Using Free Bed Surface Fluctuations in a 3-D Fluidized Bed for Dynamic Characterization

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The use of free surface fluctuations in three-dimensional (3-D) fluidized bed dynamic characterization is addressed. This technique provides a noninvasive global measure of the quality of fluidization by measuring at one position in the bed. The well-known effect of particle size on fluidized bed hydrodynamics was explored using a 3D fluidized bed operated with four different particle groups. The analytical methods used were mutual information functions, frequency, and state space analysis of time series collected from bed surface fluctuations. Turbulent, multiple, and noninteracting bubble flow patterns, occurring during bubble regimes, have been characterized. Kolmogorov entropy for the reconstructed attractor is very sensitive to the transition between fluidization regimes. Moreover, correlation dimension estimates ranging between $3 < D_2 < 5$ indicate apparent low-dimensional dynamics. Additionally for larger particle groups, D_2 reaches a value close to 3, indicating slow bubbling controlled by large bubbles before the transition between different bubble flow patterns takes place. Finally, particle size has been found to have strong influence on signal persistence. *AIChE J,* 50: 3060–3067, 2004
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Introduction

Most gas–solid fluidized beds used in industrial processes operate in the bubbling regime. However, the mass, heat transfer, and gas–solid mixing characteristics of this regime are a consequence of the bubble flow pattern inside the fluidized system, which is widely known to be highly influenced by the solid group used. This effect of particle characteristics, first described by Geldart (1986), is frequently evaluated using local measurement techniques such as determining bed pressure fluctuations (Lancia et al., 1988; Shrikant et al., 1993; Trnka et al., 2000). However, the signal obtained under these conditions depends on the local bubble flow pattern, which is very sensitive to the distance above the distributor and bed diameter. Thus, depending on the probe location the measured signal will be influenced by bubble generation (bottom bed region), bubble growth (middle bed region), and bubble eruption (top bed region). This indicates that multiple pressure sensors at different locations are needed to fully characterize the different bubble regions (Van der Schaaf et al., 1998, 2002). Analysis of such multiple measurements complicates the analysis of global bed dynamics.

It has been widely established that bubble motion inside the bed and bubbles escaping from the top give rise to fluctuations in the bed surface. Indeed, Baskakov et al. (1986) showed that the characteristic frequencies of these systems are related to bed surface fluctuation. It was thus assumed that free bed surface fluctuations could provide a global picture of the hydrodynamics of the fluidized bed. The technique used involved measuring the fluctuations produced in a laser sheet that crosses the bed, as a consequence of bed top particle-laser interactions. In contrast to the situation when local techniques are used, monitoring is performed at only one position in the bed, collapsing the global dynamics into a single measurement.

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Table 1. Characteristics of the Fluidized Bed Material*

Fraction No.	Geldart Group	$U_{mf(\exp)}$ (m/s)	d_p (μm)
1	B	0.03	210–250
2	B	0.11	420–500
3	D	0.18	590–710
4	D	0.21	710–840

*$\rho = 2650$ kg/m^3.

To evaluate the reliability of dynamic surface measurement for characterization, the technique was experimentally applied to 3-D gas–solid bed operated at a range of flows and particle sizes.

Complementary video recordings and free bed surface fluctuations collected from a 1-cm-wide 2-D gas–solid fluidized bed were used to qualitatively link the surface fluctuations and bubble characteristics.

State space analysis

During the last decade, several authors have explained the low-dimensional dynamics, which gas–solid fluidized bed systems apparently exhibit, through state space analysis (Daw et al., 1990; Hay et al., 1995; Huilin et al., 1995). Methods of state space analysis deal with the reconstruction of attractors in an embedded phase space and the study of attractor properties, such as Kolmogorov entropy and correlation dimension. Moreover, state space analysis has been successfully applied in several fields of fluidization engineering such as modeling (Van Wachem et al., 1999), control (Van Omment et al., 2000), and scale-up (Schouten et al., 1999).

Correlation dimension

Since its description by Grassberger and Procaccia (1983a), the method of estimating the correlation dimension, D_2, as a measure of the structure of reconstructed attractors has been extensively used. This parameter is obtained from the spatial correlation between random points on the reconstructed attractor. The literature describes several methods of computing the correlation integral (Ellner, 1998; Schouten et al., 1994a). Nevertheless, these methods are all based on the algorithm of Grassberger and Procaccia (1983a). Here the use of that algorithm is followed by application of an embedding dimension equal to 10, chosen by a previous false-neighbor analysis (Abarbanel, 1996), a time delay of 1 was used during the reconstruction of the attractor, and interpoint distances were computed using the maximum norm (Eckman and Ruelle, 1985).

Kolmogorov entropy

The Kolmogorov entropy K is a direct measure of the chaos level, providing qualitative and quantitative information on the underlying dynamics. Kolmogorov entropy is complementary to the mutual information function and measures the average degree of uncertainty one experiences by making a new measurement in spite of available knowledge of its past history (Daw and Hallow, 1993). Kolmogorov entropy differs from the entropy used to estimate the mutual information function because it takes into account the time correlation in the dynamics. Thus, it considers the effects that several past measurements have on the current measure. Kolmogorov entropy is usually expressed in units of bits/s, reflecting the rate of information loss by the system (unpredictability). Thus, when dealing with periodic, fully deterministic data, the Kolmogorov entropy equals zero, whereas for random time series the entropy is infinite. Finally, deterministic chaotic processes occurring between both these situations have positive Kolmogorov entropy.

There are several methods of estimating Kolmogorov entropy from experimental time series (Daw and Hallow, 1993; Grassberger and Proccacia, 1983b). The algorithm used here is based on the maximum likelihood method (Schouten et al., 1994b).

Experimental

Most of the experimental time series were collected from a cylindrical 3D fluidized bed of 5.38 cm internal diameter with a porous plate distributor. The bed was then filled with four different groups of Ballotini glass beads (Table 1) until a bed aspect ratio H/D (height/diameter) of 1.4 was reached. Finally, the bed was fluidized with air (atmospheric conditions) at several superficial gas velocities ranging from 0.04 to 0.27 m/s. The distributor pressure drop to bed pressure drop ratio at minimum fluidization velocity ranged over $0.42 < \Delta p_d/\Delta p_b < 2.9$, which according to the literature gives enough resistance to produce a uniform distribution of gas across the bed and avoids resonance between the bed and air plenum fluctuation (Svensson et al., 1996).

Once the fluidization state stabilized, free bed surface fluctuations were measured according to Villa Briongos and Guardiola (2003) with a laser sheet that was previously focused by an Oriel 12743 convergent lens and crossed the bed in a perpendicular direction, interacting with the top bed particles (Figure 1). The outlet signal arising from this laser–particle interaction was collected by a PSD photodiode 4 cm in height, and subsequently amplified before PC-controlled A/D conversion using a software package supplied by Monocrom S.A. (Barcelona, Spain).

Complementary fluidization experiments were conducted in a 2D bed where visualization of the bubble patterns was facilitated. The 2D system was a PMMA bed (1 cm wide; 11.5 cm

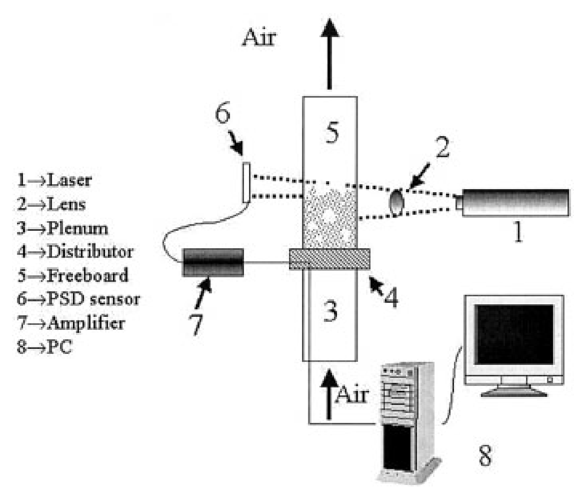

Figure 1. Experimental setup.

long), operated with the same type of porous plate distributor. For the 2-D system the distributor pressure drop to bed pressure drop ratio at minimum fluidization velocity ranged over $0.84 < \Delta p_d/\Delta p_b < 2.45$, which as for the 3-D bed suffices for both uniform distribution of gas across the bed and nonresonance between bed and air plenum fluctuation. The video recordings for the later qualitative analysis were collected with an analogical camera (25 frames/s) and, to facilitate its processing, the images were later digitized by means of a commercial software package of Pinnacle Systems.

To qualitatively compare surface fluctuation and bubble characteristics between the 2-D and 3-D systems, both fluidized beds were operated within the same range of relative particle Reynolds (Re) number

$$\mathrm{Re}_r = \frac{(U_0 - U_{mf})d_p\rho_f}{\mu_f} \quad (1)$$

which represents the balance between the inertial and viscous forces for the gas–solid fluidized system that is responsible of the macrostructure of the flow. The influence of column design has been taken into account by including the excess gas velocity ($U_0 - U_{mf}$) within the Reynolds expression. Under those conditions some of the 2-D systems qualitatively presented a surface fluctuation behavior similar to that of the 3-D bed, making it possible to use the information drawn from the image analysis to describe the bubble patterns found during the 3-D operation.

Data acquisition

The length of the experimental time series was 42,000 points (4 min). The sample frequency used was then 175 Hz and a low-pass filter with a cutoff frequency of 60 Hz was simultaneously applied over the signal, satisfying Nyquist criteria and avoiding possible aliasing problems. The time series was later divided into four blocks of 10,500 points before state space analysis, and the variables computed from each block were averaged. The scarce variation observed in attractor properties computed from each block around their mean value (<5%) confirms the reliability of the results. Further, video recordings collected during the operation of a 1-cm-wide 2-D gas–solid fluidized bed were used to establish the effect of the solid on the bubble pattern.

Results and Discussion

Fluidization quality

For the suitable design of a gas–solid process, in which the contact system is a fluidized bed, the kind of fluidization expected from each solid group needs to be known. According to Geldart's classification criteria, the groups used in the present study belong to groups B and D. This is important because it is well known that fluidization quality is strongly influenced by the solid group used. Thus, two different types of behavior, B and D, will be expected when the solid groups are fluidized.

In addition, the contacting regime that prevails within the operational range of the bed is provided by the flow regime maps (Kunii and Levenspiel, 1991). Those charts indicate that a bubbling regime is expected for all the solid particle groups used. The flow regime maps also predict two types of fluidization behavior but, unlike the case for the Geldart classification, fluidization behavior type A is expected for the first and type B for the 2nd, 3rd, and 4th groups.

Frequency domain analysis

Spectral analysis serves to characterize the bubble flow patterns that exist during operation of the 3-D fluidized bed. The frequency analysis begins with an estimation of the power spectral density; for this purpose, Welch's averaged periodogram method was used. The energy of the spectrum is dimensionless because the time series were normalized to series showing a mean of zero and standard deviation of unity. The use of a zero mean time series is necessary because the power spectral density is estimated from the FFT of the autocorrelation function and, as is well known, its Fourier transform does not exist when the mean does not equal zero (Oppemheim and Schafer, 1975). Also a series standard deviation of unity means the ordinate of the power spectrum is P_{xx}/σ^2, allowing power spectra estimated in different fluidization conditions to be compared (Shrikant et al., 1993). Thus, the power spectral density was estimated from the time series collected during performance of the 3-D fluidized bed using the four solid groups (Figure 2).

Characterizing the fluidization regime

Figure 2 shows that particle size has a pronounced effect on fluidization quality. Three different bubble flow patterns were identified according to the power spectrum. Also, at the same relative gas velocity, $U_r = U_0/U_{mf}$, different particle size groups exhibit different flow patterns. These differences reflect the multidimensional aspect of fluidized bed behavior.

Figure 3 shows photographic images and the corresponding power spectrum of several complementary experiments on a 2-D fluidized bed (experimental settings are indicated in the plot). As for the 3-D system, the surface fluctuation was used as a source of hydrodynamic data. The images reflect the characteristics of each bubble flow pattern.

Noninteracting Bubble Flow Pattern, NBF. In these conditions, most bubbles cross the bed practically without interacting. Coalescence and splitting processes are negligible in these conditions. The power spectrum is characterized by the presence of a single, narrow, high-energy peak $E \approx 100$ (showing a dominant frequency), a consequence of the uniform bubble size and velocity distributions inside the bed. This bubble flow pattern took place at low relative gas velocity when the 3rd and 4th groups were used in the system.

Multiple Bubble Flow Pattern, MBF. In this type of behavior, the bubbles continuously pass through the bed, bursting at the surface. As for the *NBF* pattern, the system shows a uniform bubble size distribution, characterizing its power spectrum by a main peak. However, the coalescence and splitting processes that take place under this regime blur the spectrum and broaden the main peak, which is of lower energy than the main *NBF* peak. *MBF* was observed for all the solid groups. Nevertheless, bubble flow characteristics and the relative gas velocity at which *MBF* takes place depend on particle size.

Turbulent Bubble Flow Pattern, TF. When the bed fluidizes in these conditions, it shows turbulent-like behavior. This

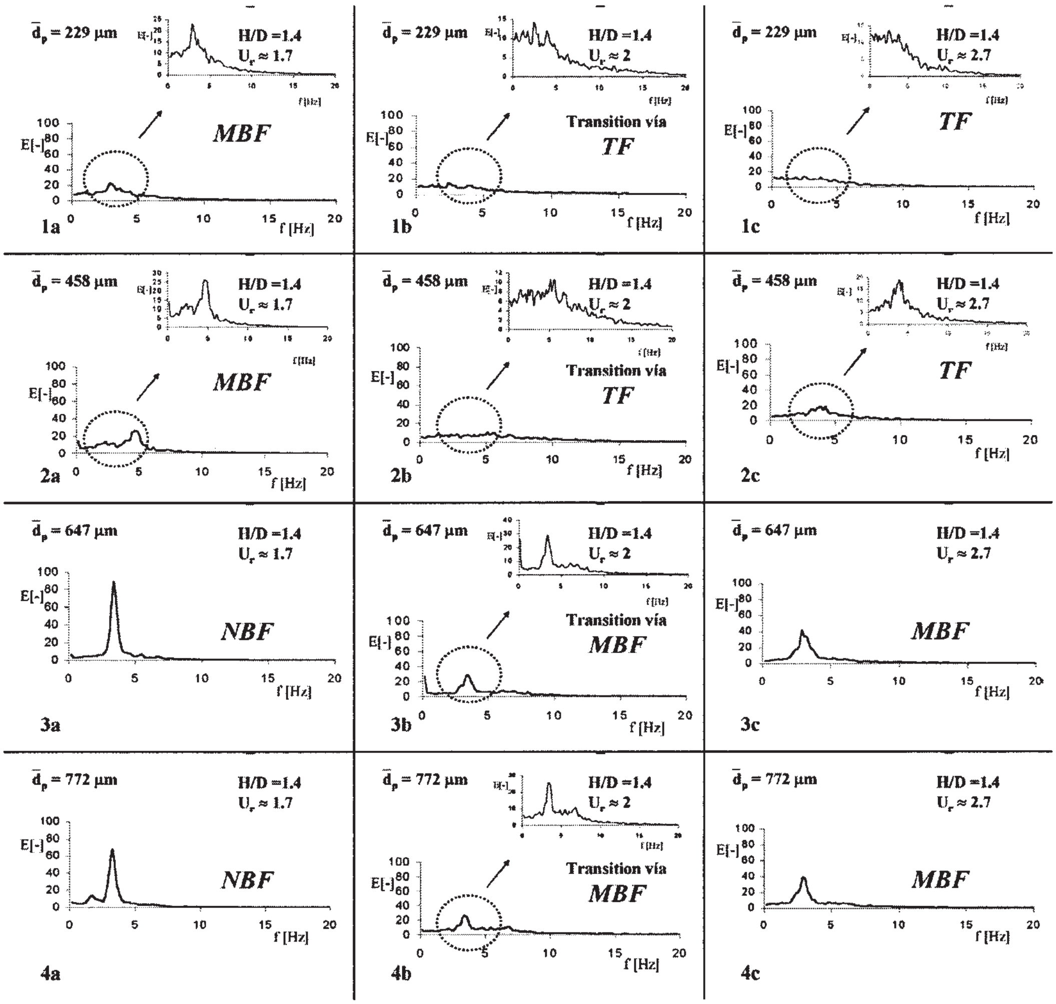

Figure 2. Normalized density power spectra estimated under several bed fluidizing conditions provoked by four different particle groups.

Note the three different bubble flow patterns.

flow pattern can therefore be described as a dispersion process, in which coalescence and bubble splitting processes control the dynamics, homogenizing the fluidized bed flow structure. Its power spectral density shows the characteristics of a turbulent regime. According to the literature, the power spectrum shows no dominant frequency (Figure 3c; Figure 2, panels 1c and 2c), exhibiting more complexity than that of *MBF* and *NBF* spectra. This regime was observed when the bed was operated at the higher relative gas velocities using the 1st and 2nd solid groups. The explanation for this is that both groups operate near the onset of the turbulence regime, such that the turbulent flow pattern is possible.

Moreover, the results from Figure 2 and visual observations suggest that the solid groups used give rise to three types of behavior related to fluidization quality, instead of the two different behaviors predicted by the Geldart classification and the fluidization regime maps. According to Figure 2, it can be argued that the 3rd and 4th groups show the same fluidization behavior and bubble flow pattern across a similar range of operational conditions. Furthermore, visual observation of the flow indicates the existence of large bubbles characteristic of large particle groups within the operational range. This finding is in agreement with the Geldart classification criteria, which predicts D type solid behavior for these groups. According to the experimental observations and the fluidization maps, the first group fluidizes like an A type solid. Finally, complementary to experimental observation and the sand-like behavior predicted by the flow regime maps and the Geldart classification, the discrete difference in the power spectrum relative to that of the 1st group indicates that the 2nd group fluidizes like a B type solid.

State space analysis

It has been widely established that complex flows can be characterized both through spectral analysis (in terms of exponential decay of the power spectrum at higher frequencies; for example, Sigeti and Horsthemke, 1987) and through state space analysis. As has been demonstrated recently, fluidized bed hydrodynamics can be efficiently characterized by reconstructed attractors (Van Ommen et al., 2000); statistical properties of the reconstructed attractor such as the correlation

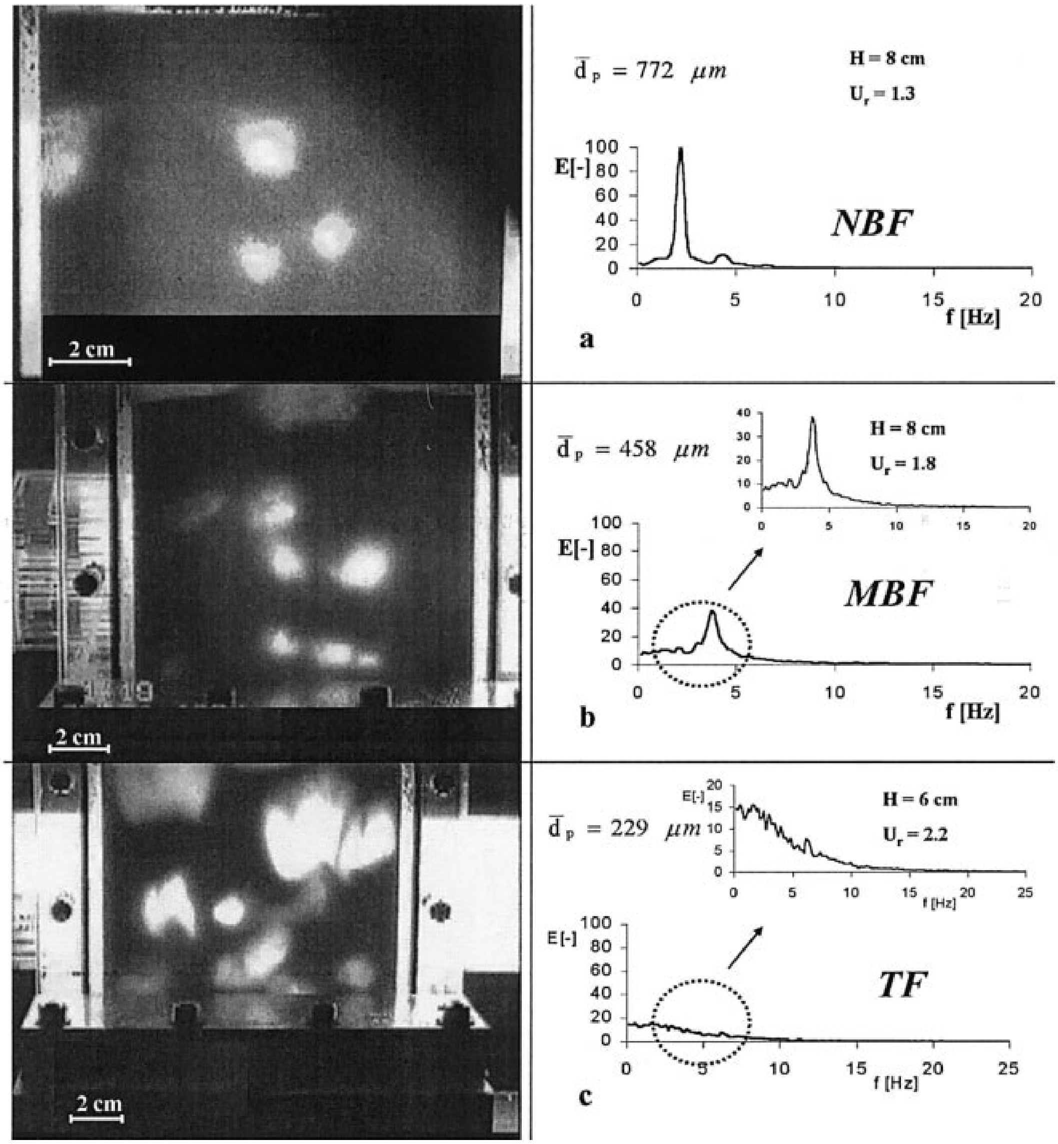

Figure 3. Images and corresponding density power spectra obtained from experiments performed on a 2-D fluidized bed to determine the characteristics of each bubble flow pattern.

The experimental settings are shown on the graph.

dimension and Kolmogorov entropy are useful for quantifying differences between fluidization states.

Correlation dimension

The original application of the correlation dimension for time series analysis was pioneered by Grassberger and Procaccia (1983a). There are many issues involved in the strict interpretation of the correlation dimension that go beyond the scope of the present study, but it is safe to say that correlation dimension reflects both the homogeneity and complexity of the reconstructed attractor.

As shown in Figures 4a and 4b, the correlation dimension evaluated for our 3D fluidized bed surface measurements falls in the range $3 < D_2 < 5.5$. This appears consistent with results found in the literature ($2 < D_2 < 3$ reported by Daw et al., 1990; $2 < D_2 < 5$ by Vander Stappen et al., 1993; $1.5 < D_2 < 1.9$ by Huilin et al., 1995; and $2.5 < D_2 < 7$ by Johnsson, 2000). It has been pointed out that a correlation dimension value around 4 characterizes the bubbling regime (Vander Stappen et al., 1993) (Figures 4a, 4b), showing that the bed performs according to this regime ($3 < D_2 < 5.5$) under the operational conditions explored. This regime would be consistent with the contacting regimes expected from the fluidization regime maps.

The correlation dimension decreases near the transition between the different bubble flow patterns, showing a local minimum in most cases. Consequently, as in the case of the spectral analysis, state space analysis seems to be sensitive to the different bubble flow patterns controlling the hydrodynamics of the fluidized bed. This minimum can be explained by the presence of large bubbles before the transition between different bubble flow patterns. The quality of fluidization provided

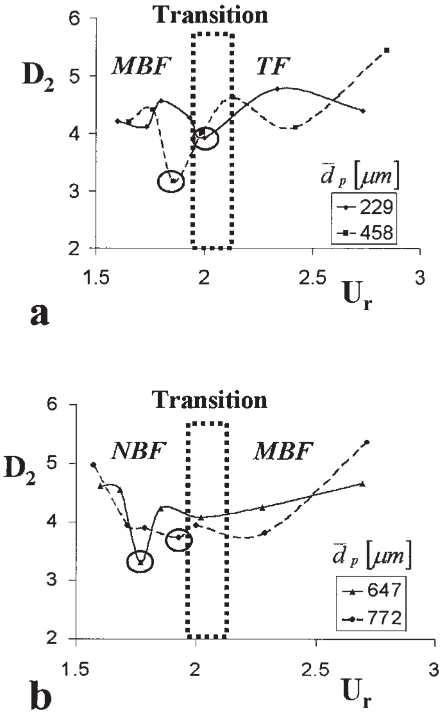

Figure 4. Correlation dimension as a function of the relative gas velocity.

The dotted line marks the transition region between the different bubble flow patterns.

by the particular particle groups used explains the different sensitivity toward dynamic change. Thus, when the relative gas velocity increases, the excess gas goes toward increasing bubble size and gas flow through the bubble. Further, as is well known, particles belonging to Geldart's B and D groups—the 2nd, 3rd, and 4th groups, respectively—lead to stabilization of bubbles, making coalescence phenomena the dominant processes. Thus, the minimum D_2 near the transition region is more pronounced. Moreover, it has been reported that the presence of large bubbles might reduce D_2 (Van der Stappen et al., 1993), a correlation dimension around 3 indicating slow bubbling or slugging. This is in agreement with the results shown in Figures 4a and 4b, in which the 2nd, 3rd, and 4th groups (type B and D) show a correlation dimension approaching 3 when the bed operates close to the transition region. On the other hand, the quality of fluidization promoted by type A Geldart particles (1st group) is determined by the coalescence and splitting process, restricting maximum bubble size. Thus, the bubbles are smaller than for the B and D particle groups, which leads to a higher and less pronounced minimum near the transition region.

Kolmogorov entropy

As previously mentioned, Kolmogorov entropy provides a measure of the loss of correlations over time in the attractor. This parameter has thus been extensively used for monitoring and characterizing fluidized bed hydrodynamics (Daw and Hallow, 1993; Huilin et al., 1995; Johsson et al., 2000; Van der Stappen et al., 1993). Accordingly, Figures 5a and 5b show how the fluidized bed hydrodynamics are monitored for all particle groups. It can be seen how the Kolmogorov entropy is more sensitive to the bubble flow pattern change than the correlation dimension. The transition is located by a peak in K when plotted against U_r.

Let us now consider the fact that the 3rd and 4th groups show a similar rate of change of information in both systems (Figure 5b). Thus, a similar dependency on the initial conditions (changes in time) will be expected. This is in line with the results of the spectral analysis that predicts similar D-like fluidization behavior for both particle groups over the same range of operational conditions (Figure 2).

Mutual information function analysis

According to the literature (Daw and Hallow, 1993; Jonhsson et al., 2000; Karamavruç et al., 1997) the mutual information function is complementary to the frequency and state space analysis. The mutual information function is based on the uncertainty concept developed by Shanon and Weaver (1949). According to this theory, the uncertainty associated with any measure depends on the probability of all possible outcomes.

The results in Figure 5, which suggest that the Kolmogorov entropy decreases with an increasing group particle size, could indicate an increase in signal persistence. We therefore went on to examine the effect of particle size on signal complexity by mutual information function analysis.

Figure 6 shows the mutual information function from time series collected under the same bubble flow operating conditions, while the bed performs with different solid groups. It can be seen that when the bed is working with the 3rd and 4th groups, the mutual information function shows some type of

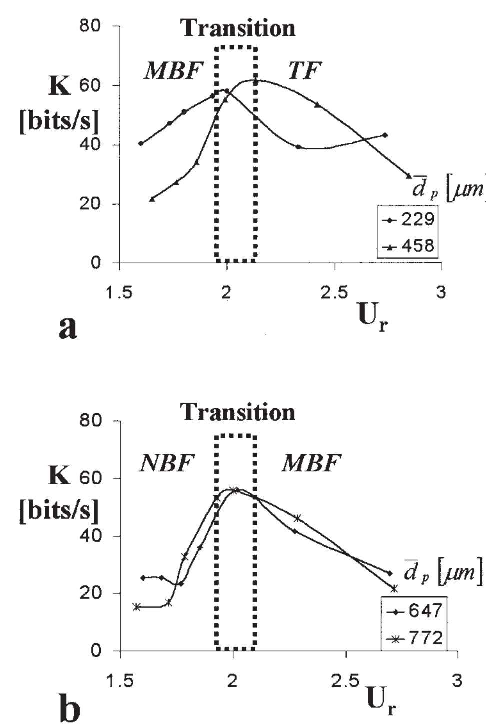

Figure 5. Kolmogorov entropy as a function of the relative gas velocity.

The dotted line marks the transition region between the different bubble flow patterns.

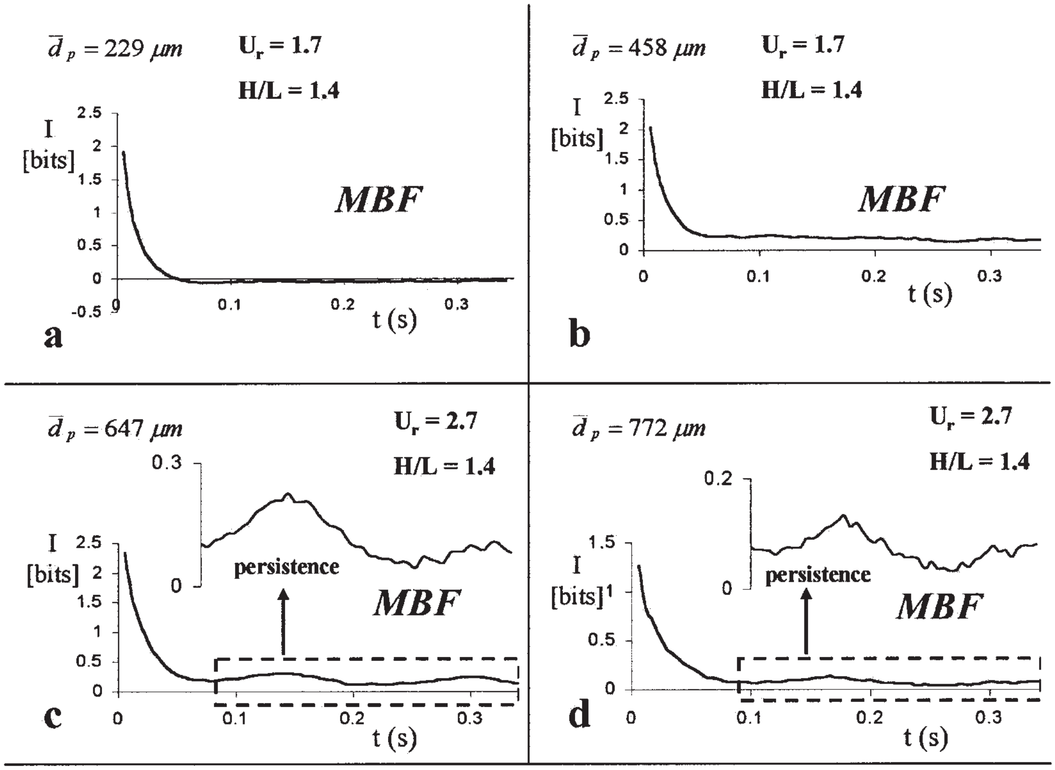

Figure 6. Mutual information function analysis for the four groups fluidized under *MBF* conditions.

Note that I increases with increasing particle size.

persistence over time. However, for the 1st and 2nd groups, the sharp decrease in I indicates a quick loss of information in time throughout the process. The quality of fluidization dominated by bubble coalescence promoted by the 3rd and 4th groups would explain the increasing signal persistence. Indeed, this was observed in a study by Karamavrus and Clark (1997), in which the bed was operated with nylon spheres (0.3 cm) leading to a slugging regime. Subsequently, the persistence induced by large bubbles detected by mutual information function analysis made it possible to use I to estimate bubble properties such as the slug frequency.

Conclusions

Nonintrusive measurement of fluctuations occurring at the free bed surface provides a useful global picture of the hydrodynamics of the fluidized bed. The signal, recorded at one position in the bed, can be characterized using conventional analytical techniques such as spectral analysis or more sophisticated approaches such as state space analysis. However, the measurement technique has not yet been fully developed, and should be improved for measuring in larger beds and at higher superficial gas velocities (other contexts different from bubbling regime).

The results of the frequency and state space analysis show consistent trends in global behavior with particle size. Three different characteristics bubble patterns are apparent with both types of analysis. Kolmogorov entropy is highly sensitive to the transition and exhibit a maximum in the transition region between regimes when plotted against U_r. The relatively low correlation dimension estimates of $3 < D_2 < 5.5$ suggest the presence of a significant low-dimensional character. Further, D_2 reaches a minimum before the transition between two different flow regimens. For the 3rd and 4th groups (type D), D_2 reaches a value close to 3, indicating slow bubbling controlled by large bubbles before the transition takes place. Mutual information analysis indicates increased signal persistence as the group particle size increases.

Acknowledgments

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Notation

D = bed diameter, m
d_p = particle diameter, μm
E = spectral dimensionless energy
F = spectral frequency, Hz
H = bed height, m
U_{mf} = minimum fluidization velocity, m/s
U_r = relative gas velocity defined as U_0/U_{mf}, where U_0 is the superficial gas velocity

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