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Particle characterization of polydisperse quartz filtration sand

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ABSTRACT

In this paper, different methods for particle characterization were applied to 16 polydisperse fractions of quartz filtration sand obtained by sieving, with sieve diameters in the interval $d_m = 0.359$ to 2.415. For each fraction, volume diameter was measured and projected diameter and 2D shape factor were obtained using the scanned image of the projection of a large number of particles. The correlations between the volume diameter, projected diameter and 2D shape factor with sieve diameter were proposed. All of the correlations show linear dependence between the variables.

The sphericity was determined for the fractions from packed-bed pressure drop measurements; from terminal velocity measurements using different correlations for the calculation of C_D, direct correlations for U_t and from direct empirical correlations. The sphericities obtained using different methods and correlations gave very different results. Both the sphericity and the 2D shape factor were shown to decrease with increase in particle sieve diameter.

1. Introduction

The systems involving fluid–particle interaction are widely used in industrial processes. One of the most widespread fluid–particle systems is fluidized bed of particles. Fluidized beds are used in many applications, such as solid separation and classification, adsorption, ion exchange, catalytic cracking, hydrometallurgical operations, wastewater treatment, etc. [1]. The periodic back-washing of down flow granular filters, especially sand filters, is one of the widest uses of liquid fluidized beds [2]. During the process of filter back-washing by upward water fluidization, the filtered solids are removed from the bed by elutriation.

The knowledge of the size and shape of the particles present in fluid–particle systems is essential for predicting the behavior of the system and for its proper design. If the system consists of relatively large uniform spherical particles its behavior can easily be described in terms of particle size and density. But in the majority of industrial applications the particles are present in a range of sizes and shapes, and sometimes densities. In the case of sand filters the filter media consists of quartz sand, which is a natural material consisting of particles of a smaller or larger range of sizes and shapes, i.e. the bed is composed of sand particles of a certain granulometric interval. When the bed consists of polydispersed particles, they have the tendency to segregate during the fluidization; the larger particles tend to migrate to the bottom and the smaller particles tend to migrate to the top of the bed, diminishing the filter effectiveness [3]. To be able to adequately predict the behavior of fluidized beds of non-spherical particles with wide size distribution and most often non-uniform shape it is very important to determine the representative particle diameter and shape factor as well as their distributions. This is very important for the design and optimization of sand filters.

It is universally accepted that the relevant particle size in packed and fluidized systems is the surface–volume diameter, d_{SV} [4]. The downside of d_{SV} is that it cannot be obtained directly, and several methods have been proposed for the empirical determination of d_{SV}. Geldart [4] proposed a method for determination of sphericity Ψ and surface–volume diameter d_{SV} based on pressure drop measurement across the packed bed. The other authors proposed the determination of sphericity based on U_t measurements and different correlations for the drag coefficient of the non-spherical particles [5].

Another diameter used in fluid–particle systems is volume diameter, d_V. This diameter can easily be determined for the particles that can be identified individually. Volume diameter is mostly used in correlations for determination of the drag coefficient and the terminal settling velocities of non-spherical particles [5].

In recent years, 2D diameter and shape factors were reported for a number of particles due to the possibility of the analysis of 2D scanned images of a sample of particles using computer software [6–8].

The goal of this paper is to evaluate different methods for particle characterization applied to the polydisperse sets of particles of quartz filtration sand and to propose correlations between equivalent diameters, sphericity and 2D shape factor. For the determination of sphericity using different methods, the following characteristics of the particles were experimentally determined: pressure drop of the packed bed of particles, terminal velocity of the particles and voidage at minimal

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fluidization. The sphericities obtained were critically evaluated and the best method for particle characterization was proposed.

2. Definition of different particle diameters and shape factors

2.1. Sieve diameter

The most widespread analysis performed to define the size distribution of a polydisperse set of particles is sieve analysis. The sieve diameter of a particle, d_m, is defined as the mean value of the size of the openings of the last sieve through which the particle had passed and the sieve on which it was retained [4]:

$$d_m = \frac{d_{s,n} + d_{s,n+1}}{2} \tag{1}$$

where $d_{s,n}$ is the size of the opening of the sieve through which the particle had passed and $d_{s,n+1}$ is the size of the opening of the sieve on which the particle was retained.

2.2. Volume diameter

Volume diameter is defined as the diameter of the sphere having the same volume as the particle. It can be determined for the particles that can be identified individually by measuring the mass of a known number of particles [4]. Volume diameter can then be calculated according to the equation [4]:

$$d_V = \left(\frac{6\,M}{N \cdot \pi\,\rho_p}\right)^{1/3} \tag{2}$$

where M is mass of the sample, N is the number of particles in the sample and ρ_p is density of the particles.

2.3. Surface–volume diameter

The universally accepted relevant particle size in packed and fluidized systems is the surface–volume diameter, d_{SV} [4]. For an individual particle, this is the diameter of a sphere which has the same ratio of the external surface area to the volume of the particle. This diameter cannot be determined directly, but through a number of empirical methods [4,5].

2.4. Sphericity

There are many shape factors defining non-spherical particles which are used for different purposes [9,10]. According to Geldart [4] the sphericity Ψ introduced by Wadell [11] is the most representative shape factor in fluid–particle systems. Wadell sphericity [11] is defined as the ratio of surface area of a sphere having the same volume as the particle to external surface area of the particle having a smooth asperity-free surface. It can be shown that sphericity is defined as the ratio of d_{SV} and d_V [4]:

$$\psi = \frac{d_{SV}}{d_V}. \tag{3}$$

2.5. Projected diameter and 2D shape factor

The procedure for the determination of the projected diameter d_A and 2D shape factor ϕ is computer software analysis of the image obtained by scanning a sample of relatively large number of particles. Projected diameter and 2D shape factor are defined according the image analysis software user manual [12] as:

$$d_A = \frac{1}{N}\sqrt{\frac{4}{\pi}\sum A_i} \tag{4}$$

and

$$\phi = \frac{1}{N}\sum \frac{4\pi A_i}{L_i^2} \tag{5}$$

where N is the number of particles in the sample, A_i is the projected area of i-th particle and L_i is perimeter of i-th particle. The 2D shape factor ϕ calculated in this way is also referred to as the circularity [13–15]. The shape factor ϕ is defined as the average value of a single projection of many particles.

The scanning resolution used in this paper was 600 dpi, which results in the pixel size of 42.3 μm. In the preliminary work, some of the particles were scanned with the resolution of 1200 dpi. The results obtained at 600 and 1200 dpi for d_A and ϕ did not show any significant difference. The pixel size of 42.3 μm allows the determination of the shape of the particle, not taking into account the surface roughness. The determination of the limit between the particle shape and its roughness is somewhat arbitrary [14]. In our work, this limit is ~40 μm for the particles of ~1 mm which is in accordance with the literature data [14]. The surface roughness largely depends on the type of particles, but in the majority of fluidization systems with particles of the order of magnitude reported in this paper, it can be neglected.

For particles with low surface roughness the exact scanning resolution is not significant for obtaining adequate particle characteristics. For particles with significant surface roughness, the standardization should be developed in the future work, depending on the application for which the particle shape/roughness is assessed. Also, it should be noted that different software calculate the image area and perimeter in different ways, yielding somewhat different results [15].

3. Methods for determining d_{SV} and sphericity

3.1. Determination of d_{SV} and sphericity from packed bed pressure drop measurements

Geldart [4] recommended the determination of d_{SV} from Ergun [16] equation for pressure drop through packed bed of particles:

$$-\frac{dP}{dz} = 150\,\frac{(1\text{-}\varepsilon)^2}{\varepsilon^3}\,\frac{\mu}{d_{SV}^2}\,U + 1.75\,\frac{(1\text{-}\varepsilon)}{\varepsilon^3}\,\frac{\rho_f}{d_{SV}}\,U^2 \tag{6}$$

where U is the superficial fluid velocity, ε is the voidage of the packed bed, μ and ρ_f are the viscosity and the density of the fluid.

The value of d_{SV} is obtained by iterating different values of d_{SV} to minimize deviations of the experimental data points from Eq. (6). Since the Ergun equation does not include the effect of particle roughness on pressure drop, in order to obtain the relevant d_{SV}, the particle Reynolds number should be less than 30 to avoid the significant influence of particle roughness on the pressure drop. From the obtained value of d_{SV}, sphericity Ψ can be determined using Eq. (3).

3.2. Determination of sphericity from terminal velocity measurements

Terminal velocity of a particle is defined from the force balance equation as:

$$U_t = \sqrt{\frac{4 g d_p (\rho_p - \rho_f)}{3 \rho_f\, C_D}} \tag{7}$$