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ONE-DIMENSIONAL PARTICLE VELOCITY PROBABILITY DENSITIES MEASURED IN TURBULENT GAS-PARTICLE DUCT FLOW

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Abstract—This paper presents measurements of the axial particle velocity probability densities made with a laser Doppler velocimeter in a 7·62 cm square duct. Spherical glass beads with mean particle diameters of 44 and 214 μm were studied at mean gas velocities near 30 m/sec. The particle–gas loading ratios were less than 1, and the Reynolds numbers close to 200,000. At all test section positions measured the particle velocity probability densities were approximately Gaussian in shape. The particle velocity intensities for the 214 μm particles were significantly greater than the gas velocity intensities at the duct center. It is felt that this was primarily a consequence of the particle size distribution variance.

1. INTRODUCTION

Extensive experimental programs have been conducted on many aspects of two-phase flows, with commendable success. Useful information has been obtained about pressure drop and friction factors, carrying capacity, and gas and particle velocity distributions, although many questions still exist on the interpretation and general applicability of these results. In other areas, such as the turbulent gas–particle interaction problem, very little has been accomplished. This has been primarily due to the lack of appropriate tools to acquire meaningful experimental information. The advent of the laser Doppler velocimeter represents an opportunity to obtain, for the first time, detailed particle velocity information in many flow regimes.

This paper gives some results that were obtained using a specially designed laser Doppler velocimeter to measure one-dimensional turbulent particle velocity probability density profiles in gas–solids flows.

2. GAS SOLIDS MEASUREMENT TECHNIQUES

Numerous measurement techniques have been developed to measure both the gas and particulate phases. These techniques have often been ingenious, but the very nature of gas–solids flows makes detailed statistical determinations extremely difficult. In addition to monitoring the flow variables, one must often contend with particle electrification, particle size resolution, and particle break-up.

For measuring the steady state variables several successful techniques have been developed (Soo 1967). These have included various kinds of induced probes and external optical techniques. The probes developed so far have limited frequency response and usually distort the flow, but they are quite useful in obtaining information about the average properties of the flow field. Photographic techniques (holographic techniques are potentially useful, but data extraction is arduous) can, in principle, be used to determine particle statistics; but difficulties are generally experienced in achieving sufficient spatial and temporal resolution. In addition, these techniques are laborious, which usually precludes the acquisition of adequate data. (These techniques are, however, superior for obtaining

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density profiles because they give an absolute measurement.) Photographic techniques have the additional virtue of not disturbing the flow.

3. DEVELOPMENT OF THE LASER DOPPLER VELOCIMETER TO MEASURE TWO PHASE FLOWS

The laser Doppler velocimeter has many advantages for measuring the flow properties in gas–solids flows. Instantaneous Eulerian statistics can be readily generated, and the disturbing effects of an induced probe are eliminated. The velocity resolution is excellent (≈ 1–2%) and the spatial resolution good (≈ 5–10 particle diameters). Also, this instrument is potentially capable of measuring the flow properties of both phases simultaneously when the velocity distributions of the two phases do not overlap.

Since many of the previous applications of the laser Doppler velocimeter have depended on small contaminant material (less than 1 μm in diameter) as light scattering centers, it was logical to extrapolate the results of earlier work to the large particle sizes of interest in gas–solids flows. There are, however, unique difficulties present in measuring the velocities of large particles which prevent the direct application of this technique.

Only three previous applications of the laser Doppler velocimeter to two-phase flows are known to these authors. The first was made by James (1966). He developed a laser Doppler scheme to measure turbulent particle velocities in supersonic nozzle flow. Although many useful concepts were developed, no absolute velocity measurements could be reported because no unambiguous relationship could be found for the received signal as a function of particle velocity. The difficulty, briefly stated, is that an uncorrected laser Doppler velocimeter would generally respond preferentially in favor of large particles over small ones, and in favor of slow particles over fast ones. It is necessary to distinguish between these two effects if the technique is to function as an accurate velocity measuring device.

Lee & Einav (1971) used a laser Doppler velocimeter to measure particle–liquid velocities in laminar flow. Both phases were measured accurately because, in laminar flow, both phases are well resolved and the received Doppler signal from each phase is easily detected.

The final application was by Carlson (1973) who successfully designed a laser Doppler velocimeter without the "large particle bias". He eliminated this difficulty by developing an optical scheme that "filtered" the received optical signal so that the amplitude of the received Doppler signal was practically independent of particle size. Particle transient time distortions were corrected electronically.

All of the results reported in this paper were measured with the laser Doppler velocimeter developed by Carlson.

4. PREVIOUS GAS–PARTICLE STATISTICS MEASUREMENTS

Soo (1960) has measured the statistical properties of both the gas and particulate phases. His facility utilized a helium tracer-diffusion technique to study the gas phase turbulence, and a multiple exposure photographic technique to determine the particle intensity. The test facility was a horizontal 7.62 cm square duct. Glass beads, approximately 100 and 200 μm in diameter, were fed into an air stream that was varied from 8 to 28 m/sec. Particle–air loading ratios up to 0.06 were investigated.

Soo reported that there was no significant alteration in the gas phase turbulence due to the presence of the particulates. (Peskin & Rin (1967) detected eddy diffusivity changes at higher loading ratios.) In the central third of the duct, where the measurements were performed, it was found that the vertical particle intensity was less than the axial particle intensity. This implies that the often-used assumption of isotropy in the central core must be reconsidered. Soo felt that the vertical disparity was directly related to the gravitational influence. Although, as this paper will show, the low vertical particle intensity is subject to a more viable explanation.

Soo also found that the particle intensities were considerably greater than the appropriate gas intensity. This is, *a priori*, a very surprising result. Soo suggested that this might be a consequence of the higher gas turbulence away from the duct center; but again, as the data in this paper shows this explanation does not seem adequate. There are other possible mechanisms that will be discussed, but it is interesting to note here that Soo did not mention the role played by the particle size variance in determining the observed particle intensity. Later Soo (1965) discussed the importance of the particle variance reality but made no retrospective comments on his previous paper. Torobin & Gauvin (1961) also speculated about Soo's results but no comment was made about the role of the particle size variance.

5. EXPERIMENTAL APPARATUS

5.1 *Laser Doppler velocimeter*

Figure 1 is a photograph of the optical instrumentation used in this investigation. Figure 2 is a schematic of this equipment with the important elements labeled. In this application monochromatic light from a laser (the output power was 150 mW at 0.514 μm) was divided evenly by a beam splitter and focused into the test section. The intersection of these two beams defined the active probe volume. As a particle traversed this volume, a Gaussian enveloped cosine wave could be detected at the photomultiplier surface. The Gaussian envelope is produced by the intensity distribution in the scattering volume, and the modulating cosine function is produced by the Doppler (or interferometric) process. For the geometry shown, and a particle moving axially, the observed frequency would be simply

$$f = \frac{2u[\sin \theta/2]}{\lambda},$$

where θ is the total angle between the entrance beams in figure 2, u is the particle velocity, and λ is the wavelength of the light incident on the particle. The light that is scattered by the particle in the active probe volume is collected by the receiving optics and sent through a pinhole. The pinhole eliminates stray light to maximize the signal-to-noise ratio of the received signal. From the pinhole the light is recollimated and sent through a variable width slit and onto the active surface of a wide-band photomultiplier. The slit performs the function of acting as a particle light scattering amplitude discriminator (Carlson 1973). It assures that over a small range of particle sizes the received signal is effectively independent of particle size. This "filter" is extremely important for these studies, and it was

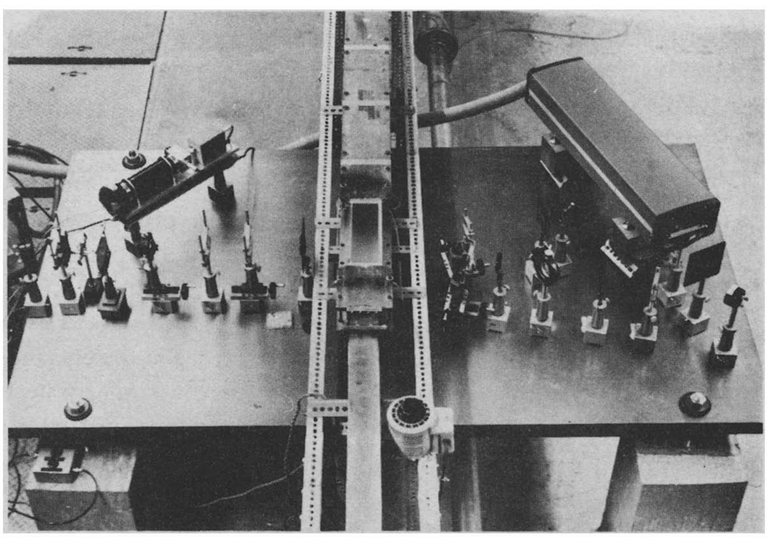

Figure 1. Photograph of the apparatus used in the investigation. The laser and entrance optics are on the right and the receiving optics and photomultiplier are on the left.

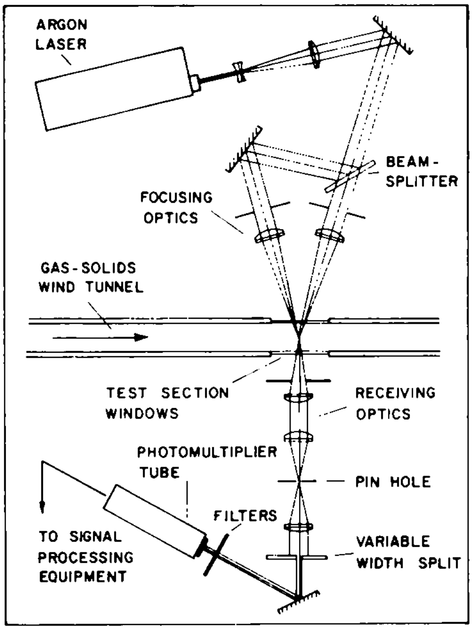

Figure 2. Schematic of the optical instrumentation used in the investigation.

necessary to determine its proper value both experimentally and analytically from the Mie light-scattering equations.

The signal detected by the photomultiplier consisted of discrete pulses of information produced by individual particles traversing the probe volume. Because of this a number count scheme was developed to count those particles moving within a finite velocity window. Basically this scheme consisted of a voltage controlled wide band superheterodyne receiver, a narrow band output filter, a detector, an amplitude discriminator, and the appropriate counting circuitry. With this system it was possible to sweep through the frequency range (the analog of the particle velocity) of interest and generate the appropriate particle statistics.

Although this system assured that the particle velocities would be recorded without bias, it did not allow the simultaneous determination of both the velocity and the size of each particle as it traversed the light scattering region. As this paper will show, the accurate determination of the turbulent particle statistics with a laser Doppler velocimeter will probably require this feature.

5.2 *Wind tunnel facility*

The results presented in this paper were carried out in the facility shown schematically in figure 3. A constant volume Roots-type blower was used to produce gas velocities up to 50 m/sec in the test section. As shown in the figure, the inlet air and particulates entered the flow loop together at atmospheric pressure. The particle feed rate was controlled by a self-monitoring gravimetric feeder, which was accurate to $\pm 1\%$, with feed rates from 10 to 200 kg/min. After the initial mixing through a series of screens in the entrance section, the solids and air were directed through a 15-m, 7.62 cm $\times$ 7.62 cm, stainless steel acceleration section to approach steady state flow conditions in the test section. The facility was designed so that 100 micron diameter particles would reach 99 % of their eventual mean velocity. The test section was a removable 7.62 cm $\times$ 7.62 cm $\times$ 25.4 cm portion with the proper optical windows. After the test section, the flow was sent through a 7.62 cm diameter return line to a cyclone separator. The separator allowed efficient particle removal down to 20 μm in diameter.

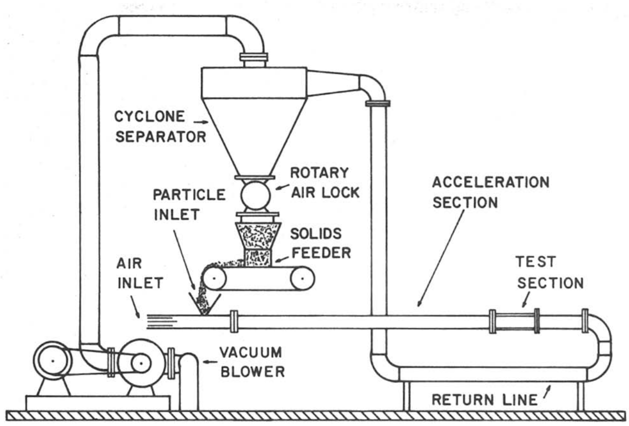

Figure 3. Schematic of the wind tunnel facility.

The air mass flow rate was obtained by measuring the velocity profile in the circular return section without particles in the flow. Since the loading ratio of the flow was low, and the blower of a constant volume design, these values were used in the calculations for the solids–gas loading ratio. Similarly the mean air velocity profiles in the test section were obtained by Pitot-static tube traverses without particles in the flow. This approach has been validated for low loading ratio flows by others (Soo 1960; Peskin & Rin 1967). This assumption was tested by making simultaneous measurements of both phases with the laser Doppler velocimeter. Small contaminate material (less than 10 μm in diameter) was used to track the mean gas velocity in the presence of the 214 μm diameter particulate phase. Complete electronic separation of the received signals could not be obtained for the 44 μm particles, so it was not possible to check the gas velocity profile for this case.

5.3 *Particulate phase*

Spherical glass beads manufactured by the 3M Corporation under the name "Superbrite" were used as the particulate phase in this investigation. The general uniformity of the beads can be seen from figure 4, which is a magnification of particles approximately 200 μm in diameter. For any particle size utilized, approximately 5–10% of the beads were not spherical.

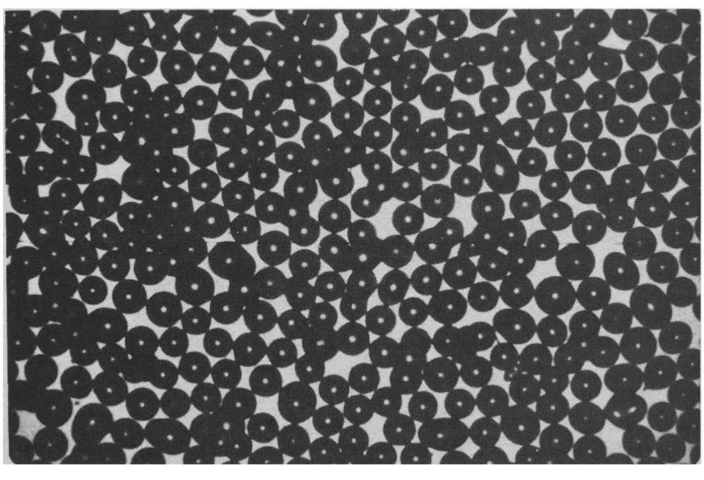

Figure 4. Glass particles approximately 200 μm in diameter. This photograph indicates the uniformity of the particles used in the investigation.

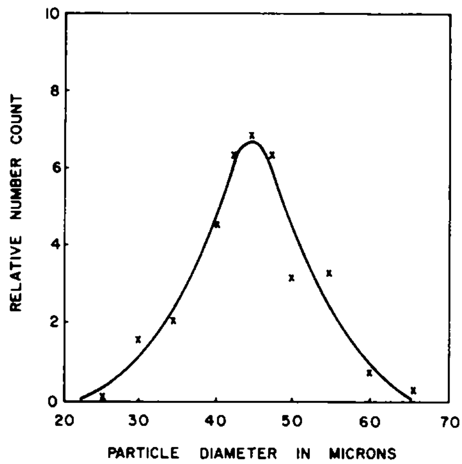

Figure 5. The particle size distribution for particles with an average diameter of 44 μm.

The bulk specific gravity of the beads was close to 1.5 and the glass had a density of 2.5 g/cm^3. The refractive index of the beads at the sodium D line was 1.52 and the beads were transparent over the visible spectrum.

Two mean particle sizes were used: 44 and 214 μm in diameter. The actual particle size distributions are shown in figures 5 and 6. These distributions were obtained by measuring a large sample of particles (about 500 samples for each distribution) on an optical comparator. Measurements were taken before, during, and after an experimental run to guarantee particle size integrity. Particle break up was not found to be a problem.

6. GAS-PARTICLE FLOW RESULTS

6.1 *Mean flow results*

The important parameters and conclusions from the two cases studied in this investigation are compiled in table 1. For both cases the particle–gas loading ratios were under one, and the Reynolds numbers close to 200,000. All the measurements were made in the vertical plane at the center of the duct, and only the axial velocity component was measured.

Figures 7 and 8 show the mean particle and mean gas velocity profiles measured in the duct. For the 214 μm diameter particles, the gas velocity at the center of the duct was obtained by both static-Pitot tube measurements, without the particles present; and by measurements with the laser Doppler velocimeter, with the particles present. The close

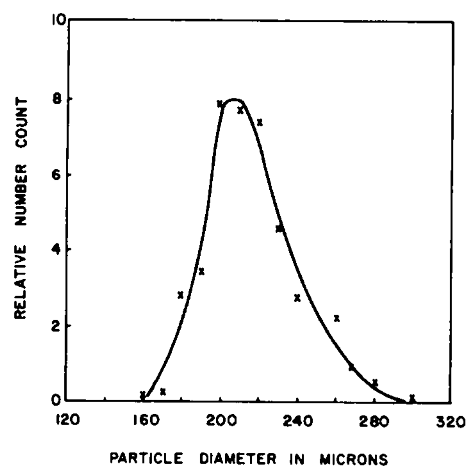

Figure 6. The particle size distribution for particles with an average diameter of 214 μm.

Table 1. A listing of the important parameters and results of this paper

Particle size diameter (μm)	44.	214.
Particle–gas loading ratio (kg of particles to kg of air)	0.81	0.56
Particle size distribution variance (μm)	4.	12.
Test section Reynolds number	194,000	202,000
Approximate q/m_p in C/kg ($\times 10^6$)	0.2	0.07
Mean gas velocity (m/sec)	37.1	39.1
Mean particle velocity in m/sec	35.6	32.3
Axial gas intensity at $Y/Y_0 = 0.5$ (m/sec)	1.00	1.08
Axial particle intensity at $Y/Y_0 = 0.5$ (m/sec)	0.82	1.95
Approximate velocity spread due to the particle size variance at $Y/Y_0 = 0.5$ (m/sec)	0.36	1.4
Average axial particle relative velocity at $Y/Y_0 = 0.5$ (m/sec)	1.4	10.2
Average axial particle Reynolds number at $Y/Y_0 = 0.5$	4.3	150.

correspondence of the two measurements substantiates the validity of the mean gas velocity profile.

Figures 7 and 8 show that the average particle relative velocity (i.e. the difference between the mean particle velocity and the mean gas velocity) is not negligible at the duct center, even for the 44 micron diameter particles. The average particle relative velocities of these figures compares well with the measurements of Kramer & Depew (1972) and confirms the dubiousness of using a Stokes-type drag law at the center of the duct. Table 1 gives the actual particle Reynolds numbers computed from the data obtained at the center of the duct.

Except at the center of the duct, the 44 μm particles track the mean gas velocity well. However, the 214 μm particles show considerable average relative velocity throughout the test section and exhibit a velocity profile that is considerably flattened. This measurement alone confirms that the large particles are not fully responsive to velocity gradients in the flow: a result that is consistent with the fact that these particles have a relaxation length comparable with the width of the test section (Soo 1969).

One can also note from figures 7 and 8 that both particle velocity profiles show a slight downward depression. At this time it is not clear whether this effect is produced by a gravitational influence, or by some vestigial inlet condition. If it were a gravitation influence alone one would expect the downward depression to be significantly less for the smaller particles (Soo 1969). Clearly the laser Doppler velocimeter can be used, in the future, to measure both the vertical particle intensity and the axial particle intensity. This measurement should help elucidate the role of the gravitational influence.

6.2 *Statistical flow results*

The measured particle velocity probability densities are shown in figures 9–12. The data points are shown as triangles in the figures, and the continuous curves are the normalized

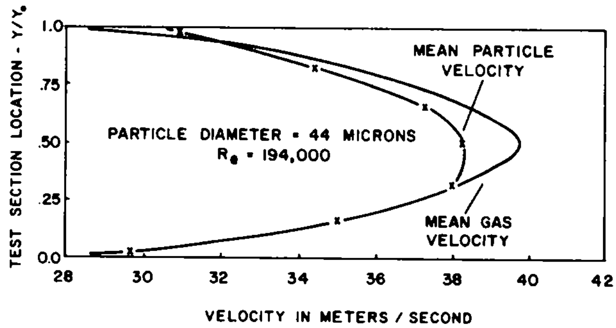

Figure 7. Mean particle and gas flow velocities in the vertical plane at the center of a 7.62 cm square duct for particles with an average diameter of 44 μm.

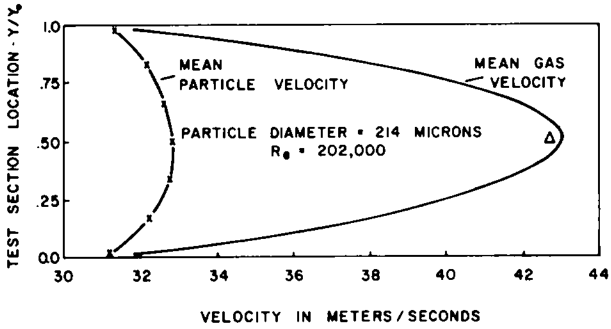

Figure 8. Mean particle and gas flow velocities in the vertical plane at the center of a 7.62 cm square duct for particles with an average diameter of 214 μm. The triangle is a measurement of the gas velocity using the L.D.V. with 10-μm diameter tracer particles.

best fit Gaussian approximations to the data points. The abscissas in the figures have been normalized by their local mean velocities U and the measured probability densities $p(u)$ have been normalized by

$$U\int_{(u/U)} p(u)\,\mathrm{d}\left(\frac{u}{U}\right)$$

to give the probability densities $P(u/U)$ shown in the figures.

All the particle velocity probability densities shown are ostensibly Gaussian in shape. Although this is unquestionably a consequence of both the particle size distribution and the fluid mechanics of the flow, it is impossible to distinguish the contributions due to each. More will be said about this later.

In figure 13 the particle and gas intensities have been plotted as a function of test section position. All the intensities have been normalized by their appropriate local mean velocities. For the two cases studied the air intensity profiles are practically identical.

Figure 13 indicates the phenomena previously reported by Soo; the particle intensity for the 214 μm diameter particles at the duct center is greater than the air intensity at the same position. In fully developed flow one might expect the opposite result, because the particle motion is a consequence of the gas turbulence. Only in the limiting case of molecular sized particles can the particles fully realize the gas intensity. Increases in the size and/or density of the individual particles should result in a decrease in the particulate motion. For enclosed flows the problem is complicated by other factors; the particles may carry an electrostatic charge, the particles have a finite size distribution, the physical boundaries cause large velocity gradients and wall interaction effects, and the particles can have relaxation times comparable with the lateral test section dimensions. Kau (1972) in considering numerical simulation of gas-solid channel flow discovered the effect of flow development time and particulate boundary conditions on the statistics of the particulate phase. The simulation studies implied that particle–wall reflection conditions influence particle interactions, and also that gas velocity gradient effects have a significant influence on particle motion throughout the duct. Strong arguments can also be made for the importance of electrification in gas–solids flows (Soo 1964), but it has yet to be shown that for enclosed flows this effect would cause a net increase in the turbulent motion of the particles. For the cases presented in this paper electrification effects were not pronounced (see table 1) and the particle velocity measurements belie the argument that electrification would increase the turbulent particle motion. The 44 μm particles had a larger charge to mass ratio than

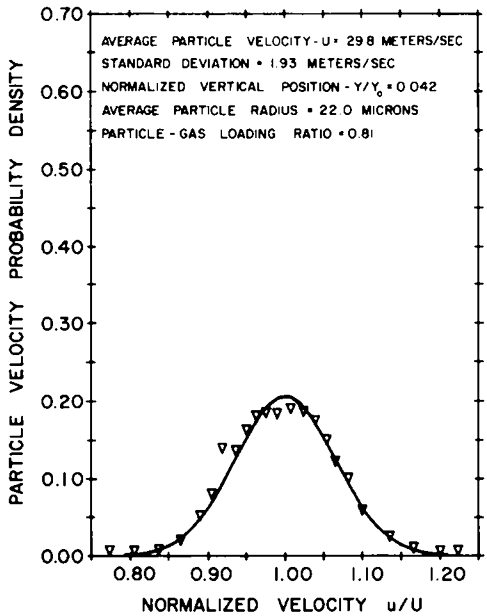

Figure 9.

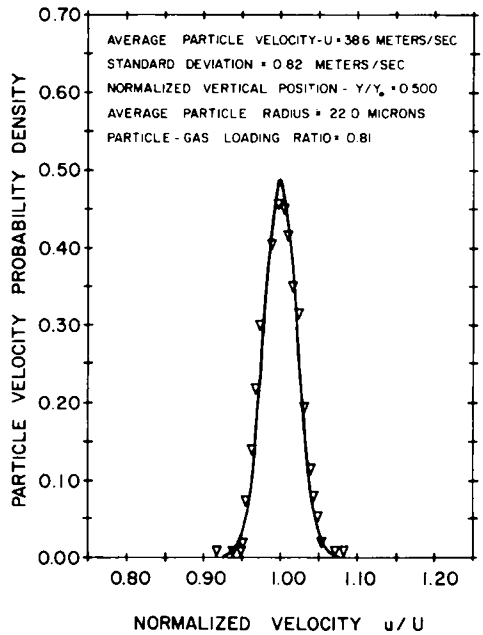

Figure 10.

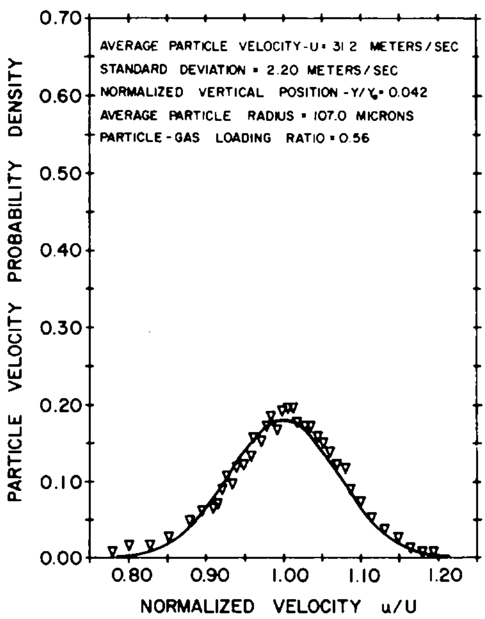

Figure 11.

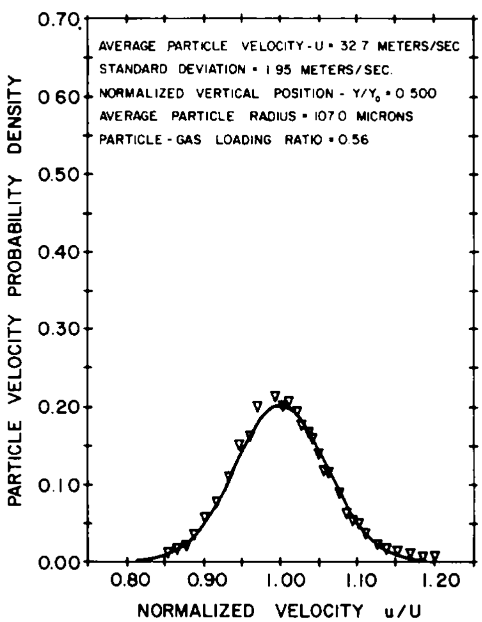

Figure 12.

Figures 9–12. Particle velocity probability densities as a function of their normalized velocity. The local mean velocity was used to normalize the velocity.

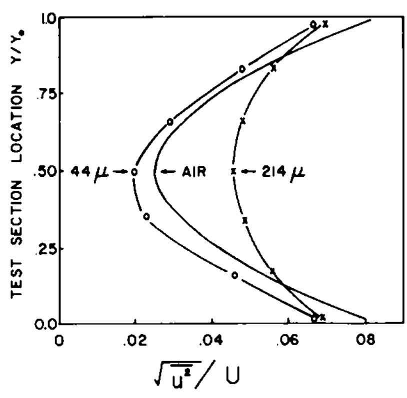

Figure 13. Particle and gas intensities relative to their local mean gas velocities. The values for the normalized gas intensity were practically identical for the two cases presented.

the 214 μm particles (and also a higher number density) and yet they exhibited a much lower turbulent intensity.

One large effect that determines the measured particle intensity which has not been given proper attention is the particle size variance. Since the average particle relative velocity increases (at any mean gas velocity) with the particle size, a particulate phase with a finite size distribution results in a measured spread in the observed velocity distribution, irrespective of the turbulence interactions. This fact is diagrammatically illustrated in figure 14 for the two cases reported in this paper. Unfortunately even an extremely well resolved particle size distribution will have a variance that is several per cent of the mean particle size. Typically the spread in particle sizes experienced in actual flows are many times this value. For these cases one would expect the effects of the particle size distribution to mask the more subtle effects mentioned previously.

An estimate can be made for the particle size variance by using the measured average relative velocity as a function of particle size at a given test section position in conjunction with the measured particle size distribution. This has been accomplished for the two cases presented in this paper, and the results are given in table 1. Even though this is a first order estimate, it is clear that the effect is significant. Also, the particle intensity broadening due

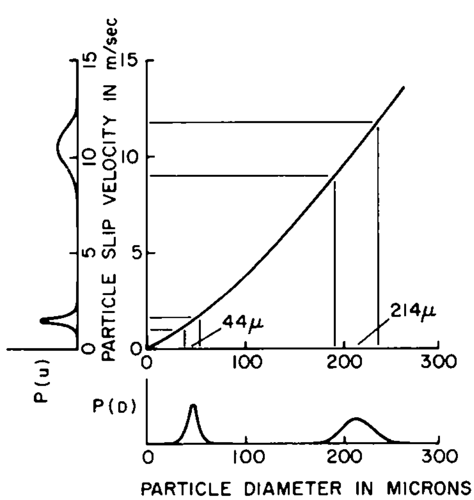

Figure 14. Qualitative representation of the consequences of a finite particle size distribution on the observed particle velocity densities. $P(D)$ is the particle size distribution density and $P(u)$ is the resultant particle velocity distribution density. The values illustrated here roughly correspond to the cases reported in this paper at the center of the text section.

to the particle size variance is proportional to the absolute spread in the particle variance. Thus, the larger particle sizes suffer more from this effect because, at a given mean particle size, the percentage spread in size is roughly the same.

This result also has consequences for the interpretation of the vertical particle turbulence. Since the particle motion is not superimposed on a mean gas velocity, the particle size variance velocity spread should be greatly reduced. This implies that the particle intensity in the vertical direction is a better indication of the particle response to the gas turbulence. Further, this result explains the measurements of Soo. For many flows the vertical particle intensity should be lower than the axial particle intensity, irrespective of the gravitational influence. Isotropy of the particle phase motion in the core of an enclosed flow would generally not exist.

Finally, this result indicates that the accurate measurement of turbulent particle velocities requires either a finely resolved distribution of particle sizes (i.e. a particle size variance of around 0.2 % for 200 μm diameter particles) or a measurement technique that can determine simultaneously the velocity and size of the particles at a given test section location with the required resolution. It is felt that the laser Doppler velocimeter is potentially capable of achieving these objectives (Carlson 1973). The far field distribution of light scattered from a particle traversing the light scattering volume of a laser Doppler velocimeter contains unambiguous information about both the particle's size and velocity.

7. CONCLUSIONS

This paper has indicated the importance of the particle size variance in determining the particle statistics in gas–solids flows. In general, the particle size variance is a major, if not the dominant, factor in determining the particle statistics. Because of this, for enclosed flows with a finite distribution of particle sizes one would expect that in general: the particle statistics are not isotropic, the deviations from isotropy increase with increasing particle size and/or density, and the radial particle intensity is less than the axial particle intensity. These conclusions are consistent with previous measured values and help to explain them.

Further, this paper has shown that the laser Doppler velocimeter can be a highly useful instrument for making detailed measurements in gas–solids flows. However, this paper also indicates that extremely careful experimental programs have to be conducted to eliminate the obfuscating properties of two-phase flows if meaningful results are to be obtained. A future paper will develop the capabilities and limitations of the laser Doppler velocimeter as they directly apply to gas–solid flows.

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Résumé—Dans cet article, on présente des mesures de densité de probabilité des composantes axiales de vitesses de particule, effectuées avec un laser Doppler dans une conduite de 7.62 cm^2 de section. Des grains de verre sphériques de 44 et 214 microns de diamètre moyen ont été observés pour des vitesses moyennes d'écoulement voisines de 30 m/s. Les rapports de charge particule–gaz étaient inférieurs à 1 et les nombres de Reynolds étaient proches de 200.000. Les probabilités de vitesse de particule avaient une forme sensiblement gaussienne en tous les points de mesure des sections d'essai. L'intensité était nettement plus grande pour les particules de 214 microns que pour le gaz au centre du canal. Il semble que ceci était principalement du à la variance de la répartition des dimensions de particule.

Auszug—Dieser Aufsatz behandelt Messungen der Wahrscheinlichkeitsdichte der axialen Teilchengeschwindigkeit, die mit einem Laser-Doppler Geschwindigkeitsmesser in einem quadratischen Kanal von 7.62 cm Kantenlaenge gemacht wurden. Kugelfoermige Glasperlen mit mittleren Teilchendurchmessern von 44 und 214 μm wurden bei mittleren Gasgeschwindigkeiten nahe 30 m/s untersucht. Die Teilchen–Gas Belastungsverhaeltnisse waren kleiner als 1, und die Reynoldsschen Zahlen lagen bei 200 000. In allen Messpunkten des Pruefabschnitts waren die Wahrscheinlichkeitsdichten der Teilchengeschwindigkeit angenaehert Gaussfoermig. Die Intensitaeten der Teilchengeschwindigkeit fuer die 214 μm Teilchen waren signifikant groesser als die Intensitaeten der Gasgeschwindigkeit in der Kanalachse. Es wird vermutet, dass dies hauptsaechlich eine Folge der Varianz der Teilchengroessenverteilung ist.

Резюме—В настоящей работе представлены результаты измерений распределения вероятностных осевых скоростей частицы, выполненные с помощью лазерного скоростемера, основанного на эффекте допплера, квадратном газоходе (со стороной сечения) размером в 7,62 см. Стеклянные шарики со средним диаметром 44 и 214 мк исследовались при скоростях газового потока, близких в среднем к 30 м/сек. Весовые пылегазовые отношения были менее единицы, а критерий Рейнольдса—близок к 200 000. Во всех исследованных сечениях измеренные рнспределения вероятностных скоростей частиц имели приблизительно гауссову форму. Плотность скоростей часиц с диаметром 214 мк были значиетльно большими, чем плотности скоростей газа в центре газохода. Предполагается, что указанное следует, главным образом, из отклонений в распределений размера частиц.