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Non-intrusive determination of bubble size in a gas–solid fluidized bed: An evaluation

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ABSTRACT

Bubble sizes measured in a column of diameter 290 mm with FCC particles utilizing both an intrusive optical probe and non-intrusive pressure analysis are compared. The pressure signals were decoupled by differential pressure analysis and incoherence analysis. It is shown that pressure fluctuations induced by jetting/bubble formation can be effectively filtered out by differential pressure and incoherence analysis. The differential pressure signals measured across a vertical interval less than half the maximum bubble size unreasonably damps the power spectral density intensity, leading to underestimation of bubble size and overestimation of mean frequency. In the present work, the incoherence analysis tends to estimate greater bubble size than differential pressure analysis. Bubble chord lengths are overestimated by optical probe signals because small bubbles are not detected. Bubble sizes calculated by the equation of Horio and Nonaka (1987) agree reasonably well with that estimated by incoherence analysis at relatively high superficial gas velocities.

1. Introduction

Fluidized beds reactors have been widely used in chemical, petrochemical, metallurgical and power generation processes as catalytic and gas–solid reactors. Understanding the hydrodynamic characteristics is vital in modeling and controlling the properties of fluidized beds. Bubble size is an important characteristic governing hydrodynamics and reactor performance in the bubbling flow regime, with small uniform bubbles well distributed over the cross-section being desirable for most applications. Extensive work has been conducted to investigate bubble size, but this has been mostly restricted to indirect methods of estimation or direct visualization at the wall or in thin columns.

Measurement techniques for bubble size can be categorized into intrusive techniques, such as optical fibre probes (Bai et al., 2005; Glicksman et al., 1987), and non-intrusive techniques, such as those based on pressure fluctuation measurements, X-rays or capacitance tomography (McKeen and Pugsley, 2003; Wu et al., 2007). The X-ray and capacitance tomography techniques are expensive and impossible to apply in large industrial units. Optical fibre probes can be utilized to determine local voidage in large fluidized beds, especially those operating at low temperatures, and intrusion can be minimized by employing very small probes. Bai et al. (2005) measured the passage time of bubbles rising through the tip of an optical probe and calculated the bubble chord length by assuming that the bubble rise velocity follows the model of Davidson–Harrison (1963). Glicksman et al. (1987) utilized a specially designed dual-channel optical fibre probe to investigate bubble size and rise velocity in a two-dimensional fluidized bed. The probe contained two emitter-detector pairs, separated by a vertical distance of 19 mm between the pairs, with a horizontal gap of 5 mm between corresponding emitters and detectors. Comparison of the probe results with video images indicated that the bubble diameters were proportional to the measured bubble chord lengths. However, bubbles were detected by the probes only when the maximum horizontal dimension of the bubble exceeded the gap, so that the probes were only able to measure bubbles with horizontal dimensions >5 mm.

Due to its ease of deployment and non-intrusive nature, pressure fluctuation analysis is a popular alternative method to indirectly estimate bubble size in both laboratory and commercial-scale gas–solid fluidized beds. Since pressure signals propagate in fluidized media with limited attenuation, pressure waves registered at a specific position are a combination of components originating from different sources (Bi, 2007). Therefore, despite the ease of measurement, interpreting pressure signals is difficult. Extensive work has been conducted on this issue.

The analysis of pressure signals can be broadly classified into two categories. The first attempts to identify components from

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different sources by retaining components related to local bubble passage while removing the other components. One such method is based on differential pressure signal analysis (Bi, 2007). Since pressure waves induced by local bubble-passage propagate at relatively low velocity ($\sim$1 m/s), whereas those originating from other sources travel significantly faster (at $\sim$10 m/s), the latter can be filtered out by a differential pressure sensor (Bi, 2007, 1994). Another approach was proposed by van der Schaaf et al. (2002), who separated single-point pressure signals into two components labeled coherent and incoherent. The incoherent component represents the power spectral density of pressure fluctuations arising from local bubble passage or local turbulence. The second category of signal analysis technique seeks to distinguish pressure signals of different scales, but not from different sources. Advanced tools such as chaotic and wavelet analysis have also been utilized to analyze raw pressure fluctuation signals, improving the understanding of their complexity (Bai et al., 1997; Zhao and Yang, 2003).

The most popular intrusive and non-intrusive measurement methods, optical probes and pressure fluctuation techniques, respectively, provide different advantages. The former is capable of determining local bubble size and rise velocity distributions, but it is largely restricted to cold-model experimental units, whereas the latter is applicable to both cold-model systems and commercial units operating at high temperature and high pressure, but provides only limited information. Although extensive attention has been devoted to each of these techniques, there has been little effort to compare the two techniques. This paper applies and compares these two techniques in a three-dimensional gas–solid fluidized bed, with pressure fluctuation signals decoupled by the methods proposed by Bi (2007, 1994) and by van der Schaaf et al. (2002), allowing the advantages and limitations of these two techniques to be identified.

2. Experimental

The experimental apparatus is shown schematically in Fig. 1. The column was made of Plexiglas, 0.29 m in inner diameter and 4.5 m in height. The gas distributor was a perforated aluminium plate containing 98 holes of 5.6 mm diameter arranged in an equilateral triangular configuration with a 32 mm pitch, leading to an open area ratio of 3.7%. A disengaging section at the top of the column, expanded to 0.4 m inner diameter, led to two external cyclones in series. Solid circulation was not controlled, but was maintained through a pressure balance between the return leg and the column. Each return leg was equipped with a flapper valve to prevent gas from short-circuiting up the standpipe. Air was supplied by a Roots blower with a maximum capability of 425 Nm^3/h at 69 kPa. The air flowrate was controlled by a bypass line close to the blower, and calculated from the pressure drop across an orifice plate. Spent FCC catalyst particles of mean diameter 78 μm and density 1560 kg/m^3 constituted the fluidized material. The minimum fluidization and critical velocity of the particles were 0.0025 and 0.6 m/s, respectively. The fluidized bed operated as a bubbling bed at superficial velocities up to 0.5 m/s. The static bed height was 1 m for all experiments. The distributor pressure drop varied from 900 to 1300 Pa with increasing superficial gas velocity for the data included in this paper. Six sampling ports were mounted flush with the wall of the column with 38 μm mesh stainless steel screens covering their tips to prevent particles from entering the pressure sensing lines, allowing simultaneous measurement of pressure fluctuations at different levels.

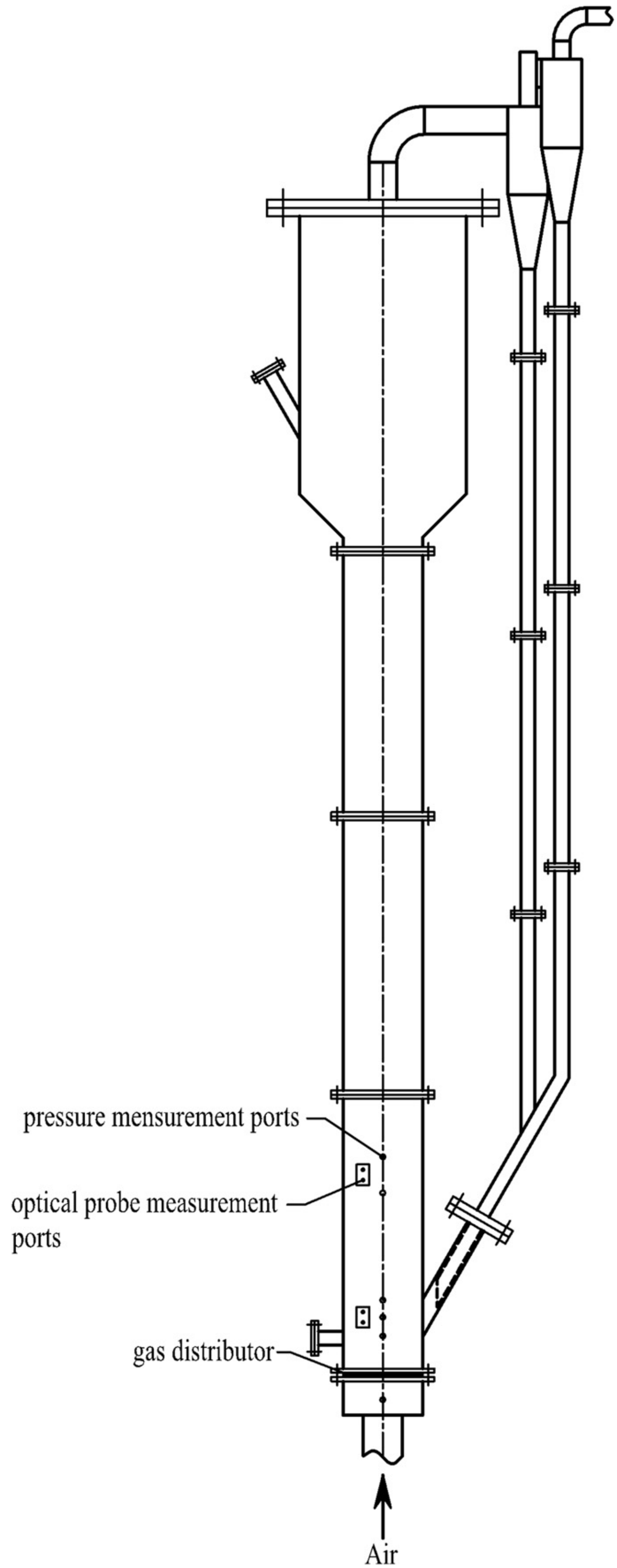

Fig. 1. Schematic of experimental cold model column.