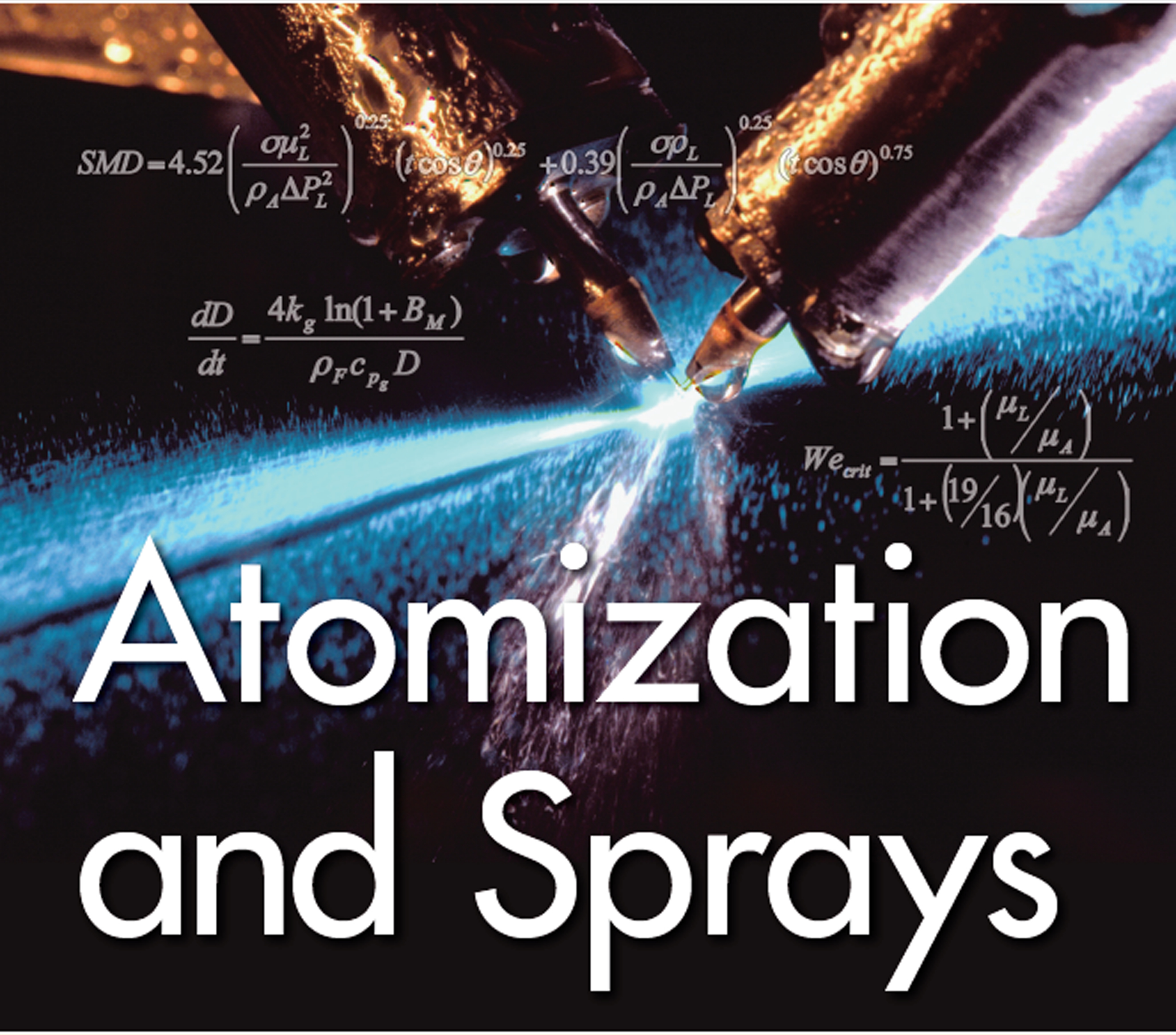
Second Edition



$$SMD = 4.52\left(\frac{\sigma\mu_L^2}{\rho_A \Delta P_L^2}\right)^{0.25}(t\cos\theta)^{0.25} + 0.39\left(\frac{\sigma\rho_L}{\rho_A \Delta P_L}\right)^{0.25}(t\cos\theta)^{0.75}$$

$$\frac{dD}{dt} = \frac{4k_g \ln(1+B_M)}{\rho_F c_{p_g} D}$$

$$We_{crit} = \frac{1+\left(\mu_L/\mu_A\right)}{1+\left(19/16\right)\left(\mu_L/\mu_A\right)}$$

Atomization and Sprays

Arthur H. Lefebvre
Vincent G. McDonell

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Atomization and Sprays

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Preface to the Second Edition

The Second Edition of the book has been long overdue and, as a result, it has been quite challenging to even attempt to address and incorporate numerous important contributions from the spray research community since the First Edition. The overarching theme of the book's content has remained connected to the practical, yet physically grounded approach taken by Arthur Lefebvre throughout his incredible career—namely, that as an engineer or practitioner of atomization and spray technology, simple to use design tools that facilitate hardware development to achieve a particular attribute in terms of spray behavior are extremely useful. While the field of atomization and sprays has expanded significantly in the last 25+ years, the guiding principles described in the First Edition remain in the Second Edition. As a result, contributions simply reporting observations, new methods, or even analytical approaches that have not distilled the information into a form that can be readily applied are not highlighted. While these contributions may have provided a path forward to generating a new model or design tool, emphasis has been given to the new model or tool themselves. And preference is given for the tools in which all necessary information to apply it is readily available. While incredibly detailed information can now be garnered about spray performance via both measurement and simulation, it is important to realize that this information is a means to the end, which in this case is to innovate, develop, and improve atomization technology.

While Arthur Lefebvre had few peers in his field during the development of the First Edition, this is no longer the case with numerous researchers and developers now very active in the field. The information he compiled from his vast research in preparing the First Edition is still very relevant, but others have, and are contributing. As only one of many contributors to this field, I remain humbled about the task of compiling updated information from throughout the world and trying to integrate it in a concise manner among the framework established within the First Edition. Undoubtedly, some fine work has been overlooked, and to those contributors, I can only apologize in advance.

I had the honor and pleasure of knowing Arthur, having met him at ASME, AIAA, and ILASS conferences. He spent a few weeks each winter in Irvine where he continued to provide his course on Gas Turbine Combustion with assistance from Scott Samuelsen and Don Bahr. He relished his time meeting with students in the UCI Combustion Laboratory and offered many excellent suggestions regarding research direction and analysis. Through these times I was able to get to know him better and to appreciate his perspective regarding engineering, combustion, and atomization and sprays.

In terms of the Second edition, a few points are worth mentioning. First, the criticality of liquid properties in applying the design tools contained in the book cannot be overemphasized and hence many new contributions have been made to Chapter 1. In addition, many new studies have been carried out regarding the basic principles of internal flow and spray behavior and hence Chapter 2 has a significant amount of new material.

While some efforts have been carried out in improving the details and subtleties associated with describing the droplet size and size distribution, the basic tools for describing these remain largely the same as they existed in the First Edition. What has changed is the ability to rapidly determine coefficients and constants through readily available regression analysis tools. In addition, observations regarding the statistical significance of the various distributions (count, surface area, volume) have been made in regards to extracting typical statistical moments, such as standard deviation, skewness, and so on from these distributions. Chapter 3 contains this information.

In terms of atomizer types, little has changed in terms of the general classification of the various types. A few interesting concepts have evolved, but pressure-based or twin-fluid approaches remain widely used. Electrostatic and ultrasonic devices continue to be utilized. Thus, Chapter 4 remains similar to the First Edition, but consideration is given regarding innovation through advanced manufacturing methods.

The internal flow of atomizers is an area in which significant progress has been made in recent years due to novel diagnostic methods and advancements in simulation. Hence, Chapter 5 contains additional details associated with cases in which cavitation is now understood to play a key role in the atomization performance.

Drop size and pattern remain a critical aspect of the performance of sprays. As a result, Chapters 6 and 7 provide details on design tools that have evolved for describing these aspects. In this area, much progress has been made regarding jets in crossflow, which are used in many applications.

For combustion applications, evaporation remains a critical step. The work described in the First Edition remains highly germane, although other developments are now included. But for application to complex turbulent sprays in practical combustion environments, some of the simplifications associated with early work remain quite appropriate for design work.

Finally, Chapter 9 is dedicated to instrumentation with some consideration for simulations. It has been well established that, by working together, experimental measurements and simulations combined offer the greatest insight.

I would like to thank the growing spray community as a whole and in particular the Institutes for Liquid Atomization and Spray Systems (ILASS) from around the world. The ILASS organizations, inspired and founded by the same people who inspired the First Edition of this book, remain a significant forum for bringing spray research together. Appreciation is also given to the journal *Atomization and Sprays*, which has provided a suitable means of archiving important spray research in a single place. Of course, many journals contain relevant works, generally they are application driven and focused, and many new contributions to diagnostic methods and simulation methods are found among numerous sources.

Ongoing discussions over the decades with Mel Roquemore, Hukam Mongia, Don Bahr, Lee Dodge, Will Bachalo, Mike Houser, Chris Edwards, Bill Sowa, Tom Jackson, Barry Kiel, Rolf Reitz, Roger Rudoff, Greg Smallwood, Michael Benjamin, Masayuki Adachi, Yannis Hardapulas, Alex Taylor, Chuck Lipp, Scott Parrish, Randy McKinney, Doug Talley, Dom Santavicca, Jon Guen Lee, May Corn, Jeff Cohen, Corinne Lengsfeld, Norman Chigier, Jiro Senda, Paul Sojka, Marcus Herrmann, David Schmidt, Rudi Schick, Jim Drallmeier, Lee Markle, Eva Gutheil, Lee Dodge, Rick Stickles, Muh Rong Wang, and, of course, Arthur Lefebvre among many others have been helpful in establishing connections and inspiration throughout.

Thanks to Josh Holt, Ryan Ehlig, Rob Miller, Elliot Sullivan Lewis, Max Venaas, and Scott Leask for assistance with various aspects of this edition. Derek Dunn-Rankin, Roger Rangel, Enrique Lavernia, and Bill Sirignano have provided perspective and insight and have been an inspiration. Long-standing colleagues and collaborators Christopher Brown and Ulises Mondragon of Energy Research Consultants have also provided friendship and in depth discussions over the years. A special thank you to Scott Samuelsen who has been a great friend, colleague, and mentor. Also, I need to thank the many graduate and undergraduate students and staff of the UCI Combustion Laboratory who have provided much enjoyment and discovery.

I must also thank my family, and especially my wife, Jan, who remained encouraging and supportive during this time consuming, but rewarding process.

Vincent McDonell

Preface to the First Edition

The transformation of bulk liquid into sprays and other physical dispersions of small particles in a gaseous atmosphere is of importance in several industrial processes. These include combustion (spray combustion in furnaces, gas turbines, diesel engines, and rockets); process industries (spray drying, evaporative cooling, powdered metallurgy, and spray painting); agriculture (crop spraying); and many other applications in medicine and meteorology. Numerous spray devices have been developed, and they are generally designated as atomizers or nozzles.

As is evident from the aforementioned applications, the subject of atomization is wide ranging and important. During the past decade, there has been a tremendous expansion of interest in the science and technology of atomization, which has now developed into a major international and interdisciplinary field of research. This growth of interest has been accompanied by large strides in the areas of laser diagnostics for spray analysis and in a proliferation of mathematical models for spray combustion processes. It is becoming increasingly important for engineers to acquire a better understanding of the basic atomization process and to be fully conversant with the capabilities and limitations of all the relevant atomization devices. In particular, it is important to know which type of atomizer is best suited for any given application and how the performance of any given atomizer is affected by variations in liquid properties and operating conditions.

This book owes its inception to a highly successful short course on atomization and sprays held at Carnegie Mellon University in April 1986 under the direction of Professor Norman Chigier. As an invited lecturer to this course, my task was by no means easy because most of the relevant information on atomization is dispersed throughout a wide variety of journal articles and conference proceedings. A fairly thorough survey of this literature culminated in the preparation of extensive course notes. The enthusiastic response accorded to this course encouraged me to expand these notes into this book, which will serve many purposes, including those of text, design manual, and research reference in the areas of atomization and sprays.

The book begins with a general review of atomizer types and their applications, in Chapter 1. This chapter also includes a glossary of terms in widespread use throughout the atomization literature. Chapter 2 provides a detailed introduction to the various mechanisms of liquid particle breakup and to the manner in which a liquid jet or sheet emerging from an atomizer is broken down into drops.

Owing to the heterogeneous nature of the atomization process, most practical atomizers generate drops in the size range from a few micrometers up to around 500 μm. Thus, in addition to mean drop size, which may be satisfactory for many engineering purposes, another parameter of importance in the definition of a spray is the distribution of drop sizes it contains. The various mathematical and empirical relationships that are used to characterize the distribution of drop sizes in a spray are described in Chapter 3.

In Chapter 4, the performance requirements and basic design features of the main types of atomizers in industrial and laboratory use are described. Primary emphasis is placed on the atomizers employed in industrial cleaning, spray cooling, and spray drying, which, along with liquid fuel–fired combustion, are their most important applications.

Chapter 5 is devoted primarily to the internal flow characteristics of plain-orifice and pressure-swirl atomizers, but consideration is also given to the complex flow situations that arise on the surface of a rotating cup or disk. These flow characteristics are important because they govern the quality of atomization and the distribution of drop sizes in the spray.

Atomization quality is usually described in terms of a mean drop size. Because the physical processes involved in atomization are not well understood, empirical equations have been developed for expressing the mean drop size in a spray in terms of liquid properties, gas properties, flow conditions, and atomizer dimensions. The equations selected for inclusion in Chapter 6 are considered to be the best available for the types of atomizers described in Chapter 4.

The function of an atomizer is not only to disintegrate a bulk liquid into small drops, but also to discharge these drops into the surrounding gas in the form of a symmetrical, uniform spray. The spray characteristics of most practical importance are discussed in Chapter 7. They include cone angle, penetration, radial liquid distribution, and circumferential liquid distribution.

Although evaporation processes are not intrinsic to the subject of atomization and sprays, it cannot be overlooked that in many applications the primary purpose of atomization is to increase the surface area of the liquid and thereby enhance its rate of evaporation. In Chapter 8, attention is focused on the evaporation of fuel drops over wide ranges of ambient gas pressures and temperatures. Consideration is given to both steady-state and unsteady-state evaporation. The concept of an effective evaporation constant is introduced, which is shown to greatly facilitate the calculation of evaporation rates and drop lifetimes for liquid hydrocarbon fuels.

The spray patterns produced by most practical atomizers are so complex that fairly precise measurements of drop-size distributions can be obtained only if accurate and reliable instrumentation and data reduction procedures are combined with a sound appreciation of their useful limits of application. In Chapter 9, the various methods employed in drop-size measurement are reviewed. Primary emphasis is placed on optical methods that have the important advantage of allowing size measurements to be made without the insertion of a physical probe into the spray. For ensemble measurements, the light diffraction method has much to commend it and is now in widespread use as a general purpose tool for spray analysis. Of the remaining methods discussed, the advanced optical techniques have the capability of measuring drop velocity and number density as well as size distribution.

Much of the material covered in this book is based on knowledge acquired during my work on atomizer design and performance over the past 30 years. However, the reader will observe that I have not hesitated in drawing on the considerable practical experience of my industrial colleagues, notably Ted Koblish of Fuel Systems TEXTRON, Hal Simmons of the Parker Hannifin Corporation, and Roger Tate of Delavan Incorporated. I am also deeply indebted to my graduate students in the School of Mechanical Engineering at Cranfield and the Gas Turbine Combustion Laboratory at Purdue. They have made significant contributions to this book through their research, and their names appear throughout the text and in the lists of references.

Professor Norman Chigier has been an enthusiastic supporter in the writing of this book. Other friends and colleagues have kindly used their expert knowledge in reviewing and commenting on individual chapters, especially Chapter 9, which covers an area that in recent years has become the subject of fairly intense research and development. They include Dr. Will Bachalo of Aerometrics, Inc., Dr. Lee Dodge of Southwest Research Institute, Dr. Patricia Meyer of Insitec, and Professor Arthur Sterling of Louisiana State University. In the task of proofreading, I have been ably assisted by Professor Norman Chigier, Professor Ju Shan Chin, and my graduate student Jeff Whitlow—their help is hereby gratefully acknowledged.

I am much indebted to Betty Gick and Angie Myers for their skillful typing of the manuscript and to Mark Bass for the high-quality artwork he provided for this book. Finally, I would like to thank my wife, Sally, for her encouragement and support during my undertaking of this time-consuming but enjoyable task.

Arthur H. Lefebvre

Authors

Arthur H. Lefebvre (1923–2003) was Emeritus Professor at Purdue University. With industrial and academic experience spanning more than four decades, he wrote more than 150 technical papers on both fundamental and practical aspects of atomization and combustion. The honors he received include the ASME Gas Turbine and ASME R. Tom Sawyer Awards, ASME George Westinghouse Gold Medal, and the IGTI Scholar Award. He was also the first recipient of the AIAA Propellants and Combustion Award.

Vincent G. McDonell is an associate director of the UCI Combustion Laboratory at the University of California, Irvine, where he also serves as an adjunct professor in the Mechanical and Aerospace Engineering Department. He earned a PhD at the University of California, Irvine in 1990 and has served on the executive committees of ILASS-Americas and ICLASS International. He has won best paper awards from ILASS-Americas and ASME for work on atomization. He has done extensive research in the areas of atomization and combustion, holds a patent in the area, and has authored or coauthored more than 150 papers in the field.

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General Considerations

Introduction

The transformation of bulk liquid into sprays and other physical dispersions of small particles in a gaseous atmosphere is of importance in several industrial processes and has many other applications in agriculture, meteorology, and medicine. Numerous spray devices have been developed, which are generally designated as atomizers or nozzles. In the process of atomization, a liquid jet or sheet is disintegrated by the kinetic energy of the liquid, by the exposure to high-velocity air or gas, or by mechanical energy applied externally through a rotating or vibrating device. Because of the random nature of the atomization process, the resultant spray is usually characterized by a wide spectrum of drop sizes. The process is highly coupled and involves a wide range of characteristics that may or may not be important depending on the application. To illustrate, Figure 1.1 summarizes the processes and resultant attributes that may be found within a typical spray [1].

Natural sprays include waterfall mists, rains, and ocean sprays. At home, sprays are produced by shower heads, garden hoses, trigger sprayers for household cleaners, propellants for hair sprays, among others. They are commonly used in applying agricultural chemicals to crops, paint spraying, spray drying of wet solids, food processing, cooling in various systems, including nuclear cores, gas–liquid mass transfer applications, dispersing liquid fuels for combustion, fire suppression, consumer sprays, snowmaking, and many other applications.

Combustion of liquid fuels in diesel engines, spark-ignition engines, gas turbines, rocket engines, and industrial furnaces is dependent on effective atomization to increase the specific surface area of the fuel and thereby achieve high rates of mixing and evaporation. In most combustion systems, reduction in mean fuel drop size leads to higher volumetric heat release rates, easier light up, a wider burning range, and lower exhaust concentrations of pollutant emissions [2–4].

In other applications, however, such as crop spraying, small droplets must be avoided because their settling velocity is low and, under certain meteorological conditions, they can drift too far downwind. Drop sizes are also important in spray drying and must be closely controlled to achieve the desired rates of heat and mass transfer. When the objective is creating metal powder, various size classes may be required for different applications. For additive manufacturing, a cut between 100 and 150 microns may be desired, with material contained in other size particles and unusable byproduct adding cost and inefficiency if it cannot be remelted.

Efforts associated with quality control, improved utilization efficiency, pollutant emissions, precision manufacturing, and the like have elevated atomization science and technology to a major international and interdisciplinary field of research. An evolving array of applications has been accompanied by large strides in the area of advanced diagnostics for spray analysis and by resulting mathematical models and simulation of atomization and spray behavior. It is important for engineers to acquire a better understanding of the basic atomization process and to be fully conversant with the capabilities and limitations of all the relevant atomization devices. In particular, it is important to know which type of atomizer is best suited for any given application and how the performance of any given atomizer is affected by variations in liquid properties and operating conditions.

Atomization

Sprays may be produced in various ways. Several basic processes are associated with all methods of atomization, such as the hydraulics of the flow within the atomizer, which governs the turbulence properties of the emerging liquid stream. The development of the jet or sheet and the growth of small disturbances, which eventually lead to disintegration into ligaments and then drops, are also of primary importance in determining the shape and penetration of the resulting spray as well as its detailed characteristics of number density, drop velocity, and drop size distributions as functions of time and space as illustrated in Figure 1.1. All of these characteristics are markedly affected by the internal geometry of the atomizer, the properties of the gaseous medium into which the liquid stream is discharged, and the physical properties of the liquid. Perhaps the simplest situation is the disintegration of a liquid jet issuing from a circular orifice, where the main velocity component lies in the axial direction and the jet is in laminar

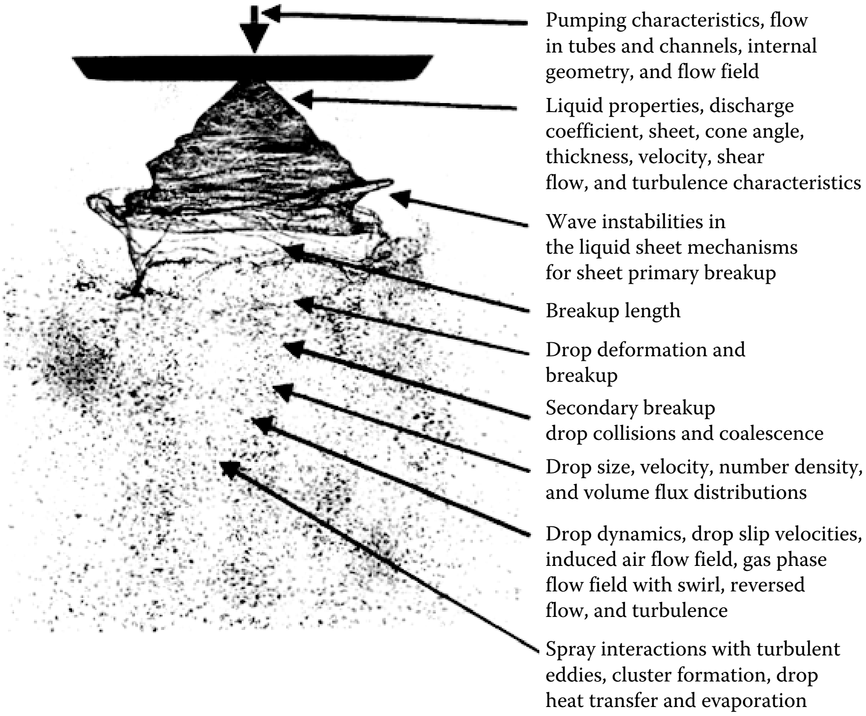

FIGURE 1.1
Example of a simple spray illustrating many features that need to be characterized. (From Bachalo, W. D., *Atomization Sprays*, 10, 439–474, 2000.)

flow. Lord Rayleigh, in his classic study [5], postulated the growth of small disturbances that eventually lead to breakup of the jet into drops having a diameter nearly twice that of the jet. A fully turbulent jet can break up without the application of any external force. Once the radial components of velocity are no longer confined by the orifice walls, they are restrained only by the surface tension, and the jet disintegrates when the surface tension forces are overcome. The role of viscosity is to inhibit the growth of instability and generally delays the onset of disintegration. This causes atomization to occur farther downstream in regions of lower relative velocity; consequently, drop sizes are larger. In most cases, turbulence in the liquid, cavitation in the nozzle, and aerodynamic interaction with the surrounding air, which increases with air density, all contribute to atomization.

Many applications call for a conical or flat spray pattern to achieve the desired dispersion of drops for liquid–gas mixing. Conical sheets may be produced by pressure-swirl nozzles in which a circular discharge orifice is preceded by a chamber in which tangential holes or slots are used to impart a swirling motion to the liquid as it leaves the nozzle. Flat sheets are generally produced either by forcing the liquid through a narrow annulus, as in fan spray nozzles, or by feeding it to the center of a rotating disk or cup. To expand the sheet against the contracting force of surface tension, a minimum sheet velocity is required and is produced by pressure in pressure-swirl and fan spray nozzles and by centrifugal force in rotary atomizers. Regardless of how the sheet is formed, its initial hydrodynamic instabilities are augmented by aerodynamic disturbances, so as the sheet expands away from the nozzle and its thickness declines, perforations are formed that expand toward one an other and coalesce to form threads and ligaments. As these ligaments vary widely in diameter, when they collapse the drops formed also vary widely in diameter. Some of the larger drops created by this process disintegrate further into smaller droplets. Eventually, a range of drop sizes is produced whose average diameter depends mainly on the initial thickness of the liquid sheet, its velocity relative to the surrounding gas, and the liquid properties of viscosity and surface tension.

A liquid sheet moving at high velocity can also disintegrate in the absence of perforations by a mechanism known as *wavy-sheet* disintegration, whereby the crests of the waves created by aerodynamic interaction with the surrounding gas are torn away in patches. Finally, at very high liquid velocities, corresponding to high injection pressures, sheet disintegration occurs close to the nozzle exit. However, although several modes of sheet disintegration have been identified, in all cases the final atomization process is one in which ligaments break up into drops according to the Rayleigh mechanism.

With prefilming airblast atomizers, a high relative velocity is achieved by exposing a slow-moving sheet of liquid to high-velocity air. Photographic evidence suggests that for low-viscosity liquids the basic mechanisms involved are essentially the same as those observed in pressure atomization, namely the production of drops from ligaments created by perforated-sheet and/or wavy-sheet disintegration.

A typical spray includes a wide range of drop sizes. Some knowledge of drop size distribution is helpful in evaluating process applications in sprays, especially in calculations of heat or mass transfer between the dispersed liquid and the surrounding gas. Unfortunately, no complete theory has yet been developed to describe the hydrodynamic and aerodynamic processes involved when jet and sheet disintegration occurs under normal atomizing conditions, so that only empirical correlations are available for predicting mean drop sizes and drop size distributions. Comparison of the distribution parameters in common use reveals that all of them have deficiencies of one kind or another. In one the maximum drop diameter is unlimited; in others the minimum possible diameter is zero or even negative. So far, no single parameter has emerged that has clear advantages over the others. For any given application the best distribution function is one that is easy to manipulate and provides the best fit to the experimental data.

The difficulties in specifying drop size distributions in sprays have led to widespread use of various mean or median diameters. A median droplet diameter divides the spray into two equal parts by number, length, surface area, or volume [6]. Median diameters may be determined from different types of cumulative distribution curves shown in Figure 3.6. In a typical spray, the value of the median diameter, expressed in micrometers, will vary by a factor of about four depending on the median diameter selected for use. It is important therefore to decide which measure is the most suitable for a particular application. Some diameters are easier to visualize and comprehend, while others may appear in prediction equations that have been derived from theory or experiment. Some drop size measurement techniques yield a result in terms of one particular median diameter. In some cases, a given median diameter is selected to emphasize some important characteristic, such as the total surface area in the spray. For liquid fuel fired combustion systems and other applications involving heat and mass transfer to liquid drops, the Sauter mean diameter, which represents the ratio of the volume to the surface area of the spray, is often preferred. The mass median diameter, which is about 15%–25% larger than the Sauter mean diameter, is also widely used. As Tate [6] has pointed out, the ratio of these two diameters is a measure of the spread of drop sizes in the spray.

Atomizers

An atomizer is generally used to produce a spray. Essentially, all that is needed is a *high relative velocity* between the liquid to be atomized and the surrounding air or gas. Some atomizers accomplish this by discharging the liquid at high velocity into a relatively slow-moving stream of air or gas. Notable examples include the various forms of pressure atomizers and also rotary atomizers, which eject the liquid at high velocity from the periphery of a rotating cup or disk. An alternative approach is to expose the relatively slow-moving liquid to a high-velocity airstream. The latter method is generally known as *twin-fluid, air-assist*, or *airblast* atomization. Other examples may involve heterogeneous processes in which air bubbles or liquid vapor become involved in disrupting the liquid phase during the injection process.

Pressure Atomizers

When a liquid is discharged through a small aperture under high applied pressure, the pressure energy is converted into the kinetic energy (velocity). For a typical hydrocarbon fuel, in the absence of frictional losses a nozzle pressure drop of 138 kPa (20 psi) produces an exit velocity of 18.6 m/s. As velocity increases as the square root of the pressure, at 689 kPa (100 psi) a velocity of 41.5 m/s is obtained, while 5.5 MPa (800 psi) produces 117 m/s.

Plain Orifice. A simple circular orifice is used to inject a round jet of liquid into the surrounding air. The finest atomization is achieved with small orifices but, in practice, the difficulty of keeping liquids free from foreign particles usually limits the minimum orifice size to around 0.3 mm. Combustion applications for plain-orifice atomizers include turbojet afterburners, ramjets, diesel engines, and rocket engines.

Pressure-Swirl (Simplex). A circular outlet orifice is preceded by a swirl chamber into which liquid flows through a number of tangential holes or slots. The swirling liquid creates a core of air or gas that extends from the discharge orifice to the rear of the swirl chamber. The liquid emerges from the discharge orifice as an annular sheet, which spreads radially outward to form a hollow conical spray. Included spray angles range from 30° to almost 180°, depending on the application. Atomization performance is generally good. The finest atomization occurs at high delivery pressures and wide spray angles.

For some applications a spray in the form of a solid cone is preferred. This can be achieved using an axial jet or some other device to inject droplets into the center of the hollow conical spray pattern produced by the swirl chamber. These two modes of injection create a bimodal distribution of drop sizes, droplets at the center of the spray being generally larger than those near the edge.

Square Spray. This is essentially a solid-cone nozzle, but the outlet orifice is specially shaped to distort the conical spray into a pattern that is roughly in the form of a square. Atomization quality is not as high as the conventional hollow-cone nozzles but, when used in multiple-nozzle combinations, a fairly uniform coverage of large areas can be achieved.

Duplex. A drawback of all types of pressure nozzles is that the liquid flow rate is proportional to the square root of the injection pressure differential. In practice, this limits the flow range of simplex nozzles to about 10:1. The duplex nozzle overcomes this limitation by feeding the swirl chamber through two sets of distributor slots, each having its own separate liquid supply. One set of slots is much smaller in cross-sectional area than the other. The small slots are termed *primary* and the large slots *secondary*. At low flow rates all the liquid to be atomized flows into the swirl chamber through the primary slots. As the flow rate increases, the injection pressure increases. At some predetermined pressure level a valve opens and admits liquid into the swirl chamber through the secondary slots.

Duplex nozzles allow good atomization to be achieved over a range of liquid flow rates of about 40:1 without the need to resort to excessively high delivery pressures. However, near the point where the secondary liquid is first admitted into the swirl chamber, there is a small range of flow rates over which atomization quality is poor. Moreover, the spray cone angle changes with flow rate, being widest at the lowest flow rate and becoming narrower as the flow rate is increased.

Dual Orifice. This is similar to the duplex nozzle except that two separate swirl chambers are provided, one for the primary flow and the other for the secondary flow. The two swirl chambers are housed concentrically within a single nozzle body to form a *nozzle within a nozzle*. At low flow rates all the liquid passes through the inner primary nozzle. At high flow rates liquid continues to flow through the primary nozzle, but most of the liquid is passed through the outer secondary nozzle that is designed for a much larger flow rate. As with the duplex nozzle, there is a transition phase, just after the pressurizing valve opens, when the secondary spray draws its energy for atomization from the primary spray, so the overall atomization quality is relatively poor.

Dual-orifice nozzles offer more flexibility than the duplex nozzles. For example, if desired, the primary and secondary sprays can be merged just downstream of the nozzle to form a single spray. Alternatively, the primary and secondary nozzles can be designed to produce different spray angles, the former being optimized for low flow rates and the latter optimized for high flow rates.

Spill Return. This is essentially a simplex nozzle, but with a return flow line at the rear or side of the swirl chamber and a valve to control the quantity of liquid removed from the swirl chamber and returned to supply. Very high turndown ratios are attainable with this design. Atomization quality is always good because the supply pressure is held constant at a high value, reductions in flow rate being accommodated by adjusting the valve in the spill return line. This construction provides a hollow-cone spray pattern, with some increase in the spray angle as the flow is reduced.

Fan Spray. Several different concepts are used to produce flat or fan-shaped sprays. The most popular type of nozzle is one in which the orifice is formed by the intersection of a V groove with a hemispheric cavity communicating with a cylindrical liquid inlet [6]. It produces a liquid sheet parallel to the major axis of the orifice, which disintegrates into a narrow elliptical spray.

An alternative method of producing a fan spray is by discharging the liquid through a plain circular hole onto a curved deflector plate. The deflector method produces a somewhat coarser spray pattern. Wide spray angles and high flow rates are attainable with this type of nozzle. Because the nozzle flow passages are relatively large, the problem of plugging is minimized.

A fan spray can also be produced by the collision of impinging jets. If two liquid jets are arranged to collide outside the nozzle, a flat liquid sheet is formed that is perpendicular to the plane of the jets. The atomization performance of this type of injector is relatively poor, and high stream velocities are necessary to approach the spray quality obtainable with other types of pressure nozzles. Extreme care must be taken to ensure that the jets are properly aligned. The main advantage of this method of atomization is the isolation of different liquids until they collide outside the nozzle. These are commonly used for hypergolic propellant systems in which an oxidizer and fuel component will react upon contact

Rotary Atomizers

One widely used type of rotary atomizer comprises a high-speed rotating disk with means for introducing liquid at its center. The liquid flows radially outward across the disk and is discharged at high velocity from its periphery. The disk may be smooth and flat or may have vanes or slots to guide the liquid to the periphery. At low flow rates, droplets form near the edge of the disk. At high flow rates, ligaments or sheets are generated at the edge and disintegrate into droplets. Small disks operating at high rotational speeds and low flow rates are capable of producing sprays in which drop sizes are fairly uniform. A 360° spray pattern is developed by rotating disks that are usually installed in a cylindrical or conical chamber where an umbrella-like spray is created by downward gas currents [6].

Some rotary atomizers employ a cup instead of a disk. The cup is usually smaller in diameter and is shaped like an elongated bowl. In some designs, the edge of the cup is serrated to encourage a more uniform drop size distribution in the spray. A flow of air around the periphery is sometimes used to shape the spray and to assist in transporting the droplets away from the atomizer. In contrast to pressure nozzles, rotary atomizers allow independent variation of flow rate and disk speed, thereby providing more flexibility in operation.

Air-Assist Atomizers

In this type of nozzle, the liquid is exposed to a stream of air or steam flowing at high velocity. In the *internal-mixing* configuration, gas and liquid are mixed within the nozzle before discharging through the outlet orifice. The liquid is sometimes supplied through tangential slots to encourage a conical discharge pattern. However, the maximum spray angle is limited to about 60°. The device tends to be energy inefficient, but it can produce a finer spray than simple pressure nozzles.

As its name suggests, in the *external-mixing* form of air-assist nozzle the high-velocity gas or steam impinges on the liquid at or outside the liquid discharge orifice. Its advantage over the internal-mixing type is that problems of back pressures are avoided because there is no internal communication between gas and liquid. However, it is less efficient than the internal-mixing concept, and higher gas flow rates are needed to achieve the same degree of atomization. Both types of nozzles can atomize high-viscosity liquids effectively.

Airblast Atomizers

These devices function in a very similar manner to air-assist nozzles, and both types fall in the general category of twin-fluid atomizers. The main difference between air-assist and airblast atomizers is that the former use relatively small quantities of air or steam flowing at very high velocities (usually sonic), whereas the latter employ large amounts of air flowing at much lower velocities (<100 m/s). Airblast nozzles are thus ideally suited for atomizing liquid fuels in continuous-flow combustion systems, such as gas turbines, where air velocities of this magnitude are usually readily available. The most common form of airblast atomizer is one in which the liquid is first spread into a thin conical sheet and then exposed to high-velocity airstreams on both sides of the sheet. The atomization performance of this *prefilming* type of airblast nozzle is superior to that of the alternative *plain-jet* airblast nozzle, in which the liquid is injected into the airstream in the form of one or more discrete jets.

Other Types

Most practical atomizers are of the pressure, rotary, or twin-fluid type. However, many other forms of atomizers have been developed that are useful in special applications.

Electrostatic. A liquid jet or film is exposed to an intense electrical pressure that tends to expand its area. This expansion is opposed by the surface tension forces. If the electrical pressure predominates, droplets are formed. Droplet size is a function of the electrical pressure, the liquid flow rate, and the physical and electrical properties of the liquid. The low liquid flow rates associated with electrostatic atomizers have tended to limit their practical applications to electrostatic painting and nonimpact printing.

Ultrasonic. The liquid to be atomized is fed through or over a transducer and horn, which vibrates at ultrasonic frequencies to produce the short wavelengths necessary for fine atomization. The system requires a high-frequency electrical input, two piezoelectric transducers, and a stepped horn. The concept is well suited for applications that require very fine atomization and a low spray velocity. At present, an important application of ultrasonic atomizers (nebulizers) is for medical inhalation therapy, where very fine sprays and the absence of gas to effect atomization are important attributes.

Sonic (Whistle). Gas is accelerated within the device to sonic velocity and impinges on a plate or annular cavity (resonation chamber). The sound waves produced are reflected into the path of the incoming liquid [7]. The frequency of the sound waves is around 20 kHz, and this serves to disintegrate the liquid into small droplets ranging downward in size from 50 μm. The sonic and pneumatic effects are difficult to isolate from each other. Efforts have been made to design nozzles that operate above the audible frequency limit to reduce the nuisance of noise [8]. However, in some applications the attendant sound field may benefit the process (e.g., combustion) for which the resultant spray is required.

Windmill. Many aerial applications of pesticides require a narrow spectrum of drop sizes. The conventional rotary disk atomizers can provide such a spectrum, but only when operating in the ligament mode at low flow rates. By making radial cuts at the periphery of a disk and twisting the tips of the segments, the disk can be converted into a windmill that will rotate rapidly when inserted into an airflow at aircraft flight speed. According to Spillmann and Sanderson [9], the disk windmill constitutes an ideal rotary atomizer for the aerial application of pesticides. It provides a narrow spectrum of drop sizes in the range most suitable for herbicides, at relatively high flow rates.

Vibrating Capillary. This type of droplet generator was first used to study the collision and coalescence of small water droplets. It consists of a hypodermic needle

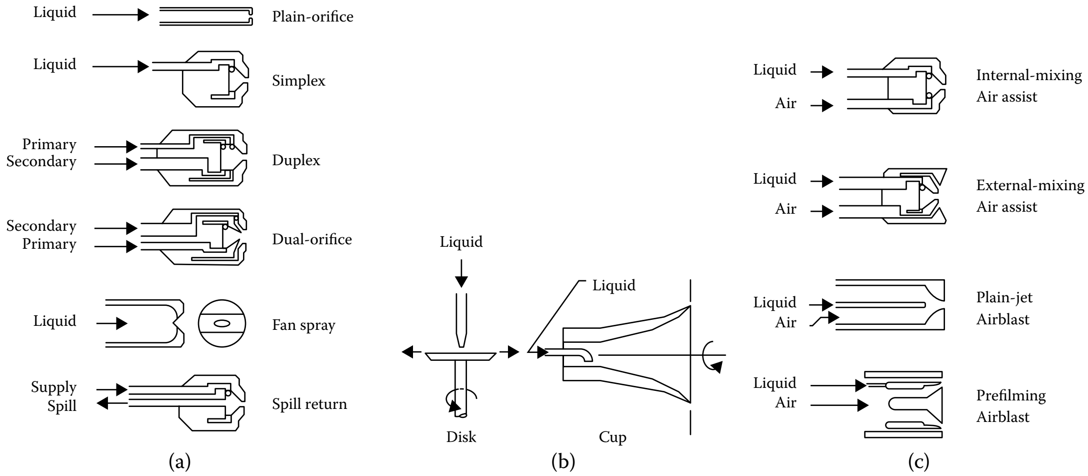

FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

vibrating at its resonant frequency and can produce uniform streams of drops down to 30 µm in diameter. The size and frequency with which the droplets can be produced depend on the flow rate of the liquid through the needle, the needle diameter, the resonant frequency, and the amplitude of oscillation of the needle tip.

Flashing Liquid Jets. An orifice downstream of which a high-pressure liquid flash vaporizes to shatter the liquid into small droplets can produce a fairly regular spray pattern. Flashing dissolved gas systems have been studied by Brown and York [10], Sher and Elata [11], Marek and Cooper [12], and Solomon et al. [13]. The results have shown that flashing even small quantities of dissolved gas (mole fractions <15%) can effect a significant improvement in atomization. However, these beneficial effects cannot be realized unless they are promoted by fitting an expansion chamber just upstream of the discharge orifice. The need for this expansion chamber stems from the low bubble growth rate for dissolved gas systems. This low bubble growth rate appears to pose a fundamental limitation to the practical application of flashing injection by means of dissolved gas systems but applications such as reciprocating engines are looking to exploit the phenomena to improve performance.

Effervescent Atomization. This method of atomization overcomes the basic problems associated with flashing dissolved gas systems. No attempt has been made to dissolve any air or gas in the liquid. Instead, the gas is injected at low velocity into the flowing liquid stream at some point upstream of the discharge orifice. The pressure differential between the atomizing gas and the liquid into which it is injected is only a few centimeters of water and is only what is needed to prevent the liquid from flowing back up the gas line. Studies by Lefebvre and coworkers [14] have shown that good atomization can be achieved at much lower liquid injection pressures than the values normally associated with pressure atomization.

Schematic diagrams illustrating the principal design features of the most important of the atomizers described above are shown in Figure 1.2. The relative merits of these and other atomizers are listed in Table 1.1.

Factors Influencing Atomization

The performance of any given type of atomizer depends on its size and geometry and on the physical properties of the dispersed phase (i.e., the liquid being atomized) and the continuous phase (i.e., the gaseous medium into which the droplets are discharged).

For plain-orifice pressure nozzles and plain-jet airblast atomizers, the dimension most important for atomization is the diameter of the final discharge orifice. For pressure-swirl, rotary, and prefilming airblast atomizers, the critical dimension is the thickness of the liquid sheet as it leaves the atomizer. Theory predicts, and experiment confirms, that mean drop size is roughly proportional to the square root of the liquid jet diameter or sheet thickness. Thus, provided the other key parameters that affect atomization are maintained constant, an increase in atomizer scale (size) will impair atomization.

Liquid Properties

The flow and spray characteristics of most atomizers are strongly influenced by the liquid properties of density, viscosity, and surface tension. In theory, the mass flow rate through a pressure nozzle varies with the square root of liquid density. However, as Tate [6] has pointed out, in practice it is seldom possible to change the density without affecting some other liquid property, so

TABLE 1.1

Relative Merits of Various Types of Atomizers

Type	Description	Advantages	Drawbacks	Applications
Pressure atomizer	Plain orifice	1. Simple, cheap	1. Narrow spray angle	Diesel engines, jet engine afterburners, ramjets
		2. Rugged	2. Solid spray cone	
	Simplex	1. Simple, cheap	1. Needs high supply pressures	Gas turbines and industrial furnaces
		2. Wide spray angle (up to 180°)	2. Cone angle varies with pressure differential and ambient gas density	
	Duplex	Same as simplex, plus good atomization over a very wide range of liquid flow rates	Spray angle narrows as liquid flow rate is increased	Gas turbine combustors
	Dual orifice	1. Good atomization	1. Atomization poor in transition range	Wide range of aircraft and industrial gas turbines
		2. Turndown ratio as high as 50:1	2. Complexity in design	
		3. Relatively constant spray angle	3. Susceptibility of small passages to blockage	
	Spill return	1. Simple construction	1. Spray angle varies with flow rates	Various types of combustor
		2. Good atomization over entire flow range	2. Power requirements higher than with other pressure nozzles except at maximum discharge	Has good potential for slurries and fuels of low thermal stability
		3. Very large turndown ratio		
		4. Large holes and flow passages obviate risk of blockage		
	Fan spray	1. Good atomization	Needs high supply pressures	High-pressure coating operations
		2. Narrow elliptical pattern sometimes advantageous		Annular combustors
Rotary	Spinning disk	1. Nearly uniform atomization possible with small disks rotating at high speeds	Produces a 360° spray pattern	Spray drying
		2. Independent control of atomization quality and flow rate		Crop spraying
	Rotary cup	Capable of handling slurries	May require air blast around periphery	Spray drying
				Spray cooling
Air-assist	Internal mixing	1 Good atomization	1. Liquid can back up in air line	Industrial furnaces
		2. Large passages prevent clogging	2. Requires auxiliary metering device	Industrial gas turbines
		3. Can atomize high-viscosity liquids	3. Needs external source of high-pressure air or steam	
	External mixing	Same as internal mixing, plus construction prevents backing up or liquid into the air line	1. Needs external source of air or steam	Same as internal mixing
			2. Does not permit high liquid/air ratios	
Airblast	Plain jet	1. Good atomization	1. Narrow spray angle	Industrial gas turbines
		2. Simple, cheap	2. Atomizing performance inferior to prefilming airblast	
	Prefilming	1. Good atomization especially at high ambient air pressures	Atomization poor at low air velocities	Wide range of industrial and aircraft gas turbines
		2. Wide spray angle		
Ultrasonic		1. Very fine atomization	Cannot handle high flow rates	Medical sprays
		2. Low spray velocity		Humidification

(Continued)

TABLE 1.1 ***(CONTINUED)***

Relative Merits of Various Types of Atomizers

Type	Description	Advantages	Drawbacks	Applications
				spray drying Acid etching combustion
Electrostatic		Very fine atomization	Cannot handle high flow rates	Paint spraying Printing

this relationship must be interpreted cautiously. The significance of density for atomization performance is diminished by the fact that most liquids exhibit only minor differences in this property. Moreover, the modest amount of available data on the effect of liquid density on mean drop size suggests that its influence is quite small.

One way of defining a spray is in terms of the increase in liquid surface area resulting from atomization. The surface area before breakup is simply that of the liquid cylinder as it emerges from the nozzle. After atomization, the area is the sum of the surface areas of all the individual droplets. This multiplication factor provides a direct indication of the level of atomization achieved and is useful in applications that emphasize surface phenomena such as evaporation and absorption. Surface tension is important in atomization because it represents the force that resists the formation of new surface area. The minimum energy required for atomization is equal to the surface tension multiplied by the increase in liquid surface area. Whenever atomization occurs under conditions where surface tension forces are important, the Weber number, which is the ratio of the inertial force to the surface tension force, is a useful dimensionless parameter for correlating drop size data. Commonly encountered surface tensions range from 0.073 kg/s^2 for water to 0.027 kg/s^2 for petroleum products. For most pure liquids in contact with air, the surface tension decreases with an increase in temperature and is independent of the age of the surface [15]. This is illustrated clearly in Figure 1.3.

In many respects, viscosity is the most important liquid property. Although in an absolute sense its influence on atomization is no greater than that of surface tension, its importance stems from the fact that it affects not only the drop size distributions in the spray but also the nozzle flow rate and spray pattern. An increase in viscosity lowers the Reynolds number and also hinders the development of any natural instability in the jet or sheet. The combined effect is to delay disintegration and increase the size of the drops in the spray.

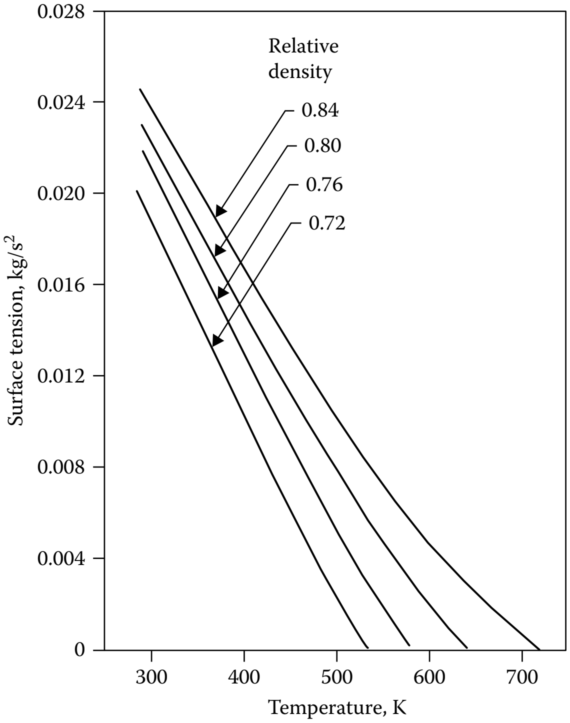

FIGURE 1.3
Surface tension–temperature relationship for hydrocarbon fuels of varying relative densities.

The effect of viscosity on flow within the nozzle is complex. In hollow-cone nozzles, a modest increase in viscosity can actually increase the flow rate. It does this by thickening the liquid film in the discharge orifice, thereby raising the effective flow area. At high viscosities, however, the flow rate usually diminishes with increasing viscosity. With pressure-swirl nozzles, an increase in viscosity generally produces a narrower spray angle. At very high viscosities the normal conical spray may collapse into a straight stream of relatively large ligaments and drops. An increase in liquid viscosity invariably has an adverse effect on atomization quality, because when viscous losses are large, less energy is available for atomization and a coarser spray results. In airblast atomizers, liquid velocities are usually much lower than in pressure nozzles. In consequence, the drop sizes produced by airblast nozzles tend to be less sensitive to variations in liquid viscosity.

Table 1.2 lists the relevant physical properties of some of the liquids used in spray applications. The viscosity of these liquids ranges from 0.001 kg/m·s for water to 0.5 kg/m·s for heavy fuel oil. The viscosity of liquids generally decreases with an increase in temperature. It is customary to heat up many of the heavier fuel oils, partly to reduce pumping power requirements but also to improve atomization.

Some fluids, for example slurries of liquids and solid powders, are characterized by a nonlinear relationship between shear stress and shear strain rate. For such liquids, which are called non-Newtonian, it is necessary to specify the shear rate with the viscosity. The apparent reduction in viscosity with increasing shear rate highlights the need to minimize pressure losses in the supply lines and nozzles. This reduction is also desirable because the viscosities of non-Newtonian fluids have less effect on atomization if a high shear rate is produced in the liquid film formed by the nozzle [15]. Very little secondary atomization will occur once the drops are formed, due to the increase in apparent viscosity at the lower shear rate.

To successfully correlate or simulate atomization behavior, it is imperative to know the key physical properties at the point of atomization. Table 1.2 provides some information for an array of liquids as a starting point. However, for many applications, the temperature dependency must be established. Also, in the case of mixtures of pure liquids, the behavior of the mixture must be understood. In some cases, the properties of the mixture are simple mass weighted averages, but for some liquids (e.g., alcohols) an azeotrope may result, which has highly nonlinear behavior. Hence, for the best results, the researcher/end-user is urged to establish measurement capability for the physical properties using various ASTM, ISO, or SAE methods (e.g., ASTM D 1343-93 for viscosity, ASTM D971; D3825-09 or D7541-11 for surface tension; ASTM D4052 for density). Extensive information (CRC Report 635) is available for the temperature-dependent properties of jet fuels due to its critical role in aircraft and associated need for ensuring safety [16]. Yet, as an illustration of the importance of knowing the actual physical properties of the liquids being worked with, the information in CRC 635 is still only *representative* and the variability in properties from batch to batch of jet fuel still requires an independent measurement to have full confidence in the actual properties of the jet fuel being worked with.

In summary, it is imperative that the physical properties of the liquids used are well understood in order to apply the concepts within this book.

Ambient Conditions

The ambient gas into which sprays are injected can vary widely in pressure and temperature. This is especially true of liquid fuel fired combustion systems. In diesel engines, critical and supercritical pressure and temperature conditions are encountered. In gas turbine combustors, fuel sprays are injected into highly turbulent, swirling recirculating streams of reacting gases. In industrial furnaces, the fuel is sprayed into high-temperature flames of recirculating combustion products. With pressure-swirl atomizers, the spray angle decreases markedly with increase in ambient gas density until a minimum angle is reached beyond which any further increase in the ambient gas density has no effect on the spray angle. The ambient gas density also has a strong influence on the mean drop sizes produced by pressure-swirl atomizers. If the ambient pressure is raised continuously above the normal atmospheric value, the mean drop size increases initially until a maximum value is reached and then slowly declines. The reasons for this unusual relationship between ambient pressure and mean drop size are discussed in Chapter 6.

The spray patterns generated by pressure-swirl atomizers are also affected by the liquid injection pressure differential ΔP_L. The ejector action of the high-velocity spray generates air currents, which causes the spray angle to contract. This effect is aggravated by the increase in spray velocity that accompanies an increase in ΔP_L. Thus, although increasing ΔP_L has no effect on the spray angle immediately downstream of the nozzle, it causes appreciable contraction of the spray pattern farther downstream.

With plain-orifice atomizers an increase in the ambient gas density leads to a wider spray angle. This is because the increase in aerodynamic drag on the droplets, created by an increase in gas density, tends to produce a greater deceleration in the axial direction than in the radial direction.

The spray patterns produced by airblast atomizers tend to be fairly insensitive to variations in the ambient gas density. All but the largest drops in the spray tend to follow the streamlines of the airflow pattern generated at the nozzle exit by the various swirlers and shaped passages within the nozzle. This airflow pattern generally remains fixed and independent of air density, apart from second-order Reynolds number and Mach number effects. However, if the *natural* cone angle of the spray, that is, the spray angle with no air flowing, is markedly different from that of the air, then the change in aerodynamic drag forces produced by a change in air density will affect the resulting spray pattern. In general, an increase in air density will cause the spray pattern to adhere more closely to the streamlines of the atomizing air.

TABLE 1.2

Properties of Liquids

Liquid	Temperature (K)	Viscosity (kg/m·s)	Density (kg/m^3)	Surface Tension (kg/s^2)
Acetone	273	0.000400		0.0261
	293	0.00032	792	0.0237
	300	0.000300		
	303	0.000295		
	313	0.00028		0.02116
Ammonia	284			0.0234
	300	0.00013		0.0181
	307			0.0181
Aniline	283	0.0065		0.0441
	288	0.0053	1,000	0.040
	323	0.00185		0.0394
	373	0.00085		
Benzene	273	0.00091	899	0.0302
	283	0.00076		
	293	0.00065	880	0.0290
	303	0.00056		0.0276
	323	0.00044		
	353	0.00039		
Butane	300	0.00016		0.0116
Carbon tetrachloride	273	0.00133		
	293	0.00097	799	0.0270
	373	0.00038		0.0176
Castor oil	283	2.42		
	288		969	
	293	0.986		
	303	0.451		
	313	0.231		
	373	0.0169		
Chloroform	273	0.0007		
	293	0.00058	1,489	0.02714
	303	0.00051	926	
Cottonseed oil	289			
	293	0.0070		
Creosote	313	0.0070		
n-Decane	293	0.00092		
	300			0.0233
Ethane	300	0.000035		0.0007
Ethyl alcohol	273	0.00177		0.02405
	293	0.0012	791	0.02275
	303	0.0010		0.02189
	323	0.0007		
	343	0.00050		
Ethylene glycol	293	0.01990		
	313	0.00913		
	333	0.00495		
	353	0.00302		
	373	0.00199		
Fuel oil (light)	288	0.172	930	0.0250
	313	0.047	916	0.0230
	356	0.0083	880	0.0210
Fuel oil (medium)	313	0.215	936	0.0230
	378	0.0134	897	0.0200

(Continued)

TABLE 1.2 ***(CONTINUED)***

Properties of Liquids

Liquid	Temperature (K)	Viscosity (kg/m·s)	Density (kg/m^3)	Surface Tension (kg/s^2)
Fuel oil (heavy)	313	0.567	970	0.0230
	366	0.037	920	0.0210
	400	0.015	900	0.0200
Gas oil	288	0.0060	850	0.0240
	313	0.0033	863	0.0230
Glycerin	273	12.1	1,260	0.0630
	288	2.33		
	293	0.622		0.0630
Heptane	273	0.00052		
	300	0.00038		0.0194
	313	0.00034		
	343	0.00026		0.0194
Hexane	273	0.00040		
	293	0.00033		0.0184
	300	0.00029		0.0176
	323	0.00025		
Hydrazine	274	0.00129		
	293	0.00097		
	298			0.0915
Kerosene	293	0.0016	800	0.0260
Linseed oil	288		942	
	303	0.0331		
	363	0.0071		
Machine oil (light)	288.6	0.114		
	310.8	0.0342		
	373	0.0049		
Machine oil (heavy)	288.6	0.661		
	310.8	0.127		
Mercury	273	0.0017	13,600	
	293	0.00153	13,550	0.480
	313	0.00045		
Methyl alcohol	273	0.00082	810	0.0245
	293	0.00060		0.0226
	300	0.00053		0.0221
	323	0.00040		
Naphthalene	353	0.00097		
	373	0.00078		
	400			0.0288
Nonane	300			0.0223
n-Octane	293	0.00054		0.0218
	300	0.0005		0.0210
Olive oil	283	0.138		
	288		918	
	291			0.0331
	293	0.0840		
	343	0.0124		
Pentane	273	0.00029		
	300	0.00022		0.0153
Propane	300	0.000098		0.0064
Toluene	273	0.00077		0.0277
	293	0.00059		0.0285
	303	0.00053		0.0274

(Continued)

TABLE 1.2 *(CONTINUED)*

Properties of Liquids

Liquid	Temperature (K)	Viscosity (kg/m·s)	Density (kg/m^3)	Surface Tension (kg/s^2)
	343	0.00035		
Turpentine	273	0.00225	870	
	283	0.00178		0.0270
	303	0.00127		
	343	0.000728		
Water	291			0.073
	300	0.00085		0.0717

Spray Characteristics

The spray process is inherently chaotic and random in nature. Further, the resulting spray is a result of several complex steps, starting with behavior within the atomizer itself. The transformation of intact liquid to droplets involves a number of dynamic processes. The resulting spray droplets sizes and distribution of the material are often the characteristics that are of interest in many applications, yet the steps to generating the size and spatial distribution of material is a result of the upstream behavior. In recent years, the focus of both simulations and measurements has moved farther upstream. However, the importance of drop size for the many processes that utilize liquid sprays remains key. Both instrumentation and simulation are driven by a desire to better understand the overall atomization process.

In the internal flow region, it is now possible to measure actual flow behavior within the flow passages using novel x-ray methods. The region immediately following the atomizer liquid exit is now being studied using various evolving methods [17]. The resulting drop size characteristics and spray spatial (and temporal) distributions are characterized using a variety of methods.

In terms of measuring drop size, due to its importance as critical parameters in atomization, a wide range of techniques have been developed over the decades. No single technique is completely satisfactory, but each technique has its own advantages and drawbacks, depending on the application. Classic direct methods include those in which individual drops are collected on slides for subsequent measurement and counting or in which droplets are frozen and sized as solid particles. With the impaction method, the drops are sorted on the basis of inertial differences. Depending on its size, a droplet may impact or fail to impact a solid surface or may follow a different trajectory. This allows all the drops in a spray to be sorted into different size categories. High-speed imaging can be used to provide instantaneous images of the drops in a spray, which are recorded for subsequent counting or analysis. High-speed pulsed microphotography, cinematography, and holography are being used to study drop size distributions and spray structure. Much of the tedium normally involved in detailed studies of drop size distributions in various regions of the spray can now be alleviated using automatic image analysis. The method has the important advantage of being nonintrusive, and can also give the temporal distribution of drop sizes as produced by the atomizer. In recent years, considerable advances have been made in the development of laser diagnostic techniques for measuring particle size and velocity in sprays.

A ubiquitous and effective method for assessing and comparing sprays is the Fraunhofer diffraction particle sizing, which uses a line-of-sight measurement through the spray. Various models of this instrument are commercially available for applications to both continuous and intermittent sprays.

More detailed information can be generated using interferometric methods both at a point as well as within a plane. Phase Doppler interferometry provides highly detailed results for the spray behavior at a point within the spray including size, multiple components of velocity, and inferred quantities such as concentration or volume flux. Such results are ideal for validation of simulations. Planar methods can capture information about size and velocity of droplets, providing additional insight into the dynamic processes within the spray and adding insight into coupling between the gas phase aerodynamics and the spray. In fact, the subject of laser diagnostics for measurement of spray has broadened to the point where it warrants its own textbook. Recent reviews of the subject are available [17, 18]. Summaries of the methods used in spray analysis prior to 1980 have been prepared by Chigier [19]. Even earlier methods are summarized by Putnam et al. [20] and Tate [21]. These and more recent developments are described in some detail in Chapter 9.

Ever evolving computational resources have facilitated detailed simulation capability which can implement sophisticated models developed to describe the atomization process and transport of the resulting droplets. Evaporation, droplet impact with surfaces and each other, and reaction of the liquid/vapor with surfaces and gases can also be readily computed.

Applications

A compilation by Tate [6] of some of the most important applications is contained in Table 1.3. While this perspective is more than four decades old, it is still quite relevant. As the cost, complexity, atomizing performance, and energy consumption vary widely between different types of atomizers, it is important to select the best atomizer for any given application. The following factors enter into the proper selection: properties of the liquid to be atomized, for example, density, viscosity, surface tension, and temperature; ambient gas properties, such as pressure, temperature, and flow pattern; particle sizes and percent solids in suspensions, slurries, and pastes; maximum flow rate; range of flow rates (turndown ratio); required mean drop size and drop size distribution; liquid or gas pressures available for nozzles, or power required for rotary atomizers; conditions that may contribute to wear and corrosion; size and shape of vessel, enclosure, or combustor containing spray; economics of spray operation taking into account initial cost, operating expenses, and depreciation; and safety considerations [6].

TABLE 1.3

Spray Applications

Production or processing
Spray drying (dairy products, coffee and tea, starch pharmaceuticals, soaps and detergents, pigments, etc.)
Spray cooling
Spray reactions (absorption, roasting, etc.)
Atomized suspension technique (effluents, waste liquors, etc.)
Powdered metals
Treatment
Evaporation and aeration
Cooling (spray ponds, towers, reactors, etc.)
Humidification and misting
Air and gas washing and scrubbing
Industrial washing and cleaning
Coating
Surface treatment
Spraypainting (pneumatic, airless, and electrostatic)
Flame spraying
Insulation, fibers, and undercoating materials
Multicomponent resins (urethanes, epoxies, polyesters, etc.)
Particle coating and encapsulation
Combustion
Oil burners (furnaces and heaters, industrial and marine boilers)
Diesel fuel injection
Gas turbines (aircraft, marine, automotive, etc.)
Rocket fuel injection
Miscellaneous
Medicinal sprays
Dispersion of chemical agents
Agricultural spraying (insecticides, herbicides, fertilizer solutions, etc.)
Foam and fog suppression
Printing
Acid etching

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Glossary

Some of the terms frequently used in descriptions of atomizers and sprays are defined in the following. These definitions are necessarily brief, and no attempt has been made to include all qualifying considerations.

Air-assist nozzle: Nozzle in which high-velocity air or steam is used to enhance pressure atomization at low liquid flow rates.

Airblast atomizer: Atomizer in which a liquid jet or sheet is exposed to air flowing at high velocity.

Air core: Cylindrical void space within the rotating liquid in a simplex swirl chamber.

Arithmetic mean diameter: Linear mean diameter of drops in spray.

Atomization: Process whereby a volume of liquid is disintegrated into a multiplicity of small drops.

Beam steering: Refraction of a laser beam due to density gradients in the continuous phase.

Breakup length: Length of continuous portion of jet measured from nozzle exit to point where breakup occurs.

Cavitation: Formation of bubbles by gas or vapor released in flow regions of low static pressure; affects discharge coefficient and jet breakup.

Cavitation number: Ratio of pressure differential to downstream pressure; indicator of propensity for cavitation.

Combined spray: Spray produced when both stages flow simultaneously in a dual-orifice or piloted-airblast nozzle.

Continuous phase: Medium, usually gaseous, in which atomization occurs.

Critical flow rate: Liquid flow rate corresponding to the transition from one mode of atomization to another.

Critical Weber number: Value of Weber number above which a single drop will split into two or more drops.

Cumulative distribution: Plot of percentage by number, surface area, or volume of drops whose diameter is less than a given drop diameter.

Discharge coefficient: Ratio of actual flow rate to theoretical flow rate.

Discharge orifice: Final orifice through which liquid is discharged into the ambient gas.

Dispersed phase: Liquid to be atomized.

Dispersion: Ratio of the volume of a spray to the volume of the liquid contained within it.

Drooling: Sluggish dripping of liquid from a nozzle while spraying, usually caused by impingement of the spray on some surface other than the orifice from which the liquid is discharging [22].

Drop coalescence: Collision of two drops to form a single drop.

Droplet size: Diameter of a spherical droplet, usually expressed in micrometers.

Droplet uniformity index: Indication of the range of drop sizes in a spray relative to the median diameter.

Drop saturation: Droplet population exceeding the capability of the sizing instrument or method.

Dual-orifice atomizer: Atomizer consisting of two simplex nozzles fitted concentrically one inside other.

Duplex nozzle: Nozzle featuring a swirl chamber with two sets of tangential swirl ports, one set being the primary ports for low flows and the other the larger secondary ports for handling high flow rates.

Effective evaporation constant: Value of evaporation constant that includes heat-up period and convective effects.

Electrostatic atomizer: Atomizer in which electrical pressure is used to overcome surface tension forces and achieve atomization.

Equivalent spray angle: Angle formed by drawing two straight lines from the nozzle discharge orifice through the center of the liquid mass in the left and right lobes of the spray.

Evaporation constant: Indication of the rate of change of drop surface area during steady-state evaporation.

External mixing nozzle: Air-assist atomizer in which high-velocity gas impinges on a liquid at or outside the final orifice.

Extinction: Percentage of light removed from original direction; indicator of the extent to which measurements of mean drop size are affected by multiple scattering. Also termed *obscuration*.

Fan spray: Spray in the shape of a sector of a circle of about 75° angle; elliptical in cross section.

Film thickness: Thickness of annular liquid sheet as it discharges from the atomizer.

Flat spray: Same as fan spray.

Flow number: Effective flow area of a nozzle, usually expressed as the ratio of mass or volumetric flow rate to the square root of injection pressure differential.

Flow rate: Amount of liquid discharged during a given period of time; normally identified with all factors that affect flow rate, such as pressure differential and liquid density.

Frequency distribution curve: Plot of liquid volume per size class.

Heat transfer number: Indicator of rate of evaporation due to heat transfer to droplet from surrounding gas.

Heat-up period: Initial phase of droplet evaporation prior to attainment of steady-state conditions.

Hollow-cone spray: Spray in which most of the droplets are concentrated at the outer edge of a conical spray pattern.

Impingement: Collision of two round liquid jets or collision of a jet of liquid with a stationary deflector.

Impinging jet atomizer: Atomizer in which two liquid jets collide outside the nozzle to produce a liquid sheet perpendicular to the plane of the jets.

Internal mixing nozzle: Air-assist atomizer in which gas and liquid mix within the nozzle before discharging through the outlet orifice.

Mass transfer number: Indicator of rate of evaporation due to mass transfer.

Mass (volume) median diameter: Diameter of a drop below or above which 50% of the total mass (volume) of drops lies.

Mean drop size: A given spray is replaced by a fictitious one in which all the drops have the same diameter while retaining certain characteristics of the original spray.

Monodisperse spray: Spray containing drops of uniform size.

Multiple scattering: When spray number density is high some drops obscure part of signal generated by others, leading to biased diffraction patterns.

Normal distribution: Distribution of drop sizes based on the random occurrence of a given drop size.

Obscuration: Percentage of light removed from original direction; indicator of the extent to which measurements of mean drop size are affected by multiple scattering. Also known as *extinction*.

Ohnesorge number: Dimensionless group obtained by dividing the square root of the Weber number by the Reynolds number, which eliminates velocity from both; indicator of jet or sheet stability.

Patternation: A measure of the uniformity of the circumferential distribution of liquid in a conical spray. The term *radial patternation* is also used to describe the radial distribution of liquid within a conical spray.

Patternator: Two types are available: one designed to measure the radial liquid distribution in a conical spray, the other to measure the uniformity of the circumferential liquid distribution.

Plain-orifice atomizer: Atomizer in which liquid is ejected at high velocity through a small round hole; the best known example is a diesel injector.

Polydisperse spray: Spray containing drops of different sizes.

Prefilmer: Solid surface on which a thin continuous liquid film is formed.

Pressure atomizer: Single-fluid atomizer in which the conversion of pressure to kinetic energy results in a high relative velocity between the liquid and the surrounding gas.

Relative density: Ratio of the mass of a given volume of liquid to the mass of an equal volume of water; the temperature of both liquids must be stated. For example, relative density = 0.81 at 289/277 K indicates that the mass of the liquid was measured at 289 K and divided by the mass of an equal volume of water at 277 K. Formerly called specific gravity.

Relative span factor: Indicator of the range of drop sizes relative to the mass median diameter.

Reynolds number: Dimensionless ratio of inertial force to viscous force.

Rosin–Rammler distribution: Drop size distribution described in terms of two parameters, one of which provides a measure of the spread of drop sizes.

Rotary atomizer: Atomizer in which liquid is discharged from the edge of a rotating disk, cup, or slotted wheel.

Sauter mean diameter: Diameter of a droplet whose surface-to-volume ratio is equal to that of the entire spray.

Shroud air: A flow of air over the atomizer face to prevent deposition of carbon; also used to modify spray characteristics at low flow rates.

Simplex nozzle: Nozzle that employs a single swirl chamber to produce a well-atomized spray of wide cone angle.

Skewness: The axis of the nozzle spray cone is not colinear with the central axis of the nozzle; the maximum departure is stated in degrees [22].

Slinger system: Rotary atomizer employed in some small gas turbines.

Solid-cone spray: Spray in which the droplets are fairly uniformly distributed throughout a conical spray volume.

Spatial sampling: Measurement of drops contained within a volume under conditions such that contents of volume do not change during any single measurement.

Spill-return nozzle: Basically a simplex atomizer with provision for liquid to be removed from the swirl chamber and returned to supply; provides good atomization even at lowest flow rates.

Spitting: Large, irregular drops of liquid intermittently produced by otherwise uniformly fine spray; sometimes caused by internal flow leaks within the nozzle [22].

Spray angle: Angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at a specific distance from the atomizer face.

Spray axis: Intersection of two planes of symmetry of the spray [6]; for symmetrical sprays the spray axis coincides with the centerline of the angle.

Stability curve: Graph showing relationship between jet velocity and breakup length.

Streak: Very narrow sector of the spray with more or less than the average concentration of droplets.

Surface tension: Property that resists expansion of liquid surface area. Surface tension forces must be overcome by aerodynamic, centrifugal, or pressure forces to achieve atomization.

Swirl chamber: Conical or cylindrical cavity having tangential inlets that impart a swirling motion to the liquid.

Temporal sampling: Measurement of drops that pass through a fixed area during a specific time interval.

Transition range: Small flow range of a dual-stage nozzle over which atomization quality is relatively poor; occurs when the pressurizing valve first opens to allow secondary liquid flow into the nozzle.

Turndown ratio: Ratio of maximum rated liquid flow to minimum rated liquid flow.

Twin-fluid atomizer: Generic term encompassing all nozzle types in which atomization is achieved using high-velocity air, gas, or steam.

Ultrasonic atomizer: Atomizer in which a vibrating surface is used to make a liquid film unstable and disintegrate into drops.

Upper critical point: Point on stability curve where breakup changes from varicose to sinuous.

Varicose: Term used to describe appearance of liquid jet during breakup without interaction with air.

Velocity coefficient: Ratio of actual discharge velocity to the theoretical velocity corresponding to the total pressure differential across the nozzle.

Viscosity: Liquid property that has a marked effect on atomization quality and spray angle and also affects pumping power requirements; very dependent on liquid temperature.

Visibility technique: Drop sizing interferometry used in conjunction with laser Doppler anemometry to measure both drop size and velocity.

Weber number: Dimensionless ratio of momentum force to surface tension force.

Web bulb temperature: Droplet surface temperature during steady-state evaporation.

Whistle atomizer: Atomizer in which sound waves are used to shatter a liquid jet into droplets.

Wide-range nozzle: Nozzle designed to provide good atomization over a wide range of liquid flow rates; best known example is dual-orifice nozzle.

Windmill atomizer: Rotary atomizer used for aerial application of pesticides; unique feature is use of wind forces to provide rotary motion.

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