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Techniques of sizing and tracking of particles: A report on Euromech 120

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The 120th Euromech Colloquium on experimental techniques pertaining to sizing and tracking of submicron- to millimetre-sized particles suspended in fluids was held at Lyngby on 20–22 August 1979 with forty-one participants from ten countries. Twenty-seven papers were presented during the two-and-a-half day meeting. Techniques included optical and acoustical sizing and velocity measurements, tracking, sedimentation and deposition of particles in various gas and liquid flows.

1. Introduction

Small particles suspended in fluids occur in numerous flow systems in industrial equipment as well as in nature. Ideally, the experimentalist desires *in situ* measurements of size, shape, material, velocity and path of individual particles, as well as the velocity field of the continuous fluid phase. In reality not more than a few of these parameters can at present be measured simultaneously. In addition, when particles interact with bounding surfaces deposition and entrainment processes are of interest. For this purpose tracking of particles, as well as their sizing, play an important role in experimental fluid mechanics.

It was the purpose of the Colloquium to bring together research workers actively engaged in the development and use of instruments that accomplish one or several of the aforementioned objectives.

Non-interference with the flow is an invaluable virtue of a measuring instrument. Techniques employing radiation, both optical and acoustical, possess this quality and have therefore received much attention. These techniques include photography, use of closed-circuit television with advanced picture reading and video signal processing, as well as various light-scattering techniques. In regard to the latter much progess has been made during the last decade in the use of laser light, as reported in the proceedings from a number of symposia on laser-Doppler anemometry (LDA) and related topics (e.g. Copenhagen in 1975, Marseille and Purdue in 1978). The progress is due in part also to the significant advances made in rapid analog and digital electronic processing.

The importance of optical methods, often related to laser-Doppler anemometry,

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was reflected in the contributions to the Colloquium. The programme was arranged with sessions on the following topics.

Optical particle sizing.

Acoustical particle sizing.

Sizing, velocity measurements and processing.

Tracking of particles.

Sedimentation, charged particles, dust.

Only the area of optical methods was introduced by a review lecture, delivered by F. Durst (University of Karlsruhe). However, several other contributors devoted part of their time to brief surveys of their specific areas. The varied background of participants (coming from statistics, physics, electronics, biochemistry, chemical engineering, aerodynamics, hydraulics, oceanography and geology) paired with the common interest in problems associated with the properties and motion of submicron- to millimetre-sized particles was a stimulus to discussions and exchange of ideas.

The present report is organized somewhat differently from the programme in order to facilitate the discussion of related papers. Because of the considerable amount of research under way – even in Europe – and the diversity of topics presented, this report does not attempt to present reviews of current activities, but confines attention to the specific topics treated by the contributors.

2. Optical size and velocity measurements

In his review lecture on optical methods for measuring size and velocity of particles F. Durst*† outlined the optical principles of current methods aiming at single-particle detection. According to Mie-theory the scattered intensity depends on scattering angle, wavelength, polarization and intensity of the incident light, and on the size (and shape, if not spherical) and index of refraction of the particle.

Single incident beam methods detect absolute intensity, using white light (Durst & Umhauer 1976) or laser light, or intensity ratios at different scattering angles (Wittig, Hirleman & Christiansen 1978), at different directions of polarization or at different frequencies. Dual incident beam methods, serving also as fringe-type laser-Doppler anemometer for velocity measurements, detect modulation depth (Farmer 1972) or pedestal (Yule *et al.* 1977) of single-particle Doppler bursts. The dual focus velocity meter may also yield information on particle size as suggested by Lading (1975) and by Hirleman (1978). Finally, by recording the scattered intensity from a single particle at a large number of angles it is possible to deduce both its size and its index of refraction (Marshall, Parmenter & Seaver 1974). As a rule, methods based on absolute intensity measurements require calibration with streams of particles of known size. Intensity ratio methods do not in principle need calibration but in practice they do.

Durst described the application of LDA to measure velocities of large particles and an integrated optical instrument yielding velocity, size and concentration of particles in a sampled stream. The velocity of large particles may be measured with the fringe-type LDA in different ways. Light collection at a small forward-scattering angle requires use of a small collection angle to ensure coherent detection (Drain 1972;

† The papers marked with an asterisk were presented at the Colloquium.

Adrian & Orloff 1977). Light collection at a large scattering angle, however, may not require coherent detection. In the early work of Farmer (1972), who used forward scattering, a large collection angle was tacitly assumed. Based on these results it was believed that the velocity of large particles could not be measured. For flows with both very small and very large particles (drops or bubbles) two detectors were recommended, one for the small particles, detecting the forward-scattered light, and one for the large particles, detecting the back-scattered light.

The rapid variation of the monochromatic Mie-scattering functions at increasing values of the size parameter $\alpha = \pi d/\lambda$, where d denotes particle diameter and λ wavelength, gives rise to ambiguity in size determination. However, use of white light and detection at a large collecting angle centred at 90° to the incident beam tend to average out the variations. Durst described an integrated optical system based on these principles (Durst & Umhauer 1976) for which the useful size range has been extended upwards to relatively large particles ($\alpha < 50$).

A single incident beam 'multi-ratio single-particle counter' was described by J. V. Christiansen* (Technical University of Denmark). The instrument measures the scattered light in three specific annular rings corresponding to narrow detection angles centred around three forward-scattering angles (3, 6 and 9°). Using two ratios of intensities more than doubles the upper range of the size parameter for unambiguous size determination from Mie theory (to about $\alpha < 20$) as compared to earlier single-ratio detectors. The electronic processor forms ratios of integrated intensities, classifies and counts particles with speeds up to 100 m s^{-1} and rates up to 12 kHz in the 0·5–5 μm size range, and rejects signals for those outside this size range (Wittig *et al.* 1978). Decreasing Mie-scattering angles further (e.g. to 2, 4 and 6°) could extend the size range upwards to 10 μm. The application of an instrument of the same type to measure metal dust (1–10 μm) was described by Kh. Sakbani & S. Wittig* (University of Karlsruhe). The size range was expanded upwards by using rigorous Mie theory for computing several intensity ratios of a given particle size. A comparison with an impactor-type counter showed the optical counter to be superior (Wittig & Sakbani 1978).

Several presentations addressed the problem of simultaneous velocity and size measurement. A. Ungut, N. A. Chigier & A. J. Yule* (University of Sheffield) described an LDA fringe-type system for solid or liquid sprays of particles in the size range 30–240 μm and concentrations up to 10^{10} particles per m^3. The particle size is inferred from the measured mean peak amplitude of a single-particle Doppler burst. Theoretical predictions, based on geometric optics and calibration with individual particles, are used to get the functional relationship between particle size and mean peak amplitude. The choice of optical geometry is critical for unambiguous particle sizing. The scattered light is collected at a small non-zero forward-scattering angle, which on the one hand minimizes the effect of the refractive index of particles and on the other hand confines the length of the measuring volume (Ungut *et al.* 1978). Possible errors, caused by the (necessary) spatial filtering of the set-up owing to lack of knowledge about the exact particle trajectory, were discussed.

F. Durst, B. Ruck & H. Umhauer* (University of Karlsruhe) elaborated on their system for simultaneous measurement of size and velocity of single particles. The white-light size detector described above has a measuring volume that coincides with that of the LDA system. Optical measurements are generally assumed to be undisturbing to the flow under study. This implies that neither fluid nor particles are affected by the radiation. With the increasing interest in the detection of submicron particles it was pointed out that the scattering power of small particles decreases rapidly with their size. Therefore, high-intensity beams are required to detect such particles, the more so the higher their velocity. Theoretical considerations on the momentum and energy transfer to small particles of different material during passage of the measuring volume were discussed. However, for most applications the interaction appears to be negligible.

The generation of preferably monosized small particles plays an important role in LDA applications. W. J. Hiller with others* (Max-Planck-Institut, Göttingen) described the development and performance of a seeding generator for producing micron- and submicron-sized NaCl particles for LDA application to unsteady transonic flows. The recondensation of NaCl vapour in a cool gas stream produced the usual irregularly shaped and coagulation-prone crystals at low bath temperature (less than about 800 °C), but perfect spheres of nearly equal size at higher temperatures (about 900–950 °C). At high vapour superheat liquid drops form prior to their rapid solidification.

A. P. Morse and co-workers* (Imperial College) considered the special problems of LDA application in forward- and backward-scattering modes as well as the data processing required to determine the evolution of mean and r.m.s. velocity distributions in the cylinder of a model and of a real combustion engine (Morse, Whitelaw & Yianneskis 1979). Backscattering was used in the real engine, yielding Doppler signals of poor quality and data rates as low as 10–50 Hz. Two signal-processing systems were described, one based on a counter, the other on a spectrum analyser.

To measure both size and index of refraction of small metal-oxide particles (1–10 μm) A. R. Jones & M. S. Atakan* (Imperial College) employed the properties of modulation depth of a single-particle Doppler burst. At small forward-scattering angles it depends primarily on particle size and is insensitive to refractive index (Farmer 1972). At large angles it depends significantly on both parameters (Hong & Jones 1976, 1978). Sample results were presented, obtained with a set-up employing scattering angles of 3·6 and 40°.

A novel system for determining size distributions of alumina particles in rocket exhaust flows was described by M. Laug & A. Delfour* (ONERA/CERT/DERO, Toulouse Cedex). The technique is based on measuring the angular distribution of intensity of scattered light at one wavelength. A large number of small plane mirrors are fixed along an ellipse having one focal point at the measuring volume and the other at a rotating mirror. A discrete sample of the angular intensity distribution is recorded during one revolution of the latter mirror, which is inclined at 45° to transmit signals to a photomultiplier. The system functions with many particles in the measuring volume at a time, the limit being that multiple scattering is negligible. The computational procedure leading to a unique particle size distribution for a given set of angular intensities was discussed. The maximum particle size (50 μm) is dictated by the divergence of the calculations. However, if necessary the computer program can be improved.

For the calibration of particle sizers test particles or a suitably collected sample ultimately has to be absolute-sized using optical or electron microscopy. R. Kleine & F. Durst* (University of Karlsruhe) reviewed various collection methods for solid and liquid particles and described progress in the developments of an improved isokinetic dust sampler used with CuO whisker collectors. The unidirectional crystals of CuO (0·01 μm by 30 μm long) are grown on a copper-bronze net substrate by a long time (24 h) thermal oxidizing process (430 °C). Based on comparative tests with stacks of whisker collectors, it is believed that a single collector will usually withhold a representative sample distribution of solid particles.

With the increasing accessibility of measured size distributions and with their use in the modelling of suspension flows and processes such as grain sorting by currents in alluvial streams (Deigaard & Fredsøe 1978), there is a need for improved parametric representations of distributions. Since the early observations by Bagnold (1937, 1941) on particle sizes of wind-blown desert sands, suggesting exponentially decreasing tails in distributions, there have in recent years been a number of investigations of the properties of these distributions. O. Barndorff-Nielsen* (Århus University) showed how a large class of statistical phenomena appears to be well approximated by a hyperbola in a log–log plot of the probability density function (Barndorff-Nielsen 1977, 1979). The logarithmic-hyperbolic distribution involves four parameters, the two slopes of asymptotes, the location and the scale. The possible physical applicability of this distribution function may be related to the property that it is the limit of sums of independent random variables (Halgreen 1977; Shanbhag & Sreehari 1979). It can also be represented as a mixture of normal distributions (Barndorff-Nielsen 1979).

We conclude this section by summarizing some characteristics and the state of the optical sizers using light scattering. Other optical techniques, such as beam interruption and holography, were not discussed (see Azzopardi 1979 for a recent review of these and other techniques suitable primarily for sizing drops and particles greater than about 10 μm).

Two important parameters to consider in selecting a technique are particle size and concentration. One may distinguish roughly between particles that are small (0·2–10 μm) and large (50–1000 μm); and between the single particle, a low and a high concentration of suspended particles. From diffraction theory (see, for example, Kerker 1969) one may show approximately that the concentration is low if the mean particle spacing is much larger than d^2/λ, where $d > \lambda$ is assumed. For large particles this condition may be relaxed to requiring a low probability of having more than one particle in the beam path.

Recalling the previously described techniques for small particles (Durst *et al.**, Christiansen*, Sakbani & Wittig*) and large particles (Ungut *et al.**) the theoretical and experimental problems are largely solved for these cases, involving the scattering from a single particle in the measuring volume and a comparatively narrow size range. The same is true for the technique of Laug & Delfour* for small particles at low concentration, involving the scattering from many particles in the measuring volume, although results here depend on the possible relative motion of particles. The modulation depth (visibility) technique of Jones & Atakan* for single small particles is particularly sensitive to whether coherence or incoherence is ensured in the detected signal. The experimental uncertainty of the foregoing methods, although rarely given, is estimated to be of the order of 10–50 %. Particle calibration and drift of photomultipliers in absolute intensity methods here play an important role.

For all cases of high concentration of suspended particles there are many unsolved problems, e.g. the poor definition of the measuring volume. Results from optical turbulence theory may here become applicable.

3. Acoustical size and velocity measurements

In analogy to light-scattering methods the scattering of sound in liquids may be used to count or size larger particles (> 30 μm) or measure their velocity. Amongst major difficulties are the formation of highly directional (focused) beams, the low signal and signal-to-noise ratios, the temperature and salinity sensitivity. Also, if gas bubbles are not removed, e.g. by centrifuging, they may erroneously be detected as solid particles. J.-Å. Langeland & H. Engan* (The Norwegian Institue of Technology, Trondheim) reported on backscattered pulse shape analysis as a means of discrimination, the reflected pulse train being inverted for the case of a bubble at frequencies above its resonance. Other methods of discrimination include differences in frequency response and scattering functions (Bowman, Senior & Uslenghi 1969; Medwin 1977).

Discrimination between large particles of sand (25–250 μm) and small particles of silt (< 25 μm) is reasonably ensured by choice of a high-frequency sound (> 2 MHz). A mobile ultrasonic Doppler scatterometer (Jansen 1979) for *in situ* measurement of concentration and one or two velocity components of suspended sand particles in the ocean was described by R. H. J. Jansen* (Delft Hydraulics Laboratory). The measuring volume is formed in the far field of intersecting highly directional piezoelectric transducers. One serves transmission (4·5 MHz) and two reception. A novel signal-processing system is incorporated. The actual demodulation of the Doppler signals is performed with phase-lock loops. Quadrature detection is used for resolving the sign of the velocity. Each Doppler frequency yields a horizontal velocity component while the short-time average of amplitude squared is proportional (for a given particle size) to concentration. The latter therefore requires careful calibration with particles of representative size distributions. However, the sensitivity to particle size diminishes with increasing signal frequency, suggesting use of higher frequency (8 MHz), on which results were also reported.

Acoustical techniques seem to be less developed than their optical counterparts. It may therefore be relevant to mention a few facts that could encourage further interest in acoustical techniques: (i) the relative refractive index can be much higher for an acoustical wave than for an optical wave, thus providing for a much stronger interaction; (ii) an acoustical wave can penetrate conductors, optical waves cannot; (iii) the output of an acoustical detector is in general proportional to the amplitude of the signal, while an optical detector can only give the intensity (this difference is essential for the design of Doppler systems); (iv) the price of an acoustical system is often lower than that of an equivalent optical system serving the same purpose.

4. Tracking

Flow visualization has long been an important experimental tool in studying the motion of fluids and particles suspended in fluids. When perfected with the use of advanced two- and three-dimensional photographic recording and analysing equipment accurate quantitative data may be produced with moderate labour. The same applies, and perhaps to a greater degree, in regard to the more recently developed techniques of closed-circuit television with video-recording and subsequent electronic signal analysis.

Stereo photogrammetry was used by B. M. Sumer & R. Deigaard* (Technical

University of Denmark) in their experimental work on particle motions in a turbulent open-channel flow. Their objective was to get an insight into the mechanics of suspension of heavy particles near the channel bottom, keeping in mind the particular application to sediment suspension in rivers. They recorded paths of individual particles in three dimensions and time, near a smooth and a rough bottom, using a stereo photogrammetric camera system coupled with a stroboscope (see the following paragraph). Various characteristics of particle motion were obtained from the recorded data, showing that the three-dimensional longitudinal and transverse motions of suspended particles near the bottom are in accord with the bursting process occuring near the smooth wall of a turbulent boundary layer. This experimental evidence has provided further support for the mechanism of particle suspension proposed in an earlier study (Sumer & Oguz 1978). Regarding the rough bottom case, the relevant findings suggested that a similar mechanism seems to occur but with a more violent appearance.

O. Jacobi & O. Mærsk-Møller* (Technical University of Denmark) described the theory and apparatus of stereo photogrammetric tracking of a moving particle, with particular reference to the foregoing work. Although photogrammetry has been developed especially for land surveying from aerial photographs it is equally useful for laboratory experiments. Two cameras placed in different locations take simultaneous pictures of the object point and a few control points with accurately known positions in the object space. The three co-ordinates of the object point are determined by calculating the intersection between the two rays going from the cameras to the point. This calculation is done by a computer feed with the data read off the pictures in a stereo comparator. The particular technique employed in recording the particle paths in Sumer & Deigaard's* work was as follows. A stroboscope was activated, illuminating a single suspended particle from the top of the flume and following it throughout its path. The two special cameras viewed the working section through the glass side wall of the flume with shutters open during the passage of the particle. The particle path was therefore pictured as a series of dots on each photographic film, the time interval between the dots being the reciprocal of the flash frequency of the stroboscope. The path data on films were reduced to the three-dimensional co-ordinates of the particle in the object space by the computing method developed at the Institute of Landsurvey & Photogrammetry (Technical University of Denmark). The relative accuracy of photogrammetry is about 5×10^{-5}, corresponding to 0·12 mm on particle position in the longitudinal plane and 0·28 mm in the transverse direction for the set-up described (a 0·3 m deep by 0·3 m wide flume viewed at a distance of 3 m).

A. Giovannini, P. Hebrard & G. Toulouse* (ONERA/CETR/DERMES, Toulouse Cedex) reported on the use of closed-circuit television to study fluid-dynamical aspects of the combustion process in a hydraulic, 'cold' model of a combustion chamber. With illumination of a thin plane slice of the flow field the motion of an added neutrally buoyant tracer (either a fluorescing dye or small Perspex particles) was viewed by a television camera. The video signal was processed to obtain particle velocities and the probability density function of residence time of particles in the chamber. These results were used to develop a model of the flow field in the primary zone of a combustion chamber, based on a combination of the plug flow reactor and the perfectly stirred reactor concepts. Model calculations were shown to compare well with experimental results, both for the cold flow model and for actual combustion conditions. Reference was made to other research on flow modelling (Hebrard, Magre & Collin 1978).

Closed-circuit television with video signal analysis was also used by M. Alquier & J. F. Alquier* (E.N.S.E.E.I.H.T., Toulouse Cedex) to study the statistics of the positions of solid particles in a pipe flow. In the experimental system a thin, cross-sectional plane slice of the pipe was illuminated. This object plane was viewed by a television camera through a periscope placed in the pipe downstream, while single particles were periodically introduced into the flow upstream of the object plane. Analysis of the video signal yielded directly the co-ordinates of each particle in the cross-section of the object plane. This data was plotted and analysed statistically to describe particle distributions in the flow. As the investigation is at an early stage no conclusive results were given, but the planned extension of the experimental technique to detect the successive streamwise positions of a single particle was discussed. The technique appears to be valuable for future comparison with the results of the series of paper by Batchelor, Binnie, Phillips and Barnard (see, for example, Barnard & Binnie 1963).

The related demixing problem of transverse drift towards equilibrium positions of spherical particles in low-Reynolds-number shear flows (see Cox & Mason 1971 for a review) was studied by G. E. A. Meier and co-workers* (Max-Planck-Institut Göttingen), using LDA. The fringes of the measuring volume covered the full width (0·1–0·5 mm) of the parallel plate, developed Poiseuille flow of water seeded with 2 μm polystyrene spheres. The recorded velocity probability distribution function was mapped into the corresponding function for particle position on the assumption of a symmetrical parabolic velocity profile. A variety of nonuniform particle concentration distributions ensued over the Reynolds number range 0·1–100 studied, with several peaks at the higher range.

5. Sedimentation, suspensions, charged particles

The determination of the fall velocity of sediment particles is a basic problem in the analysis of natural processes involving sediment transport. Two papers were devoted specifically to this problem.

H. J. Geldof & R. E. Slot* (Delft University of Technology), gave a thorough discussion of the practical problems involved in measuring fall velocities by settling-tube analysis. Particular emphasis was given to the possible sources of error associated with sample introduction, wall effects, concentration effects and detection of the time of arrival of the particles at the bottom of the settling tube. Existing settling-tube systems for sand samples were discussed and a new type developed at Delft University of Technology (Slot & Geldof 1979) was described in some detail, including devices intended to minimize the instrumentation errors.

In order to study the influence of grain characteristic shape on size determination B. B. Willetts* (University of Aberdeen) adopted elutriation, i.e. fall velocity as determined by position in a vertical diffuser, as the primary means of sorting a large sample from a parent population into subsets with chosen demarcation sizes. Other techniques are available (fall velocity in water, sieving) and one of the results was that each technique is influenced differently by grain shape, so that for chosen demarcation sizes each technique produces a slightly different subset from the same parent population. Willetts described an extensive research programme using elutriation, where each cut-off point is determined by comparison with a volumetric size determination. Shape determination is then made for each fraction. Preliminary results were reported and discussed.

A. J. Rowe* (University of Leicester) discussed the viscous flow and sedimentation of concentrated dispersions of particles. While the hydrodynamic properties (effective viscosity, sedimentation) of dispersions of particles in fluids are well described at very high particle dilution, no theory has proved adequate at real (finite) particle concentrations, as they occur in many fields, for instance in biochemistry. Referring to a recent paper (Rowe 1977), which gives a first part of a theory describing higher concentrations, Rowe sketched an extension of this theory, resulting in an equation which predicts the high-shear viscosity of latex spheres over the entire concentration range in case of Newtonian flow. The comparison with available empirical results looks promising.

G. Kullenberg* (University of Copenhagen) reported on the studies of suspended matter in the sea using optical techniques. The distribution of suspended matter in various areas of the ocean can in some cases be used as one characteristic of water masses. Examples of observations from oceanic frontal zones and upwelling areas were used to illustrate the tracking of water masses and suspended matter (Kullenberg 1978*a*). Light-scattering observations, including observations of polarization characteristics, in combination with chemical studies can be used to study the size distribution of the suspended matter in the sea. The particle light scattering was also used to study the small-scale field of motion in boundary layers in the sea by means of LDA (Kullenberg 1978*b*).

L. Rákóczi* (Budapest) reported on measuring problems and recent results of an extensive research project concerning selective erosion and deposition of sediment. The basic problem is the progressive pollution of Hungarian rivers carrying, e.g., heavy metals attached to suspended particles or to the bottom sediment. The sandy gravel bed of the River Sajó is selectively eroded, the finest particles being washed out and transported in suspension, while the coarser fractions are carried away as bed load. These processes were simulated in the laboratory under controlled conditions using a special suspended sediment sampler and a photo-optical concentration gauge-recorder.

Detailed investigations were carried out with a moving bed consisting of various sand-gravel mixtures. The effects of grain size composition on the entrainment of selected finer fractions were studied, using a luminescent tracing technique (Rákóczi 1975).

The rate at which particles impact the wall is an important parameter in the modelling of turbulent suspension flows. J. Wildi* (Eidgenössische Technische Hochschule, Zürich) measured deposition rates and size distributions (4–30 μm) of drops from vertical air–water mist flow at pipe Reynolds numbers from 5000 to 20000 by photomicroscopy of the deposits on the silicone oil film on a flush wall-mounted plate. The plate was slowly rotated to keep a uniform film during a measurement. Measured deposition rates increased with the dimensionless particle relaxation time $\tau = t_p u_*^2/\nu$ in the range 0·4–20, where t_p denotes the usual particle relaxation time for momentum exchange. The study falls within the inertia and impaction ranges for particle transport near a wall (Gudmundsson & Bolt 1977).

Small particles in a carrier gas are used in nuclear-physics experiments to capture recoil atoms or molecules from nuclear reactions for later analysis, and thus prevent their diffusion to walls. As each recoil species can be recognized by its radioactive-decay properties one is able to trace the path of the carrier particles in their flow from the reaction chamber through capillary tubes and possible deposition there. A. J. Hautojärvi and co-workers* (Max-Planck-Institut, Göttingen) reported on measured transmission efficiencies of particles in laminar flow through capillary tubes as a function of particle size and temperature.

In air filtration processes velocity, size, angle of impact and material properties of small solid particles determine whether they adhere when impacting in the solid substrate. To measure the probability of adhesion and coefficient of restitution J. I. T. Stenhouse & G. P. Broom* (Loughborough University of Technology) dropped mono-sized glass beads (4·7, 8·6 and 11 μm) onto the flat edge of a slowly rotating disk and recorded the events by high-speed ciné photography through a microscope (0·5 × 0·3mm viewing field). The particle impact velocity was varied by regulating the degree of vacuum to which the system was subjected. The probability of particle adhesion becomes greater for smaller impact velocities, for smaller particle sizes, for greater values of impact angle and for greater values of the restitution coefficient.

In the foregoing study electrostatic-charge effects were minimized by ionizing radiation. Many applications in particle technology, however, expressly take advantage of electrical-charge effects, e.g. electrostatic precipitation for gas purification, electrostatic dry powder coating followed by fusing in an oven to replace conventional wet spray painting. Powder coating is characterized by small loss of powder in the application phase, the loss can be collected and recycled, and health hazards are diminished.

A. G. Bailey* (University of Southampton) described two projects undertaken by the Applied Electrostatics Research Group at Southampton, which is a centre with international participation for this kind of research. LDA and high-speed photography is used to study charged particle behaviour from powder gun to target including adhesion and sputtering-off processes due to back ionization. In a more fundamental study of electrophoretic and dielectrophoretic effects single particles in liquids are suspended in the non-uniform electrical field formed between a ring-shaped and a plate electrode, and dielectric and surface properties of particles can be inferred. The technique will enable the current throries of the electrical double layer to be improved. Furthermore, the technique permits the suspension of a single bubble in a liquid.

6. Concluding remarks

Although no entirely new techniques were presented at the meeting there was ample evidence of progress in the refinement of methods as well as ingenuity in their application. The relatively few contributions in each of the many different areas neither warrant an attempt to review each area, nor do they permit general conclusions to be drawn (beyond those already given in each section).

It is possible, however, to suggest some needs for future work. Regarding particle sizing by light-scattering methods there is an obvious need to improve the accuracy and to extend size ranges for each method, notably to cover the important intermediate size range c. 5–100 μm by a single instrument. Also, calibration of particle sizers remains a practical problem so far without a ready solution. The even more difficult problem of shape determination of particles may also deserve more attention in the future. It is already in use, for example, in a qualitative sense for the detection of sickle cells (Bessis & Mohandas 1977).

Most presentations dealt with instruments constructed for laboratory use, often requiring very elaborate supporting equipment. However, a few instruments applicable for field use were described. There is a need for further development of such instruments, for example for the study of sediment and other moving objects in oceans and rivers.

Also, it is recognized that a number of important topics were not covered at the Colloquium. Holography, for example, is a powerful tool for recording the diffraction pattern of complex three-dimensional structures, and thus applicable for determination of the shape of particles that are not too small. Particle sizing in remote sensing, which must rely on backscattering using several wavelengths, is an important topic in experimental meteorology. It was the subject of several papers at the recent Ninth International Laser Radar Conference in Munich, July 1979.

REFERENCES

ADRIAN, R. J. & ORLOFF, K. L. 1977 Laser anemometer signals: visibility characteristics and application to particle sizing. *Appl. Optics* **16**, 677.

ALQUIER, M. & ALQUIER, J. F.* Automatic detection of successive positions of solid particles in suspension by using closed-circuit television.

AZZOPARDI, B. J. 1979 Measurement of drop sizes. *Int. J. Heat Mass Transfer* **22**, 1245–1279.

BAGNOLD, R. A. 1937 The size-grading of sand by wind. *Proc. Roy. Soc.* A **163**, 250–264.

BAGNOLD, R. A. 1941 *The Physics of Blown Sands and Desert Dunes*. Methuen.

BAILEY, A. G.* Research of charged particle dynamics.

BARNARD, B. J. S. & BINNIE, A. M. 1963 The vertical diffusivity and mean velocity of particles in a horizontal water pipe. *J. Fluid Mech.* **15**, 35–48.

BARNDORFF-NIELSEN, O.* Exponentially decreasing distributions.

BARNDORFF-NIELSEN, O. 1977 Exponentially decreasing distributions for the logarithm of particle size. *Proc. Roy. Soc.* A **353**, 401–419.

BARNDORFF-NIELSEN, O. 1979 Models for non-Gaussian variation with applications to turbulence. *Proc. Roy. Soc.* A **368**, 501–520.

BESSIS, M. & MOHANDAS, N. 1977 Laser diffraction patterns of sickle cells in fluid shear fields. *Blood Cells* **3**, 229–239.

BOWMAN, J. J., SENIOR, T. A. B. & USLENGHI, P. L. E. 1969 *Electromagnetic and Acoustic Scattering by Simple Shapes*. North Holland.

CHRISTIANSEN, J. V.* A multi-ratio single-particle counter (MRSPC).

COX, R. G. & MASON, S. G. 1971 Suspended particles in fluid flow through tubes. *Ann. Rev. Fluid Mech.* **3**, 291–316.

DEIGAARD, R. & FREDSØE, J. 1978 Longitudinal grain sorting by current in alluvial streams. *Nordic Hydrology* **9**, 7–16.

DRAIN, L. E. 1972 Coherent and non-coherent methods in optical beat velocity measurements. *J. Phys.* D, *Appl. Phys.* **5**, 481–495.

DURST, F.* Optical techniques to measure particle velocities and other particle properties.

DURST, F., RUCK, B. & UMHAUER, H.* Combined measurements of particle size, particle velocity and particle concentration by an integrated optical instrument.

DURST, F. & UMHAUER, H. 1976 Local measurements of particle velocity, size distribution and concentration with a combined laser Doppler particle sizing system. In *Proc. LDA-Symp. Copenhagen* 1975, P.O. Box 121, DK-2740 Skovlunde, Denmark.

FARMER, W. M. 1972 Measurements of particle size, number density and velocity using a laser interferometer. *Appl. Optics* **11**, 2603–2612.

GELDOF, H. J. & SLOT, R. E.* Settling-tube analysis of sand.

GIOVANNINI, A., HEBRARD, P. & TOULOUSE, G.* Quantitative results of flow visualization by treatment of video signal.

GUDMUNDSSON, J. S. & BOLT, T. R. 1977 Particle diffusivity in turbulent pipe flow. *J. Aerosol Sci.* **8**, 317–319.

HALGREEN, C. 1977 Self-decomposability of the generalized inverse Gaussian and hyperbolic distributions. *Z. WahrscheinlTheorie verw. Geb.* **47**, 13–18.

HAUTOJÄRVI, A. J., HILLER, W. J., DORNHÖFER, H. & SCHMIDT-OTT, W.-D.* Transport and separation of radioactive nuclei by aerosol–gas mixtures.

HEBRARD, P., MAGRE, PH. & COLLIN, G. 1978 Analyse et modélisation de l'écoulement dans un foyer de turbomachine. *La Recherche Aérosp.* **5**.

HILLER, W. J., ALBERS, M., BECKER, F., MEIER, G. E. A. & SCHMIDT, M.* Generation and measurement of scattering crystals in LDA.

HIRLEMAN, E. D. 1978 Laser technique for simultaneous particle-size and -velocity measurements. *Optics Lett.* **3**, 19–21.

HONG, N. S. & JONES, A. R. 1976 Light scattering by particles in laser–Doppler velocimeter using Mie-theory. *Appl. Optics* **15**, 2951–2953.

HONG, N. S. & JONES, A. R. 1978 Some aspects of light scattering in laser-fringe anemometers. *J. Phys.* D, *Appl. Phys.* **11**, 1963–1967.

JACOBI, O. & MÆRSK-MØLLER, O.* Photogrammetric tracking of a particle in running water.

JANSEN, R. H. J.* The determination of concentration, velocity and direction of suspended sediment.

JANSEN, R. H. J. 1979 An ultrasonic Doppler scatterometer for measuring suspended sand transport. In *Proc. Ultrasonics Int.* 79 *Conf., Graz, Austria.* IPC Science and Technology.

JONES, A. R. & ATAKAN, M. S.* Refractive index measurement by light scattering in a laser-fringe anemometer.

KERKER, M. 1969 *The Scattering of Light and other Electronic Radiation.* Academic.

KLEINE, R. & DURST, F.* Isokinetic dust probing and absolute particle sizing with copper-oxide whisker collectors.

KULLENBERG, G.* Studies of suspended matter in the sea using optical techniques.

KULLENBERG, G. 1978*a* Light scattering observations in frontal zones. *J. Geophys. Res.* **83**, 4683.

KULLENBERG, G. 1978*b* Preliminary results of near bottom current measurements in the Bothnian sea. *Havsforskningsinst. Skrift* **244**, 42–51.

LADING, L. 1975 Analysis of a laser correlation anemometer. In *Turbulence in Liquids* (ed. G. K. Patterson & J. L. Zakin), pp. 205–219. University of Missouri.

LANGELAND, J.-Å. & ENGAN, H.* An acoustic particle-sizing system with discriminating properties.

LAUG, M. & DELFOUR, A.* Particle sizing by Mie scattering.

MARSHALL, T. R., PARMENTER, C. S. & SEAVER, M. 1974 360° scattering diagrams from individual aerosols in a flowing stream. In *Aerosol Measurements*, NBS Special Publication no. 412. Washington National Bureau of Standards.

MEDWIN, H. 1977 Counting bubbles acoustically. *Ultrasonics* **15**, 7–13.

MEIER, G. E. A., HEERTSCH, A., HILLER, W. J. & PALKA, S.* LDA investigation of demixing processes in plane Hagen–Poisseuille microflows.

MORSE, A., CRABB, D., DURÃO, D. F. G., LAKER, J., WHITELAW, J. H. & YIANNESKIS, M.* Two signal-processing arrangements for in-cylinder velocity measurements.

MORSE, A. P., WHITELAW, J. H. & YIANNESKIS, M. 1979 Turbulent flow measurements by laser-Doppler anemometry in motored piston-cylinder assemblies. *Trans. A.S.M.E.* I, *J. Fluids Engng* **101**, 208–216.

RÁKÓCZI, L.* Laboratory experiments on selective erosion and deposition of sediments.

RÁKÓCZI, L. 1975 Influence of grain-size composition on the incipient motion and self-pavement of bed materials. *Proc. 16th Cong. of IAHR, São Paulo*, vol. II, pp. 150–157.

ROWE, A. J.* Viscous flow and sedimentation of concentrated dispersions of particles.

ROWE, A. J. 1977 The concentration dependence of transport processes: A general description applicable to sedimentation, translational diffusion, and viscosity coefficients of macromolecular solutes. *Biopolymers* **16**, 2595–2611.

SAKBANI, KH. & WITTIG, S.* Determination of particle size distribution of a metal dust by means of the MRSPC-counter.

SHANBHAG, D. N. & SREEHARI, M. 1979 An extension of Goldie's result and further results in infinite divisibility. *Z. WahrscheinlTheorie verw. Geb.* **47**, 19–26.

SLOT, R. E. & GELDOF, H. J. 1979 Design aspects and performance of settling tube systems. *Lab. of Fluid Mech., Delft Univ. of Tech. Internal Rep.* no. 6–79.

STENHOUSE, J. I. T. & BROOM, G. P.* The measurement of small particle impact.

SUMER, B. M. & DEIGAARD, R.* Experiments on particle motions near the bottom in turbulent open channel flow.

SUMER, B. M. & OGUZ, B. 1978 Particle motions near the bottom in turbulent flow in an open channel. *J. Fluid Mech.* **86**, 109–127.

UNGUT, A., CHIGIER, N. A. & YULE, A. J.* Sizing and tracking of single particles by LDA in flows with combustion.

UNGUT, A., YULE, A. J., TAYLOR, D. S. & CHIGIER, N. A. 1978 Particle size measurement by laser anemometry. *J. Energy* **2**, 330–336.

WILDI, J.* Direct measurement of the wall deposition of aerosol particles from turbulent pipe flow.

WILLETTS, B. B.* The influence of grain characteristic shape on size determination, with particular reference to elutriation.

WITTIG, S. L. K., HIRLEMAN, E. D. & CHRISTIANSEN, J. V. 1978 Non-interfering optical single-particle counter – studies of automobile smoke emissions. In *Evaporation–combustion of Fuels, Advances in Chemistry Series*, no. 166.

WITTIG, S. L. K. & SAKBANI, KH. 1978 Teilschengrössenbestimmung mit dem optischen Vielverhältnis-Partikelzähler im Vergleich mit den Andersen-Sampler. 6. *Fachtung der Gesellschaft für Aerosolforschung, Wien*, Tagungsband GAF, p. 195.

YULE, A. J., CHIGIER, N. A., ATAKAN, S. & UNGUT, A. 1977 Particle size and velocity measurements by laser anemometry. *J. Energy* **1**, 220–228.