An Engineer's Practical Guide to Drop Size

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Preface

The importance of drop size information, particularly in industry, has increased considerably over the last ten years. Many spray applications such as evaporative cooling, gas conditioning, fire suppression, spray drying, and agriculture rely on this information for effective spray use. It is increasingly important for engineers to possess a better understanding of the basic atomization process and means for evaluating this process.

These industry needs fueled a rapid expansion in the science and technology of atomization. This growth has been accompanied by major advancements in spray analysis, and in particular, the area of instrumentation. Today, this field is in a mature stage. Several research and regulatory organizations (ILASS, ASTM, ISO) are dedicated to the advancement of atomization research and technology. These efforts have been well documented in the proceedings of many conferences and in the publication of drop size related standards.

This booklet is designed to provide a practical approach to drop size related issues. There are ten sections. The booklet begins with a brief introduction to atomization. Sections on drop size sampling techniques and drop size analyzers follow. These two sections discuss the methods available for capturing and recording data and types of drop size analyzers in use. Sections 4, 5, and 6 discuss the statistics and terminology used in drop size data analysis. Several drop size distribution functions and drop size mean diameter terms are defined and discussed. Factors affecting drop size distribution are discussed in Section 7. Section 8 explains several forms of drop size data, such as graphical and tabular, and their significance and use.

Section 9 addresses some practical considerations to take into account when evaluating drop size data. This section is intended to shed some light on the various aspects of data interpretation and reduce the uncertainty and confusion associated with this field. Finally, Section 10 provides a list of reference materials, suggested readings, and information pertaining to drop size related organizations.

Table of Contents

Introduction

Accurate drop size information is an important factor in the overall effectiveness of spray nozzle operation. Drop size is especially of interest in applications such as gas cooling, gas conditioning, fire suppression, spray drying, and agriculture, among others. Drop size is a by-product of atomization.

What is atomization?

The process of generating drops is called atomization. The process of atomization begins by forcing liquid through a nozzle. The potential energy of the liquid (measured as liquid pressure for hydraulic nozzles, or liquid and air pressure for two fluid nozzles) along with the geometry of the nozzles cause the liquid to emerge as small ligaments. These ligaments then break up further into very small "pieces" which are usually called drops, droplets, or liquid particles.

Each spray provides a range of drop sizes; this range is referred to as drop size distribution. Perhaps the most simplistic explanation of this process would be the breakup of a liquid from a simple circular orifice. However, in industry many various spray types, such as hollow cone, full cone, and flat spray, are widely used. The drop size distribution will be dependent on the nozzle type and will vary significantly from one type to another.

Other factors such as liquid properties, nozzle capacity, spraying pressure, and spray angle affect drop size to some extent. Finally, the methods of measuring and reporting drop size also have a considerable effect on the drop size distribution.

Understanding drop size

In order to accurately assess and understand drop size data, all of the key variables such as nozzle type, pressure, capacity, liquid properties, and spray angle have to be taken into consideration. Furthermore, the drop size testing method should be fully understood. The measurement techniques, type of drop size analyzer, sampling, data analysis, and reporting techniques all have a strong influence on the results.

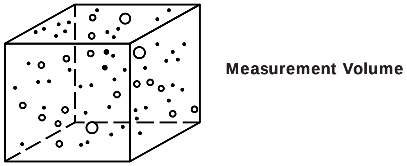
About this booklet

This booklet is meant to serve as a practical guide to drop size related issues. The topics covered in this booklet will include measurement techniques, drop size instrumentation, statistics and terminology, factors affecting drop size, data forms, and practical uses for drop size data. This booklet will also provide a list of reference material, suggested readings, and information relating to drop size related organizations.

There are two different types of drop size sampling techniques: one is known as spatial and the other is called flux (also known as temporal).

Spatial technique

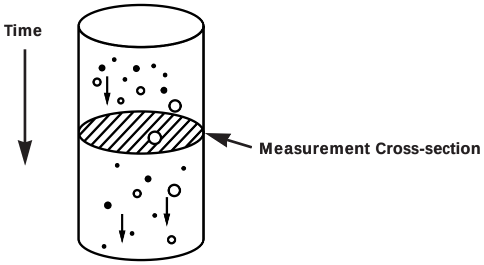
The spatial technique (i.e., spatial distribution) is implied when a collection of droplets occupying a given volume is sampled instantaneously. Generally, spatial measurements are collected with the aid of holographic means, high-speed photography, or light scattering instruments. This type of measurement is sensitive to the number density in each class size and the number of particles per unit volume.



- Averaged of finite volume
- Instantaneous sample
- Sensitive to number density

Flux technique

The flux technique (i.e., flux distribution) is implied when individual droplets that pass through the cross-section of a sampling region are examined during an interval of time. Flux measurements are generally collected by optical measurements that are capable of sensing individual drops. This type of measurement is sensitive to the particle flux.



- Time averaged
- Sensitive to particle flux

The sampling technique is critical for understanding drop size data. Typically, nozzles measured using the spatial technique will report drops smaller on average than nozzles measured using the flux technique. Sampling technique plays an important role when comparing data from different sources, and understanding this issue would help resolve many data discrepancies.

The flux distribution may be transformed to a spatial distribution by dividing the number of samples in each class size by the average velocity of the drops in that size class. If all drops in a spray are moving at the same velocity, the flux and spatial distribution are identical. However, the spray will generally exhibit differences in drop velocities that vary from class size to class size. In addition, these differences depend on the type of nozzle, capacity, and spraying pressure. The table below lists the Volume Median Diameter (VMD or $D_{V0.5}$) in Micrometres (μm) for a single nozzle at identical conditions using both flux and spatial sampling techniques.

Volume Median Diameter (μm)	
Flux	*Spatial*
530	650

The sampling technique used can also be application driven. Applications such as gas conditioning, cooling, or similar processes would be better served with a spatial sampling technique. In applications requiring accurate spray deposition such as painting and agriculture, a flux sampling technique would be more appropriate.

There are many drop size analyzers available on the market nowadays, most of which use optical methods to characterize sprays. Optical methods fall into two main categories: imaging and non-imaging. Imaging includes photography and holography. Non-imaging methods can be subdivided into two classes: those that measure a large number of drops simultaneously (ensemble) and those that count and size individual drops one at a time (single particle counters). These analyzers are typically non-intrusive, and thus they do not influence the spray behavior during testing.

Since repeatable test results are essential in comparing drop size data, it is also essential to use proper testing procedures and take into account all testing variables, including the analyzer's limitations.

The following is an overview of these methods and a reference to the most popular drop size analyzers.

Optical imaging analyzers

Optical imaging analyzers incorporate the spatial sampling technique, and they fall into the optical imaging category. These analyzers consist of a light source (typically a strobe light), a video camera, and a computer. The light is used to illuminate the spray which is recorded using the video camera. The image is then scanned and the drops are sized and separated into different classes. Sources of error early in the development of this device included blurring, depth of field variations, and improper sample size. These error sources were recognized and corrected to some extent.

Some nozzle manufacturers still actively promote this type of analyzer. The limited availability of this instrument, however, prevents independent researchers and other interested members of the drop size analysis community from verifying data or comparing performance from similar nozzle designs. A schematic of a typical optical imaging analyzer is shown in Figure 1.

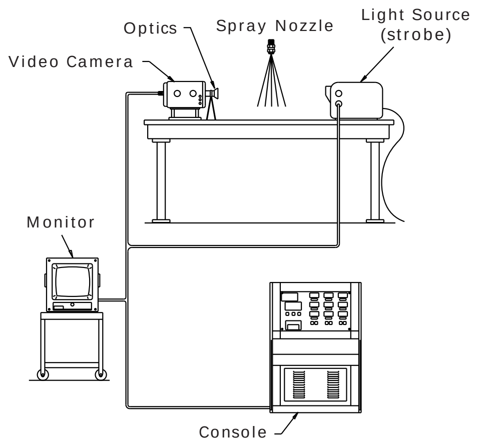


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Figure 1. Typical Optical Imaging Analyzer

Laser diffraction analyzers

Laser diffraction analyzers are also spatial sampling devices, and they fall into the non-imaging (ensemble) category. These analyzers consist of a transmitter, a receiver, and a computer. The technique is based on measuring the scattered light intensity caused by the drops as they pass through the analyzer sampling area.

The scattered light intensity is measured using a series of semicircular photodiodes housed in the receiver unit. A curve-fitting program is used to convert the light intensity distribution into any of several empirical drop size distribution functions. The range of instruments using this technique is 1.2 - 1,800 µm, although recently some manufacturers have increased the measurement range up to 3000 µm.

This instrument is best suited for measuring small capacity air atomizing, hydraulic and flat spray nozzles, and is useful for comparisons and quick evaluations of prototype nozzles. The most serious limitation of this technique is known as multiple scattering. Multiple scattering occurs when spray densities are too high; the light may be scattered by multiple drops before reaching the detector. This introduces errors in computing the drop size distribution. The most common laser diffraction instrument in use today is the Malvern Analyzer (manufactured by Malvern Instruments, England). A schematic of the Malvern Analyzer is shown in Figure 2.

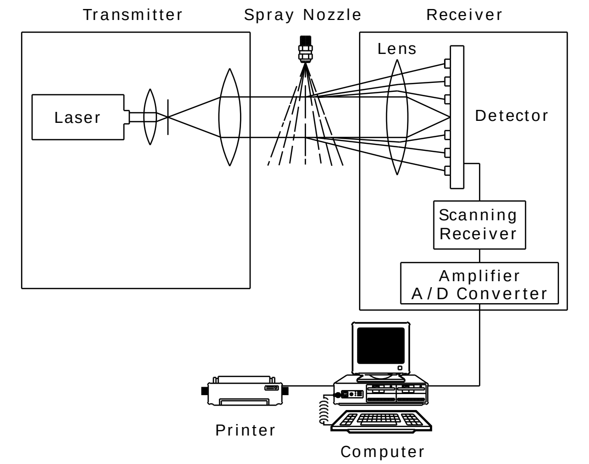

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Figure 2. Malvern Analyzer

Optical array probes

Optical array probes are flux-sampling instruments, and they fall into the non-imaging (single particle counter) category. They consist of a light source (a low power laser beam), a photodiode array, and a computer. As the droplets pass through the sampling plane, they are sized and counted — providing information that can be used to determine velocity. The data collection is based on measuring the amount of laser light shadowed by the drops passing through the sampling region.

A data analysis routine is needed to convert the raw drop count into a meaningful drop size distribution. The typical measurement range for these probes can vary from 100 - 12,400 µm. These instruments are best suited for large capacity nozzles. The most common optical array probe in use today is the PMS-OAP (manufactured by Particle Measuring Systems, Boulder, CO). A schematic of the PMS-OAP probe is shown in Figure 3.

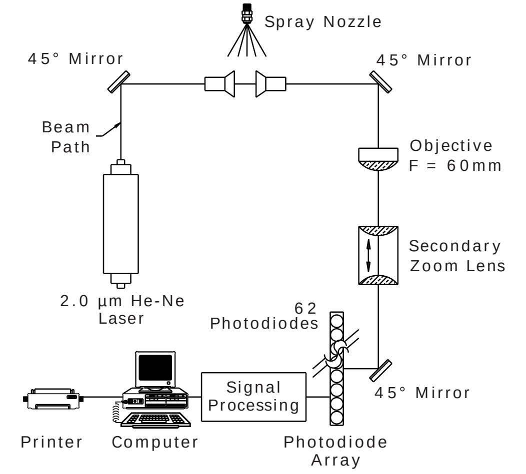

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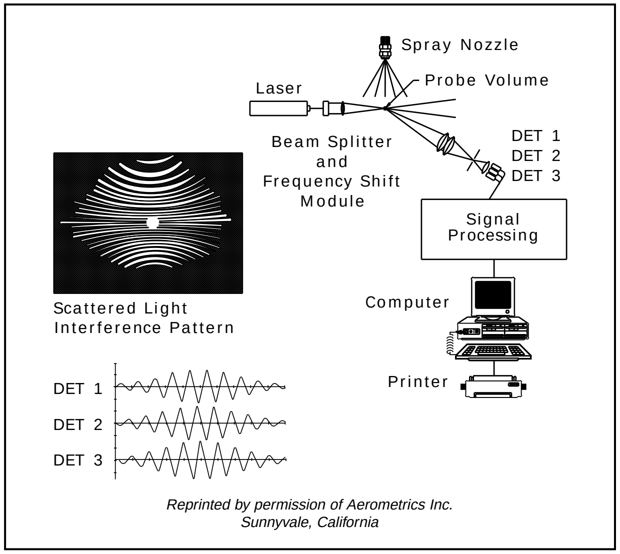
Figure 3. PMS-OAP Probe

Phase doppler particle analyzers

Phase doppler particle analyzers (PDPA) are flux-sampling instruments, and they fall into the non-imaging (single particle counter) category. These analyzers consist of a transmitter, a receiver, a signal processor, and a computer. The PDPA uses a low power laser that is split into two beams by utilizing a beam splitter and a frequency module. These two laser beams intersect again at a point referred to as the probe volume. When a drop passes through the probe volume, the scattered light forms an interference fringe pattern.

The scattered interference sweeps past the receiver unit at the Doppler difference frequency, which is proportional to the drop velocity. The spatial frequency of the interference fringe pattern is inversely proportional to the drop diameter. A data analysis routine is used to convert the raw drop count into a meaningful drop size distribution. The PDPA measures sizes in the 0.5 - 10,000 µm range using various optical configurations.

The PDPA is best suited for small, medium, and large capacity air atomizing, hydraulic, and flat spray nozzles, and is ideal for complete spray evaluation and where drop velocities are required. The most common Phase Doppler Analyzer in use is the PDPA (manufactured by Aerometrics Inc., Sunnyvale, CA). A schematic of the PDPA is shown in Figure 4.



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Sunnyvale, California

Figure 4. PDPA

Each analyzer is best suited for specific types of testing. Whereas some overlap in measurement range might be present between these instruments, it is virtually impossible to compare data from these different instruments without a clear understanding of the test conditions and methodology.

Similarly, it is very difficult to compare data from various nozzle manufacturers even when the same type of instrument was used, because optical configuration and data sampling methods might differ. Finally, proper calibration and maintenance of the measuring equipment can't be overlooked. Properly scheduled calibration tests are important, particularly in laboratories where many researchers use the equipment.

Drop size analyzers collect and record data that is typically in the form of a number count per class size. The data is arranged into a mathematical representation referred to as a drop size distribution. The mathematical representation is most often dependent on the analyzer used. Recently, however, some analyzer manufacturers have allowed the user to select from a list of distribution functions rather than a default drop size distribution function.

The two most common drop size distribution functions used in industry are the Rosin-Rammler(1) distribution function and the ASTM Standard E799-92(2) analysis.

Rosin-Rammler Distribution Function

The Rosin-Rammler distribution function

$$\mathbf{F(D) = 1 - exp}\left[-\left(\frac{\mathbf{D}}{\bar{\mathbf{X}}}\right)^{\mathbf{N}}\right]$$

is the default function for the Malvern Analyzer. The ($\bar{X}$ and N) parameters obtained from the measurement are used in this equation to calculate the distribution and the characteristic or mean diameters.

ASTM Standard E799-92

The ASTM Standard E799-92

$$d_{pq}^{(p-q)} = \left[\frac{\sum N_i d_i^{p}\square}{\sum N_i d_i^{q}\square}\right]$$

is best suited for use with analyzers that are classified as single particle counters, such as the PMS and PDPA analyzers. This analysis is used to classify the drop counts/diameters and also to calculate the distribution and the characteristic or mean diameters.

There are many other drop size distributions that are often used. They include the Log Normal, Upper Limit Log Normal, and Model Independent distribution.

Regardless of what drop size distribution function is used, they all essentially perform the same task. The result is a mathematical drop size distribution from which a collection of characteristic or mean diameters can be extracted. These diameters are single values that express the various mean sizes in the spray. Drop diameters are usually expressed in Micrometres (Microns, µm). One Micrometre equals 1/25,400 inch or 0.001 inches.

Terminology

Terminology is often the major source of discrepancy and confusion in understanding drop size. The mean and characteristic diameters are the diameters extracted from the drop size distribution. To compare the drop size from one nozzle to another, the same diameters have to be used as the source for comparison. For example, one cannot compare the $D_{V0.5}$ from one nozzle to the D_{32} from another nozzle. The following lists the most popular mean and characteristic diameters, their definitions, and their most appropriate uses. Drop size terminology can be found in ASTM Standard E1296-92(1,3).

$D_{V0.5}$: Volume Median Diameter (also known as VMD or MVD). A means of expressing drop size in terms of the volume of liquid sprayed. The VMD is a value where 50 percent of the total volume (or mass) of liquid sprayed is made up of drops with diameters larger than the median value and 50 percent smaller than the median value.

$D_{V0.1}$: is a value where 10 percent of the total volume (or mass) of liquid sprayed is made up of drops with diameters smaller or equal to this value. This diameter is best suited to evaluate a nozzle's drift potential.

D_{min}: is the minimum drop size by volume (or mass) present in the spray. This diameter is also used to evaluate a nozzle's drift potential.

$D_{V0.9}$: is a value where 90 percent of the total volume (or mass) of liquid sprayed is made up of drops with diameters smaller or equal to this value. This diameter is best suited when complete evaporation of the spray is required.

D_{max}: is the maximum drop size by volume (or mass) present in the spray. This diameter is also used when complete evaporation of the spray is required.

D_{32}: Sauter Mean Diameter (also known as SMD) is a means of expressing the fineness of a spray in terms of the surface area produced by the spray. The SMD is the diameter of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops. This diameter is best suited to calculate the efficiency and mass transfer rates in chemical reactions.

D_{10}: Arithmetic mean diameter. This diameter is best suited for calculating evaporation rates.

D_{20}: Surface mean diameter. This diameter is best suited for surface controlling applications such as absorption.

D_{30}: Volume mean diameter. This diameter is best suited for volume controlling applications such as hydrology.

D_{21}: Surface mean diameter. This diameter is best suited for absorption studies.

D_{31}: Mean evaporative diameter. This diameter is best suited for evaporation and molecular diffusion studies.

D_{43}: Herdan diameter. This diameter is best suited for combustion studies.

Terms Related to Drop Population

Drop size distribution: The size distribution of drop present in a spray sample. This distribution is typically expressed by the size versus the cumulative volume percent.

Flux: The number of drops flowing through a given plane area per unit time.

Flux-sensitive: A sampling process where the magnitude measured responds to the traffic of drops through the sampling region.

Flux/temporal size distribution: The size distribution of drops passing through a planar sampling zone during a given interval of time, wherein individual drops are counted and sized.

Global: Indicates measurements or observations of a total dispersion of drops (e.g., a sample representative of an entire liquid spray).

Local: Indicates measurements or observations of a small part of a larger region of interest.

Number density: The number of drops contained in a specified volume of space at a given instant.

Relative Span Factor (RSF): A dimensionless parameter indicative of the uniformity of the drop size distribution. RSF is defined as

$$\frac{D_{VO.9} - D_{VO.1}}{D_{VO.5}}$$

Representative sample: A sample containing enough measured elements that the effect of random fluctuations is acceptably small.

Spatial averaging: The combination of drop size distributions for regions or locations within a liquid dispersion into a distribution representative of a larger sampling region.

Spatial resolution: The size and physical separation of drop samples relative to the total region of interest, taking into account the magnitude of drop size variations within the region.

Factors Affecting Drop Size

Nozzle type: Typically, full cone nozzles have the largest drop size followed by flat spray nozzles and hollow cone nozzles. This trend applies equally to hydraulic and air assisted nozzles; however, air assisted nozzles provide very fine drops that are smaller in size than traditional hydraulic nozzles.

Full cone nozzle

Flat spray nozzle

Hollow cone nozzle

Flow rate: Flow rate has a direct relationship effect on drop size. An increase in flow rate will increase the drop size; similarly, a decrease in flow rate will decrease drop size.

Example: A 250 gpm hollow cone nozzle at 10 psi has a larger drop size than a 225 gpm hollow cone at 10 psi; similarly, a 120 gpm full cone nozzle at 7 psi has a smaller drop size than a 160 gpm full cone nozzle at the same pressure.

Pressure: Pressure has an inverse relationship effect on drop size. An increase in pressure will reduce the drop size, whereas a reduction in pressure will increase the drop size.

Example: A 0.5 gpm flat spray nozzle has a larger drop size at 20 psi than at 50 psi; similarly, a 250 gpm spiral nozzle has a smaller drop size at 15 psi than at 10 psi.

Spray angle: Spray angle has an inverse relationship effect on drop size. An increase in spray angle pressure will reduce the drop size, whereas a reduction in spray angle will increase the drop size.

Example: A 1 gpm flat spray nozzle with a 50° spray angle has a larger drop size than a 1 gpm flat spray nozzle with a 110° spray angle.

Liquid properties: Viscosity and surface tension increase the amount of energy required to atomize the spray. An increase in any of these properties will typically increase the drop size.

Drop Size Data Form

Drop size data is published or reported in many forms. The most common forms are characteristic diameter (VMD/SMD) reports and graphs, and drop size distributions (Graphical and Tabular). Depending on the intended use, some data forms could be more useful than others. The following is a guide for the suggested use of each data form.

VMD/SMD report: A tabular representation of the requested drop size information. These reports will often list the VMD or SMD of specific nozzles at specific pressure or flow rate conditions. This data is best used to compare the drop size from one nozzle to another at specific operating conditions.

VMD/SMD graphs: A graphical representation of the requested drop size information. This will often contain several nozzles on the same graph. The representation is VMD or SMD plotted against requested pressure or flow rate range. This type of data is best used to illustrate the effect on increased pressure or flow rate on drop size.

Drop size distributions: A tabular or graphical representation of the drop size distribution of a particular nozzle at a specific operating condition. The tabular data form will typically list the analyzer used, sampling method, and data processing criteria(4). Also included are the cumulative volume distribution, the percent count for each size class, and the characteristic diameters. The graphical data form will typically include all the information included on the tabular form; however, the cumulative volume percent versus drop size is represented with a graph. This type of data is best used to study the complete drop size distribution of a spray.

Practical Considerations for Drop Size Data Use

As shown in this booklet, drop size data does not only depend on many variables, but is subject to interpretation as well. The following are some suggested guidelines to facilitate understanding the drop size data and to help one use it effectively.

Data collection repeatability and accuracy: A drop size test is said to be repeatable if the data from individual tests does not deviate by more than ±6 percent. This figure could be larger for nozzles with a non-uniform surface finish (silicone carbide, ceramics). In other words, if a test result indicates a VMD of 100 µm; another test with results ranging from 94 - 106 µm can be considered identical.

Instrumentation and reporting bias: While instrumentation and reporting bias have been discussed in great detail, it is important to realize this bias will directly affect those responsible for evaluating nozzle performance and making recommendations. There are a number of formats used for reporting drop size data. When evaluating data, particularly from different sources, it is extremely important to know the type of instrument and range used, the sampling technique, and the percent volume for each size class in order to make valid data comparisons.

Relative Span Factor: Comparing drop size distributions from alternate nozzles can be confusing. The Relative Span Factor (RSF) reduces the distribution to a single number. This parameter is indicative of the uniformity of the drop size distribution. The closer this number is to 1, the more uniform the spray will be (i.e., tightest distribution, smallest variance from D_{max} to D_{min}). RSF provides a practical means for comparing various drop size distributions and should be used when possible.

Section 8/9

Practical Considerations for Drop Size Data Use - *continued*

Consider the application: Select the drop size mean diameter of interest that is best suited for the application. If the object is to simply compare the drop size of alternate nozzles, then the VMD/SMD report should suffice. More elaborate information such as D_{max}, D_{min}, and others should be used when appropriate. Simple reports are generally adequate for comparative purposes and often reduce the confusion in understanding drop size data.

Liquid properties: Virtually all drop size data supplied from nozzle manufacturers is based on spraying water under laboratory conditions. The effect of liquid properties should be understood and accounted for when selecting a nozzle for a process that is drop size sensitive.

Nozzle wear: Nozzle wear has an effect on nozzle performance. Typically, the spray appearance deteriorates, and flow rate and drop size increase. One should always expect a difference between the drop size of a new nozzle versus one that has been in service.

References

(1) *Atomization and Spray Drying.* W.R. Marshall. Department of Chemical Engineering. University of Wisconsin, Madison, June 1954, PP 50-56.

(2) E799-92: Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis. *"1996 Annual Book of ASTM Standards, General Methods and Instrumentation, Volume 14.02,"* PP 535-539.

(3) E1296-92: Standard terminology relating to liquid particle statistics. *"1996 Annual Book of ASTM Standards, General Methods and Instrumentation, Volume 14.02,"* PP 810-812.

(4) *Spray nozzle drop size: How to evaluate measurement techniques and interpret data and reporting procedures.* Ferrazza, Bartell, Schick. Spraying Systems Co., Bulletin No. 336, 1992.

Suggested Readings

Atomization and Sprays Journal

Atomization and Sprays is the official journal of ILASS-Americas, Europe, and Asia, publishing archival-quality research on the science and engineering of atomization and sprays. Both institutional and personal subscriptions are available. Inquiries about the journal may be sent to:

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Atomization and Sprays

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Organizations

ILASS-Americas

The Institute for Liquid Atomization and Spray Systems, North and South America, is an organization of industrialists, researchers, academics, and students engaged in professional activities connected with the spraying of liquids. It was established as an outgrowth of the International Conference on Liquid Atomization and Spray Systems (ICLASS). To date ICLASS conferences have been held in Japan (1978 and 1988), the USA (1982 and 1991), Europe (1985 and 1994), and South Korea (1997). The purpose of ILASS is to foster interactions between scientists and engineers in the diverse fields that utilize atomization and spray processes. ILASS-Americas' membership is limited to residents of countries that are part of the American continents.

Organizations - *continued*

ILASS-Americas is interdisciplinary, but focuses on four topic areas:

1. Transfer processes in which liquids are used, such as spray combustion, pesticide application, spray reactors, dryers, humidifiers, spray coating, and spray cooling.
2. Fluid mechanics of sprays, theory, and implementation of spray modeling.
3. Instrumentation for the measurement of drop size, velocity, concentration, and patternation.
4. The design and operation of liquid atomizers and spray systems. In addition to providing liaison with the international ILASS organization, a primary activity of ILASS-America, is its annual conference at which current research on both practical applications and fundamental topics is reported. Extended abstracts of each presentation are compiled in a volume that is distributed at the conference and subsequently available to the membership. Inquiries about ILASS activities may be addressed to:

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ASTM E29.04 Subcommittee

This committee is involved in writing standards on particle terminology, data processing, imaging and non-imaging instrumentation, and reticle calibration equipment. The subcommittee meets twice a year, typically in the spring and fall. Standards developed by this subcommittee can be found in the Annual Book of ASTM Standards, General Methods and Instrumentation, Volume 14.02. For more information about ASTM and ASTM standards, contact:

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Rudolf J. Schick, senior research engineer, is actively involved in the international drop size community. Currently serving on the Board of the Institute of Liquid Atomization and Spraying Systems (ILASS), he is also active in the American Society of Testing and Materials (ASTM/Subcommittee E29 on Particle Size Measurement). Schick has more than 10 years of experience in the area of spray characterization and research at Spraying Systems Co. He oversees all drop size measurement and information activities for the company, as well as coordinating standardization programs among the company's worldwide drop size laboratories.

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