LDA Technique for Measurements in Freeboards of Fluidized Beds

Y. Levy
Department of Aeronautical Engineering
Technion–Israel Institute of Technology
Haifa 32000, Israel

A technique specially developed to enable local measurements of instantaneous velocities of two phases (gas and solid particles) in the freeboard of a fluidized bed is described. A laser Doppler anemometer (LDA) system was modified to enable the simultaneous measurements of the velocities and the size of the measured particles. The size range of the solid particles is 0.2–1.5 mm, while the gas phase is represented by micron-size tracking particles. The particle size measurement is performed by recording the pedestal amplitude of the signal and applying two cutoff level criteria for discrimination between the two phases. A special effort was given to development toward an automated technique. This was to allow for the collection of large samples of data to increase statistical accuracy.

Preliminary measurements and validation tests confirmed qualitatively and quantitatively the accuracy of the measurement technique. The initial use of the system has already revealed some flow phenomena in the freeboard that were not known before (Levy and Lockwood, 1983); some controversies are discussed in Levy (1985). Those measurements indicated a specific gas velocity profile with maximum values near the walls and minimum values at the center of the freeboard. The existence of large toroidial vortices generated during the bursting of bubbles at the bed surface was also reported.

The relevance of the technique is in its flexibility to be used without any further modification in other types of similar two-phase flows such as particle-laden free jet, two-phase pipe flows, particle separators, and the like.

Two-phase Flow Measurements Using LDA

In two-phase flow measurement using the LDA technique each velocity field must be measured independently. Two different types of scattering particles are usually present: small (tracking) particles that follow the flow and represent the continuum phase, and larger particles, which form the dispersed phase.

Various techniques are applied in order to evaluate the size as well as the velocity of the particles. Some extract all the information from the photodetector signal, others require extension of the optical system to obtain additional information for measuring the particle size. A review of two-phase flow measurements using LDA is given by Durst (1982). Specific conditions for measurements in a fluidized bed originate from the fluid mechanics of the bed and the characteristics of the bed particles.

Flow characteristics

The flow in the freeboard is two-phase. Three categories may be identified:

1. *Gas phase.* Air flows from the distribution plate through the dense bed to the freeboard and exits to the surrounding atmosphere. In the freeboard the flow is turbulent with $4{,}000 < Re < 50{,}000$ based on the hydraulic diameter of the freeboard.
2. *Fine bed material.* Solid particles created by attrition, having terminal velocities smaller than the maximum instantaneous gas velocity, will be carried over (elutriated) outside the freeboard. These particles will record a positive mean velocity value.
3. *Coarse particles.* Particles having terminal velocities greater than the maximum instantaneous gas velocity in the freeboard should record a zero or slightly positive mean velocity, due to the drag force from the upward gas flow.

All three flow categories exist simultaneously and are three-dimensional.

Particle characteristics

Silica sand of the type normally used in a real bed was chosen as the bed material. The typical diameter of the sand particles is 1 mm. This value is bigger than a LDA control volume diameter. The particles are irregular in shape and the refractive index varies from one particle to another. The particles are nonspherical and may have randomly distributed flat surfaces with sharp edges. They vary in color from bright white to completely opaque black particles, the majority being bright and partially transparent.

Signal characteristics

In order to analyze the characteristics of a typical sand particle signal, tests were performed with particles fastened to a rotating disc. Most of the sand particles produced a processable signal in the forward direction with adequate amplitude of Doppler frequency modulation and acceptable levels of signal-to-noise ratio. The backscattered signal of the sand particles, which is of a much smaller pedestal amplitude and Doppler modulation, and the gas signals, as obtained from the very fine particles representing the gas flow, were unprocessable.

Two important observations resulted from the rotating pin test:

1. The existence of a certain maximum for the pedestal amplitude above which amplitude does not increase with particle size. Maximum pedestal amplitude was about 20 to 100 times bigger than that of particles marking the gas flow (depending on operating conditions).
2. The possibility of obtaining a processable signal from the sand particles as well as from a gas representing particles with the same operating conditions.

The chosen technique

Due to the unconventional flow conditions in the fluidized bed, a strategy was adopted by which monosize particles have been used as bed material, effectively eliminating the necessity to measure the absolute size of the scattering particle and reducing the problem to that of simply identifying the phase to which it belongs.

The most convenient technique for discriminating between the signals of the two phases is by measuring the pedestal amplitude, which is the low-frequency component of the signal, Figure 1. Signals of high pedestal amplitude are generated by the solid phase, while much lower ones are attributable to the gas phase.

The technique applies a LDA system for velocity measurements of the two phases and an additional (parallel) processing signal system for detection of the pedestal amplitude enabling identification of the phase to which each measured signal belongs. Discrimination threshold levels are determined in software according to specific experimental conditions. Data are recorded as groups of Doppler frequency, pedestal values, and when needed, the time of measurement. Upon termination of data acquisition, a data processing program is applied to resolve the two-phase flow properties.

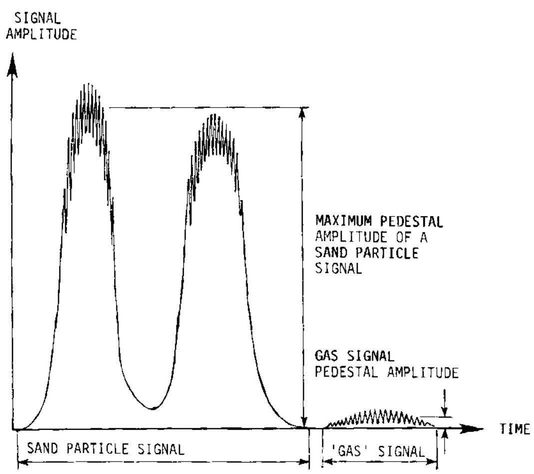

Figure 1. Typical forward-scattered signals.

Experimental System

The fluidized bed system as described in Levy and Lockwood (1983) consists of a fluidized bed (0.6 × 0.3 × 2.4 m) with large glass walls, a three-dimensional traversing mechanism, an optical bench for the forward-scattered LDA measurement system, and a facility for periodic single bubble release. The optical dimensions of the system are: focal length of the transmitting optics, 450 mm; half-beam crossing angle, 3.90°; magnification of collecting optics, 3.0; and pinhole diameter, 0.50 mm.

Signal processing system

The signal processing system was designed to measure steady and unsteady two-phase flows. The flows considered in the present study may be classified as follows: single-phase (gas) flow, two-phase (gas and sand) flow, and periodic two-phase flow.

It became evident that the Doppler signals obtained during measurements in the freeboard of the fluidized bed were of sufficient quality to be processed by a frequency counter. The counter (Hewlett Packard 5345A including option 011) requires a signal of the highest possible quality and with an amplitude of Doppler frequency oscillation above 60 mV, peak to peak. Accordingly, the Doppler signal had to be amplified and filtered before processing. At the end of each measurement the counter supplies (in the "computer dump" mode) the signal duration and the number of cycles within the Doppler burst. To increase the accuracy of the frequency measurements, a condition in the data acquisition routine was set so that only signals with more than 50 cycles would be accepted.

Measurement of signal pedestal amplitude

Information about the particle size is contained in the pedestal amplitude of the signal. The pedestal amplitude changes as the particle travels through the control volume. The maximum of the pedestal amplitude can be viewed as characterizing the particle size. A system was devised to detect the maximum amplitude of the instantaneous pedestal signal within a defined time interval. The pedestal signal is recovered by passing the photomultiplier signal through a low-pass filter, and a trigger pulse is generated from the pedestal signal whenever it is above a preset level. At the end of the time interval, the peak detector holds the value of the maximum pedestal amplitude. This value is converted to a binary number by an analog-to-digital converter.

Upon termination of data acquisition and when convenient, a data processing program is executed to resolve the velocity information of the two phases from the blocks of data that were recorded by the data acquisition programs. The processing programs follow a certain logical procedure described as follows. A first full data scanning is performed to evaluate a histogram of the pedestal amplitudes. The histogram, composed of 50 equal-amplitude intervals, is displayed on the screen. For each group of signals of equal pedestal amplitude intervals, the mean and rms velocity values are calculated. The result is displayed in two forms:

1. As a relation between the mean velocity values and pedestal amplitudes.

2. Where mean and rms velocity values are calculated for all signals of which the pedestal amplitude is greater than the pedestal value on the abscissa.

Two pedestal amplitude range limits are selected: a low value, which acts as the highest pedestal amplitude of signal to represent the gas phase, and a high value, which represents the lower pedestal amplitude limit for signals representing the solid phase. Velocity data with corresponding pedestal amplitude values between these two limits are ignored. The effect of the two limits is shown schematically in Figure 2.

From observation of several pedestal amplitude histograms and velocity-pedestal amplitude relations it was found that a repetitive pattern exists.

1. About half of the measured velocity signals had zero pedestal amplitude value, i.e., their pedestal amplitude was below the preset trigger level, corresponding to the gas phase. The rest of the signal had a relatively wide pedestal amplitude distribution.

2. The mean velocity values maintained a relatively constant value for signals down to a certain pedestal amplitude limit. The constant value indicates that all velocity measurements with corresponding pedestal amplitude values down to that limit originate from sand particles.

Further reduction in the higher limit value causes a steady change in the recorded mean value, a phenomenon that represents an interference or overlapping between the two phases. The lower limit (i.e., highest pedestal value still to represent the gas phase) is usually selected as the value of the first (of the 50) pedestal amplitude interval. This is due to the fact that most of the gas signals fall in that category. After the two limits are selected and applied in the program, a second data scan is performed to produce velocity histograms of the two phases. The histograms are displayed on the screen to confirm the quality of the results (a nearly Gaussian distribution is usually required) and when necessary, cursor limits (mean value $\pm$ 4 $\times$ rms) are applied for noisy signal rejection. If a cursor is applied, a third data run is performed to calculate the final mean and rms values of the two phases. The fact that the two pedestal threshold levels can be selected in the data processing program after the measurements are performed, eliminates the need for adjustment of some of the operating parameters, which otherwise might have been necessary. This applies to the laser beam intensity, photomultiplier high-voltage power supply, the peak detector amplifier, and related factors.

As can be seen, the system is not fully automatic and results can be somewhat dependent on operator decision (setting pedestal levels, applying cursor limit, etc.). The decision to develop the system to such a structure came after many preliminary experiments, which indicated that a fully automatic system (although possible to be constructed) might sometimes indicate erroneous results. The consequent advantage of this processing procedure is greater flexibility in operating the experimental setup, thus obtaining higher quality results.

Validation of the technique

In order to confirm the accuracy of the measurement technique, a preliminary test was conducted. Two-phase flow measurements were performed in a particle-laden free jet of the kind described in Levy and Lockwood (1981). A schematic description of the experimental arrangement is given in Figure 3. Accuracy is defined in the test as the ability of the measurement sys-

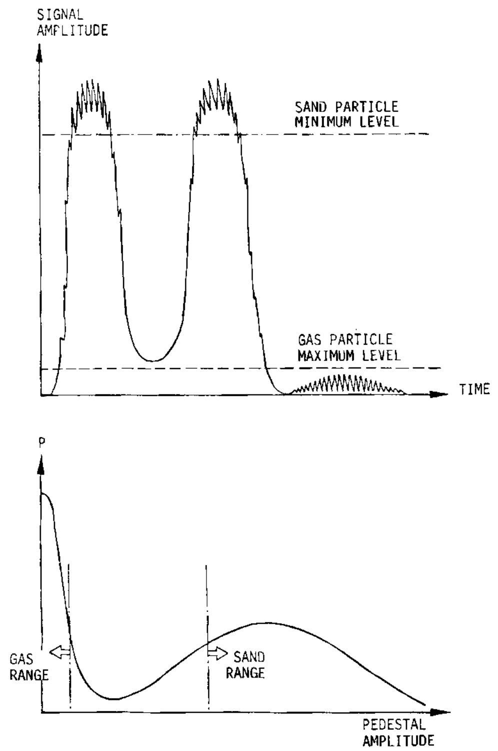

Figure 2. Principle of two-phase discrimination.

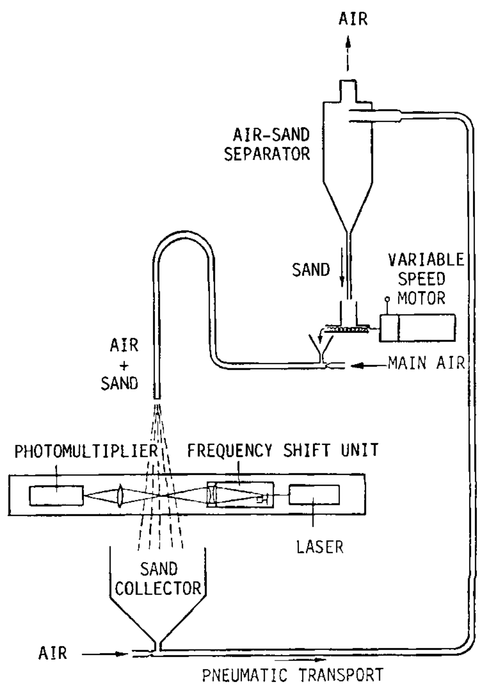

Figure 3. Particle-laden free jet experimental arrangement.

tem to discriminate between the Doppler signals of the two phases and to relate each signal to the flow phase to which it belongs. In the test, sand particles were injected downward in an air free jet. The particles used were silica sand with mean diameter of about 200 μm. The mass flow rate of the sand particles was 8.45 g/s and the sand to air mass flow rate was 2.33. The results of that test are illustrated in Figure 4. Velocity histograms of three measurements made under identical operating conditions are presented:

1. The gas velocity histogram (curve A in the figure).
2. Sand velocity histogram (curve B).
3. Measurement results in which all signals were displayed without discrimination between the phases (curve C).

All curves were normalized to illustrate probability histogram values. The sand velocity readings were those with pedestal amplitudes above a certain threshold level, and the gas phase signals were those with pedestal amplitudes lower than another, lower threshold level. It is seen that by using appropriate upper and lower limits for the pedestal threshold levels (curves A and B), the velocity distribution of each phase can be isolated. This is especially evident in the overlapping region of the velocity distributions of the two phases ($8.5 < v < 12$ m/s). It is further seen that the mean sand velocity value, as approximately represented by the velocity value at the peak of curve B, and the velocity value at the right peak in curve C are equal. As for the mean gas velocity, it is seen that its value is somewhat lower than the value at the left peak in curve C. The reason for the latter is that curve A is composed only of signals originating from fine particles with very low pedestal amplitude, representing the gas flow, whereas the left peak in curve C is the result of a much wider particle size range that extends to larger size values. The bigger particles in that size range, which are very small sand particles created by attrition, are traveling at somewhat higher velocity, shifting the gas velocity peak to the right. These particles scatter light of intermediate pedestal amplitude and are usually excluded from gas measurements by selecting a low threshold level for the gas phase.

As a conclusion for this preliminary test it can be said that the results clearly demonstrate the ability of the system to discriminate between flows of the two phases and can serve as justification for the use of the chosen measurement technique.

Bias effect

A bias effect specific to measurements in the freeboard of fluidized beds was encountered. The phenomenon affects velocity measurements in the lower part of the freeboard, in the region where the bubbles are still in the process of bursting. This effect is present during normal bed operation but can be demonstrated more easily with repetitive single bubble release operation. The eruption of the bubbles tends to occur in such a way that during the initial part of the process velocity measurements cannot be obtained; this is illustrated in Figure 5. As this phenomenon is repeated during all of the bubble bursts, and at that part of the cycle at which the velocities are positive (rising), a tendency for the recorded mean velocity to be biased toward lower values is inevitable. The biasing affects both phases with the same tendency and decreases as the measurement level increases.

The biasing phenomenon was confirmed by a simple test using the periodic single bubble release mechanism. The number of measurements of the two phases was recorded at different time intervals during the bubble burst cycle, Figure 6. The variation in number of measurements at different time intervals during the bubble burst cycle directly affects the recorded mean velocity (averaged over complete cycles). Sand particles exist, and theoretically should have been recorded, in nearly equal amounts in the ascending and descending parts of the bubble burst cycle. As for the gas, in which a nearly uniform concentration of fine dust particles is suspended, equal signal detection rates should occur, resulting in constant numbers of measurements through the burst cycle.

The particulate phase is affected because only the first layer of particles, at the top of the bubble bulge, can be measured. The succeeding particles, still within the top part of the bulge, are prevented from being measured because of the blockage of the laser beam, Figure 5. However, some particles were detected. It can be seen from Figure 6 that the number of ascending particles measured is far lower than those detected while descending (these particles probably existed somewhat in advance of the main bulge). When the bed was operated with fluidizing velocities, which cause a more sluggish situation, all previously mentioned effects were encountered with the addition of some large agglomerations of particles that were ejected upward. These

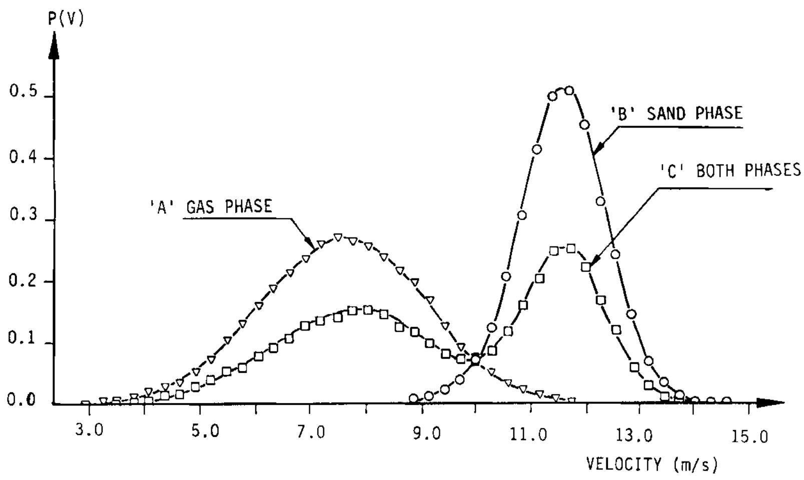

Figure 4. Velocity probability histograms of gas, sand, and no phase discrimination for a particle-laden free jet.

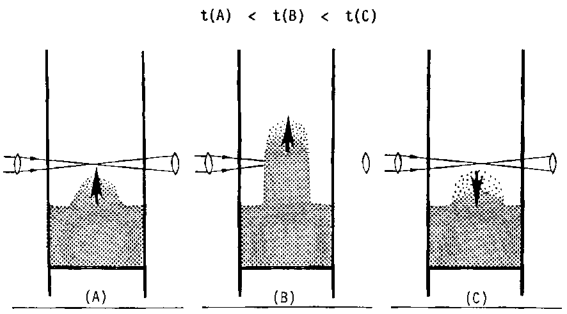

Figure 5. Bubble burst process.

agglomerations tend to preserve some of their shape as they ascend, separating to a more dispersed form and thus becoming measurable while descending, a characteristic that reinforces the sand particle bias effect.

Gas phase velocity measurements could be performed until the bulge encountered the laser beam (Figure 5.A) and after the burst of the bubble was completed (Figure 5.C). Gas discharged during the bursting process of the bubbles is therefore measurable only at higher levels. As the mean gas velocity inside the bubbles is positive, a biasing toward lower velocity values will be recorded at low freeboard levels. Enhancement of the phenomenon is also seen in Figure 6, as the numbers of gas measurements just before the bubble emerge are at much lower rates than at the end of the cycle.

Results

Justification for the use of the present technique was demonstrated in its ability to distinguish between the flows of the two phases in the free jet test. Although quantitative results are difficult to obtain, the qualitative consequences are convincing.

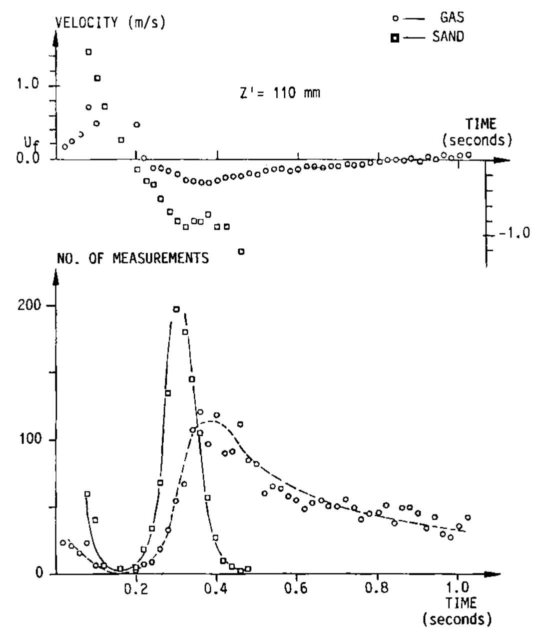

Figure 6. Time variation of gas and sand velocities and number of measurements at centerline 110 mm above static bed surface.

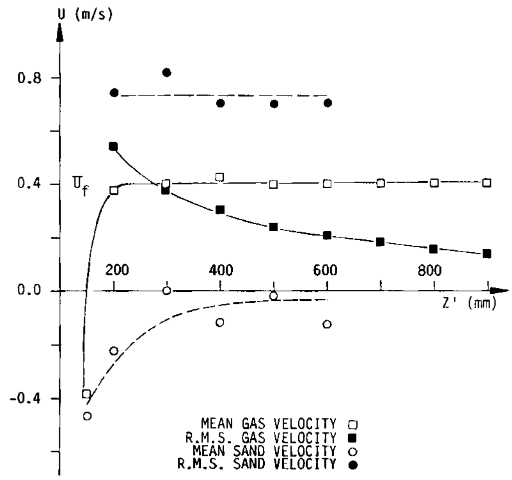

Figure 7. Variation of gas and sand mean and rms velocities with freeboard height along centerline of freeboard.

$d_p = 0.40$ mm; $U_F = 0.4$ m/s.

The main phenomenon, unique to LDA measurements in the freeboards of fluidized beds, is the bias effect. It tends to shift the recorded mean velocity value of the gas phase and of the sand particles toward lower values.

The level at which the bias effect becomes insignificant depends on the operating conditions of the bed, and mainly upon the bed height and fluidizing velocity. For example, with a bed height of 200 mm, particle mean diameter $d_p = 0.40$ mm and fluidizing velocity $\overline{U}_f = 0.4$ m/s, a level of about 250 mm above the static bed level (when $\overline{U}_f = 0$) is about the upper limit of the region influenced by the bias effect; Figure 7. This is evident due to the fact that mean velocity values of the gas and of the sand particles are not expected to vary significantly with freeboard height; however, lower values were recorded in the bottom of the freeboard.

The performance requirement from the measurement system is also evident from the typical set of results shown in Figure 7. The large rms velocity values that exist all over the freeboard indicate that a significant fraction of the instantaneous velocities are negative (velocity histograms usually stretch to the limits of mean values ± 4 rms). This indicates that the hot wire technique is not appropriate for gas measurements in the freeboard and that when a LDA is used an adequate frequency-shift unit (for reverse flow measurements) must be applied.

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