Powder Technology 246 (2013) 695–706

Contents lists available at SciVerse ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Segregation dynamics in dense polydisperse gas-fluidized beds

O.O. Olaofe [a], K.A. Buist [a], N.G. Deen [a,*], M.A. van der Hoef [a,b], J.A.M. Kuipers [a]

[a] Eindhoven University of Technology, Department of Chemical Engineering and Chemistry, PO Box 513, 5600 MB Eindhoven, The Netherlands
[b] University of Twente, Faculty of Science and Technology, PO Box 217, 7500 AE Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 23 May 2013
Accepted 25 May 2013
Available online 26 June 2013

Keywords:
Fluidization
Segregation
Digital Image Analysis
Binary particle systems
Ternary particle systems
Pseudo-2D bed

ABSTRACT

New fluidization experiments have been carried out with: a binary mixture containing 2.5 and 3.5 mm particles in equal proportions, some binary mixtures containing 1.5 and 2.5 mm particles in several proportions, and a ternary mixture containing 1.5, 2.5 and 3.5 mm particles in equal proportions. The segregation behavior of the mixtures of spherical glass particles was studied in a pseudo two-dimensional laboratory scale gas-fluidized bed with the aid of a newly developed non-intrusive Digital Image Analysis technique. The segregation index introduced by Goldschmidt et al. [1] has been used to quantify the segregation dynamics in binary mixtures, and two adapted forms of it have been used to study the segregation dynamics of the ternary mixture. Furthermore, a (mean) height index was introduced to provide more details about the dynamics of the ternary system. Our experiments reveal that while the binary systems could segregate slightly at fluidization velocities exceeding the incipient velocities of the individual components, the ternary mixture becomes well mixed at velocities even well below the incipient fluidization velocity of the large, 3.5 mm particle.

1. Introduction

The mixing and segregation of particles of various types in gas–solid fluidized beds are a common phenomenon that has been observed in experimental investigations [1–5 etc.], where the importance of understanding the dynamics of this phenomenon cannot be overemphasized. Mixing and segregation behavior of systems with different particulate species affects the particle distribution in such systems and this in turn influences the heat and mass transfer rates, bed expansion and chemical conversion rates in the systems.

There are many examples of systems where detailed understanding of this phenomenon is important. An example of a process in which mixing is important is the combustion of biomass and coal. A detailed knowledge of the dynamics of mixing of the fuel particles is crucial to minimize the number of fuel feeding ports as well as lowering the excess air in the combustion of the solid fuels [6]. The production of some crystalline chemicals is another example. In order to meet powder specifications, fine crystalline chemicals or their intermediates are often dried or blended with other components. Furthermore, in spray granulation, the degree of mixing at the surface is important [7]; and in fluidized bed drying operations encountered in the pharmaceutical industry, it is necessary that small drug particles are uniformly blended with larger particles, avoiding separation [8]. There are also processes in which the enhancement of segregation is desirable. In fluidized beds for the incineration of sewage sludge or other waste materials, segregation of the larger fuel particles is desirable because the vertical location of fuel particles influences the in-bed combustion efficiency of volatile matter [9]. Furthermore, in gas–solid olefin polymerization reactors, the segregation of the larger product particles to the bottom of the bed is desirable for separation purposes [10]. In these reactors, a concurrent mixing of polymer particles is even necessary to avoid hot spots. Generally speaking, segregation is more desirable when fluidized beds are used as separation units and less desirable when they are used as reaction units. Segregation enhances the performance of processes in which the physical separation of solid particles in columns is desirable and diminishes the efficiency of chemical processes where a well-mixed heterogeneous system is desirable. In essence, a detailed understanding of the behavior of polydisperse beds will help in improving the performance of these processes and the efficient design and operation of new ones.

In a mixture with particles of different densities, the denser particles tend to act as the sinking component (jetsam) with a decreasing degree of segregation as the fluidization velocity increases [5], and for mixtures containing particles of same densities, the smaller particles tend to act as the rising component (flotsam). However, it is important to note here that exceptions do exist. Under some very constrained conditions of limited direct practical value, layer inversion, in which the flotsam and jetsam switch roles as gas velocity increases, has been reported by Rasul et al. [11].

Numerous experiments have been conducted in attempts to quantify the mixing/segregation dynamics of binary mixtures in gas-fluidized beds in terms of fluidization conditions and particle properties. Rowe et al. [12] investigated the fluidization behavior of six binary combinations of particles that differed in size, in density and in both ways. They observed that three different mechanisms, which were all

* Corresponding author.
E-mail address: N.G.Deen@tue.nl (N.G. Deen).

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http://dx.doi.org/10.1016/j.powtec.2013.05.047

associated with bubble motion as suggested by Zenz et al. [13] for fine particles, describe the mixing and segregation behavior of mixtures in cylindrical or two dimensional beds. While mixtures differing in densities were more easily segregated, the ones differing in size alone were more easily mixed. Gibilaro and Rowe [14] derived a model to quantify the equilibrium segregation profiles in binary mixtures, but their model involved some parameters which were rather difficult to evaluate. Chiba et al. [15] introduced a simple concept of segregation maps to predict which of the particle classes in a binary mixture will become the flotsam or jetsam or whether the whole bed will be well mixed. The prediction is based on the sizes, densities and minimum fluidization velocities of the two solids. Geldart et al. [16], from experiments they conducted in cylindrical beds, posited that segregation by size increases with increasing difference in the sizes of the particles, an increase in their mean size, and as the fluidization velocity in the medium approaches the incipient fluidization velocity of the smaller particles. Horio et al. [17] classified the behavior of binary beds based on the diameter ratios of their contents [18]. After conducting experiments in rectangular beds, Tanaka et al. [19] presented the optimum operating conditions for the separation of mixtures containing two different-sized glass beads from experimental studies. Focusing on the need for detailed experimental conditions and results for validation of fundamental hydrodynamic models, Goldschmidt et al. [1] carried out some fluidization experiments using binary mixtures in pseudo-2D beds. More recently, Joseph et al. [20] investigated the segregation behavior of glass polystyrene mixtures of different sizes and densities in cylindrical columns, and Gao et al. [21] investigated the hydrodynamics of binary mixtures in turbulent fluidized bed in cylindrical columns. Furthermore, Zhang et al. [22] evaluated the mixing and segregation behavior of biomass–sand mixtures, in rectangular columns, in terms of flow patterns, solid concentration profile and mixing index; and Rao et al. [23], from the studies they conducted in cylindrical columns, categorized the behavior of binary mixtures in a map by using the ratio of the minimum fluidization velocities of the components which they computed from density and size ratios. Following successful quantitative verification based on earlier works, Di Maio et al. [24] developed a model for predicting the flotsam and jetsam in binary mixtures in which the diameter difference of the two solid components contrasts with the density difference. Their model had size and diameter ratio, voidage and bed composition as inputs and addresses only initial segregation direction without any information on rates of segregation. Most of the aforementioned works, with the exception of Goldschmidt et al. [1], do not give detailed information on the time evolution of the extents of segregation in the systems they investigated.

Some studies have gone ahead to study experimental ternary mixtures specifically although with rather limited scope. San Jose et al. [25] looked at the segregation behavior of glass spheres in conical spouted beds. To describe the segregation profile in the bed, they measured the radial and axial distribution of the Sauter diameter of the mixture at various positions in the bed. Furthermore, they adopted a mixing index that is not durable for describing the time evolution of segregation. San Jena et al. [26] measured the bed voidage, fixed bed pressure drop and the minimum fluidization velocities of ternary mixtures in square beds without looking at the segregation behavior of the individual components. Sahoo et al. [27] investigated the fluidization behavior of ternary mixtures of equi-density particles in a cylindrical column. In their work, they developed a correlation for the mixing index that was not very sensitive to the segregation pattern in the bed. None of these works studied the fluidization of ternary mixtures in pseudo-2D fluidized beds.

Tremendous research efforts are ongoing to improve the predictive capabilities of fundamental hydrodynamic models. For a model to be valid, not only must it predict adequately the bubbling characteristics and porosity distribution in a multi-component system but also the degree, rates and trend of mixing and segregation. This work serves to address the dearth in detailed experimental results for the validation of these models. A newly developed non-intrusive Digital Image Analysis technique [28], that exploits the advancements in photography, has been deployed to provide reliable 'in situ' experimental data to augment the results from the binary experiments conducted by Goldschmidt et al. [1]. In addition new fluidization experiments have been carried out to investigate the segregation behavior of a ternary system. Consequently, deeper insights into the dynamics of segregation of binary and ternary mixtures are elucidated.

2. Experimental set-up

Full details of our novel experimental technique are given in Olaofe et al. [28], but for clarity and convenience a brief description is given here. In our technique, new improvements in the capabilities of state-of-the-art photographic equipments are used for the identification of bubbles, determination of local compositions and the extents of segregation at small time intervals. Digital frame shots of the fluidized bed are taken at 15 fps, and the images obtained are processed by a program script that identifies the colored particles on the basis of the unique HSV color space attributes that they express in pixels. This processing is done after the bubble void areas have been removed. After the bubble removal and particle detection, cells are drawn across the bed and the actual compositions in these cells are evaluated using a calibration fit that takes into account the disproportion in the representation of particles of different sizes at the wall. The actual compositions, together with their positions, are then substituted in the relations introduced by Goldschmidt et al. [1] for the evaluation of extents of segregation.

In this work, the fluidization experiments were carried out for unary, binary and ternary mixtures in a pseudo-2D fluidized bed with a width of 30 cm, a height of 80 cm and a depth of 1.5 cm, and pressurized utility air is applied as the fluidization gas. Initially, the required amount of particles of the various types were weighed and then poured into the bed. Thereafter, the mixture was fluidized vigorously for thorough mixing and then stopped abruptly for the bed to collapse. The mass flow controllers were then set to values just below the flow rate required for fluidization with the bed remaining static. Subsequently, the velocity was switched

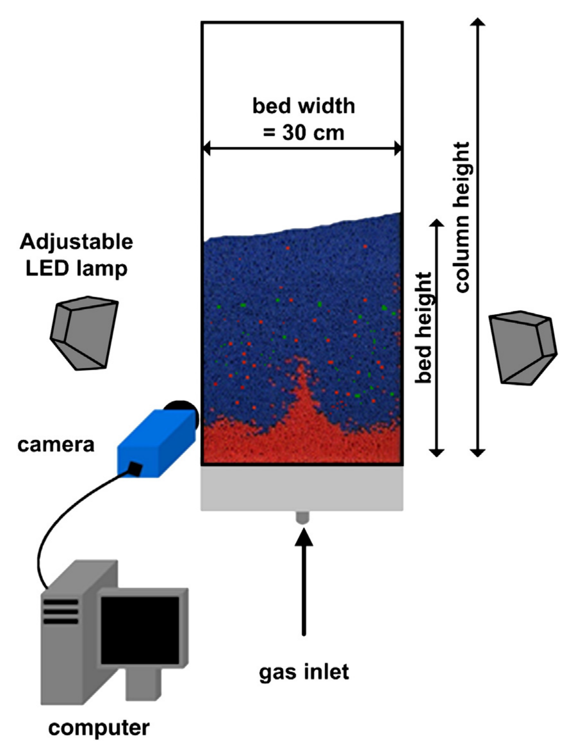

Fig. 1. Fluidized bed schematic of segregation experiments. The bed width, height and depth are 30 cm, 80 cm and 1.5 cm respectively.