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Standard Guide for
Determining Cross-Section Averaged Characteristics of a Spray Using Laser-Diffraction Instruments in a Wind Tunnel Apparatus[1]

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INTRODUCTION

In this guide, test methodologies are described specifically relating to the use of laser diffraction (LD) instrumentation to estimate the droplet-size distribution for liquid sprays released into moving air streams. This guide presented is primarily applicable to aerial agricultural spraying, aerial forest sprays, or air-blast spraying. Cases in which the spray is ejected into a quiescent gas environment that lacks the unifying effect of a well-defined gas co-flow may require different techniques or instrumentation or both. In this guide, an average droplet size distribution for the entire spray is determined. It requires that the spray be statistically steady in time, but it may be polydisperse and spatially non-uniform.

The droplet-size distribution used for characterization of a moving spray source must be determined from a "flux-sensitive sample" or equivalent. This is because a flux-sensitive sample provides the fraction of the total liquid flow rate contributed by each size class of droplets and, therefore, is directly related to the spray coverage. In contrast, the LD instrument derives its droplet-size distribution from a "spatial sample," and therefore, its use for spray characterization is limited to test conditions under which equivalence between flux-sensitive samples and spatial samples can be established. Such equivalence exists when the velocity of all droplets of the spray is equal and creating these conditions is the basis of this guide.

All tests relating to this guide require a wind tunnel with a test section of sufficient size that it contains the entire spray plume up to the plane of measurement without droplets impacting the test section walls under the prescribed operating conditions. The unobstructed wind tunnel air stream shall be uniform and free of turbulence. The test air speed shall be chosen to match the relative speed of the sprayer to the ambient conditions.

1. Scope

1.1 The purpose of this guide is to define a test procedure for applying the laser diffraction (LD) method to estimate an average droplet size distribution that characterizes the flux of liquid droplets produced by a specified spray generation device under specified gas co-flow conditions using a specified liquid. The intended scope is limited to artificially generated sprays with high speed co-flow. The droplets are assumed to be in the size range of 1 to 2000 µm in diameter and occur in sprays that are contained within a volume as small as a few cubic centimetres or as large as a cubic metre. The droplet sizes are assumed to be distributed non-uniformly within the spray volume.

1.2 This guide is intended primarily to guide measurement of performance of nozzles and atomizers using LD instruments.

1.3 Non-uniform sprays require measurements across the entire spray cross section or through several chords providing a representative sample of the overall spray cross section. The aim of multiple-chord measurements is to obtain a single droplet size distribution that characterizes the whole spray rather than values from a single chordal measurement.

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1.4 Use of this guide requires that the instrument does not interfere with spray production and does not significantly impinge upon or disturb the co-flow of gas and the spray. This technique is, therefore, considered non-intrusive.

1.5 The computation of droplet size distributions from the light-scattering distributions is done using Mie scattering theory or Fraunhofer diffraction approximation. The use of Mie theory accounts for light refracted through the droplet and there is a specific requirement for knowledge of both real (refractive) and imaginary (absorptive) components of the complex index of refraction. Mie theory also relies on an assumption of droplet homogeneity. The Fraunhofer diffraction approximation does not account for light refracted through the droplet and does not require knowledge of the index of refraction.

1.6 The instruments shall include data-processing capabilities to convert the LD scattering intensities into droplet size distribution parameters in accordance with Practice E799 and Test Method E1260.

1.7 The spray is visible and accessible to the collimated beam produced by the transmitter optics of the LD instrument. The shape and size of the spray shall be contained within the working distance of the LD system optics as specified by the instrument manufacturer.

1.8 The size range of the LD optic should be appropriate to the spray generation device under study. For example, the upper bound of the smallest droplet size class reported by the instrument shall be not more than ¼ the size of $D_{V0.1}$.

1.9 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.10 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety ~~problems~~ concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.11 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E799 Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis

E1260 Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Nonimaging Light-Scattering Instruments

E1620 Terminology Relating to Liquid Particles and Atomization

2.2 *ISO Standards:*[3]

ISO 13320:2009 Particle Size ~~Analysis—Laser~~ Analysis — Laser Diffraction Methods, General Principles

3. Terminology

3.1 *Definitions*—For definitions of terms used in this standard, refer to Terminology E1620 and ISO 13320:2009.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aerial spraying, n*—practice of delivering spray via an airborne vehicle such as a fixed-wing aircraft or helicopter.

3.2.2 *atomizer, n*—spray generation apparatus.

3.2.2.1 *Discussion—*

Various definitions for "atomizer" are defined in Terminology E1620 by construction and atomization method.

3.2.3 *co-flow, n*—coherent, moving gas phase surrounding a plume of spray droplets that significantly influences the direction of movement of droplets in a spray plume.

3.2.4 *co-flow generation device, n*—wind tunnel or other device that creates a steady, uniform air stream in the plane of measurement.

3.2.5 *concentration sensitive, adj*—statistical quantity derived from a spatial sample.

3.2.6 *droplet size distribution, DSD, n*—mathematical or graphical representation of droplet sizes of a given spray frequently shown as a volume fraction, number fraction, or cumulative fraction distributions.

3.2.7 *laser diffraction, LD, n*—used in this guide to refer to a class of laser droplet-sizing instruments known collectively as laser diffraction instruments, also used to qualify data gathered using an instrument of this type.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the ~~standard's~~standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3.2.8 *monodisperse, adj*—refers to a spray in which all droplets have identical size.

3.2.9 *nozzle, n*—spray generation apparatus.

3.2.9.1 *Discussion*—

Various definitions for "nozzle" are defined in Terminology E1620 by construction and atomization method.

3.2.10 *number concentration, n*—number of particles in a unit volume of space.

3.2.11 ~~*obscuration ,*~~ *obscuration, n*—percentage or fraction of incident light that is attenuated as a result of extinction (scattering or absorption or both) by droplets.

3.2.12 *obstructed, adj*—refers to co-flow generation device when the spray generation device is mounted such that it interferes with the gas-phase co-flow.

3.2.13 *plume, n*—ensemble of droplets that constitutes a spray.

3.2.14 *polydisperse, adj*—refers to a spray in which droplets have different sizes.

3.2.15 *sample distance, n*—separation between the sample volume of the LD system and the spray nozzle.

3.2.16 *sample volume, n*—intersection of LD beam and the portion of the spray plume containing a measurable concentration of droplets.

3.2.17 *model liquid, n*—fluid used to simulate the properties of density, viscosity, and surface tension of another fluid.

3.2.17.1 *Discussion*—

Typically used to replace sprays that are flammable, toxic, or otherwise deemed too dangerous to use in a spray test.

3.2.18 *spatial segregation, n*—spatial non-uniformity of droplet sizes resulting from aerodynamic forces or atomization characteristics or both.

3.2.19 *spray characterization, n*—process of describing a spray based on a theory of measurement in terms of parameters such as liquid flow rate, flux, patternation, particle size, and velocity.

3.2.20 *spray generation apparatus, n*—device specially designed to transform a bulk liquid into droplets.

3.2.21 *traverse, n*—device used to move beam from one position to another in space with documented precision and accuracy.

3.2.22 *traverse, v*—act of moving laboratory equipment in space.

3.2.23 *vignetting, n*—in the context of this guide, refers to the inability of an LD instrument to accurately estimate the size of those droplets in a spectrum whose contribution to the diffraction pattern falls outside the reach of the LD receiver optics.

3.2.24 *volume concentration, n*—volume of droplets in a unit volume of space.

3.2.25 *working distance, n*—distance within which a droplet of the minimum diameter of the range—as defined by the LD system manufacturer—of a given optical arrangement is said to have been measured accurately by the LD instrument.

4. Summary of Guide

4.1 A description of the principles of LD measurements is provided in ISO 13320:2009.

4.2 A method of data interpretation for LD data analysis is provided in Practice E799.

4.3 A typical LD sample volume is idealized as a long, thin cylinder passing through the spray plume. The sample volume is delineated by the diameter of the laser beam and the edges of the spray plume. The procedure in this guide covers methods of traversing the sample volume across the spray plume suitable for LD measurements of spatially irregular and non-uniform sprays. The aim of the procedure is to determine a single droplet size distribution that is equivalent to a flux sensitive sample.

4.4 It is important to position the LD instrument at an appropriate axial distance from the nozzle or atomizer along the mean direction of co-flow to ensure complete primary and secondary droplet breakup, minimal droplet velocity variation, and avoidance of vignetting and multiple scattering. The manufacturer's specification should be consulted regarding vignetting and multiple scattering limitations of a particular instrument.

5. Significance and Use

5.1 This guide provides a means of using an LD instrument to obtain a droplet size distribution from a spray in gas co-flow that approximates a flux-sensitive sample.[4]

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[4] Bagherpour et al., "Droplet Sizing and Velocimetry in the Wake of Rotary Cage Atomizers," *Transactions of the ASABE*, Vol 55, No. 3, 2012, pp. 579–772.

5.2 In many sprays, the experimenter shall account for spatial segregation of droplets by size. This guide provides a means of spatial averaging the droplet distribution.

5.3 The results obtained will be statistical in nature and refer to the time average of droplet size distribution of the entire spray.

5.4 This guide is used to calibrate a spray generation device to produce a desired droplet size distribution under prespecified environmental and co-flow conditions or characterize an unknown spray while minimizing the uncertainty in the measurement.

6. Apparatus

6.1 The measurement apparatus includes an LD system. This system should provide means for producing a collimated laser beam that passes through a region of the spray, a detector, or detectors for recording scattered light from droplets and a means for transforming the observations into statistical droplet size spectrum.

6.2 Spray generation apparatuses vary widely and provision for their mounting depends on the type of spray they produce and the conditions under which the spray is typically used. The spray generation apparatus should be mounted in the test section of a wind tunnel that provides a constant, uniform, low-turbulence, incident gas stream of a size sufficient to enclose the entire spray generation apparatus, its aerodynamic wake, and the plume up to the plane of measurement.

6.3 Gas phase velocity at the measurement plane shall be measured for uniformity and steadiness with respect to turbulence intensity. Any number of available instruments including, but not limited to, pitot tubes, hot-wire anemometers, and ultrasonic anemometers may be used, Such equipment shall be calibrated against an appropriate primary standard.

6.4 The wind tunnel used to enclose the spray shall provide gas co-flow velocities representative of relative velocity between the sprayer and the environment in the simulated spray application.

6.5 Optical access to the spray may be direct or via viewports (approved by the LD manufacturer), slots, or holes in the walls of the test section. Wherever possible, the LD instrumentation should be mounted such that its housing is entirely outside the spray and co-flow region or, at the very least, in a location where it does not significantly impinge on the spray plume or uniform co-flow region. In situations in which aerodynamic fairing or waterproofing or both is applied to the LD device to minimize the effect of the obstruction, care shall be taken to prevent any accumulation and shedding of droplets from the obstruction into the LD beam path.

6.6 The spray may remain stationary in the center of the air stream and the beam traversed relative to it, or the beam may remain stationary and the nozzle or atomizer traversed relative to the beam. Choice of traversing method should reflect the size of the spray and the dimension of the uniform gas phase velocity region. At no time may a spray be traversed to a location where wind tunnel walls or boundary layers alter the spray plume or the aerodynamic wake of the spray generation device. Traversing systems for either case should be robust, enable position repeatability to ±0.5 %, and preserve alignment of the LD system within the manufacturer's specification.

6.7 LD systems are very sensitive to changes in optical alignment, and wherever possible, the instrument should be clamped to a rigid optical table or rail to ensure alignment of the transmitter and receiver throughout a given test. Changes in optical alignment can result from non instrument-related influences such as excessive vibration, surface variation in viewports, and significant changes in the gas refractive index from heating or the presence of volatiles. Care should be taken to avoid causes of misalignment and correct problems in the apparatus wherever possible. Remedial action for vibration-caused misalignment is described in Section 9. Bear in mind that LD may not be an appropriate droplet-sizing method if the wind tunnel apparatus cannot be made to accommodate alignment sensitivity restrictions.

6.8 When optical access is through viewports, it may be necessary to evaluate a background measurement at each traverse location to account for the variation in optical path at each position. At no time may the spray droplets impinge on the windows during a test. If the viewports cause beam misalignment to the extent that inner become disabled or if the incident intensity of the laser beam is reduced by more than ~~20 %~~ 20 % or both, as compared to beam intensity in the absence of viewports, the viewports shall be cleaned or replaced.

6.9 In situations with evident and high-amplitude vibration that causes misalignment of the apparatus, there should be provision on the optical bench for vibration isolation.

6.10 Operating instructions supplied by the manufacturer shall be followed for correct operation of the LD instrument except when such instructions contravene this guide. The instructions should contain:

6.10.1 A description of the operational principles of the instrument oriented towards a trained technical operator;

6.10.2 Recommendations for installation and use of the apparatus;

6.10.3 Range of ambient temperature, humidity, and line-voltage variation for reliable operation;

6.10.4 Ranges of liquid droplet size, velocity, and obscuration for which the instrument is designed;

6.10.5 Maintenance procedures recommended and required; and

6.10.6 Statement of bias, reproducibility of the result statistics, and uncertainty for $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ for measurements of known calibration standards. The range of obscuration for the stated uncertainties shall be respected in all testing.

7. Reagents and Materials

7.1 In many cases, the spray generation device is designed to operate with a single specific liquid. This may be of any kind including flammable, toxic, or otherwise hazardous substances. Such formulations are manufactured in bulk by companies and are typically marketed under a brand name. All testing fluids should be accompanied by information sheets (Material Safety Data Sheet [MSDS] and Workplace Hazardous Materials Information System [WHMIS]).

7.2 For environmental or safety reasons, it may be desirable to use an alternate model liquid that simulates the physical properties of the specified liquid such as viscosity, surface tension, and density. These fluid properties are central in determining the size of the droplets that will be produced under a given set of ambient conditions.

7.3 Whatever liquid is used for testing purposes, its physical properties shall be carefully measured and noted as part of the test record. It is advisable to maintain the test liquid at a controlled temperature since temperature affects density and viscosity, which in turn affect the droplet sizes produced by a given device.

8. Calibration and Standardization

8.1 Calibration standards are necessary to verify the correct operation of the LD instrument, software and internal alignment of optical components is according to specification.

8.2 Correct operation of the LD instrument shall be confirmed using the LD system manufacturer's current specification, at the manufacturer- recommended frequency. Certification documents shall be kept on file.

8.3 The instrument shall be fully serviced per manufacturer recommendation, and its performance verified by a manufacturer-certified technician on a regular basis. Instrument performance shall be verified by a manufacturer-certified technician in the event of a major disturbance or effect.

8.4 Wind tunnel velocity measurement should be periodically calibrated without obstruction of the gas flow. Flow non-uniformity in the region of interest without the spray generation device in place should be less than ±1 % of the mean gas phase velocity. Unsteadiness should be less than ~~±1 %~~ ±1 % of the mean gas phase velocity.

8.5 With the spray generation device and mount in place, the wind tunnel velocity profile should be measured for each mounting arrangement to quantify the extent of the mount's aerodynamic wake. Streamwise velocity uniformity at any point in the plane of LD measurements, with the sprayer placed in the flow, shall be less than 10 % of the mean gas phase velocity upwind of the sprayer. Flow unsteadiness (that is, turbulence intensity) shall be less than ±5 % of the mean gas phase velocity. Mean centerline velocity upstream of the sprayer must not deviate more than 1 % during testing and the speed must be repeatable if the air flow is stopped between tests.

9. Procedure

9.1 Verify performance of instrument in accordance with Section 8.

9.2 Choose the correct distance downstream from sprayer to sample the spray.

9.2.1 The correct distance between the sprayer and the measurement plane is based on the following considerations:

9.2.1.1 The gas phase velocity profile non-uniformity shall satisfy the condition:

$$\frac{U_{\max} - U_{\min}}{U_{avg}} < 10\ \% \tag{1}$$

9.2.1.2 Droplets must have accelerated to 90 % of U_{avg} when they cross the measurement plane. The distance required to meet this condition depends on the relative velocity of the gas phase and hydraulic velocity of the liquid at the point the spray is introduced. An upper bound for it can be based on the distance required for a droplet released from rest into a uniform airstream. Fig. 1 shows this distance for a range of droplet diameters and gas co-flow velocities.

9.2.1.3 An estimate of hydraulic velocity for droplets exiting a direct pressure hydraulic spray generation device is calculated from Bernoulli's equation:

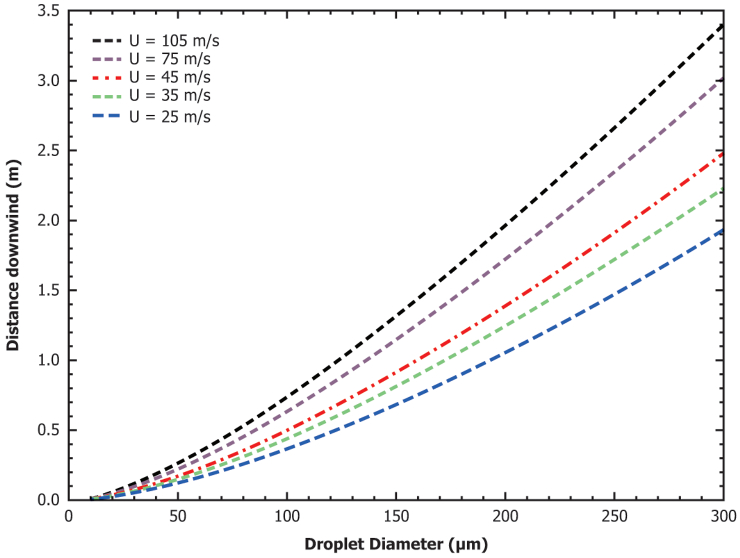
$$V_h = \sqrt{\frac{2}{\rho_l}(P_l - P_a)} \tag{2}$$

where:

P_l = the liquid supply pressure,
P_a = the ambient pressure, and
ρ_l = the liquid density.

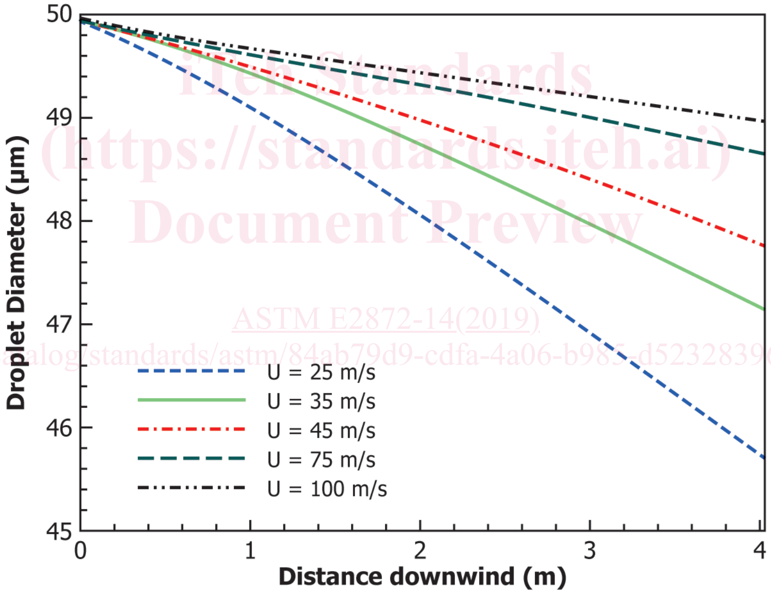
NOTE 1—Bernoulli's equation may not apply for air-assisted spray generation devices. Manufacturer data may exist for V_h estimates, or it can be measured in a laboratory with imaging (for example, Particle Image Velocimetry) or a droplet counting device (for example, Phase Doppler Interferometry).

9.2.1.4 The entire spray plume should be included in the region of uniform gas phase velocity, that is, not in the boundary layer along the wind tunnel walls. This is best done using a combination of obscuration profiles across the plume and visualization.



Source: Clift, R., and Gauvin, ~~W.H.,~~ W. H., "The Motion of Particles in Turbulent Gas Streams," *Proceedings of the Chemeca '70*, Melbourne and Sydney, Australia, 1970, Vol 1, pp. 14–28.

FIG. 1 Distance Required for Spherical Water Droplets to Reach 90 % of Airstream Velocity *U* When Released from Rest



Source: Clift, R., and Gauvin, ~~W.H.,~~ W. H., "The Motion of Particles in Turbulent Gas Streams," *Proceedings of the Chemeca '70*, Melbourne and Sydney, Australia, 1970, Vol 1, pp. 14–28.

FIG. 3 Diameter Reduction of a 50-µm Droplet Released from Rest in a Uniform Airstream at 20°C and 50 % Relative Humidity

9.2.1.5 Spray droplets shall not have vertically settled under the influence of gravity between the point of emission and the measurement plane, such that they leave the region of flow uniformity prior to the measurement plane. The vertical settling of a droplet released from rest in a uniform airstream, at the point it reaches 90 % of U_{avg} is shown for a range of co-flow velocities in Fig. 2.

9.2.1.6 The spray should be fully developed with respect to secondary droplet breakup before their reaching the measurement plane. The stability of the largest droplets can be evaluated by comparing to the following stability criterion:[5]

$$d < \frac{12\sigma}{\rho_g U_r^2} \tag{3}$$

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[5] Reitz, R. D., and Diwakar, R., *Structure of High-Pressure Fuel Sprays* (No. CONF-870204), Fluid Mechanics Dept., GM Research Labs., Warren, MI, 1987.