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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 associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

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 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.

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 , 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.

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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 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.

3.2.18 *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]

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.

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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.

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 % 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 % 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.

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]

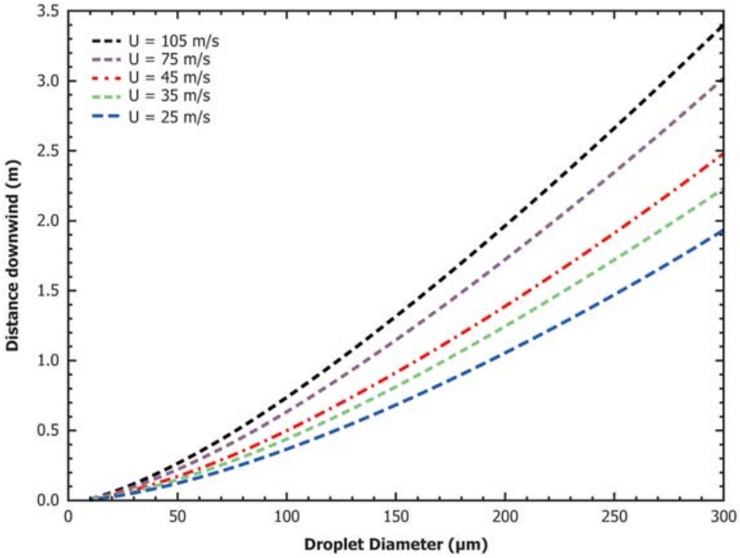
$$d < \frac{12\sigma}{\rho_g U_r^2} \tag{3}$$

$$d < \frac{\sigma^2}{\rho_g \mu_g U_r^3} \tag{4}$$

where:

ρ_g = the gas phase density,
σ = the liquid surface tension,
μ_g = the gas phase viscosity, and
U_r = the relative velocity between the droplet and gas phases.

9.2.1.7 The relative velocity is estimated as the difference between the gas phase velocity and the component of the hydraulic velocity (Eq 2) in the direction of the gas flow. See Note 1 regarding the use of Eq 2 for air-assisted nozzles.



Source: Clift, R., and Gauvin, 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

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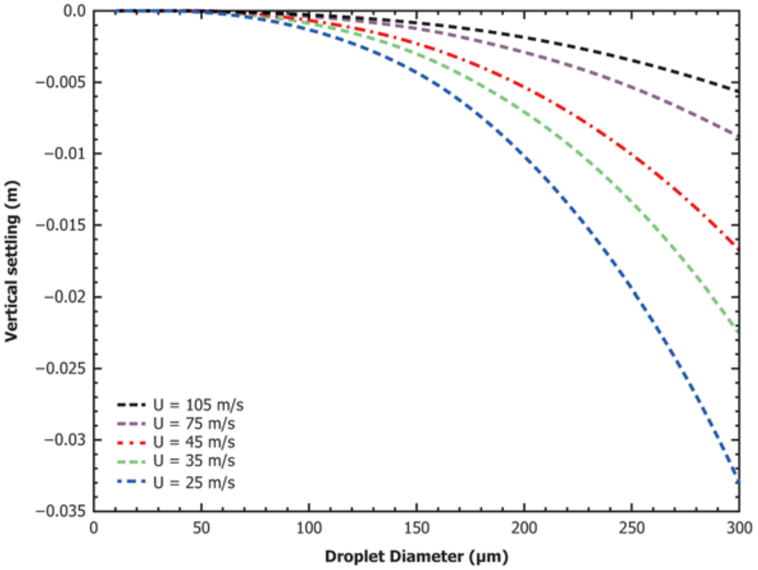
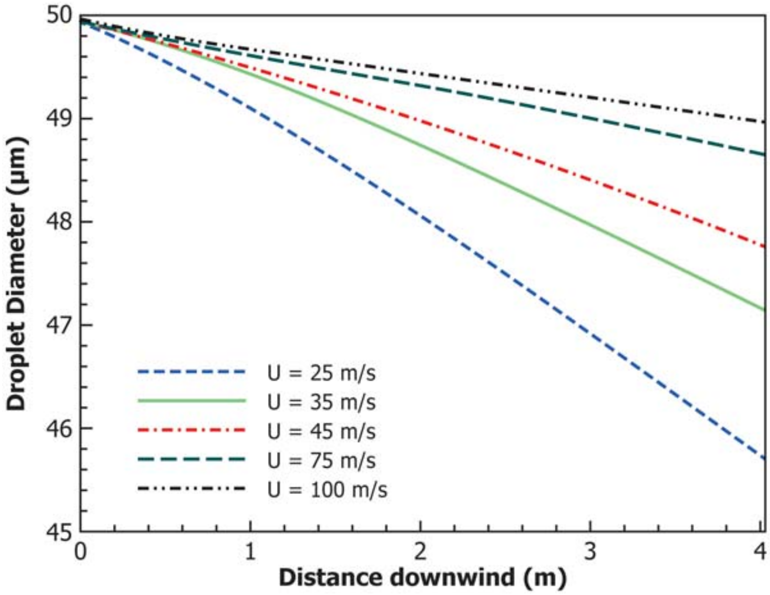
[5] Reitz, R. D., and Diwakar, R., *Structure of High-Pressure Fuel Sprays* (No. CONF-870204), Fluid Mechanics Dept., GM Research Labs., Warren, MI, 1987.



Source: Clift, R., and Gauvin, 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. 2 Vertical Settling of Water Droplets Released from Rest Under the Influence of Gravity, at the Point Where Droplets Reach 90 % of Uniform Airstream Velocity *U*

9.2.1.8 Evaporation can reduce the size of a droplet between the emission point and the measurement plane. The extent of evaporation depends on the droplet size and composition, the relative humidity of the gas co-flow, the temperature, and the relative velocity between the droplet and the gas phase. The diameter reduction of a 50-μm water droplet released from rest in a uniform air stream is shown in Fig. 3 for standard conditions.



Source: Clift, R., and Gauvin, 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

9.3 Choose an LD optic appropriate to the spray in terms of size range and working distance.

9.4 The entire spray plume should reside within the working distance of the optic and the estimated size of droplets shall be between minimum and maximum size ranges for the optic to minimize vignetting effects.

9.5 Measure the spray at a single location according to manufacturer recommended procedures.

9.6 Use this initial test to determine obscuration levels. Obscuration by the spray should be within manufacturer's specifications (typically greater than 2 % and should not exceed 20 %) at any point on the measurement plane traverse. This step reduces multiple scattering errors and ensures the LD system is operating at a sufficient signal-to-noise ratio to obtain meaningful results.

9.7 Ensure during the initial test that the spray does not significantly contaminate any optical viewports on the spray chamber or wind tunnel. Clean the viewports, then activate the spray for a time period equal to the chosen LD measurement duration. Deactivate the spray and inspect the glass for contamination. Inspection may be accomplished visually or by observing detector channel signal level of the LD reference measurement before and after spray activation. If there is significant contamination, provision shall be made for purging the viewport or otherwise restricting the possibility of spray impact on the viewport surfaces.

9.8 Check for spurious isolated peaks in LD distribution results. Vibration of viewports or other dynamic misalignment sources manifest in the results as false large droplets in the upper end of the LD optic's range. If the LD system reports large droplets where none are thought to exist, then it is necessary to:

9.8.1 Correct the source of the misalignment or vibration, and

9.8.2 Provide active or passive vibration isolation for the viewport and the LD instrument, or as required.

9.9 Ensure that there are no significant refractive index gradients as a result of temperature and humidity variations in the gas phase. The presence of highly volatile materials can also influence the refractive index along the beam path. Under these conditions, measurements with a LD instrument are invalid unless the adverse conditions are remediated.

9.10 LD instrument manufacturers provide the option of deactivating specific detectors to reduce the occurrence of spurious peaks. This is not an acceptable solution for correcting sources of dynamic misalignment unless it is verified by means of a second instrument such as a phase Doppler or an imaging system that there is no actual large droplet content.

9.11 Choose the appropriate algorithm, Mie or Fraunhofer for the spray under study.

9.12 Where both algorithms are available, the results using Mie and Fraunhofer algorithms should be compared for values of D_{V10}, D_{V50}, and D_{V90}. For guidance on algorithm choice, consult ISO 13320:2009.

9.13 It shall be assumed that droplets are spatially segregated by size through the spray plume until demonstrated otherwise by direct measurement. More than two transects across a given plume cross section are required to determine the average droplet size distribution that characterizes the entire spray plume.

9.14 The two techniques for gathering multiple transect data samples that are described in this guide are the Continuous Scan Technique (CST) and the Weighted Line of Sight Technique (WLST).

9.15 CST is applicable only to optically thin sprays in which obscuration does not exceed the multiple scattering threshold stated by the LD instrument manufacturer or the limits imposed by this guide. The CST involves continuously scanning the laser beam relative to the spray or scanning the spray relative to the laser beam while performing a running average of spray measurements during the traverse action, where each member of the average is weighted by obscuration. The CST is not recommended in the case in which the laser beam shall pass through viewports or areas of the spray having obscuration greater than 20 %.

9.15.1 Determine the speed of the CST traverse.

9.15.1.1 The speed of the traverse shall be uniform to ensure equal weighting of each section of the spray and it shall be sufficiently slow to ensure an adequate statistical sample is acquired. To determine the sampling rate, make two successive LD measurements of the spray near the center of the plume cross section, separated by z, where:

$$z = aD \tag{5}$$

where:

a = 0.1, and
D = the estimated plume diameter.

9.15.1.2 Compare $D_{V0.5}$, from the two samples. Multiply a by 0.5 and take two more measurements at the new value for z. Continue until:

$$\frac{2\left|D_{V0.5,1} - D_{V0.5,2}\right|}{\left(D_{V0.5,1} + D_{V0.5,2}\right)} \leq 0.05 \tag{6}$$

When an acceptable value for z is found that satisfies the inequalities in 9.15.1.2, calculate the maximum traverse velocity:

$$V_{t,\,\max} = \frac{z}{t_s} \tag{7}$$

where:

t_s = the time required for the LD system to acquire a repeatable (within 0.5 %) for $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ at any one location.

9.15.2 Set the LD instrument to sample throughout the duration of a plume traverse at velocity, V_t.

9.15.3 Continuously scan the spray, acquiring data at the maximum LD sample rate. Be sure to start the traverse where the obscuration meets minimum requirements.

9.15.4 Repeat the continuous scan using identical settings to ensure repeatability of $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$.

9.16 WLST is applicable to optically dense sprays. It involves the measurement of scattered light energies at a series of discrete transects spanning the cross section of the spray. WLST permits the use of an optical viewport provided that an LD reference measurement is performed for each transect position. WLST also permits the use of multiple scattering correction algorithms as appropriate. The number of measurement locations shall be chosen to give a representative sample of the spray plume.

9.16.1 Begin with the number of transects, $N = 5$, and measure the spray at each location. The measurement locations should be located so that one is at the centerline, one falls on either fringe of the plume, and the two remaining locations are midway between center and fringe on either side of center.

9.16.2 Using obscuration as a weighting factor, average $D_{V0.5}$ for the N transects:

$$\bar{D}_{V0.5} = \frac{\sum_{j=1}^{N} Ob_j D_{V0.5,\,j}}{\sum_{j=1}^{N} Ob_j} \tag{8}$$

where:

j = the transect number.

9.16.3 Increment the number of transects to $N^1 = N + 2$.

9.16.4 Repeat calculation in 9.16.2, substituting N^1 for N.

9.16.5 Compare the results from 9.16.4 with the results from 9.16.2 using Eq 9. If the difference, Δ, is less than 0.05, then use N locations for the test:

$$\Delta = \frac{2\left|\overline{D_{V0.5,1}} - \overline{D_{V0.5,2}}\right|}{\left(\overline{D_{V0.5,1}} + \overline{D_{V0.5,2}}\right)} \tag{9}$$

9.16.6 If Δ is greater than 0.05, add 2 to N, recalculate N^1, and repeat 9.16.2 – 9.16.5 until Δ is less than 0.05.

9.16.7 Sample the entire spray plume cross section at N equidistant locations.

10. Calculation

10.1 Use procedures given in Practice E799 as applicable for individual LD measurements.

10.2 Use procedures given in Practice E799 as applicable on multiplexed results of CST LD measurements.

10.3 The WLST requires that several measurements taken from transects across the spray plume be assembled in a weighted average. Obscuration is used as the weighting factor in the average.

10.3.1 For each size class i in the droplet size distribution:

$$\bar{V}_{f,i} = \frac{\sum_{j=1}^{N} Ob_j V_{f,i,j}}{\sum_{j=1}^{N} Ob_j} \tag{10}$$

TABLE 1 Details of LD Instrument

Instrument manufacturer	
Instrument model number	
Instrument software version	
Year of manufacture	
Beam diameter	
Manufacturer's LD optic designation	
LD optic working distance	
LD optic size range	
Date of last calibration	
Size range of last calibration and obscuration	
Maximum sample rate	
Fraunhofer or Mie Algorithm	

TABLE 2 Details of Test Fluid

Test fluid name	
Generic name (if applicable)	
Proprietary name (if applicable)	
Density	
Viscosity	
Surface tension	
Temperature of fluid during test	
Refractive index, Real and Imaginary components (if known)	

TABLE 3 Details of Co-Flow Generation Device

Test section dimensions	
Mean co-flow velocity	
Flow non-uniformity (unobstructed)	
Co-flow turbulent intensity (unobstructed)	
Means of optical access	
Gas phase temperature during tests	
Gas phase relative humidity during tests	
Flow non-uniformity in the plane of measurement with the sprayer in place	

TABLE 4 Details of Spray Generation Devices

Manufacturer of spray generation device	
Model of spray generation device	
Method of spray production	
Operating pressure	
Flow rate	
Estimated droplet size ($D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$), if known	
Mounting method	
Distance from nozzle to measurement location	
Known or suspected droplet segregation by size within the spray plume?	

11. Report

11.1 Details of the air flow apparatus are important to the test results and a schematic of the apparatus used should be provided with key dimensions shown. Specifically, the schematic should include the test section dimensions and the locations of the spray atomizer and the plane of measurement. Details shall also include a report of the measured flow non-uniformity, turbulent intensity, and transect profiles of each at the measurement location for unobstructed and obstructed conditions with the sprayer in position. Fill in the Tables 1-5 and include them with all results and reports on spray measurements.

11.1.1 Complete Table 1 regarding the LD instrument used in the tests. Include this table with the results of all experiments.

11.1.2 Complete in Table 2 to provide information on the test fluid. Include this table with the results of all experiments.

11.1.3 Complete in Table 3 to provide information on the wind tunnel flow. Include this table with the results of all experiments.

11.1.4 Complete in Table 4 to provide information on each spray generation device configuration. Include this table with the results of all experiments.

TABLE 5 Details of Spray Generation Devices

Maximum obscuration value	
Sample rate, Hz	
Reference measurement length, s	
Dataset length, s	
Traversing technique	
CST traverse speed, m/s (if applicable)	
No of WLST transects (if applicable)	
Calculation algorithm (Mie or Fraunhofer or both)	
Number of detectors deactivated (if applicable)	
Any other special factors that may have influenced the results of test?	

11.1.5 Complete in Table 5 to accompany results of specific tests. Include this table with the results of all experiments.

12. Precision and Bias

12.1 The precision and bias of this guide are affected by the precision and bias of the laser diffraction instrument and the variability of the spray as a result of variations in liquid and air flow rates, liquid temperature, and other conditions.

12.2 LD instruments are verified using specially manufactured solid-phase calibration standards dispersed in gas or liquid. Calibration standards are often micron-sized beads, can be spherical or otherwise, and are of known size distribution. LD instrument manufacturers do not typically supply a statement of measurement uncertainty; rather, they present instrument precision and repeatability by comparing the measured size distribution results to known distributions of the calibration standard for a series of calibration tests.

12.3 The user of the LD system shall supply a statement of the most recent instrument precision figures for that instrument using manufacturer-prescribed calibration standards with each report.

12.4 A user may rely on the precision of the instrument only for sprays that are comparable in droplet size and obscuration levels to the calibration standard. If the intended use of the LD instrument is for sprays with smaller or larger droplets or higher obscuration than the usual calibration standards, LD instrument users should request calibrations using standards of similar conditions to the spray under study. Guidance on the choice of standards is outlined in ISO 13320:2009.

13. Keywords

13.1 drop size distribution; laser diffraction instrument; liquid droplet size characteristics; spray