SPRAYS

1. Introduction

A spray is a cloud of moving liquid droplets dispersed in gas. Due to the dynamic nature of a spray, its definition must include both liquid drops and the entrained gas. The spray image in Figure 1 illustrates the entrainment of gas by the drops. The drops exchange momentum with the gas consequently farther from the nozzle the relative velocity of the liquid and gas is less.

The basic purposes of sprays are to (*1*) create droplet surface area for enhanced heat and mass transfer, (*2*) disperse a liquid over an area, (*3*) meter or control liquid throughput, and (*4*) generate droplet velocity and momentum. Depending upon the application need, many types of sprays can be produced. Hundreds of spray producing devices have been developed to achieve these purposes.

The mechanical devices designed to generate sprays are commonly called spray nozzles or atomizers. Liquid atomizers are widely used in modern industry to improve process performance. They are found in many industrial, agricultural, and propulsion systems. Processes that require atomizing systems include spray drying, scrubbing, micropowder formation of pharmaceuticals and catalysts, cooling, fuel combustion, spray painting and coating, application of herbicides and pesticides, food processing, molten-metal solidification, medical nebulizers, and aerosol sprays for consumer products.

Selection of the technology best suited for a specific application starts with the desired function. Table 1 shows a classification of functions with example applications and the desired benefit. This table is ordered with the most frequent usages first. The degree of sophistication required in the selection varies from matching pressure drop and desired liquid flow to the other extreme where detailed measurements of drop size and velocity distributions are utilized with computational fluid dynamics, CFD, to model the application.

Spray technology was improved as a result of environmental regulations in several areas. Reducing emissions of pollutants from combustion of liquid hydrocarbon fuel including carbon monoxide, unburned hydrocarbons, oxides of nitrogen, and smoke required more sophisticated atomizers. For example, aircraft jet engines and automotive engines utilize atomizers to inject hydrocarbon fuel. When paints and coating formulations were changed to reduce the solvent emission, the devices used to atomize the products had to be designed to accommodate increased liquid viscosity. Spray technology is also applied to abate emissions with scrubbers and gas quenching. Because of the potential problems associated with sprays, it has become increasingly important to understand the process of atomization. Liquid atomizers must be properly designed and selected to minimize unnecessary hazards.

In the past, the design of atomizers and spray processes was based on traditional fluid dynamic principles and empirical methods. Fuel atomizers for gas jet engines (gas turbines) illustrate the development of technology. This application is demanding due to a factor of 10 in the range operating pressure of the combustion and the limited volume available for the combustion chamber. In the 1950 to 1960 period, atomizer design and selection to optimize performance used trial-and-error methods by building a device and testing in a combustion test stand. This slow and expensive method allowed for only a few designs to be evaluated as a new engine was being designed. In the 1970 to 1980 time frame, innovative methods with practical instruments measuring the drop size were developed which enabled quantitative evaluation of the spray, the drop size, and other parameters independent of combustion. Engine emissions were reduced and the length between service intervals increased. In the 1990s, spray technology advanced rapidly through the synergism of the next generation of reliable spray drop size and velocity measurements and mathematical modeling, including computational fluid dynamics (CFD). The science also developed better fundamental understanding of the mechanisms of liquid break-up and dispersion, and prediction of important spray parameters with improved accuracy. More confident prediction of process performance resulted in innovations and optimized designs, further enhancing systems.

Because high quality, low cost, and optimum performance are required of spray equipment, improved analytical and experimental tools are indispensable for increasing productivity in many industries. In most instances, it is no longer adequate to characterize a spray solely on the basis of flow rate and spray pattern. Information on droplet size, velocity, volume flux, and number density is often needed and can be determined using advanced laser diagnostic techniques. These improvements have benefited a wide spectrum of consumer and specialized industrial products.

Atomization technology will continue to expand because more development will be needed to address specific concerns in a wide variety of applications. Industry standards must be established and maintained in spray terminology, testing, and design procedures to avoid confusion and misunderstanding. Innovative concepts will also be required to meet more stringent environmental standards.

2. Liquid Atomizers

A specialized vocabulary of terms has evolved in the spray community because of the diverse applications involving liquid atomizers. The American Society for Testing and Materials, ASTM Subcommittee E29.04 on Liquid Particle Characterization, created a standard for terminology relating to atomizing devices (1). The definitions adopted by ASTM are used herein.

The transformation of bulk liquid to sprays can be achieved in many different ways. Basic techniques include applying hydraulic pressure, electrical, acoustic, or mechanical energy to overcome the cohesive forces within the liquid. Work is required to overcome the liquid surface tension generating a smaller particle size and to accelerate the liquid that forms the collection drops in the spray.

Atomizers can be classified according to the energy source used to achieve liquid breakup. Figure 2 shows this classification diagram. Typical sources of energy include kinetic energy of the liquid and additional gas if added for this purpose. Mechanical energy is used in the form of a rotating or vibration (ultrasonic) surface. When an electric charge is the primary source of energy, it is called an electrostatic atomizer.

Pressure or hydraulic atomizers are the most commonly used due to simplicity and effectiveness in many applications. Two fluid nozzles are often used where a wide range of operating rates are required, because the atomizing gas provides an independent means of adjusting performance and the control in internal flows enables a smaller drop size to be produced. Flashing flow nozzle use has increased with the development of supercritical atomizers (2) for both paint application and pharmaceutical micro powder production. Liquid atomizers classified by distinct design features and spray characteristics are summarized in Table 2. More detailed information on various atomizers is available (3–7).

3. Physics of Liquid Atomization

Liquid atomization involves a series of complicated physical processes. These processes are generally divided into three different flow regimes: internal flow, breakup, and droplet dispersion. The internal flow regime extends from the atomizer inlets to the discharge orifice where liquid emerges. The liquid breakup regime starts at the atomizer exit plane and ends downstream where primary atomization is complete. The interaction of the primary particles with the surrounding gas can result in further break-up of the largest drops called, secondary atomization. The final process of atomization is the dispersion regime where spherical droplets gradually evolve and exchange momentum with the surrounding gas to result in a specific spray pattern.

3.1. Internal Flow. Depending on the atomizer type and operating conditions, the internal fluid flow can involve complicated phenomena such as flow separation, boundary layer growth, cavitation, turbulence, vortex formation, and two-phase flow. The internal flow regime is often considered one of the most important stages of liquid atomization because it determines the initial liquid disturbances and conditions that affect the subsequent liquid breakup and droplet dispersion.

The flow characteristics inside liquid atomizers have been studied by numerous investigators (8–12). Of special interest to designers is the work reported on swirl atomizers (4,8), fan spray atomizers (10,11), and plain jets (10). An example of a nozzle with a simple internal flow pattern is a deflector plate nozzle as shown in Figure 3. This atomizer is intuitively simple; a stream of liquid is deflected by a surface, causing a sheet of liquid which breaks-up downstream. This results in a spray pattern with a rectangular cross section. If this defector is wrapped to form a spiral, the spiral type of atomizer as shown in Figure 4 results. This class of nozzle is effective in producing a small drop size relative to outlet orifice size.

Swirl Atomizer. Many atomizers utilize tangential slots or passages to produce swirl to facilitate atomization. Figure 5 is a schematic diagram of a swirl atomizer in the simplest form. Under high pressure, liquid flow is forced into the swirl chamber through several tangential slots on the distributor, Figure 6. As liquid enters into the swirl chamber, it spins in the manner of a whirlpool. The liquid swirling effect creates a central low pressure region that draws external air into the chamber to form an air vortex. This air vortex extends from the rear of the chamber through the center of the exit orifice. Because of this air core, the exit orifice is not completely filled with liquid. Figure 7 shows the air core structure inside a typical swirl chamber.

A thorough description of the internal flow structure inside a swirl atomizer requires both velocity and pressure distribution information. Useful insights on the boundary layer flow through the swirl chamber are available (13–15). Because of the existence of an air core, the flow structure inside a swirl atomizer is a difficult to analyze free-surface problem. If the location and surface pressure of the liquid boundary are known, however, the equations of motion of the liquid phase can be applied to reveal the detailed distributions of the pressure and velocity.

One proposed simplified theory (13) provides reasonably accurate predictions of the internal flow characteristics. In this analysis, conservation of mass as well as angular and total momentum of the liquid is assumed. To determine the exit film velocity, size of the air core, and discharge coefficient, one must assume the maximum flow through the orifice is attained.

The flow through single fluid atomizers can be related with this simple relationship $Q = C_d A_2 (2 g_c \Delta P/\rho_L)^{1/2}$, where the typical values of C_d range between 0.3 and 0.5. Numerous studies for the discharge coefficient have been published to account for the effect of liquid properties (16), operating conditions (17), atomizer geometry (18), vortex flow pattern (19), and conservation of axial momentum (20). From one analysis (21), the following empirical equation appears to correlate well with the actual data obtained for swirl atomizers over a wide range of parameters. Sometimes several of these factors $(C_d A_2 (2 g_c/\rho_L)^{1/2})$ are lumped together to form a flow characteristic or flow number (parameters with dimensions), to characterize the pressure drop as a function of flow.

$$C_d = 0.45 \left(\frac{d_0 \rho_L U}{\mu_L}\right)^{-0.02} \left(\frac{l_0}{d_0}\right)^{-0.03} \left(\frac{L_s}{D_s}\right)^{0.05} \left(\frac{A_p}{D_s d_0}\right)^{0.52} \left(\frac{D_s}{d_0}\right)^{0.23} \tag{1}$$

3.2. Liquid Breakup. In the breakup regime, high magnification photography reveals that liquid atomization is associated with the phenomena of wave formation and propagation, rupture of ligaments, ligament collision and coalescence, and continuous disintegration caused by shear, rotation, impingement, and pulsation. Depending on the atomizer types and operating conditions, liquid breakup can be governed by different mechanisms.

The fundamental principle of liquid disintegration lies in the balance between disruptive and cohesive forces. The common disruptive forces in atomizer systems include kinetic energy, turbulent fluctuation, pressure fluctuation, interface shearing, friction, and gravity. The cohesive forces within the liquid are viscosity, and surface tension.

Fan Sprays. The mechanistic theory to explain the film break-up was developed and verified in the 1950s. Instability theory can be used to analyze the wave growth on a thin liquid sheet (22). This analysis predicted the existence of an optimum wavelength at which a wave would grow rapidly. This optimum wavelength, λ_{opt}, corresponds to a condition that leads to liquid sheet disintegration. It can be expressed as in equation 2. The surface waves grow until the sheet is disrupted to form irregular ligaments, which further break-up to drops.

$$\lambda_{opt} = \frac{4\pi\sigma}{\rho_G U_R^2} \tag{2}$$

The theory has been extended to evaluate sheet breakup (23). The resultant model assumes that the fastest growing wave detaches at the leading edge in the form of a ribbon with a width of a half-wavelength. The ribbon immediately contracts into multiple ligaments, which subsequently reshape themselves into spherical droplets. In accordance with Rayleigh's analysis (24), the characteristic dimension, D_L, of a ligament is related to the droplet mean diameter in the form of $D = 1.89\ D_L$, therefore $k = 1.89$ experimentally $k \cong 2.2$. Sheet break-up theory results in equation 3, which provides basic insight on film break-up controlled systems. Several factors, relative velocity, film thickness, surface tension and gas density, will influence drop size if this is the controlling mechanism.

$$\overline{D} = k\left(\frac{8}{\pi}\frac{\pi\sigma}{\rho_G U_R^2}t\right)^{1/2} \tag{3}$$

Hollow-Cone Sprays. In swirl atomizers, the liquid emerges from the exit orifice in the form of a conical sheet. As the liquid sheet spreads radially outward, aerodynamic instability immediately takes place and leads to the formation of waves which subsequently disintegrate into ligaments and droplets. Figure 8 illustrates the breakup process in an annular liquid sheet.

In the analysis of hollow-cone sprays, two models are required, air cone development and sheet break-up. This complex process has been thoroughly investigated; wave instability theory has been extended to this system where the sheet thickness decreases due to inherent geometry. As the distance from the nozzle increases the perimeter increases so the sheet thickness must decrease.

Jet Spray. The mechanism that controls the breakup of a liquid jet has been analyzed by many researchers (25,26). These studies indicate that liquid jet atomization can be attributed to various effects such as liquid–gas aerodynamic interaction, gas- and liquid-phase turbulence and turbulence length scales, capillary pinching, gas pressure fluctuation, and disturbances initiated inside the atomizer. In spite of different theories and experimental observations, there is agreement that capillary pinching is the dominant mechanism for low velocity jets. As jet velocity increases, there is some uncertainty as to which effect is most important in causing breakup. A universal model of droplet break-up has yet to be established, thought several are in use depending on the range of application.

3.3. Droplet Dispersion Zone. The primary feature of the dispersed flow regime is the spray contains generally spherical droplets. In most practical sprays, the volume fraction of the liquid droplets in the dispersed region is relatively small compared with the continuous gas phase because gas is ingested into the collection of drops forming the spray. Depending on the gas-phase conditions, liquid droplets can encounter acceleration, deceleration, collision, coalescence, evaporation, and secondary breakup during their evolution. The aerodynamic forces on an individual drop are characterized by Weber number and the drop break-up mechanisms are characterized by a combination of Weber and Ohnesorge numbers (5). Through droplet and gas-phase interaction, turbulence plays a significant and complex role in the redistribution of droplets and spray characteristics.

Another important dimensionless number used to characterize the interaction between the gas in liquid is the Stokes number. This is ratio of the response time of the particle to the characteristic time of the particle, as defined in equation 4. For nearly all sprays C_c can be approximated by the value of 1 because the particles are much larger than the mean free path of the gas molecules. Large Stokes numbers ($St \gg 1$) indicate particles have little momentum exchange with the gas and will follow a ballistic trajectory. While very small ($St \ll 1$) have trajectories that are influenced by the gas flow. The characteristic time of the particle (L/V) depends on the length scale of the particle trajectory and the initial velocity. The momentum moving gas surrounding a cloud of droplets effects many spray usages. High rates of momentum exchange can have high rates of evaporation (mass transfer) and heat transfer.

$$St = \frac{\rho_l D^2 V_i C_c}{18 \mu_g L} \tag{4}$$

For water like fluids, Weber numbers greater than 1 will result in deformation of the spherical shape and if in excess of 12 will result in break-up. The break-up process is constrained by the reduction in relative velocity between the gas and liquid phases. After breakup, droplets continue to interact with the surrounding environment before reaching their final destination. Droplet size and velocity can be determined as a function of spatial locations. Computational fluid dynamics is often used in critical design problems to provide design insight along with the laser based experimental methods described later.

Evaporation of droplets in sprays is often the most important result desired in creating a spray, such as for combustion systems. This involves complex time varying local quantities of both heat and mass transfer consequently which are affected by turbulence and relative velocity. A steady state approximation indicates the evaporation time is directly proportional to the square of the initial drop diameter. Combustion time for drops is often expressed in the D squared law $t = \lambda_C D_i^2$ with lambda as the constant of a specific fuel and gas phase environment. This simplification ignores the initial heating of the drop and the complexity of the internal circulation within the drop (Fig. 9). This toroidal vortex is sometimes referred to as a Hill's vortex. The internal circulation reduces internal profiles of concentration and temperature. More complex and more accurate estimation of drop mass transfer and evaporation often incorporate the internal drop motion (27,28).

4. Spray Characteristics

Spray characteristics are fluid dynamic quantities that can be observed or measured during liquid breakup and dispersal. They are used to identify and quantify the features of sprays for the purpose of evaluating atomizer and system performance, for establishing practical correlations, and for verifying computer model predictions. Spray characteristics provide information necessary to understand the fundamental physical laws that govern liquid atomization.

In the breakup regime, spray characteristics include film angle, film velocity and thickness, breakup length, breakup rate, surface wave frequency, wavelength, growth rate, and penetration distance. These quantities are extremely difficult to measure due to the very small size and rapidly changing features of disintegrating liquid jets or films.

In the dispersed regime, the physical and instrumental limitations are not as stringent as those in the breakup regime because primary atomization has been completed and the droplets have been dispersed into a much larger volume of space. Therefore, the dynamic quantities can be measured by most instruments. Parameters that are useful in describing the dispersed regime include droplet size and velocity, number density, volume flux, turbulence, gas dynamics quantities, spray pattern and angle, skewness, droplet arrival statistics, droplet trajectories and angles of flight, and vapor concentration.

During formation spray fluid properties for each phase vary with time and location. Depending on the atomizing system and operating conditions, variations can result from droplet dispersion, acceleration, deceleration, collision, coalescence, secondary breakup, evaporation, entrainment, oxidation, and solidification. Thus, it may be extremely difficult to identify the dominant physical processes that control the spray dynamics and configuration.

4.1. Spray Parameters. The more common spray parameters are as follows.

Droplet Size Distribution. Most sprays comprise a wide range of droplet sizes. Some knowledge of the size distribution is usually required, particularly when evaluating the overall atomizer performance. The size distribution may be expressed in various ways. Several empirical functions, including the Rosin-Rammler (29) and Nukiyama-Tanasawa (30) equations have been commonly used. Lefebvre (3) describe other distributions, such log normal expression that are sometimes used to better represent the large and small diameter extremes of the size distribution.

Most distribution functions contain an average size and a variance parameter typically based on the cumulative droplet number or volume distributions. For example, the Rosin-Rammler function uses the cumulative liquid volume as a means of expressing the distribution. It can be expressed as follows, where V_f is the fraction of the total volume contained in droplets of diameter less than D, n is a measure of the spread in the reported diameters, and $\overline{D}$ is a characteristic average diameter.

$$V_F = 1 - \exp\left[-\left(\frac{D}{\overline{D}}\right)^n\right] \tag{5}$$

Larger the value of n result in a more uniform is the size distribution. A typical value for n with a high performance nozzle may be in the range of 2 to 2.5. Other types of distribution functions can be found in Ref. 3. Distribution functions based on two parameters sometimes do not accurately match the actual distributions. In these cases a higher order polynomial fit, using multiple parameters, must be considered to obtain a better representation of the raw data. Often computational models that utilize drop size data can use the drop distribution, in drop frequency form, without the need of characterizing the spray with a distribution function.

Mean Diameters. Several mean diameters are frequently used to represent the statistical properties of droplets produced by liquid atomizers. These mean diameters may be expressed according to the following notation (31):

$$\overline{D}_{pq} = \left[\frac{\sum_{i=1}^{k}(N_i D_i^p)}{\sum_{i=1}^{k}(N_i D_i^q)}\right]^{\frac{1}{(p-q)}} \tag{6}$$

The p and q denote the integral exponents of $\overline{D}$ in the respective summations, and thereby explicitly define the diameter that is being used. N_i and D_i are the number and representative diameter of sampled drops in each size class i. For example, the arithmetic mean diameter, $\overline{D}_{10}$, is a simple average based on the diameters of all the individual droplets in the spray sample. The volume mean diameter, $\overline{D}_{32}$, is the diameter of a droplet whose volume, if multiplied by the total number of droplets, equals the total volume of the sample. The Sauter mean diameter, $\overline{D}_{32}$, is the diameter of a droplet whose ratio of volume-to-surface area is equal to that of the entire sample. This diameter is frequently used because it permits quick estimation of the total liquid surface area available for a particular industrial process or combustion system where the D squared law is significant.

Median Diameter. The median droplet diameter is the diameter that divides the spray into two equal portions by number, length, surface area, or volume. Median diameters may be easily determined from cumulative distribution curves. Volume weighted representative diameters are such examples: $D_{V0.1}$ is the diameter such that 10% of total liquid volume in the spray is smaller than this diameter, $D_{V0.5}$ is the diameter such that 50% of total liquid volume in the spray is smaller than this diameter (also known as Mass Mean Diameter, MMD), and similarly for the $D_{V0.9}$. The relative span, defined in the equation 7, is a useful metric of the width of the spray size distribution. Effectiveness of many spray applications is determined by the large diameter or small diameter fraction of the spray, therefore one or more of these volume weighted measures are used.

$$\text{Relative span} = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \tag{7}$$

Number Density and Volume Flux. The determination of number density and volume flux requires accurate information on the sample volume cross-sectional area, droplet size and velocity, as well as the number of droplets passing through the sample volume at any given instant of time. Depending on the instrumentation, the sample volume may vary with the optical components and droplet sizes. The number density, equation 8, represents the number of droplets contained in a specified volume of space at a given instant. It can be expressed as follows, where $\bar{u}$ is the mean droplet velocity, t the sample time, and A the representative cross-sectional area at the sampling location.

$$N = \frac{\sum_{i=1}^{k} N_i}{\bar{u}tA} \tag{8}$$

Volume flux is the volume contained by the droplets passing through a unit cross-sectional area per unit interval of time. It can be calculated as follows, where $\overline{D}_{30}$ is the volume mean diameter and n is the total number of droplets.

$$F = \frac{\frac{\pi}{6} n \overline{D}_{30}^{3}}{tA} \tag{9}$$

Measurements of local volume flux distributions may be used to establish the degree of symmetry of a spray. Flux values must be integrated across the measurement planes and verified against the liquid flow rate of the atomizer.

Cone Angle. The spray cone angle is one of the most important parameters in the specification of atomizers. Unfortunately, it is very difficult to define and measure because typical sprays have curved and fuzzy boundaries. A common method of defining the spray cone angle is to draw two tangent lines originating at the orifice and extending to the outermost spray edges at a specified axial distance. Several devices are commonly used to make quick estimates of spray angle. These devices include goniometers, needle probes equipped with linear displacement transducers, and projectors for back-lighting spray images.

Patternation. The quantitative spatial distribution of liquid flux in a spray pattern is patternation. The spray pattern provides important information for many spray applications. It is directly related to the atomizer performance. For example, in spray drying, an asymmetric spray pattern may cause inadequate liquid–gas mixing, thereby resulting in poor efficiency and product quality. Instruments that provide quantitative information on spray patterns are, therefore, essential for many processes. The pattern information must be able to reveal characteristics such as skewness, degree of pattern hollowness, and the uniformity of liquid flux over the entire cross-sectional area.

Patternators, or device to measure patternation, may comprise an array of tubes or concentric circular vessels to collect liquid droplets at specified axial and radial distances. Depending on the patternator, various statistical measures can be used to express the deviation between the actual performance and the ideal perfectly uniform distribution.

4.2. Spray Dynamic Structure. Detailed measurements of spray dynamic parameters are necessary to understand the process of droplet dispersion. Improvements in phase Doppler particle analyzers (PDPA), or phase

Doppler interferometry (PDI) (32) permit *in situ* measurements of droplet size, velocity, number density, and liquid flux, as well as detailed turbulence characteristics for very small regions within the spray. Such measurements allow designers to evaluate differences in atomizers, changes in droplet size distributions, radial and circumferential symmetry, size–velocity correlations, interactions between droplets and the surrounding gas, droplet time-dependent behavior, and droplet drag and trajectories. In addition, the information can be extremely valuable for verifying physical and computational models and establishing general correlations for atomizer performance.

Spray dynamic structures vary significantly depending on the operating conditions and atomizer types. One of the most common patterns is the hollow spray.

Hollow Sprays. Most atomizers that impart swirl to the liquid tend to produce a cone-shaped hollow spray. Although swirl atomizers can produce varying degrees of hollowness in the spray pattern, they all seem to exhibit similar spray dynamic features. For example, detailed measurements made with simplex, duplex, dual-orifice, and pure airblast atomizers show similar dynamic structures in radial distributions of mean droplet diameter, velocity, and liquid volume flux. Extensive studies have been made (33,34) on the spray dynamics associated with pressure swirl atomizers. Based on these studies, some common features were observed. Test results obtained from a pressure swirl atomizer spray could be used to illustrate typical dynamic structures in hollow sprays. The measurements were made using a phase Doppler spray analyzer.

Figure 10 shows a three-dimensional distribution of the Sauter mean diameter, $\overline{D}_{32}$, measured 38.1-mm downstream from the nozzle using a Delavan 1GPH-80°A pressure atomizer. The operating pressure was 690 kPa (100 psi). Typically, the mean diameters gradually increase with an increase in radial distance. This indicates that, in hollow sprays, the small droplets are mainly distributed in the center region, whereas the large droplets are found near the outer edge of the pattern. This figure shows an example where spatially resolved drop size may allow a performance issue to be identified. The small zone of larger drop size shown in the upper left may affect performance in some applications.

Figure 11 shows the variation of the droplet mean axial velocity at the same axial location. The primary feature of this velocity profile is that the maximum velocity peaks at the centerline. The velocity magnitude and direction in the center region tend to be related to the liquid swirl strength and axial distance. A reverse (recirculation) flow with negative velocity is possible if the swirl is intense. Under such conditions, the maximum velocity tends to shift away from the centerline.

4.3. Spray Correlations. One of the most important aspects of spray characterization is the development of meaningful correlations between spray parameters and atomizer performance. The parameters can be presented as mathematical expressions that involve liquid properties, physical dimensions of the atomizer, as well as operating and ambient conditions that are likely to affect the nature of the dispersion. Empirical correlations provide useful information for designing and assessing the performance of atomizers. Dimensional analysis has been widely used to determine dimensionless parameters that are useful in describing sprays. The most common variables affecting spray characteristics include a characteristic dimension of atomizer, d; liquid density, ρ_L; liquid dynamic viscosity, μ_L; surface tension, σ; pressure, ΔP; liquid velocity, v_L; gas density, ρ_G; and gas velocity, v_G.

Based on such analyses, the Reynolds, Weber, Stokes, and Ohnesorge numbers are considered the most important dimensionless groups describing the spray characteristics. The Reynolds number, *Re*, represents the ratio of inertial forces to viscous forces.

$$Re = \frac{\rho_L v_L L}{\mu_L} \tag{10}$$

The Reynolds number is sufficient as a parameter for describing the internal flow characteristics, such as discharge coefficient, air core ratio, and spray angle at the atomizer exit.

The Weber number, *We*, is defined as follows and represents the ratio of the disruptive aerodynamic forces to the restoring surface tension forces.

$$We = \frac{\rho_L d(v_L - v_G)^2}{\sigma} \tag{11}$$

The Weber number becomes important at conditions of high relative velocity between the injected liquid and surrounding gas. Other dimensionless parameters Euler ($\Delta P/\rho_L V_L$), and Taylor (*Re/We*) numbers, have also been used to correlate spray characteristics. These parameters, however, are not used as often as the Reynolds, Weber and Ohnesorge numbers. The Ohnesorge number represents the ratio of viscous and surface tension forces.

$$Oh = \frac{\mu_L}{\sqrt{\rho_L D \sigma}} = \frac{\sqrt{We}}{Re} \tag{12}$$

Many empirical correlations published in the literature for various types of liquid atomizers (3–5) provide an extensive collection of empirical equations. Unfortunately, most of the correlations share some common problems. For example, they are only valid for a specific type of atomizer, thereby imposing strict limitations on their use. They do not represent any specific physical processes and seldom relate to the design of the atomizer. More important, they do not reveal the effect of interactions among key variables. This indicates the difficulty of finding a universal expression that can cover a wide range of operating conditions and atomizer designs.

Droplet Size Correlations. The majority of correlations found in the literature deal with mean droplet diameters. A useful equation for Sauter mean diameters produced by pressure swirl atomizers (equation 13) has been proposed (32). It consists of two separate terms, one dominated by liquid viscosity and pressure, the other by film thickness. To estimate the Sauter mean diameter, it is necessary to calculate first the film thickness, t_0, at the discharge orifice of the atomizer. Equation 14 may be used, where t_0 is the initial film thickness in meters, d the orifice diameter in meters, m_L the mass flow rate in kg/s, μ_L the dynamic viscosity in kg/m/s, ρ_L the liquid density in kg/m^3, and ΔP the pressure drop in Pascal. In equation 13, $\overline{D}_{32}$ is in meters, σ is the surface tension in N/m, and ρ_G is the gas density in kg/m^3.

$$\overline{D}_{32} = 2.29\left(\frac{\sigma\mu_L^2}{\rho_G}\right)^{0.25}\Delta P^{-0.5}t_0^{0.25} + 0.89\left(\frac{\sigma\mu_L}{\rho_G}\right)^{0.25}\Delta P^{-0.25}t_0^{0.75} \tag{13}$$

$$t_0 = 3.66\left(\frac{dm_L\mu_L}{\rho_L\Delta P}\right)^{0.25} \tag{14}$$

Using equations 9 and 10, the estimated Sauter mean diameters agree quite well with experimental data obtained for a wide range of atomizer designs. Note that the two constants in equation 11 differ from those shown in Lefebvre's equation (34). These constants have been changed to fit a wide range of experimental data.

For airblast-type atomizers, it has been speculated (35) that the Sauter mean diameter is governed by two factors, one controlled by aerodynamic forces of air velocity and density, the other by liquid viscosity. Equation 15 has been proposed for the estimation of $\overline{D}_{32}$. In this equation, A and B are constants whose values depend on atomizer design; GLR is the gas–liquid mass ratio.

$$\overline{D}_{32} = L\left[1+\frac{1}{GLR}\right]\left[A\left(\frac{\sigma}{\rho_G U_R^2 L}\right)^{0.5} + B\left(\frac{\mu_L^2}{\rho_L\sigma L}\right)^{0.5}\right] \tag{15}$$

This equation accounts for drop size with two terms, one of which is dominated by the aerodynamic effects with A coefficient, and the second term to account for liquid viscosity, with B coefficient. The term with the A coefficient is the reciprocal of the Weber number and the second term is a function of the Ohnesorge number. Equation 15 may be invalid for airblast atomizers operating at high pressures, >1MPa (>10 atm), or with high viscosity liquids (0.4 Pa · s).

Effect of Variables on Mean Droplet Size. Some of the principal variables affecting the mean droplet diameters for pressure swirl atomizers may be expressed by equation 16.

$$\overline{D}_{32} \propto \sigma^a\mu_L^b m_L^c\Delta P^{-d} \tag{16}$$

Because of the wide range of applications and complexity of the physical phenomena, the values of the exponents reported in the literature vary significantly. Depending on the range of Reynolds and Weber numbers, constant a ranges between 0.25 and 0.6, constant b between 0.16 and 0.25, constant c between 0.2 and 0.35, and constant d from 0.35 to 1.36.

Equation 16 indicates that liquid pressure has a dominant effect in controlling the mean droplet sizes for pressure atomizers. The higher the liquid pressure, the finer the droplets are. An increase in liquid viscosity generally results in a coarser spray. The effect of liquid surface tension usually diminishes with an increase in liquid pressure. At a given liquid pressure, the mean droplet size typically increases with an increase in flow capacity. High capacity atomizers require larger orifices and therefore produce larger droplets.

The principal parameters affecting the size of droplets produced by twin-fluid atomizers have also been discussed (36). These parameters include liquid viscosity, surface tension, initial jet diameter (or film thickness), air density, relative velocity, and air–liquid ratio. However, these parameters may have an insignificant effect on droplet size if atomization occurs very rapidly near the atomizer exit.

Most studies indicate that air velocity has a profound influence on mean droplet size in twin-fluid atomizers. Generally, the droplet size is inversely proportional to the atomizing air velocity. However, the relative velocity between the liquid and air stream is more important than the absolute air velocity.

Liquid viscosity generally produces adverse effects on drop size. It increases the initial film thickness and hinders the growth of unstable waves. Both effects can produce coarser atomization. However, the influence of liquid viscosity on atomization appears to diminish for high Reynolds or Weber numbers. Liquid surface tension appears to be the only parameter independent of the mode of atomization. Mean droplet size increases with increasing surface tension in twin-fluid atomizers (37). $\overline{D}_{32}$ is proportional to σ^n, where the exponent n varies between 0.25 and 0.5. At high values of Weber number, however, drop size is nearly proportional to surface tension.

The practice of establishing empirical equations has provided useful information, but also exhibits some deficiencies. For example, a single spray parameter, such as $\overline{D}_{32}$, may not be the only parameter that characterizes the performance of a spray system. The effect of cross-correlations or interactions between variables has received scant attention. Using the approach of varying one parameter at a time to develop correlations cannot completely reveal the true physics of complicated spray phenomena. Hence, methods employing the statistical design of experiments must be utilized to investigate multiple factors simultaneously.

The discussion above describes the correlations for one atomizer. Others are summarized in Refs. 3–5. The correlations provide significant insight into design and operational sensitivity. For example, a preliminary assessment of the impact of a change in liquid viscosity of 1 to 10 centipoise can be bounded with the use of the various correlations.

5. Spray Instrumentation

Instrumentation developed to measure the critical application parameters has enabled better designs of nozzles and nozzle applications. Drop size, spray angle, liquid flux distribution, spray impact force are the most common measures of performance.

Quantification of the size of drops is the primary objective of many of these instruments, although some quantify liquid flux. Significant advances continue to be made in laser diagnostics and imaging instruments. The user of spray measurements results should have an understanding of the capabilities and limitation of the method used to produce the data. Because of the dynamic behavior of sprays no primary standard is available, calibration or verification of measurement performance is often required.

Measurements are either single particle or ensemble where a collection of droplets are measured simultaneously. Instrument measurement volume is often small, on the order of a 1 to 3 mm, which measures only a small portion of the spray. The spray flux and drop size distribution often require sampling the spray systematically in a number of locations to access the overall spray characteristics desired for a specific application. Moments or averages used to characterize a spray require measurement of 10,000 to 50,000 drops to assure the uncertainty of these moments is reasonable.

5.1. Optical Nonimaging Techniques. *Phase Doppler.* In the phase Doppler technique, interference fringe patterns are produced by the reflected and refracted components of scattered light as droplets pass through the intersection of two laser beams. The light rays emerging from the droplet will have different optical path lengths, depending on the scattering angle and droplet diameter. Pairs of detectors are positioned in the receiver plane at off-axis angles to detect the Doppler signals and phase shift resulting from the different path lengths. From optics theory, it may be shown that the change in phase is directly proportional to the droplet diameter. The phase Doppler method utilizes the wavelength of light as the basis of measurement. Hence, performance is not vulnerable to fluctuations in light intensity. The technique has been successfully applied to dense sprays, highly turbulent flows, and combustion systems. It is capable of making simultaneous measurements of droplet size, velocity, number density, and volume flux.

Phase Doppler particle interferometry is a single-particle measurement methodology. Although the sample volume must be kept small to achieve a single particle in the measurement volume, measurements are routinely made in large scale high liquid flux sprays. The current state of the art of the phase Doppler interferometry method and use are provided by (32,38,39). PDI has become the accepted standard for measurement of many sprays due to the robustness of the method and the value of the simultaneous measurement of liquid particle velocity.

Laser Diffraction. A laser diffraction methodology is one of the most common ensemble methods. This family of instruments utilizes Fraunhofer diffraction to determine droplet size. A collimated laser beam is directed through the spray, and is focused on a spot in the focal plane of the receiving lens located in the forward direction. Diffraction patterns produced by droplets passing through the beam are detected by multiple-element photodetectors. Because the intensity of the scattered light at various distances from the optical axis is a function only of droplet size and the scattering angle, measurement of the scattered light energy at various radial locations in the near-forward direction allows the determination of the entire droplet size distribution.

Diffraction techniques can be used only if three conditions are satisfied. The droplet diameters must be larger than the optical wavelength, the refractive index of the liquid particles must be different from that of the surrounding medium, and the scattering angles must be relatively narrow. Diffraction techniques are usually effective and reliable when obtaining global measurement of droplet ensembles. The diffraction patterns are not affected by the location or refractive index of the particles. Also, measurements are possible over a wide range of droplet velocities.

In practical applications, diffraction instruments may exhibit certain problems. For example, there may be poor resolution for the larger droplets. Also, it is not possible to obtain an absolute measure of droplet number density or concentration. Furthermore, the Fraunhofer diffraction theory cannot be applied when the droplet number density or optical path length is too large. Errors may also be introduced by a number of causes, therefore as with any complex method expertise is involved in the application to a specific situation.

5.2. Optical Imaging Techniques. Optical imaging methods are advantageous with large drops ($>$ 500 microns) and in regions of the spray where drop formation is continuing. This methodology has a 10 microns lower limit of measurement by the wavelength of light. This method captures a back-lighted, shadowgraph, image that is processed to isolate the image of the drop and quantify the size of each drop. Pulsed laser or high speed strobe is used for illumination to minimize the motion of the drop during the image capture. The digitized image is typically analyzed automatically picking the in focus drops and determining the diameter of each droplet. In addition smaller droplets are in-focus over a narrower depth of field than large droplets which creates a bias.

5.3. Other Techniques. Nonoptical techniques involve the use of mechanical or electrical devices to determine droplet size. The mechanical methods involve the collection of droplet samples on a solid surface or in cells containing a special immersion fluid whose density is slightly lower than that of the sprayed liquid. The captured droplets are then photographed at high magnification to provide images that can be sized manually or by an automatic scanning machine. Most of the electrical methods are based on the detection and analysis of electronic pulses generated by the droplets as they contact an electrically charged or heated wire. Many of the nonoptical techniques have gradually become obsolete because of the broader capabilities of the laser and optical instruments.

5.4. Patternation. The spatial distribution of liquid flux is referred to as patternation and is measured by collecting liquid with a group of tubes or pans. Quantification of the liquid flux can be a manual or automated level measurement. Circumferential patternators use pie slice shaped pans to evaluate uniformity about the centerline of the nozzle. Radial patternators consist of a linear array of collection tubes and a shuttering system to collect liquid for only a specific time (3). Patternators are typically built for a specific application testing. Recently commercial laser based patternators have been developed to quantify liquid flux across the spray.

5.5. Spray Impact. The nozzles developed specifically for high performance cleaning and descaling applications often require spray impact measurements. Quantification of the aggregated impact force has been correlated with performance of some spray applications. Spray impact is measured with the use of one or more force sensors placed in the spray pattern to measure the reaction force caused by the spray. These instruments are built to achieve the spatial and sometimes temporal resolution necessary for a specific application.

6. Industrial Applications

Spray technology has thousands of industrial applications, with combustion of liquid hydrocarbon fuels being the most economically and environmentally significant. Traditional fuels is one of the most economically important spray applications due to the shear amount of fuel consumed and the environment impact of the resultant combustion gas. More stringent control of fuel combustion, for process heaters, gas turbines, and boilers has been achieved with better atomization technology and control. Combustion of non-traditional fuels (higher viscosity relative to Diesel fuel) including heavy fuel oil and process waste streams poses additional challenges due to the more constrained requirements and material properties. These requirements have prompted research and design engineers in many industries to improve the design, manufacture, quality control, and testing of atomizers.

Some concerns directly related to atomizer operation include inadequate mixing of liquid and gas, incomplete droplet evaporation, hydrodynamic instability, formation of nonuniform sprays, uneven deposition of liquid particles on solid surfaces, and drifting of small droplets. Other possible problems include difficulty in achieving ignition, poor combustion efficiency, and incorrect rates of evaporation, chemical reaction, solidification, or deposition. Atomizers must also provide the desired spray angle and pattern, penetration, concentration, and particle size distribution. In certain applications, they must handle high viscosity or non-Newtonian fluids, or provide extremely fine sprays for rapid cooling.

Commercially tens of thousands of nozzles are available from vendor catalogs. The process of selecting a nozzle that will achieve the desired result often links the knowledge of use requirements with the knowledge of the spray nozzle manufacturer. Several factors must be considered, the first is to match the spray pattern. Although atomizers are usually small components in many industrial spray applications, they play an important role in determining the performance and efficiency of the entire process. It has long been recognized that atomizers must be properly selected to achieve optimum performance.

Because of the complexity of designs and performance characteristics, it can be difficult to select the optimum atomizer for a given application. The best approach is to consult and work with atomizer manufacturers. Their technical staffs are familiar with diverse applications and can provide valuable assistance. They will require the following information: properties of the liquid to be atomized, ie, density, viscosity, and surface tension; operating conditions and range of operation required, such as flow rate, pressure, and temperature range; required mean droplet size and size distribution; desired spray pattern; spray angle requirement; ambient environment; flow field velocity requirements; dimensional restrictions; flow rate tolerance; material to be used for atomizer construction; cost; and safety considerations.

6.1. Noncombustion Applications. The varied applications can be grouped into four broad groups as shown in the Table 3 with examples of each. The type of nozzles and criteria for selection of a specific family of nozzles and choice of a specific nozzle size differs for these applications. The process of design is iterative. A preliminary design cycle removes some designs from further consideration because of constraints such as range of operation that can achieve the required performance; hydraulic capacity; operational limitations; such as pressure drop; reliability requirements. This is followed by a selection cycle to select critical parameters, such a drop size and spray pattern. Tables 3 and 4 provide guidance in selection.

For example, spraying a liquid that contains solids will often preclude nozzles with extremely small internal passages to assure reliable operation. Similarly, a very small flow (0.1 L/h) may eliminate the possibility of using a single fluid nozzle because the small orifice is not feasible.

Aerosol Delivery. The delivery of a pharmaceutical containing aerosol in medical applications continues to grow. A spray to create the appropriate particle size is crucial. Production of "nanostructure particles" such as catalysts is described by (40).

Droplet Surface. Applications that require heat and mass transfer are the most complex and require specific in depth understanding to effectively design systems and choose specific nozzles (3–6).

Surface Application. Complete coverage and uniformity of application are the key measures of performance for distribution usages. The requirements are process specific as the most appropriate quantitative measure. The portion of the spray not deposited on the intended surface is critical in many spray distribution system. This can be due to fines entrained by the surrounding gas or large drops with trajectories missing the desired surface. Often fixed nozzle designs include a number of nozzles with overlapping spray patterns to achieve the desired coverage. The spray pattern may be a flat fan or a full or hollow cone depending on the specific results desired. Distribution types tend to fall in two groups, one where very large drop size is advantageous to minimize adverse effects and the second type where the film quality of the deposition has specific requirements, spray painting for example.

In agricultural spraying, one of the biggest concerns is the drifting of small droplets. Drifting sprays not only lead to waste and environment problems, but also could endanger other nearby crops. Droplets smaller than 150 μm can be easily blown away from the intended target area by a cross wind in aircraft mounted spray delivery. A typical herbicide atomizer produces a spray with 15–20% of the liquid volume contained in droplets less than 150 μm. Atomizer improvements can be made so that the spray contains a narrow droplet size distribution with liquid volume less than 5% contributed by the smaller droplets. Correlations between droplet size and surrounding field conditions are also important.

Spray Impact. Surface cleaning nozzle selection depends on the specific process requirements related to the performance parameters required. A number of specialized nozzles have been developed for tank cleaning to remove residual materials. The three types of nozzles are fixed, multi-orifice "spray ball" type nozzles, and self powered rotating. The cleaning fluid provides the rotational power for turning the nozzle and an external shaft provides a rotational power. The selection of nozzle depends on specific process requirements. Spray impact is often the critical criterion. Therefore a small drop size is of little relevance, perhaps even a disadvantage (6). Because these smaller drops will more rapidly loose momentum to the surrounding gas.

General surface cleaning nozzles are often of a specialized design to achieve maximum surface impact. The stand-off distance, the spacing between the solid surface and the nozzle is a critical optimization parameter. The web or moving sheet of material is treated as it moves through the spray plumes. Fixed cleaning and descaling systems often have a number of nozzles together in overlapping patterns. Examples are shown in Figure 12.

6.2. Multiple Nozzles. Many spray applications use compound nozzles where there are multiple outlets on a single nozzle body. This approach is most commonly used with single fluid nozzles. This usage achieves a wider spray application area and a smaller drop size than a single nozzle due the smaller outlet orifice size. A similar function is achieved with an array of nozzles on one or more piping headers. The segmentation of the flow achieves dispersion of the spray across a larger cross-sectional area.

6.3. Spray Pattern Selection Criteria. Although spray requirements differ from one application to another, the spray pattern or shape is a reasonable criterion for selecting liquid atomizers for certain processes. Table 4 lists a variety of applications based on the pattern of the spray.

7. Future Directions

Modeling of the dispersion of drops in spray will continue to advance into greater detail and more rapid prediction. The disparity of length scales between the drop size and the computation grid size results in approximations today. Models that robustly and efficiently deal with the subcomputation grid physics will advance the state of the art. In addition, prediction of drop size directly from break-up predictions may become an engineering design tool in the future. Perhaps new diagnostics will allow the physics of the dense spray region to be examined to better understand the beginnings of the drop formation process. The synergism between modeling and experiment continues as a primary theme (28). Environmental regulatory pressures continue to drive change and optimization of all aspects of spray systems. Atomizer design methods are becoming more systematic allowing energy optimization of the device. The economic drivers are largest in the fuel sprays applications along with the continued drive for higher reliability and increasing performance.

8. Nomenclature

Symbol	Definition	Units
A	cross-sectional area of sampling area	m^2
A_p	cross-sectional area of inlet ports	m^2
A_2	cross-sectional area of orifice	m^2
C_c	Cunniningham slip correction factor (typically $\sim$1 for spray applications)	
C_d	discharge coefficient	
d_0	orifice diameter	m

d_s	swirl chamber diameter	m
D	droplet diameter	m
$\overline{D}$	characteristic mean diameter	μm
D_s	diameter swirl chamber	m
F	liquid volume flux	$cm^3/(cm^2 \cdot s)$
g_c	gravitational constant	
GLR	gas–liquid ratio by mass	
h	one-half of the film thickness	m
l_0	orifice length	m
L	characteristic dimension of atomizer or spray travel	
L_s	swirl chamber length	m
m	mass flow rate of gas or liquid	kg/s
n	wave number, $n = 2\ \pi/\lambda$	
N_i	number of droplets in the size class i	
Oh	Ohnesorge number	
ΔP	pressure drop across atomizer	Pa
Q	volume flow rate	m^3/s
Re	Reynolds number	
St	Stokes number	
t	film thickness, or time scale	m or s
V_F	volume fraction	
V_i	velocity of drops, initial	m/s
U	mean axial velocity at exit	m/s
U_R	relative velocity	m/s
We	Weber number	
w_i	normalized volume or mass flow rate percentage in each sector	
x	axial distance	m
α	wave growth rate	1/s
λ	wavelength	m
λ_C	drop evaporation constant	s/m^2
μ_G	gas dynamic viscosity	$kg/(m \cdot s)$
μ_L	liquid dynamic viscosity	$kg/(m \cdot s)$
ρ_G	gas density	kg/m^3
ρ_L	liquid density	kg/m^3
σ	liquid surface tension	kg/s^2

BIBLIOGRAPHY

"Sprays" in *ECT* 1st ed., Vol. 12, pp. 703–721, by W. E. Meyer and W. E. Ranz, Pennsylvania State University; in *ECT* 2nd ed., Vol. 18, pp. 634–654, by R. W. Tate, Delavan Manufacturing Co.; in *ECT* 3rd ed., Vol. 21, pp. 466–483, by J. Fair, University of Texas; in *ECT* 4th ed., Vol. 22, pp. 670–691, by C.-P. Mao and R. Tate, Delavan Inc.; "Sprays" in *ECT* (online), posting date: December 4, 2000, by C.-P. Mao and R. Tate, Delavan Inc.

CITED PUBLICATIONS

1. *ASTM E1620-96, Terminology Relating to Liquid Particles and Atomization*, ASTM, Philadelphia, Pa., 1996.
2. U.S. Pat. 5,009,367 (1991), K. A. Nielson.
3. A. H. Lefebvre, *Atomization and Sprays*, Hemisphere Publishing Corp., New York, 1989.
4. L. Bayvel and Z. Orzechowski, *Liquid Atomization*, Taylor & Francis, 1993.
5. H. Liu, *Science and Engineering of Droplets- Fundamentals and Applications*, Noyse Publications, 2000.
6. G. G. Nasr, A. J. Yuel, and L. Bendig, *Industrial Sprays and Atomization, Design, Analysis, and Applications*, Springer-Verlag, London, 2002.
7. *Proceedings of International Conferences on Liquid Atomization and Spray Systems*, ICLASS-1978, ICLASS-1982, ICLASS-1985, ICLASS-1988, ICLASS-1991, and ICLASS-1994, ICLASS-2000 Begell House, Inc., New York.
8. M. Doumas and R. Laster, *Chem. Eng. Prog.* **49**(10), 519–526 (Oct. 1953).
9. N. K. Rizk and A. H. Lefebvre, *J. Propulsion* **1**(3), 193–199 (1985).
10. N. Dombrowski, D. Hasson, and D. E. Ward, *Chem. Eng. Sci.* **12**, 35–50 (1960).
11. H. Zhu and co-workers, *Atom. Sprays* **5**(3), 343–356 (1995).
12. V. I. Asihmin, Z. I. Geller, and Y. A. Skobel'cyn, *Oil Ind.* (*Moscow*) **9** (1961).
13. J. C. Cooke, *Numerical Solution of Taylor's Swirl Atomizer Problem*, Technical Report No. 66128, Royal Aircraft Establishment, U.D.C. No. 532.527, U.K. Government, 1966.
14. C. Dumouchel and co-workers, *Atom. Sprays* (2), 225–237 (1992).
15. G. I. Taylor, *Proc. 7th Int. Cong. Appl. Mechanics* **2**, 280–285 (1948).
16. A. Radcliffe, *Proc. Inst. Mech. Eng.* **169**, 93–106 (1955).
17. M. Suyari and A. H. Lefebvre, *J. Propulsion* **2**(6), 528–533 (1986).
18. N. Dombrowski and D. Hasson, *AIChE J.* **15**, 604 (1969).
19. K. R. Babu, M. V. Narasimhan, and K. Narayanaswamy, *Proceedings of the 2nd International Conference on Liquid Atomization and Spray Systems*, Madison, Wis., 1982, pp. 91–97.
20. A. J. Yule and J. J. Chinn, *International Conferences on Liquid Atomization and Spray Systems*, ICLASS-94, Rouen, France, July 1994.
21. A. R. Jones, in Ref. 15, pp. 181–185.
22. H. B. Squire, *Brit. J. Appl. Phys.* **4**, 167–169 (1953).
23. R. P. Fraser and co-workers, *AIChE J.* **8**(5), 672–680 (1962).
24. Lord Rayleigh, *Proc. London Math. Soc.* **10**, 4–13 (1878).
25. M. J. McCarthy and N. A. Malloy, *Chem. Eng. J.* **7**, 1–20 (1974).
26. S. P. Lin and R. D. Rietz, *Annu. Rev. Fluid Mech.* **30**, 85–105 (1998).
27. W. A. Sirignano, *Fluid Dynamics and Transport of Droplets and Sprays*, Cambridge University Press, 1999.
28. Institute for Liquid Atomization and Spray System, www.ilass.org.
29. P. Rosin and E. Rammler, *J. Inst. Fuel* **7**(31), 29–36 (1933).
30. S. Nukiyama and Y. Tanasawa, *Trans. Soc. Mech. Eng. Japan* **5**(18), 62–67 (1939).
31. R. A. Mugele and H. D. Evans, *Ind. Eng. Chem.* **43**(6), 1317–1324 (1951).
32. W. D. Bachalo and M. J. Houser, *Opt. Eng.* **23**(5), 583 (1984).
33. C.-P. Mao, G. Wang, and N. Chigier, *Atom. Spray Tech.* **2**(2), 151–169 (1986).
34. A. H. Lefebvre, *Atom. Spray Tech.* **3**(1), 37–51 (1987).
35. A. H. Lefebvre, *Prog. Energy Combust. Sci.* **6**, 233–261 (1980).
36. A. H. Lefebvre, *Proceedings of 5th International Conference on Liquid Atomization and Spray Systems*, Gaithersburg, Md., 1991, pp. 49–64.

37. N. Chigier, *Prog. Energy Combust. Sci.* **9**, 155–177 (1983).
38. C. R. Mercer, ed., *Optical Metrology for Fluids, Combustion, and Solids*, Kluwer Academic Publishers, Boston/Dordrecht/London, 2003, Chapt. 9; W. D. Bachalo, *Part. Part. Syst. Charact.* **11**, 73–83 (1994).
39. H. Albrecht, M. Borys, N. Damaschke, and C. Tropea, *Doppler and Phase Doppler Measurement Techniques*, Springer-Verlag, 2003.
40. T. V. Kadas and M. Hamptden-Smith, *Aerosol Processing of Materials*, Wiley-VCH, Weinheim, Germany, 1999.

CHARLES W. LIPP
The Dow Chemical Company

Table 1. **Spray Function and Benefit Summary**

Application type	Functions achieved	Examples	Benefit
surface application or dispersion	uniform distribution of liquid on surface	tablet coating, spray painting, agricultural (herbicide and insecticide application), application of spray of a web of a paper, fire protection, distribution on packed tower, land irrigation, consumer products such as cleaners	uniform coating minimizes the amount of material applied, reducing cost and adverse effects of too high an application rate; spray transported to the surface
drop surface area	enhanced mass and heat transfer—more rapid evaporation	spray quenching, spray drying, scrubbing, dust control, humidification	reduces equipment size and maximizes throughput; wide and stable region of operation; avoids defects caused by too little or too much heat or mass transport
spray impact	momentum transport to surface	cleaning, descaling of steel strip, tank cleaning (clean-in-place), debarking (paper)	uniform removal of material – no defects caused by lack of removal
aerosol delivery and particle production	sized to achieve aerodynamic particle characteristics – liquid and solid particles	biopharmaceutical aerosol, delivery aerosol	narrow size distribution achieves desired particle characteristic and uniform particle morphology

Table 2. **Summary of Atomizers Types and Design Features**

Atomizer	Description	Design and spray features
	Single Fluid	
pressure swirl	circular orifice outlet preceded by swirl chamber having ≥1 tangential inlets;	hollow conical pattern with spray angles between 30 and 120°; flow rate varies with square root of operating pressure; widely used in oil heating equipment spray;
deflector	liquid stream impinged on solid surface to create liquid sheet	flat spray pattern or spiral form very common usage due to effectiveness in producing fine drop size and general solid cone pattern; impingement–spray angle achieved 10° to 180°; wide industrial usage; modified design allows for solid cone spray pattern; many types of designs of swirling devices
profiled orifice (cross-cut)	single orifice with inlet and outlet profile	oval or flat spray pattern – simple design; frequently used if spray pattern is appropriate
plain orifice	cylindrical outlet orifice and inlet	designed to produce a solid stream of liquid achieving high impact; limited usage
pulsed liquid	pressure or acoustic pulse applied to liquid upstream of the nozzle	similar to single fluid nozzle with narrow drop size width or relative span; limited usage
	Vaporization	
boiling flow	liquid flashes within or downstream of nozzle	vapor from boiling liquid induces break-up of liquid; rare usage
supercritical	added atomizing agent and sufficient superheat to vaporize	supercritical carbon dioxide used in some spray painting and pharmaceutical applications
	Two Fluid – Internal Mix	
pneumatic (twin-fluid)	movement of gas/vapor is primary source of energy utilized to produce spray	gas stream directed through various configurations to impinge or lift a liquid stream; tangential slots and a chamber often used to enhance mixing and fluid interaction; large variety of commercial applications; all two fluid nozzles allow the gas to be varied independent of the liquid flow providing an operational and design degree of freedom
air-assisted	pneumatic atomizer in which pressurized air is utilized to enhance atomization produced by pressurized liquid	requires external source of pressurized air; device tends to be energy inefficient, but can produce very fine droplets; commonly used in industrial furnaces or gas turbines
airblast	pneumatic atomizer that utilizes a relatively large volume of low pressure air	liquid is spread into a thin conical sheet exposed to high velocity air on both sides of sheet; widely used in aircraft gas turbine engines

Table 2. (*Continued*)

Atomizer	Description	Design and spray features
piloted airblast	airblast atomizer combined with a lower capacity pressure atomizer	typically a small pressure atomizer tip surrounded by an annular orifice; atomizing air flows between and outside the two concentric sprays; used in gas turbine engines
	Two Fluid – External Mix	
impinging gas-liquid jets	a central stream of liquid is impacted by a number of high velocity gas jets causing break-up	requires more atomizing gas. Large internal passages for liquid-less tendency to plug if the liquid contains solids; robust design; used in waste incineration
sonic	pneumatic or vibratory atomizer in which energy is imparted to liquid (frequencies $<$20 KHz)	high speed gas jet directed to impinge on plate or resonant cavity to produce high frequency sound waves; produces droplets $<$50 μm, but acoustic noise may be problem
	Mechanical Energy	
centrifugal	rotating solid surface is the primary source of energy utilized to produce spray	liquid is fed into center of spinning disk, cup, or wheel, and spreads out toward rim; produces a 360° spray pattern and relatively uniform drop size; used in spray drying and cooling applications; also used in spray painting, rotary bell, with air flow to shape spray. High rotational speeds common 5,000 to 25,000 RPM; drop size adjusted by rotation speed
ultrasonic	energy is imparted to the liquid with a ultrasonic transducer and discharge surface at ultrasonic frequency of 25 to 120 KHz	drop size depends on the nozzle design and frequency of transducer; generally small scale 10 liters/hr; Sauter mean diameter 40 to 120 microns; widely used in medical inhalation therapy
vibratory (piezoelectric)	oscillating solid surface is primary source of energy	consists of hypodermic needle vibrating at controlled frequency; can produce uniform droplet sizes to 30 μm, determined by liquid flow rate, resonant frequency, and needle orifice size; used primarily in laboratory studies
	Electric Potential – Electrostatic	
electrostatic	electric charge is imparted on the liquid relative to ground to produce spray	some devices use capillary tubes or conical disks directly charged at high voltage; others charge liquid film or jet by electrodes outside atomizer; produces very fine droplets, but cannot handle high flow rates; electrical properties of liquid are constrained; used in printing or painting processes

Table 3. **Summary of Application Performance**

Application type	Functions achieved	Typical values
aerosol delivery and particle production	size to achieve aerodynamic particle characteristics – liquid and solid particles	$D_{V0.50}$ 1 to 10 or 15 to 30 micron
drop surface area	enhanced mass and heat transfer—more rapid evaporation	$D_{V0.50}$ 50 to 300 micron; typical values of $\overline{D}_{32}$ for pressure swirl atomizers range from 50 to 100 μm for fuel combustion
surface application or dispersion	uniform distribution of liquid on surface	$D_{V0.5}$ 200 to 500 for many agricultural applications; up to 5000 micron- for flow distribution
spray impact	momentum transport to surface	spatial uniformity of impact force

Table 4. **Summary of Atomizer Sprays for Specific Applications**

Atomizer spray	Special application
cone spray, hollow or solid	aerating water, brine sprays, chemical processing, coil defrosting, dust control, evaporative condensers, evaporative coolers, industrial washers, roof cooling, spray ponds, spray coating, spray drying, gas scrubbing and washing, humidification, gas cooling, cooling towers, coal washing, degreasing, gravel washing, dish wash-in, foam control, suspensions and slurries for food and chemical products, pollution control, and oil heating
flat spray	asphalt or tar laying, bottle washing, coal and gravel washing, foam control, degreasing, metal cleaning–rinsing, spray coating, vehicle washing and water mist-in, descaling, roll cooling, quenching, and agricultural spraying
plain jet spray	rocket engines, diesel engines, mixing of liquids, metering and cutting
air atomizing spray	aerating water, dust control, evaporative condensers, evaporative coolers, industrial washers, spray coating, spray drying, gas scrubbing and washing, humidification, gas cooling, continuous casting, cooling casting and molds, curing concrete products, evaporative coolers, foam control, incineration, quenching, spray coating, spray painting, spray drying, flue gas desulfurization, pollution control, gas turbine engines, and medical spray

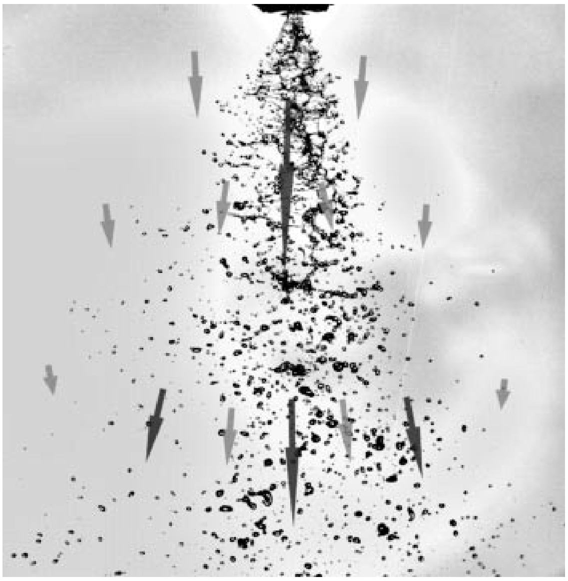

Fig. 1. Spray image (strobe back lighted) showing many sizes of drop in a spray and schematically the relative velocity of liquid (blue) and gas (green).

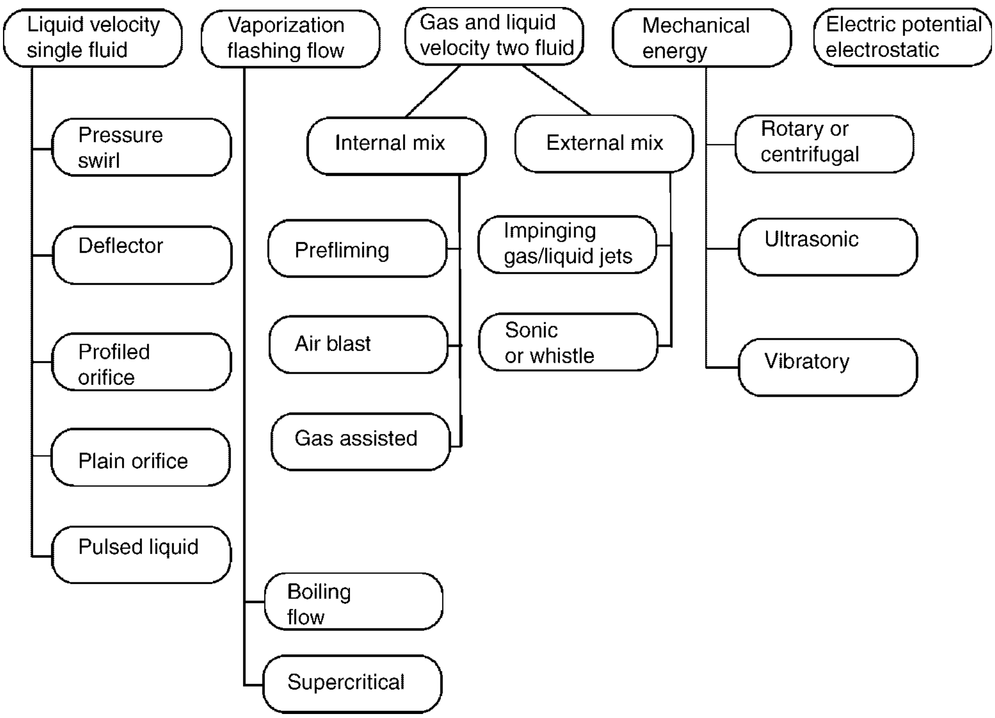

Fig. 2. Classification atomizers based on source of energy.

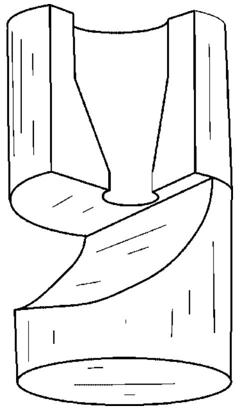

Fig. 3. Impingement nozzle showing impingement plate and internal flow passage.

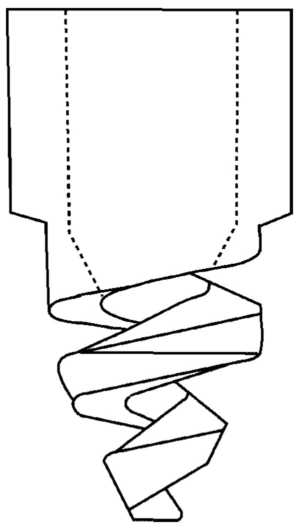

Fig. 4. Spiral type of impingement nozzle.

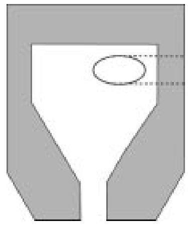

Fig. 5. Schematic of swirl nozzle showing tangential inlet to swirl chamber.

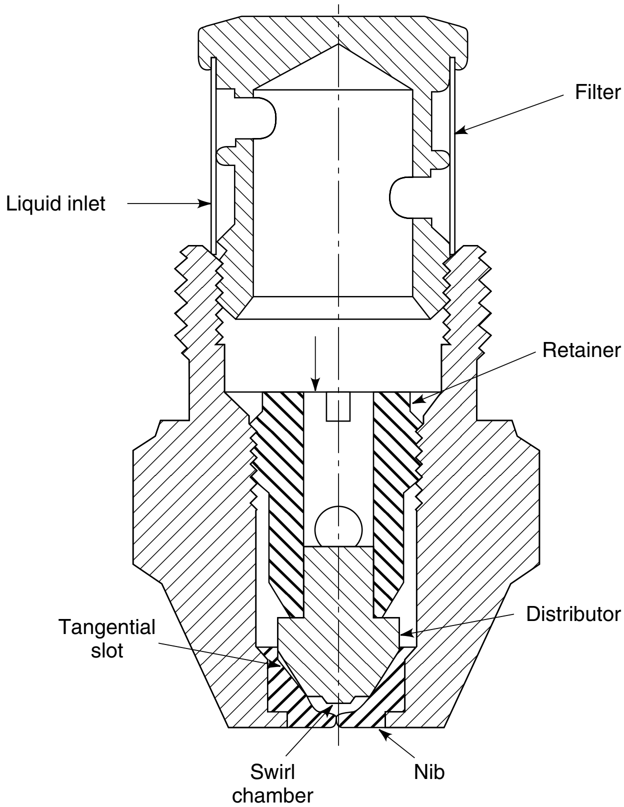

Fig. 6. Schematic diagram of a commercial pressure swirl atomizer.

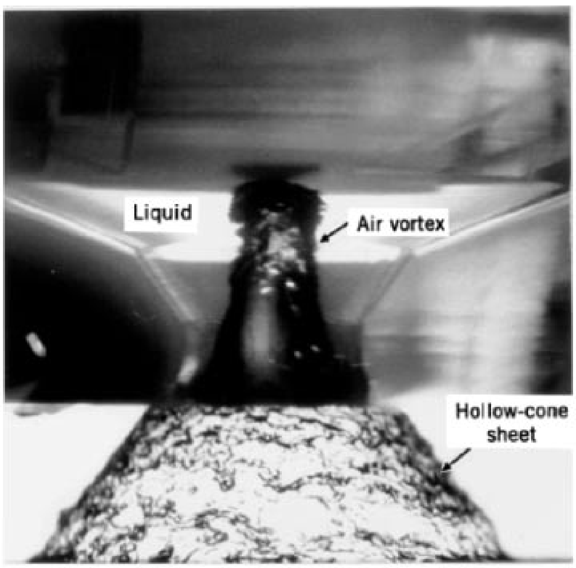

Fig. 7. Structure of an air core inside a swirl chamber and the outlet liquid film forming a hollow cone spray pattern.

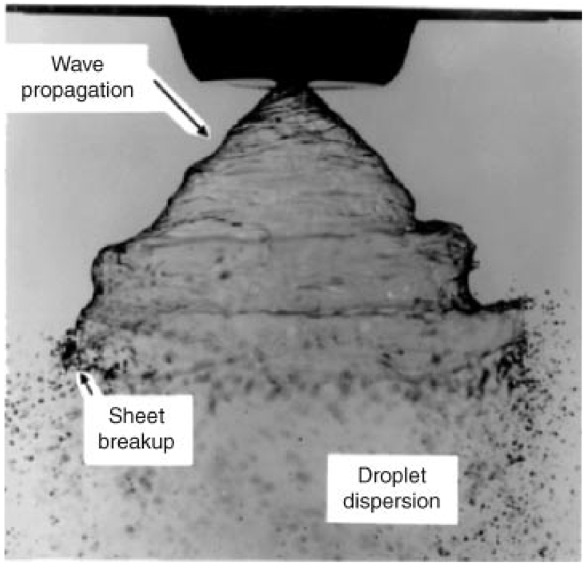

Fig. 8. Pressure swirl nozzle showing liquid sheet waves and break-up.

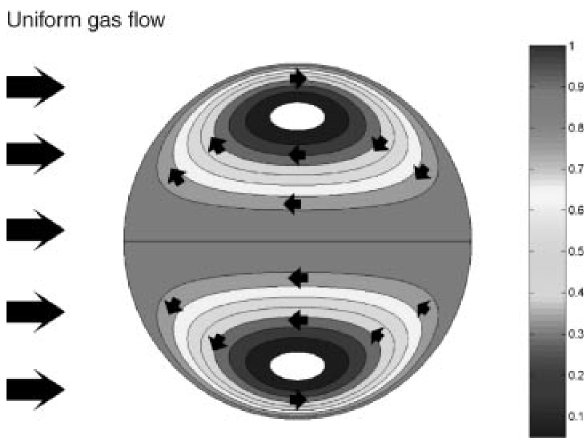

Fig. 9. Stream lines of the internal flow pattern due to shear forces on the drop surface caused by motion in gas. Higher velocities are represented by higher values on the colorbar.

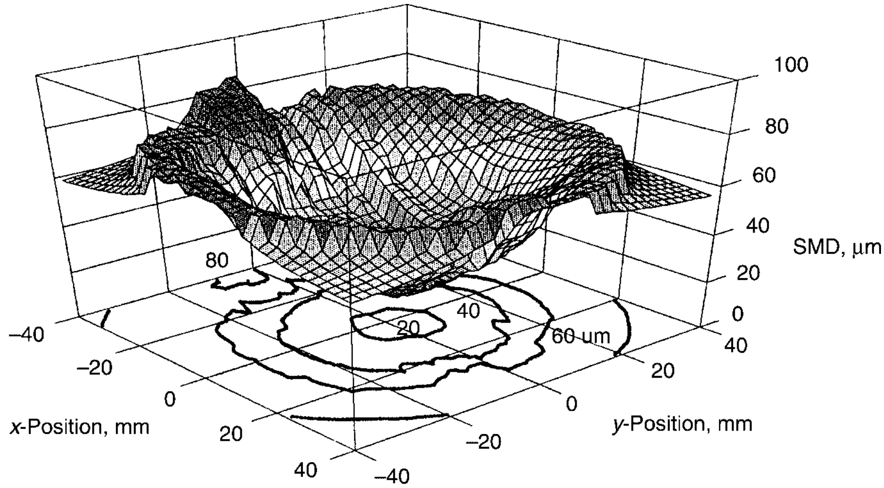

Fig. 10. Three-dimensional distribution of Sauter mean diameter (SMD) in a typical hollow-cone spray.

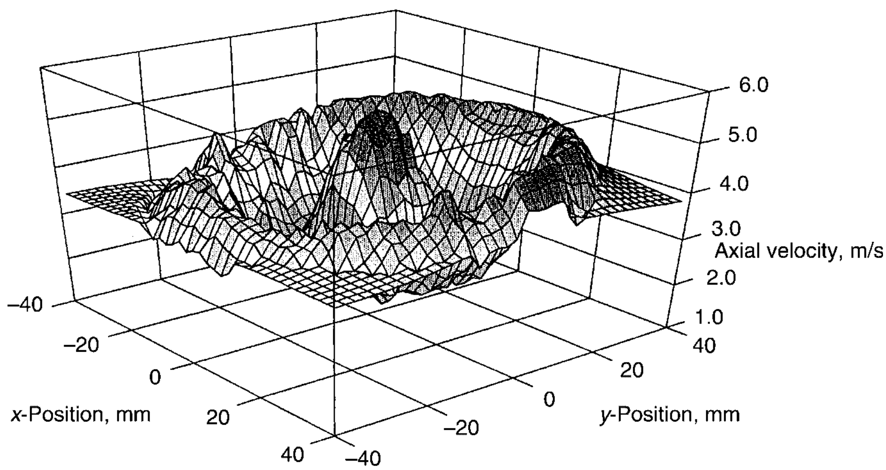

Fig. 11. Variation of droplet mean axial velocity in a typical hollow-cone spray. The axial velocity is substantially higher on right portion of this spray.

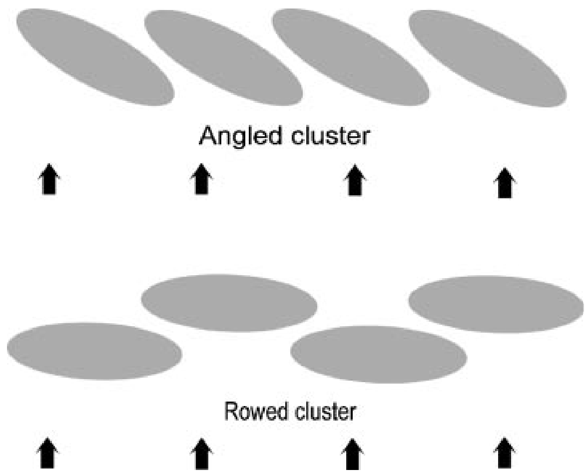

Fig. 12. Overlapping spray pattern for cleaning or descaling moving web of material.