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Characterizing the Hydrodynamics of Bubbling Fluidized Beds with Multivariate Pressure Measurements

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Abstract
Quantitative characterization of fluidized-bed hydrodynamics is important for process monitoring and validation of dynamic models. Using a two-dimensional fluidized bed of Geldart Group B particles, we experimentally investigated the situation where multiple pressure sensors were mounted on the walls of a bubbling fluidized bed. Our objective was to identify multivariate dynamic characteristics in the pressure signals that can be correlated with specific physical phenomena in the bed, including spatial distribution of bubbles, characteristic bubble sizes, bubble velocities, and global bed oscillations. We summarize preliminary results from laboratory experiments in which both high-speed pressure measurements and digital video images were collected. By comparing the two types of measurements, it is possible to draw conclusions about important information that can be extracted from multiple pressure signals. In addition to the expected Group B bubble behavior, we observed very long-time-scale oscillations that have not been previously reported. These dynamics may be important for practical fluidized-bed performance as well as for interpreting CFD models.

Introduction
In many industrial situations, there is little opportunity to directly visualize fluidized-bed flows using techniques such as X-ray or gamma densitometry, capacitance tomography, or radioactive particle tracking because of constraints in physical access, cost, and/or safety. Instead it is necessary to rely on more indirect types of measurements to provide information about the bed condition. One of the most commonly available measurements is pressure, and this is typically detected at one or more tap locations on the wall of the fluidized-bed vessel. Our interest in this study is to explore what types of information can be extracted from multiple, simultaneous pressure measurements in gas-fluidized beds of Group B particles and how this information potentially could be used to improve bed performance. We are particularly interested in resolving details about the spatial distribution, size, and speed of bubbles and about the global solids circulation. If such details can be monitored over time, it is reasonable to expect that one could detect important process problems such as solids agglomeration and maldistribution of fluidizing gas.

One expects that simultaneous measurements made at different spatial locations should have inherent advantages over single-point measurements, but it is not necessarily obvious how such multivariate data can be used to the best advantage. Our experimental approach is based on making multiple pressure measurements at the walls of a two-dimensional laboratory fluidized bed, while at the same time capturing video images of the bubble patterns. We subsequently characterize the multivariate dynamic properties of the pressure signals to determine which features correlate with the observed bubble patterns.

In the following discussion, we explain our experimental setup in detail and describe our techniques for processing the pressure signals and video images. We then summarize preliminary observations and draw conclusions regarding the use of multiple pressure measurements for bubbling-bed diagnostics. We end our discussion with recommendations for follow-on studies.

Experimental Apparatus

The two-dimensional fluidized-bed (shown schematically in **Fig. 1**) is 25.3 cm wide, 1.9 cm deep and 77.5 cm tall (internal dimensions), constructed of 0.5 cm thick Plexiglas sheets. Fluidizing air is regulated with rotameters before passing through a sintered-metal plate distributor. Pressure drop across the distributor is sufficiently high that at most fluidizing conditions it exceeds the pressure drop over the rest of the bed. Six pressure taps are located on the narrow side walls (three on each side) at 7.5 (taps BL and BR), 18.7 (taps ML and MR) and 28.7 cm (taps UL and UR) above the distributor. The taps are made from 0.318-cm-diameter stainless steel tubing and are mounted flush with the inside wall of the bed. The bed is mounted on a heavy steel frame (61 cm tall) placed on a 48 cm square plate (floor level) with leveling screws at each corner for very minute adjustment of the bed's vertical orientation. As we discuss below, such adjustment capability is important for investigating some of the long-time-scale oscillations that were observed.

For the experiments discussed here, the fluidized-bed particles were 316 stainless steel with a Sauter mean diameter of 175 microns and a particle density of 8.0 g/cc (classified under Geldart Group B). The minimum fluidization velocity and void fraction have been experimentally measured as 0.098 m/s and 0.42, respectively. The static bed height was adjusted to 32.5 cm above the distributor. The electrical properties of these solids are extremely good for this type of experiment because they tend to quickly conduct static charge to any available ground. In this case the metal distributor was well grounded and the constant contact with the metal particles eliminated any significant static charge buildup.

Pressure measurements at each tap were made with Baratron diaphragm-type differential pressure transducers (model 223 BD), with one side of each transducer open to atmosphere. As a result, each transducer measured the in-bed pressure relative to atmosphere (i.e., gauge pressure). The output from each transducer was also low-pass filtered at 40 Hz before being sent to the data-acquisition system. This particular sensor configuration was chosen in order to permit measurement of pressure changes at very low frequencies (e.g., well below 1 Hz), which is typically not done for fluidized-bed measurements. In fact, it is common practice to include high-pass filtering as part of the signal-conditioning process or as a result of using piezoelectric type pressure transducers, which have an inherent high-pass frequency of approximately 0.1 Hz [see, for example, **1-4**]. The use of intentional or inadvertent high-pass filtering has not been previously considered an important issue for bubbling beds because bubble frequencies are typically well above 0.1 Hz. Also, there is an inherent practical advantage in using high-pass-filtered signals because the digital resolution of the AC component is usually enhanced. However, as we discuss below, there appear to be some important dynamic features that are being excluded by using such high-pass-filtered measurements, and the practice bears further consideration.

Pressure signals were recorded at 200 Hz with a four-channel digital recording oscilloscope (12-bit precision). Typically, measurements from two of the three pressure taps on each side were recorded simultaneously. In all cases discussed here, one of the pressure taps selected on each side was the lowest tap (taps BL and BR, positioned at 7.5 cm). For this study, each recorded time series had 60,000 contiguous records, spanning a total time of 5 minutes.

Video records of the dynamic bed patterns were recorded with a Sony Mavica FD-91 digital camera located normal to the bed's front (wide) surface on a tripod. For each fluidizing condition, multiple video segments (MPEG format) of 15 seconds duration were recorded at 25 frames per second with a resolution of 320 by 240 pixels. The camera was adjusted to capture a marked reference area on the bed front wall 25 cm across and 39.5 cm high. For post-processing, individual frames from the MPEG movie were extracted using a video editor.

General Observations

As we visually observed the bed at various states of fluidization over several tens of minutes, it appeared that the bubbling behavior was rarely distributed uniformly across the width of the bed. In general, it appeared that larger bubbles tended to concentrate either on the left or right, forming a kind of bubble "plume". Once

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a plume formed, it tended to remain for long periods (e.g., 5 to 10 minutes or longer) and then would abruptly shift to the opposite side. The time interval between shifts also appeared to be longer for conditions near minimum fluidization. Examples of left and right plumes are illustrated in **Fig. 2**, which shows frames extracted from video segments taken approximately 15 minutes apart at a fluidization flow 2.08 times the minimum. In this case, the shift between right-oriented and centered plume was completely spontaneous and not induced by any deliberate adjustments on our part.

We subsequently found that the frequency of shifts was related to the vertical orientation of the bed and that we could induce shifts by manipulating the bed orientation with very small adjustments to the screws on the bottom plate. In most cases, the adjustments required to cause these shifts were so small that we could not detect any significant deviation on a level measurement (using a bubble level indicator) of the bed itself. When the bed was clearly tilted to the left or right of vertical, the plume would shift to the opposite side and remain there indefinitely. When the bed was very close to vertical (allowing for the inevitable deviations within construction tolerances), the plume migrated much more freely from side to side over the periods of several minutes. Under these conditions, shifts could be introduced simply by tapping on the side of the bed. We surmised that at the nearly vertical condition, the plume is quite unstable, and very small changes can cause it to shift one way or the other. In some sense, it is reminiscent of a stick balanced on end.

Analysis of Multivariate Pressure Signals
In evaluating the simultaneous pressure data, we found that the asymmetric behavior of the bubble plume could be readily detected. One of the easiest methods for detecting this condition is to evaluate the cross correlation between pressure taps on opposite sides of the bed as illustrated in **Figs. 3** and **4**. In both of these figures, the cross correlation between the upper and lower pressure taps and their counterparts on opposite sides of the bed is depicted (vertical axis) as a function of the time interval between the measurements (horizontal axis). For positive (+) delay values, the cross correlation is evaluated between the left-hand side signals and the corresponding right-hand signals after a lapse of the indicated time delay. For negative (-) delay values, the cross correlation is evaluated between the left-hand signals and the corresponding right-hand signals as they were earlier in time by the indicated delay. The labeling convention used herein is the reference signal versus the test signal, so that when cross correlation is reported for “Left vs. Right”, correlation in positive time delays means that events in the “Right” signal occur later in time than in the “Left”.

Figure 3 is a relatively rare example where, on-average, the bubble plume remained nearly vertical and centered for the 5-minute sampling period. In this case the cross correlation is almost completely symmetric about zero time delay. The large peak at zero time delay implies that taps on both sides of the bed experienced pressure changes that were approximately simultaneous. The symmetry in behavior as one shifts to both positive and negative time delays implies that neither side experienced pressure changes earlier or later than the other (i.e., neither side preferentially generated events that propagated toward the other).

Figure 4, on the other hand, represents a condition where the bubble plume is biased toward the left side of the bed. In this case, there is a significant asymmetry in the cross-correlation functions between corresponding taps on the two sides. The shape of the asymmetry implies that pressure events (bubbles) occurred more frequently on the left side, and the resulting pressure waves propagated toward the right.

It is also interesting to consider cross-correlations between lower and upper pressure taps on the same side. **Figure 5** illustrates examples for both the left and right sides of the bed at a single fluidization condition. Here we observe that the bubble rise time is indicated by the time-shifted peak in the cross correlation (i.e., the delay between a bubble being sensed at the lower tap and its subsequent detection at the upper tap), thereby indicating the average rise velocity for bubbles on both sides (this was visually confirmed from video sequences). Note that the average velocity for the right side was significantly lower than on the left. Assuming that bubble rise velocity is approximately proportional to the square root of the bubble diameter as is usual for Group B solids, the difference in bubble velocities implies that the average bubble size on the left side was approximately twice that on the right side (although this observation is not conclusive, as factors other than bubble size can influence bubble rise velocity).

We find that a more sensitive and precise estimate of bubble rise time can be obtained using another type of bivariate statistic we refer to as differential time asymmetry. This particular statistic also measures the relationship between two measurements as a function of time delay, but instead of covariance it indicates shifts in time asymmetry (i.e., differences between how things appear in forward and reverse time). Our particular statistic is a variant of the univariate statistic proposed for applications in nonlinear dynamics [**5-8**] and is defined by

$$\mathbf{T32(\tau) = \sum_{t=1}^{N} [p2(t+\tau) - p1(t)]^3 \,/\, \left[\sum_{t=1}^{N} [p2(t+\tau) - p1(t)]^2 \right]^{3/2}}$$

where p1(t) is the value for a pressure measurement from location 1 at time t, p2(t+τ) is the value for a pressure measurement from location 2 at time t+τ, and N is the number of pairs p2(t+τ) and p1(t) in the two measurement time series.

Large positive or negative values of this statistic are indicative of strong nonlinear coupling between two sets of measurements. As shown in **Fig. 6**, a large negative T32 value occurs between the upper and lower pressure taps on each wall at the time delay associated with rising bubbles. Because of the steeper slope of this function around the critical time delay, it is possible to estimate the bubble velocity with greater accuracy than is possible with the cross-correlation function. In this case the average bubble velocity was higher on the right side, consistent with the visual observation that the bubble plume was shifted to the right.

The lack of high-pass filtering in the pressure signals also makes it possible to observe global bed time scales that are significantly longer than those associated with bubble generation and transit. In particular, we have found that very regular, slow oscillations can be observed in the pressure time series, as shown in **Fig. 7(a)**. Here there is a clear variation in the mean pressure superimposed on the much faster pressure spikes from the bubbles. By applying a special low-pass filter that does not introduce phase distortion [**9**], the underlying motion of the mean pressure signal can be recovered [**Fig. 7(b)**]. Cross-correlations between the low-pass-filtered signals from opposite sides of the bed reveal a very regular, slow vertical oscillation of the bed with a period of slightly over 100 seconds [see **Fig. 8**]. Once the bubble effects are removed, the strength of this low-frequency oscillation is remarkably strong and appears to be responsible for variations in the overall bed pressure drop of several percent.

Conclusions and Recommendations

Our experience with the above experiment suggests that there are some important aspects of bubbling-bed hydrodynamics that are still not understood. In particular, it appears that there are important long-time-scale phenomena associated with lateral and vertical oscillation modes of the bed solids. Such oscillations could account for variations in bed expansion and gas-solids mixing that would be expected to have a significant impact on bed performance. We conjecture that more cohesive solids may exhibit even longer-time-scale oscillations because of the dissipative effects of particle-particle interactions. In light of the apparent sensitivity of some of these oscillations to small perturbations, controlled manipulation of their occurrence (e.g., with selective gas injection through controlled jets) is a distinct possibility.

Additional experiments with other bed designs and solids are needed to verify and extend these preliminary observations. In planning such experiments, the issue of high-pass filtering of pressure signals needs to be carefully considered. One of the motivating factors behind our beginning this study was the observation of apparent long-time-scale oscillations in low-order bubble models and CFD models [**10-11**]. It now appears that these models may be revealing important aspects of the physics that have been overlooked up to now. We are now presented with an interesting opportunity for using these models to help guide a new frontier of experimental investigation.

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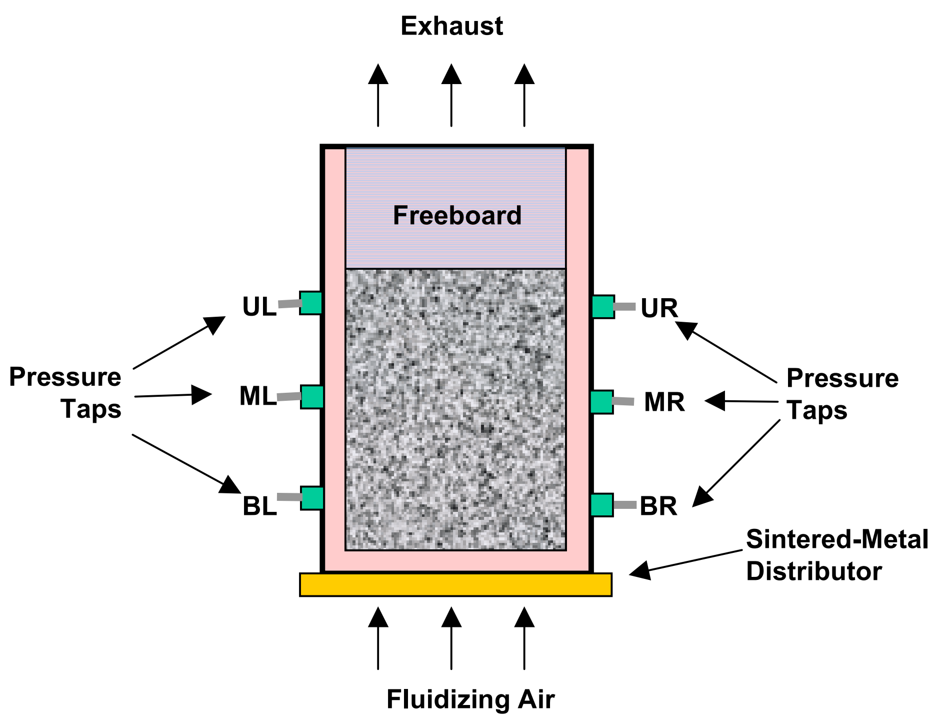


Figure 1. Schematic of two-dimensional fluidized bed.

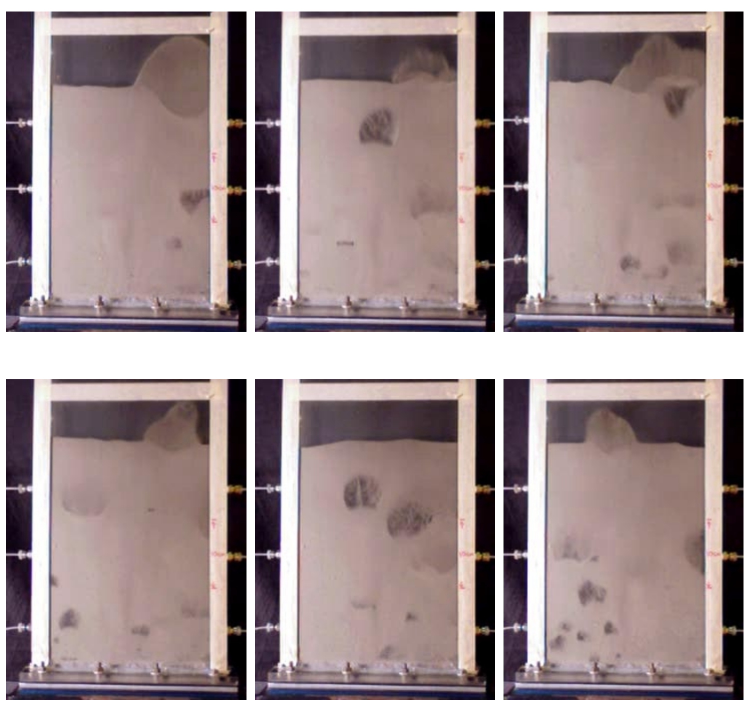


Figure 2. Example video images (randomly selected) from the 2-D bed illustrating bubble concentration toward the right side (top row) and even bubble distribution (bottom row). Fluidizing air flow is 2.08 times the minimum.

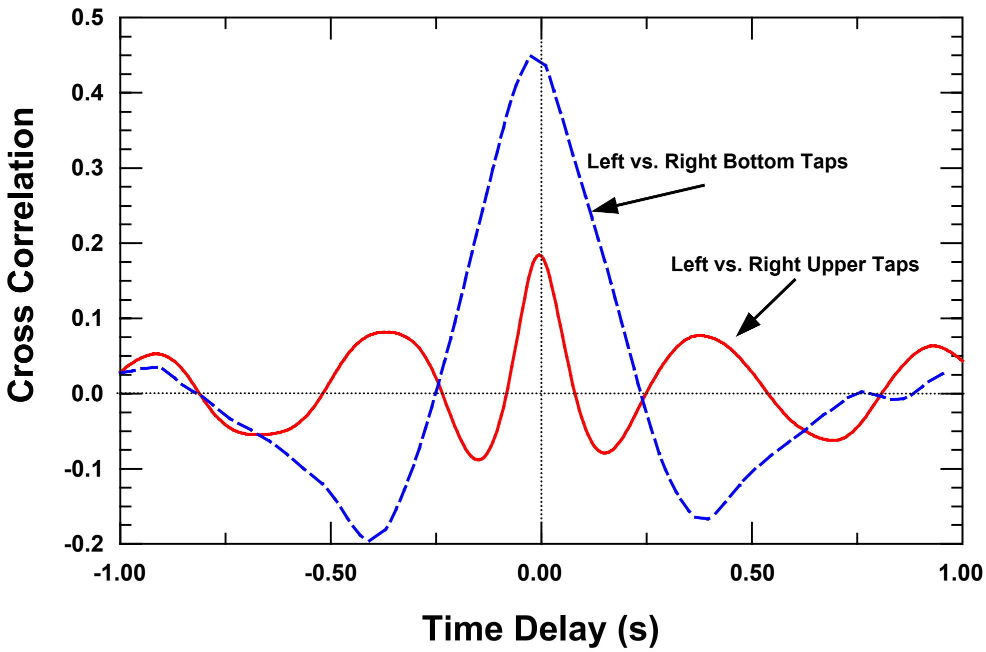


Figure 3. Cross correlation between taps on opposite sides of the bed when the bubbles are uniformly distributed. The fluidizing air flow was 2.35 times minimum.

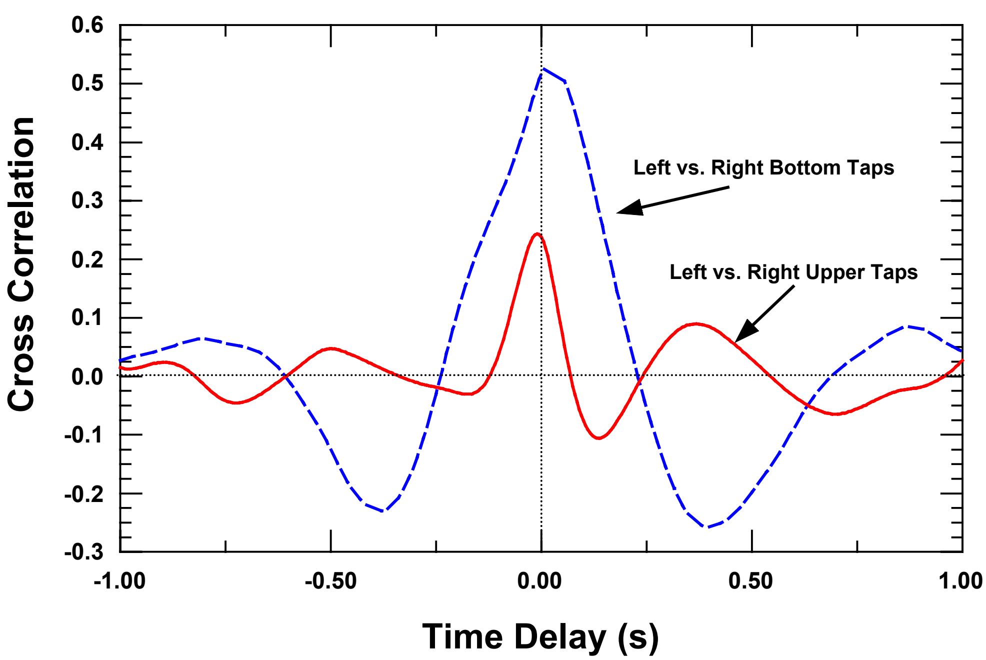


Figure 4. Cross correlation between taps on opposite sides of the bed when the bubble plume is shifted to the left. The fluidizing condition is the same as in **Fig. 3**.

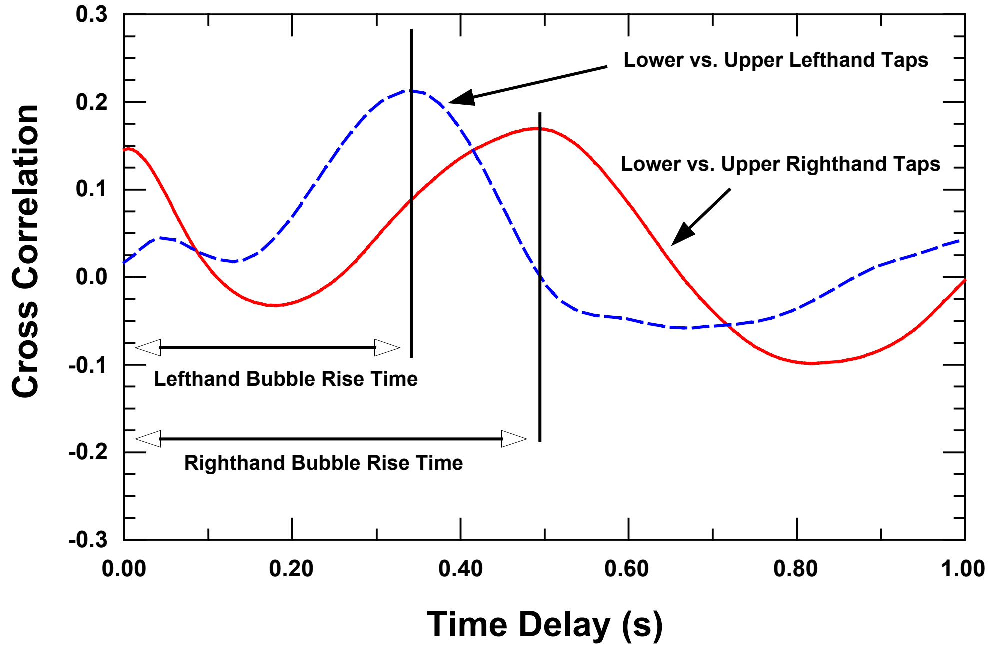


Figure 5. Cross correlation between vertically spaced pressure taps. Bubble plume is shifted to the left. Fluidizing air flow is 2.35 times the minimum.

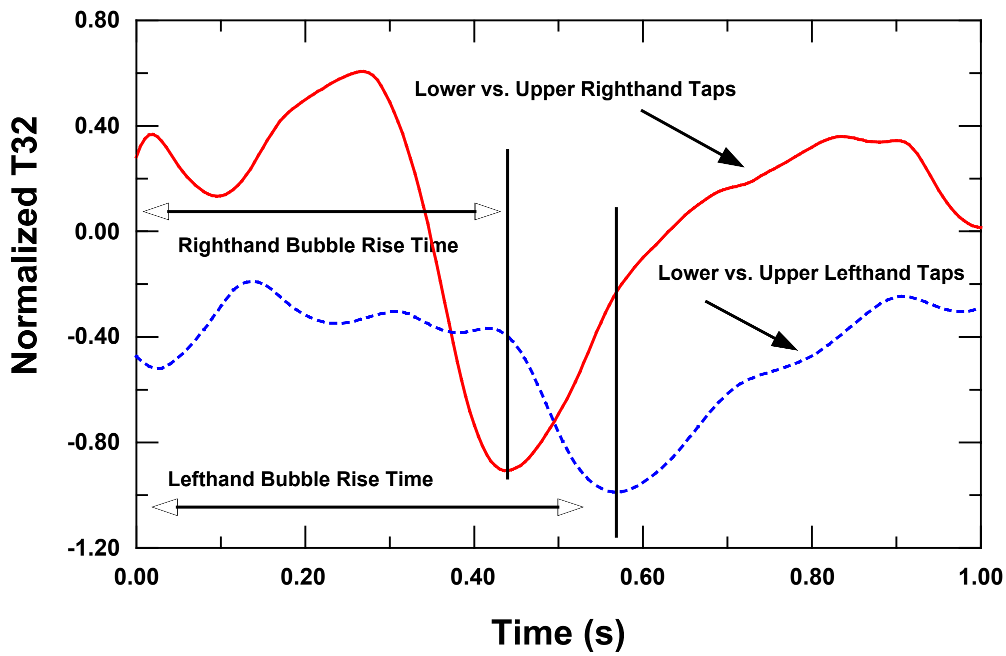
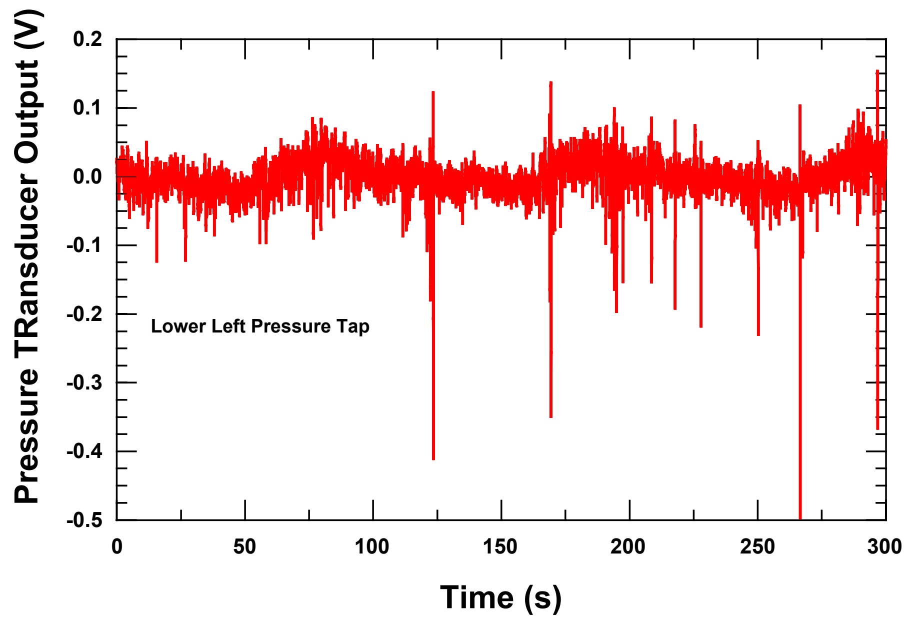
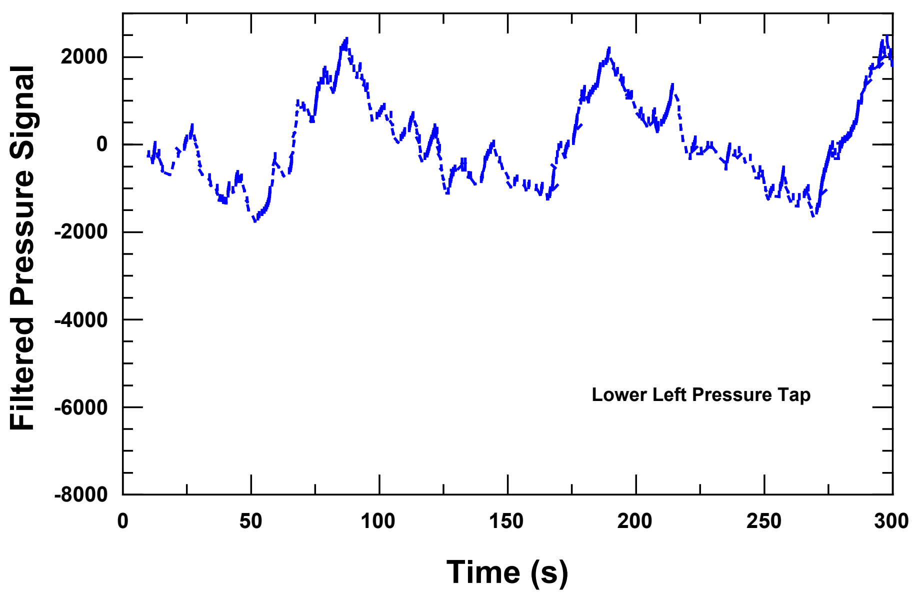


Figure 6. Time asymmetry between vertically spaced pressure taps. Bubble plume is shifted to the right. Fluidizing air flow is 2.35 times the minimum. These data were observed at the same flow condition but at a later time than in **Fig. 5**.



(a)



(b)

Figure 7. **(a)** Original time series from the bottom left pressure tap during an episode where the bubble plume was shifted to the right. Fluidizing air flow is 1.56 times the minimum. **(b)** Bottom left pressure signal after low-pass filtering with zero-phase-shift filter.

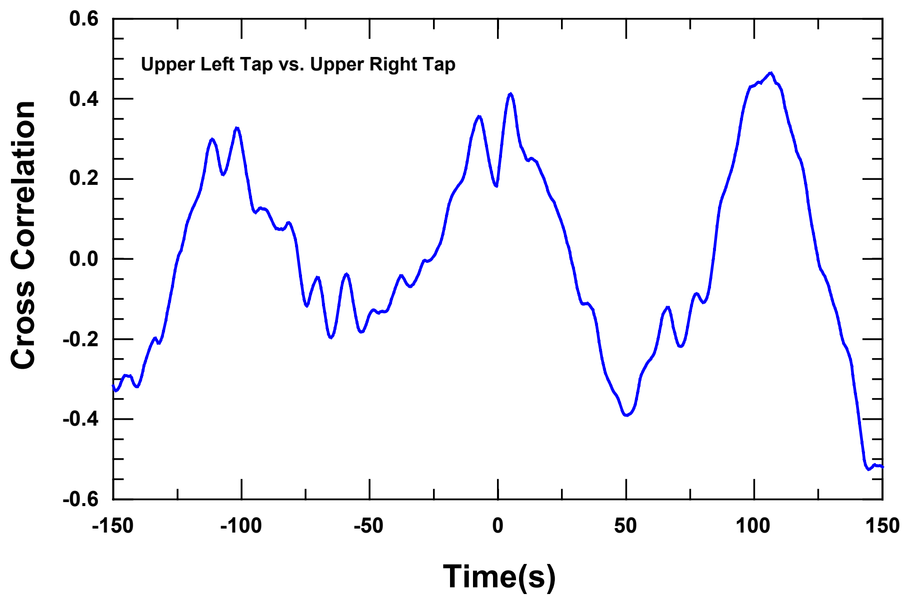


Figure 8. Cross correlation between the upper two taps after low-pass filtering. Note the roughly symmetric, long-time-scale oscillation.