Chemical Engineering Journal 255 (2014) 114–125

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Experimental study on the motion of isolated bubbles in a vertically vibrated fluidized bed

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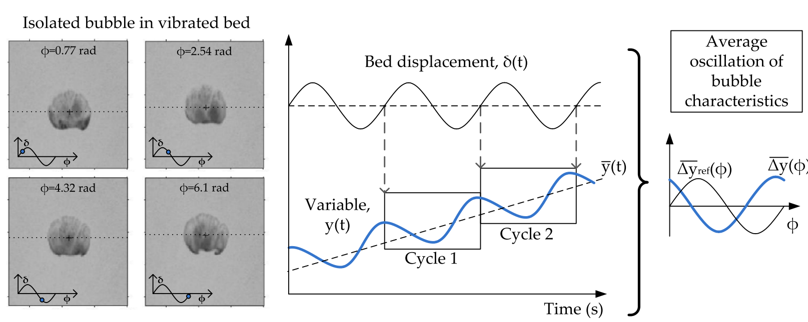
HIGHLIGHTS

- Isolated bubbles in a vibrated pseudo-2D bed were experimentally measured using DIA.
- Oscillations and phase delays of bubble centroid, diameter and velocity were obtained.
- Vibration amplitude affects the oscillation amplitude of bubbles.
- Vibration frequency influences the phase delay of bubble oscillations.
- Bubble velocity decreases with vibration amplitude for a given diameter.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 4 June 2014
Accepted 7 June 2014
Available online 14 June 2014

Keywords:
Fluidization
Pseudo-2D
Bubble
Vibrated fluidized bed
Oscillation

ABSTRACT

In this work the motion of isolated bubbles in a pseudo-2D fluidized bed subjected to vertical sinusoidal vibration is experimentally studied by means of Digital Image Analysis (DIA). The oscillatory behavior of the bed bulk as well as the bubble position, equivalent diameter and velocity, is studied using an averaging of cycles method that takes into account the intrinsic unsteadiness produced by the bed vibration. The results indicate that the bed is compressed and expanded by the system vibration, the movement of the bed surface being opposed to that of the bed vessel. Besides, the bubble diameter, centroid position and velocity oscillate with similar frequency as the bed vessel vibration. A phase delay was found between these bubble characteristics and the bed vessel displacement. This delay grows with the distance between the bubble centroid and the bed bottom, which suggests that the oscillation of the bubble characteristics is caused by compression–expansion waves traveling upwards through the bed. Both the phase delay and the amplitude of the oscillation of the bubble characteristics are affected differently by the frequency and the amplitude of vibration. The experimental results show that the amplitude of the vibration has an important role on the link between the average bubble diameter and velocity. In particular, increasing the amplitude of vibration produces a decrease of the average rising velocity of a bubble for a given bubble diameter.

1. Introduction

Fluidization is a process extensively used in chemical reactors and materials processing owing to the good performance in solid mixing and the high solid–solid and gas–solid contact efficiencies it provides [1]. Nevertheless, the ease with which particles fluidize may be affected by diverse factors. For example, fine particles tend to agglomerate, which can end up defluidizing the bed. Several strategies have been employed to eliminate agglomeration and improve fluidization homogeneity, e.g. the introduction of a mechanical stirrer or the pulsation of the gas flow [2]. The

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http://dx.doi.org/10.1016/j.cej.2014.06.016
1385-8947/

formation of bubble preferential paths inside the bed, that cause large heterogeneities in the particle spatial distribution, may be another effect to be avoided. Many efforts have been made to modify the particle and bubble behavior inside a fluidized bed also by external means. For example, ferromagnetic particles subjected to magnetic fields can extend the way the bed fluidizes, extending the bubble-free operation range in fluidization state [3] or diminishing the bubble size [4]. Similarly, acoustic fields have also been employed for the improvement of the fluidization quality of group C cohesive powders [5].

Additionally, the use of special methods of gas injection have been considered to improve the fluidization quality by breaking bubble paths and rupturing agglomerates. Sobrino et al. [6] and Gómez-Hernández et al. [7] studied the use of a rotatory distributor. Recently, Nakamura et al. [8] proposed the improvement of particle mixing and fluidization quality by an inclined injection of fluidizing air.

When agglomeration and channeling are severe in bed reactors and dryers, the improvement of fluidization quality requires methods capable of introducing high levels of energy in all the bed volume. In this regard, mechanical vibration of fluidized beds, i.e. vibrating fluidized beds (VFB), is a process intensification technology consisting in introducing vibratory kinetic energy to a fluidized bed [9–12]. This can be done by applying an oscillatory displacement to the bed-containing vessel, which transmits the vibration to the rest of the bed. Vibration of the bed reduces minimum fluidization velocity [13], and provides the necessary energy to break interparticle bonds, reduce agglomerates and avoid channeling. Thus, it is a very effective technique for the fluidization of cohesive particles [14,15], drying of granular material [16,17] and agglomeration control [18]. Vibration can be also used to control particle segregation in a fluidized bed [19].

Despite its advantages, vibration substantially increases the complexity of the fluidized bed behavior and introduces new phenomena that are still not completely understood or are even unexplored. Additionally, the complexity of the system is magnified by the interaction between multiple bubbles when the bed is operating in bubbling regime. Therefore, as there is a need of experimental and simulation characterization of fluidized beds in general, this need is even more true for vibrating fluidized beds in particular.

Concerning experiments aimed at characterizing fluidized beds, beds of small thickness, i.e. pseudo two-dimensional beds (pseudo-2D beds), have shown to be of great importance for the understanding of fluidized beds [20–22]. This kind of beds typically has a transparent wall and possesses a small thickness, so that optical access to the system is allowed and the behavior of the visualized particles is representative of the whole system.

Of all the experimental techniques employed for the study of fluidized beds, Digital Image Analysis (DIA) is one of the most used, proving to be a valuable tool for the understanding of bed and bubble behavior in fluidized beds, as demonstrated by numerous studies [20–28]. The DIA technique has also been employed to study the bubble behavior in VFBs [12,29–31], however, the number of works at this respect is relatively scarce compared to non-vibrated pseudo-2D beds.

Existing computational and experimental bubble studies in VFBs are mainly centered on beds working under bubbling regime [12,30–35]. Global indicators such as bubble mean diameter and velocity [12,29–32], air pressure and void fraction fluctuations [34,33] as well as solids circulation promoted by vibration [35] are included in these works, in which the presence of multiple interacting bubbles complicates the elucidation of the basic effects that vibration induces on each individual bubble. Eccles and Mujumdar [29] studied a train of bubbles in a vibrated thin bed. They observed that for the smallest particles (100 μm) the bubble size reached a maximum while the bubble passing frequency and velocity reached minima. Zhou et al. [12] carried out experiments to study the particle flow pattern and its interaction with bubble paths, pressure drop and bed expansion ratio in a pseudo-2D bed filled with spherical particles of 198 μm and subjected to horizontal and vertical vibration. They found that, for gas fluidization velocities above the minimum fluidization conditions, the effect of sinusoidal vibration was only significant when applied in vertical direction. Also, Mawatari et al. [30] and Zhou et al. [31] experimentally studied pseudo-2D beds under vertical vibration, using particles of 60 and 198 μm of average diameter, respectively. Mawatari et al. [30] obtained the averaged bubble size and velocity as well as the bed expansion ratio, and Zhou et al. [31] measured the locally averaged bubble size and velocity at two different height intervals. The vibrated bed conditions of [31] were reproduced by Acosta-Iborra et al. [32] using two-fluid models simulations. All these three studies [30–32] revealed that, once a fluidized bed is vibrated, the averaged bubble diameter increases with the amplitude or frequency of vibration, though a more complicated dependence is experienced by the averaged bubble velocity. However, to the Author's best knowledge, the oscillating behavior of an isolated bubble in a vibrated fluidized bed remains unstudied, despite the fact that it could provide clear and valuable information on the impact of the vibration on the fundamental bubble behavior in fluidized beds. In the related field of gas bubbles in liquid columns, this methodology of studying isolated bubbles has been successfully applied for the understanding of the effects of vibration on bubbles [36–41]. In one of these works, Jameson and Davidson [37] analyzed the time oscillations of the displacement of a bubble in the vibrated liquid column using a phase representation of averaged oscillation cycles. This method allowed for the comparison of the amplitude and the relative phase of the bubble and liquid displacements.

The aim of this work is to experimentally study the effect of the vertical vibration on a fluidized bed concerning the bed bulk motion and the resulting behavior of an isolated bubble rising alone in the bed. These results can be useful for clarifying the essential mechanisms affecting a bubble in a vibrated bed, which constitutes a necessary first step in the understanding and model development of more complex bubbling beds dryers and reactors subjected to vibration. As a novelty, results are presented using a phase frame of reference, so that the local fluctuations caused by the bed vibration on the bed bulk motion and bubble properties, i.e. bubble diameter and velocity, can be systematically analyzed. Besides, the effect of the vibration amplitude and frequency on the oscillation and mean motion of isolated bubbles in a fluidized bed is studied. The results show that the vibration amplitude and frequency have a complex and coupled impact on the bed bulk behavior and the bubble size and motion.

2. Experimental setup

The experimental facility used in this work consists of a pseudo-2D fluidized bed of dimensions $0.3 \times 0.6 \times 0.01$ m (width W, height H and thickness K, respectively) which is placed on a vibrating structure. Fig. 1 shows a sketch of the facility. The air distributor consists of a perforated plate with one row of 20 holes of 1 mm diameter that are spaced 1.5 cm apart. The bed was filled with ballotini glass beads with a density of 2500 kg/m^3 and a size range between 150 and 250 μm (DV10 = 177 μm, DV50 = 215 μm and DV90 = 245 μm). The mean diameter of the particles was 213 μm (Geldart's classification type B). The settled bed height was fixed to $h_0 = 45$ cm. For static conditions, the minimum fluidization velocity was measured using a pressure probe placed in the plenum, resulting on a value of $U_{mf} = 0.055$ m/s. The front and rear