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LINKING OF THE PRESSURE OSCILLATION IN A PSEUDO TWO-DIMENSIONAL BED WITH THE SPATIOTEMPORAL DISTRIBUTION OF PARTICLES

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ABSTRACT

In this work the pressure signal in a pseudo-2D fluidized bed is processed in combination with the solids distribution (i.e. centre of mass velocity and acceleration) obtained from digital image analysis in order to give an estimation of the overall frictional force between the solids and the front and rear walls of the bed. For doing this, a friction coefficient is obtained assuming that the overall frictional force is proportional to the centre of mass velocity. The friction coefficients obtained using this technique are of the order of 10 to 100 kg/m^{2}s. The contribution of the friction on the fluctuations of the pressure measured in the pseudo-2D bed is not negligible, except at small superficial velocities and bed aspect ratios.

INTRODUCTION

Pressure signal analysis is widely used in the literature to characterize the dynamics of fluidized 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 fluidized bed, e.g. van Ommen et al. (1). Another important measurement technique is digital image analysis of particles in fluidized beds. This technique has experienced great progress in the last decades, from digital image acquisition, where the bubble phase can be directly characterized, to particle image velocimetry, where the velocity of the dense phase can be calculated. In this regard, the fluidized bed system must have a transparent wall, in order to allow optical access to the system, and possess a small thickness to ensure that the visualization is representative of the whole system (Shen et al. (2), Hernández-Jiménez et al. (3)). In these beds having small thickness, i.e. pseudo two-dimensional (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 (Hernández-Jiménez et al. (3), Li et al. (4)). However, there is a lack of experimental quantification of the wall frictional forces in pseudo-2D beds.

In this work, the pressure signal analysis is coupled with the digital image acquisition of a fluidized pseudo-2D bed in order to give an estimation of the frictional forces of the front and rear walls of the bed. 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, as well as the velocity and acceleration of the centre of mass obtained from digital image acquisition techniques. This estimation of the frictional force can be useful in the understanding of pseudo-2D fluidized beds.

EXPERIMENTAL SETUP

The experimental facility to be studied is a two-dimensional cold fluidized bed of dimensions 0.3 m×1 m×0.01 m (width *W*, height *H*, and thickness *Z*). The fluidized bed was filled with ballotini glass particles of 2500 kg/m^3 density and 400-600 μm diameter. The superficial gas velocity at minimum fluidization conditions was $U_{mf}\approx 0.27$ m/s. The air distributor consists of a perforated plate of two rows with 30 holes of 1 mm diameter and spaced 1 cm apart. The front and rear walls were made of glass and the rear wall was painted in black to increase contrast in the images.

Two pressure probes were used during the measurements. One of the probes was placed in the plenum chamber and the other in the bed axis at 5 cm above the distributor plate. The pressure fluctuations in the plenum chamber were measured with a *LUCAS* differential pressure transducer and the pressure fluctuations in the bed were measured with an *ELLISON* differential pressure transducer. Both transducers were connected to the probes by means of a silicon tube with a total length of 50 cm and a diameter of 4 mm. In addition, two spotlights were used to get a uniform illumination of the bed. A digital camera, *Basler A640,* took images of the front view of the fluidized bed at 100 frames per second and, simultaneously, the pressure transducers recorded the pressure signal at 2000 Hz. Figure 1 shows a scheme of the facility and an example of a greyscale image acquired with the digital camera.

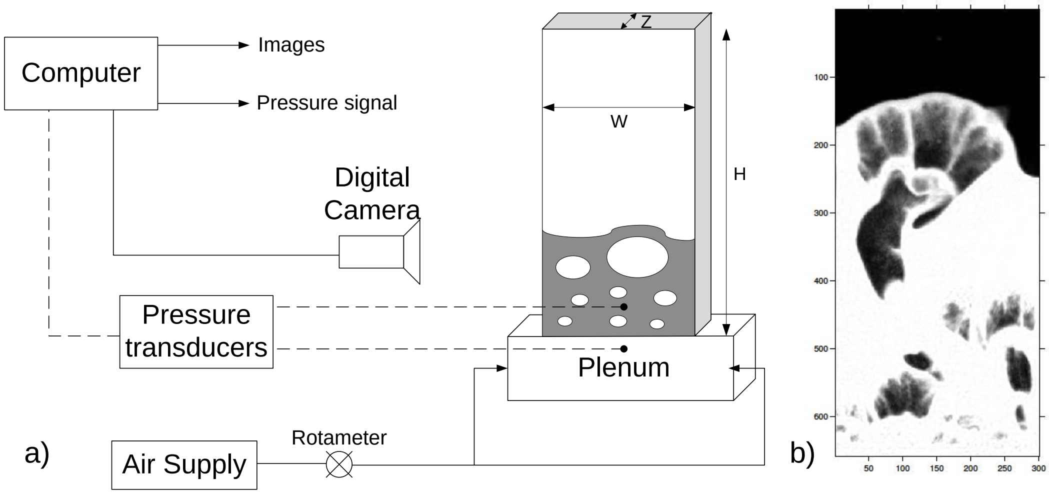

Figure 1: a) Sketch of the experimental facility and b) an example of a front view image of the fluidized bed.

THEORY

A simple force balance in a fluidized bed, shown in Figure 2, 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. $F_{\Delta P} = A_T \Delta P$, is equal 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} :

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

Where $m = A_T (1 - \varepsilon_0) \rho_s h_0$ is the mass of the bed particles, y_{cm} is the vertical position of the centre of mass, and $d^2 y_{cm} \big/ dt^2$ is the acceleration of the centre of mass.

In Equation 1 the gas inertia and weight forces have been neglected since the gas density is much smaller than the particle density. Also, the contribution of the gas phase to the friction force F_{fric} is expected to be very reduced compared to the friction force between particles and wall.

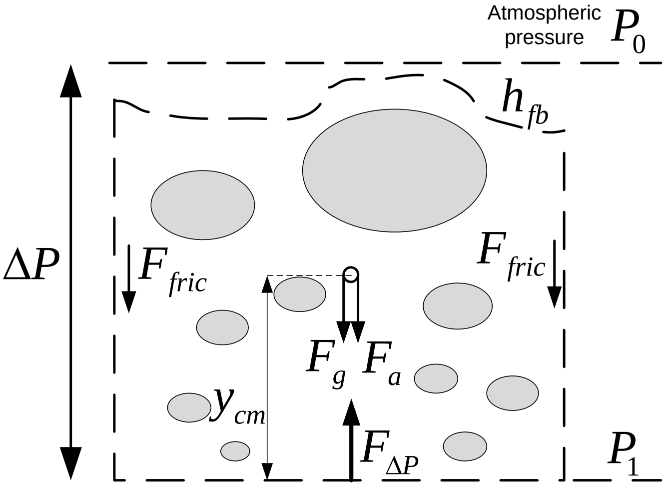

Figure 2: Balance of forces acting on the bed material

The frictional force is equal to the shear stress, τ , times the surface area of the lateral walls in contact with the bed, $A_L = (2W + 2Z) h_{fb} \approx 2W h_{fb}$, where h_{fb} is the time-averaged height of the fluidized bed. As a first approximation, it will be assumed that the shear stress is of dissipative form and can be expressed as the product of the local velocity of particles, v_s , their solid volume fraction, α_s , and a friction constant *c*. After integrating τ all over the area of the bed walls A_L , the frictional force is found to be proportional to the velocity of the centre of mass of the bed because the bed thickness is small (pseudo-2D bed):

$$F_{frict} = \int_{A_L} \tau dA = \int_{A_L} c \alpha_s v_s dA \approx c A_L \frac{dy_{cm}}{dt} \tag{2}$$

The whole balance of forces Equation 1 can be divided by the transversal area A_T of the bed to deal with pressures instead of forces:

$$\Delta P = (1 - \varepsilon_0) \rho_s h_0 \left[\frac{d^2 y_{cm}}{dt^2} + g \right] + c \frac{A_L}{A_T} \frac{dy_{cm}}{dt} \tag{3}$$

Therefore, the friction coefficient can be obtained by measuring the time evolution of the pressure drop in the bed, ΔP_{meas} (i.e. pressure drop measured), together with the vertical position of the centre of mass of the bed, y_{cm}, and then performing a least square minimization of Equation 3 over the time period of measurement (*T*):

$$\min_{C}\left[\int_0^T\left(\Delta P_{meas}-(1-\varepsilon_0)\rho_s h_0\left[\frac{d^2y_{cm}}{dt^2}+g\right]-c\frac{A_L}{A_T}\frac{dy_{cm}}{dt}\right)^2dt\right] \tag{4}$$

Note that $\Delta P_{calculated}=(1-\varepsilon_0)\rho_s h_0\left[d^2y_{cm}/dt^2+g\right]+c\left(A_L/A_T\right)\left(dy_{cm}/dt\right)$ is the pressure drop in the bed calculated (i.e. pressure drop calculated) only with information from the digital image analysis.

DATA PROCESSING

Pressure signals and front-view images of the pseudo-2D bed were acquired simultaneously using *LabView*, at 2000 Hz and 100 Hz respectively. As mentioned previously, the pressure signals corresponded to probes in the plenum and in the bed at 5 cm above the distributor. These signals were resampled to 100 Hz to make their temporal resolution equal to the images. Two different procedures were followed to estimate the pressure drop in the bed, ΔP. One procedure was to use the pressure measured in the plenum and eliminate the pressure drop (experimentally characterized) of the air-flow in the distributor. Another option was to employ the pressure measured at 5 cm over the distributor and correct it with the averaged weight of the column of particles within this measurement point and the distributor.

Digital Image Analysis was applied to the acquired images of the bed in order to distinguish between bubbles and dense phase. This allowed for the calculation of the vertical position of the centre of mass of the bed, y_{cm}, at each time instant. The centre of mass is calculated with the grey scale images recorded by the camera using the grey level on each pixel, $y_{cm}=\sum_{i=1}^{N}y_i\cdot GL_i\Big/\sum_{i=1}^{N}GL_i$, where y is the vertical distance to the distributor, i is the pixel number, N is the total number of pixels in the image and GL is the grey level (255 for the particle phase and 0 for the bubble phase).The result is a discrete time series of y_{cm} that was numerically differentiated to obtain the time series of the centre of mass velocity, dy_{cm}/dt, and acceleration, d^2y_{cm}/dt^2. A moving average filter was applied on the velocity and acceleration series to reduce the noise amplified during of the differentiation. The measurements recorded $T=60$ seconds of both pressure signal and images.

Using the time series of ΔP, dy_{cm}/dt, d^2y_{cm}/dt^2 obtained from the experiment, the friction coefficient between the wall and the bed was determined through the algorithm sketched in Figure 3. The calculus starts with an estimation of *c* that is utilized to obtain the pressure drop calculated, $\Delta P_{calculated}$, which uses only information from the digital images. Despite the images and the pressure were acquired simultaneously, their synchronization is not perfect because of a small hardware delay produced by differences in the time response of activation of the pressure and the digital image measurement systems. The hardware delay is estimated with the maximum of the cross-correlation of the signals, ΔP_{meas} and $\Delta P_{calculated}$. After adjusting the delay between the two signals, the friction coefficient *c* is obtained from Equation 4, whose integral has been simplified into a summation extended over all the signal terms. The procedure is repeated starting with the obtained value of *c* until convergence, which requires over 10 iterations.

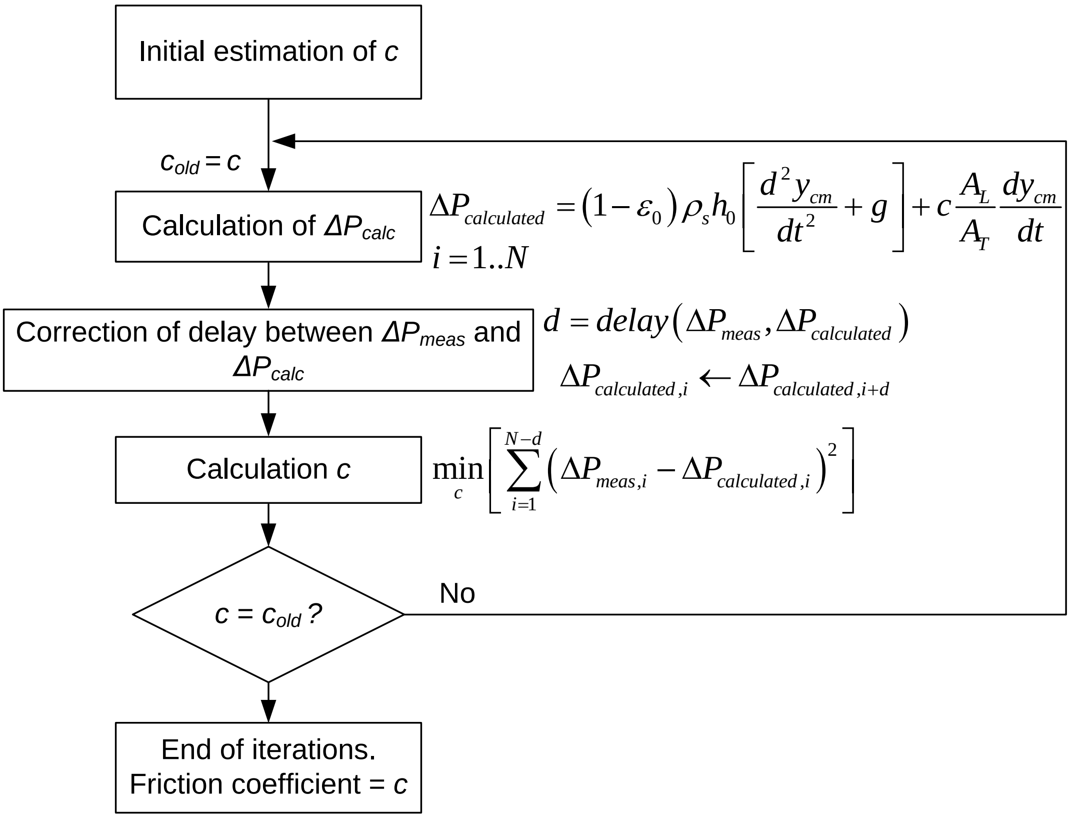

Figure 3: Iterative loop to calculate the friction coefficient, *C*.

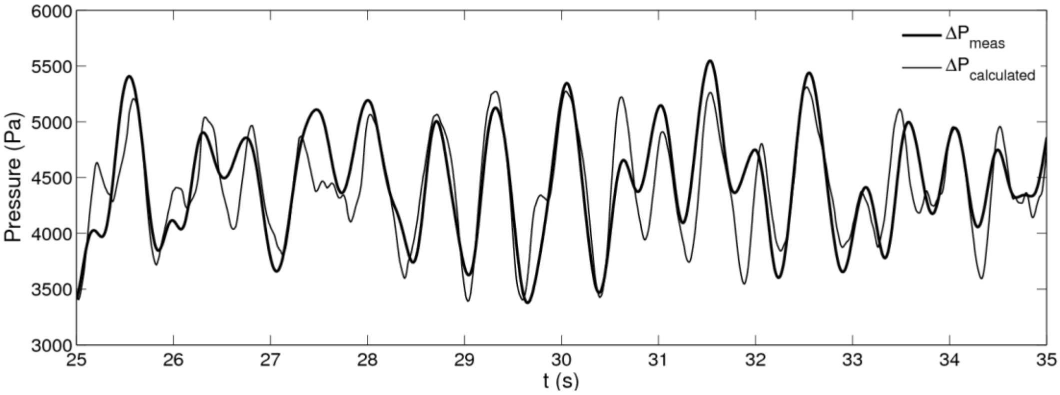

Figure 4: Pressure signals measured with a probe (ΔP_{meas}) and calculated with digital image analysis ($\Delta P_{calculated}$). $U/U_{mf} = 2.5$, $h_0/W = 1$.

As an illustrative result, Figure 4 shows the time evolution of the pressure drop in the bed, ΔP_{meas} , measured by extrapolation from a pressure probe in the plenum, as explained before. The figure also includes the pressure drop calculated, $\Delta P_{calculated}$, obtained with digital image analysis (bed weight, acceleration and friction) using the friction coefficient, *c*, that is estimated with the algorithm proposed in Figure 3. Clearly, the calculation of the pressure drop in the bed with digital image analysis is able to reproduce reasonably well most of the oscillations experienced by the measured pressure.

RESULTS

The friction coefficient, *c*, in the pseudo-2D fluidized bed presented previously was estimated under different operative conditions. A set of experiments were done for a range of superficial gas velocities (U/U_{mf} = 1.5, 2, 2.5, 3) and static bed aspect ratios (h_0/W = 0.75, 1, 1.25).

Firstly, the time-averaged height of the fluidized bed, h_{fb} , was estimated using digital image analysis to discriminate between the bed and the freeboard in each of the acquired images. The results are listed in Table 1 for the four superficial gas velocities and three aspect ratios studied. The time-average height of the bed suffers a large increment when passing from 1.5 to 2 U_{mf}, and for the rest of superficial velocities this increment relatively smaller. Obviously, the greater is h_0/W the larger is h_{fb} .

	U/U_{mf} (-)			
h_0/W	**1.5**	**2**	**2.5**	**3**
0.75	0.2932 m	0.3339 m	0.3654 m	0.3897 m
1	0.3808 m	0.4293 m	0.4625 m	0.4848 m
1.25	0.4605 m	0.5123 m	0.5479 m	0.5712 m

Table 1: Time-averaged height h_{fb} of the pseudo-2D fluidized bed.

Using the algorithm in Figure 3 and the values of h_{fb} in Table 1, the friction coefficient *c* for the pseudo-2D bed was calculated and the results are shown in Figure 5 for the different operative conditions studied.

Figure 5a contains the friction coefficient *c* as a function of the gas superficial velocity for $h_0/W = 1$. As the figure indicates, the friction coefficient increases with the gas superficial velocity and is within the range 13-73 kg/m^{2}s. According to Figure 5b, the friction coefficient also grows with the static bed height, but to a lesser extend compared to the effect of the gas superficial velocity. Note that, if the pressure drop measured, ΔP_{meas} , is extrapolated from the pressure probe at 5 cm over the distributor, the estimated coefficient of friction *c* is higher than the one obtained using the pressure drop extrapolated from the plenum, see Figure 5a. This discrepancy may be explained noticing that the pressure measurement at 5 cm over the distributor can gather the local behaviour of the bed while the pressure taken from the plenum integrates the pressure fluctuations along the distributor and is more representative of the global behaviour of the bed. Since the bed is also considered globally during the calculation of the centre of mass of the bed, the pressure drop extrapolated from the plenum is the option used in Figure 5b and in the rest of the results presented in this work.

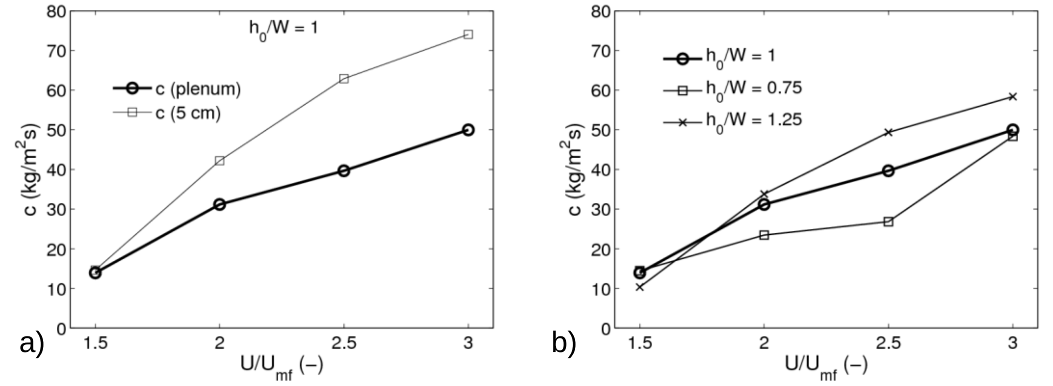

Figure 5: Friction coefficient *c* versus the superficial gas velocity: a) comparison of different alternatives in extrapolating ΔP_{meas} and b) effect of the aspect ratio using the plenum alternative.

Figure 6 compares the standard deviation σ of the following pressure terms: the pressure drop in the bed, ΔP_{meas}, the pressure associated to the acceleration of the centre of mass, $\Delta P_a = (1-\varepsilon_0) h_0 \rho_s \, d^2 y_{cm} / dt$, and the pressure contribution of the friction with walls, $\Delta P_{fric} = c(A_L / A_T)\, dy_{cm} / dt$. As expected, the standard deviation of all the pressure terms increases with U/U_{mf} and h_0/W. In view of Figure 6 the relative contribution of the frictional forces to the fluctuations of the pressure drop in the bed becomes more important as the superficial gas velocity (Figure 6a) or the bed aspect ratio (Figure 6b) is increased, becoming even greater than the contribution of the acceleration of the centre of mass.

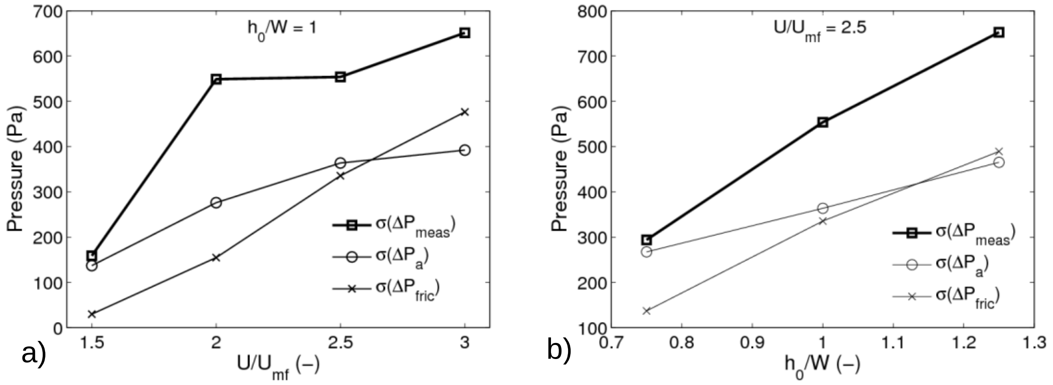

Figure 6: Standard deviation of the different pressure terms studied (ΔP_{meas}, ΔP_a, ΔP_{fric}) versus a) the superficial velocity and b) the aspect ratio.

CONCLUSIONS

In this work, the frictional forces exerted by the front and rear walls on the solids of a pseudo-2D fluidized bed were characterized. This was done linking the pressure drop measured in the bed with the acceleration and velocity of its centre of the mass obtained from digital image measurements of the solids distribution. The frictional forces were assumed to be proportional to the velocity of the centre of mass of the bed, times a friction constant, *c*. The friction constant was found to be very sensitive to the superficial gas velocity and less affected by the bed aspect ratio. The relative contribution of the frictional forces on the fluctuations of the pressure drop in the bed (i.e. the standard deviation of the pressure drop) can be even larger than the pressure fluctuation induced by the acceleration of the bulk of the bed. These empirical results evidence that the friction of particles with the walls plays an important role in the pressure fluctuations measured in a pseudo-2D.

NOTATION

A_L	lateral area (m^2)
A_T	transversal area (m^2)
c	friction constant in the force balance (kg/m^2s)
$F_{\Delta P}$	force due to the pressure drop in the bed (N)
F_a	force due to the acceleration of the cente of mass of the bed (N)
F_g	force due to hydrostatic pressure (N)
F_{fric}	frictional forces (N)
h_{fb}	mean freeboard height (m)
h_0	static bed height (m)
ΔP	pressure drop in the bed (Pa)
T	measurement time period (s)
U	superficial gas velocity (m/s)
U_{mf}	min. fluidization velocity (m/s)
y_{cm}	vertical position of the mass centre of the bed (m)
W	bed width (m)
Z	bed thickness (m)
α_s	solids volume fraction (-)
ε_0	static bed void fraction(–)
ρ_s	solids density (kg/m^3)
τ	shear stress (N/m^2)

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REFERENCES

1. J. Ruud van Ommen, Srdjan Sasic, John van der Schaaf, Stefan Gheorghiu, Filip Johnsson, Marc-Olivier Coppens, Time-series analysis of pressure fluctuations in gas–solid fluidized beds – A review. Int. Jou. Multiphase Flow 37 (2011) 403-428.
2. L. Shen, F. Johnsson, B. Leckner. Digital image analysis of hydrodynamics two-dimensional bubbling fluidized beds. Chem. Eng. Sci. 59 (2004) 2607-2617.
3. F. Hernández-Jiménez, S. Sánchez-Delgado, A. Gómez-García, A. Acosta-Iborra, Comparison between two-fluid model simulations and particle image analysis & velocimetry (PIV) results for a two-dimensional gas-solid fluidized bed. Chem. Eng. Sci. 66 (2011) 3753-3772.
4. T. Li, J. R. Grace, X. Bi, Study of wall boundary condition in numerical simulations of bubbling fluidized beds. Powder Tech. 203 (2010) 447-457.