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The sequential elutriation behavior of wide particle size distributions

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ABSTRACT

Batch elutriation of a metallurgical-grade silicon powder with a wide particle size distribution in a laboratory scale fluidized bed was studied, highlighting the influence of carryover polydispersity. The smallest elutriable fines, namely superfines (<10 μm), whose terminal velocity U_t is far lower than the superficial gas velocity U_g are entrained first, while the largest elutriable particles ($U_t \approx U_g$) begin to be entrained with a delay that is as long as the time required for the superfines to leave the bed, thus inducing sequential elutriation. When no superfines were present, the entrainment was not delayed. This peculiar phenomenon was observed at all of the tested gas velocities (0.05–0.2 m s^{-1}) and for different wide particle size distributions belonging overall to the Geldart group A. The superfines thus seem to strongly limit the elutriation of the larger elutriable particles. In addition, the elutriation rate constants were found to increase with increasing superficial gas velocity and with decreasing particle size. When superfines were present, the elutriation rate constant leveled off under a critical size. Increasing the superfine particle content appears to reduce the elutriation rate constant of all of the elutriable particles. These phenomena are related to interparticle interactions within the bed and/or the freeboard and confirm the importance of polydispersity in the elutriation behavior.

1. Introduction

Fluidized bed reactors are widely used in the chemical industry in fields as various as catalytic reactions, coal and biomass gasification, fluid catalytic cracking (FCC) in the petroleum industry, mineral processing, and other solid processing industries [1]. Yet, the complex phenomena involved in fluidization, including the entrainment of fines, still suffer from a lack of understanding. When a powder bed is fluidized by a gas, the superficial gas velocity U_g can overcome the free fall terminal velocity U_t of part or all of the particles of the bed, so that they are carried out of the fluidization column. Entrainment thus refers to the total flux of particles leaving the bed while elutriation refers to the classifying effect of entrainment because particles with different sizes or shapes can be entrained under different kinetics. Although this topic has been studied for years, a recent and very comprehensive review by Chew and co-workers [2] emphasized the dramatic discrepancies between the correlations proposed in the literature for the elutriation rate constant. They underlined the need for more physical understanding of the dominating parameters affecting entrainment.

Most of entrainment studies use the elutriation rate constant approach, whose theory is developed in part 2 of the present paper. The determination of the elutriation rate constant is mainly empirical, with experimental work relying on pilot fluidization columns of various scales and with various designs, especially running batchwise (unsteady-state system) or recycling the entrained fines back to the bed (steady-state recirculating system) [3]. The fluidized powder itself, with a given true density and particle size distribution (PSD), will determine the fluidization properties as indicated in the Geldart classification [4]. This classification distinguishes among four groups of particles: D (spoutable; e.g., roast coffee beans), B (sand-like; e.g., coarse sand, glass beads), A (aeratable; e.g., FCC catalyst), and C (cohesive; e.g., dust). The nature of the material itself is usually taken into account for the true density of the powder. Many studies are devoted to the entrainment of well-separated binary PSDs, e.g., elutriable group C particles in a bed mainly composed of non-elutriable group A or group B particles [5–11]. Fully elutriable group A–group C mixtures [12–15] have also been studied but wider PSDs have attracted far less attention [16,17]. It seems well-established that the smaller the particle is, the more easily it is entrained out of the bed and the higher the elutriation rate constant until a critical size is reached, at which point smaller particles experience significant interparticle forces and the elutriation rate constant levels off or even decreases [1,7–9,12,14,15]. Nevertheless, it is not clear whether the entrained particles of different sizes behave independently or if they interact with each other. By implicitly stating that an elutriable particle of a given size class has no influence on the other elutriable size classes, the polydispersity of the elutriable fines is sometimes neglected [6,9]. This lack of influence is often explained by

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the fact that in the bed, the fine-coarse interaction should be greater than fine–fine interaction. In addition, some researchers claim that the presence of superfines reduces the elutriation rate of larger elutriable fines. Li and co-workers [11] found the elutriation rate constant of group C and group A particles to be dependent on the weight fraction of the group C particles in the bed: an increased fraction of superfines decreases the elutriation rate of the fines because of increased interparticle adhesion. On the contrary, other researchers found that large entrainment of fines provoked an upward force on the particles in the freeboard, so that the elutriation rate of the larger fines is increased, even causing coarse bed particles whose terminal velocity U_t is less than the superficial gas velocity to be entrained [17–19].

The present work investigates the influence of the polydispersity of the entrained flux (or carryover) on entrainment by experimentally studying the entrainment out of a powder bed run batchwise with a wide PSD, ranging from group C to group B. The powder is metallurgical-grade silicon (MG-Si), obtained by comminution of silicon [20]. The ground powders have PSDs close to Rosin–Rammler distributions, that have proven useful in describing the product distribution of a number of comminution systems [21]. Such PSDs are therefore of significant interest for the fluidization of materials produced by size reduction in general and for the silicones industry in particular. In this latter industry, MG-Si is used in fluidized-bed reactors to synthesize dimethyldichlorosilane, a monomer of silicone polymers [22,23]. The impurity concentration in the reactive powder depends on particle size [24], emphasizing the importance of elutriation.

2. Theoretical background

2.1. Freeboard and transport disengagement height (TDH)

The freeboard is the section of the fluidization column between the bed surface and the column outlet. Bubbles bursting at the bed surface spray particles in the freeboard: coarse particles (with $U_t > U_g$) can fall back to the bed, while so-called elutriable particles (with $U_t < U_g$) are entrained, regardless of the height of the column. A description of the upward and downward motion of the particles in the freeboard was proposed by Pemberton and Davidson [19]. A critical height over the bed surface called the transport disengagement height (TDH) is defined, yet ambivalently [5]: often considered to be the height over which the solid density in the freeboard does not vary with increasing height, it can also refer to the height above which coarse particles cannot be found; these heights are referred to as TDH(F) and TDH(C) respectively [5]. TDH(C) is usually calculated based on ballistic models [25]. On one hand, TDH(C) relies on the assumption that there is neither momentum transfer between particles in the freeboard nor interactions of any type. This assumption is valid only with low solid concentration in the freeboard. On the other hand, the definition of TDH(F) is more versatile because it takes into account the fact that interparticle interactions can occur in the freeboard. For example, entrained particles can form clusters or agglomerates whose terminal velocity U_t is different from that of the individual particles. A theoretical description is more complicated and TDH(F) is generally determined on the basis of empirical correlations [1,26]. This latter definition will be adopted in the present paper because of its validity in the case of larger entrainment fluxes and polydisperse carryover. Note that it has been suggested to refer to aggregates formed due to cohesive forces as agglomerates and formed due to hydrodynamic forces as clusters [27]. However, Cocco et al., who experimentally observed “clusters” in the freeboard of fluidized beds for the first time, proposed a more complex mechanism: the formation of clusters would be assisted by hydrodynamic forces inside the bed, locally making cohesive forces dominant [28]. Once formed, these agglomerates or clusters can be ejected in the freeboard.

Entrainment studies are usually conducted with a freeboard height higher than the TDH, for the sake of reproducibility and because industrial applications generally attempt to minimize the carryover.

2.2. Definition of the elutriation rate constant

The total entrainment flux $E(h)$ (kg s^{-1} m^{-2}) is the weight of particles entrained per unit area and time at height h. If the particle sizes are divided into discrete size intervals, then the fraction of $E(h)$ due to particles of a given particle diameter d_{pi} (belonging to size interval i) is $E_i(h)$. The elutriation rate constant approach relies on the assumption that the entrainment flux $E_i(h)$ is directly proportional to the weight fraction of this particle size in the bed x_i^B, with their ratio being the elutriation rate constant $K_i^*(h)$. Above TDH, the entrainment flux is nearly constant and the notation becomes $K_{i\infty}^*$, by definition:

$$K_{i\infty}^* = \frac{E_{i\infty}}{x_i^B}. \tag{1}$$

In other words, a bed composed of particles with size d_{pi} only ($x_i^B = 1$) yields an entrainment flux $K_{i\infty}^*$. The main interest of this constant is to predict the individual $E_{i\infty}$ and the total entrainment E_∞ for a bed with any PSD:

$$E_\infty = \sum_i E_{i\infty} = \sum_i x_i^B K_{i\infty}^*. \tag{2}$$

Nevertheless, as mentioned in the Introduction, correlations for the elutriation rate constant are reliable under a narrow sets of conditions, because it is not clear if or when the elutriation rate constant of size d_{pi} particles $K_{i\infty}^*$ is impacted by the bed weight fraction x_j^B or the entrainment flux $E_{j\infty}$ of the other particles j.

2.3. Back-calculation of the elutriation rate constant from batch experiments

Starting from the definition in Eq. (1) and the definition of a flux, the following equation is obtained:

$$E_{i\infty} = -\frac{1}{A_B}\frac{d}{dt}\left(x_i^B W^B\right) = x_i^B K_{i\infty}^* \tag{3}$$

where A_B is the cross-sectional area of the bed (m^2) and W^B is the total weight of the bed (kg). For batch experiments, entrained particles are removed definitively, so that x_i^B and W^B depend on time. However, if the total entrained weight is relatively small, e.g., less than 20% of the total bed weight, then W^B may be regarded as constant for the integration [3]. Assuming the weight of fines adhered on the freeboard wall negligible, each particle leaving the bed is then entrained out of the column ($\frac{d}{dt}w_i^E = -\frac{d}{dt}w_i^B$) and Eq. (3) can be integrated as

$$w_i^E(t) = w_i^B(0)\left[1 - \exp\left(-\frac{K_{i\infty}^* A_B}{W^B}\,t\right)\right]. \tag{4}$$

In Eq. (4), $w_i^E(t)$ is the total cumulative weight entrained out of the bed, and $w_i^B(0) = x_i^B(0)W^B$ is the total weight of particles of the size interval i in the initial powder bed. The exponential coefficient is often expressed as the rate $K_{i\,\infty}$:

$$K_{i\infty} = \frac{K_{i\infty}^* A_B}{W^B}. \tag{5}$$

The elutriation rate constant $K_{i\infty}^*$ must be used because it is supposed to be unaffected by bed weight or column diameter [3] and does not depend on size discretization. Note that some authors alternatively chose to normalize: $K_{i\infty} = K_{i\infty}^* A_B / (x_i^B(0)W^B)$ [6,9].

The initial condition for the above integration relies on the hypothesis that every particle entrained after a long time was already present in the bed at the beginning of the experiment. This fact is not obvious, since particles can actually be created during fluidization. Colakyan and Levenspiel first presented a model accounting for elutriable