New Description of Fluidization Regimes

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Two pressure probes and an intrusive bioptical probe provide experimental data in the bubbling and turbulent regimes to improve our understanding of the transition from the bubbling regime to the fast fluidization regime. Assessment of pressure, voidage, and bubbling properties allows for a new description of turbulent fluidization hydrodynamics. Appreciable changes in the hydrodynamics appear well below the transition criterion U_c, determined based on pressure fluctuations: bubbles are fast bubbles below U_c, in bubble–emulsion equilibrium state at U_c, and then become slow bubbles for higher fluidizing velocity; the maximum of the total fluidizing gas fraction in the bubble phase is reached below U_c and never exceeds 75–80%. The fluidizing velocity at which major modifications in hydrodynamics are observed is lower than U_c. This critical velocity is detected with pressure drop assessment or frequency analysis of voidage fluctuations. Moreover, it can be theoretically calculated from the two-phase modeling correlations supplemented with a new criterion deduced from our experiments. *AIChE J,* 51: 1125–1130, 2005
Keywords: experiments, optical probe, transition, bubbling regime, turbulent regime

Introduction

What is occurring in the turbulent fluidization regime? Since the earlier investigations by Lanneau,[1] this regime has been widely investigated over the years and is today considered to be the transition between bubbling and fast fluidization, beginning at the gas velocity transition criterion U_c. However, its hydrodynamics is still not well understood and controversy remains about what it really is. Misunderstanding is reinforced by the transition criterion U_c, found to be greatly dependent on the measurement technique, static bed height, column diameter, particle size distribution, temperature, pressure, and so forth. Nowadays, the turbulent fluidization regime is alternately understood and modeled as a peculiar regime with sharp beginning and ending transitions, or as a combination of features pertaining to different fluidization regimes. The reader is directed to the publications of Horio et al.,[2] Rhodes,[3] and Bi et al.[4] for reviews of gas–solid turbulent fluidization and the questions raised.

Understanding the turbulent fluidization requires knowledge of the transition criterion, voidages, bubble size and velocity, holdup, instantaneous bubble shape, and local interstitial gas velocity. However, previous experimental studies have always been restricted to the bubbling property or the solid behavior assessments either to describe or to confirm the different fluidization regimes: pressure drop fluctuation measurements still constitute the conventional experimental techniques for analyzing the regime transition[5,6]; the nonintrusive electrical ca-

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pacitance tomography technique has recently been used to show that U_c, determined based on standard deviation, amplitude, and solid fraction distribution analysis, coincide[7]; the optical probe technique has sometimes been used to describe the fluidization regimes based on the description of the bubbling regimes[8]; and, finally, visual observations have always provided interesting descriptions of the bubbling phenomena through the entire fluidization/transition regime.[9,10]

We are convinced that the study of the interstitial gas in the emulsion phase is as relevant as the bed property measurements to understand the fluidization regimes. Then, pressure drop probes and bioptical probes are used to assess full instantaneous and averaged bed behaviors. Mass and momentum balances are then performed to assess nonmeasurable data to carry the analysis to its conclusion. Thus, the velocity transition criterion U_c will be found not to be the only critical parameter in the bubbling to fast fluidization regimes.

The threefold aim of the work described in the present article is (1) to establish an extensive database of experimental results in gas–solid bubbling and turbulent regimes, (2) to measure peculiar variables in the whole transition regime, and (3) to describe current emerging trends in the bubbling to fast fluidization regimes.

Experimental

The experiments were carried out in a transparent cold air–fluidized bed (152 mm in diameter and 1.5 m high) with solids returned to the freeboard region. Air ($\rho_1 = 1.2$ kg/m^3, $\mu_1 = 1.8 \times 10^{-5}$ Pa·s) was introduced through a nozzle-type distributor placed above a porous plate providing high pressure drop. Typical sand particles ($\rho_2 = 2585 \pm 35$ kg/m^3, $d_p = 1/\Sigma\ (x_i/d_i) = 250\ \mu$m, $\varepsilon_{mf} = 44\%$) were fluidized between 0.12 and 1.50 m/s. The static height of the bed is 30 cm.

The local instantaneous pressure drop between 25 and 35 cm above the distributor is provided by two sensors connected to pressure taps with 4-mm internal-diameter pipes, following Xie and Geldart.[11] Data are acquired with a sampling frequency of 20 Hz. The transition criterion U_c is determined based on the standard deviation of the pressure fluctuations.

The local instantaneous hydrodynamics were measured at 30 cm above the distributor with a bioptical probe (3 mm in diameter). The two measurement volumes were 1 mm^3 and 1.8 mm apart. Data are acquired with a sampling frequency of 15,630 Hz over 202 s. Voidages are obtained with a preliminary calibration of the optical signals provided by the probe. Bubble and emulsion phases are discriminated with the upper threshold voidage ε_{th}, defined as the minimum of the probability density function (PDF) of the local voidage ε_f.[12] Bubble chord and velocity are calculated with intercorrelation between the two signals given by the probe.[13] The local instantaneous bubble holdup is calculated as $\delta = (\varepsilon_f - \varepsilon_e)/(\varepsilon_b - \varepsilon_e)$, using the local instantaneous bubble and emulsion phase, and bed voidages. Mean values are obtained by arithmetic averaging. The bubbling frequency is defined as the number of bubbles detected during the sampling time, reported to 1 s. The dominant frequency of the local voidage is given by FFT (fast Fourier transform) treatment combined with optimized mobile-averaging filtering.

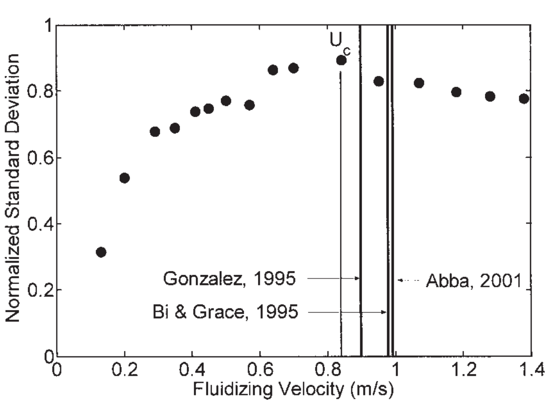

Figure 1. Experimental determination of the transition criterion U_c determined based on pressure fluctuations.

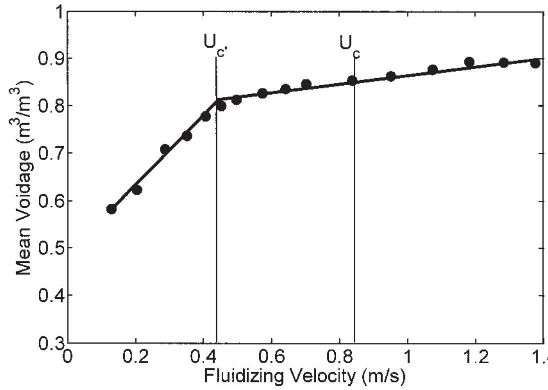

Figure 2. Time-averaged voidage at 30 cm above the distributor, determined based on the local pressure drop.

Results and Discussion

Bubbling to turbulent regime transition

The transition criterion U_c, determined based on pressure fluctuations, is equal to $U_c = 0.85$ m/s (Figure 1), which agrees with the correlation value proposed by Gonzalez et al.,[14] Bi and Grace,[15] and Abba.[16]

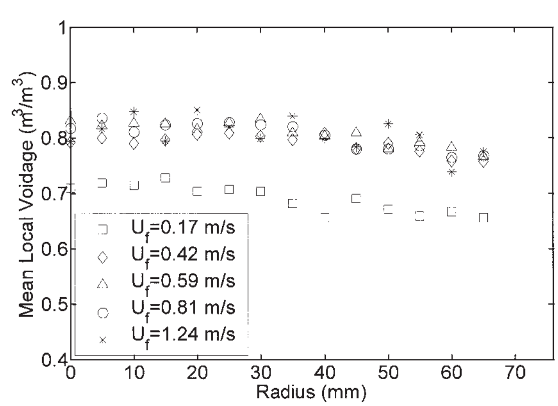

Figure 3. Time-averaged profiles of the local voidage at 30 cm above the distributor.

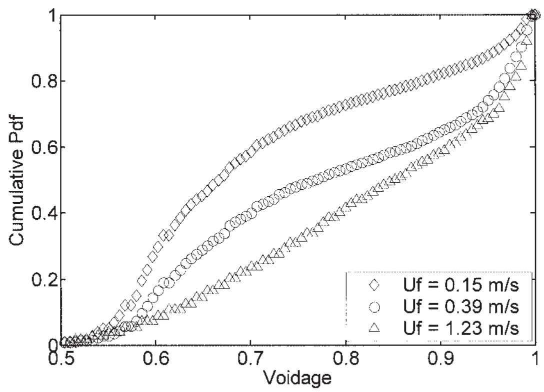

Figure 4. Cumulative probability density function of the local voidage at the center of the bed and 30 cm above the distributor.

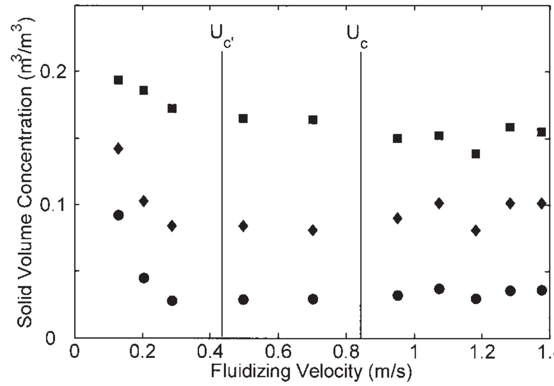

Figure 6. Solid volume concentration threshold (◆) of the bubble phase (●) and emulsion phase (■) at the center of the bed and 30 cm above the distributor.

Hydrodynamics properties

Time-averaged voidage calculated with the local pressure drop is consistent with that of the literature (Figure 2): it strongly increases at low fluidizing velocity and is nearly constant in the transition from the bubbling regime to the turbulent regime.[17] Breakup in the experimental curve appears at a fluidizing velocity $U_{c'}$, 0.45 m/s lower than U_c. It is not caused by a sudden change in the global bed structure, appearance of core-annulus, or bypassing the gas: the time-averaged radial profile of the local voidage keeps its flat shape with increasing fluidizing velocity (Figure 3). It may be the resulting effect of the modification of the local bed structure, characterized by a decrease in the predominance of the emulsion phase of the PDF of local voidage (Figure 4) and a maximum in fluctuations of the dominant frequency of the voidage time (Figure 5). These trends are discussed below. No change in the fluidized bed behaviors is observed at U_c.

Bubbling properties

The upper threshold voidage ε_{th} is nearly constant over most of the whole fluidizing velocity range (Figure 6). The emulsion-phase voidage ε_e increases with the fluidizing velocity, thus concurring with the classic description of the turbulent fluidization regime, whereas the bubble phase, which is not free of particles, becomes increasingly diluted. Roughly, however, the emulsion and bubble phase voidages remain constant when the fluidizing velocity is $>U_{c'}$, 70 and 95%, respectively. This agrees with previous experiments of Cui et al.[18] under similar operating conditions.

The measured mean bubble chord d_b is consistent with the value from the correlation of Darton et al.[19] obtained in the formalism of two-phase modeling (Figure 7):

$$d_b = \frac{0.54(U - U_{mf})^{0.4}(z + 4\sqrt{5.52 \times 10^{-5}})^{0.8}}{g^{0.2}}$$

The same approach, using the Davidson–Harrison model[20] correlation, $U_b = U - U_{mf} + 0.711\sqrt{gd_b}$ (U_{mf} is given by the correlation proposed by either Ergun[21] or Grace[22]), gives acceptable estimation of the bubble velocity U_b, when the fluidizing velocity ranges between U_{mf} and $U_{c'}$ (Figure 8). However, it leads to skewed estimations for higher fluidizing velocities, and predictions are different from the experimental data by a factor of nearly 2.

Void-phase fractions δ are compared to the correlation in the

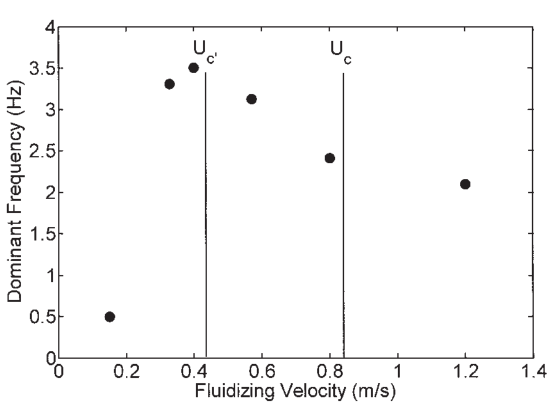

Figure 5. Dominant frequency of the local voidage at the center of the bed and 30 cm above the distributor.

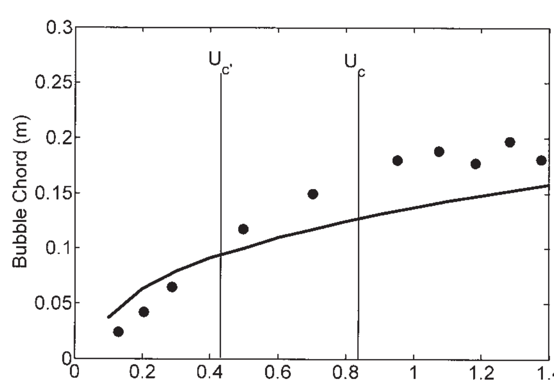

Figure 7. Time-averaged bubble chord at the center of the bed and 30 cm above the distributor.

●, experiments; —, two-phase modeling.

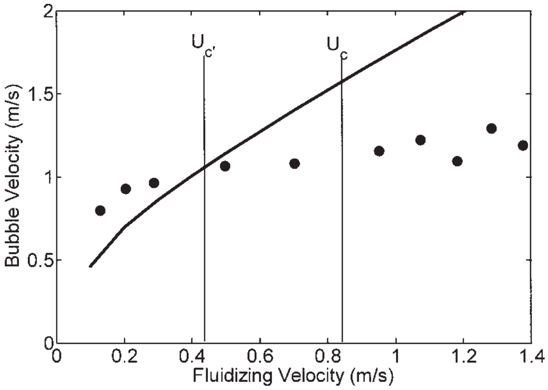

Figure 8. Time-averaged bubble velocity at the center of the bed and 30 cm above the distributor.

●, experiments; —, two-phase modeling.

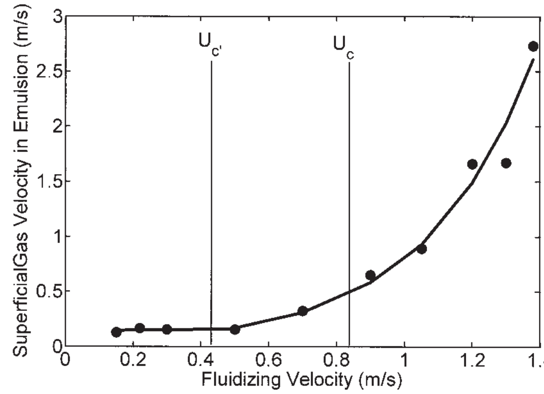

Figure 10. Experimental superficial gas velocity in the emulsion phase.

Davidson–Harrison model, which follows from the assumptions of empty bubbles and superficial gas velocity in the emulsion equal to U_{mf}: $\delta = (U - U_{mf})/U_b$, where U_b is given by the model (Figure 9). Surprisingly, the model predictions agree reasonably well with the experimental data, even though (1) bubbles are considered free of particles and (2) bubble velocity values are overestimated.

Extra data assessments

Considering the correlations in the Davidson–Harrison model, the superficial gas velocity in the emulsion phase (U_{1e}) must be greater than U_{mf} when the fluidizing velocity is $>U_{c'}$, to cancel out their wrong assumptions. By combining the experimental results of ε_f, ε_e, ε_b, U_b, and δ, one can estimate U_{1e}, which is accepted to be equal to U_{mf} at low fluidizing velocity. Rigorously, the superficial gas velocity in the emulsion phase must be calculated using a gas volumetric flow balance leading to the expression $U_{1e} = (U_f - \delta\varepsilon_b U_b)/(1 - \delta)$, and the variables are experimental data integrated over the whole fluidized bed section. Thus, the superficial gas velocity in the emulsion phase remains constant and is close to U_{mf} when the fluidizing velocity is $<U_{c'}$ (Figure 10). Nevertheless, the superficial gas velocity in the emulsion phase exponentially increases for higher fluidizing velocities, reaching twice the fluidizing velocity value, and the model assumptions are then not acceptable.

The increase in the superficial gas velocity in the emulsion phase leads to modifications in bubble behavior through the fluidizing regimes. Indeed, the ratio of the interstitial gas velocity in both the bubble and the emulsion phases, $U_b/(U_{1e}/\varepsilon_e)$ (see Figure 11), shows that (1) bubbles are fast bubbles $[U_b/(U_{1e}/\varepsilon_e) \approx 4]$ when fluidizing velocity ranges between U_{mf} and $U_{c'}$; (2) bubbles evolve from fast bubbles to the emulsion–bubble equilibrium state $[U_b/(U_{1e}/\varepsilon_e) \approx 1]$ when the fluidizing velocity increases from $U_{c'}$ to U_c; and (3) bubbles evolve from the emulsion–bubble equilibrium state to slow bubbles $[U_b/(U_{1e}/\varepsilon_e) \approx 0.5]$ above U_c.

Finally, the importance of $U_{c'}$ is also illustrated with the fraction of the total gas mass flux through the bubble phase (Figure 12). Although the empirical correlations and the classic description of the bubbling phenomena show an increase in this value with increasing fluidizing velocity, experiments show that a maximum of gas travels in the bubble phase around $U_{c'}$, and that the total fraction of gas in bubbles, $\delta\varepsilon_b U_b/U_f$, never exceeds 75–80%. Furthermore, the total fraction of gas in bubbles remains constant when the fluidizing velocity is increased above U_c.

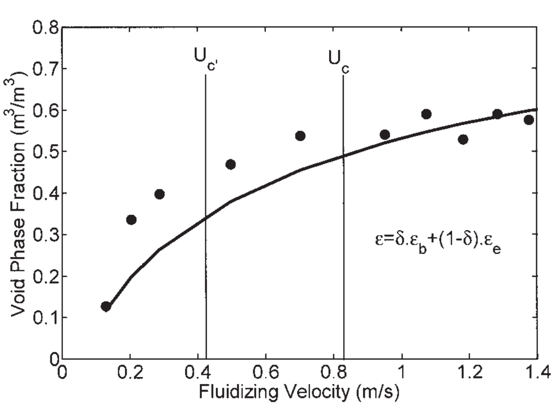

Figure 9. Void-phase fraction at the center of the bed and 30 cm above the distributor.

●, experiments; —, two-phase modeling.

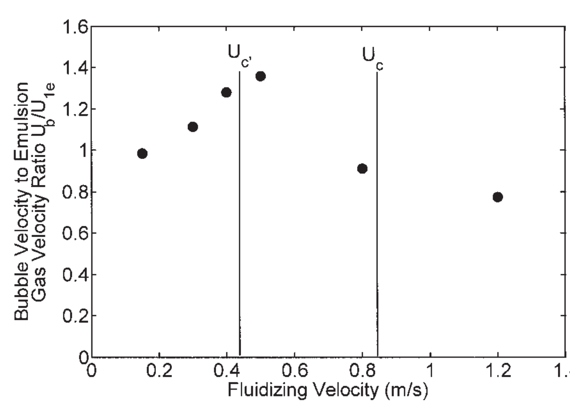

Figure 11. Plot of ratio of bubble velocity to interstitial gas velocity in the emulsion.

Theoretical Determination of $U_{c'}$ and Consequences

The Davidson–Harrison model, supplemented with the maximum fraction of gas criterion of 75–80% through the bubble phase, leads to the estimation of $U_{c'}$ for any B-particle:

$$\begin{cases} \delta\varepsilon_b U_b / U_{c'} < 0.75\text{–}0.8 \\ \delta = (U_{c'} - U_{mf})/U_b \\ U_b = U_{c'} - U_{mf} + 0.711\sqrt{g d_b} \end{cases}$$

Results are plotted in Figure 13. The largest B-particles ($U_{mf} \approx$ 0.25 m/s, that is, $d_p \approx 550$ μm and $\rho_p \approx 2500$ kg/m^3) exhibit a value of $U_{c'}$ equal to the transition criterion U_c. Conversely, the smallest B-particles ($U_{mf} \approx 0.01$ m/s, that is, $d_p \approx 100$ μm and $\rho_p \approx 2500$ kg/m^3) exhibit a $U_{c'}$ value close to the minimum bubbling velocity of the largest A-particles. Thus, $U_{c'}$ is a criterion of particle aerability, thus introducing a new description of B-particle fluidization:

(1) When the fluidizing velocity is well below $U_{c'}$, fluidized beds are strongly emulsion-aerated, and bed aeration from the bubble phase is low.

(2) When increasing the fluidizing velocity, bed aeration from the bubble phase increases, whereas bed aeration from the emulsion phase decreases.

(3) When the fluidizing velocity reaches $U_{c'}$, aeration from the bubble phase is maximum, whereas bed aeration from the emulsion phase is minimum, and increasing the fluidizing velocity above $U_{c'}$ does not change the bed aeration rate from the emulsion and the bubble phases.

Conclusions

Extensive experiments are performed to investigate the transition between the bubbling and turbulent regimes in the fluidized bed using pressure and bioptical probes.

First, standard data are provided to characterize the fluidized bed hydrodynamics: (1) time-averaged local pressure drops; (2) time-averaged values, standard deviations, probability density function distributions, dominant frequencies of the local voidage fluctuations; and (3) time-averaged bubble chords and velocities, bubbling frequency.

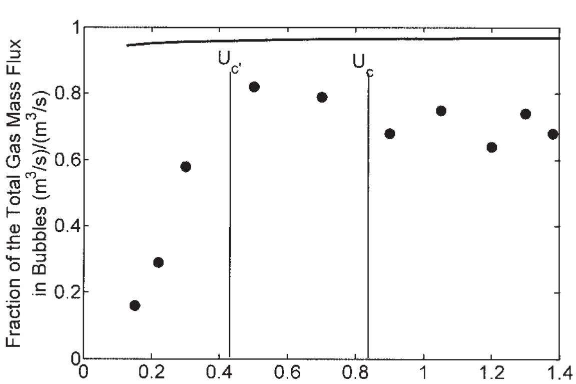

Figure 12. Fraction of the total gas mass flux in the bubble phase.

●, experiments; —, two-phase modeling.

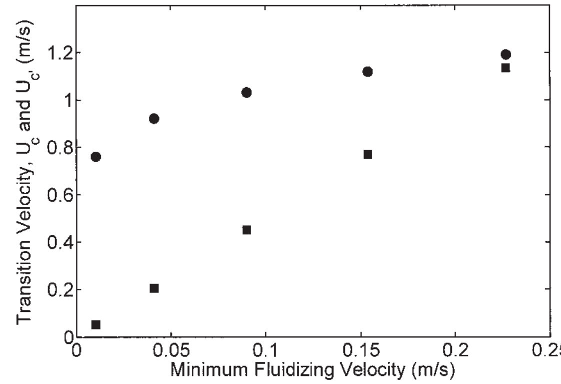

Figure 13. Transition criterion velocity.

●, U_c; ■, $U_{c'}$.

Second, extra data are provided to improve our understanding of the bubbling phenomena: (1) interstitial gas velocity of the emulsion phase; (2) fraction of the total gas mass flux through the bubble phase.

No peculiar phenomenon suddenly appears or disappears at the gas velocity transition criterion, U_c, determined based on pressure fluctuations. A peculiar velocity, $U_{c'}$, is a more critical parameter in the bubbling to fast fluidization regime transition. Indeed, we observe the following:

(1) Standard two-phase modeling assumptions are acceptable for fluidizing velocities lower than $U_{c'}$; they are not acceptable for higher fluidizing velocities, and the model leads to partial slanted predictions for higher fluidizing velocity.

(2) The fraction of total gas mass flux through the bubble phase reaches a maximum value at $U_{c'}$, never exceeding 75–80% and remaining constant above $U_{c'}$.

(3) Bubbles are fast bubbles below $U_{c'}$; bubbles evolve to emulsion–bubble equilibrium state when the fluidizing velocity reaches U_c; and bubbles are low bubbles with increasing fluidizing velocity.

Moreover, $U_{c'}$ is equal to U_c for the largest B-particles and is of the same order of magnitude as that of the minimum bubbling velocity of A-particles for the smallest B-particles. Thus, $U_{c'}$ is a criterion of particle aerability.

The value of $U_{c'}$ could be determined either by the break point in the pressure drop curve, or by the maximum of the local voidage dominant frequency, both observed with increasing fluidizing velocity from U_{mf} to U_c. It can also be determined theoretically using the criterion of maximum fraction of gas in the bubble phase, equal to 75–80%.

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Notation

Ar = Archimedes number
d_b = mean bubble chord, m

d_p = particle-phase mean diameter, m
g = gravity, m^2/s
U_b = mean bubble velocity, m
U_c = transition criterion determined based on the pressure fluctuations, m/s
$U_{c'}$ = transition criterion determined based on the break point of ΔP curve, m/s
U_f = fluidizing velocity, m
U_{1e} = superficial gas velocity in the emulsion phase, m/s
U_{mf} = minimum fluidizing velocity, m/s

Greek letters

δ = void-phase fraction in the two-phase modeling formalism
ε_k = voidage of phase k in the two-phase modeling formalism
ε_f = local bed voidage
ε_{mf} = bed voidage at minimum fluidizing velocity
μ_l = fluid dynamic laminar viscosity, Pa·s
ρ = density, kg/m^3

Subscripts

b = bubble phase in the two-phase modeling formalism
e = emulsion phase in the two-phase modeling formalism

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