Summary

The following papers present reviews of several different techniques used to determine the drop size of sprays under various conditions and for certain applications. The main drop size measurement techniques that are discussed are; light scattering, resonance light scattering, laser-video imaging, collection of drops on glass plates, and drop interaction with a hot wire. The usefulness of the various techniques is demonstrated by the writers who cite a wide variety of applications in the field of liquid atomization. Also, new developments of various techniques are presented, and improvements over past approaches to measurement of drop size are demonstrated.

The paper by Bachalo presents an overview of drop size measurement problems encountered in the application of measurement techniques to the investigation of agricultural sprays, liquid fuel spray combustion, the atmospheric study of cloud droplets and icing research, and the design of industrial equipment such as spray scrubbers. General requirements for the selection of a drop-size measuring instrument for a particular application are discussed with emphasis being placed on instrument capability in covering a wide drop-size range while providing good resolution and accuracy. The desirability of nonintrusive techniques and systems having automated data acquisition and processing are recommended. Light-scattering and imaging techniques are compared in terms of their relative advantages and disadvantages. The writer concludes that careful selection of a measurement technique must be made on the basis of application requirements in order to obtain drop-size data that can be used to satisfactorily characterize a spray. To do this, nine criteria of instrument capability are listed, and it is emphasized that no single instrument can be expected to meet all of the nine requirements. In the final selection of a technique, the weighing of the cost of the instrument in dollars and the time needed to learn how to obtain and process the data must be also considered. Finally, the writer concludes that "it is normal for manufacturers to expound the capabilities and virtues of their instruments and overlook the limitations."

An improved light-scattering technique is discussed in the paper by Rizk and Lefebvre. The original technique was used to measure Sauter mean diameter, D_{32}, whereas the improved technique yields not only mean drop diameter data but also drop size distribution data. To accomplish this, the light intensity profile used to measure mean drop size is converted into an energy distribution which is then related to drop-size distribution. Values of D_{32} show fairly good agreement with those determined by an imaging or photographic technique. Also, the drop-size distribution calculated from energy distribution was found to agree well with both the particle size distribution of a standard calibration reticle and the drop-size distribution measured with a Malvern light-scattering instrument. Although the authors neglect discussing how they deal with background light when there is no spray in the light path and it is not clear how a light energy distribution curve is obtained from a relative light intensity curve, the authors' improved technique does show a marked improvement in usefulness over that of their original light-scattering technique.

In the paper by Dodge and Cerwin, the modification of a forward light-scattering technique is discussed in terms of extending the applicability of the Malvern instrument to the measurement of drop size of fuel sprays evaporating in high-temperature air with high-thermal gradients and high levels of background light such as that produced by flame radiation. Light distribution from a spray is "corrected" and Sauter mean drop diameter, D_{32}, is determined from the Rosin-Rammler distribution. Actually, the correction is made by recomputing a light distribution based on the outer 24 channels of the 30 channel detector so that the "corrected" light distribution "follows the shape expected for the scattering from a spray." Errors inherent in such a correction "increase with the number of detector signals which have to be ignored." By means of the modified technique, the usefulness of the Malvern instrument has been substantially extended by the writers to include drop-size measurements of evaporating sprays at distances relatively close to the atomizer with air temperatures and pressures as high as 700 K and 586 kPa. However, farther downstream from the nozzle the technique proved ineffective due to the high concentration of vapor. Also, attempts to apply the technique as a method of discriminating against background radiation produced by the flame did not produce "reasonable data under these conditions."

The survey type of paper written by Ferrenberg covers the state of the art of fuel spray investigations involving rocket combustors, discusses various droplet measurement techniques, and presents droplet sizing interferometry data. The writer emphasizes the importance of measuring gas velocity profiles in combustors in order to determine droplet velocity relative to gas velocity. Also, he points up limitations of previously applied techniques of measuring fuel drop size in rocket combustor studies and discusses the need for collecting temporal drop-size data rather than spatial drop-size data, since the former is more applicable to computer modeling atomization and other rocket combustion processes. An interferometric technique, which yields temporal drop-size data, is discussed, and an improved version employing principals of both signal visibility and peak intensity appears to be quite promising in providing drop-size data for a more dense concentration of droplets.

A review of resonance light scattering as a means of obtaining ultrahigh resolution sizing of 5 to 50-μm-diameter liquid drops is presented by Lettieri and Jenkins. The status of this technique is reviewed from the beginning of the theory of the resonance phenomenon in light scattered from dielectric spheres up to the present. The review also addresses the usefulness of resonance to experimentally determine the size of evaporating and nonevaporating drops as well as the mean drop size of "growing" aerosol drops. Finally, resonance light scattering from aspherical drops is briefly discussed, since very few theoretical or experimental studies have been made on this subject. Most investigations involving the technique of resonance light scattering have been made with individually levitated liquid drops. However, a reference is cited in which light-scattering resonances were obtained with a narrow size distribution aerosol of "growing" water droplets. The mean drop size was measured as a function of time. This technique appears only to be valid if the percent variation in drop size is quite narrow, that is, between 0.6 and 2.4%.

A description of a laser-video imaging system employing "computer vision algorithms to reduce the effects of shading and to segment candidate drops from each image" is presented by Oberdier. Pulsed-laser illumination of fuel sprays producing droplet images are stored on magnetic video disks and analyzed with an image processor and minicomputer. Various methods of pattern recognition are considered to determine drop size and to reject those outside of the sample volume. The shading of video droplet images due to films on windows and instrument nonuniformities required four image processing steps, that is, restoration, segmentation, feature extraction, and classification of in-focus and out-of-focus drop images. For image restoration, the Log-Sobel edge enhancement method and shading estimation by ensemble averaging appeared attractive. It was found that "the use of ensemble averaging of multiple images to estimate a shading function followed by the normalization of each image by that function works well on the images tested." Finally it is stated that "edge enhancement of log-compressed images using the Sobel operator is promising but needs more testing."

The paper by Popa and Varde presents drop-size distribution data for diesel No. 2 fuel atomized in a chamber at atmospheric pressure with very high fuel pressures. The fuel injection system was specially designed to operate at fuel pressures up to 150 MPa (22 050 psig). When fuel pressure was increased from 50 to 140 MPa, the Sauter mean diameter, D_{32}, decreased from 26.5 to 17.5 μm with a 0.19 mm orifice-diameter fuel nozzle. Fuel flow rate was 4.5 to 9 g/s. The technique used to obtain drop-size data consisted of collecting fuel drops on glass plates treated with a surface modifier, photographing the collected drops, and measuring them with an image analyzer. Automation in the analysis process gave accurate measurement of a large number of drops including those having a diameter as small as 0.5 μm. A good discussion of this method of measurement is given in the paper, and the drop size data are compared with that obtained for the same test conditions by using direct photography of the spray and also by collecting the drops and freezing them in liquid nitrogen. The results obtained with the three methods showed that values of D_{32} agreed within $\pm 5\%$.

A review of the usefulness of the hot-wire technique in obtaining drop diameter data for sprays is discussed by Mahler and Magnus in terms of advantages, limitations, and applications of the technique in comparison with other techniques. The writers address methods of calibration, factors affecting drop and wire interaction, and calculations of mean drop size, volume concentrations, and flow rates. Calibration is achieved by determining the size of a drop photographed while contacting a constant temperature, 5-μm-diameter platinum hot-wire sensor and then correlating drop diameter with the measured electronic pulse occurring from the droplet and wire interaction. Factors are discussed that introduce errors in spray analysis with the hot-wire technique, such as, aerodynamic effects on small drops, eccentric collision effects for various liquids, and wire temperature distribution effects. The method of analyzing drop-size data obtained with the hot-wire technique is also described. Applications of the technique to in situ drop size measurements of sprays in demister towers and scrubbers and sprays produced by liquid aerosol generators are discussed. Features such as simplicity of design and operation, light weight, and battery operation are given as some of the advantages of the hot-wire technique as compared with other techniques.

In the paper by Simmons, instruments that are commercially available for measuring liquid particle size are discussed from the standpoint of matching user requirements with instrument capabilities and characteristics. The characteristics of imaging or photographic techniques and nonimaging or light-scattering techniques are contrasted and the advantages in some cases of using both techniques is brought by the writer. Commercial instruments are available to cover the entire size range of general interest in spray investigations although some may have a limited range. If drop-size distribution is to be determined, an instrument that is not based on an assumed size distribution is to be preferred, and the choice of a size class interval often requires further investigation. Instruments are available that will give either spatial or temporal size distribution data. The choice usually depends on the type of data required in the study. Drop-size measurement accuracy is generally not clearly stated by instrument manufacturers nor are the users' requirements of accuracy. Calibration checks are more frequently needed than anticipated by instrument designers, and there is generally insufficient data available to predict the useful life of an instrument. Also, cost aspects of equipment usage need to be investigated more thoroughly by both instrument manufacturers and users of the equipment. Finally, the writer emphasizes the current need for better communication between potential users and particle size measurement instrument manufacturers, particularly in terms of the scope and needs inherent in the application of the instrument to liquid spray studies.

The emphasis of Hirleman's review is on particle sizing by optical nonimaging instruments that will measure liquid particle diameters greater than 1 μm and fall within the class of multiparticle analyzers or that of single particle counters (SPC). The theoretical basis, performance characteristics and calibration considerations for the various methods in each class are discussed. Also, the writer addresses the three subjects of laser diffraction ensemble techniques, cross-beam dual-scattering interferometric SPC, and finally single beam SPC based on the measurement of partial light-scattering cross sections of the particles. Various problems such as multiple scattering effects due to a high number density of particles or due to a varying refractive index produced by evaporation or thermal gradients are discussed and possible corrections are suggested. Calibration standards for optical nonimaging instruments are discussed, that is, polystyrene latex spheres, glass microspheres, photo-mask reticles, droplet generators, and spray nozzles capable of producing a standard polydisperse spray. The writer stresses the need for both size and concentration standards of measurement. He refutes the view that laser diffraction instruments might not require calibration. Finally, it is pointed up that, in attempting to reconcile drop size data obtained with various instruments, the characteristics of each instrument is very important and whether the technique yields spatial or temporal data must be known before making the comparison.

In discussing droplet characteristics determined with conventional and holographic imaging techniques, Thompson points up the satisfaction of actually seeing drop images that are directly recorded and stored by imaging techniques of drop measurement as compared with results obtained with indirect nonimaging methods. Comments are made concerning conventional imaging methods using both one and two-lens systems, with both incoherent and coherent light. The problem of determining the exact image plane and magnification with a single lens imaging technique is pointed up as a cause of size measurement error. The use of the two-lens method removes this error which is inherent in the single lens system. In discussing holographic methods, the writer concentrates on the inline far-field method of producing holograms that contain information on both the cross-sectional geometry of each particle and its position. The major limitation of the far-field holographic method results from the use of transmitted light by which particles are transilluminated. Although the method can not be used with scattered or reflected light, limited success can be achieved with the use of a separate reference beam. Finally, it is suggested that holography "might well provide an imput for calibration of other methods."

A review of techniques used to determine the size and velocity of liquid particles in spray analysis studies is presented by Chigier. Pulsed laser photography, holography, TV, and cinematography are discussed as well as laser diffraction, laser anemometry, and interferometry using visibility, peak amplitude, and intensity rationing. Methods of instrument calibration and statistical analysis are examined. Previous comparisons of imaging, interferometric, and diffraction instruments are also reviewed. Those who select a commercially available instrument are warned against over estimating its capability and under estimating the experience, time, and effort required to effectively use it. Also, it is noted that it is difficult to compare the measurement of drop size obtained with different instruments due to the erratic nature of spray formation caused by hydrodynamic and aerodynamic instabilities. Since it is generally not feasible to make simultaneous measurements with different instruments, the writer suggests that a spray generator is needed which will reliably and continually reproduce a polydisperse standard spray drop-size distribution for instrument calibration. Finally the writer discusses a project to simultaneously, "where possible," and sequentially obtain "measurements of sections of standard sprays . . . using pulsed laser photography, cinematography, interferometry (visibility, peak amplitude), and diffraction." The results will be a combination of information rather than a direct comparison of instruments, and "an assessment of the limitations and inaccuracies of current instruments will be made."

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