Overview

Over the last 13 years, during which time ASTM Subcommittee E29.04 has been concerned with Liquid Particle Size Measurement Techniques, there have been profound changes in the technology available to study the processes associated with the creation and use of liquid sprays. Today there is information available from spray measurements which characterize the physical properties of sprays at levels of accuracy and resolution that were, not too many years earlier, thought impossible. The availability of this level of quantitative spray data has the potential to help engineers revolutionize the performance of spray systems in many important applications. The need for improved understanding of liquid spray mechanics has been a significant driving force in the development of instrumentation and techniques to make these measurements possible. The papers in this volume are concerned with these *methods* for characterizing the sizes and velocities of liquid particles (or the percursor liquid fragments), both as individual droplets and as ensembles of droplets in a spray.

The first ASTM Symposium on Liquid Particle Size Measurement Techniques sponsored by Subcommittee E29.04 was held in November 1983 in Kansas City. Twelve technical contributions from that symposium were included as papers in *ASTM STP 848*, which was published in 1984. The present volume includes papers from the second symposium on the same topic which was held in Atlanta in November 1988. The impetus for the second symposium was the accelerating rate of significant advances in the instrumentation and applications of instrumentation in the intervening five years. The papers in this volume provide a necessary addition to the literature beyond that which is available from the archival record of the first symposium.

The Second ASTM Symposium on Liquid Particle Size Measurement Techniques included the presentation of 22 contributed and 4 invited papers. Of these original papers, 19 passed through the peer review process and are included in this volume. The papers naturally divide into 4 subject areas including: calibration and standardization, instruments based on ensemble scattering, instruments based on scattering by individual droplets, and finally, spray measurements and applications.

Calibration and Standardization

One measure of the maturity of an area of technology is the emergence of broad efforts directed toward calibration and standardization. There has been a significant amount of work in standards and calibration for liquid particle and spray characterization instrumentation over the past 13 or so years, with a significant acceleration in the past few years. There are 3 papers in this volume dedicated to calibration methods and standards associated

Copyright© 1990 by ASTM International www.astm.org

with particle-sizing instruments. The first, by Scarlett et al., is a very informative discussion of European efforts in the area. There are some differences between the approach of the European community and that of groups in the United States as delineated in the paper. The significant difficulties associated with preparing and maintaining a sample are discussed, and the need for multiple near-monodisperse modes in a calibration material is presented. The authors suggest that the equivalent volume diameter is the correct parameter to use as a calibrating parameter when nonspherical particles are present. European efforts on standardization will become increasingly important to the United States as the 1992 European Economic Community (EEC) agreements approach.

The next two contributions are concerned with the rather common approach of actively driving Rayleigh instabilities to cause the breakup of a jet into a sequence of constant volume fluid parcels which become near-monodisperse spherical droplets. The performance of an early commercial device based on this process, the Berglund-Liu droplet generator manufactured by TSI, Inc., was discussed in the contribution by Bayvel et al. In this paper, the interaction of light with particles is analyzed at high spectral resolution to elucidate the morphology-dependent resonances (MDR) in Raman and fluorescence spectra. The droplets are illuminated with a neodymium:yttrium aluminum garnet (Nd:YAG) laser, and the fluorescence spectra, which contain a regular array of morphology dependent resonances, are analyzed using an optical multichannel analyzer. The resonance peaks in the spectra can be fitted to those predicted using Lorenz-Mie theory to give a measurement of the size of spherical particles with an estimated accuracy of 0.01%.

A potentially important advance in the technology of monodisperse droplet generators was presented by Dressler and Kraemer. The authors have developed a next-generation device which uses an array of liquid jets of different diameters (each forced through a different orifice in a precise array of orifices) to produce a polydisperse aerosol made up of a number of monodisperse components. This method holds very good promise for a more complete characterization of the performance of droplet-sizing instruments than is possible with conventional single-stream generators or "standard" spray nozzles. The orifice plates discussed in this paper have three rows with seven orifices in each row which produce trimodal droplet streams with diameters from 50 to 450 μm, and measurements indicate that the seven orifices of any one size produce particles of diameters within ±1%. The temporal variation in drop size based on mass flow measurements typically varied less than 1% over many hours of operation.

Spray Diagnostics: Ensemble Scattering Techniques

In the hierarchy of methods that might be used to extract some useful portion of the total information contained in a dynamic three-dimensional spray, the most simple are methods that provide only representative diameters or other aggregate measures describing the ensemble of droplets comprising the spray. A review paper by Felton covered one of these ensemble scattering methods, the so-called Fraunhofer diffraction particle-sizing technique. This method, based on analysis of near-forward scattered light, has been used for more than 40 years in various forms. About 15 years ago, the technologies of monolithic, multi-element photodiode detector arrays and laboratory microcomputers enabled the evolution of a class of instruments which are still very much in use today. Some of the important points of the Felton paper include discussions of calibration techniques, the effects of optically thick (multiple-scattering) sprays, vignetting in the collection optics, and tomographic reconstructions to obtain spatially resolved data from the line-of-sight measurements. Finally, studies comparing the results obtained with the ensemble diffraction method and other optical techniques are considered.

The paper by Mroczka also is involved with the inversion of near-forward scattered light signatures produced by ensembles of particles or droplets. The unique viewpoint expressed here is concerned with the determination of *moments* of the particle size distribution function rather than the distribution itself. The moments can be obtained from measurements of integral or cumulative measures of the near-forward scattered light signature and does not require differentiation of the measured scattered light pattern as do some common integral transform inversion techniques.

Ingebo and Buchele discuss measurement of the sizes of small droplets using a system that scans the near-forward scattered light with one detector. This technique does not require the development or use of a custom photodiode array detector, but does require physical movement of the one detector. In the case of time-independent analysis of sprays, this method can provide a rather simple optical system with which to make droplet-size measurements. The application area covered in this paper involved two-phase flow in pneumatic two-fluid nozzles. The effect of gas velocity on the breakup of small diameter liquid jets in high-velocity gas streams was investigated and an empirical correlation for D_{32} was developed.

Another paper on the generic Fraunhofer diffraction technique as integrated into an instrument is that of Hayashi. This instrument, developed at the National Aerospace Laboratory in Japan, evolved somewhat independently of the U.S. and European instruments based on very similar principles. Hayashi developed a photodiode array detector with a geometry which uses alternating detector rings on both sides of a full circle such that the outer radius of each detector element is equal to the inner radius of the next detector element. This design produces an instrument scattering matrix that has some important advantages over those applicable to other ring detectors. Also, an Abel inversion scheme was used to provide both line-of-sight and local droplet size and concentration information.

The only paper on ensemble methods based on other than the near-forward scattering direction was that of Presser et al. A system was developed wherein polarization properties of the scattered light were used to infer a mean droplet size for an assumed droplet-size distribution function (log-normal). The authors compare their experimental results with those obtained using a phase-Doppler system on a kerosene spray and found some significant differences in the data obtained with two instruments. The authors showed that the assumption that the distribution function was log-normal could not explain the discrepancies.

Optical Single-Particle Analyzers

An approach that potentially provides much more information about the spray than the ensemble methods is one that analyzes individual particles. The tradeoff is one of instrument complexity and measurement time, but there are many applications when the improved resolution and velocity information are absolutely necessary for a complete understanding of the spray mechanics. There are five papers dedicated to various issues related to single-particle counting devices.

Baumgardner et al. provide a thorough study of the performance of the Forward Scattering Spectrometer Probe (FSSP) manufactured by Particle Measuring Systems Inc. The complete characterization included consideration of the instrument performance as indicated by measurement accuracy and considered both sizing errors and the often overlooked contributions resulting from counting errors. The results of this theoretical analysis clarified some significant errors which may occur in practical applications, and these errors were shown to result from the effects of instrument response time, spatial nonuniformity in the laser beam intensity profile, and coincidence. Off-line algorithms were developed to adjust data obtained from the FSSP and correct for these sources of error.

Zhang and Talley were concerned in their paper with imaging techniques and, in particular, image-processing schemes that might be used to determine automatically focus quality and statistical information about nonspherical particles. Methods for objectively quantifying data on nonspherical liquid fragments or particles are crucial for understanding the important processes that occur at the very beginning of spray formation in which typically a liquid sheet is broken up into liquid fragments which eventually relax into droplets. Most non-imaging optical particle-sizing instruments make some type of a spherical particle assumption and, for that reason, are generally not useful in extracting morphology information on nonspherical particles. In this case, imaging schemes are probably the only hope of obtaining useful experimental data, and Zhang and Talley have carefully addressed some of the issues that are faced when the image of a particle field must be *quantitatively* analyzed.

Picot et al. compared several optical methods for characterizing the sprays produced by aerial spray nozzles. The instruments used included imaging (OAP-260X) and light-scattering (FSSP-100) probes from Particle Measuring Systems and a flash photography system developed by the investigators. In the experiments, a multiple-jet boom system was operated in a laminar flow wind tunnel. An interesting aspect of the work was the combination of the data provided by the three instruments which covered partially overlapping droplet size ranges. A correlation was developed based on the research for predicting volume median diameters as a function of the relevant nondimensional flow parameters.

Another general class of methods of obtaining size information from the scattering signature of individual droplets are those based on interference. In this class of instruments, two coherent beams are intersected to form the optical sample volume. Particles passing through this intersection region scatter light from both illuminating beams, and various aspects of the interference pattern formed by the coherent mixing of scattered light deriving from the two beams are used to produce droplet size information. The temporal behavior of the scattered light interference is used as in the conventional laser-Doppler velocimetry (LDV) techniques for velocity determination, and particle size information is obtained from the spatial properties of the scattered light interference pattern.

Jackson provided an invited review paper on interferometric methods for particle size and velocity analysis. He covered two general methods, one based on the visibility or contrast of the scattered light interference pattern. The other method, which involves analysis of the phase difference between the two scattered light patterns emanating from the two incident beams, is the basis of an instrument known as the phase-Doppler particle analyzer (PDPA) manufactured by Aerometrics Inc. The phase-Doppler instrument has made a great impact on the droplet-sizing community as discussed by Jackson, and most of the impact has occurred since the first symposium.

McDonell and Samuelsen present a very detailed and thorough study of the performance of PDPA available from Aerometrics, Inc. as a function of some of the user-specified parameter settings. The authors provide a very careful experimental assessment of the accuracy of the instrument, particularly relative to the effects of user-specified instrument parameter settings such as photomultiplier tube supply voltage, filter settings, and size ranges. Further, the effects of chemical reaction and dense sprays were considered, and the effects of these factors on measured droplet size, velocity, and concentration were investigated. The authors suggest that user experience in operating the PDPA is crucial in obtaining good data in practical spray-fired combustion systems.

Spray Measurements

The final group of papers in the volume is dedicated to spray measurements, that is, quantitative measurement of droplet size and velocity distributions in practical sprays. The first contribution, by Sellens, is concerned with phase-Doppler measurements of droplet size and velocity distributions near-field of a swirl jet burner nozzle. The phase-Doppler instrument used in this study was developed by Sellens and coworkers. The detailed spray data demonstrated good agreement when compared with a maximum entropy formalism used to model the liquid fragmentation processes occuring in the nozzle.

Bachalo et al. used the Aerometrics PDPA to obtain time-resolved measurements in a swirl-stabilized flame. The time of arrival of drops was measured, and the data revealed droplet clustering or pulsations in the spray in which the clusters appeared to be correlated with the periodic instabilities in the flame. The clusters were most pronounced when injection was into large-scale turbulence. The local drop density was estimated to be an order of magnitude greater than the long-term average number density.

Reitz presented a combined theoretical and experimental work on the effects of vaporization and turbulence on droplet sizes and dynamics. Of particular interest were the effects of the interaction of vaporizing, noncombusting sprays formed by a pressure swirl atomizer with coflowing gas streams of various thermodynamic and flow properties (for example, gas/liquid density ratio, gas velocity, and turbulence intensity). The Aerometrics phase-Doppler instrument was used for measurements of droplet size and velocity, and particularly important in this study was the ability to measure size-velocity correlations with the PDPA. The detailed data on droplet flux, number-density distributions, and drop penetration for a range of flow parameters presented in this paper and the associated spray model will be important in the design of more efficient fuel injectors.

Mitchell et al. were concerned with methods that could be used in sampling a spray to obtain representative measures of the spray characteristics. The authors considered fan nozzles and used a commercial droplet-imaging probe (OAP) from Particle Measuring Systems. In particular, data obtained by sampling at a series of specified discrete locations and by sweeping the instrument across the entire spray plume were considered. Reasonable agreement was found between the two sampling schemes.

The application of advanced optical droplet-sizing insruments to a flat fan spray of water was considered by Dannehl et al. The authors used both ensemble near-forward scattering and the phase-Doppler techniques, which give line-of-sight averaged drop-size distribution data in the former case and point (spatially resolved) data in the latter. Another difference in the techniques involves the fact that the primary data obtained from the instruments used by these authors are a volume distribution for the ensemble scattering and number (count) for the phase-Doppler instrument. After accounting for these differences in instrument properties, the authors found adequate agreement between the data obtained from the two measurement techniques.

Summary

In summary, this volume presents a set of papers which covers the full range of the important diagnostic techniques currently in use for detailed spray characterization. They cover topics from calibration systems to careful instrument performance characterization to applications in practical spray nozzles. It provides a necessary update for the first symposium and follows in the footsteps of the first in providing detailed information on topics spanning the broad range of issues important in the field of liquid particle characterization.

E. Dan Hirleman
Arizona State University, Tempe, AZ; symposium chairman and editor