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Experimental quantification of the particle–wall frictional forces in pseudo-2D gas fluidised beds

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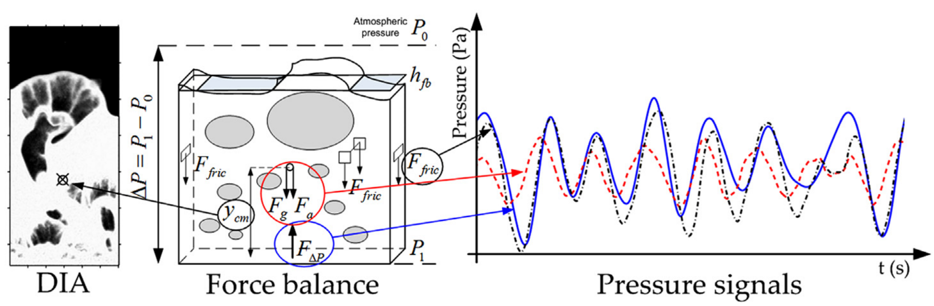
HIGHLIGHTS

- A novel measurement technique for pseudo-2D fluidised beds is developed.
- The pressure signal is processed in combination with the solids distribution.
- A particle–wall interaction coefficient is obtained.
- The frictional force is found to correlate with the centre of mass velocity.
- The effect of the wall friction on the pressure fluctuations is not negligible.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work a novel measurement technique for pseudo-2D fluidised beds is developed. The objective is to give an estimation of the overall frictional force between the solids and the front and rear walls of the bed. For doing this, the measured pressure signal in the bed is processed in combination with the solids distribution (i.e. centre of mass position, velocity and acceleration) obtained from digital image analysis of the optically accessible front view of the bed. This is performed by acquiring the pressure signal in the bed simultaneously to the digital images. Both the pressure and the digital images are connected through a simple force balance in the bed, and a particle–wall interaction coefficient is obtained assuming that the overall frictional force is proportional to the centre of mass velocity. The particle–wall interaction coefficient found using this technique is of the order of 40–120 kg/m^2 s in the bed tested, and the standard deviation of the frictional forces reaches more than 70% of the weight of the bed. Therefore, the results indicate that the contribution of the particle-to-wall friction on the fluctuation of the pressure drop in a pseudo-2D bed is not negligible.

1. Introduction

Fluidised beds have various applications in industry, such as fluid catalytic cracking (FCC), gasification, combustion of solid fuels, and Fischer–Tropsch synthesis (Kunii and Levenspiel, 1991). Despite the fact that fluidised beds have been used in industry since the 1920s and great progress has been made, some aspects of fluidised bed dynamics are still far from being fully understood.

Beds having small thickness, i.e. pseudo two-dimensional (2D) beds, have been crucial for the understanding of the dynamics of gas-particle systems. In this regard, pseudo-2D fluidised bed systems typically have a transparent wall, in order to allow optical access to the system, and possess a small thickness to ensure that the visualisation is representative of the whole system. In this kind of systems, Digital Image Analysis (DIA) or Particle Image Velocimetry

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(PIV) can be applied to characterise the bubble phase and the solids motion, respectively. Such studies have been proved to be a valuable tool for the understanding of fluidised bed systems (Shen et al., 2004; Santana et al., 2005; Almendros-Ibáñez et al., 2006; Müller et al., 2007; Laverman et al., 2008; Busciglio et al., 2008; Sánchez-Delgado et al., 2010; Hernández-Jiménez et al., 2011a,b; Soria-Verdugo et al., 2011a,b; Sánchez-Delgado et al., 2013).

Alternatively, pressure signal analysis is widely used in the literature to characterise the dynamics of fluidised bed systems. Many works have been done in this field and nowadays the pressure signal is routinely employed to obtain a large amount of information concerning the dynamics of a fluidised bed, c.f. the review by van Ommen et al. (2011).

Computational Fluid Dynamics (CFD) can be a very effective complementary tool to the experiments for achieving a detailed analysis of hydrodynamics in complex gas-solids flows. Note that, in these pseudo-2D beds, the front and the rear walls restrict the solids motion, leading to a different flow behaviour compared to fully three- dimensional (3D) systems. For thin bed thicknesses, the effect of the front and the rear wall on the particle motion can be significant and should not be neglected in numerical simulations of pseudo-2D beds (Li et al., 2010; Hernández-Jiménez et al., 2011a). However, there is a lack of experimental quantification of the wall frictional forces in pseudo-2D beds. Knowledge of the wall frictional forces in thin beds can be useful in the understanding of fluidised beds and will facilitate the development of particle–wall interaction models and the validation of the different simulation approaches such as two-fluid models.

The gas pressure field in the bed can be inferred from the solids distribution since these two parameters are inextricably linked in bubbling fluidisation (Davidson and Harrison, 1963; Baskakov et al., 1986; van Ommen et al., 2011). This was verified by Croxford and Gilbertson (2011), who estimated the spatial distribution of the pressure in a pseudo 2-D bubbling bed by numerically solving the Davidson and Harrison (1963) quasi-steady potential flow equations of the gas phase. They used, as an input for the equations, the bubbles size and location experimentally measured with a digital camera. Their simulation successfully reproduced the pressure field when the bubbles over a wide region of the bed were considered.

In the present work, a different approach for the pressure drop prediction in the bed is followed noticing that the dynamics of the bed is also described by its centre of mass. In particular, a novel methodology is proposed for coupling the pressure signal analysis with the digital image acquisition of a fluidised pseudo-2D bed in order to give an estimation of the frictional forces exerted by the front and rear walls on the bed particles. Using a force balance, the frictional force between the bed and the walls is estimated here as a function of the instantaneous pressure drop in the bed, the bed weight, and the velocity and acceleration of the centre of mass of the bed. Additionally, results from a pure 2D simulation, i.e. without incorporating the front and rear walls, have been included to show that in the absence of the front and rear walls the pressure and the acceleration of the centre of mass of the bed are perfectly correlated.

2. Experimental setup

The experimental facility employed in this work is a pseudo-2D cold fluidised bed of dimensions 0.3 m × 1 m × 0.01 m (width W, height H, and thickness Z). The bed was filled with ballotini glass particles of 2500 kg/m^3 density. The experiments were carried out for three different particle sizes: Geldart's classification type B of 0.4–0.6 mm diameter, type B-D particles of 0.6–0.8 mm diameter, and type D particles of 1–1.3 mm diameter. The air distributor consists of a perforated plate with two rows of 30 holes of 1 mm diameter arranged in a triangular configuration with 1 cm pitch. The front and rear walls of the bed were made of glass and the rear wall was painted in black to increase contrast in the front images. A sum up of the experimental parameters is included in Table 1.

Table 1
Experimental setup.

Parameter		Value
Bed height, H (m)		1
Bed width, W (m)		0.3
Bed thickness, Z (m)		0.01
Aspect ratio, h_0/W (-)		0.75, 1, 1.25
Particles density, ρ_s (kg/m^3)		2500
Small particles	d_p (mm)	0.4–0.6
	U_{mf} (m/s)	0.27
Medium particles	d_p (mm)	0.6–0.8
	U_{mf} (m/s)	0.44
Big particles	d_p (mm)	1–1.3
	U_{mf} (m/s)	0.67

A pressure probe was used to carry out the measurements. The probe was placed inside the bed at 5 cm above the distributor plate. The pressure fluctuations in the bed were measured with an ELLISON (PR 3110) differential pressure transducer. The transducer was connected to the probe by means of a silicon tube with a total length of 50 cm and an inner diameter of 4 mm. According to van Ommen et al. (2004) pressure waves in a bubbling bed at $2U_{mf}$ can be detected at radial distances up to 0.3 m from their origin. Also, Croxford et al. (2005) reported that for a small-scale fluidised bed one probe is sufficient, in principle, to characterise the bed hydrodynamics. Therefore, only the pressure probe at 5 cm above the distributor will be used in the bed studied here. In addition, two spotlights were used to get a uniform illumination of the front of the bed. A digital camera, Basler A640, took images of the front view of the fluidised bed at 100 frames per second and, simultaneously, the pressure transducers recorded the pressure signal at 2000 Hz. Fig. 1 shows a scheme of the facility and an example of a greyscale image acquired with the digital camera.

3. Theory

A simple balance of vertical forces in a control volume comprising the gas and particles in a fluidised bed is shown in Fig. 2. The balance indicates that the force exerted by the pressure drop in the bed, ΔP, just over the area $A_T = WZ$ of the distributor, i.e. $F_{\Delta P} = A_T \Delta P$, must compensate to the inertia force due to the acceleration of the centre of mass of the bed, F_a, plus the force due to the weight of the bed, F_g, (i.e. hydrostatic pressure) and the frictional force of the bed walls on the gas and solids phases, F_{fric}:

$$F_{\Delta P} = F_a + F_g + F_{fric} = m\frac{d^2 y_{cm}}{dt^2} + mg + F_{fric} \qquad (1)$$

where $m = A_T(1-\epsilon_0)\rho_s h_0$ is the mass of the bed particles, y_{cm} is the vertical position of the centre of mass of the bed, and $d^2 y_{cm}/dt^2$ is the acceleration of the centre of mass.

In Eq. (1) the inertia and weight of the gas have been neglected since the gas density is much smaller than the particle density. Also, the contribution of the gas phase to the frictional force F_{fric} is expected to be very reduced compared to the frictional force between particles and wall. Note that $F_{\Delta P}$ is equivalent to the force produced by the gas on all the bed particles.

In general, the frictional force is equal to the shear stress, τ, times the surface area of the lateral walls in contact with the bed, $A_L = (2W + 2Z)h_{fb} \approx 2Wh_{fb}$, where h_{fb} is the time-averaged height of the fluidised bed. Following the classical Coulomb's friction