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Comparative study of two non-intrusive measurement methods for bubbling gas-solids fluidized beds: Electrical capacitance tomography and pressure fluctuations

Xiaoxu Li, Artur J. Jaworski*, Xiaoan Mao

Faculty of Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, United Kingdom

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ABSTRACT

Conventional measurement techniques used to investigate the internal fluid flow processes in gas-solids fluidized beds are known to introduce disturbances to the flow. Two non-intrusive methods: pressure fluctuation measurement and electrical capacitance tomography (ECT) techniques have been usually used separately to study the complex two phase flow phenomena in fluidized beds. However, no systematic study has been carried out to compare these two methods in terms of their capabilities to reveal the hydrodynamic characteristics of fluidized beds. This paper presents a comparative study between these two non-intrusive measurement techniques within a bench-scale fluidized bed. Experiments were carried out using two alternative test sections (one equipped with pressure transducers, one with ECT sensor) for the same operating conditions. The performance of these two methods was evaluated against some important hydrodynamic parameters within fluidized beds, such as the determination of the minimum fluidization velocity, the minimum slugging velocity, dominant frequency and bubble rise velocity. The results demonstrate that the two measurement techniques can both provide broadly consistent results, although ECT tends to be more reliable with respect to estimating bubble rise velocity.

1. Introduction

Gas-solids fluidized beds have been widely used in both traditional and modern industrial applications, especially in the areas of chemical engineering, energy conversion, recovery of valuable materials from waste streams and biomass gasification [12,26,30]. Undoubtedly, the excellent mixing and an attractive high heat and mass transfer rate between gas and solids phases are attributed to their popularity in industrial applications [25]. Therefore, for the purpose of safe operation, reliable scale-up and plant troubleshooting, it is vital to understand the internal performance of the beds with the highest possible degree of accuracy, which, in turn, brings considerable challenges to the implementation of reliable measurement techniques [22].

Numerous conventional measurement techniques have been tried out to investigate the properties of fluidized bed behaviour. Intrusive pressure probes were used to determine the bubble rise velocity in a 15 in. diameter column [3]. The opening sides of all five sets of probes were positioned in the centre of the bed. Two types of fibre optic probes, forward light scattering and backscattering, were applied by many researchers to investigate the bed and bubble behaviour in terms of the local movement of solid particles, particle concentration, bubble frequency, bubble rise velocity and bubble size distribution, to name but a few [20,24,29]. A parallel plate capacitor probe was applied to study the uniformity of fluidization with a bed of fine particles [23]. Optimized needle type capacitor probes were employed to derive bubble characteristics, for example, bubble size (pierced length) and bubble rise velocity [38]. However, despite the achievements that the above mentioned probes can bring about in studying gas-solids fluidized beds, it is recognized by many researchers that the disturbances and interference introduced by the probes cannot be avoided completely [27,8].

The current comparative study involves two non-intrusive measurement techniques. The first one, electrical capacitance tomography (ECT), can provide qualitative and quantitative data in monitoring a multi-phase fluid flow system by measuring the electrical capacitances between sets of electrodes placed around a process vessel [8]. ECT has the advantage of being simple to construct, fast in measurement speed, of low cost and able to withstand harsh operating conditions, i.e. high temperatures and pressures. The second non-intrusive method relies on pressure fluctuation measurements through small diameter and short pressure tappings which lead to the pressure sensing elements inside the pressure transducers. Therefore there is no pressure probe

* Corresponding author.
E-mail addresses: a.j.jaworski@leeds.ac.uk, a.jaworski@yahoo.co.uk (A.J. Jaworski).

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protruding into the bed. The sensors typically used in the pressure measurements, are robust and relatively cheap [30]. The resulting measurements are recorded with an adequately high frequency, enabling the collection of a large amount of information about the internal fluid dynamics of the fluidized bed.

2. Literature review

As one of the most attractive tomography measurement techniques, ECT has been used by many researchers to study the gas-solids fluidized beds in the bubbling regime, in particular in terms of the bed behaviour and bubble characteristics [21,25,35,36,7]. Bed behaviour just above an air distributor was initially observed by Wang et al. [36] and Wang [35]. In addition, three flow regimes were identified by means of the cross-sectional solids concentration distribution as a function of time. More flow regimes, such as single bubble, slugging bed, turbulent flow and fast fluidization regime, have been then classified by means of ECT measurements in a conventional gas-solids fluidized bed.

The main parameters used in characterizing flow regimes are solid fraction profile, average solid fraction and its standard deviation and dominant frequency of the power spectral density (PSD) function [21]. Also, the standard deviation of solids concentration was found to peak at the transition velocity from bubbling to turbulent regime in a 0.3 m diameter bed [7]. Numerous studies have also been focused on the factors influencing the transition velocities. For example, the effect of the ratio of the static bed height to the bed diameter on the transition velocity to turbulent regime was studied by Qiu et al. [25]. However, very few studies were conducted to determine the minimum fluidization velocity and the minimum slugging velocity.

With respect to bubble characteristics within bubbling regime, a great deal of interesting features have been revealed by virtue of the ECT measurements. A method of deriving bubble length within bubbling regime via real time ECT measurements was reported by Wang et al. [36]. Bubble rise velocity has been estimated by means of a twin-plane ECT sensor [22]. Bubble diameter was studied by several researchers, although some debate still exists regarding the choice of criterion defining the bubble boundary [11,17,4]. Dominant frequencies from PSD function were used to characterize the bubble frequency [21].

Meanwhile, non-intrusive pressure fluctuation measurements have also been extensively used to identify a wide-range of bed behaviour and bubble characteristics within bubbling regime [14,30,40]. The minimum fluidization velocity can be estimated either by means of the pressure drop or the standard deviation of the pressure fluctuations [32,40]. The latter method was reported to have been able to avoid the need to de-fluidize the bed by decreasing the gas superficial velocity from a vigorous fluidization state when trying to measure the minimum fluidization velocity. Hence, this approach would be much more useful and effective in industrial applications where continuous operations are preferable on account of the financial cost and efficiency of operations. In addition, the standard deviation of the pressure fluctuations has often been utilized to determine the transition velocity, usually denoted by U_c, from bubbling to turbulent regime [34]. Here the transition is marked by the maximum value of the standard deviation. Some researchers pointed out that the transition velocity was influenced by many factors including measuring locations and bed geometries when testing Group A and Group B particles [1]. However, very few studies involved identifying the minimum slugging velocity. Qiu et al. [25] provided a plot of standard deviation of pressure fluctuations versus various gas superficial velocity values. It is possible to infer that the minimum slugging velocity can be determined from the graph. However, the authors have not made this point clear.

Concerning the bubble characteristics within bubbling regime, pressure fluctuations measured at plenum location were used to identify related frequencies within fluidized beds using Fast Fourier Transform (FFT) analysis [15]. Three peak frequencies derived from the modified PSD function were confirmed to be consistent with the bubble eruption frequency at the freeboard, the bubble generation frequency above gas distributor and the spontaneous frequency of the fluidized bed. It was reported that bubble rise velocities were obtained from different pairs of pressure taps by means of cross-correlation function [9]. However, the origin of the derived velocities has not been fully discussed and also the obtained results have not been validated with empirical correlations.

Very few studies have been conducted to compare the performance of these two non-intrusive measurement techniques in revealing the complex fluid flow processes. For example, Qiu et al. [25] carried out experiments choosing different measuring locations and different sampling rates (60 frames per second for ECT and 170 samples per second for pressure acquisition). In addition, some critical parameters such as the minimum fluidization velocity and the minimum slugging velocity have not been dealt with.

The objective of this paper is to compare and evaluate the performance of two non-intrusive measurement techniques: electrical capacitance tomography (ECT) and pressure fluctuation measurement (using small pressure tappings in the bed wall connected to pressure transducers), within a bench-scale gas-solids fluidized bed in terms of characterising the bed hydrodynamic behaviour. It is hoped that this will allow researchers to make more informed choices when it comes to choosing the suitable non-intrusive measurement techniques. More specifically, different approaches for estimating minimum fluidization velocity and minimum slugging velocity from these two methods are compared and assessed. Similarly, dominant frequency obtained from the PSD function and bubble rise velocity estimated from these two methods are obtained and evaluated in a detail.

3. Experimental

Experimental set-ups for both ECT and pressure fluctuation measurements will be dealt with in this section. The description of experimental set-up for ECT measurement includes the description of the bench-scale fluidized bed together with the details of the employed ECT system. For the experimental set-up for pressure fluctuations, pressure transducers' specifications, pressure transducer holder design and fabrication and the data acquisition system will be given accordingly.

3.1. Experimental set-up for ECT measurement

The schematic diagram of the experimental rig equipped with ECT is presented on the left of Fig. 1. The fluidizing medium is air at atmospheric pressure, provided from a compressed air cylinder (1). A needle valve (2) acts as the isolation valve and controls the air flowing into the fluidized bed. Gas flow rate was obtained via a float type flow meter (3) before the air was introduced into the bed. The corresponding gas superficial velocity was acquired from the gas flow rate divided by the cross-sectional area. The bench-scale gas-solids fluidized bed comprises a 59 mm internal diameter (3 mm wall thickness) acrylic pipe with the length of 1 m which forms the fluidized bed vessel (7). Use of transparent material allows visual observation to assist preliminary qualitative analysis.

A perforated PVC distributor (5) was designed and sandwiched by flanges between the bed pipe (7) and the air plenum (4) to make the upward air flow uniform. The distributor has 48 holes of 1 mm diameter giving the total area of the holes in the distributor of 3.768×10^{-5} m^2 (1.38% of the total effective area). A piece of fine mesh was placed on top of the air distributor to prevent any particles from falling down into the plenum. Silica sand was used as granular material. The density of silica sand is 2650 kg/m^3, and its mean diameter is 276 μm, i.e. it belongs to the Geldard classification of Group B particles for fluidization [10]. In order to prevent the solids from blowing out of the bed, a customized cap (8) with an embedded fine mesh disk was mounted on top of the bed pipe. The static height of the fluidized bed is kept at 170 mm, which ensures that the