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AN LDA TECHNIQUE FOR *IN SITU* SIMULTANEOUS VELOCITY AND SIZE MEASUREMENT OF LARGE SPHERICAL PARTICLES IN A TWO-PHASE SUSPENSION FLOW

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Abstract—A relatively simple optical scheme using the reference-mode laser Doppler anemometry for the *in situ* measurement of flow properties of a dilute particle-fluid two-phase suspension having a predominant flow direction is hereby proposed. It is an extension of the established technique of optical gating for particle sizing which is fully integrated into the established technique of laser Doppler anemometry for velocity measurement. Particles that can be measured by this scheme are limited to those with sizes greater than the smaller dimension of the optical measuring volume. Inherent in the methodology is a procedure for providing information on the local particle number density and velocity distributions for each size range of the particles and the local velocity distribution of the continuous phase. The accompanying electronics and interfaces are also established for data processing and analysis in a mini computer. Validation of the scheme has been accomplished by controlled experiments using stainless steel balls and water droplets of 1 mm and greater in diameter.

INTRODUCTION

The behavior of two-phase systems which are characterized by the motion of a suspension of solid particles or droplets relative to the continuous carrier fluid covers a wide range of phenomena of great technical importance. Many examples can be cited, including the collection of dust and mist from chemical processes for pollution control, the combustion of liquid fuel droplets and solid coal particles, spray cooling, etc. Consequently, there has been considerable number of efforts in the measurements of velocity and size of particulates in such flow systems (Delhay 1979). Because of the attractive feature of the absence of direct mechanical interference with the flow, optical schemes have been attempted for this purpose for a long time. The conventional optical schemes include high-speed photography, extinction techniques, tracing techniques, cross correlation and optical gating, and, in general, suffer in their spatial and temporal resolutions. In recent years, much work has been done in the development of laser-Doppler anemometry schemes which actually measure the velocity of the scattering particles entrained in the flow rather than the velocity of the flow itself. Therefore, it seems logical to use such new optical schemes in two-phase suspension flows where the velocity of particulates is to be measured (Riethmuller 1973).

The application of laser-Doppler anemometry to two-phase flows, however, unlike in the case of single-phase flows, presents considerable problems and consequently most earlier measurements in this area are restricted to some rather simplified circumstances (Matthes *et al.* 1970, Grolovin *et al.* 1971, Lee & Einav 1972, Einav & Lee 1973, Ben-Yosef *et al.* 1975, Durst & Zare 1975, Mason & Birchenaugh 1975). More recently there have been a number of efforts aimed at measuring solid particle-gas flows by dual-beam anemometry (Farmer 1978, Carlson & Peskin 1975, Popper *et al.* 1975, Rolansky *et al.* 1976, Stumke & Umhauer 1978). Examples of such efforts are those by Farmer (1978) and Stumke & Umhauer (1978) in which the amplitude and modulation depth of the Doppler bursts were related to particle size for glass spheres of up to several hundred microns in size.

One of the most serious difficulties concerns the signal ambiguity originating from the inherent nonuniformity of illumination in the optical measuring volume (Farmer 1972). Some earlier effort was attempted to by-pass this difficulty by incorporating a second optical system designed solely for particle sizing (Durst & Umhauer 1975). Ungut *et al.* (1977, 1978) related the ensemble number count of Doppler bursts as a function of amplitude to the number count of particles as a function of size with a Gaussian distribution of the illumination intensity in the measuring volume to yield the number flux instead of the number density of particles for particles of 30–200 μ in diameter. Lee and Srinivasan (1978a, 1978b) and Srinvasan & Lee (1978, 1979) developed a method in which a particle's resident path length in passing through the optical measuring volume was used to resolve the same ambiguity difficulty to obtain the local statistics on the size number density distribution and, for each size range, velocity distribution of the particulate phase together with the velocity probability distribution of the fluid phase. However, this technique requires the upper limit on the particulate size to be smaller than the smaller dimension of the optical measuring volume and therefore cannot be readily used to measure the flow of a dispersion with large-size particulates.

There have been relatively few studies of two-phase suspension flows of large size particulates using laser-Doppler anemometry. An early attempt by Davies (1973) demonstrated that in a bubble flow the velocity of the bubble could be measured separately from that of the water. Durst & Zaré (1975) and Styles (1974) reported observing Doppler velocity signals with exceedingly good modulation from large steel balls and oil droplets respectively. Durst and Zaré proposed a scheme of determining the velocity of the sphere by measuring the beat frequency of the moving fringe pattern formed by the interference of two beams reflected and/or refracted from the surface of moving reflecting and transparent spheres. In this scheme, the information on particle's size is contained in the size of the fringe spacing. Ohba *et al.* (1976, 1977) and Ohba & Yuhara (1979) used this technique to make simultaneous measurements of local velocities of both phases in two-phase bubbly flows. However, they did not report any accompanying result on the *in situ* measurement of bubble size. Using this technique, Durst (1979) and Lee & Durst (1979) reported velocity measurements of particles and air in a turbulent dilute suspension flow of glass spheres of one uniform size from 100 to 800 μ in diameter in air in a vertical pipe. Durst (1978) gives additional description of this technique.

In recent years, another method has been proposed for the simultaneous measurements of size and velocity of large particles. This method combines the conventional technique of optical gating for particle sizing and dual-beam laser-Doppler anemometry for velocity measurements. Optical gating is a well established technique for particle sizing (Barczewski 1978) the usefulness of which depends on the accuracy of the accompanying velocity measurement. Its combination with laser-Doppler anemometry, therefore, offers much promise as a practical tool for studies of two-phase suspension flows with large particles. Wigley (1977) proposed a dual-beam laser-Doppler anemometry arrangement in which the transit time could be measured by observing the glancing angle reflections from a large droplet falling through the control volume and crossing the optical axis. This transit time when correlated with the back scattered Doppler signal would lead to a measurement of the droplet size. It was during the final stage of preparation of the manuscript of this paper that the recent work of Liska (1979) came to the attention of these authors. Liska applied Wigley's technique to bubbly flows in which the measured transit time when correlated with the forward scattered Doppler signal similarly led to a measurement of the bubble size.

The present work combines the conventional technique of optical gating for particle sizing and reference-beam laser-Doppler anemometry for velocity measurement. The optical gating is done by observing the blocking of the stationary reference beam by the moving particle and the velocity Doppler signal is generated by scattering from either the forward or backward scattering point on the surface of the particle. In this arrangement, the location of the scattering point on the surface of the particle for velocity measurement coincides with the location corresponding to either the beginning or the ending of the blocking period for size measurement. The appearance of a velocity Doppler signal at either the beginning or the ending of the blocking period thus assures an accuracy of the particle size measurement to within the error of the chord length corresponding to a dislocation of the blocking path from the particle axis by half the smaller dimension of the optical measuring volume. Furthermore, the relatively small uncertainty of the location of the particle's trajectory on the order of the dimensions of the optical measuring volume in this technique can be readily utilized to provide a basis for the determination of local number density distribution of particles in a two-phase suspension flow.

OPERATIONAL ARRANGEMENT AND METHODOLOGY

The operational arrangement of the reference-mode laser-Doppler anemometer is shown in the sketch of figure 1. The incoming laser beam from a 15-mW He–Ne laser is split into two beams of unequal intensity, the weaker one for the reference beam and the stronger one for the scattering beam, which are then so polarized that they form a 45° polarization angle with each other. These beams are focussed by a focussing lens to the same point at an angle of 8.14° to form a small measuring volume with a short dimension of about 240 μ as shown in the sketch to figure 1. Both the reference beam and the scattered light from the scattering beam on hitting a moving scattering body in the measuring volume are picked up along the direction of the reference beam by a matching receiving lens. The received beam is then passed through a polarization splitter to be split into two beams, one with a polarization orientation in the perpendicular direction and the other with a polarization orientation the same as that of the scattering beam. The beam with a polarization orientation the same as that of the scattering beam consists of the scattered beam and the component of the reference beam in the same polarization direction and is received through a small aperture by the photo multiplier tube to produce the Doppler signal through heterodyning. The beam with a polarization orientation perpendicular to that of the scattering beam consists of the component of the reference beam in this direction and is received by a photo diode for the purpose of measuring the size of the scattering body by measuring the time of blocking of the reference beam due to its cutting across the measuring volume.

If there is no blocking of the reference beam, its two components, which are perpendicular to each other in orientation of polarization, excite the sensing elements of the photo multiplier tube and the photo diode respectively resulting in added d.c. voltage outputs at both places. On the other hand, if there is a blocking of the reference beam, these added d.c. voltage outputs at the photo multiplier tube and the photo diode will disappear and the voltage outputs will reflect the normal system electronics noise levels at these places. When a moving spherical particle of a size larger than the size of the reference beam cuts across the reference beam, the outputs of both the photo miltiplier tube and the photo diode will show a drop from an elevated d.c. voltage to the system electronics noise voltage to be followed by a return to the same elevated d.c. voltage after a drop-off period. This drop-off period represents the time taken for the center line of the reference beam to traverse across the circular area formed in its plane of intersection with the spherical particle. If this plane of intersection coincides with a vertical plane of symmetry of the spherical body, after the multiplication of a geometrical factor of the cosine of

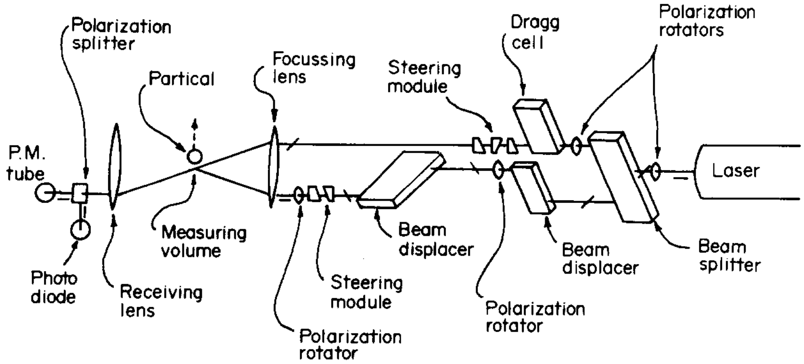

Figure 1. Optical arrangement.

the small angle between the reference beam and the horizontal, this block-off period than represents the time taken for the spherical particle to move a distance of one length of its diameter at the same vertical velocity as outlined in the sketch of figure 2. With a knowledge of the vertical velocity from the Doppler signal, one can then obtain the diameter of the spherical particle.

When the vertical plane passing through the center line of the reference beam lies within half of the smaller dimension of the optical measuring volume from the vertical axis of the particle, and the particle's final point of detachment from the axis of the reference beam lies within half of the larger dimension of the measuring volume, a Doppler signal is registered at the end of the block-off period as shown in figure 3(a). Such a Doppler signal which is due to the scattering from the surface of the particle is shown on an enlarged time scale in figure 3(b). The frequency of the Doppler signal gives the vertical velocity of the particle and thus also provides the needed input for converting the measured result of block-off period to the size of the particle. However, the size of the particle so calculated can only be considered approximate due to the combined effects of the finiteness of the size of the optical measuring volume and the size of the effective scattering area of surface of the particle. For large particles of a size larger by an order of magnitude or more than the smaller dimension of the optical measuring volume, the error in the particle size so calculated is usually far below 1 per cent. For small particles of a size a few times the magnitude of the smaller dimension of the optical measuring volume, these two effects seem to compensate each other to a great extent in the calculation of the size of the particle. While the relative size of the optical measuring volume becomes more pronounced for smaller particles, the size of the effective scattering area of surface of the particle becomes less extensive due to its larger curvature. The errors in the calculated particle size for such small particles, because of these effects, are found to be still as low as 2 per cent. Furthermore, precisely due to these same effects, there always exists the uncertainty of the location of trajectory of the particle within a horizontal cross-sectional area, which is related to the dimension of the optical measuring volume. Additional information, therefore, would have to be extracted from the measurements for the removal of the uncertainty of the location of trajectory of the particle in order to measure the dynamic behavior of an ensemble of particles of relatively large size in a two-phase suspension flow.

The amplitude of the Doppler signal which appears at the end of the block-off period can be readily utilized to fill this need. When the point of detachment of the surface of the particle passes through the center of the optical measuring volume, the amplitude of the Doppler signal assumes the maximum value for that particle. For particles of the same surface optical properties but different sizes, this maximum Doppler signal amplitude is expected to increase monotonically with the increase of particle size due to the monotonical increase of the effective scattering area of surface of the particle. At the same time, the block-off period from the photo

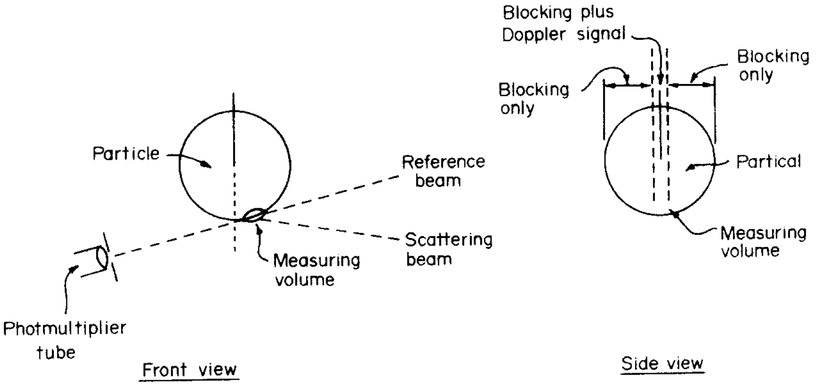

Figure 2. Laser-Doppler Anemometry scheme developed for large-size particle measurement.

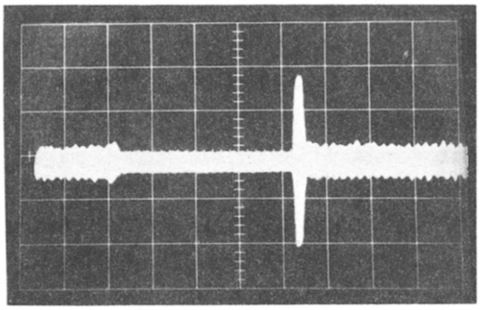

Figure 3(a). Blocking length (size).

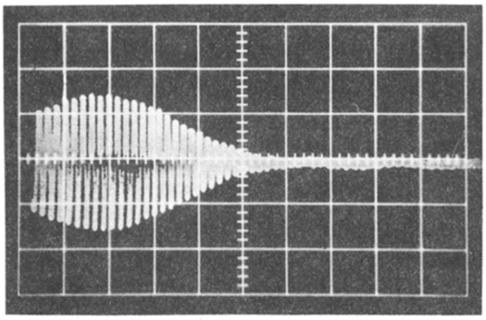

Figure 3(b). Doppler signal (velocity, location).

diode output will produce an accurate measurement of the size of the particle. However, for the very same particle, if the particle trajectory is displaced horizontally by amounts closely related to the dimensions of the optical measuring volume, the Doppler signal amplitude will drop off rapidly. The related block-off period from the photo diode output will produce measurement of the size of the particle with an error of the order of up to 2 per cent. For particles having identical size and surface optical properties and identical fixed trajectories but passing across the optical measuring volume at different times, a two-dimensional traversing of the optical measuring volume in a horizontal plane will produce a scattering diagram with contours of constant relative Doppler signal amplitude. Similar scattering diagrams for particles of different sizes but identical surface optical properties can be produced in the same way. Therefore, by knowing the exact size of a particle of such surface optical properties having a vertical trajectory in a two-phase suspension flow, one can readily identify the particular contour in the horizontal plane through which the particle trajectory passes. With the exception of the particle trajectory passing through the optimum position, the information on the particle size deduced from the block-off period of the photo diode output and the frequency of the Doppler signal will always have an accuracy of within 2 per cent.

By selecting a limiting boundary contour on this scattering diagram and using the area bounded by this limiting boundary contour as a basis, one can then obtain the local number flux per unit horizontal area for particles of that particular size in a suspension flow. In addition, if one also makes use of the velocity information from the frequency of the Doppler signal, one can obtain the number density for such particles in a suspension flow even for the case in which there exists a distribution in particle velocity. By extending this concept to small, discrete size ranges, similar results can be obtained for the flow of a suspension in which there is a distribution of the particle size and within each small, discrete size range, there is a distribution of particle velocity.

INSTRUMENTATION DEVELOPMENT

For the reasons discussed above, the block-off time for each individual particle must be measured if and only if an acceptable Doppler signal follows at the end of the blocking in the present optical arrangement. Hence a scheme making use of the various signal processors was devised for the validation of the Doppler signal. After such validation, information on the block-off time, the velocity and the amplitude of Doppler signal for each particle was recorded. The velocity information was easily obtained from the Doppler signal frequency in digital form by using a counter signal processor (T.S.I. Model 1990). The Doppler signal amplitude was detected by first rectifying the signal using a custom-built linear rectifier, passing the rectified signal through a low-pass filter to obtain the envelope of the signal and finally using a peak detector.

The block-off time of the reference beam for the particle was obtained by using the output of the photo diode with the proper selection of the threshold level of voltage for the determination of the starting and ending of the blockage. A typical photo-diode output together with the accompanying Doppler signal on the same time scale is shown in the oscilloscope trace of figure 4. Using a high-speed amplifier and a comparator, a rectangular pulse, the width of which was proportional to the block-off time, was obtained. The width of this rectangular pulse was then measured using a 5-MHz oscillator (Bailey Model TCCO-26LA) and a 20-bit digital counter using integrated circuits (74LS93). Thus all the required parameters were obtained in the digital form.

COMPUTER INTERFACES

For the storage, processing and analysis of data, a PDP-11/34 mini-computer was used. Custom designed computer interfaces (T.S.I. Models 1998-D-1, 1998-S and 1998-Y) were used to interface the aforementioned electronic circuits to the PDP-11/34 computer interface (DR-11B). Another custom-built electronic circuit was used to validate the signals. The velocity information from the counter signal processor and the Doppler signal amplitude information from the signal peak amplitude detector circuit were latched to produce an output only when a blocking was immediately followed by a valid Doppler signal. For signals from each particle which satisfied the aforementioned validation requirements, the four pieces of digital data, viz. (a) the number of cycles N selected for the validation of the the Doppler signal, (b) the time measured for the selected N number of cycles of the Doppler signal, (c) the block-off time, and (d) the Doppler signal amplitude were read into the mini computer. These data were stored in the memory of a hard disc (RK-05). The data acquisition system had been so automated that it was possible to collect as many data points as required under software control. The instrumentation block diagram for signal processing and data acquisition is illustrated in figure 5.

PROCEDURE AND RESULTS OF VALIDATION EXPERIMENTS

For more positive control of the location of the particle's trajectory relative to that of the optical measuring volume, the idea of attaching the particle to a vertical rotating platform was

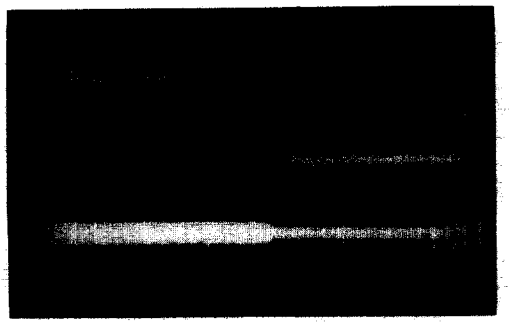

Figure 4. Photo diode output and Doppler signal.

adopted. Stainless steel balls from ball bearings of a total of six different sizes ranging from 1.588 mm to 6.530 mm in diameter with a sphericity of 1.27 μ were used. The steel ball was rigidly attached to the end of a large vertical rotating disc driven by a variable speed motor. The disc was rotated in such a direction that the ball would periodically move vertically upward on passing across the optical measuring volume. The optical measuring volume was then two-dimensionally traversed in the horizontal plane to reach an optimum location at which the amplitude of the Doppler signal from the photo multiplier tube attains a maxima. The maximum Doppler signal amplitudes so measured for the six sizes of steel balls were plotted against the size of the ball as shown in figure 6. Equal Doppler signal amplitude contours for the same steel ball were then mapped out by traversing the optical measuring volume over a more extended area in the horizontal plane. The same procedure was applied to all six sizes of steel balls. a sample scattering diagram containing such equal Doppler signal amplitude contours for one of the steel balls is shown in the sketch of figure 7. The diameter of the steel ball obtained from the block-off time measurement from the photo diode is compared with direct micrometer measurement of the diameter of the steel ball as shown in the plot of figure 8. The accuracy has

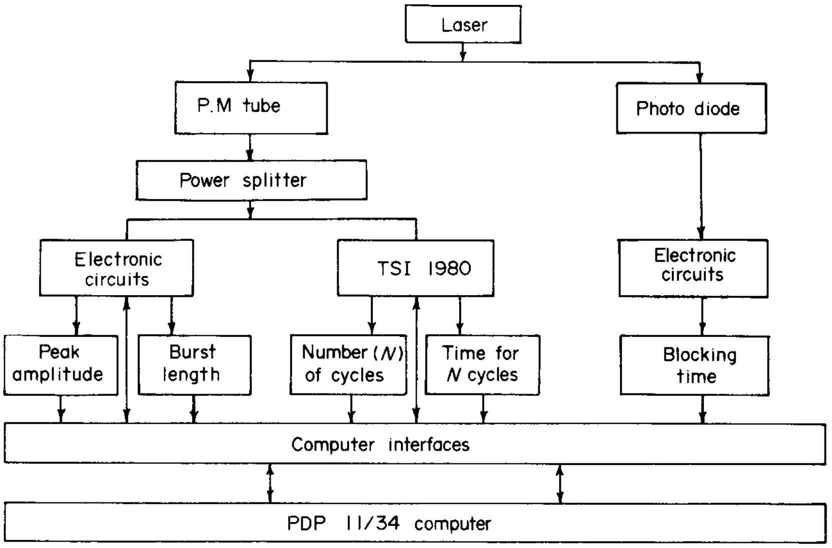

Figure 5. Instrumentation block diagram.

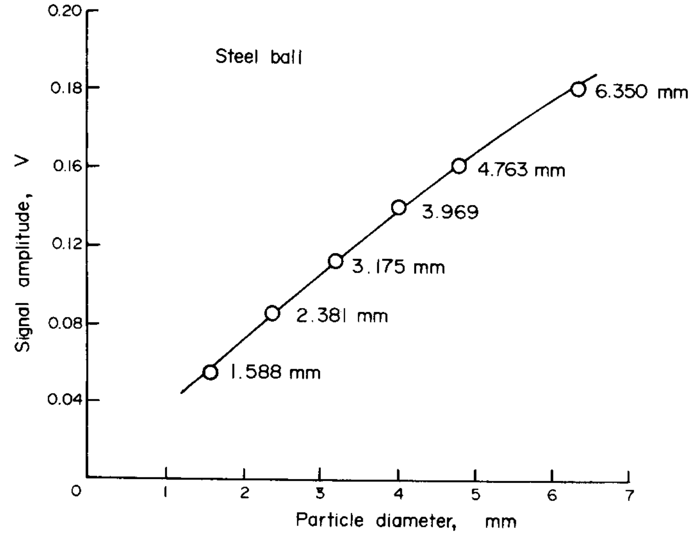

Figure 6. Doppler signal amplitude vs size (steel ball).

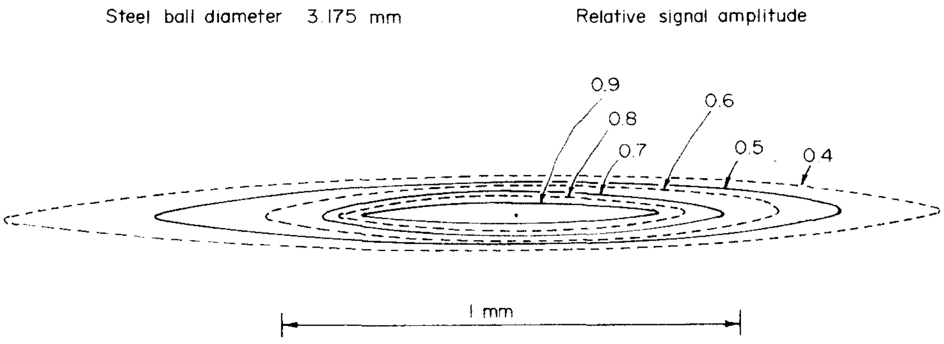

Figure 7. Sample scattering diagram.

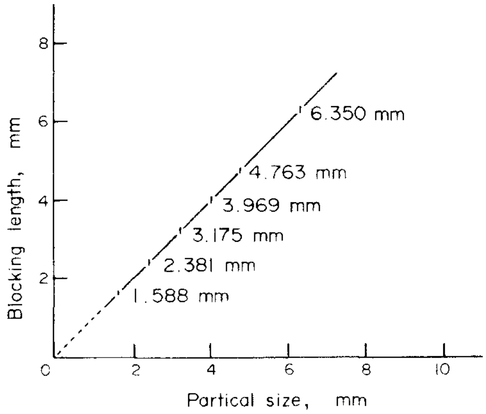

Figure 8. Blocking length against measured size (steel ball).

been found to be within 2 per cent. Next, water droplets of a controlled size from a droplet generator were consecutively sent upward vertically by air flow through the optical measuring volume. Even under most careful experimental conditions, the droplets were not found to follow exactly the same path. Instead, they always showed a small horizontal spread in their trajectories. By analyzing signals from a large number of droplets, the maximum Doppler signal amplitude for droplets of that particular size was obtained. This calibration experiment using water droplets was done for a total of five droplet sizes. Close agreement was found between results of steel ball and water droplet measurements in the dependence of the relative maximum Doppler signal amplitude on the particle size. A combined plot of the normalized maximum Doppler signal amplitude for both the steel ball and the water droplet, using its value for a selected particle size of 3 mm as the respective normalizing factor, against particle size as shown in figure 9.

CONCLUSION

An optical technique using the reference-mode laser-Doppler anemometry for the *in situ* local simultaneous measurements of the size and velocity of the particles as well as the velocity of the continuous phase in the flow of a two-phase suspension with particles greater in size than the smaller dimension of the optical measuring volume has been established. The technique makes use of a relatively simple optical arrangement in which a particle's velocity is measured by the Doppler signal produced by the heterodyning of the reference beam and light scattered from the scattering beam over the scattering area on the particle's surface. Information on the particle's size is obtained from the measurement of the time of blocking of the very same reference beam, which remains stationary, by a simple photo diode.

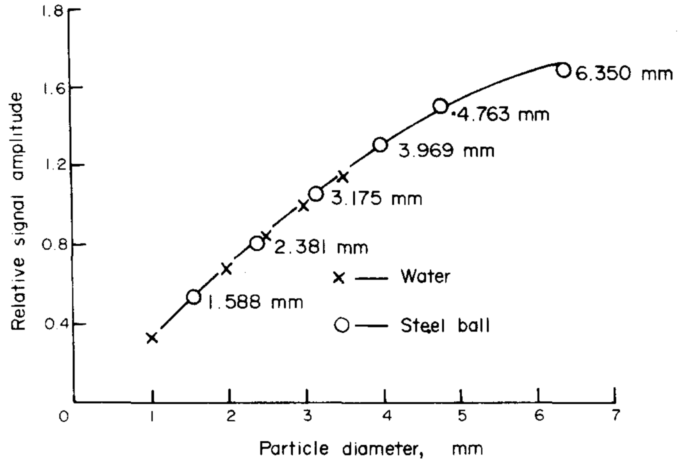

Figure 9. Doppler signal amplitude vs size (water droplet).

Inherent in the methodology of the scheme is a procedure for providing a basis for the direct measurement of the local dynamic structure of the two-phase suspension. The velocity of the continuous phase, if enough minute contaminants are contained therein to serve as tracers, can be readily measured by using exactly the same optics, thus eliminating the needs for the addition of extra optical and electronic arrangements. Furthermore, the technique is also capable of providing information on the local particle number density and velocity distributions for each size range of the particles.

The accompanying analog and digital electronics and electronic and computer interfaces are also established for providing data in the digital form for storage and analysis in a mini computer. Validation of the scheme has been accomplished by controlled experiments using stainless steel balls and water droplets of 1 mm and greater in diameter.

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