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On the bubbling dynamics of binary mixtures of powders in 2D gas-solid fluidized beds

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ABSTRACT

The bubbling behavior of fluidized beds has been thoroughly investigated in the last decades by means of several techniques (e.g. X-ray, Inductance, Resistance and Impedance based techniques). In recent years, Digital Image Analysis Techniques have shown their potential for accurate and cost effective measurements.

Most of the works related to the experimental analysis of bubble behavior in the field of gas-solid fluidization actually deal with monodispersed particles although almost all industrial equipments operate with mixtures of particles. Among the works available in literature dealing with mixtures of particles having different diameters and/or densities, most of them aim at the assessment of minimum fluidization conditions and mixing/segregation phenomena. A lack of knowledge exists in the experimental analysis of bubble properties measurements of polydispersed systems.

In this work, a Digital Image Analysis procedure has been applied to the case of binary mixtures of particles in bubbling fluidized beds, in order to measure bubble fundamental characteristics such as bubble diameter, bubble number and bubble rise velocity, i.e. data actually unavailable in the literature. The experiments have been carried out at steady state conditions with binary mixtures of corundum particles and glass particles, at various inlet gas velocities. A preliminary statistical analysis has been performed to describe bubbling dynamics, which may well be a starting point for future development of predictive correlations.

1. Introduction

Gas–solid flows are often encountered in industrial processes. Discharge from hoppers and pneumatic transport of large quantities of powders are some of the industrial applications where gas–solid flows are involved. In the area of chemical processes, fluidization is actually a widely employed technology. The success of fluidized bed processes in chemical, petrochemical, food and pharmaceutical industries is due to the fact that a fluidized system enables higher heat and mass transfer rates between the solid phase and the gas phase than in a fixed bed operating with the same pressure drop. Moreover it allows an easier handling of the particulate phase.

Industrial applications take advantage of the high availability of effective particle surface area that exist in the bed. The high degree of mixing between the particles and the gas flowing through them can improve significantly the efficiency of a process. Mixing within the bed is driven by the particle-free voids that form when the gas flow rate exceeds the superficial velocity of minimum bubbling. Bubbles ensure that the particles are circulated through the bed so that properties and process conditions may be considered uniform within the bed. In fluidized solid–gas systems bubbles govern hydrodynamics and determine the efficiency of the operation [1]. The fluidization quality of a bed is, therefore, highly dependent on bubble distribution and bubble physical properties. Ideally, for optimal fluidization quality, the population of bubbles in a bed should be large, but the bubbles should be small in size, and homogeneously occupy the bed [2].

2. Literature review

The fluidization behavior of mixed powders with different diameter or density strongly depends on the nature and composition of the mixture. One of the main characteristics of fluidized mixed powders is the possible onset of segregation or mixing dynamics, depending on inlet gas velocity and particle characteristics. In particular, the heavier (or larger) particles, hereafter referred to as jetsam component, show the tendency to segregate toward the bottom of the bed, while the lighter (or smaller) particles, hereafter referred to as flotsam component, tend to float above the segregated particles [3].

Traditional studies dealing with bi-dispersed fluidized beds are often focused on the link between operating conditions and mixing/segregation extent, as derived from measured solid concentration profile along the bed [4], on the determination of minimum fluid velocity necessary to fully fluidized them, [4–7], on the fluidization regimes characterization [8–10] or on the mixing index characterization [11–13]. In practice, differently from single-sized particles that generally exhibit an unambiguous minimum fluidization velocity, bi-dispersed granular systems often

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show different fluidization modes, depending on the particle characteristics and initial state of the bed itself. Two characteristic velocities U_{if} and U_{ff} (initial and final fluidization velocity respectively) can be observed [8], which define a range where a transient fluidization regime is obtained, corresponding to systems with partial tendency to segregation. Fully mixed states occur only at inlet gas velocities exceeding the U_{ff}.

Researchers have also extensively investigated how dissimilar fluidized particles mix and segregate, aiming at predicting the behavior and understanding the underlying mechanisms of mixing and segregation [12,13,11]. Several techniques have been used to characterize mixing extent at different operating conditions, *i.e.* by means of the frozen bed technique [14–17] or image analysis [18–22].

A great number of researchers have chosen digital visual methods to be applied in the field of experimental fluid dynamics thanks to the continuous development of digital imaging systems and digital image processing. These techniques play a fundamental role in analysis and data acquisition for multiphase flows such as gas–solid, gas–liquid, solid–liquid flows, where the observation of inter-phase boundaries is relatively simple. Digital visual methods are limited of course to the case of bidimensional fluidized beds, as in this case bubbles can be easily observed [18,23,24,2,25–27].

Digital Image Analysis techniques were also used for quantification of the extent of mixing and segregation in a bidispersed gas–solid fluidized bed. [1] studied the extent of mixing and segregation in a bidispersed gas–solid fluidized bed induced by a single bubble injected in a monodispersed and bidispersed fluidized bed at incipient fluidization and in freely bubbling fluidized beds with both experiments and numerical simulation performed with the Discrete Particle Model. Experiments were with a pseudo-2D fluidized bed, front-illuminated by halogen lamps. Fluid bed images were taken by means of a high-speed digital camera. The Particle Image Velocimetry (PIV) technique was applied for obtaining experimental particle velocity fields. The PIV technique adopted is the same widely used for single phase fluid flows, with the only exception that fluid seeding is substituted by direct particle tracking. [28] developed Digital Image Analysis Technique to measure bed expansion and segregation dynamics in dense gas-fluidized beds with mono-dispersed particles and binary mixtures. They employed different colored particles and RGB image decomposition to study the extent of mixing and segregation.

Surprisingly no paper dealing with systematic measurement of bubble properties as a function of bed composition can be found in the literature, even if some data can be occasionally found [29,30].

Notably, this lack of pertinent literature is actually quite odd. In fact, it is well accepted that bubble motion through the bed is the main factor affecting the mixing of powders within fluidized beds [31–36,2] and therefore the mixing/segregation behavior of bi-dispersed fluidized beds [37,38,32,39,40].

On this basis, the present paper is aimed at the measurement of bubble characteristics in a bi-dispersed gas fluidized bed using a Digital Image Analysis procedure. In particular, several mixtures of particles having the same density but different sizes were fluidized at various inlet gas velocities. Thanks to the digital image analysis technique adopted, a number of relevant characteristics were simultaneously measured such as bubble sizes and positions, bubble number and rise velocity.

3. Experimental set-up and methods

Two different fluid-bed reactors were adopted for the present investigation. The first one is entirely made of Perspex with dimensions equal to 800 (h)×182 ($width$)×15 ($depth$) mm. Front wall is made of glass in order to avoid loss of transparency due to attrition with solid particles. The second reactor is made of aluminum and equipped with glass walls at front and back with dimensions equal to 1200 ($height$)×240 (width)×10 ($depth$) mm. Both reactors are therefore almost two-dimensional, and allow visual observation of bubble dynamics within the bed. As already mentioned, the 2D geometry for fluidized bed has been widely used in the past year by researchers, being the only technical solution that allows a detailed observation of bubble dynamics within the bed without the use of very expensive instrumentation.

In general, the width of the bed should be kept as large as possible to limit the influence of lateral walls on bubble growth inside the bed, while the influence of front and back walls is intrinsically unavoidable. The choice of the bed width derives from the maximum stable air flow rate made available by the air compressor (i.e. 140 l/min). Finally, if a bed height equal to twice the bed width is chosen for experiments, a sufficient freeboard space must be ensured above the bed surface to avoid solids losses during experiments even at the largest velocities allowed by air supply system. Of course, the data so far obtained cannot be extended for the prediction bubble behavior in 3D beds, anyway the quantity and quality of data readily available from 2D geometries can be effectively used as a demanding benchmark for the validation of advanced mathematical models and/or CFD simulations.

Sintered plastic porous distributor (average particle diameter 150 μm, average porosity equal to 0.35 determined by SEM analysis), with thickness equal to 10 mm, is placed at the bottom of the particle bed. The measured pressure drop along the distributor is in accordance with the well accepted Ergun equation for porous media [41]. Below the distributor a wind box filled with large glass particles (2–5 mm) allows to fully equalize the gas flow.

Air was used as fluidizing gas, whose flow rate was accurately measured through a set of four flow-meters, covering the range of 0–140 l/min. Different particles were used for the experimental runs, summarized in Table 1 together with relevant minimum fluidization velocities. The particles were filled up to a bed height of twice the bed width. For particle mixtures, the initial filling of the bed is made by two separate (unmixed) layers of particles. The filling procedure is of crucial importance to ensure the reproducibility of experiments. In fact, each component of particle mixtures settles, after vigorous vibration of the bed, to a well defined settled height, mainly depending on particle shape. Conversely, when powder mixtures are considered, the settled height also depends on particle size ratio and composition. Since a perfect and homogeneous mixture is unattainable in practice during the filling of the bed, this would lead to a settled bed height depending on the local mixedness conditions that exist within the bed. This in turn could lead to two different conditions, once fixed the overall bed composition: a) variable weight of particles loaded if a fixed settled height is reached, or b) variable settled bed height if a fixed weight load of particles is inserted. Both conditions are of course undesirable if reproducibility of experiments is to be attained.

The bubbling behavior of some corundum mixtures was investigated. The $U_{mf,mix}$ value was found by means of literature correlation [42] reported below:

$$d_m = \frac{X}{d_{p,flot}} + \frac{1-X}{d_{p,jet}} \tag{1}$$

$$Ar = \frac{g d_m^3 \left(\rho_p - \rho_f\right) \rho_f}{\mu_f^2} \tag{2}$$

Table 1
Particle systems adopted.

Material		ρ_p	d_p	U_{mf}
		kg/m³	μm	m/s
Corundum	C230	4000	212–250	0.095
Corundum	C550	4000	500–600	0.401
Glass	G230	2500	212–250	0.052
Glass	G550	2500	500–600	0.287