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Experimental study on orientation and de-mixing phenomena of elongated particles in gas-fluidized beds

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ABSTRACT

In this experimental study the segregation behavior for fluidized mixtures of spherical and cylindrical particles is investigated. In industry, fluidization of particles featuring a wide range of shapes is common in various applications such as biomass gasification, drying applications, food processing and production of pharmaceuticals. Earlier publications have mainly focused on segregation of spherical particles of different volume or density. The particles used in this study have equal volume and density but a different shape. The main purpose of this work is to study de-mixing driven by particle shape.

To analyze the particle distributions inside the fluidized bed, a Digital Image Analysis (DIA) technique has been developed, capable of capturing the particle positions and orientations within the bed over time. The experiments show that in the non-bubbling flow regime (at low fluidization velocities) rod-shaped particles may segregate, sinking to the bottom of the bed. In the bubbling flow regime (at higher fluidization velocities) segregation does not occur, because of bubble-induced mixing. Here strong alignment of the cylindrical particle's long axis with the flow is observed. The experimental results obtained give qualitative and quantitative insight in the behavior of non-spherical particles in fluidized beds and can be used for validation of numerical models concerning non-spherical particle mixing.

1. Introduction

Ideal particulate systems consisting of mono-sized particles of equal densities seldom occur in practical fluidized bed applications. Instead, in practical applications particles of a wide size distribution and/or different densities are used. In these non-ideal systems, particle mixing and segregation can occur at specific operating conditions. A bed may be 'well fluidized' in the sense that all the particles are fully supported by the gas, but may still be segregated in the sense that the local bed composition does not correspond to the average [1]. Segregation is likely to occur when there is a substantial difference in the drag force per unit mass between different particles.

In this paper, segregation induced by differences in particle shape is examined. Most of the research reported so far focuses on segregation of spherical particles ([2–11]). The effect of particle size and density on segregation behavior has been documented [1,12] and is understood quite well in a qualitative sense. But non-spherical particles are often encountered in fluidized process equipment. An important example is the production of syngas from biomass in fluidized bed gasifiers. The used bio-materials are typically milled before being fed to the gasifier, resulting in particles with common aspect ratios of 3 to 5, sometimes up to 12 [13]. The expected segregation behavior of such elongated particles is quite different from that of spheres [14]. Vollmari et al. [15] investigated mixing of bi-disperse systems of various particle shapes (spheres, cubes and plates) and showed that particle shape plays an important role in the mixing process. For elongated particles the projected area of a particle changes with orientation, and particles tend to align with the walls of the bed, leading to very different mixing dynamics [16]. The aforementioned studies analyzed mixing of an initially completely segregated system. In this work the opposite problem is studied; we will analyze segregation behavior in a fluidized bed starting from a well-mixed state. We will limit our studies to mixtures of spheres and rods of equal volume and density.

Mixing studies in fluidized beds require information on the transient particle positions in the bed. Several experimental techniques are available to measure the position and orientation of non-spherical particles, such as Position Emission Particle Tracking (PEPT) [17], Particle Tracking Velocimetry (PTV) [18], and Magnetic Particle Tracking (MPT) [19,20]. So far, these techniques were only used to study the orientation of individual particles. This requires long measurement times to obtain statistically significant data for the entire bed. Also, to

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our knowledge, the co-alignment of particles has not been addressed yet. Particle tracking techniques are not capable of measuring this feature because only one particle is tracked. Using imaging techniques, such as Digital Image Analysis (DIA), it is possible to study the position and orientation of multiple particles simultaneously. The technique developed in this work builds on a technique developed by Olaofe et al. [21,22], but has now been extended to elongated particle shapes. Because the technique is intrinsically 2D, only the position and orientation of cylinders that are in plane with the front wall of the fluidized bed can be determined.

The outline of this paper is as follows. First the experimental methods and image analysis techniques are discussed in Sections 2 and 3 respectively. Section 4 deals with the basic theory on quantification of mixing phenomena. In Section 5 the experimental results are discussed. Finally, we present the main conclusions in Section 6.

2. Materials and methods

2.1. Materials

For the experiments, a shallow pseudo-2D fluidized bed was used, with dimensions listed in Table 1. The depth of the bed is approximately 5 particle diameters, which increases the visibility of the particles. Air is supplied to the bed by three tubes and redistributed evenly by a sintered metal porous plate at the bottom of the bed (see Fig. 1). The air supply is regulated by a mass flow controller, coupled to a PC. The maximum airflow is 630 NL/min, which corresponds to a superficial velocity of 8 m/s. Near the distributor plate a digital pressure sensor was mounted to dynamically measure the pressure drop over the bed.

The bed material consisted of stainless steel spheres and cylinders, mixed in various ratios. For visualization purposes some of the particles were painted (as seen in Fig. 1), but most of the experiments were performed using untreated particles featuring a bare metallic surface. Care was taken to give both particle species equal mass and volume but a different shape, since the subject of this study is shape-driven segregation.

The motion of the solid particles in the bed was captured by a 3-CCD camera (model JAI AT-200 GE) at a resolution of 1624 × 1236 pixels with a magnification of 7.8, yielding 90 μm/pixel. Consequently, the spheres are recorded with a resolution of 30 pixels across the diameter and the cylinders are recorded with about 130 pixels along the length. A short shutter time combined with a relatively large aperture was used, yielding images with little motion blur, even at high particle velocities. Appropriate lighting is provided by two LED arrays, each consisting of 72 LED's giving 250 W of illumination per array.

3. Digital Image Analysis techniques

Digital Image Analysis (DIA) is used to analyze the images that were recorded during the experiments. The composition of the fluidized bed and the orientation of the cylindrical particles were determined using several image analysis techniques.

3.1. Determining bed composition

The spherical particles used in this research have a metallic finish and show distinguishable reflection spots when illuminated by a strong light (see Fig. 2a). Since the bed is illuminated by two LED light sources, each spherical particle -in principle- yields two reflections that can be clearly identified from the images. The cylindrical particles, on the other hand, have a rather dull surface that reflects light in a much more scattered way; no clearly defined reflection spot is observed. This difference in reflective properties between the particle species has been exploited to identify the two different particles species and subsequently determine the bed composition.

Table 1
Dimensions and properties of the fluidized bed and particles.

Vessel dimensions	500 × 100 × 15 mm (height, width, depth)
Bed material	0.5 kg stainless steel particles, ±100 mm bed height
Spherical particle diameter	3 mm
Cylindrical particle diameter × length	1.2 × 12 mm
Minimum fluidization velocity (spheres)	3.15 m/s

For the analysis, first the image is cropped, removing the side walls of the fluidized bed (Fig. 2a). Secondly the fraction of the image occupied by the solid phase is determined (see Fig. 2b). Since the particles and the background have a distinctly different color, this could be determined with relative ease. In the third step the DIA script counts the number of reflection spots in each grid cell (Fig. 2c, d). This is done using a circular Hough transform, available in MATLAB as the function imfindcircles. For the analysis of mixing the bed is divided into grid cells. For each cell the occupancy (2d solid volume fraction) and the number of reflections per unit of solids area can be computed (see Fig. 2e, f).

Finally, calibration was used to relate the number of reflections in each grid cell to the actual composition in that grid cell. In this way the number of reflections per grid cell N_r is obtained from the images, which can directly be used as a measure for the bed composition.

$$r = \frac{N_r}{A_{grid} \times \varepsilon_{solid}^{2D}} \tag{1}$$

The area of each grid cell occupied by the solid phase equals $A_{grid} \times \varepsilon_{solid}^{2D}$, where A_{grid} is the area of the grid cell, and ε_{solid}^{2D} is the fraction of the cell occupied by solid particles (in 2D). To obtain the number of reflections per unit of solid area (r), the number of reflections (N_r) is divided by the area occupied by the solid phase.

The maximum number of reflections one may encounter for a given grid size is obtained when spherical particles are packed in the most dense state possible. For circles in the 2D plane, this corresponds to a hexagonal packing, where the maximum number of reflections equals:

$$r_{max} = \frac{4}{\sqrt{3}d_p^2} \tag{2}$$

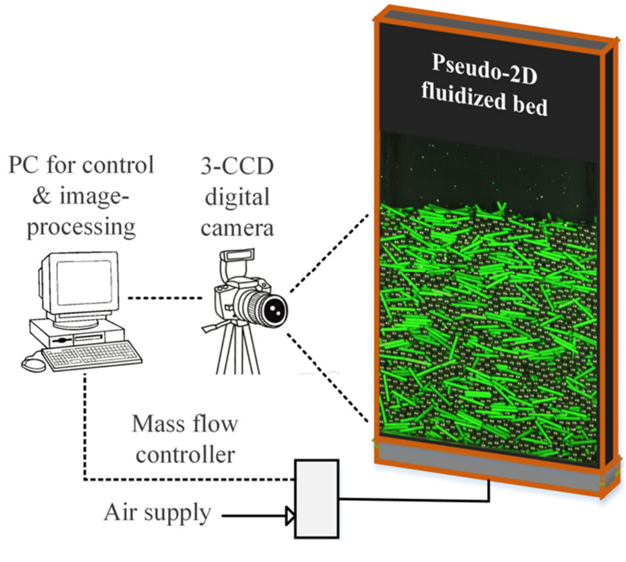

Fig. 1. Schematic of the experimental setup.