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DROP SIZE AND VELOCITY INSTRUMENTATION

N. Chigier

Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.

Abstract—A general review is made of a wide range of commercially available instruments for investigating the structure of liquid sprays. The techniques include photographic recording, visualization, drop size and velocity measurement. A brief mention is made of non-optical probing methods including phase discriminating suction probes and a submicron particle size analyzer using a radioactive source.

Following the discussion of the major requirements for detailed spatial and temporal analysis of continuous and pulsed liquid sprays, the major portion of the paper is devoted to discussion of optical techniques. Imaging techniques including still and motion photography, holography and video recording are reviewed. The basic principles and practice in the use of optical interferometry for simultaneous particle sizing and velocity measurement of individual particles are examined and described in detail. The concepts of visibility and peak amplitude of doppler signals are related to problems associated with light intensity distributions within the measurement control volume. Calibration methods and spatial and temporal averaging procedures are presented. In the section on anemometry, simultaneous measurement of drop size and velocity as well as differentiation between drop and gas velocity is examined. The laser Fraunhofer diffraction method for particle size analysis of droplet clouds is also discussed. This instrument is being widely used for rapid and convenient testing of overall spray characteristics. Additional spatial resolution is achieved by using tomography in which slices of a spray are examined at various locations and at different angles. The laser diffraction meter has also been specially adapted for making more rapid measurements in high frequency pulsed Diesel sprays. The final section of the paper is devoted to recent and future developments. These include uniform laser light intensity distributions within the measurement control volume to reduce spatial ambiguity; use of 3-D motion picture photography for determination of individual droplet trajectories; automatic image analysis and numerical holographic reconstruction.

1. INTRODUCTION

The characterization of liquid sprays requires detailed quantitative information of drop size and velocity distributions throughout the spray as a function of space and time. Spray boundaries and changes in spray angle need to be determined together with average particle size and particle size distribution for global descriptions of sprays. More detailed studies of spray structure seek information on trajectories and ballistics of individual droplets and their interaction with gas flows and solid wall surfaces. Differential velocities between drops and gas (particle lag) together with particle size, yield local Reynolds numbers from which individual particle drag coefficients can be determined. Interaction between particle and fluid dynamics leads to the formation of two-phase jets for which turbulence characteristics, entrainment rates and interaction with surrounding gas flows need to be determined.

Under vaporizing conditions the rate of vaporization is determined by the rate of change of diameter of individual droplets. This is a function of drop aerodynamics and rates of heat and mass transfer which are dependent upon local distributions of temperature and vapor pressure. The vapor pressure of evaporated gas is used to determine local air/fuel ratios for combustion systems.

There are very significant differences in the characteristics of continuous sprays compared to those of pulsed sprays. In pulsed sprays, usually of short time duration, spray characteristics require to be determined both as a function of time and space. Spray penetration, coalescence and droplet interaction need to be examined. In considering the interactions with gas flows, the influence of large eddy structures in the jet leads to segregation of droplets according to size. Both in theoretical analyses and in making measurements, the relationship between the Lagrangian, as viewed by motion picture, and the Eulerian, as determined by local point measurements, reference frameworks needs to be considered.

The purpose of this paper is to review the instrumentation available for drop size and velocity measurement in sprays and discuss the special requirements to provide detailed information on spray structure. Brief mention will be made of the classical photo-optical size measurement techniques followed by a detailed discussion of the principles and practice of optical techniques. The optical techniques include imaging by photography and holography followed by interferometry and laser anemometry for simultaneous velocity and size measurement of individual particles. The laser diffraction methods for overall sizing of particle clouds and their use in pulsed sprays will be discussed as well as more recent developments in automatic image analysis.

2. SPRAY STRUCTURE AND ANALYSIS

At any one instant of time, a typical spray contains of the order of 10^6 drops and has an injection rate of the order of 10^8 drops/sec. Significant variations in composition and quality occur both spatially and temporally. The overall requirement is to observe a

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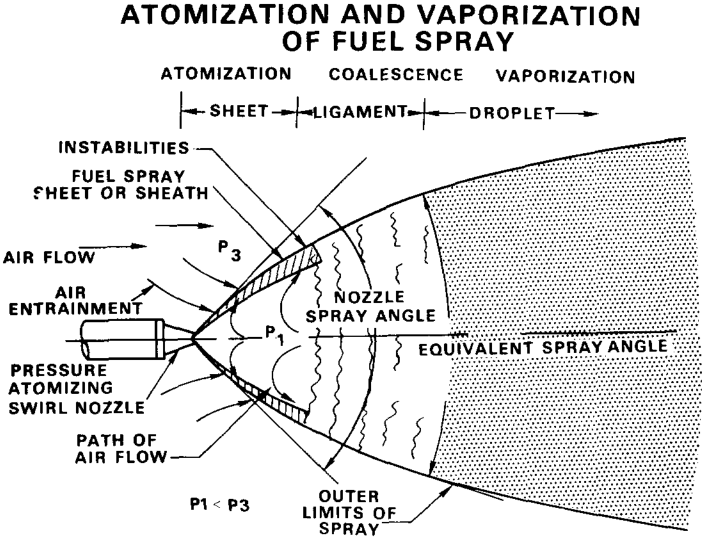

FIG. 1. General characteristics of sprays.[21]

large number of drops, sampled at high speed, from selected volumes of the spray to give a large number of samples in a reasonably short period of time. Both the average drop size and mass distributions of liquid vary with axial and radial distance within the spray. The data obtained from the measurements must be recorded and processed by a digital computer so that computed results are available shortly after completion of the test.

Figure 1 shows the atomization and vaporization processes of fuel sprays. In the atomization region, instabilities, perforations of liquid sheets and formation of ligaments are examined by direct visualization with still and motion picture photography.

The initial conditions of the spray are specified at the end of the break-up region by measurement of the drop size, velocity and direction of flight of droplets across the initial plane of the spray. Nominal spray angles are defined in terms of liquid sheet angles at the nozzle exit. Actual spray angles are determined by the outer limits of the spray and the equivalent spray angle varies as a function of distance downstream. For some hollow-cone sprays an inner spray boundary may also be determined as a bounding surface for the annular spray. Detailed analysis of the spray requires determination of the following quantities:

(a) spray image—still and motion pictures;
(b) droplet size distributions;
(c) droplet number density;
(d) droplet velocities;
(e) droplet size/velocity correlation;
(f) liquid distribution;
(g) air distribution;
(h) vaporization rates.

Droplet sizing techniques for sprays should have the following characteristics:

(a) no disturbance to the fuel spray pattern or atomization;
(b) rapid means of sampling and counting;
(c) good size distinction over the whole range of measured drop sizes;
(d) distinguish between liquid and gas phases and determine separate properties of each phase;
(e) measure droplet size and velocity distributions in space and time.

The various methods for drop characterization can be classified as follows:

(1) Non-optical
  (a) drop collection;
  (b) physical probes;
(2) Optical
  (a) imaging photography;
  (b) interferometry;
  (c) diffraction;
  (d) absolute light intensity;
  (e) intensity ratioing.

The major difficulties encountered in applying methods to measure droplet characteristics are:

(a) great number of droplets *or* large droplet field;
(b) large droplet number density;
(c) coalescence of droplets;
(d) relatively high and varying velocity of droplets;
(e) great variation in droplet size (factor of 100);
(f) change in droplet size with time due to evaporation or combustion;
(g) fouling, deposition and fogging of probe and optical surfaces;
(h) uncertainty in depth of field determination (imaging only).

Several books have been written on particle size measurement and analysis. References 1–4 cover the general field of particle size measurement while references 5–8 deal with more specific problems of spray characterization in combustion systems. The importance of detailed spray analysis for combustion systems is now well recognized in the overall aim of increasing combustion efficiency and reducing emission of pollutants. This interest has spurred a very considerable amount of activity in the development of advanced laser diagnostic techniques for measurements in two-phase flow, high temperature systems.

Most of the instruments discussed in this review are commercially available while several instrument manufacturers are engaged in intensive research and development to improve the accuracy of measurement, facilitate the data acquisition and analysis and ultimately reduce the overall cost. A review of instrumentation techniques for studying heterogeneous combustion was given by Chigier in 1977[9].

3. NON-OPTICAL TECHNIQUES

Prior to the advent of lasers, except for photography, the classical methods of drop sizing were essentially non-optical. These techniques involve collection of drops or solidified drops with subsequent sizing. Alternatively, solid probes are inserted into the spray for collection of drops locally or for measuring the interaction between electrical probes and individual droplets. Most non-optical techniques are crude and inexpensive relative to laser diagnostic techniques. They can be divided into the following two categories:

(1) Drop collection
  (a) Solidified molten wax drops with separation by sieving (50–300 μm).
  (b) Liquid drops frozen in low temperature gas, with subsequent analysis by microscope (20–200 μm).
  (c) Liquid drops collected in cells containing an immiscible liquid and then analyzed by photography (1–3000 μm).

Many of these drop collection methods involve sampling at distances far downstream from the nozzle where samples are made of the spray as a whole. Compartmented collection vessels (patternators) are used for testing the symmetry of sprays. By sampling along a narrow sector some measurements can be made at various radial and peripheral locations.

(2) Indirect physical determination
  (a) Cascade impactors (3–150 μm).
  (b) Heated wire, cooled by impacting drops (1–500 μm).
  (c) Electrical charging of drops and capacitance measurement.
  (d) Kinetic methods for measuring the momentum of the spray by impaction.

All of the above mentioned techniques have significant limitations and appear to be in a state of general phase out in particle size analysis. There are two probes which are of special interest and are worthy of more detailed description.

3.1. *Phase Discriminating Sampling Probe*

The phase discriminating sampling probe shown in Fig. 2 was used by McVey *et al.*[10] for measurements in burning sprays. The phase discriminating sampling probe withdraws samples from the spray for measurement of the separate mole fractions of liquid and vapor in the sample. The central passage of the probe acts as a conventional gas sampling probe collecting the total (liquid plus vapor) sample. Isokinetic flow is established within this passage by adjusting the flow so that the static pressure close to the tube lip is equal to the local static pressure in the spray. A tube oriented perpendicular to the axis of the total sampling tube is used to extract the vapor sample. A suction tube surrounding the vapor tube is used to purge any liquid which collects on the surface of the total sample tube and which otherwise would spill over into the vapor sample tube and contaminate the vapor sample. Water jackets surround the sampling tubes so that collected samples can be quickly quenched and a flow of nitrogen is introduced into the sample tube close to the probe tip in order to quench vaporization and chemical reaction. The sample is

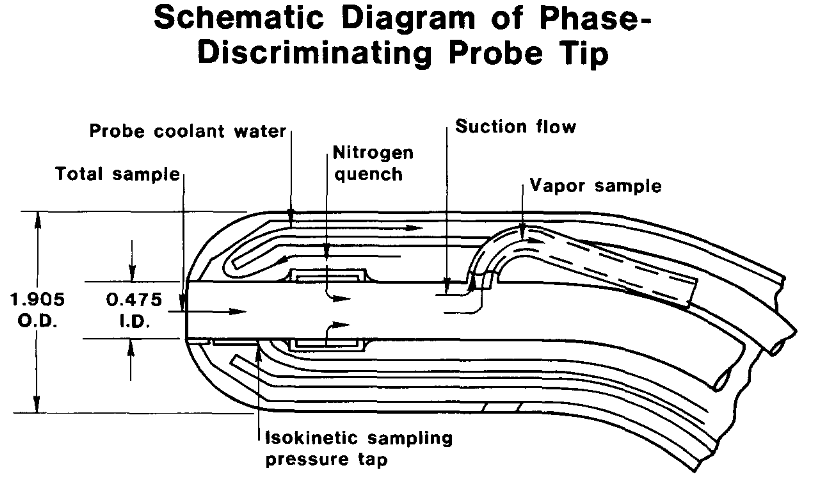

FIG. 2. Phase-discriminating probe.[21]

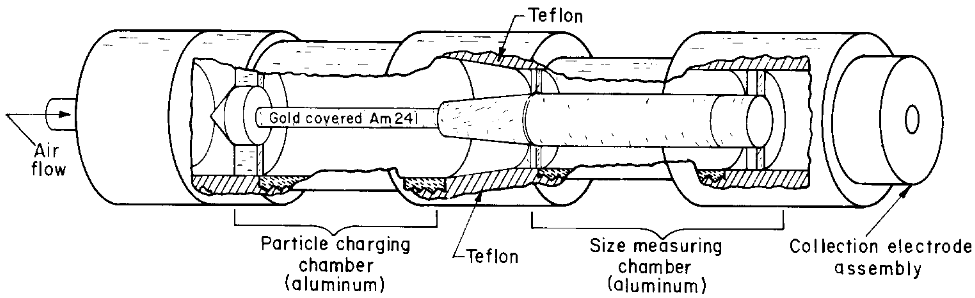

FIG. 3. Submicron radioactive particle sizer.[11]

pumped from the probe through electrically heated stainless steel lines which maintain a sample temperature of approximately 500 K, through glass wool particulate filters, to the on-line gas analysis equipment. This probe is particularly useful for studying dense sprays and for use in combustor environments.

3.2. *Submicron Size Analyzer with Radioactive Source*

Measurement of submicron droplets poses special problems associated with the very small size of the drops and their very large number. By withdrawing gas samples from the spray, submicron particle size and concentration can be measured, using the analyzer developed at the Bureau of Mines by Litton *et al.*[11] The instrument was designed primarily as an incipient fire detector in mines but can also be used for studying aerosols. The portable instrument measures concentrations of particles with diameters ranging from 0.005 to 1.0 μm, with concentrations as low as 750 particles/cm^3 at small diameters and 25 particles/cm^3 at larger diameters. Figure 3 shows the sensor chamber of the instrument which consists of a particle charging chamber where attenuated α particles from an Americium 241 radioactive source positively charge particles passing through the chamber. The charged particles then flow through the size measuring chamber. Concentric electrodes with an adjustable electric potential are programmed to precipitate out the particles in a selective manner: the smaller particles drop out at the lower voltages, since their charge:mass ratios are greatest. As the electrode voltage is increased, the larger particles with lower charge:mass ratios are precipitated in the sizing chamber. The remaining charged particles are then gathered on the collection electrode assembly.

Current flows are measured at the size measuring chamber and at the collection electrode assembly. These currents represent the charges given up by the small-sized and the large-sized fractions of the particles, respectively. Following data reduction and manipulation, the total particle count and total particle mass as functions of particle size are determined. This ionization-type instrument is useful for moderate particle densities, up to 500,000 particles/cm^3. Heavier particulate loadings may require dilution or other preconditioning of the measured stream. Calibrations against TSI particle generators and membrane filters are consistent with ionization-meter theory.

4. OPTICAL TECHNIQUES

4.1. *Imaging*

Imaging techniques include microscopy, photography, video and holography. In optical characterization by imaging, incandescent lights, mercury vapor lamps, flash and laser light sources are used. Flash light sources have time durations of the order of 1 μsec while pulsed lasers have pulse durations of the order of nanoseconds. Direct still photography with narrow depths of field allows measurement of particles in the range between 10 and 10,000 μm. Photographic characterization is a well established, reliable and accurate technique, but it suffers from the following disadvantages. A large number of particles needs to be counted to obtain a statistically representative sample. The required number of samples is dependent on the frequency and nature of variations within the spray as a function of time. Manual analysis of photographs is very time consuming and subject to operator fatigue and bias. Automatic image analysis is an improvement but must be used with care, and the cost of the equipment is significantly increased. Shape analysis can best be achieved by direct photography and subsequent image analysis. Significant progress has been made in computer analysis of photographic prints and direct electronic processing.

4.2. *TV Image Scanning Spray Analyzer*

Simmons and Lapera[12] developed a TV image scanning system for analyzing gas turbine nozzle sprays. The Parker Hannifin spray analyzer is shown in Fig. 4. The instrument is based on the synchronous operation of an illumination source and a closed circuit TV camera. By flashing (or shuttering) a high intensity light source focused at a preset point in the spray, the image of the drops at that point is transferred to the photosensitized surface of the Vidicon in the TV camera. A scanning technique is utilized to count and size the droplet images on the Vidicon. A detection circuit is used to establish whether or not a

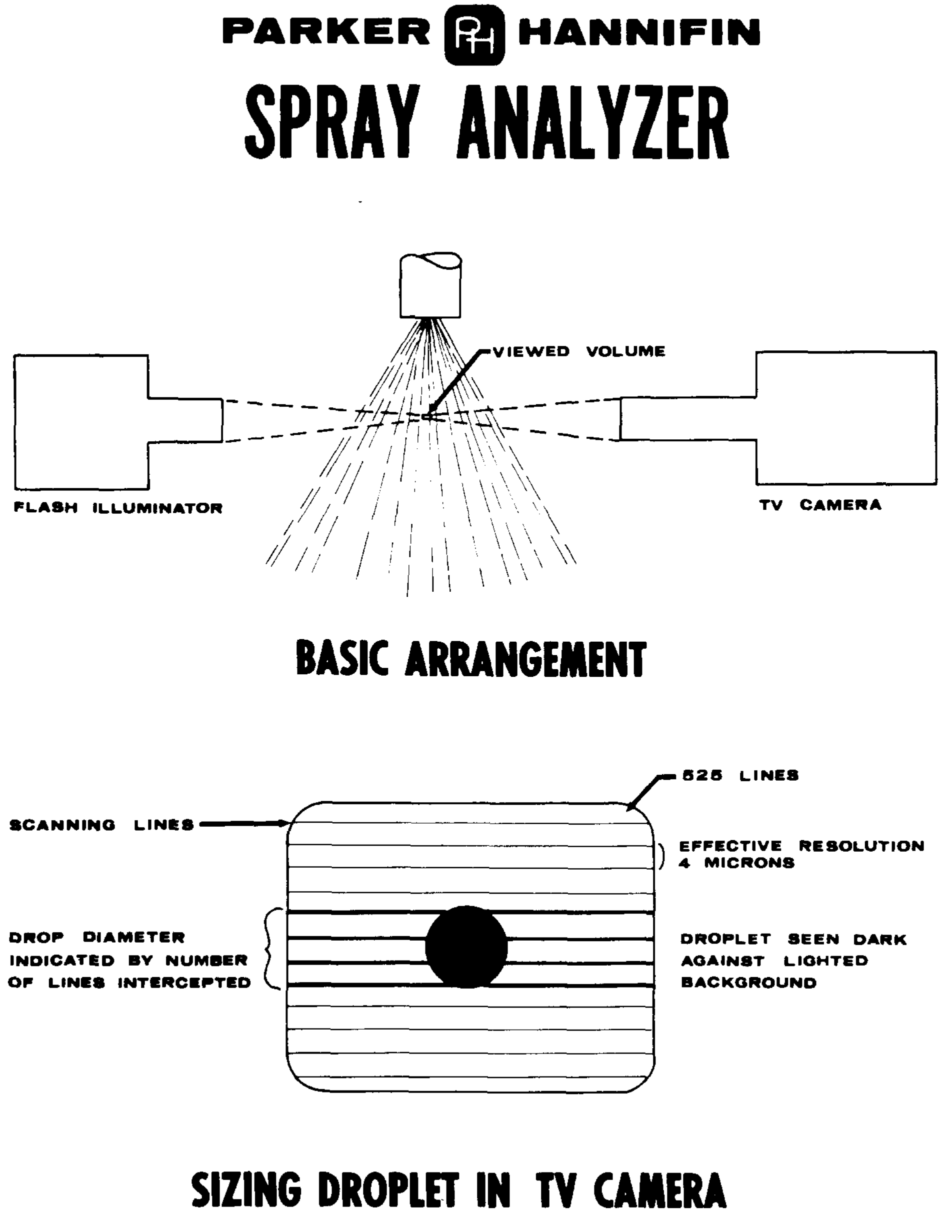

FIG. 4. TV image analyzer.[13]

droplet is in focus by monitoring the scanning line voltage change. Once a drop is classified as being in focus it is electronically identified to the counting circuits which size and place the drop in the proper storage group. The observed data is reduced to a common unit volume basis before being displayed.

The flash illumination is produced by a Xenon flash lamp powered by a parallel capacitor charged to 1600 V. The externally triggered lamp is capable of producing a high intensity flash for a duration of 0.5 μsec. Back lighting is used to produce the maximum amount of contrast on the Vidicon face. Drop images appear as dark images on a bright background.

The TV camera is specially modified in the vertical trace mode to remove the interlaced tracing while retaining the basic 525 horizontal line scan. The operation of the illuminator is synchronized with a camera so that the flash stores the droplet images on the Vidicon. The Vidicon is scanned to obtain drop size information and then erased to prepare for the next flash cycle. This cycle is repeated 15 times each second. This is analogous to taking 15 photographs of the spray per second. Coupled with the camera is a telemicroscope with capability of various degrees of magnification. With a magnification of 6, the usable area of the Vidicon face is about 2 mm^2. The resolution, as determined by the spacing of the scanning lines, is 4 μm.

The camera and illuminator are rigidly fixed to pre-

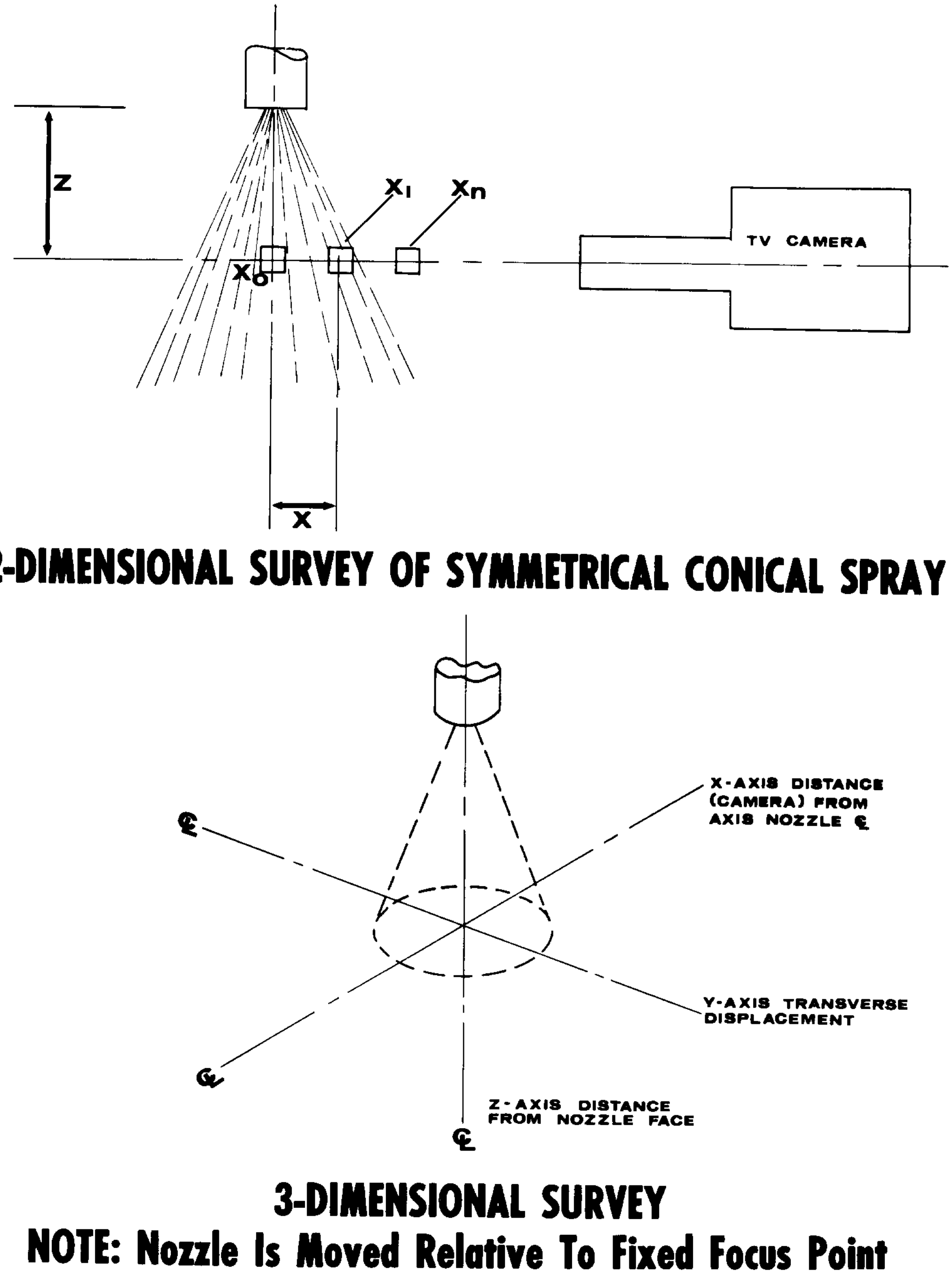

FIG. 5. Survey of conical sprays by TV camera.[13]

serve the delicate alignment while the nozzle is moved (Fig. 5). Where the point of interest or view volume is located in the spray, encoders on the positioning device transmit the tri-axial position of the point to the logic circuits in the system. The information is displayed and recorded. A selection is made between 100 and 1000 flash counts.

Drop size calibration is made with transparent slides holding simulated droplets with known dimensions. A depth of field curve is measured and plotted against drop diameter from which the probe volume is determined. Dynamic calibration is made using a video tape recording of a suitable test run. A high-resolution video-tape recorder is used for frame-by-frame examination of high speed runs (Fig. 6). The focus discrimination method is described in Fig. 7. Sufficient data is obtained to plot contour maps of the spray cross-section as shown in Fig. 8. Calculations are made of Sauter mean diameter, mass mean diameter, liquid concentration, liquid/gas ratio, cumulative volume and drop diameters.

Simmons[13] claims that the amount of data produced and the computerized reduction and analysis were (15 years ago) and still are (1982) superior to any other system. The original spray analyzer is being rebuilt with a 10 nsec pulse laser and a new micropro-

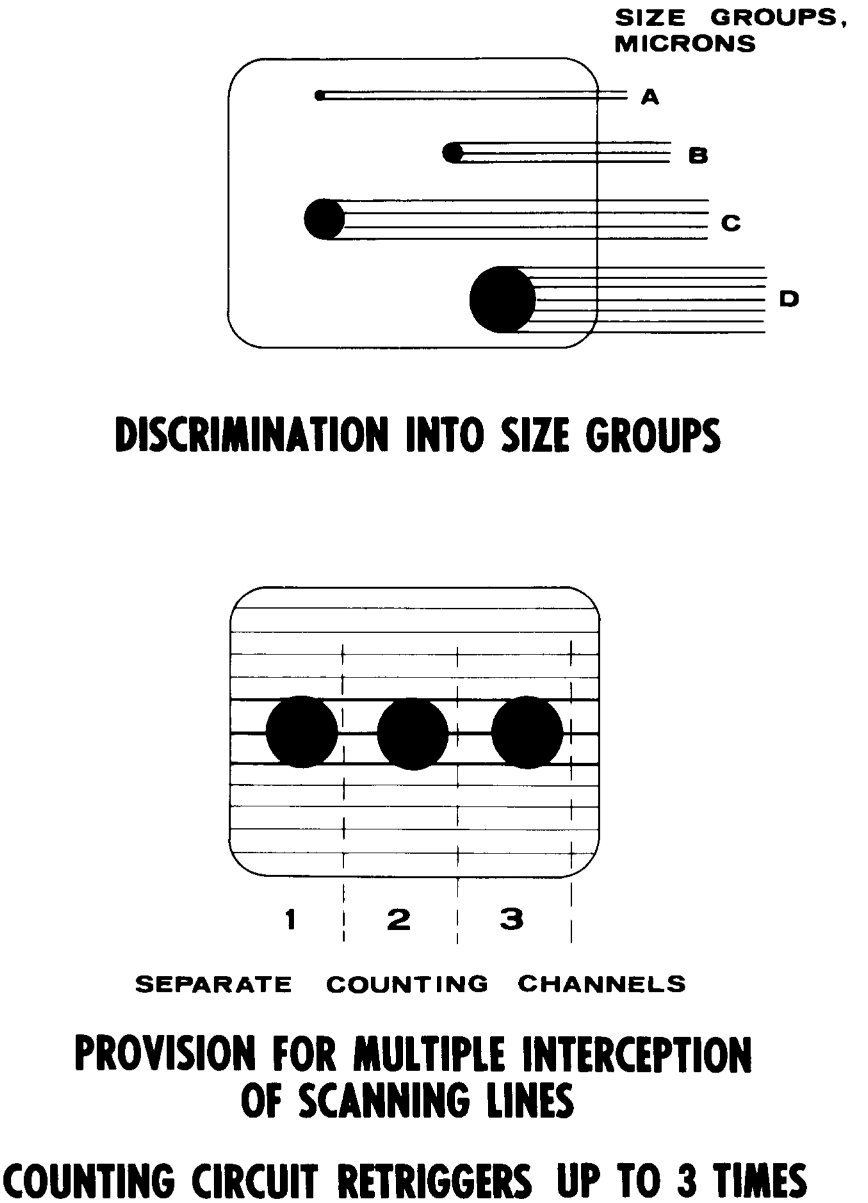

FIG. 6. Size analysis on TV screen.[13]

cessor to provide more information on spray nozzles for gas turbines.

Ow and Crane[14] have developed a simple automatic image analysis system based on a conventional television camera and minicomputer for droplet size determination in sprays. A 625-line television camera with Vidicon tube, scans a selected region of a photographic negative illuminated by a diffuse, direct-current light source. The digitizer divides each TV line into 384 picture points and assigns to each point a grey level on an equal-interval scale from 0 to 7. The grey levels are contained in a window which can be stretched or compressed while the video signal level can be translated relative to this window giving the same flexibility as the large number of fixed levels on a typical proprietary image analyzer. Measured data is stored on a disc of a conventional minicomputer for subsequent decoding to give the coordinates in the TV frame of each data item. Data are recalled on a Tektronix display unit as a map of detected images at or above any chosen grey level. A digitizer working on 1024 picture points per TV line will be incorporated and will be matched with a higher resolution camera. A terminal with graphics capability will replace the teletype and display unit. The image recognition procedure uses a file of transition parameters to identify and index the cells which may be drop images or other isolated features on the negative. The indexed cell parameters are then refined and their area and shape is computed. Unwanted cells are rejected by shape and focus discrimination tests. Algorithms for image regulation, based on detection at two or more of eight

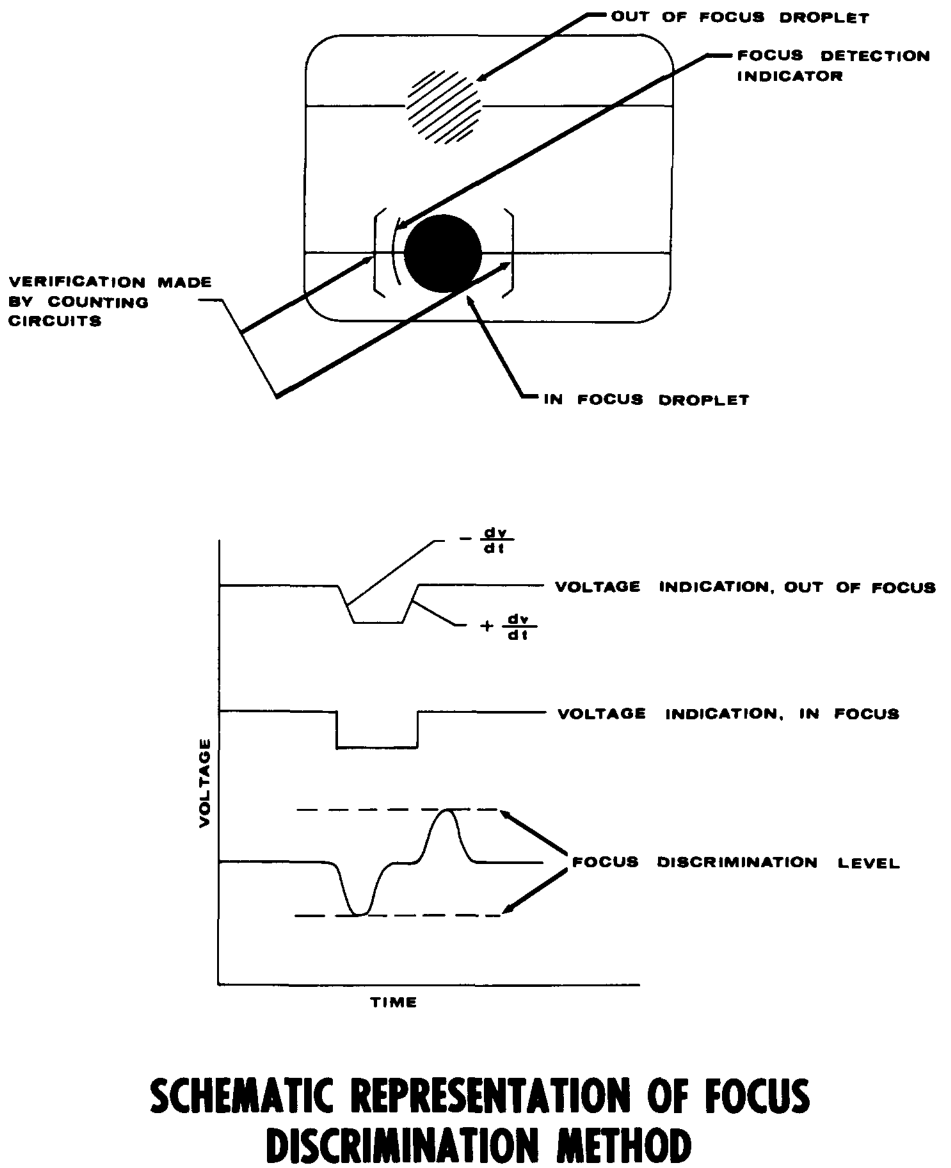

FIG. 7. Focus discrimination for image analysis.[13]

grey levels, were devised for identifying images of spray droplets on photographs in which considerable nonuniformity in background contrast is possible.

4.3. *High Speed Motion Picture and Television Recording*

Continuous recording of spray behavior by high speed motion and TV camera shows the dynamic characteristics of sprays. Unsteadiness and nonuniformities such as the appearance of large quantities of liquid appearing intermittently at various circumferential locations around the injector can be clearly seen. The uniformity of liquid flow patterns can be well established by high speed motion picture examination. Direct filming of the nozzle exit region can also show the development of liquid films on exterior surfaces of nozzles which, in combustors, can result in carbon formation and deposition on the nozzle.

High speed motion pictures with framing rates up to 6000 frames/sec can be used with synchronized strobe illumination.

Higher speeds—up to 12,000 full frames per second under continuous illumination—show turbulent structure within the sprays with separation of smaller droplets into large eddy structures. Three dimensional motion picture photography offers the possibility of following trajectories of individual droplets within sprays. Recent development of high-speed television systems promises to add speed and convenience to the data reduction process at some sacrifice in image resolution compared with conventional photography. The Spin Physics (Eastman Kodak) is an excellent example of developments in this direction.

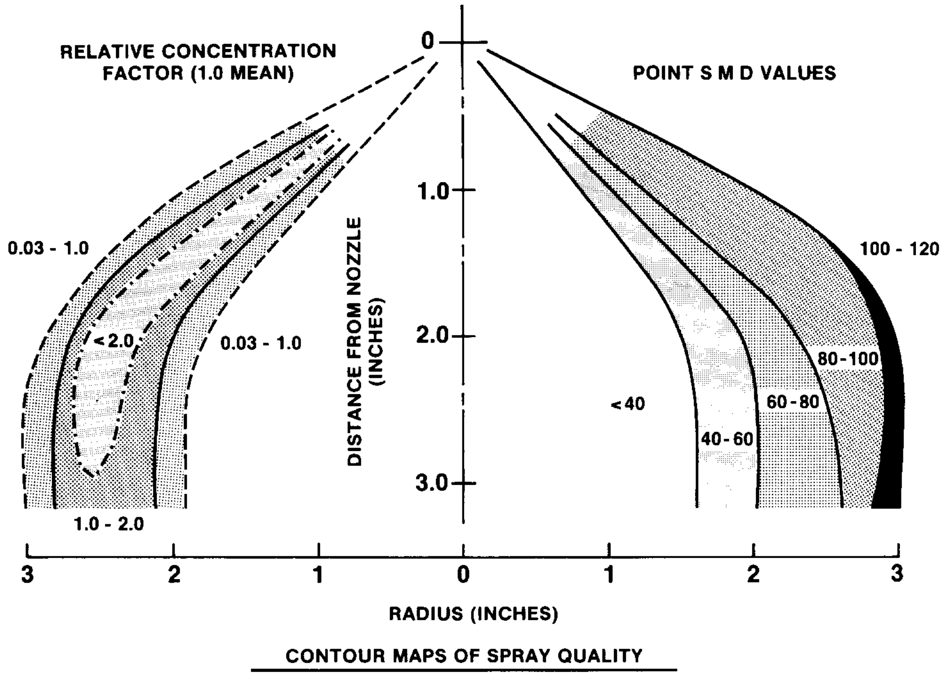

FIG. 8. Contour maps of spray quality by TV camera.[13]

5. HOLOGRAPHY

Conventional photographic techniques are restricted to cases where objects of interest are known to exist in a certain plane. The depth of field of conventional photographic systems is determined by the optical geometry; particles which are outside the depth of field are out of focus and cannot be resolved. For the study of dynamic events in sprays a system is required that provides high optical resolution over large volumes for very short time periods. Holography provides distinct advantages for the study of three dimensional particle fields in sprays.

Optical holography is a recording technique which stores, for later reconstruction, all of the coherent optical information that has passed through, or is reflected from, a volume and is subsequently projected onto a holographic plate. The basic requirement for producing a hologram is that a wavefront (object wave) which has passed through, or is reflected from, the volume of interest, be mixed coherently with a reproducible reference beam and recorded on a photographic plate (the hologram). When the processed hologram is illuminated by a duplicate of the reference beam, usually a continuous wave laser, a complete three-dimensional image of the object field is reconstructed in space in its original position relative to the hologram. The reconstructed image is available for detailed plane-by-plane study. The three-dimensional image of a field, as viewed through a hologram, is as if the hologram were a window behind which the actual field is frozen in time. The virtual image which lies behind the hologram is converted to a real spatial image which lies on the viewer's side of the hologram. When the hologram is illuminated by the reference beam the hologram acts as a special type of diffraction grating.

Conventional photographic systems resolve particles that lie within $R^2/2\lambda$ from the plane of interest, where R is the required resolution and λ is the light wavelength. This limitation is relaxed in holography. High resolution (2 μm) can be achieved in volumes that are several orders of magnitude larger than can be examined by conventional photographic techniques. A hologram can resolve R if the element lies within RD/λ of the focal plane, where D is the effective hologram diameter. The ratio of sample volumes for holography to photography is approximately $2D/R$. For 10 μm resolution and a 50 mm hologram diameter, the ratio is 10^4 for a typical light wavelength of 0.69 μm. The effective depth of field for photography is 72 μm whereas for holography it is 0.72 m. The ultimate image quality in holography is slightly lower than the equivalent conventional photographic imaging method. The hologram serves primarily as a storage device. Holography has special advantages when it is desired to examine individual particles within a spray system. The basic principles of optical holography and holographic interferometry are described in a series of books.[15-17] Trolinger describes the basic principles of particle field holography[18] and the application of holographic interferometry as a diagnostic tool for study of sprays in combustion systems.[19] Wuerer *et al.*[20] describe a system which is commercially available.

The laser holographic system used for the study of sprays at the United Technology Research Center by

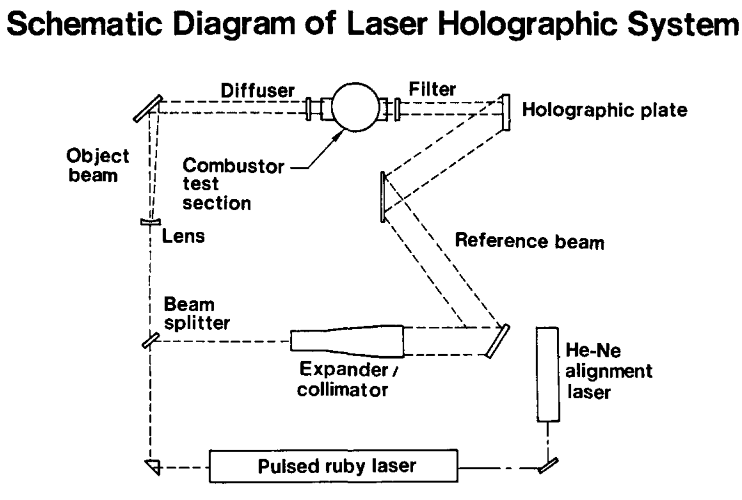

FIG. 9. Laser holographic system.[21]

McVey *et al.*[10] is shown schematically in Fig. 9. This is an off-axis holographic system in which a Q-switched ruby laser beam is separated into an object beam and a reference beam by a beam splitter. The portion of the laser beam which is undeflected by the beam splitter (object beam) passes through a lens to the diffuser. The diffuser causes the rays of light to be transmitted to the spray over a large range of angles relative to the optical axis. Light from each point in the spray reaches all points on the holographic plate. The reference beam passes through an expander which expands the reference beam and a collimator which adjusts the beam so that wave fronts emanating from the lens of the collimator are planar. The reference beam is oriented so that the angle of the reference beam with respect to the object beam is 45°. Larger angles cause fringe patterns on the holographic plate to be very closely spaced, thereby reducing resolution, while smaller angles would require the holographic plate to be moved away from the object, thereby reducing resolution and increasing the depth of field.

In transmission holography, light is transmitted from the diffuser through the spray to the holographic plate. The reconstructed images of the objects appear as silhouettes if the objects are opaque. In the case of transparent drops, the edge of the drop appears dark because the light at the edge of the drop is refracted out of the field of view of the holographic plate and the center of the drop appears bright due to transmitted light. The dark outer edge represents the true dimension of the transparent drop in the object field. Holograms are recorded on an emulsion on a glass base. A remotely controlled film magazine can be used to hold several film plates which enables a series of holograms to be obtained.

Reconstruction of the holograms (Fig. 10) is accom-

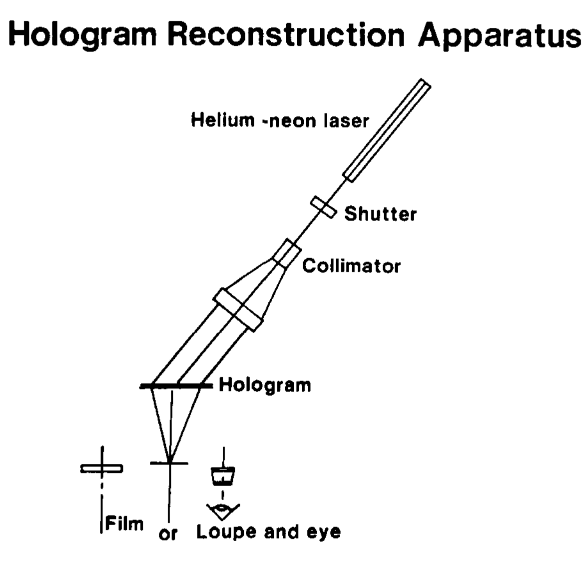

FIG. 10. Hologram reconstruction.[21]

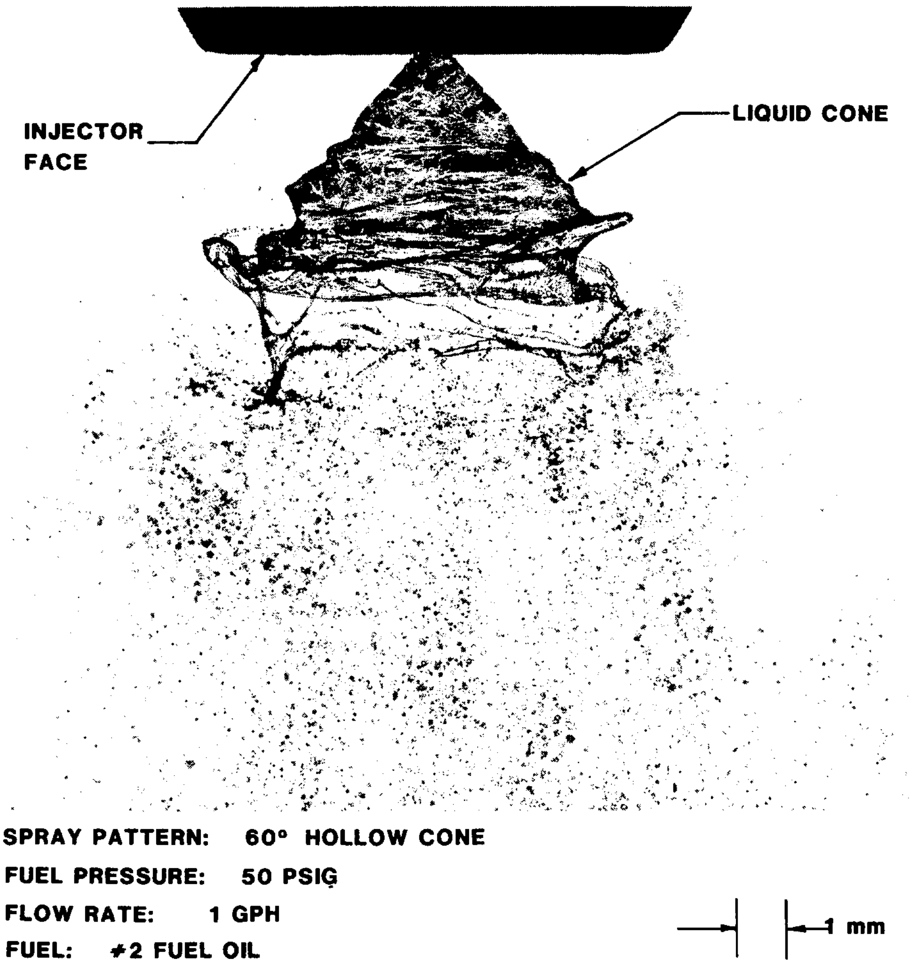

FIG. 11. Hologram of pressure jet fuel spray.[21]

plished with a second optical system using a He–Ne laser as a light source. The laser beam is expanded by an expander/collimator to illuminate the holographic plate mounted in a holder which is articulated to facilitate precise orientation of the hologram relative to the incident laser beam. Light diffracted from the hologram forms a real image of the spray. Figure 11 shows a reconstructed hologram for a hollow cone pressure jet spray obtained at Spectron by Wuerer *et al.*[20] Spray cone angles are measured by obtaining the best fit between surface coordinate data and the surface coordinates of a right circular cone by using a regression analysis. A double pulsed image is shown in Fig. 12 for a pulse spacing of 5 μsec. A 70 μm droplet with a velocity of 14 m/sec can readily be detected and velocities can be measured for droplets down to 15 μm in diameter. Liquid flow rates (flux) were calculated from the measured droplet size, number density and velocity.[21]

The holocamera developed by Spectron[20] has a laser with a pulse duration of 20 nsec and a double pulse capability with adjustable pulse separations from 1 to 500 sec. The laser output energy is 50 J/pulse. By multiple pulsing the velocity and trajectory of particles can be evaluated. Lenses are used to magnify particle images up to 15 times before recording which relaxes requirements on the holographic recording. With some modification to the standard optics, particles may be simultaneously illuminated with both front light (reflected) and transmitted light. The front light provides details of the surface of the particle while the transmitted light defines the periphery. Using high magnification (15 ×) on a 2 mm optical probe volume has yielded a resolution of 2.5 μm. At high magnification, a triggering system activated by scattered light from c–w laser illumination of the control volume may be used to fire the holocamera. This ensures the presence of an image in the field of view.

Velocity information is stored on the hologram by double pulsing (Fig. 12). Displacement occurring over the 5 μsec pulse separation can easily be seen and allows direct determination of droplet velocity. Changes in the shape of liquid elements can be examined to provide information about the dynamics of the formation process. Droplets as small as 15 μm are clearly visible. The hologram provides a full three-dimensional frozen image of the spray. Photographs are obtained from the reconstructed hologram.

The major advantage that holography possesses

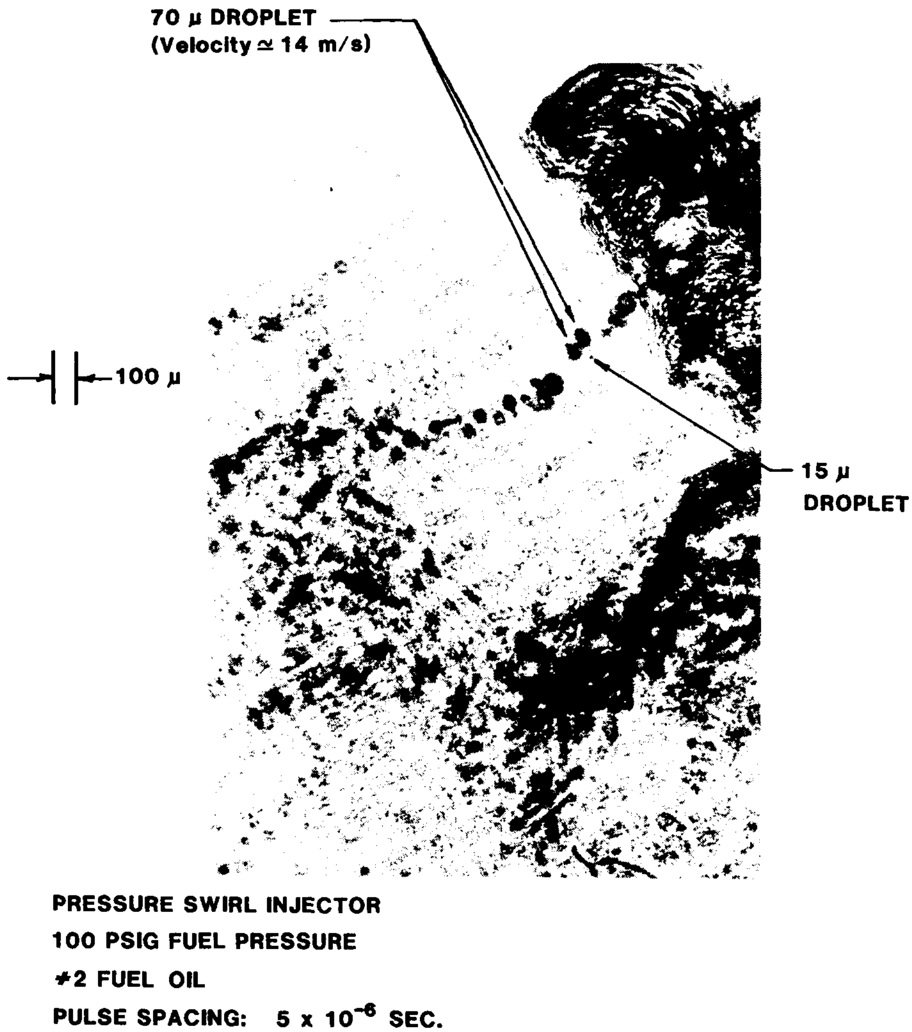

FIG. 12. Hologram with double pulse laser for velocity determination.[21]

over other probing techniques for characterizing sprays is that an instantaneous picture is obtained of the entire volume under inspection, whereas most other probing techniques provide time-averaged properties at selected points within the volume. With holography, anomalous behavior such as streaking (spatial nonuniformity) or spitting (temporal nonuniformity) can readily be detected. Recording of holograms is achieved in a few seconds but holography has the disadvantages of high equipment costs and tedious data reduction procedures. Also, difficulties are encountered in using holography in dense sprays.

5.1. *Numerical Holographic Reconstruction*

A limiting factor in the use of holography for routine particle sizing applications has been the tediousness of obtaining statistical properties from a large number of reconstructed holograms. Denton at the Tau Corporation[22] is developing a numerical data retrieval process for reconstructed holographic recordings. This will allow automatic particle size and shape discrimination. The approach is to digitize the hologram and reconstruct the image by digital rather than optical means. Following the reconstruction process, image processing techniques appropriate for automatic data retrieval from the reconstructed image will be applied. This will include a preprocessing stage, a detection stage (matched filter) and sizing, localization and focusing of the particles. By this means, all processing after the initial hologram recording can be carried out on the computer automatically with acceptable resolution. Rapid advances in digital computing development should make this a cost effective process. Particle resolution of the order of 5 μm is considered to be achievable.

6. DROP SIZING INTERFEROMETRY

Drop sizing interferometry is used in conjunction with laser doppler anemometry. Real time, *in situ*, simultaneous size and velocity measurements of single

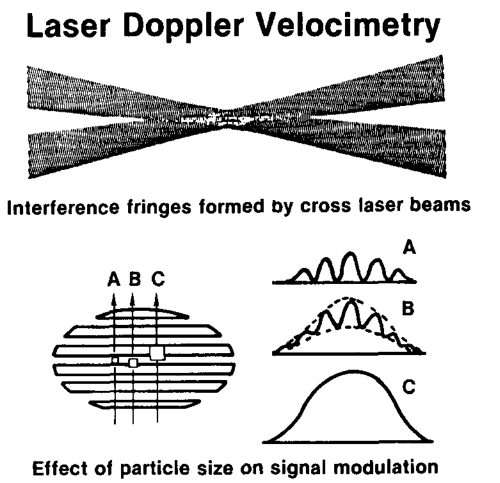

FIG. 13. Laser doppler velocimetry and interferometry.[21]

particles are made using crossed-beam interferometry. Systems have been developed which provide sufficient size-measuring resolution over a broad range of sizes, providing droplet size distributions throughout the spray with high spatial resolution and with the capability of simultaneous measurement of droplet velocity. The principles and practice of laser doppler anemometry are described in the book by Durst *et al.*[23] Interferometric techniques for particle sizing based upon light scattering have been developed using the concepts of visibility,[24] peak amplitude[30,31] and angle ratioing.[33]

Theories of light scattering from spherical particles are dependent upon the ratio of the particle diameter to the wavelength of light. For lasers with light beams in the visible spectrum the Rayleigh approximation can only be used for very small particles with diameters less than 0.05 μm. For sprays with small droplets (between 0.05 and 2 μm) the Mie theory is applicable for light scattering from spherical particles. The pattern of redistribution, by scattering, of a collimated ray of light is a unique function of the index of refraction, wavelength and particle diameter. If the index of refraction and the wavelength of the light are known, particle size can be determined. For large particles (> 10 μm) the diffraction approximation of geometric optics is applied.

In the interferometric techniques, the shape of the forward scatter distribution, or the shape by refraction at an off-forward direction, is determined. A laser beam is split into two coherent beams of equal intensity and made to cross (Fig. 13). The configuration is identical to that used in laser doppler anemometry.[23] When the two beams intersect, stationary interference fringes appear. When the particle traverses these fringes, the forward scatter reproduces the intensity modulation of the fringes. Van de Hulst[32] demonstrated that for $\pi d/\lambda$ (where d is particle diameter and λ is the wavelength of light) more than 10, geometrical optical laws, which are asymptotic approximations to laws for electromagnetic waves, apply. The scattering of electromagnetic radiation is separable into simplified theories of diffraction, refraction and reflection. Diffractive scatter is concentrated in a lobe in the forward direction which becomes smaller in width with increasing particle size. The other half of the incident radiation is scattered in ordered directions by reflection and refraction. The effect of particle size on signal modulation is shown in Fig. 13.

6.1. *Visibility*

Figure 14 shows the fringe modulated signal as a doppler burst. Farmer[24] in 1973 defined the visibility:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Farmer identified the visibility as a universal function of the dimensionless size, d/δ, where d is the particle diameter and δ is the separation between adjacent fringes. The size of the particle is determined from the visibility of forward scattered light. The technique is applicable to both opaque and transparent particles,

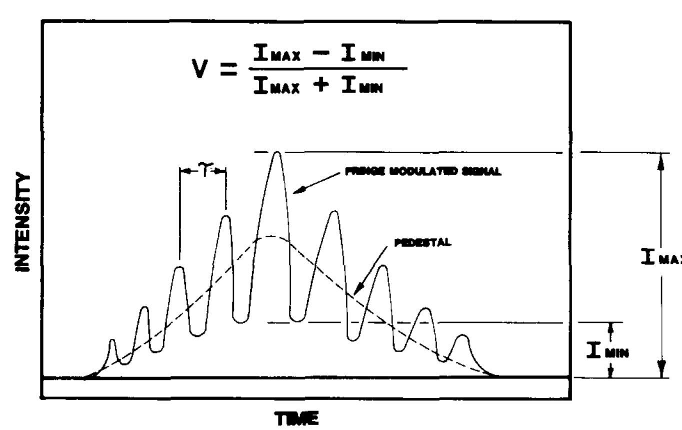

FIG. 14. Visibility and pedestal of doppler signal.[20]

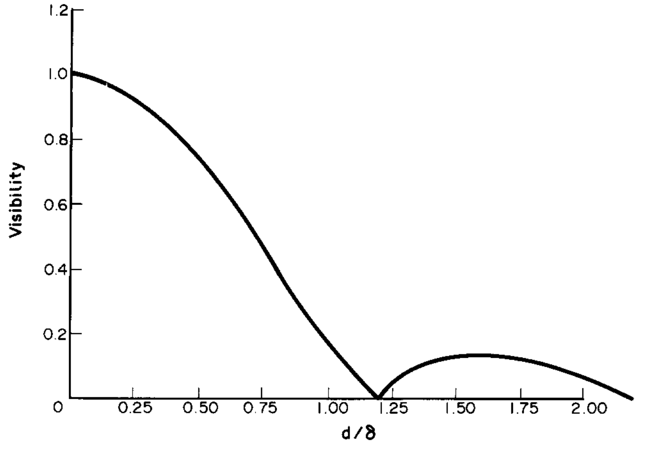

FIG. 15. Visibility as function of ratio of particle diameter to fringe spacing.[20]

since the forward scattered light has little dependence on transmitted rays. In applying the visibility technique it is essential that the entire main lobe in the forward scatter be observed. The lower limit of applicability is 2 μm.

In the original work of Farmer[24] it was assumed that the simplified visibility relationship (Fig. 15) was only applicable for particles with diameters smaller than the fringe spacing. As particle size increased, the fringe spacing had to be increased.with an upper size limit of about 200 μm. Under conditions of large fringe spacing (200 μm), beam crossover angles become very small, resulting in long measurement control volumes and inaccuracies in velocity measurement. In a spray with typical large variation in particle size the adjustment of fringe spacing according to measured particle size becomes impractical. At Sheffield University early attempts at using visibility for size measurement in sprays, while retaining the recommended fringe spacing for velocity measurement of approximately 5 μm, showed that there was no one-to-one relationship between visibility and particle size.[30,31] This led to the development at Sheffield University of the concept of measuring peak amplitude directly. In reviewing the development of the concept of visibility, Farmer[28] in 1980 described how in 1978 he had developed an approximate model correlating experimental data with theoretical predictions. He had concluded (1978) that scattered light must be observed with a large receiver aperture centered on the symmetry axis of the transmitting optical system. Particle diameters were required to be less than the fringe spacing if unambiguous measurements were to be obtained. In making visibility measurements the receiving optical geometry and alignment was very critical.

In 1980 Bachalo[29] used geometric optics theory to relate the scattered fringe pattern to the droplet diameter. He made use of the suggestion of Farmer[24] in 1974 that off-axis collection yields higher visibility. Bachalo[29] showed that for particles with diameters much greater than the wavelength of light, and at viewing angles where the reflected or refracted component of the scattered light is greater than the diffracted component, particle diameter can be related to a visibility function that is monotonic over a significant size range. The visibility function depends on the receiving optics, the particle index of refraction and the viewing angle. The rigorous analysis performed by Bachalo[29] consisted of numerical integrations of the classical electromagnetic field equations describing refraction and reflection by homogeneous spheres illuminated by plane waves. It was, however, difficult to discern or physically visualize the scaling laws that relate visibility to particle index of refraction, receiver lens, f/No., or viewing angle. Farmer in 1980[28] developed a simple model that elucidated the results obtained by Bachalo[29] and yielded simple scaling laws that can be used to configure optical systems for measuring a broad range of particle sizes for a fixed fringe period. Farmer's analysis[28] showed the effects of the principal parameters on the phase of the doppler signal. He also showed that receiving apertures can be shaped to obtain visibility functions that are consistent with a desired range for a given fringe period. The ability to adjust the measurable size range by simply adjusting an iris in front of the receiving lens is a significant operational simplification over previous paraxial interferometers which

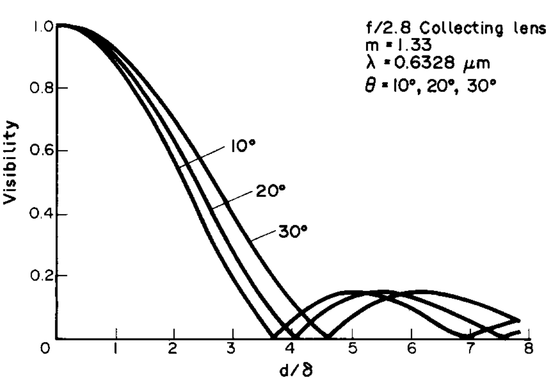

FIG. 16. Effect of variation of off-axis collection angle on visibility.[20]

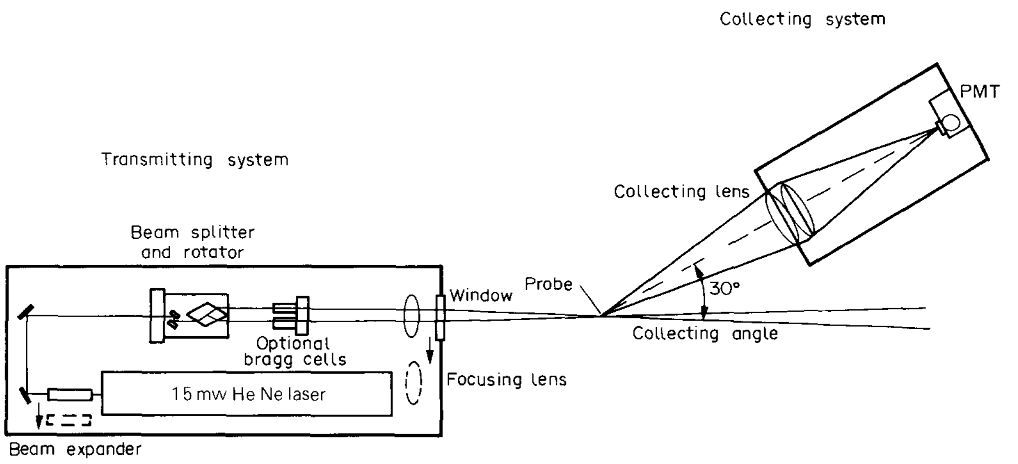

FIG. 17. Laser velocimeter and interferometer system with off-axis collection.[20]

were designed to produce very large fringe spacings for very large particle measurements. The effect of variation of off-axis collection angle on the visibility is shown in Fig. 16.

A Droplet Sizing Interferometer system, incorporating a visibility processor, is available commercially through Spectron[34] and is shown in Fig. 17. The beam from a 15 mW He–Ne laser passes through a beam splitter, rotator, and a lens to provide the measurement control volume at the beam crossover point. The detector is located away from the forward direction. Depending on the off-axis collection angle, typically between 30–150°, from the forward direction, the detector observes either refracted or reflected rays. Such a configuration is applicable for transparent droplets and reflective spherical droplets or solid particles, and results in a usable size range of up to 3000 μm. Bachalo's analysis[29] based on geometric optics, is applicable for droplets as small as 3 μm. The functional form of the visibility curve resembles the case of forward scatter (Fig. 16) except that the location of the first zero ($d/\delta = 1.22$ for forward scatter) takes on a larger value and depends on the index of refraction, angle of observation and the numerical aperture of the receiving lens. References 25–27 discuss further aspects of particle sizing using laser interferometry. Bachalo *et al.*[34] points out that off-axis scatter detection is very effective in reducing the probe volume, thus allowing measurements in higher density sprays. The scattered light intensity is not measured directly so that the method can be used in sprays where some significant extinction occurs. However, if only one of the beams is partially extinguished by a droplet, the fringe pattern has reduced visibility and the recorded drop size is larger than the true drop size. In order to maintain high visibility of the fringe pattern, it is important to obtain highly coherent beams, equal beam intensities and complete beam overlap at the crossover. Even under these ideal conditions, the measurement range is limited to about a decade. This can be improved by using an optical design that covers two ranges simultaneously. The measurement cross-section needs to be normalized as a function of droplet size and droplet frequency differences.

6.2. *Mean Peak Amplitude*

The development of the concept of mean peak amplitude for simultaneous measurement of velocity and particle size in sprays as developed at Sheffield University is described by Chigier.[6,9,30,31] By attaching particles of known size to a transparent section of a rotating disc traversed through various sections of the measurement control volume, it was demonstrated that linear relationships between pedestal peak amplitude (Fig. 14) and particle diameter could be obtained for particles between 30 and 300 μm in diameter. This was only valid for particles passing through the center of the measurement control volume and differences in calibration were found between transparent and opaque particles. By using an additional collection system and photomultiplier at right angles to the axis, a discrimination system was fitted to the logic of the signal diagnostics so that only particles passing within 100 μm of the center of the measurement volume were measured.

By using an optical system with off-axis forward-scatter mode with a narrow vertical slit photomultiplier aperture, the dimensions of the region in which particles produce scattered light at the collecting photomultiplier were reduced, so that the effective length of the measurement control volume was reduced. A collection angle of 6.8° was selected to preserve signal-to-noise ratios sufficiently high to obtain accurate velocity measurements and yet large enough to produce a significant reduction in the length of the measurement volume in which particles were detected. A vertical slit aperture (84 μm wide) resulted in signals being accepted in a diagonal slice (230 μm wide) of the measurement volume. The reductions in dimensions of the measurement volume were not as great as could be achieved by using the gate photomultiplier at 90°, but the off-axis geometry had the advantage of eliminating the requirement of a second photomultiplier. This off-axis geometry enabled high particle densities of at least $10^{10}/m^3$ to be measured without the statistical probability of more than one particle being measured at the same time. This density limit is sufficiently high for most low-to-medium flow-rate fuel sprays except very close to the atomizer. In addition to the calibrations made by traversing individual particles through the measurement volume, further calibrations were made using mono- and polydisperse sprays. Direct comparisons were made of size distributions measured by the laser anemometer and with those measured by a standard impaction technique.

The distribution of light intensity across laser beams is generally Gaussian resulting in spatial ambiguity inside the measurement volume. Small particles passing through the center of the measurement volume may scatter the same amount of light power as larger particles passing through the outer edges. The off-axis light collection system minimized this spatial ambiguity along the optical axis by reducing the length of the measurement volume "seen" by the photomultiplier tube. In order to eliminate the spatial ambiguity along dimensions perpendicular to the optical axis, statistical inversion techniques were used. These, however, caused a statistical bias in the measured size distributions towards smaller particle diameters.

More recently at Sheffield University, a system has been developed to provide a uniformly illuminated, "top hat" profile, measurement volume. A Spectra-physics 2 W argon ion laser producing a beam with an approximately Gaussian light intensity profile with a $1/e^2$ diameter of 1.2 mm was used. The incident laser beam is expanded by a beam expander to a beam with a $1/e^2$ diameter of 48 mm which illuminates an iris aperture of 16 mm diameter. The beam from the iris passes through a second beam expander, a prism beam splitter and two lenses to produce an image of a uniformly illuminated measurement control volume at the crossover region of the two laser beams. Particles traversing the interference fringes in the control volume produce doppler signals of "top-hat" profile instead of the conventional Gaussian distributions. Since the light intensity distribution is approximately normal to the optical axis the spatial ambiguity is minimized and the measured amplitude of the mean doppler signal is directly proportional to the particle diameter. Using a beam spacing of 50 mm and a cross beam angle of 5.71°, provided a measurement volume of 353 μm in diameter with a length of 100 μm. An off-axis collection angle of 27° is used and the light collection angle, defined by an iris aperture of 10 mm diameter, is 1.52°. The image of the control volume is focused on the front surface of the photomultiplier tube housing with a collection lens of 2.6 magnification. A slit aperture of 260 μm width is used to define the dimensions of the control volume.

For signal processing and data analysis, the peak amplitude of each doppler signal is measured. Fringe modulations are averaged out by a low pass filter unit. A differential level detector circuit, in conjunction with a sample and hold circuit, detects the peak of each filtered doppler signal above a variable threshold level, and outputs a voltage proportional to the signal height. This voltage level is kept constant until the circuitry is triggered by the arrival of a new particle inside the measurement volume. A frequency tracker is used to measure particle velocity. Two analog signals, one proportional to particle size and the other proportional to particle velocity are digitized and stored in a minicomputer. The system is calibrated using a vibrating orifice droplet generator.

6.3. *Simultaneous Measurement of Visibility and Pedestal Amplitude*

Spectron has recently extended the capability of the Droplet Sizing Interferometer (DSI) to include the utilization of the pedestal intensity. The simultaneous determination of visibility, intensity, and fringe period provides the basis for establishing droplet size via a validation criteria as well as droplet velocity. Droplet size distribution, velocity distribution, and velocity correlations are provided by appropriate data reduction software. The need for a direct calibration of intensity is alleviated by an automated setting of the voltage to the photomultiplier. The added capability has resulted in a significant increase in instrument accuracy, especially for measurements in dense sprays. The new Spectron visibility, intensity, period processor can be utilized with the DSI optical system or with LDV optical systems having proper beam quality and appropriate lens selection.

TSI[35] is currently developing a visibility module for use in conjunction with a TSI laser anemometer system. This provides simultaneous measurement of velocity, visibility and pedestal amplitude operating in conjunction with the TSI LDV signal processor. The system has a large input doppler frequency range from 1 kHz to 2 MHz with high data rates up to 50 kHz.

The photodetector output is fed to the visibility module. The signal is passed through a variable gain amplifier where amplitude levels are appropriately adapted and then split into three by a power splitter. One output from the splitter is sent to the pedestal integrator, from which pedestal amplitude information is obtained as a 16 bit binary word. The second output passes through a high pass filter to remove the pedestal and then to a doppler burst rectifier-integrator door in the visibility module. The third output from the splitter goes to the LDV signal processor for velocity measurement. At the end of a burst, the integrals are auto-ranged to the twelve most significant bits and amplified for amplitude levels. A Hardward "divide" function is then performed giving visibility as a 9 bit word.

In conjunction with computer simulations for

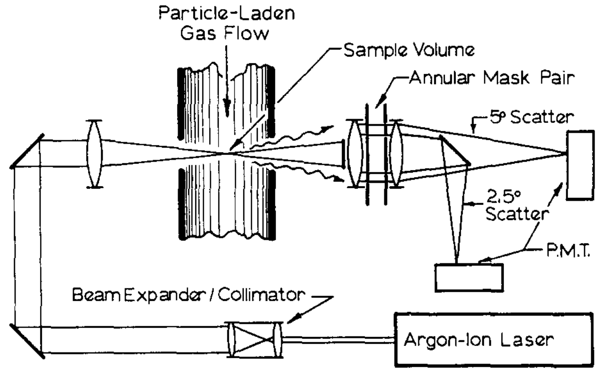

FIG. 18. Ratioing optics system for particle sizing.[20]

system synthesis and performance optimization, three major operational areas are evaluated:

(1) For optimizing overall system performance, calibrations under controlled conditions are made.
(2) Determination of fringe spacing. For large fringe spacing, ambiguity associated with multiple valued regimes of visibility–particle size relations must be avoided. A rotating wheel is used to provide higher accuracy for fringe spacing than can be determined from optical geometry criteria.
(3) Anomalies and ambiguities arising from particles passing through different sections of the probe volume are "corrected for" on the basis of experimental conditions.

Calibrations using a rotating disc, vibrating orifice generator, electrostatic classifier, and aerodynamic particle sizes are used with the results loaded directly on the computer. The counter processor is interfaced directly with the computer.

6.4. *Scattering Intensity Ratioing*

The scattering ratio technique described by Hirleman[33] is used to analyze the angular scattering pattern. This method eliminates the incident intensity ambiguity and effectively normalizes out the incident intensity factor. This approach is commonly used in light scattering ensemble analyzing techniques (nephelometry). The scattering pattern, on the average, is constant in time; a single detector can be rotated around the sample to different scattering angles relative to the incident laser beam. To observe the normalized scattering pattern in real time requires an array of detectors placed at strategic scattering angles. A response curve for the ratio technique as calculated by Lorenz–Mie theory indicates multivalued response problems, and the addition of more angles providing additional signal ratios eliminates the ambiguity as discussed by Hirleman.[33] The multiple ratio single particle counter concept was used by Hirleman,[33] with four angles, although it becomes less practical as the number of angles increases.

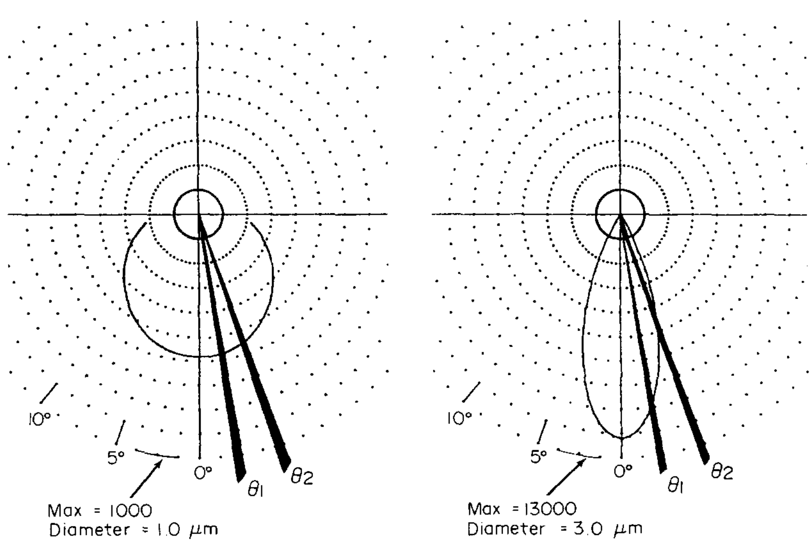

FIG. 19. Expanded forward scatter lobes showing collection angles for intensity ratioing.[20]

Barthiuldi *et al.*[38] have used a photodiode array to get a finely resolved measurement of the angular scattering pattern from individual particles. Hirleman[36] in a review of single particle counters considers that the diode approach has considerable promise and will probably be used in the future.

A ratioing processor has been developed by Spectron[20] and is included in the integrated particle sizing system. A schematic diagram of the ratioing optics system is shown in Fig. 18. An annular mask pair is introduced into the collection optics system so that scattered light at two angles (5° and 2.5°) in the near forward direction is observed. The ratio of the two measurements is a function of particle size. The expanded forward scatter lobes and the collection angles for intensity ratioing are shown in Fig. 19. The actual form of the ratio/size function also depends on the wavelength, angles and to some extent (for non-absorbing particles) the index of refraction. In the Spectron ratioing processor, subtraction of two input signals is performed. When these input signals are derived from the logarithmic amplifier, the processor in effect produces the quotient, which can be related to particle size from the intensity ratioing sizing technique. The quotient is available in digital format for computer interfacing. High speed data acquisition, up to 100 kHz, can be achieved. The lower limit on size is 0.3 μm. The ratio of received flux versus particle size diameter for various angle pairs, for the forward lobe ratio method is shown in Fig. 20. A small angle ratio counter is applicable for particles from 0.3 to 5 μm.

An extension of the above technique to smaller particle sizes is described by Wuerer *et al.*[20] The two ratioing detectors are placed at large angles, e.g. 20°/40° and 20°/60°. This allows the lower size limit to be extended to 0.08 μm. A system has been built[20] which utilizes small and large angle ratioing simultaneously to obtain a size range of 0.08–5 μm.

7. VELOCITY MEASUREMENT IN SPRAYS

Measurement of velocity of particles of all sizes encountered in sprays can be accurately made by using conventional commercially available laser anemometry. Measurements of local gas velocity can be determined either from measurements of very small droplets in the spray or by artificially seeding the gas flow with submicron sized solid particles. Measurements of velocity in sprays have been made at Sheffield University by Chigier *et al.*[39] since 1975 and at UTRC by Kennedy *et al.*[10] since 1976. The early measurements by Chigier *et al.*[39] and at UTRC[10,40] could not obtain an accurate measure of drop size but distinction was made between droplet and gas velocities.

In the study at UTRC[10,40] measurements of local gas and droplet velocity, and mean spray trajectory were made using a dual-beam anemometer, utilizing a crystal Bragg cell acting as a beam-splitter to frequency-shift the first deflected beam. The sensing volume, determined by beam crossover volume, off-axis collection and photomultiplier-hole size, was elliptic with principal axes of 0.2 and 2.0 mm respectively. The measured velocity component was in the plane of the two incident beams and perpendicular to their bisector. Single-particle, time-domain, signal processing was used to build up the velocity probability density distributions from which both mean and RMS velocities were obtained. On-line signal processing by microprocessor was used to compute, display and record local mean velocity, turbulent intensity and probability density functions.

The optical sensitivity of the forward scatter system was sufficient to detect signals from naturally occurring submicron particles in the air flow far from the fuel spray. The signal-to-noise ratio and the data-acquisition rate were increased by seeding the air flow

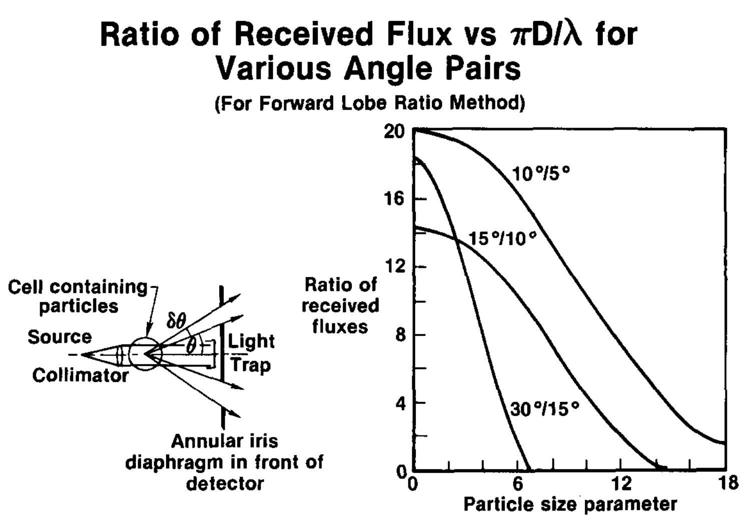

FIG. 20. Ratio of received flux as function of particle size parameter for forward lobe ratio method.[21]

with micron-sized particles. The size and density of the particles were such that the particles could follow velocity fluctuations in the Eulerian frame of reference with frequencies below 25 kHz to within 10%.

To circumvent problems associated with directional ambiguity (which can result in data interpretation errors in highly turbulent and/or recirculating flows), zero velocity frequency offset was achieved by combining the primary and modulated beams at the detection volume where they generated moving fringes so that a stationary particle produced a doppler frequency.

For measurements of droplet velocity, a moving fringe system has an additional advantage. The maximum number of fringes within the probe volume is determined solely by the input beam spacing to diameter ratio. Most commercial counting devices require a minimum of eight cycles. Liquid fuel sprays from pressure-atomizing injectors have a size distribution over a wide range (up to 250 μm) with typical Sauter mean diameters between 75 and 150 μm. The minimum fringe number requirements may produce problems of spatial resolution associated with stationary fringe systems since optimum signal/noise is reached when the fringe spacing is greater than or equal to the maximum droplet diameter.

In regions of the spray where there is substantial difference between gas and droplet velocities, bimodal velocity probability density functions were obtained. Without seeding, droplet velocity distributions were determined directly. This distribution was normalized by the total number of velocity determinations used, and then subtracted from the bimodal distribution obtained at the same location with air seeding. Local gas mean velocity and the variance were then determined.

Measurements showed large differences between local droplet and gas velocity. Probability density distributions indicated that the local gas velocity fluctuations were larger than the corresponding droplet velocity fluctuations. Close to the injector, large differences between local droplet and gas velocities were found with evidence of gas flow recirculation.

In regions of high droplet number density, particle visibility variations were employed to infer local gas velocity. The doppler frequency produced by moving fringes over a stationary particle was adjusted so that only particles passing through the center of the focal volume generated sufficient fringes for valid velocity measurements. Velocities for different ranges of particle size were obtained by altering the amplitude threshold (visibility level) required for velocity determination. Since the relative velocity between a particle and the local gas velocity (particle lag) is a function of the square of its diameter, these velocity measurements should be linearly related to the square of the visibility level. Extrapolation to zero visibility was used to obtain local gas velocity. By this means local droplet velocity was distinguished from local gas velocity in regions of high droplet concentration.

Following the development of the simultaneous measurement of droplet size and velocity at Sheffield,[6] direct correlations could be obtained between particle size and velocity in sprays. A series of measurements were made in nonburning and burning spray systems. Temporal size distributions for measurements were made at the same position in cold and burning kerosene sprays by the laser anemometer.[41] The cold spray was found to have a wider size distribution over the size range measured between 15 and 50 μm. These changes were explained as being due to preferential evaporation of small droplets, leading to total evaporation of the smallest droplets with a residue of larger droplets. The calculated local volume flux of droplets after ignition was found to be greatly reduced, due to combustion and evaporation. The mean droplet velocity and the variance of droplet velocity were measured as functions of droplet diameter. These results showed that the mean velocities of larger droplets were higher than those for the small droplets. This demonstrated that the relatively small droplets lose most of their momentum soon after leaving the nozzle exit, due to their higher drag/inertia ratios, but the larger droplets are less affected because of their lower drag/inertia ratios. These measurements demonstrate the capability of the laser anemometer to measure local particle-velocity differentials, from which local Reynolds numbers and drag coefficients can be determined under conditions of vaporization and burning.

7.1. *Laser Transit Anemometry* (*LTA*)

In the two-spot laser transit anemometer, two separated ellipsoidal volumes are formed by precisely focused waists of two laser beams. The differences between laser transit anemometry and laser doppler anemometry are demonstrated in Fig. 21. In laser transit anemometry the velocity is obtained by dividing the spot separation by the measured flight time. Spot diameters of the order of 15 μm with separation distances of 350 μm are used, but probe volume lengths can be reduced by using off-axis collection.

In laser transit anemometry, a single laser beam is split into two equal power beams which are focused to form two intensely illuminated spots, whose separation-to-size ratio may be between 20 and 40. Each spot is viewed with a separate photomultiplier to detect back-scattered light from particles crossing the spots. Suitably discriminated signals from these particles which move through the spots can be cross correlated to yield a histogram of transit times for particles which may be inverted to give speed probability in a chosen direction. The plane containing the spots may be rotated to explore different flow directions.

Spots must be free of aberrations and be closely parallel near the region of focus to avoid spurious broadening of velocity probabilities. Lenses used in the system must have good freedom from aberrations.

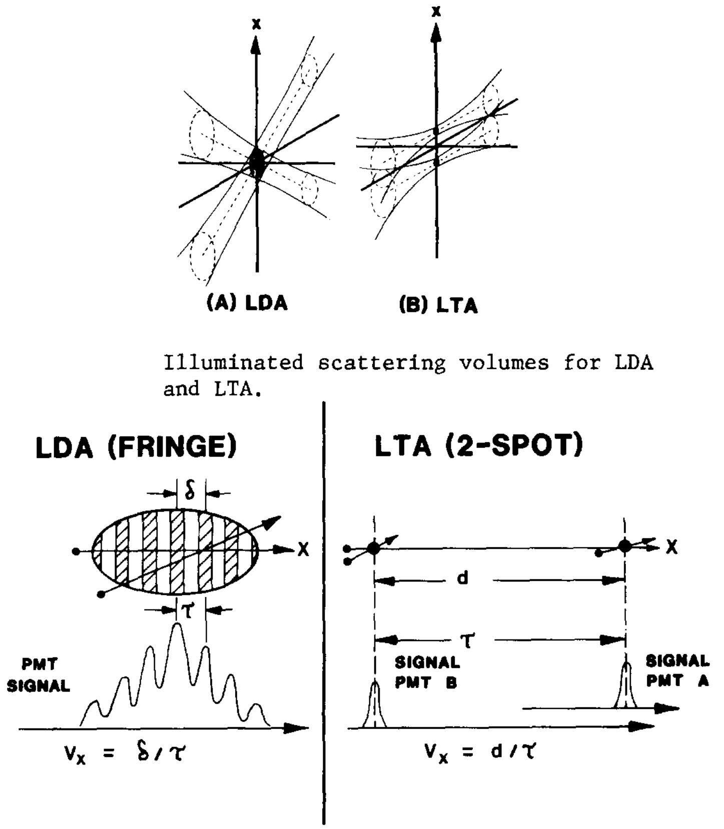

FIG. 21. Velocity determination by laser doppler anemometry and laser transit anemometry.[20]

Stops must be used to reject light from all places except from the region of the spots. The use of a Wollaston prism beam splitter enables the relative beam intensity to be adjusted and disposes the transmitted beams symmetrically about the optical axis. The focusing lens produces two spots from the diverging, but almost collimated beams. The center of the beamsplitter is near to the back focal plane of the lens which acts as a Fourier transforming element.

The rotator prism allows precise, computer controlled spot rotation about a common center. The mirror image rotator is designed to be aberrationless, short and efficient for easy and precise rotation of the mirror. The optical system is supported by a data management system based on a microprocessor and software having limited user program ability. Recent advances in laser transit anemometry are reported by Smart.[42]

Laser transit anemometer systems can be configured in many ways ranging from direct forward to direct back scatter. Back scatter is used only when single optical port access is available in test sections. Scattered light intensity is several orders of magnitude less in back scatter than in forward scatter, producing low signal-to-noise ratios. Commercial LTA systems use concentric transmitting optics to provide a compact rotatable optics unit requiring a minimum diameter optical access. More effective back scatter collection is possible because of the much greater spot intensity compared to fringe intensities for comparable laser power. Good quality signals can be obtained using seeding particles as small as 0.2 μm. LTA offers significant advantages over LDA for high speed flows and for measurements close to walls. The more sophisticated LTA systems[42] have rugged concentric back scattered optics, automated flow direction scanning and a 256 channel/64 station multiplex correlator.

8. FRAUNHOFER DIFFRACTION PARTICLE ANALYZER

For measurement of average size distributions of clouds of particles in sprays, the Fraunhofer diffraction particle analyzer is proving to be one of the most convenient and reliable instruments. It is particularly useful for testing global characteristics of sprays from a wide variety of injector nozzles. The instrument is based on well known optical principles and requires no calibration. It can be used for particles larger than 1 μm. The instrument was developed at the University of Sheffield by Swithenbank *et al.*[43] and is commercially available through Malvern Instruments.[44]

The technique is based on the Fraunhofer diffraction of a parallel beam of monochromatic laser light

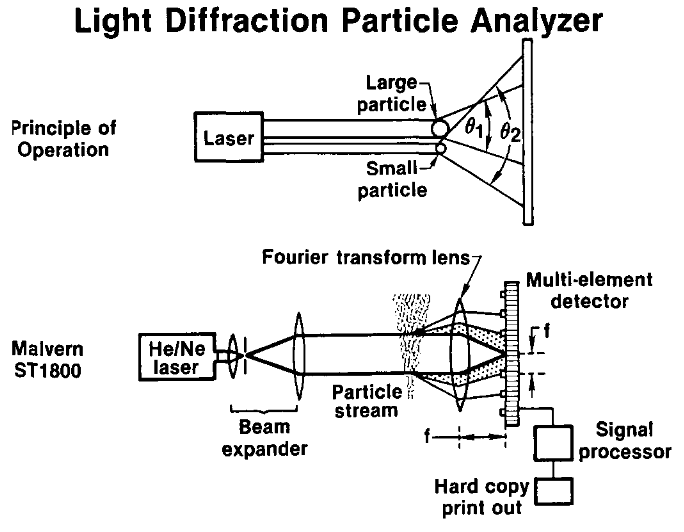

FIG. 22. Fraunhofer light diffraction particle analyzer.[44]

by moving particles. When a parallel beam of monochromatic light (Fig. 22) interacts with a particle, a diffraction pattern is formed whereby some of the light is deflected by an amount depending on the size of the particle. A Fourier transform lens is used to focus a stationary light pattern onto a multi-element photodetector to measure the diffracted light energy distribution. When particles of different diameter are present in the light beam, a series of focused rings are generated at various radii, each focused light ring being a function of the particle size. These focused rings are detected by a special multi-element detector, the output of which is multiplexed through an analog-to-digital converter.

The analysis of the measured light energy distribution into particle-size distribution is carried out by the computer, providing an immediate display of the measured size distribution. One particular advantage of this technique of measurement, is that the diffraction pattern generated by particles is independent of the position of the particle in the beam. Hence, measurements can be made with the particles moving at any speed. Also, for a group of particles, the combined diffraction pattern is directly related to their size distribution.

In the Malvern instrument, three focal length lenses are used: 63, 100 and 300 mm. The lens focuses the light on to a 30-element, concentric, semi-circular, light-sensitive, ring detector with a hole in the center. Behind the hole is a photodiode which is used for alignment and for measuring the intensity at the center of the pattern. Data are collected for background alone and then for signal plus background. Data is taken by sweeping all 30 rings a number of times. During a single sweep, ring signals are collected serially digitized, and stored in the computer for averaging with the next sweep. Typically, a few hundred sweeps are taken to ensure that a representative randomly oriented sample from all size classes has been measured.

New software developed by Malvern[44] allows for a variety of user selectable features. The data may be analyzed in terms of a histogram with 15 size classes. Data sets are stored in any one of 32 RAM memory blocks. Mass storage of data is available on magnetic tape or discs.

With the live display of data it takes 35 msec to serially sweep all 30 rings. For faster, snapshot-like measurements, a new system is available which takes data from all 30 rings, in parallel, in 10 μsec. This may be repeated at 35 msec intervals by simultaneously recording signals from each ring. Measurements have been made, at the University of Sheffield, in high-speed, pulsed diesel spray systems. Several investigators have made independent comparisons of measured size distributions with the Malvern instrument by using standard latex particles and monosize drop generators. These comparisons and a discussion of an increasingly wide number of applications are discussed in detail by Weiner.[45] The basic advantages and disadvantages of the Malvern instrument have been summarized by Weiner[45] as follows:

(1) The instrument is very versatile. It can be used for size distribution analysis in sprays over a broad size range. The computer and printer allow for a large choice in data analysis, manipulation and presentation.

(2) The measurement is nonintrusive. There is no probe to disturb the flow and introduce sampling errors.

(3) In the range where Fraunhofer diffraction theory is applicable, no calibration is necessary. Results are independent of the refractive index and absolute accuracy is of the order of 5 %. Below about 10 μm some systematic errors may occur.

(4) Repeatability is the order of 3 %. Resolution is good, provided the correct lens is used to make the measurements.

(5) The instrument is quite easy to set up and

operate. There are no orifices to clog, no images to analyze, and no extensive calibration procedures to follow. Typically, measurements take a few seconds, and results are calculated in a few minutes.

(6) Although it is not possible to use the technique when the transmittance is low, the range of concentration over which the results are obtainable is competitive with most other techniques.

(7) The instrument is not a single particle counter and does not provide absolute concentration measurements. It does, however, on sample, average over a large number of particles rapidly and over a region of space.

9. CONCLUSIONS

From the review that has been given of optical instruments for measurement of particle size and velocity, it can be seen that there is a wide range of instruments that are now commercially available. Imaging techniques still have an important role to play providing some of the simplest techniques in the form of direct photography to the more sophisticated TV image scanning systems. The newer developments in automatic image analysis will lead to substantial reduction in the tediousness of analysis of results.

High speed motion and TV cameras are required in order to record the dynamic characteristics of the sprays for detailed analysis of individual particle trajectories and also for determination of general unsteadiness and nonuniformities in the sprays.

Holography is re-emerging as an important method for obtaining two- and three-dimensional "frozen" pictures of large volumes of the spray. Holography has a distinct advantage over other imaging techniques with small depths of field.

Substantial advances have been made in single particle counting using laser interferometry for particle sizing. Visibility can now be used over a wide range of particle sizes including particles larger than the fringe spacing. The combination of measurement of visibility and pedestal amplitude is leading to more accurate measurements of individual particle size in sprays. The use of the scattering ratio technique is an additional means of determining particle size, being particularly applicable to small droplets and particles, less than 5 μm diameter.

Velocity measurements by conventional laser doppler anemometry are well established and measurements of particle and gas velocity can be readily made. Laser transit anemometry offers an alternative method for velocity measurement particularly in the proximity of wall surfaces.

The Fraunhofer diffraction particle sizer for global measurements of size distribution is the simplest method for use and is being extensively adopted in laboratories for testing overall spray characteristics. It provides accurate, repeatable and reliable results in a wide range of environments, but it does not give information on individual particles.

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