Chemical Engineering Journal 243 (2014) 411–420

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Acoustic fluidized bed hydrodynamics characterization using X-ray computed tomography

David R. Escudero [*], Theodore J. Heindel

Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, United States

HIGHLIGHTS

- Acoustic vibration enhances the fluidization quality of particulate matter.
- Hydrodynamic structures were studied using X-ray computed tomography images.
- Local gas holdup for acoustic fluidized beds exhibits a more uniform fluidization.
- Jetting phenomena near the aeration plate is affected by the acoustic field.
- Acoustic field effects for walnut shell beds are dependent of particle size.

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form 2 January 2014
Accepted 10 January 2014
Available online 18 January 2014

Keywords:
Acoustics
Fluidized bed
Hydrodynamics
X-ray computed tomography

ABSTRACT

Acoustic vibration in a fluidized bed can be used to enhance the fluidization quality of particulate matter; this particular noninvasive method provides no internal changes to the bed material structure. However, due to the complexity of this multiphase flow system, characterizing the hydrodynamics of a fluidized bed has become critical in understanding this system behavior. The local void fraction behavior in a cold flow 3D fluidized bed with and without acoustic intervention is investigated in this research. Several non-invasive techniques like gamma-ray computed tomography (GRT), X-ray computed tomography (XCT), or electrical capacitance tomography (ECT), can be used to study the void fraction distribution in multiphase flow systems. In this study, XCT imaging is used to determine the time-average local void fraction or gas holdup. Experiments are implemented in a 10.2 cm ID fluidized bed filled with glass beads or ground walnut shell, having a material density of 2500 kg/m^3 and 1440 kg/m^3, respectively, and particle size ranges between 212 and 600 μm. In this study, three different bed height-to-diameter ratios are examined: H/D = 0.5, 1 and 1.5. The loudspeaker's frequency, used as the acoustic source, is fixed at 150 Hz with a sound pressure level of 120 dB for glass beads, and 200 Hz and 110 dB for ground walnut shell. Local time-average gas holdup results show that the fluidized bed under the presence of an acoustic field provides a more uniform fluidization, the bed exhibits less channeling, and the jetting phenomena produced by the distributor plate is less prominent when compared to no acoustic field. Thus, acoustic intervention affects the local hydrodynamic behavior of the fluidized bed.

1. Introduction

Multiphase hydrodynamics have a large impact on the performance of a fluidized bed. Gas holdup or void fraction is a parameter used to characterize the hydrodynamic structure of a multiphase flow system, and is defined as the volumetric gas fraction within the bed material. Several studies in the literature have determined the solid concentration (the inverse of gas holdup) in a gas–solid system for different fluidization regimes and different operational conditions in an attempt to understand the flow structures found in fluidized beds [1,2].

Several methods, both intrusive and nonintrusive, have been studied to improve the fluidization quality of granular material. These methods may also produce changes in the hydrodynamic behavior of the fluidized material. External stimuli, in the form of vibrations, have been used together with fluidization to treat cohesion problems. Vibrations, in fact, are able to interact directly with cohesive structures such as aggregates and channels [3]. These vibrations can be applied to the fluidized bed in the form of mechanical vibrations or acoustic vibrations.

Studies in the literature have used mechanical vibrations to improve the fluidization quality of material that shows poor fluidization behavior [4,5]. For example, Barletta et al. [6] studied the

---

[*] Corresponding author. Tel.: +1 515 451 6194.
E-mail addresses: drescude@iastate.edu (D.R. Escudero), theindel@iastate.edu (T.J. Heindel).

http://dx.doi.org/10.1016/j.cej.2014.01.025

effects of mechanical vibration on fine powders. They found that bed packing degree reached by the vibrated bed without gas flow was always higher than that reached without vibration. Conversely, the pressure drop for a fluidized bed with vibration was equal to or less than the pressure drop obtained without vibration. These differences between conditions were more prominent when the frequencies tested were low and they become less noticeable at high frequencies. More recent studies performed by Barletta and Poletto [7], Barletta et al. [3] and Levy and Celeste [8] revealed similar results.

Acoustic fluidized beds have been researched intensively to understand the effects produced by the acoustic field on the fluidization behavior and quality in beds filled with different Geldart type particles. Leu et al. [9], Guo et al. [10], Kaliyaperumal et al. [11], and Levy et al. [12] all have used acoustic fields in fluidized beds to observed the different behavior that sound vibrations produced on the fluidization structure of the system.

Escudero and Heindel [13] studied the effects produced on the minimum fluidization velocity by the inclusion of an acoustic field for different Geldart type B particles. They showed that the presence of the acoustic field improved the ease of material fluidization by lowering the minimum fluidization velocity of every particle size and type they tested. Also, they found that fluidized beds enhanced with an acoustic source exhibited a dependence between bed height and minimum fluidization velocity; these changes where not observed when the acoustic field was not present, confirming the results of Leu et al. [9].

Herrera and Levy [14] used visual observations as well as invasive techniques such as fiber optic probes to measure the bubbling characteristics of a Geldart type A fluidized bed. Using these techniques, they determined that high values of the sound pressure level affected the fluidization behavior of the bed and had a large impact on the bubble characteristics, such as size and frequency. Other studies have shown additional effects in the fluidization characteristics of granular material under the presence of an acoustic source [15,16].

Different noninvasive techniques can be used to determine local void fraction distributions in multiphase systems. Mandal et al. [17] used gamma densitometry to study the void fraction distribution in an unary and packed fluidized bed. They determined that packed beds produced a more homogeneous fluidization than unary fluidized beds. Parasu Veera [18] also used gamma densitometry to study gas holdup profiles in bubble columns and showed how useful this technique can be for understanding different flow behaviors in laboratory or industrial scale bubble columns. Finally, Du et al. [19] used electrical capacitance tomography to investigate local void fraction distributions in various fluidized beds; they showed that radial symmetry was observed when the bed was operated in the turbulent fluidization regime.

X-rays have been used to study multiphase fluidized systems for several decades [20]. They are a commonly employed noninvasive technique because they are safer than other nuclear based techniques (they can be turned on and off at will), have high resolution, and can be controlled by varying the voltage or current to improve penetration or contrast [21].

Heindel et al. [22] developed an X-ray visualization facility to study the different characteristics of opaque multiphase flows, from bubble columns to fluidized beds, with good both spatial and temporal resolution depending on the type of imaging technique used. Their facility is capable of producing three different X-ray imaging techniques: X-ray radiography, X-ray stereography, and X-ray computed tomography.

X-ray computed tomography (XCT) generates a 3D image of the object of interest. X-rays pass through the object and the intensity values are recorded from several projections by an imaging device. After the images are collected, computer algorithms reconstruct the images to produce a 3D representation of the object. However, due to the high amount of projections that must be acquired in order to obtain a whole reconstruction of the object, this technique does not have a good temporal resolution. On the other hand, the multiple projections give a high spatial resolution to this technique, a characteristic that can be used to determine the local time-average gas holdup in a very efficient way [23].

Moreover, XCT data analysis allows for the calculation of time-average local gas or solid holdup. Escudero and Heindel [23,24] studied the effects of bed height, superficial gas velocity, and bed material on the local time-average gas holdup of a 10.2 cm fluidized bed. They identified fluidization hydrodynamic affects using different bed materials (glass beads, ground corncob, and ground walnut shell), superficial gas velocities (U_g), and height-to-diameter ratios (H/D). They found that as superficial gas velocity increased, the overall gas holdup increased for every bed height studied. Flow behavior was also affected by the increase in superficial gas velocity. Increasing bed height, particularly at the higher gas flow rates, enhanced bubble coalescence creating slugs that flow thorough the center of the bed, producing regions of low gas holdup near the walls of the fluidized bed. Also, the effects of bed height observed in the time-average local gas holdup varied depending of the bed material tested. Finally, they determined that as material density decreased, gas holdup increased.

Most of the studies concerning acoustic fluidized beds available in the literature used both invasive and noninvasive measurement techniques to describe the hydrodynamic characteristics of the bed. Fiber optic systems, visual observations, pressure fluctuation analysis, or camcorder systems are some of the techniques used in the studies summarized in the previous paragraphs. However, non-invasive techniques such as X-ray computed tomography have not been used in sound assisted fluidized beds to determine qualitative and quantitative local void fraction distribution characteristics. The goal of this study is to alleviate this shortcoming and characterize the local void fraction distribution of an acoustic 3D fluidized bed using X-ray computed tomography.

2. Experimental setup

A cylindrical cold flow fluidized bed reactor is used in this study. A detailed description of the fluidized bed reactor, as well as the equipment used for supplying the fluidizing gas for the specific conditions of each experiment can be found in [23,24], since the same equipment was used for these studies. Fig. 1 shows a schematic of the fluidized bed reactor.

In order to modify the fluidized bed into an acoustic fluidized bed, acoustic vibrations have to be added to the system. The details of the different sound equipment used in this research can be found in [13]. To measure the power of the sound (Sound Pressure Level) that is emitted by the speaker, a mini digital sound level meter with a maximum pressure level of 130 dB and an approximate error of less than 1% is located at the top of the bed chamber. Refer to Fig. 1 to see the setup for the entire experiment.

The fluidizing materials are glass beads ($\rho_{\text{glass}} = 2500\ \text{kg/m}^3$) and ground walnut shell ($\rho_{\text{walnut shell}} = 1440\ \text{kg/m}^3$) over three different size ranges (212–425 μm, 425–500 μm, and 500–600 μm). The materials are divided into the different size classes by initially filling a 600–800 μm sieve with the desired material. The 500–600 μm, 425–500 μm, and 212–425 μm sieves are then added sequentially to the sieve stack, with a bottom under the smallest sieve. With the help of a mechanical shaker, the sieve stack is vibrated for about 20 min; this process is repeated several times to ensure that the desired particle size range is retained in the respective sieve.