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Wide band energy analysis of fluidized bed pressure fluctuation signals using a frequency division method

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HIGHLIGHTS

- A systematic and unbiased methodology is proposed for the frequency domain division.
- Cumulative energy distribution of the power spectrum is fitted to the *t*-Student.
- The cut-off frequencies are identified using the Kolmogorov–Smirnov test.
- An excellent capability of the method to the frequency domain division was found.
- The sensibility of this method is improved compared with the traditional approach.

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ABSTRACT

A statistical method based on approximation of the cumulative energy distribution by Student's *t*-distribution is proposed for the unbiased frequency domain division. The proposed method fixes the number of samples needed to estimate the power spectrum and its corresponding cumulative energy distribution using the Kolmogorov–Smirnov test. The reliability of the method to divide the frequency domain was shown for different fluidization velocities by changing the bed aspect ratio and using different pressure probes. Water-induced defluidization tests were conducted to illustrate the use of wide band energy as a monitoring tool. The Student's *t*-distribution results are compared with an analysis performed using the traditional visual inspection method. The energy of the power spectrum contained within the frequency regions obtained by the visual method is not able to detect changes in the bed aspect ratio or the start of the rotating distributor. No meaningful differences could be observed in the frequency regions using different quality pressure sensors because the approach using Student's *t*-distribution focuses on the sharp energy increase produced by the primary frequencies of the power spectrum. The sensitivity exhibited by the proposed frequency division approach for the range of fluidization conditions tested improves the use of the energy contained in these regions as a diagnostic tool in fluidized bed processes.

1. Introduction

Pressure fluctuations are one of the most commonly measured parameters used for the monitoring of fluidized beds (van der Schaaf et al., 1998). There are several methods proposed in the literature to analyze such signals, which can be grouped into three categories as a function of the domain type: (1) time, (2) frequency and (3) state space (van Ommen et al., 2011). Focusing on the frequency domain analysis type, it is typically performed using power spectral density (PSD) analysis (Brown and Brue, 2001).

The frequency analysis of pressure fluctuations is used to obtain information about the fluidization dynamics and to diagnose the fluidization state (Kage et al., 2000). Characteristic features of the power spectrum have been used for the description of the fluidization regime. For example, the frequency peak and the dominant frequency have been used to detect defluidization in coating and drying processes (Parise et al., 2011; de Martin et al., 2011). The coherent standard deviation and the average frequency of pressure fluctuations have also been used to estimate the bubble size and to detect the regime transitions in slurry bubble columns (Chilekar et al., 2005; Ruthiya et al., 2005). Similarly, the type of the power spectrum fall-off with frequency has been used as a tool for distinguishing between deterministic and noise systems (Johnsson et al., 2000; van der Schaaf et al., 1999, 2004; van Ommen et al., 2011; Vander Stappen, 1996). Another important parameter obtained

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from the frequency domain is the energy contained within the power spectrum. According to Johnsson et al. (2000), this variable, the wide band energy, reflects the change in operational regimes and can be used to characterize the structure of a fluidized bed. More recently, the wide band energy has been used to detect defluidization phenomena (Gómez-Hernández et al., 2012).

The use of the wide band energy as a monitoring tool presents some advantages in comparison to other parameters obtained from the frequency domain. The easy and fast computation of the wide band energy provides a reliable view of the dynamic behavior of the system once the power spectrum is properly divided into a set of frequency regions (Briongos and Guardiola, 2003; Gómez-Hernández et al., 2012; van der Schaaf et al., 2002, 2004). Traditionally, this type of frequency division has been conducted using visual selection of the cut-off frequencies between the different spectral regions. In this procedure, the observer visually identifies the frequency limits by studying the behavior of the frequency domain either in the power spectrum (Johnsson et al., 2000; van der Schaaf et al., 1999; Vander Stappen, 1996) or as the cumulative energy distribution (Gómez-Hernández et al., 2012). However, the visual inspection approach has at least two major drawbacks, as follows: (i) the cut-off frequencies obtained through the visual inspection depend on the observer and (ii) the power spectrum fall-off is unavoidably affected by the quality of the measured signal, i.e., the transducer type and the signal conditioning. Consequently, the division of the frequency domain as a function of the power spectra or the cumulative energy distribution is not always a reliable process. Therefore, to conduct a reliable wide band energy computation, it is necessary to remove the bias introduced by the observer.

In this study, a procedure for the systematic computation of the wide band energy is developed. The proposed methodology is based on a Student's t-distribution fitting of the power spectrum cumulative energy (CE). The Kolmogorov–Smirnov test is used to compare the cumulative energy with Student's t-distribution. As a result, three frequency regions are found. The differences that appear at the distribution tails when comparing the cumulative energy with the corresponding Student's t-distribution discriminate the cut-off frequencies that separate the three frequency regions.

2. Experimental setup

Two cylindrical lab-scale Bubbling Fluidized Beds (BFBs) were used for the experiments. The first apparatus is a cylindrical poly methyl methacrylate (PMMA) vessel with a 0.07 m inner diameter, d, and a 1 m height. The air distributor consists of 7 tuyeres with eight 0.5 mm diameter holes in each. The plenum is filled with a metallic mesh to ensure homogeneous air distribution. The bed aspect ratio is fixed at $h_b/d = 1$.

The second fluidized bed facility (Fig. 1) is equipped with an electric motor to rotate the distributor. The cylindrical vessel has an inner diameter, D, of 0.192 m, and a height of 1 m (Soria-Verdugo et al., 2011). The fixed bed height, h_b, is fixed at $0.75 \cdot D$. The rotating distributor consists of a perforated plate with 275 orifices of 2 mm diameter each, arranged in a triangular configuration with an 11 mm pitch. There are two types of experiments conducted in this facility, those with the distributor rotating at an angular velocity of 100 rpm and those with a static distributor.

The bed material was silica sand particles for all experiments, classified as Group B according to the Geldart's classification (Geldart, 1973). The particle density was measured at 2645.5 kg/m^3 with a standard deviation of 2.5 kg/m^3, and a mean diameter of 683 μm. The beds were fluidized with air at ambient conditions, and the airflow was measured with a rotameter. The minimum fluidization velocity was measured at $U_{mf,s} = 0.33$ m/s and $U_{mf,r} = 0.31$ m/s for the static and rotating distributor, respectively (Sobrino et al., 2008).

The measurement system in the small facility ($d = 0.07$ m) consisted of one pressure probe placed at the plenum chamber with 4 mm inner diameter and 0.10 m length. These dimensions guarantee an undisturbed transfer of the signal (van Ommen et al., 1999). A Kistler sensor, type 7261, was connected to this probe to measure the differential pressure fluctuations.

The pressure fluctuations in the rotating distributor bed ($D = 0.19$ m) were measured using 2 pressure probes (Fig. 1). The pressure probes were placed through the bed wall; one probe was placed at the plenum and the other was placed above the distributor at a height of $0.75D/2$. The probe dimensions for this facility are similar to those of the smaller facility. Two Kistler and Honeywell (SPT type) pressure sensors were placed in the plenum

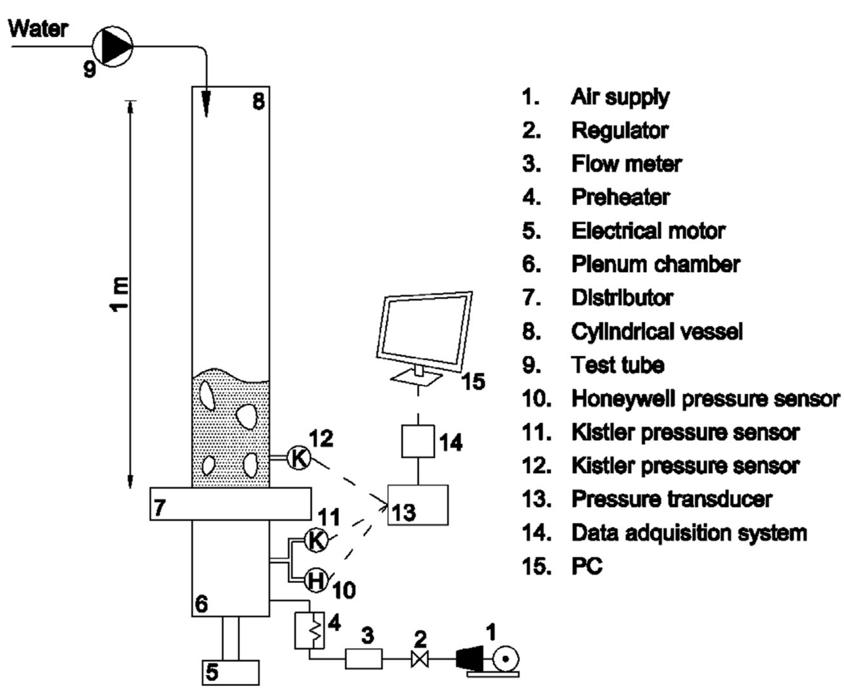

Fig. 1. Schematic diagram of the experimental fluidized bed equipped with a rotating distributor.