably the most widely used application is backwashing of downflow granular filters, especially sand filters. During fluidization by water, the filtered solids are primarily removed from the bed by elutriation. The efficiency of this process depends on the friction between the fluid and the particles as well as on collisions between the fluidized particles. In such an application, the bed is composed of sand particles of a certain granulometric interval. Beds consisting of single-sized particles show smooth expansion as the liquid superficial velocity is increased from the minimum fluidization velocity to the single particle terminal velocity. When the bed consists of different size particles, the particles have tendency to segregate according to size during the fluidization; the larger particles tends to migrate to the bottom and the smaller particles tend to migrate to the top of the bed. On the other hand, when the particles differ in density, particle segregation according to density occurs. The particles of lower density will fluidize in the upper part of the bed and particles of higher density will fluidize at the column bottom. If the particles vary both in size and density then under certain conditions, the bed inversion phenomenon appears. Escudie et al. [2,3] and Barghi [4] showed that segregation can also occur according to particle shape. Generally, when particles of mixed size, shape, and/or density are fluidized by a liquid, they may segregate completely according to species (a given size, shape, and density), segregate incompletely (i.e., mix partially), or mix completely. In practical applications, the size, density or shape of particles can change due to attrition, collisions, chemical decomposition, and deposition of impurities or growth of microorganisms [4]. These effects, as well as channeling and bulk circulation due to nonideal liquid distribution at the bed bottom can further complicate the overall picture in real applications.

A fluidized bed of sand particles of a certain granulometric interval can be approximated by a series of successive binary fluidized beds of particles of equal density. As illustrated in Fig. 1, four different segregation or mixing patterns were identified by Gibilaro et al. [5]: (A) complete segregation; (B) perfect mixing; (C) partial segregation 1; and (D) partial segregation 2.

Much work has been devoted to investigating the segregation of particles by size and density. Different models and experimental techniques have been proposed, as reviewed by Epstein [1], Di Felice [6], and Chavan and Joshi [7].

According to Hofman [8], in a binary fluidized bed of particles of the same density, segregation occurs when the size ratio d_R, the diameter of the largest to that of the smallest particle size present in the bed is greater than 1.56. Al-Dibouni and Garside [9] investigated mixing in a bed composed of spherical glass particles with various size distributions using a specially designed column equipped with sliders. In such a way, they were able to measure the composition

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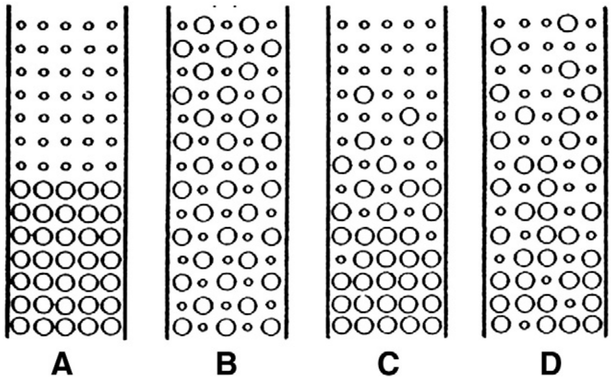

Fig. 1. Segregation and mixing in a liquid fluidized bed of binary-sized particles of equal density, after Gibilaro et al. (1985): (A) complete segregation; (B) perfect mixing; (C) partial segregation 1; and (D) partial segregation 2.

and voidage in different bed sectors. Their main conclusion was that at size ratios up to $d_R \approx 2$, particle mixing occurs through the bed and that maximum mixing intensity occurs at $\varepsilon \approx 0.7$. For size ratios d_R greater than about 2.2, classification of the particles by size is dominant. A maximum mixing intensity at a bed voidage $\varepsilon \approx 0.7$ agrees with the observation that at nearly the same voidage, axial mixing of a liquid reaches a maximum [10], as do the heat transfer coefficients and the frequency of interparticle collisions [11], collisional particle pressure [12] and axial liquid fluctuations [13].

Extending the work of Epstein and Pruden [14], Epstein [15] proposed that the degree of segregation depends on the difference between the bulk densities of the two particle species when each is fluidized separately at the same superficial liquid velocity. For binary systems of equal density spheres with diameters d_L (larger) and d_S (smaller), the bulk density difference is:

$$\rho_{bL} - \rho_{bS} = \left[\varepsilon_L \rho_f + (1-\varepsilon_L)\rho_p\right] - \left[\varepsilon_S \rho_f + (1-\varepsilon_S)\rho_p\right] = \left(\rho_p - \rho_f\right)(\varepsilon_S - \varepsilon_L) \quad (1)$$

Introducing the reduced bulk density difference (γ), the governing mechanism for segregation becomes:

$$\gamma = \frac{\rho_{bL} - \rho_{bS}}{\rho_p - \rho_f} \varepsilon_S - \varepsilon_L \quad (2)$$

Epstein [15] described somewhat precisely the bed behavior depicted in Fig. 1 and proposed the following criteria:

- $\gamma < 0.015 \pm 0.005$ corresponds to perfect particle mixing (Fig. 1B)
- $0.015 \pm 0.005 < \gamma < 0.045 \pm 0.015$ corresponds to continuous stratification from the bottom to the top with no interface (Fig. 1D)
- $0.045 \pm 0.015 < \gamma < 0.10 \pm 0.005$ corresponds to segregation at the bottom and the top with a transition zone or fuzzy interface in between (Fig. 1C), and
- $\gamma > 0.10 \pm 0.005$ corresponds to a clean-cut segregation with a sharp interface (Fig. 1A).

The last criterion ($\gamma > 0.1$) agrees with the finding of Di Felice [16] that complete segregation will occur when the size ratio is greater than about 2.

Chavan and Joshi [7] also found that the reduced bulk density indicates the degree of segregation or intermixing. The degree of segregation is a function of the size ratio of the particles with respect to the other particles present in the bed. In binary particle systems, segregation dominates above a size ratio of 1.55. Partial segregation occurs between a size ratio of 1.4 and 1.55, while complete intermixing occurs below a size ratio of 1.4. In addition, in a multiparticle system, particles of different sizes will be positioned in the bed according to the size ratio with respect to the other particles.

Most of the previous investigations were performed using binary or eventually ternary mixtures of particles. In this work, segregation phenomena were studied using real filtration materials where the particle size changes more or less continuously from min to max size in a certain sieving interval.

2. Experimental

The measurements of the fluidization parameters were conducted in two acrylic straight-walled cylindrical columns 144 mm i.d. (height 3 m) and 64 mm i.d. (height 2 m). The columns were equipped with a distributor, calming section, piezometers and Yamatake-Honeywell electromagnetic flowmeters, as shown schematically in Fig. 2. The fluid was deaerated water at a nearly constant temperature of 20 °C. In each run, the water temperature was recorded and calculations corresponding to the water density and viscosity were considered. Fluidization experiments were conducted with four fractions of filtration (quartz) sand with density $\rho_p = 2638$ kg/m^3. The raw material was washed (by fluidization) in order to eliminate dust, dried and after that sieved to four fractions: $d_p = 0.75$–1.25 mm; 1.166–2.00 mm; 1.40–2.00 mm; and 1.60–200 mm. Two groups of experiments were conducted. In the first group of experiments, the fluidization parameters were determined in a column $D_c = 144$ mm and after that this bed was hydraulically classified into 10 sub-fractions. For each sub-fraction, the fluidization parameters were determined using a column $D_c = 64$ mm. In the second group of experiments, conducted in a column $D_c = 64$ mm, the fluidized beds were hydraulically classified into 11 sub-fractions. Samples from the top and the bottom, as well as overall samples were analyzed using the image processing technique in order to determine the size distribution.

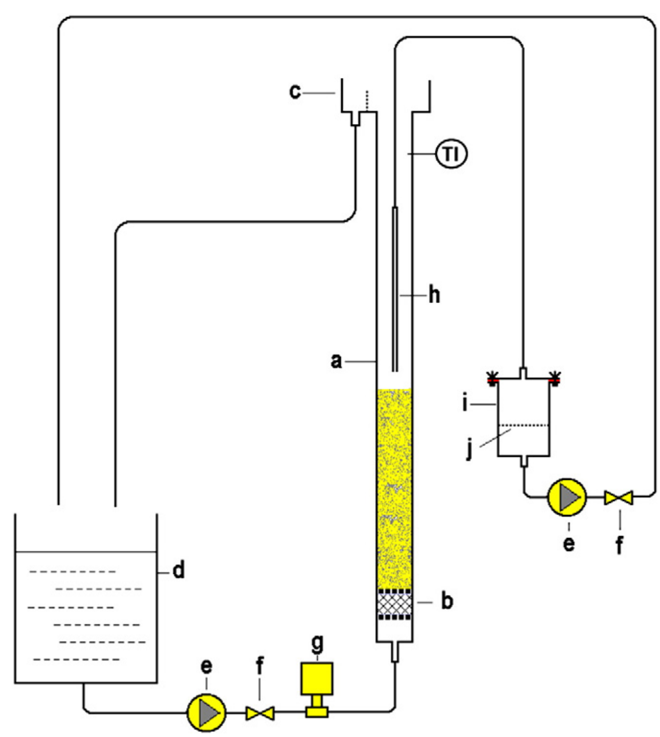

Fig. 2. Schematic diagram of the experimental system (a-column, b-calming section, c-over flow, d-reservoir, e-pump, f-valve, g-flowmeter, h-sampling tube 9 mm i.d., i-sampling reservoir, j-screen 0.2×0.2 mm, TI-temperature indicator).