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Investigation of the particle flowpattern and segregation in tapered fluidized bed granulators

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Abstract

The particle flowpattern and granule segregation in tapered fluidized beds have been studied using two techniques. The first technique is to fluidize beds of varying total mass and granule fractions, then defluidize them suddenly to "freeze" the composition, section the bed in layers, and determine the composition of each layer by sieving. The second technique is to track a radioactive particle mimicking a granule as it moves in the bed. The results show that the segregation behaviour of granules is complex, their behaviour changing from flotsam at low granule concentrations to slightly jetsam at higher concentrations. The flow in the tapered bed is very different from what is expected based on relations derived for cylindrical beds. In the tapered bed a central region of high bubble activity and upward flow was a dominant feature. This "gulf streaming" became more pronounced as the total bed mass, and therefore the bed height, was increased, resulting in a bed turn-over time almost independent of the total bed mass. Quantitative data are given for upward and downward particle velocities and flows, bed turnover times, and axial granule concentration profiles.

Keywords: Granulation; Particle flowpattern; Segregation; Tapered fluidized bed; PEPT; Gulf streaming

1. Introduction

Mixing of solids in gas fluidized beds is of great importance for a variety of processes throughout industry. Fluidized beds are used for coal gasification, coking, catalytic cracking of heavier hydrocarbons, drying, granulation and coating. In these processes, mixing and segregation may be important for various reasons, depending on the application. For example, the surface renewal rate (surface mixing) is important in "top-down" spraying granulation.

Much research has been focused on the mixing of solids in cylindrical fluidized beds because of their extensive use in industry, or in rectangular beds for practical experimental reasons, e.g. for the study of bubble and wake volumes by X-ray techniques. Tapered beds, however, are favoured for some important processes, such as granulation, drying and coating. In some of these processes, spouted beds are used, but processes are also operated in a bubbling bed regime where less shear is applied to the fluidized particles (Schaafsma et al., 1999). Much less is known about the particle flowpattern in tapered fluidized beds than in cylindrical ones.

1.1. Particle flow in cylindrical beds

The research literature about the particle flow pattern in cylindrical fluidized beds is very voluminous, and we only mention a few aspects particularly relevant to this investigation.

Particle mixing in fluidized beds is induced by fluidization bubbles, which carry bed material from the bottom to the top of the bed. Upwards flow of particles takes place in the bubble wakes, which is material following the bubble, just as for gas bubbles in liquids, although the wakes generally are smaller in fluidization. Another additional, and potentially much larger, flow may take place due to "gulf streaming" in the bed: if the bubble density is much higher in one part of the cross-section than another—due, for instance, to inferior gas distribution or, in large beds, bubble concentration in the cross-sectional

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middle because of coalescence—material interstitial between the bubbles may be carried upwards in this region, causing a compensating downflow in regions with low bubbling intensity. A number of empirical relationships have been put forward for all aspects of the flowpattern in cylindrical fluidized beds, except "gulf-streaming". Many aspects are discussed in Baeyens and Geldart (1986).

Generally the bubbling intensity is calculated from the well-known "two-phase law":

$$U_b = U - U_{mf}, \tag{1}$$

stating that the gas flow in the form of bubble voids, U_b per unit area, equals the total fluidizing gas flow, U per unit area, minus the gas flow required to just fluidize the bed, U_{mf} per unit area. In other words: the gas in excess of that required to just fluidize the bed (the "excess gas flow") goes through the bed in the bubble phase. A corollary is that the voidage fraction, ε of the fluidized particles interstitial between the fluidization bubbles (the emulsion phase) remains approximately equal to that for minimum fluidization, ε_{mf} throughout the bubbling bed regime.

1.2. Fluidization and segregation in binary mixtures

In a binary mixture the fluidization behaviour is mainly determined by the smaller particles (fines), as long as they constitute more then 30% by volume (Rowe and Nienow, 1975); below that volume percentage they can no longer fill the interstitial space between the larger particles. Thus for a fluidized bed granulation process, it is expected that the behaviour of the bed during the granulation process will, to a large extent, depend on the primary particles during the early stages of the process.

If a bed contains particles with different physical properties, density and/or size, segregation may occur. The component that tends to segregate to the bottom is called jetsam and that tending to float is called flotsam (Gibilaro and Rowe, 1974). Various mechanisms for segregation have been proposed (Williams, 1990). We mention those that are relevant for this work below.

Visual observation of individual particle behaviour of group B powders shows that particles are most of the time immobile in a structure-like arrangement while being fluidized (Hartholt et al., 1996), and that this structure is able to support particles that are denser than the bulk bed particles. Shearing of the structure by fluidization bubbles rising in the vicinity gives individual denser particles the opportunity to descend.

In general denser and larger particles will tend to act as jetsam, if both density and size differ between two fractions present in the bed, density will have the dominating effect, except in very special cases (Chiba et al., 1980).

Literature provides several relations for quantifying the segregation (Rowe et al., 1972; Rowe and Nienow, 1975; Tanimoto et al., 1981; Bosma and Hoffmann, 2003). Tanimoto et al. (1981) introduced the term "segregation distance" $\bar{Y}_s$. This is a measure of the amount of segregation of a given particle fraction in the bed caused by the passage of one fluidization bubble. Bosma and Hoffmann (2003) rearranged the original relation of Tanimoto et al.:

$$\bar{Y}_s = 0.8\left(\frac{(\rho d_p^{1/3})_j}{(\rho d_p^{1/3})_{av}} - 1\right), \tag{2}$$

where ρ and d_p are the particle density and diameter, respectively, and subscripts j and av signify the jetsam and the volumetric averages, respectively.

Rowe et al. (1972) found for a binary system that the fraction jetsam in the uniform mid section of the bed ($x_{\mathrm{mid},j}$) can be described with:

$$x_{\mathrm{mid},j} = f(U - U_{mf})\left(\frac{\rho_j}{\rho_f}\right)^{-2.5}\left(\frac{d_{p,j}}{d_{p,f}}\right)^{-0.2}, \tag{3}$$

where subscript f signifies the flotsam fraction.

Both of these relations show how the density dominates the particle size in determining the extent of segregation. Depending on the local composition of the bed material, a certain fraction of particles may change character, from jetsam to flotsam or vice versa (Hoffmann and Romp, 1991).

When one fraction of particles, e.g. granules, is much larger than the other, e.g. the primary particles, there is, however, a simpler way of looking at the issue of segregation. A large object, with a volume V_g in a fluidized bed of particles with volume V_p will experience the macroscopic (on a scale large compared to the small particles) pressure gradient in the bed if $V_g > \approx 30 V_p$ (Clift et al., 1987), and will therefore experience a "buoyancy force", F_b given by

$$F_b = V_g g(\varepsilon_{mf}\rho_g + (1 - \varepsilon_{mf})\rho_p) = V_g g \rho_{\mathrm{bulk},mf}, \tag{4}$$

where subscript g signifies the fluidizing gas, and we have defined the bulk density, $\rho_{\mathrm{bulk},mf}$, of the emulsion phase.

Comparing this with the force of gravity acting on the large particles: $V_g g \rho_g$, where ρ_g is the envelope density (thus including any internal pores) reveals whether the large particles will act as flotsam or jetsam in the bed.

1.3. Particle flow and mixing and segregation in a tapered fluidized bed

As mentioned above, investigations of particle mixing in fluidized beds have been performed mostly in cylindrical or rectangular beds, and to some extent in tapered beds with small air inlets operated in the spouted region. Little research has been done on the bubbling fluidizing regime of a tapered bed (Ridgway, 1965; Toyohara and Kawamura, 1991).

The main difference between tapered fluidized beds and other fluidized beds is that in the former the fluidization velocity decreases axially. Thus according to conventional wisdom, and the two-phase theory given above, the bubbling intensity, and therefore particle mixing, should decrease when moving up the bed. However, tapered beds do not act entirely in this way. Toyohara and Kawamura (1991) distinguished three flow regimes in tapered beds (Fig. 1). Which regime prevails depends on the fluidization velocity and the bed geometry, in particular the cone