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Hydrodynamics of shallow fluidized bed of coarse particles

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Abstract

The aim of the present study is experimental investigation of hydrodynamics of shallow fluidized bed of coarse particles. Air was fluidizing fluid. γ-Al_2O_3 particles of 1 mm and 1.8 mm in diameter and density of 1080 kg m^{-3} (both Geldart D) were used. Experiments were carried out in a column with rectangular cross-section area of 100 mm × 100 mm, at temperatures of 20 °C and 500 °C. Measurements of absolute and differential pressure fluctuations were employed. Standard deviation and amplitude spectra analysis were used to determine fluidization regimes. In the range of superficial velocities 0–4.5 m s^{-1}, three different regimes were found: single bubble regime, rapidly growing bubble regime and turbulent fluidization. General qualitative characteristics of those regimes regarding bed structure were ascertained. Transition velocities between regimes were experimentally determined and compared with literature correlations. A new correlation for prediction the velocity at the beginning of turbulent fluidization in the coarse particle systems was proposed as follows: $Re_c = 0.326Ar^{0.52}$.

Keywords: Regimes of fluidization; Coarse particles; Pressure fluctuation; Transition velocities

1. Introduction

Gas–solid fluidized beds have been widely used for many physical and chemical industrial processes. Shallow fluidized beds are applied for the processes which require short contact time between gas and particles (i.e. for reaching higher selectivity of intermediate component in a complex reaction net). For efficient designing of these processes hydrodynamics of the bed is of great importance. Therefore, many authors have investigated hydrodynamics of circulating and non-circulating fluidized beds of moderate and fine particles [1–7]. However, fluidized beds of coarse particles ($d_p > 1$ mm) were much less investigated [8–11].

For investigation of hydrodynamics different measurement techniques are applied such as: visual observation and video recording [4], pressure fluctuation measurements [2–4,6,7,12], local voidage fluctuation measurements by means of optical fiber probes [13] and electrical capacitance tomography [5]. Also, different approaches for data analysis could be used such as time and frequency domain analysis as well as chaos analysis. Time domain approaches include: (a) observation of the time sequence of measured signal of pressure or voidage fluctuations [1,4,11]; (b) standard deviation analysis [1,2,5,7]; (c) analysis of other statistical moments like skewness and flatness [1], autocorrelation and crosscorrelation functions [11]. Standard deviation analysis is the most common method based on plotting the standard deviation of pressure or voidage fluctuations versus gas velocity where the magnitude of standard deviation is proportional to the bubble size. Frequency domain approach is based on applying Fast Fourier Transform (FFT) on fluctuating pressure or voidage signal and obtaining amplitude spectra or power density spectra. Broadness of spectrum, existence and shifting of dominant frequencies are parameters connected to the structure of the bed. Frequency domain analysis is useful tool to prove the existence of the same regime in different systems (or under different conditions) by comparing the amplitude spectra in the same range of frequencies [14]. In the frame of chaos analysis, many researchers have used the Kolmogorov entropy in order to characterize fluidization regimes [3,6].

Previous investigations have confirmed the existence of six main fluidization regimes: particulate fluidization (only Geldart A particles), bubbling fluidization, slugging, turbulent fluidiza-

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Nomenclature

Am	amplitude of pressure fluctuations, Pa
Ar	Archimedes number, $\left(= gd_p^3(\rho_p - \rho_f)\rho_f/\mu^2\right)$
d_p	particle diameter, mm
D	equivalent column diameter, m
f	frequency, Hz
g	gravity acceleration, m s^{-2}
h	distance from distributor plate in Eq. (2), cm
H_0	settled bed height, m
P_2	measured absolute pressure at position H2, Pa
ΔP_{1-3}	measured differential pressure between positions H1and H3, Pa
Re_c	Reynolds number at U_c, $(= \rho_f d_p U_c/\mu)$
S.D.	standard deviation of pressure fluctuations, Pa
t	time, s
U	superficial gas velocity, m s^{-1}
U_c	transition velocity rapidly growing bubble to turbulent regime, m s^{-1}
U_{mb}	minimum bubbling velocity, m s^{-1}
U_{mf}	minimum fluidization velocity, m s^{-1}
U_r	transition velocity single bubble to rapidly growing bubble regime, m s^{-1}
U_t	terminal velocity of particles, m s^{-1}

Greek letters

μ	gas viscosity, Pa s
θ	temperature, °C
ρ_p	particle density, kg m^{-3}
ρ_f	gas density, kg m^{-3}

tion, fast fluidization and pneumatic conveying. In addition, some researchers pointed out that within bubbling fluidization several modes could exist. Catipovic et al. [9] have found three sub-regimes within the bubbling fluidization, depending mainly on the particle size: slow bubble, fast bubble and rapidly growing bubble regime. Svensson et al. [15] have reported the existence of single bubble and multiple bubble regimes depending on the distributor pressure drop.

From available literature, it can be concluded that regime of fluidization depends on: size and density of particles, superficial gas velocity, physical properties of gas, type of gas distributor and its pressure drop, temperature and pressure, settled bed height and diameter of the fluidization column. Furthermore, the regime is a complex function of these parameters and therefore its theoretical prediction is still hard and uncertain. Several maps of fluidization regimes which could be found in literature [16–18] are mainly based on results of investigations of fluidized beds of Geldart A and B particles, while data concerning fluidized beds of Geldart D particles are missing.

In this work, an experimental study of existing regimes in shallow fluidized bed of Geldart D particles is presented. Experiments were based on absolute and differential pressure measurements. Data were further processed by means of standard deviation and amplitude spectra analysis. We aimed to determine experimentally the transition velocities between regimes and to develop a correlation for prediction the velocity at the beginning of turbulent fluidization in the coarse particle systems. The general goal was to contribute to the development of general criteria for fluidization regime prediction.

2. Experimental

2.1. Experimental set up

Experiments were carried out in the experimental apparatus schematically shown in Fig. 1. A column with rectangular cross-section area of 100 mm × 100 mm and total height of 1.5 m was made of stainless steel. At opposite walls of the column two round glass windows (6 cm in diameter) were inserted for visual observation. Perforated plate gas distributor with 4.2% open area and rectangular arrangement of holes (0.3 mm in diameter) was used. Pressure drop through the gas distributor was up to 2.7 kPa at operating conditions in this study.

Spherical γ-Al_2O_3 particles (Condea Chemie) of 1 mm and 1.8 mm in diameter and density of 1080 kg m^{-3} (both Geldart D) were used as fluidizing particles. Important features of the particles at both tested temperatures were given in Table 1. Minimum fluidization velocity (U_{mf}) was calculated from Wen–Yu correlation [19] and the terminal velocity of particles (U_t) was determined from theoretical equations [19].

Air for fluidization was introduced at the bottom of the column by a compressor followed by an oil filter. Air flowrate was adjusted by the electronic massflow controller (F-203AC-FBB-55-V, Bronkhorst). For high temperature measurements air was heated by an electrical pre-heater with maximum power of 5 kW. Spiral electrical heater wound around the outside wall of the column (with maximum power of 700 W) was used to provide constant temperature of the bed. Column was coated by thermal insulation to avoid heat loss.

2.2. Measuring instruments and operating conditions

Temperature in the centre of the bed was measured by Ni–Cr–Ni thermocouples located at three positions: H1—20 mm below the distributor plate, H2—47 mm above the distributor plate and H3—248 mm above the distributor plate (Fig. 1).

Pressure taps were installed at the same positions H1, H2 and H3. Differential pressure transducer (PD-23, Keller) was used to measure differential pressure fluctuations between positions H1 and H3. Absolute pressure transducer (PA-23/25, Keller) was used to measure absolute pressure fluctuations at position H2. Pressure transducers were connected via A/D converter to

Table 1
Properties of bed materials

d_p (mm)	θ (°C)	U_{mf} (m s^{-1})	U_t (m s^{-1})	Ar (−)
1.8	20	0.57	7.05	226833
	500	0.50	8.99	22064
1.0	20	0.28	4.53	38895
	500	0.17	5.00	3783

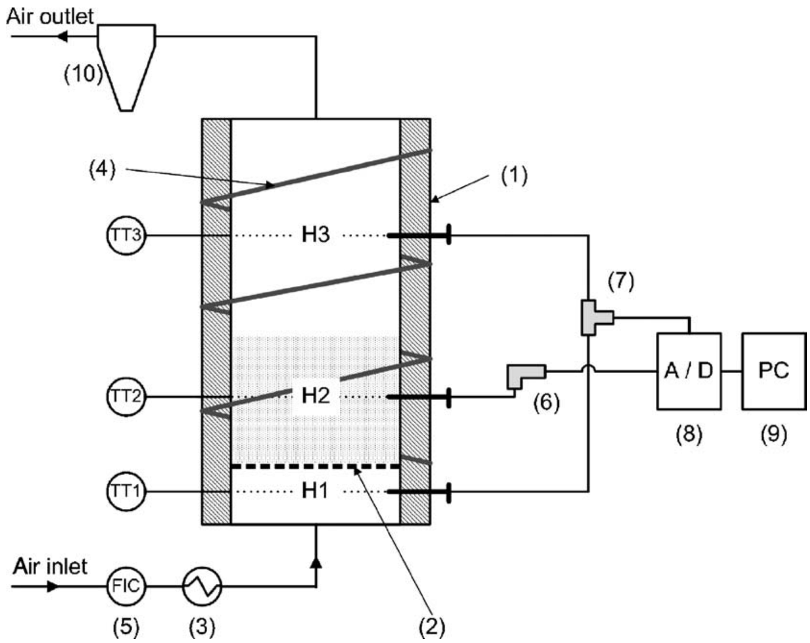

Fig. 1. Experimental equipment: (1) fluidized bed apparatus, (2) gas distributor, (3) electrical pre-heater, (4) spiral heater, (5) massflow controller, (6) absolute pressure sensor, (7) differential pressure sensor, (8) A/D converter, (9) computer and (10) cyclone.

a PC with DIA/DAGO software for data acquisition. Sampling frequency was in both cases (absolute and differential pressure measurements) 100 Hz and 2048 data points were recorded for 20 s in each run.

During the experimental measurements, particle diameter, settled bed height and bed temperature were operating variables as it is summarized in Table 2. At 500 °C, it was not possible to keep the temperature absolutely constant due to the variations in volumetric flow of gas, such that the temperature was in the range of 500 ± 10 °C.

Standard deviation of pressure fluctuations (S.D.) was calculated as:

$$\text{S.D.} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \quad (1)$$

where x_i is the sample i from time series and $\overline{x}$ is the mean value of time series (of pressure fluctuations). N is the number of sample points in one time series (2048).

The amplitude spectra were obtained by Fast Fourier Transform of the pressure–time series data.

3. Results and discussion

3.1. Regimes of fluidization

3.1.1. Determination of regimes

Fluidization regimes were determined by using a common method of standard deviation of pressure fluctuations. The standard deviation of pressure fluctuations versus superficial gas velocity plot for both tested particle diameters is presented in Fig. 2. A careful observation of the change in standard deviation with increasing gas velocity between 0 m s^{-1} and 5 m s^{-1} reveals three velocities which bound the areas of different dynamical behavior of the bed.

A point at which standard deviation starts increasing due to the bubble formation is known as a minimum bubbling velocity (U_{mb}). In a narrow range of gas velocities above U_{mb}, it can be

Table 2
Experimental operating variables

d_p (mm)	H_0 (m)	θ (°C)	Measured quantity (Pa)	Velocity range (m s^{-1})	Number of experiments (−)
1.8	0.046	20	$\Delta P_{1\text{–}3}$	0–2	17
		500 ± 10		0–2.4	18
	0.093	20		0–2	18
		500 ± 10		0–4.3	25
		20	P_2	0–2	17
		500 ± 10		0–4.3	25
1.0	0.093	20	P_2	0–2.2	26
		20	$\Delta P_{1\text{–}3}$	0–2.2	23
		500 ± 10		0–4.3	33

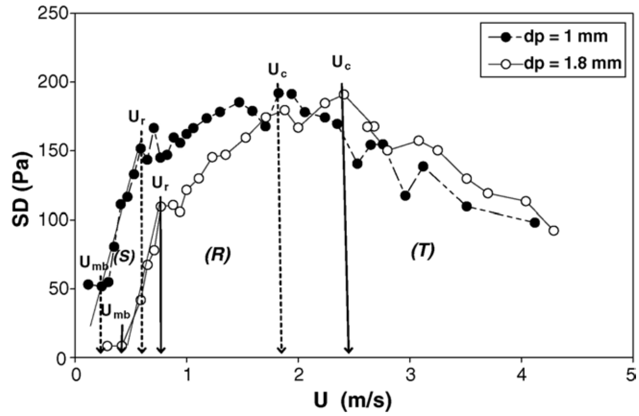

Fig. 2. Standard deviation of differential pressure fluctuations as function of superficial gas velocity ($H_0 = 0.093$ m, $\theta = 500\,^{\circ}$C).

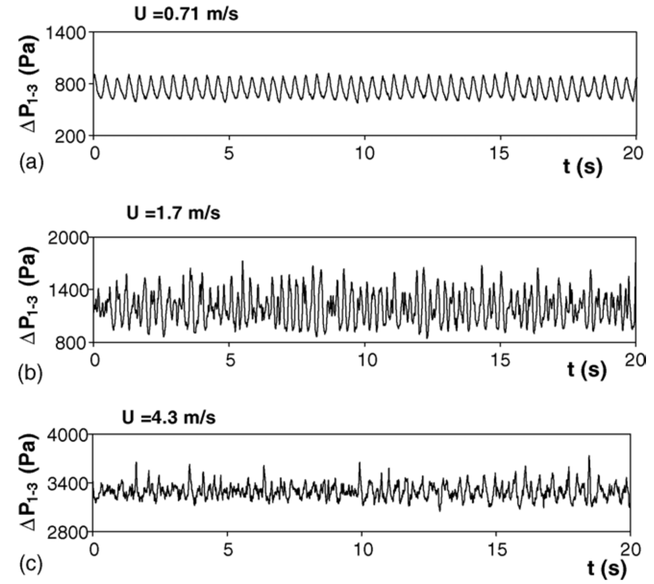

Fig. 3. Differential pressure signals measured in the bed with 1.8 mm particles for $H_0 = 0.093$ m and $\theta = 500\,^{\circ}$C: (a) in single bubble regime, (b) in rapidly growing bubble regime and (c) in turbulent regime.

seen a rising linear trend of S.D. versus U dependence, which is, according to Makkawi and Wright [5], characteristic for the single bubble regime (S). Sharp slope means very fast growth of the bubbles with small increase in gas velocity. Since the slope is the same for both particle diameters, it can be concluded that dynamics of bubble growth is the same in both systems.

At the velocity marked as U_r linear trend of standard deviation is suddenly changed. This change in the trend of standard deviation could be connected to the redistribution of gas in the bed due to the formation of a large bubble reaching in size the equivalent column diameter and its explosion. The velocity U_r is taken as a transition to rapidly growing bubble regime (R). Some authors call this regime exploding bubble regime [3,4]. In this regime large oscillations of the bed surface were observed visually.

The most obvious transition velocity is the velocity U_c corresponding to the maximum of standard deviation. Above this velocity S.D. shows a falling trend indicating a decrease in the bubble diameter. The velocity U_c is well known as a beginning of turbulent fluidization (T). Nakajima et al. [20] have suggested that at this velocity emulsion phase starts expanding, causing bubble breakage and disappearance. It can be seen in Fig. 2 that in the coarse particle systems disappearance of bubbles occurs very gradually in a wide range of superficial gas velocities (up to 4.5 m s^{-1}).

3.1.2. Influence of temperature and settled bed height on transition velocity U_c

Experimental values of U_{mb}, U_r and U_c (determined as it was described in Section 3.1.1) for all investigated operating conditions are given in Table 3.

Obtained values of U_c are in the range (3–4) × U_{mf} for 1.8 mm particles and (4–6) × U_{mf} for 1 mm particles. For very shallow bed ($H_0 = 0.046\,\text{m} \approx D/2$) no influence of bed temperature on transition velocity U_c was observed, while for beds with $H_0 = 0.093\,\text{m} \approx D$, higher U_c was obtained for temperature of 500 °C. This could be probably a consequence of the higher gas-particle frictional resistance in emulsion phase at 500 °C, since the gas viscosity is increased and gas density is decreased.

Table 3 also shows that lower values for U_c were obtained for the smaller settled bed height. Smaller settled bed height corresponds to the lower apparent weight of the emulsion phase and requires lower energy of gas for expansion and breakage of the bubbles. Satija and Fan [11] have also reported lower values of U_c for smaller settled bed heights in the fluidized beds of particles ranging 1–7 mm in diameter.

Table 3
Experimental values for U_{mb}, U_r and U_c

d_p (mm)	H_0 (m)	θ (°C)	U_{mb} (m s^{-1})	U_r (m s^{-1})	U_c (m s^{-1})	From fluctuations of
1.8	0.046	20	0.61	0.79	1.23	Differential pressure
		500	0.59	0.80	1.23	
	0.093	20	0.60	0.70	1.7	
		500	0.59	0.77	2.4	
		20	0.60	0.70	1.5	Absolute pressure
		500	0.48	0.77	2.0	
1.0	0.093	20	0.33	0.56	1.23	
		20	0.33	0.60	1.50	Differential pressure
		200	0.30	0.59	1.82	

Values of transition velocity U_c determined from absolute pressure fluctuations data are lower then those from differential pressure fluctuations data for the same conditions (Table 3), which is in agreement with results reported by Bi and Grace [21]. This fact is important to be known when results of different studies are compared.

3.1.3. Qualitative characteristics of the regimes

In order to show the qualitative differences in bed structure at three observed fluidization regimes, experimental data are presented in time and frequency domain.

Original pressure signals as functions of time, concerning different regimes in the bed with 1.8 mm particles, are shown in Fig. 3. Signals are presented in the windows of the same width (of 1200 Pa) for comparison of amplitudes. Although the analysis of pressure signals is subjective, the differences in magnitudes of fluctuations and randomness are obvious. For velocity of 0.71 m s^{-1}, corresponding to the single bubble regime (S in Fig. 2), strong periodicity of signal can be observed (Fig. 3a) and attributed to the cyclic appearance and rising of large single bubbles through the bed. This shape of the signal might be observed in deeper beds at slugging regime, leading Canada et al. [8] to call this regime 'apparent slugging'. However, for velocity of 1.7 m s^{-1} corresponding to the rapidly growing bubble regime (R in Fig. 2), signal without clear periodicity (Fig. 3b) confirms that regular dynamics of large single bubbles is disturbed and more complex flow takes place. In addition, higher amplitudes indicate that sizes of bubbles are larger. Sharp decreases of pressure drop could be the consequence of explosion of large bubbles under the top of the bed. This was visually observed as the whole bed movements up and down. For the velocity of 4.3 m s^{-1} corresponding to the turbulent regime (T in Fig. 2), significant decrease of amplitudes and very random nature of pressure fluctuations could be seen (Fig. 3c), indicating a relatively high degree of homogeneity of the bed in this regime.

In the frequency domain, amplitude spectra of pressure fluctuations were analyzed and frequency distribution was used

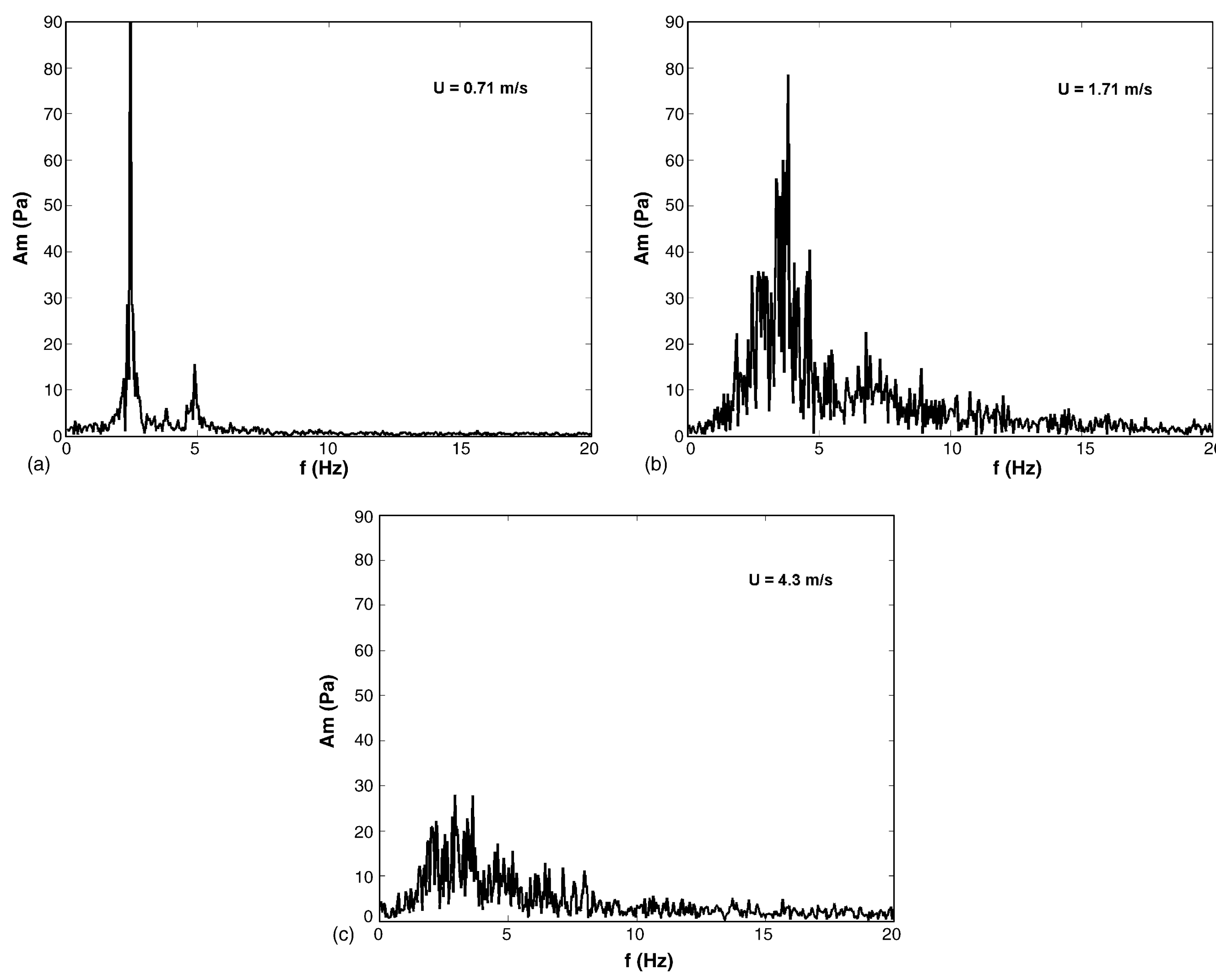

Fig. 4. Amplitude spectra of differential pressure signals measured in the bed with 1.8 mm particles (H_0 = 0.093 m and θ = 500 °C): (a) in single bubble regime, (b) in rapidly growing bubble regime and (c) in turbulent regime.

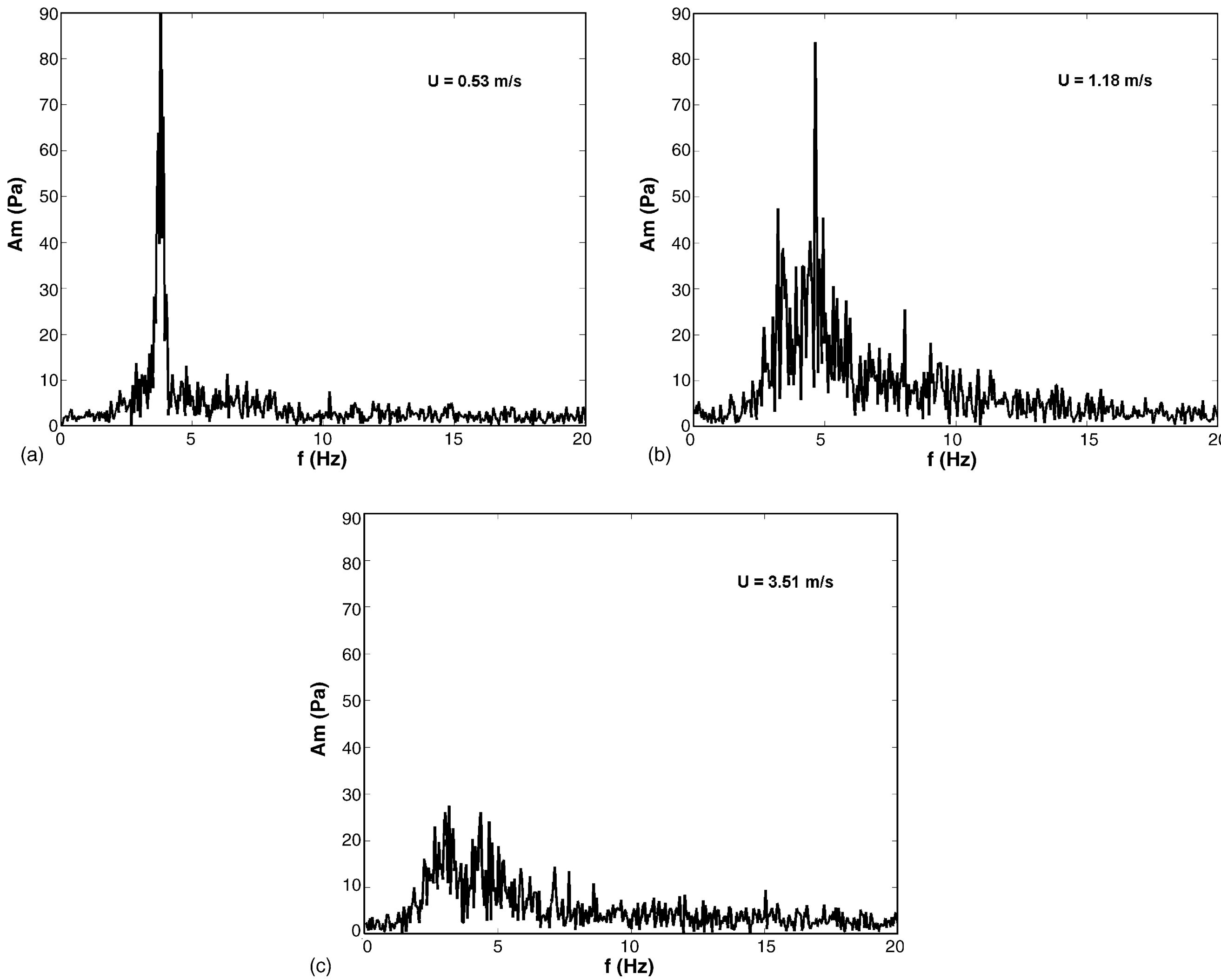

Fig. 5. Amplitude spectra of differential pressure signals measured in the bed with 1 mm particles ($H_0 = 0.093$ m and $\theta = 500\,^{\circ}$C): (a) in single bubble regime, (b) in rapidly growing bubble regime and (c) in turbulent regime.

as an index of flow pattern. Amplitude spectra corresponding to pressure signals shown in Fig. 3 (measured in bed with 1.8 mm particles) are shown in Fig. 4. Three amplitude spectra of pressure signals measured in the bed with 1 mm particles, also concerning different regimes, are presented in Fig. 5. By comparing, for example, the amplitude spectra for 0.71 m s^{-1} in 1.8 mm particle bed with amplitude spectra for 0.53 m s^{-1} in 1 mm particle bed (Figs. 4a and 5a), it is obvious that frequency distribution is almost equal confirming the same regime in these two systems. Similarly, comparison of other two pairs of amplitude spectra (Figs. 4b and c and 5b and c) leads to the same conclusion. On the other hand, in one single system, broadness of spectrum, magnitudes and dominant frequencies alter significantly with the change in gas velocity. Single bubble regime (Figs. 4a and 5a) is characterized by very sharp narrow peak which represents passes of large single bubbles through the bed. Dominant frequencies of bubbles are 2.5 Hz (for 1.8 mm particles, $U = 0.71$ m s^{-1}) and 3.8 Hz (for 1 mm particles, $U = 0.53$ m s^{-1}). Makkawi and Wright [5] have reported bubble frequencies ∼3 Hz for this regime (at a level of 3.8 cm above the distributor plate). In the rapidly growing bubble regime (Figs. 4b and 5b) broadening of spectrum between 2 Hz and 10 Hz could be seen. Higher dominant frequencies (3.7 Hz and 4.8 Hz for 1.8 mm and 1 mm particles, respectively) indicate that residence time of bubbles in the bed is very short. Turbulent regime (Figs. 4c and 5c) is recognized in both systems by extremely low amplitudes (less then 30 Pa). Complete disappearance of dominant frequency confirms the absence of bubbles in the bed.

3.2. Correlations for transition velocities

For the transition velocity U_r following equation proposed by Catipovic et al. [9] was found in literature:

$$U_r - U_{mf} = 21.58 \times h^{0.17}. \quad (2)$$

We have calculated U_r from the Eq. (2) using theoretical values of U_{mf} (Table 1) and the distance of absolute pressure sensor from the distributor plate (47 mm) as h. Comparison of

Table 4
Comparison of experimental values for U_r with correlation of Catipovic et al. [9]

d_p (mm)	θ (°C)	Predicted U_r (ms^{-1})	Relative error (%)
1.0	20	0.56	0
1.8	20	0.84	20
	500	0.76	1.29

our experimental values of U_r (obtained from absolute pressure data, Table 3) with those predicted by Eq. (2) is given in Table 4. Good agreement was obtained as it was expected since the Eq. (2) had been derived for Geldart D particle systems.

For the transition velocity U_c numerous correlations could be found in literature and they were summarized by Makkawi and Wright [5] and Arnaldos and Casal [18]. However, there are no correlations concerning coarse particles only. We have chosen several of the proposed correlations according to applicable range regarding our conditions and compared with our experimental values of U_c in the Table 5. Comparison was done by taking into account the origin of data which correlations are based on. Eq. (4) from Bi and Grace [21] and Eq. (7) from Nakajima et al. [20] showed reasonably good agreement with experimental data regarding both particle diameters. Other correlations gave poor predictions especially for 1.8 mm particles implying the need for development of correlations for U_c prediction in the coarse particle systems.

For this reason, we have attempted to correlate data of U_c obtained in this work (from differential pressure measurements for both particle diameter at both temperatures) together with data of U_c reported in literature for particles larger then 1 mm [8,22–24] as it is shown in Fig. 6. Data were expressed in terms of Reynolds and Archimedes numbers and the following correlation was obtained by the least squares fit:

$$Re_c = 0.326Ar^{0.52} \quad (8)$$

Obtained correlation agreed well with the experimental data ($R^2 = 0.984$) in the range of Ar number $2 \times 10^3 < Ar < 2 \times 10^6$.

Although the simple form of equation as $Re_c = aAr^b$ does not take into account bed diameter and settled bed height, it was shown to be the most adequate form according to the wide statistical analysis of Arnaldos and Casal [18], and also suitable for making maps of fluidization regimes and for scale-up.

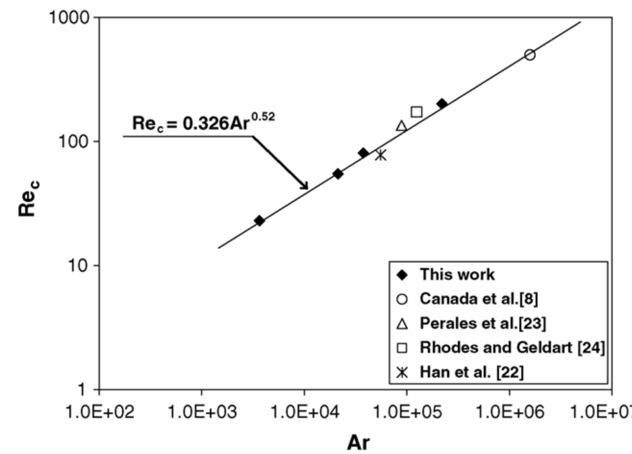

Fig. 6. Correlation for U_c prediction in the coarse particle systems.

4. Conclusions

In spite of numerous interesting studies regarding fluidization regimes in beds of Geldart A and B particles, information concerning dynamical behavior of Geldart D particle fluidized beds is rather limited.

By using the standard deviation of pressure fluctuations and amplitude spectra analysis, in this work it was found that shallow fluidized beds of coarse particles passed through three different fluidization regimes with increasing gas velocity: single bubble regime ($U_{mb} < U < U_r$), rapidly growing bubble regime ($U_{mb} < U < U_r$) and turbulent fluidization ($U > U_c$). Single bubble regime exists in a very narrow range of velocities above U_{mb} and it is characterized by periodic risings of large single bubbles through the bed. In rapidly growing bubble regime large voids of gas pass very fast through the bed so that this regime should be avoided due to the poor contact between gas and particles and high instabilities of the system. Turbulent regime in the coarse particle systems investigated in this work, starts at gas velocities $(3–6) \times U_{mf}$, and it is characterized by very gradual disappearance of bubbles with increase in gas velocity. Transition velocity U_c was found to depend on settled bed height and temperature such that it was lower for smaller settled bed height and lower temperature.

It is worth noting that values for the transition velocity U_c obtained from absolute and differential pressure data are different. This fact should be taken into account when comparisons or generalizations are made.

Table 5
Comparison of experimental values for U_c with literature correlations

Author	Correlation	Predicted U_c (ms^{-1})		Relative error (%)		Applicable range
		$d_p = 1$ mm	$d_p = 1.8$ mm	$d_p = 1$ mm	$d_p = 1.8$ mm	
Bi and Grace [21]	$Re_c = 1.24Ar^{0.45}$ (3)	2.18	2.68	45.3	57.6	$2 < Ar < 10^8$
Bi and Grace [21]	$Re_c = 0.57Ar^{0.46}$ (4)	1.11	1.39	9.75	7.33	$1 < Ar < 10^6$
Horio [23]	$Re_c = 0.936Ar^{0.472}$ (5)	2.08	2.65	38.7	55.9	$54 < d_p < 2600$ μm
Lee and Kim [17]	$Re_c = 0.7Ar^{0.485}$ (6)	1.78	2.33	18.6	37.0	$0.44 < Ar < 4 \times 10^7$
Nakajima et al. [20]	$Re_c = 0.633Ar^{0.467}$ (7)	1.33	1.69	11.3	0.58	$1 < Ar < 10^5$

Eqs. (3), (5) and (7) are from differential pressure data. Eq. (4) is from absolute pressure data. Eq. (6) is from bed expansion data.

In order to provide the prediction of transition velocity U_c in coarse particle systems the new correlation was proposed as follows: $Re_c = 0.326Ar^{0.52}$ and it could be used with a high level of confidence in the range of Ar numbers $2 \times 10^3 < Ar < 2 \times 10^6$.

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