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A numerical study of the bubble induced pressure fluctuation in gas-fluidized beds

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ABSTRACT

Pressure fluctuation analysis has been widely accepted as an efficient way for bubble size estimation in fluidized beds since the local bubble induced pressure fluctuation, which is believed to be a function of bubble size, can be separated away from the global pressure waves. The spectral data decomposition method developed by van der Schaaf et al. (2002) Van der Schaaf et al. (2002) has been widely used in this regard. However, it has been found in various experimental studies that the proportionality constant between the reference data (obtained via measurements by various techniques or predicted by well-established correlations) and the estimated bubble size differs significantly in different applications. In this work we try to understand the scattered proportionality constants via a numerical study based on the Euler-Euler two-fluid model. The simulation results indicate that the local bubble induced pressure fluctuation is affected not only by bubble size, but also by the lateral distance between the rising bubble and detecting point, bubble shape, bed diameter, and bubble coalescence. Without consideration of these factors, the spectral data decomposition method is subject to large deviation for bubble size estimation.

1. Introduction

Gas-fluidized beds have been widely used in the industry. Bubbles have been considered as the motor of fluidization, and the performance of a fluidized bed reactor can be well characterized by accurate estimation of the bubble parameters. In the past decades many techniques have been successfully applied in measuring bubble parameters in fluidized beds, like capacitance/optical fiber probes [1,2], X/γ-ray [3–5], and Electrical capacitance tomography [6,7]. Despite the applications in a diversity of processes, the aforementioned measuring technologies are mostly limited to ambient temperature and low pressure. Yet many fluidized bed reactors are running at high temperature and high pressure, and accurate measurement of bubble parameters under extreme conditions is relatively difficult.

The pressure fluctuation analysis [8] is one of the few measurement techniques suitable for fluidized beds operated under high pressure and high temperature. The in-bed pressure signal is a combination of the global fast compression waves and the local bubble induced slow pressure waves. The global fast compression waves originate from bubble eruption at the bed surface, bubble formation near the gas distributor, bubble coalescence, mechanical bed mass oscillations, gas fluctuations in the windbox, and among others [9,10]. The passage of a bubble, referring to classical Davidson and Harrison model [11], can produce a local slow kinematic pressure wave with the amplitude proportion to the bubble size. Van der Schaaf et al. [12] proposed a spectral data decomposition method to obtain bubble size based on the different propagation velocity of the global and local pressure waves, in which the bubble induced local kinetic pressure wave information is first extracted from a coherence analysis of the pressure signal series detected simultaneously in the bed and in the windbox, and the bubble size is then inferred accordingly.

Though the spectral data decomposition method can well capture the bubble behavior in fluidized beds [13–16], it is challenged by its semi-quantitative nature in the bubble size estimation. The proportionality constant between the reference data (obtained via measurements by various techniques or predicted by well-established correlations) and the estimated bubble size (or called the characteristic length scale by van der Schaaf et al. [12]) differs significantly in different applications. Kleijn van Willigen et al. [17] reported in their 2D experiments that the proportionality constant is 1.3 for Geldart B particle and 8.1 for Geldart A particles. Rüdisüli et al. [16] found the proportionality in the range of 2.0–8.0. The scattered proportionality constants apparently hinder the pressure fluctuation analysis as a robust measurement technique for quantitative bubble size estimation. The reasons underlying the large variation of the proportionality constants are yet to be understood.

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The Euler-Euler two-fluid model, incorporated with the kinetic theory of granular flow (KTGF) [18,19] for formulating the rheologic parameters of particle phase, is capable of modeling gas-fluidized beds effectively [18–21]. Particularly, it can be used as a learning tool for studying the complicate hydrodynamic phenomena which are difficult to measure with advanced instruments. In this work, we try to understand the reason underlying the large variation of the proportionality constants in gas-fluidized beds by use of the Euler-Euler two-fluid model, in which both the bubble size and pressure fluctuation signal can be directly retrieved. To this end, the spectral data decomposition method by Van der Schaaf et al. is first validated and evaluated by the simulation results. Since the simulation results can correlate bubble size and the corresponding pressure fluctuation signals in a direct way, we then analyze the underlying reasons for the large variation of the proportionality constant. A detailed discussion on the scattered proportionality constants in bubble size estimation from pressure fluctuation signals is given out. And last this paper is concluded with some suggestions on improving bubble size estimation via pressure fluctuation analysis.

2. Model descriptions

In the Euler-Euler two-fluid model, both the gas and particle phase are considered as continuous medium and described by volume-averaged Navier-Stokes equations. The relevant equations are listed in Table 1. The rheologic properties of the fluidized particles formulated by the kinetic theory of granular flows (KTGF) are used to achieve the closures of the governing equations for particle phase [18,19]. The granular viscosity and granular conductivity are calculated by use of the expressions by Gidaspow et al. [18]. The solid phase pressure, the radial distribution, and the granular bulk viscosity are proposed by Lun et al. [19]. The frictional viscosity of the solid phase is according to that by Johnson and Jackson [22]. The inter-phase momentum transfer coefficient is obtained via the correlation of Wen and Yu [23] for dilute regime, and Ergun [24] equation for dense regime. The boundary conditions follow that by Sinclair and Jackson [25], where a no-slip boundary condition is used for gas phase while a half slip boundary condition for particle phase, with the specularity coefficient of 0.25 and restitution coefficient of 0.2.

Table 1
Equations of the Euler-Euler two-fluid model.

The continuity equations:

For gas phase

$$\frac{\partial(\varepsilon_g\rho_g)}{\partial t} + \nabla\cdot(\varepsilon_g\rho_g\,\vec{u_g}) = 0$$

For particle phase

$$\frac{\partial(\varepsilon_s\rho_s)}{\partial t} + \nabla\cdot(\varepsilon_s\rho_s\,\vec{u_s}) = 0$$

The momentum equations:

For gas phase

$$\frac{\partial(\varepsilon_g\rho_g\vec{u}_g)}{\partial t+\nabla\cdot(\varepsilon_g\rho_g\vec{u}_g\vec{u}_g)=-\varepsilon_g\nabla p+\nabla\cdot\overline{\overline{\tau}}_g+\varepsilon_g\rho_g\,\vec{g}-\beta(\vec{u}_g-\vec{u}_s)}$$

For particle phase

$$\frac{\partial(\varepsilon_s\rho_s\vec{u}_s)}{\partial t+\nabla\cdot(\varepsilon_s\rho_s\vec{u}_s\vec{u}_s)=-\varepsilon_s\nabla p-\nabla p_s+\nabla\cdot\overline{\overline{\tau}}_s+\varepsilon_s\rho_s\,\vec{g}+\beta(\vec{u}_g-\vec{u}_s)}$$

The Granular temperature equation:

$$\frac{3}{2}\left\{\frac{\partial(\varepsilon_s\rho_s\vartheta)}{\partial t}+\nabla\cdot(\varepsilon_s\rho_s\vec{u}_s\vartheta)\right\} = -(P_s\overline{\overline{I}}+\overline{\overline{\tau}}_s):\nabla\vec{u}_s+\nabla\cdot(k_s\nabla\vartheta)-\gamma_s-3\beta\vartheta$$

The inter-phase momentum transfer coefficient β:

$$\beta = \left\{ \frac{\frac{\frac{4}{3}C_D(1-\varepsilon_g)\varepsilon_g\rho_g|\vec{u}_g-\vec{u}_s|}{d_p\varepsilon_g^{-2.65},\quad \varepsilon_g\ge 0.8150\frac{(1-\varepsilon_g)^2\mu_g}{\varepsilon_g d_p^2}+\frac{7}{4}(1-\varepsilon_g)\rho_g|\vec{u}_g-\vec{u}_s|}}{d_p,\varepsilon_g<0.8} \right.$$

where

$$C_D = \begin{cases} \frac{24}{Re}(1+0.15Re^{0.687}), & Re<1000 \\ 0.44, Re\ge 1000 \end{cases}$$

$$\frac{Re = \varepsilon_g\rho_g|\vec{u}_g-\vec{u}_s|}{\mu_g d_p}$$

3. Simulation setup

The modeling approach described above has been implemented into the commercial CFD code, Fluent 6.3. The simulations were carried out for 2D fluidized beds. As illustrated in Fig. 1, three reactors with different sizes were used in the simulations:

Reactor I: 2D fluidized bed reactor with a width of 0.15 m, height of 0.8 m, and initial bed height of 0.5 m;
Reactor II: 2D fluidized bed reactor with a width of 0.5 m, height of 1.5 m, and initial bed height of 1.0 m;
Reactor III: 2D fluidized bed reactor with a width of 0.15 m, height of 1.5 m, and initial bed height of 0.8/1.0 m;

In order to evaluate the spectral data decomposition method, *Reactor I* (cf. Fig. 1 (a)) is used for simulation of freely bubbling fluidized bed with a uniform gas velocity at the inlet. *Reactor II* and *Reactor III*, as displayed in Fig. 1 (b), are used for simulation of single-bubble or twin-bubble to find the reasons underlying the large variation of the proportionality constants. Single bubble was injected into *Reactor II* and *Reactor III* operated at incipient fluidization through a central jet orifice. The width of the central jet orifice, as shown in Fig. 1 (b), is 0.005 m. The injected bubble size can be controlled by altering the jetting velocities. The labels a, b and c in Fig. 1 (b) are the detecting points for pressure signals, representing different radial distances between the detecting point and the bubble centerline. The grid dependence was first examined for these three reactors. A computational grid with uniform grid size of 0.0025 m × 0.0025 m and a time step of 1×10^{-4} s were used in all simulations. Typical parameters describing the particle properties and operating conditions are listed in Table 2.

4. Data processing

4.1. Bubble size from the spectral data decomposition method

In the bubbling fluidized bed simulations, the sampling frequency for the pressure signals here is 1000 Hz, with a total number of data points of 61,440 (61.44 s) chosen from each measurement. And each time series is divided into 30 segments with each subset of 2048 data points for spectral analysis. According to the spectral data decomposition method by Van der Schaaf et al. [12], the coherence between the two time series of pressure signals at the gas distributor and in the bed is first analyzed:

$$C_{XY}^2(f) = \frac{\varphi_{XY}(f)\cdot\varphi_{XY}^*(f)}{\varphi_{XX}(f)\cdot\varphi_{YY}(f)} \tag{1}$$

where $\varphi_{XX}(f)$ is the power spectral density (PSD) of the pressure time series at the gas distributor, $\varphi_{YY}(f)$ is PSD of the in-bed pressure time series, and $\varphi_{XY}(f)$ is the cross PSD for the two time series.

The coherence ranges from 0 to 1. A coherence of 1 means that the time series are totally coupled while a coherence of 0 means not coupled. Owing to the absence of bubbles, the time series of pressure fluctuations at the gas distributor only contain the global pressure fluctuations. While the pressure fluctuations in the bed are composed of the global pressure fluctuations and the local pressure fluctuation due to bubble passage. Hence the coherent part between the two is the global ones while the incoherent part is the local ones. Then $\varphi_{YY}(f)$is further divided into a coherent output PSD (refer to $COP_{XY}(f)$) and incoherent output PSD (refer to$IOP_{XY}(f)$) by the coherence, which correspond to the global fast compression waves and bubble passage induced local pressure fluctuations, respectively:

$$COP_{XY}(f) = C_{XY}^2(f)\cdot\varphi_{XX}(f) \tag{2}$$

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