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Simulation and experimental study on the motion of non-reacting objects in the freeboard of a fluidized bed

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ABSTRACT

The motion of a large non-reacting object in the freeboard of a bubbling fluidized bed was characterized experimentally and compared with Monte Carlo simulations. A tracking technique was developed to study the object motion both when it is immersed in the dense bed and in the freeboard. Monte Carlo simulations, based on the kinematic equations of the motion, and relying on a minimum set of experimental data, were used to obtain the relevant characteristics of the process.

The non-reacting object motion in the freeboard is only affected by gravity and can be described as a ballistic motion, characterized by the initial velocity of the object, or ejection velocity. The ejection velocity modulus and angle were experimentally determined for several conditions, varying the gas velocity and the bed height. The results showed a good correlation between the ejection velocity and the bubble velocity. Probability distributions for the modulus and angle of the ejection velocity were obtained from the experimental data.

The object lateral displacement and the time spent by the object in the freeboard were calculated using three parallel approaches, with different degrees of simplicity and accuracy, employing the Monte Carlo model. The results of the model were compared to the experimental results, showing a good agreement.

1. Introduction

Fluidized beds are used in many applications in industrial processes because of their high heat and mass transfer capacity. These applications range from pharmaceutical processes to energy conversion systems. Several applications are characterized by the existence of large objects in the bed, such as fuel particles, catalysts or agglomerates. In such cases, the object behavior inside the bed and in the freeboard is a key parameter to improve the efficiency of processes, or avoid the incidence of hot and cold spots or de-fluidized zones.

Several authors have studied the behavior of objects in bubbling fluidized beds, employing different experimental techniques in 2D and 3D facilities. These studies can be divided in two main groups: objects with size and density similar to the dense phase, and thus tracers, and objects larger than the dense phase. The latter category is the aim of this study, which will use an object with characteristics similar to those of a fuel particle.

Some works have focused in the vertical motion of an object inside the bed. Pallarès and Johnsson [1] observed in a 2D bed the sinking and rising process of large objects and related the motion inside the bed to that of the bubble and the dense phase. They showed that objects were lifted to the surface following the preferential path of the bubbles, and sank on the sides of the bed with dense phase. The rising motion of an object shows a jerky behavior composed of a series of jumps due to a succession of passing bubbles, as presented by [2]. This leads to a mean rising velocity of the object which is a fraction of the bubble velocity, while the sinking velocity of the object relates to the dense phase velocity, as stated by [3]. Soria-Verdugo et al. [4] showed that a neutrally buoyant object sinks with a velocity similar to the dense phase velocity and rises to the surface with a velocity around 20% of the mean bubble velocity. Furthermore, the circulation time of an object inside the bed was experimentally obtained in 2D and 3D beds [5] and compared to Monte Carlo simulations by [6].

In general, fuel particles have lower densities than the dense phase, showing a flotsam behavior in a fluidized bed. Even for denser fuels that circulate throughout the whole bed, when the devolatilization process occurs, the volatile matter escapes from the particle varying its properties and the particles tend to lift to the surface of the bed or remain there [7–9]. A gas velocity increase can minimize this flotsam behavior, resulting in a proper circulation throughout the bed [10–12]. Soria-Verdugo et al. [13], varying the size and density of an object, and analyzing the effect of gas velocity on the object circulation, reported a range of densities and gas velocities where an object passes from a circulation characterized by a flotsam behavior to a proper circulation in the whole bed.

Other studies have focused on the lateral motion of objects ([14] and references therein). Fluidized beds are characterized by a higher mixing rate in the vertical than in the lateral direction [15], but the latter may be relevant in some applications and a lateral dispersion coefficient should

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be obtained. This parameter can be estimated as a function of the average lateral displacement and the average dispersion time [14,16], using the Einstein's equation for the Brownian movement [17]. The motion of objects in the freeboard is relevant for lateral displacement and dispersion time estimations. The ratio of time spent immersed in the dense bed to the total time, and the ratio of the net lateral displacement while the object remains immersed in the dense bed with respect to the total net lateral displacement, were calculated by Olsson et al. 2012 [14] for a wood chip, with a flotsam behavior, in a scale-up fluidized bed. The results showed, for $U/U_{mf} = 5$, that 40% of the time is spent on the freeboard, while 45% of the net lateral displacement was produced there. For higher gas velocities, $U/U_{mf} = 7.5$, only 3% of the time is spent in the freeboard, but it corresponded to 22% of the net lateral displacement. Thus, although the ratio of time spent in the freeboard reduces with the dimensionless gas velocity, the lateral displacement remains relevant. These two parameters are important in the design of the fuel feeding ports, in order to obtain a homogeneous distribution of the fuel particles in the bed. On the other hand, numerical works have studied the influence of the drag force on fuel particles in the freeboard during processes of fast pyrolysis. Papadikis et al. [18–20] observed a significant density drop of fuel particles with diameters lower than 500 μm during a process of fast pyrolysis (residence times of 4 s). This means that the drag force was the relevant force in the freeboard for different fuel particle shapes, diameters (lower than 500 μm) and drag forces models.

In this work the time spent by a non-reacting object in the freeboard and its lateral displacement were obtained experimentally in a cold 2D bubbling fluidized bed, using a tracking technique based on digital image analysis, and for different gas velocities and fixed bed heights. The experimental results were compared with Monte Carlo simulations based on the kinematic equations and operational conditions.

2. Experimental procedure

2.1. Experimental setup

The experimental facility consisted of a 2D bubbling fluidized bed with a height, H, of 2 m, a width, W, of 0.5 m and a thickness, T, of 0.005 m. The bed material used was glass spheres, Ballotini particles, with a diameter between 600 and 800 μm. The dense phase particle density was 2500 kg/m^3, corresponding to Geldart's B classification [21] and the bulk density of the bed was measured to be 1560 kg/m^3. Two different fixed bed heights, h_{fb}, were used during the experiments, 0.3 m and 0.5 m. The minimum fluidization velocity, U_{mf} was measured for both fixed bed heights, giving 0.43 m/s and 0.49 m/s respectively. The different values of the minimum fluidization velocity with the fixed bed heights were in accordance with the literature for the same bed characteristics [22]. Four values of the dimensionless gas velocity, U/U_{mf}, were employed, 1.8, 2.3, 2.8 and 3.4 for a fixed bed height of 0.3 m and 1.6, 2, 2.5 and 3 for a fixed bed height of 0.5 m obtaining a total of eight different experimental cases. The gas pressure drop through the distributor was high enough to ensure that the bed on the air supply system was not coupled [23]. The object used in the tests had a disc shape with a diameter of 0.02 m and a thickness of 0.003 m and no variations in the form, size and density were studied. The density of the object was selected to be 1200 kg/m^3 and thus the behavior of the object in the bed was flotsam for low gas velocities, $U/U_{mf} < 2.5$, spending more than 75% of the time in the upper half of the bed. Nevertheless, this object shows a neutrally buoyant behavior for higher velocities, $U/U_{mf} \geq 2.5$, presenting a proper circulation in the whole bed [13]. Therefore, two different behaviors can be studied using this object, as a function of the U/U_{mf}.

A tracking technique was developed to characterize the motion of the object in the bed, visualizing the dense phase, the bubbles and the object at the same time using Digital Image Analysis. The acquisition system consisted of a high speed video camera, 125 fps Redlake Motion pro X3 4 Gb, and an illuminating system. The illumination was carried out with four spotlights of 650 W, giving a homogeneous illumination of the whole bed. During the tests, more than 1.5 million of images were taken that correspond to a running time of around 3.5 h. A threshold was used to characterize the position of the object in all the images, obtaining the velocity of the object at each instant. On the other hand, the dense phase and the bubbles were discriminated using a threshold of the grayscale map [24]. The Digital Image Analysis was performed using a MatLab® algorithm.

2.2. Data analysis

In the freeboard of the bed, the motion of a non-reacting object is defined by gravity as there are no other relevant interactions: the drag force of the air stream over the large object can be neglected, 0.056 m/s^2 for $U = 2.5\ U_{mf}$, the friction with the 2D walls proved to be hardly noticeable and interactions with the dense phase are seldom occurs. Thus, when the object is in the freeboard, its motion follows a ballistic trajectory. Nevertheless, sometimes the object can collide with dense phase particles coming from previous bubble eruptions, and, in other occasions, it may hit with the 2D bed width limits, modifying its trajectory.

The ballistic paths described by the object in the freeboard were obtained from the results of the tracking measurements. For these paths, the ejection velocity, displacement and time interval between the initial and final positions were calculated. The number of ballistic paths obtained for all cases was 750. Table 1 shows the number of the ballistic trajectories found for each configuration.

3. Results

3.1. Experimental results for the object velocity

The ballistic motion of the object in the freeboard can be described by its ejection velocity vector. The ejection velocity vector can be expressed in terms of its modulus, U_{obj}, and angle, θ. This angle is defined as the angle between the velocity vector and the vertical coordinate. A vertical symmetry is considered since the object is ejected to both sides of the bubble path with the same probability. Both parameters, the modulus and the angle, were obtained experimentally from the object ballistic trajectories in the freeboard.

There is a general agreement that objects with proper circulation and dense phase are raised by bubbles. Several works have studied the ejection velocity of the dense phase and its relationship with the bubble velocity, using experimental techniques [25–28] and numerical simulations [29]; but to the authors' knowledge, there is no work available concerning the ejection velocity of a large object. For dense phase particles, the results for different authors differ. Fung and Hamdullahpur [25] observed that the particles are ejected radially and with a velocity that correlates with the bubble velocity and the ejection angle. Correlations differ between different authors, but there is a certain agreement that particle velocities are larger than the bubble velocity and that there is a decrease of velocity with increasing angle.

The ejection velocity for large objects may differ from that for the particles of the dense phase. Particles are subjected to the drag force of the gas flow, while the negligible incidence of the gas drag force in large objects was previously stated in Section 2.2.

Table 1
Ballistic trajectories obtained from the data analysis for each configuration.

	$h_{fb} = 0.3$ m				$h_{fb} = 0.5$ m				All
U/U_{mf}	1.8	2.3	2.8	3.4	1.6	2	2.5	3	
No. of data	54	124	69	66	64	166	92	115	750