Particuology 21 (2015) 55–64

Contents lists available at ScienceDirect

Particuology

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

A solids mixing rate correlation for small scale fluidized beds

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ARTICLE INFO

Article history:
Received 16 July 2014
Received in revised form
18 September 2014
Accepted 6 October 2014

Keywords:
Fluidized bed
Solids mixing
Tracer
Digital image processing
Mixing index
Mixing rate

ABSTRACT

A new first degree solids mixing rate is proposed to evaluate the mixing of solids in small scale fluidized beds. Particle mixing experiments were carried out in a 2D fluidized bed with a cross-section of 0.02 m × 0.2 m and a height of 1 m. White and black particles with average diameters of 850 and 450 μm were used in our experiments. Image processing was used to measure the concentration of the tracers at different times. The effects of four representative operating parameters (superficial gas velocity, ratio of tracer particles to bed particles, tracer particle position, and particle size) on mixing are discussed with reference to the mixing index. We found that the Lacey index depends on the concentration of the tracers. The position of the tracers affects the initial mixing rate but not the final degree of mixing. However, the new mixing rate equation does not depend on the initial configuration of the particles because this situation is considered to be the initial condition. Using the data obtained in this work and that found in literature, an empirical correlation is proposed to evaluate the mixing rate constant as a function of dimensionless numbers (Archimedes, Reynolds, and Froude) in small scale fluidized beds. This correlation allows for an estimation of the mixing rate under different operating conditions and for the detection of the end point and/or the time of mixing.

Introduction

Fluidized bed technology is widely applied in the chemical, mineral, petroleum, energy, environment, pharmaceutical, and biochemical industries (Kunii & Levenspiel, 1991; Yang, Luo, Fang, Fan, & Cen, 2014). The high specific surface area of the solids in fluidized beds benefits many operations such as those requiring gas–solid reactions, cooling, and drying (Godlieb, Deen, & Kuipers, 2007). The mixing of particles influences the rates of heat and mass transfer in fluidized beds and enables the final conversion of the chemical reactions carried out in these beds to be controlled (Mostoufi & Chaouki, 2000, 2001). In many cases, the proper mixing of particles is crucial in ensuring uniform cooling, reaction, or the drying of particles and it also prevents the formation of hot spots (Bokkers, van Sint Annaland, & Kuipers, 2004; Zhang, Jin, & Zhong, 2008).

Recently, some experimental and numerical investigations into fluidized beds have been undertaken with the focus on solids mixing (Deen, Willem, Sander, & Kuipers, 2010; Derksen, 2008; Di Renzo, Di Maio, Girimonte, & Formisani, 2008; Huang, Wang, & Wei, 2008; Lu & Hsiau, 2005; Norouzi, Mostoufi, Mansourpour, Sotudeh-Gharebagh, & Chaouki, 2011; Norouzi, Mostoufi, & Sotudeh-Gharebagh, 2012; Westphalen & Glicksman, 1995; Wu & Zhan, 2007; Wu, Men, & Chen, 2011). Shen and Zhang (1998) studied the effect of particle size on the mixing of particles in a 2D fluidized bed. They observed that fluctuations of concentration in both the vertical and horizontal axes increased as a result of particle growth. Hull, Chen, and Agarwal (2000) investigated the mixing of solids in a 2D fluidized bed by analyzing videos. They concluded that the speed of mixing is higher for tracer particles that enter the middle of bed compared with those below and above the bed particles. Pallares and Johnsson (2006) studied the mixing mechanisms of solids in 2D fluidized beds. They showed that a reduction in the size of the tracer particles results in a more homogeneous concentration distribution and an increase in vertical dispersion whereas horizontal dispersion remains nearly unaffected. Wirsum, Fett, Iwanowa, and Lukjanow (2001) indicated that smaller and denser flotsams in general improve vertical mixing at high superficial velocity. Rhodes, Wang, Nguyen, Stewart, and Liffman (2001) studied the effects of gas velocity and particle properties on mixing based on a DEM simulation. Their results indicated that the time required for mixing decreases upon an increase in the gas

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http://dx.doi.org/10.1016/j.partic.2014.10.003

Table 1
Properties of the solid particles.

Particles	d_p (μm)	ρ_p (kg/m^3)	U_{mf} (m/s)	U_t (m/s)
Glass bead	850	2600	0.44	6.41
Glass bead	780	2600	0.39	6.05
Glass bead	450	2600	0.153	3.95

velocity and the degree of mixing decreases with an increase in particle size.

Solids mixing is important in small scale fluidized beds which are used in many industries including the food and pharmaceutical industries, and in processes involving physical and chemical changes. A quantitative assessment of solids mixing is required to improve product quality in applications such as the coating of particles, the drying of powders, and in granulation (Kulah & Kaya, 2011; Liu & Chen, 2012; Smith, 2007; Yang et al., 2014). Moreover, a sufficient understanding of the mixing behavior of powders is vital for the mechanical design of fluidized bed accessories such as the position and the number of solids feed and solids withdrawal points (Mostoufi & Chaouki, 2000, 2001). A significant parameter of solids mixing is the time required to reach the desired level of homogeneity in a fluidized bed. This time is related to the mixing rate, which can be used to scale up a particular process. The prediction of mixing rate under various operating conditions is thus necessary. In this work, an image processing method was used to investigate the mixing behavior of spherical particles in a 2D fluidized bed. The effects of four fundamental operating parameters (superficial gas velocity, ratio of tracer particles to bed particles, tracer particle position, and particle size) were investigated with regard to solids mixing by assessing the mixing index. The rate and degree of mixing was evaluated by comparing the mixing index against time. An empirical correlation is proposed to estimate the mixing rate in a small scale (lumped) fluidized bed.

Materials and methods

Experimental apparatus

All experiments were carried out in a 2D fluidized bed. This bed is schematically shown in Fig. 1. The column was made of glass with a cross-section of 0.2 m × 0.02 m and a height of 1 m. A distributor was placed symmetrically at the bottom of the bed. Air at room temperature was supplied to the bed by a compressor. The air flow rate was adjusted in the range 1–2000 L/min by a mass flow controller (MFC).

Particle characterization

The solid particles used in the experiments were glass beads with mean diameters of 850 and 450 μm. The properties of the particles are given in Table 1. The tracers were beads that were dyed black with ink and dried in an oven at 150 °C for approximately 2 h. Therefore, the tracer particles had the same physical properties (shape, size, density) as the bed material.

Experimental procedure

A photographic method was used to study mixing in the 2D fluidized bed in this work. Gray cardboard was placed behind the bed as a background. Two halogen lamps were used for uniform lighting, each located on opposite sides of the bed, as shown in Fig. 1. Pictures of the column were taken with a Canon PowerShot SX260 HS at a resolution of 12.1 megapixels. This digital camera included a consecutive shooting mode of up to 2.4 frames/s in JPEG format.

Table 2
Experimental conditions and particle positions in the 2D bed.

No.	Type of particles (size in μm)	Height (m)	Initial loading pattern
1	White (850)	0.1	Initially, the bed is filled with white particles, then the black particles are located on them
	Black (850)	0.1	
2	White (850)	0.18	As
	Black (850)	0.02	above
3	White (850)	0.1	First, 50% of white particles are fed in the bed, then black particles followed by the remaining 50% of white particles
	Black (850)	0.1	
4	White (90% 850–10% 450)	0.1	As
			in
	Black (90% 850–10% 450)	0.1	No.
			1

Each experiment was carried out following the procedure: the particles were initially packed into two individual layers. The order of the particles, the ratio of tracer particles to the bed particles, and the particle composition are shown in Table 2. Air was introduced into the bed by tuning the MFC. Photos were then captured by the digital camera.

Image analysis

An image processing method was used to determine the concentration of the tracer particles for each figure captured by the digital camera. In this method, each image was divided into 36 (6 × 6) cells of the same size as shown in Fig. 2. A code was developed in which the gray scale image was quantized into three intensity levels: black, white, and gray. White, black, and gray pixels represented white particles, tracer particles, and bubbles, respectively. Distinguishing between black, white, and the background was achieved using a histogram of the image. The image was quantized into a three intensity level image. The black particles, white particles, and background were identified according to their intensities using two threshold points. The fraction of black particles in each of these parts was evaluated by counting the number of black, white, and gray pixels. Computation details are described in the next session.

Mixing characterization

Various mixing indexes can be used to describe the effectiveness of different mixers in processing industries. Most of these indexes have been developed based on statistical analysis and especially on the definition of standard deviation (Lacey, 1954; Rhodes et al., 2001; Zhang, Jin, & Zhong, 2009). To quantify the quality of mixing in the binary mixture the well-known Lacey index was used in this work.

In this work, the concentration of the tracer particles was calculated as follows:

$$c_i = \frac{n_i}{n_{it}}, \tag{1}$$

where n_i and n_{it} are the number of tracer particles in a given sampling cell and the total number of particles in each sampling cell (including the tracer and bed particles), respectively. The variance, σ^2, of the concentration of tracer particles in each cell is defined as:

$$\sigma^2 = \frac{\sum_{i=1}^{N}(c_i - c_m)^2}{N}, \tag{2}$$

where c_m is the average concentration of black particles in the bed (Deen et al., 2010; Zhang et al., 2009). The standard deviation is