# RECENT ADVANCES IN SPRAY SCIENCE AND TECHNOLOGY

**Norman Chigier**

Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213 USA
chigier@andrew.cmu.edu

Recent research and advances in fundamental physics, understanding, measurement, theory and computation of fluid flow, breakup and characterization of sprays are reviewed. Topics include: Liquid sheet, round jet and drop breakup with feedback control of drop size; impaction of drops on solid surfaces with film formation; internal flow structure in atomizers and cavitation; effervescent atomizers; fully-developed sprays and entrainment; liquid jets injected into air cross flows; high-energy x-ray measurements in diesel sprays; direct injection gasoline and diesel engines; spray combustion in gas turbine engines and agricultural sprays. The review describes the extent to which selected areas of spray technology have developed and matured towards spray science.

## Introduction

In the proceedings of the annual conferences of ILASS Americas, Asia and Europe, the international conferences of ICLASS and the papers published in the archival journal *Atomization and Sprays*, we have documented and recorded the progressive development of the science and technology of sprays. Major advances have been made in understanding the physics of liquid jet and drop breakup, design of atomizers, spray structure and spray impingement on solid surfaces. Spray combustion for gasoline, diesel and gas turbine engines has provided improved combustion efficiency and very substantial reduction in emission of pollutants. Agricultural spraying of pesticides, herbicides and insecticides has significantly reduced wind drift and improved the target transfer efficiencies. A major breakthrough in instrumentation has been achieved by the use of advanced photon source x-rays to measure detailed liquid mass distributions in pulsed diesel sprays. Highly sophisticated measurements have been made of drop size and velocity characteristics in a wide range of sprays. Detailed theoretical analyses have been made of cylindrical and planar liquid jet instabilities. Super computers have been used for computational fluid dynamics, heat transfer and combustion of sprays in engines, chemical and pharmaceutical spraying systems. High speed motion picture cameras provide dramatic images of breakup of liquid jets and drops, and impingement of drops on solid surfaces and liquid films. Our spray community conducts research and development for government and industry in many countries in the world. We provide consulting services to industries which seek advice and help in the design and performance of spray systems. By narrowly focusing on spray science and technology, we have made major contributions to the very wide range of scientific and industrial systems and technologies that use spray systems.

**Liquid Sheets – Linear Instability Analysis**

Linear instability analysis is a technique frequently used in fluid mechanics. Linear instability analysis of liquid sheets was initiated by Squire [1] and York [2], followed by Hagerty and Shea [3]. The early analyses assumed a shear-free surface, so that gas dynamic effects on the liquid sheet were ignored. Barreras et al., [4] studied a 2-D liquid sheet considering viscosity in the perturbations of both liquid and gas streams.

When a liquid sheet exits from a plane nozzle, in the neighborhood of the orifice edges, the basic velocity profiles start their transition from non-slip boundary conditions on the plate surfaces to a free gas/liquid interface. At certain gas velocities, vortex shedding occurs at the corners of the trailing edge. These vortices induce perturbations of the velocity and pressure fields at both gas/liquid interfaces. Asymmetric perturbations may easily develop, and as a result, viscous and pressure forces deform the sheet, generating strong curvatures on the interfaces, allowing the surface tension to act. At low air velocities (compared to the liquid velocity), varicose perturbations appear on the liquid sheet, which subsequently disappear further downstream. As the air-to-liquid velocity ratio increases, unstable sinusoidal perturbations, with growing amplitudes, are generated, leading eventually to downstream breakup. In this regime, the initial growth rate of the wave can be well predicted by linear instability theory. For large values of the velocity ratio, the growth behavior soon departs from that described by linear instability theory; waves in the span-wise direction are also induced and the liquid sheet finally breaks into ligaments and droplets.

Linear perturbation analysis is based on perturbing a steady-state solution of the flow with a small-amplitude wave in normal modes and analyzing its growth rate with the linearized Navier-Stokes equations. The wave amplitude has to be small, compared with its wavelength, or with the sheet thickness. A simplified steady-state solution is usually assumed, such as quiescent air, zero air viscosity, uniform velocity profile, etc. The growth of the temporal instability is usually analyzed in an infinite sheet. A propagation phase velocity must be postulated.

Waves propagating on the liquid sheet will be either sinusoidal, with both interfaces moving in phase, or dilational, with the interfaces oscillating in opposite phase. Experimental observations indicate that under the most efficient atomization conditions, the sheet oscillates in a dominant sinusoidal model.

Barreras et al., [4] obtained solutions of the dispersion relation relating the behavior of the non-dimensional growth rate with the non-dimensional wave number of the perturbation. Their results show the influence of the air co-flow on the sheet longitudinal instability. As the air/liquid velocity ratio increases, the unstable region broadens and the maximum growth rates increase and displace toward larger wave numbers. The dominant oscillation frequencies correspond to those wave numbers of maximum growth. For higher frequencies, the corresponding wavelengths are shorter. The analytical results are in good agreement with the experimental results of Mansour and Chigier [5], which indicate that the dependence of sheet oscillation frequency on liquid velocity is much weaker than the variation with air speed. The reduction in growth for increasing liquid velocity agrees with the fact that, for low air/liquid velocity ratios, the sheet does not oscillate in a dominant sinusoidal mode with high-amplitude growth rate, but a mixture of dilational and sinusoidal modes with lower amplitude.

The linear theory analysis of Barreras et al., [4] shows the strong destabilizing effect of the air stream velocities on liquid sheet stability. Increasing air velocity causes a reduction of wavelength and an increase of growth rate. Predicted theoretical results of Barreras et al. have been compared directly with experimental results of Mansour and Chigier [5]. Qualitative behavior predicted by temporal linear stability analysis agrees reasonably well with the experimental measurements.

**Breakup Length of Cylindrical Liquid Jets**

The breakup length of a cylindrical liquid jet as a function of velocity increase--known as the jet stability curve—has been widely investigated for the past 20 years. Dumouchel [6], recently conducted accurate and reliable measurements that provide more definitive information and explanation of the fundamental breakup phenomenon. The theoretical analysis of Lord Rayleigh [7], in 1879, of a liquid jet in a vacuum, showed that the disintegration of the jet is controlled by the growth of a capillary wave with wavelengths and growth rates that are functions of the jet diameter, the surface tension, and the liquid density and viscosity. The characteristic time of the growth of this wave remains constant when the velocity increase, resulting in an initial linear increase of the breakup length in zone A of the stability curve.

According to Weber's theory [8], the critical point (first maximum in the stability curve, associated with the critical velocity $V_c$), is related to the critical Weber number $We_c = \rho_g V_c^2 d / \sigma$ whose value is a single function of the Ohnesorge number Z $Z = (\mu / \rho_l d\sigma)^{0.5}$

Sterling and Sleicher [9] modified Weber's analysis by including the viscosity of the surrounding gas for a uniform initial velocity profile. When the initial velocity profile of the liquid emerging from the nozzle is not uniform, the profile will relax towards a uniform profile. When the liquid viscosity is high, the velocity profile relaxes rapidly and plug flow is reached before the disintegration process takes place. Before the critical point, the breakup is a function of the liquid jet only. At the critical point, interaction with the surrounding gaseous medium begins to play a role. The decrease of the breakup length, just after the critical point, is due to an increase of the initial perturbation amplitude with the liquid velocity. The critical point is directly related to the velocity distribution inside the liquid jet. The mean breakup lengths measured by Dumouchel [6], were based on 1000 measurements for each set of operating conditions. Also, the standard deviation of the breakup length is reported. These results provide a valuable database.

The variation of critical velocity with ambient gas density is divided into three different regimes: In regime 1, the critical velocity is independent of the ambient pressure and the gas density is smaller than the critical value $\rho_g$ . In regime 1, the critical velocity is far less than the theoretical predictions. The instability that develops at the critical velocity results from non-linear effects, such as instability associated with turbulence. This instability does not depend on the external gas—rather; it is related to the presence of velocity gradients in the liquid jet. When the gas density is increased beyond the critical gas density, regime 2, the critical velocity begins to decrease. In regime 3, the instability is initiated by the presence of a liquid gas interface and a velocity difference between the liquid and gas. The critical gas density decreases as the jet Ohnesorge number increases.

For regime 1, the growing wave process and breakup are controlled by the surface tension forces only, for velocities both smaller and greater than the critical velocity. The length of the nozzle has no effect on the resulting drop sizes. The whole disintegration process is not a function of the instabilities of the internal jet. The influence of the jet diameter on the drop size distributions is similar to that described by the Rayleigh linear theory. For jets of regime 1, the parameter that mainly influences the drop size distribution is the jet diameter, and this can be explained by capillary wave growth, due to surface tension forces only. The temporal growth rate of the perturbation is independent of the velocity. The reduction of the breakup length after the critical velocity is due to a variation of the initial conditions of the perturbation. The effect of the internal jet instabilities that develop when the velocity is at least of the order of the critical velocity is to impose specific initial conditions which activate a capillary instability, different from the natural capillary wave developing before the critical conditions. These initial conditions are functions of the nozzle design, including the length and diameter, as well as the jet velocity. The initial conditions are imposed by the instabilities developing in the jet, because of the presence of a velocity gradient. The turbulence in the liquid results from sub-critical instabilities.

For jets of regime 3, the critical conditions are not related to a change in the type of instability. Whatever the velocity, the disintegration of the jet results from a linear instability. This supercritical instability is due to the presence of a liquid gas interface, with velocity gradients in both phases. The reduction of the breakup length, when critical conditions are reached, is related to an increase of the temporal growth of the instability with the velocity.

## Breakup Mechanisms of Liquid Drops in High Velocity Air Flows

The combustion and exhaust emissions of engines are highly dependent upon the effective atomization and vaporization of liquid fuels. Drop disintegration is controlled by fuel nozzle geometry, the injection system parameters, the physical and chemical properties of the fuel, and the ambient air conditions. It is well established that atomization can be enhanced by increasing the relative velocity between liquid drops and the surrounding gas.

The Weber number: $We_g = \rho_g V^2 d / \sigma$ (where $\rho_g$ is the gas density, $V$ is the relative velocity between the liquid drop and the ambient gas, $d$ is the drop diameter, and $\sigma$ is the surface tension), and the Ohnesorge number $Z = \mu_L / (\rho_L d \sigma)^{\frac{1}{2}}$ (where $\mu_L$ is the liquid viscosity and $\rho_L$ is the liquid density), have been found to be important non-dimensional parameters. Reitz and co-workers [10], [11], [12], have investigated the drop distortion and fundamental breakup mechanisms of drops injected into transverse high-velocity gas flows at atmospheric and pressurized conditions. The studies demonstrate the effects of gas velocity, liquid properties and the ambient gas pressure on the breakup phenomena and the trajectories of the distorting liquid drops.

The most important parameters affecting droplet deformation and breakup processes are the gas and liquid densities, the gas and liquid viscosities, and surface tension, the droplet diameter, the relative velocity between the drop and the ambient gas, and the acceleration between the gas and droplet. These characteristics are represented in terms of dimensionless parameters such as Weber number, We, the Laplace number, $L_p = \mathrm{Re}^2 / We$, the Ohnesorge Number, Z, and—for accelerating drops—the bond number, Bo. Breakup of liquid drops can be divided into two stages. During the first stage of breakup, the drop shape changes into a flattened disk shape. During the second stage, the distorted drops disintegrate into small drops. Lee and Reitz [10], describe the various stages of breakup.

*First Breakup Stage*

When a drop is exposed to steady gas flows, the drop is influenced by the distribution of pressure around the drop. Under equilibrium conditions, the internal pressure at any point on the drop surface is just sufficient to balance the external pressure and the surface tension pressure. At the stagnation point, the gas velocity is zero and the gas pressure is at a maximum. Around the drop, from the stagnation point, the gas velocity increases until it reaches a maximum, while the gas pressure decreases until it reaches a minimum. This aerodynamic pressure causes the drop to deform from its spherical shape to become flattened in the form of an oblate ellipsoid, aligned normal to the gas flow direction. At early times, the drop distortion depends on the relationship between the Bernoulli pressure and the surface tension pressure. Thereafter, the rate of drop deformation increases rapidly. As the relative velocity between the drop and ambient gas increases, the breakup proceeds through the following stages: 1) bag; 2) boundary layer or shear; 3) stretching and thinning; 4) catastrophic.

*Bag Breakup*

When the relative velocity between drop and gas is low $(12 < We < 80)$, the drop is flattened and a thin hollow bag is blown downstream. The thin bag is attached to a toroidal rim of liquid. The bag subsequently bursts into a number of small fragments; the liquid rim disintegrates a short time later into a small number of large fragments.

*Shear or Boundary Layer Stripping*

As the relative velocity is further increased, a boundary layer is formed around the drop. The accelerated surface liquid layer is stripped from the drop at its equator for We>80. Reitz has cast considerable doubt on the validity of this theory, for which there is no convincing experimental evidence.

*Stretching and Thinning Breakup*

As the gas stream velocity is increased (We>80), a suction stress towards the outside of the drop occurs transverse to the flow, because of the high velocity at the equator of the drop. This leads to a lateral extension and distortion of the drop. The thickness of the flattened drop decreases from its center to its edge. Since the edge is very thin, it tends to follow the gas flow direction, due to its low inertia.

*Catastrophic Breakup*

As the gas velocity is further increased, We~350, the dynamic pressure on the drop surface becomes so large that a very high intensity shock wave is generated, with formation of large-scale instability waves on the flattened drop surface. The accelerating sheet breaks into large fragments due to Rayleigh-Taylor instability. Short wave length Kelvin-Helmholz waves originate at the edges of fragments and these waves are stretched to produce ligaments which break up into micro-sized droplets.

## Feedback Control of Drop Size

Control of spray characteristics, including spray angle, drop size, drop velocity and drop trajectory, is a major challenge in spray technology. Effective control must be directly related to the complex breakup process, which can be affected by slight changes in supply pressures and flow rates, physical properties of the liquid chamber pressure and temperature. There is neither knowledge nor control of temporal variations of drop size, velocity, spacing and trajectory in industrial spray systems. Control over the spray requires control over the breakup process. The dense multidimensional packing of droplets with chaotic velocity distributions--typical in spray systems--makes analytical studies nearly impossible, and numerical studies very challenging.

Orme and Muntz [13], developed means of controlling breakup in order to obtain a given droplet size by producing highly uniform droplet streams. They used amplitude-modulation techniques to produce droplet sizes outside the range achievable using single frequency perturbation. In addition, amplitude modulation decreases speed variations between droplets. This technique represents an open-loop type of control over the breakup process, without feedback. Strayer and Dunn-Rankin [14], used linear theory and compared analytical profiles of a disturbed liquid stream with experimental profiles. The disturbance imposed on the surface of the stream at the orifice exit consists of multiple frequency components, due to either the input waveform directly, or external disturbances acting on the surface of the stream. With sinusoidal modulation, droplet diameter variations can be controlled to within 1%. With a known disturbance, the system is deterministic (everything is the necessary result of a sequence of causes.) A system with forcing is not entirely deterministic. The stochastic component of the imposed disturbance propagates along the surface of the liquid jet and alters the breakup. Frequencies are superimposed in order to determine a realistic transfer function from the applied signal to the disturbance growing on the stream. A transfer function relates the output of a linear system to the input, in the frequency domain, using a complex variable. Once a suitable transfer function is found, application of feedback control allows more precise control of the breakup, despite stochastic perturbations, as well as operation off of the peak growth rate of the applied disturbance.

The growth rate of an applied disturbance to a capillary jet is a function of the liquid viscosity, the wave number of the disturbance, the liquid density, the liquid surface tension, the orifice radius, the fluid velocity, and the air density. The initial disturbance will grow until a fluid parcel is pinched off the liquid jet. This parcel is not initially spherical, but oscillates due to surface tension forces until viscous dissipation dampens out the oscillatory motion. The resulting droplet stream consists of uniform droplets with an average separation equal to the wavelength of the applied disturbance. It is the combination of initial disturbance amplitude and growth rate that we strive to control. *A priori* knowledge of the component waves superimposed on the jet surface allows determination of the primary breakup mechanism. Normally, we do not have *a priori* knowledge of the competing wave modes on the liquid jet surface. An appropriately designed control system, with requisite transfer functions of the disturbance generator and breakup process, allows for control of the spray.

**Drops Impacting on Solid Surfaces**

When a drop impacts on a solid surface, the time evolution of the spreading can be divided into three phases: 1) propagation of an internal shock wave at the very beginning of the impact (lasting 2ns for an impact of a 3mm drop at 5 m/s); 2) generation of a spreading lamella; and 3) formation of a pancake shape. Impact can result in deposition, rebound or splashing, depending upon the solid material properties and surface wettability. Wettability describes the ability of a liquid to spread on a solid surface in a surrounding gas phase, and is quantified by the static contact angle between the liquid/gas interface, and the solid surface. The system is completely wettable when the static contact angle is zero; it is partially wettable when the static contact angle is less than $90^{o}$; it is non-wettable when the static contact angle is above $90^{o}$. The dynamic contact angle considers the changes of velocity of the contact line. Chemical or topological inhomogeneities of the solid surface can result in hysteresis between advancing and receding contact lines. Impaction and wettability are influenced by the liquid properties, such as surface tension and viscosity, the drop diameter and impact velocity, and the solid surface roughness.

Six categories of deposition phenomenon have been identified by Rioboo et al. [15]:

- *Deposition:* The drop deforms and remains attached to the solid surface during the entire impacting process, without any breakup.
- *Prompt Splash:* Droplets are generated at the contact line at the beginning of the spreading phase, when the lamella has a high radial velocity. It is observed only with rough surfaces.
- *Corono Splash:* Droplets are formed around the rim of a corona, away from the solid surface—it occurs at a later stage of the impact process. It is very characteristic of drops impacting on liquid films.
- *Receding Breakup:* As the liquid retracts from its maximum spreading radius, the dynamic contact angle decreases. If the limiting value of zero is reached, some drops are left behind by the receding lamella.
- *Rebound:* The entire drop rebounds on the surface. For partial rebound, part of the drop remains attached to the solid surface, while the other part rebounds. Rebound is affected by the maximum diameter reached by the spreading drop and the receding contact angle. For very energetic impacts, the maximum diameter is large and the drop begins to recede. If the impact is sufficiently energetic, partial rebound occurs for low dynamic receding contact angles. For high values, complete rebound occurs. The receding contact angle is the principal parameter that governs the receding phase, the receding breakup and partial or complete rebound.

Industrial processes that involve spraying of drops on solid surfaces include: spray painting, spray coating, liquid cooling of surfaces, spraying of agricultural pesticides onto foliage, fire suppression by water sprinklers, and inhalation of medicinal aerosols. The general objective of all these deposition processes is to cover the target surface with a uniform thickness liquid film, while minimizing wastage in the off-spray.

The extent of droplet bounding, splatting, recoil, splashing, coalescing and liquid film formation, depends on many parameters, such as droplet size, impact velocity, liquid properties and substrate geometry. Relationships among these parameters are complex. Rein [16], has surveyed the extensive literature on the phenomena of liquid drop impact on solid and liquid surfaces. Chandra and Avedisian [17], studied liquid droplet deformation after droplets fell vertically onto a flat horizontal plate. Yao, Hochreiter and Cai [18], presented results of water droplets impacting onto the edges of heated thin steel strips, a phenomenon that occurs during reflooding of a nuclear reactor after a loss-of-coolant accident. Hung and Yao [19], identified complex behavior patterns of small droplets impacting on cylindrical wires, when droplets either disintegrate upon impact, or cling to the wire, slowly dripping off. Hardalupas, Taylor and Wilkins [20], investigated sub-millimeter droplet impingement onto solid spheres, with application to spraying into fluidized beds. Hung and Yao [19], characterized the phenomena of water droplets impacting on cylindrical tubes. When drop size is small and tube diameter is large, the liquid has a larger surface area to adhere to, so that droplets tend to accumulate on the solid surface and then drip off. When the tube diameter is smaller than that of the droplet, droplets disintegrate after landing on the tube. Impaction and accumulation of fluid depend not only on the geometry during impact, but also on the fluid properties and the wettability of the solid surface.

Pasandideh-Fard et al [21], developed a three-dimensional model of free surface flows for droplets impacting on tubes. For a 2mm droplet, impacting on a 6mm diameter tube, the entire droplet clung to the tube surface. For a 2mm drop impacting on a 3mm tube, most of the liquid drop fell off the tube. For a 2mm drop impacting on a 1mm tube, most of the liquid drop fell off the tube. The falling liquid column usually became unstable and broke up as it descended.

**Internal Flow Structure in Plain Orifice Atomizers**

It has long been recognized that the design of internal atomizer flow passages has important implications for the type of spray pattern produced by the orifice. A high-pressure drop atomizer can generate either a very fine spray or a high speed water-jet cutter with very little atomization. Cavitation near the entrance to the nozzle can induce very significant atomization. The diesel injector is one example of a plain orifice atomizer. As liquid flow enters the small diameter cylindrical nozzle, there is a large fluid acceleration near the inlet lip with an associated large reduction in the fluid pressure. A *vena contracta* is formed and a cavitation zone can readily be generated. The cavitation region is inherently unsteady and unstable. The collapsing bubbles at the aft end of the cavitation region cause local pressure rises, which are fed upstream and which affect subsequent shapes of the cavity. This partial cavitation enhances instabilities in the jet produced by the orifice, thereby promoting and enhancing atomization. The *vena contracta*, even under non-cavitation conditions, is subject to instabilities arising from the abrupt pressure rise at the end of the recirculation zone. As the total pressure drop along the nozzle increases, the flow in the passage will eventually reach the hydraulic flip condition in which the *vena contracta* extends over the entire length of the passage. Atomization is generally poorer under these conditions than under partial cavitation conditions.

The unsteady internal flow behavior in plain orifice atomizers is attributed to instabilities in the *vena contracta* and the presence of cavitation which are inherently unsteady. The collapsing bubbles cause local pressure rises, which are fed upstream and affect subsequent shapes of the cavity. This “partial cavitation’ enhances instabilities in the liquid jet, thereby promoting atomization. Xu et al [22], conducted a series of parametric simulations to investigate the unsteady internal flow in plain-orifice atomizers. Laminar, axisymmetric, incompressible flow was assumed, and the Navier Stokes equations were solved on a fixed structured mesh using a marker-and-cell algorithm.

The liquid density $\rho_l$, the orifice diameter D, and the Bernoulli velocity in nozzle $v = (2(P_1 - P_2)/\rho_l)^{\frac{1}{2}}$ are chosen as dimensions. The two dimensionless parameters are: where $P_v$ = fluid vapor pressure, and K = cavitation number. $\mu_l$ $P_1 - P_1$ The viscosity in the two-phase mixture is $\mu = \alpha\mu_g + (1-\alpha)\mu_l$ where $\alpha$ = local void fraction.

Since $\mu_g << \mu_l$ *and* $\rho_g << \rho_l$, we can neglect the influence of gas-phase viscosity. The discharge coefficient $C_D$ is defined as the ratio of the measured (or calculated) flow rate to the ideal flow rate, based on the Bernoulli velocity. This parameter is a measure of the contraction and friction losses in a particular flow field. $\rho_l v A$ where A = nozzle cross-sectional area. Cavitation number K is a function of pressure drop, vapor pressure and inlet pressure.

The *vena contracta* is formed at the inlet lip of the nozzle. The pressure increases at the aft end of the *vena contracta* and this affects the subsequent shape of the flow field. When cavitation is present, the recirculation zone can detach from the main *vena contracta* and be convected downstream. These *vena contracta* instabilities generate unsteadiness in the flow and influence the discharge characteristics. Variations in mass flow lead to high-amplitude perturbations. Cavitation oscillations are responsible for mass flow variations. Atomizers that produce fine sprays tend to produce droplets at high frequencies.

Cavitation becomes evident at supply pressures in the range 2-3 atm for sharp-edged inlets. Since many applications utilize high supply pressures, cavitation is presumed to be present in most pressure atomizers. The highest mass flow variations occur at high supply pressures. The violence associated with cavity collapse (or partial collapse), and re-formation, lead to significant changes in mass flow. High pressure applications, such as combustion chambers, are subject to cavitating flow over a much wider range of pressures than under ambient pressure test conditions.

Rounding of the inlet lip of the nozzle can delay the occurrence of cavitation and result in increased discharge coefficients through reductions in contraction losses. Mass flow variations are reduced dramatically for even a small amount of inlet rounding. An inlet radius of 10% of the orifice radius can substantially reduce mass flow variations. Cavitation sites will most likely appear at burrs or notches formed during the fabrication process. Diesel orifices are typically 200-300 $\mu m$ in diameter where defects are a significant fraction of this diameter and reproducibility is difficult to obtain and guarantee.

Direct injection diesel engines use simple pressure-atomized nozzles with holes of 0.2-0.5mm diameter. Difficulties are encountered with atomization at low injection pressures. There is a need to maintain good atomization over the full range of injection pressures, especially when hole diameters are decreased towards 0.1mm. Studies have established that the primary factor affecting atomization is the disturbance of the liquid flow due to cavitation in the nozzle. Tamaki et al [23], introduced wire nets over the inlet of the nozzle hole to introduce a disturbance to the liquid flow; the nozzle hole became filled with cavitation bubbles. Without the wire net, the surface of the liquid jet was very smooth, without any sign of atomization. Significant reduction in breakup length, due to the wire net, was found, over a wide range of injection pressures. Tamaki et al [23], also studied the effect of variation of the length-to-hole diameter ratio L/D. They found that when L/D is very small, atomization is improved, the spread of the spray is wide, and the breakup length becomes extremely short. Conversely, as L/D is increased, up to 20, the spread of the spray becomes narrow, the breakup length becomes long, and the atomization is poor. The wire net causes a pressure drop to the flow. The reduced pressure downstream the wire net causes inception and collapse of cavitation bubbles. This cavitation is independent of L/D. When L/D is of the order of 1, the collapse of cavitation bubbles causes the atomization to be considerably enhanced. On the other hand, when L/D is of the order of 20, the disturbance caused by the wire net is damped along the length of the hole and atomization is decreased.

**Effervescent Atomizers**

In an effervescent atomizer, bubbly flow is generated inside the body of the nozzle, and as this flow is forcresult ined through the outlet orifice, the pressure drops and the bubbles expand. This expansion through the outlet orifice squeezes the liquid into thin ligaments, which are subsequently broken up by the combined effect of the liquid velocity and the expansion of the gas bubbles. The bubbles can be generated by forcing air through small holes into the liquid flow, or by liquid flashing in which the expansion of the vapor phase inside the liquid breaks up the liquid into small droplets.

This simple design requires the creation of a stable bubbly flow inside the nozzle. The pressure in the aerator is slightly higher than the pressure in the liquid. Air flows through a large number of small orifices to generate a continuous stream of bubbles which are subsequently dragged by the liquid into the outlet orifice. Since the concept was formulated by Lefebvre [24], the successful operation of effervescent atomizers has been dependent on the ability to maintain a stable uniform sized bubble flow. Bubbly flows depend on nozzle geometry, air and liquid flow rates, and they become influenced by pressure and velocity instabilities. The stability of bubbly flows, up to large void fractions, depends upon two factors: (1) bubble coalescence, and (2) characteristics of the bubble formation, which may affect their coalescence. The bubble formation may occur at various regimes, which depend on the velocity of the gas phase through the orifice. The size of these bubbles affects their transport in the liquid flow and also the interaction between the bubbles. Contact between the bubbles leading to coalescence disrupts the stability of the bubbly flow regime. The very large difference in density between the air and the liquid causes a delay in the acceleration of the newly-injected bubbles, which enhances the possibility of bubble coalescence.

Most detailed studies have been conducted by Lefebvre and his co-workers at Purdue University [24]. They have investigated both Newtonian and non-Newtonian liquids using air/liquid ratios up to 24% in mass. The results show very little dependence on liquid flow rate; good atomization was obtained at high liquid flow rates. (Effects of liquid viscosity were found to be negligible.)

Ferreira et al [25], used an effervescent atomizer for atomization of a residual diesel oil. They designed a modular atomizer in which the outlet orifice and aerator could be changed. The aerator had 96 orifices of 0.45mm, or 0.77mm diameter, with oil viscosity up to 200 $mm^2/s$. Contrary to previous observations, the liquid viscosity was found to have a significant influence on both the quality of atomization and the detailed structure of the spray field.

**Fully Developed Sprays and Entrainment**

Sprays can be described as the interaction of two phases due to the injection of the liquid dispersed phase into the continuous gas flow. For a plain jet atomizer near the nozzle exit, a core of liquid is surrounded by a dense dispersed mixing layer. All the energy required to generate the spray is in the form of liquid kinetic energy. The surrounding gas, which is initially at rest, is gradually dragged by the interfacial forces exerted by the high-speed liquid core and droplets. Initially, the amount of gas entrained is very small. Following the formation of ligaments and drops with high momentum, gas entrainment increases due to the strong interaction between the two phases. The gas flow is still driven by the liquid dispersed flow whose kinetic energy is high. In the fully-developed spray regime, further downstream of the nozzle, the spray reaches an asymptotic state in which the development of the jet spray is controlled by the continuous gas phase only, and the small drops are in equilibrium with the gas flow.

The origin of the transition to the fully-developed regime is defined as the location where the ratio of the initial liquid jet velocity to the downstream centerline mean axial velocity of the droplets, $U_o / U_c$, increases linearly with the axial distance. This coincides with the axial distance from which the mass of entrained gas also grows linearly and the entrainment coefficient becomes constant. In the fully-developed regime, the spray is essentially a gas jet with dispersed droplets where the profiles of the dimensionless fluctuations of drop axial velocity are similar and size-independent at different cross sections of the spray.

Boëdec et al [26], measured drop diameter and the two components of drop velocity in a pressure jet plain jet atomizer water spray using a phase Doppler anemometer. The drop velocities along the spray centerline are plotted for drop sizes between 1 and 50 micron, as a function of x/d. The origin of the fully-developed region of the spray is defined from the asymptote of $U_o / U_c$, far from the nozzle exit, where $U_o$ is the initial velocity of the liquid jet, calculated from the Bernouilli equation, and $U_c$ is the axial mean velocity of droplets on the spray centerline. The experimental data show that the slope of the asymptote is approximately the same for all size classes below 50 micron. The velocity of the smallest droplets, of the order of 5 microns, is a direct measure of the gas velocity because the drag forces on very small droplets are very high. In the fully developed region, the mean motion of the droplets is the same as the asymptotic mean motion of the continuous gas phase. The asymptotic state is reached at different locations, depending on drop size; it varies from 400d for drops less than 10 microns to 500d for drops more than 40 microns. This difference is due to the difference in relaxation time (the time required for drops to respond to gas velocity fluctuations), which increases with drop diameter. As the quality of the nozzle is improved by using polished, smooth surfaces and rounded inlets with less cavitation, the breakup length increases and the origin of the fully-developed spry regime can be extended to x/d = 1500 and beyond.

All gaseous jets and sprays entrain gas from the surroundings across the spray boundary into the spray, leading to a progressive increase in the mass flow rate as downstream distance increases. As a consequence, the spray is progressively diluted and the liquid-to-gas-mass-ratio decreases. Entrainment of gas was first measured by attempting to make a direct measurement of the entrained air flow [27. The first and subsequent attempts to directly measure entrained air flow rate have been inaccurate. Georjon [28], measured air velocity using smoke seeding particles and a two-component laser Doppler anemometer in a cylindrical probe volume surrounding the spray. By ensemble averaging of 500 samples, the entrained air mass $m_e$ was evaluated from the measurement of the air velocity perpendicular to the cylindrical probe volume.

Four entrainment zones can be distinguished:

- Zone 1: up to 50d, where $\dot{m}_e$ is close to zero.
- Zone 2, where the liquid core is present with dense layers of ligaments and large drops. $\dot{m}_e$ Increases slowly, but linearly between 50d and 200d.
- Zone 3, where the rate of entrainment increases significantly between 200d and 350d. This is an intermediate zone.
- Zone 4. Beyond 350d, the mass flow rate of entrained air reaches an asymptotic linear evolution whose slope is about twice that of the initial region.

The entrained mass is a function of $d_o$, the nozzle diameter, $m_o$, the injected liquid mass flow rate, $p_o$, the density of the injected liquid, and $p_e$, the density of the entrained air. The coefficient of entrainment K is defined as

$$dx \quad m_o \quad \rho_e$$

The value of K is 0.05 between x/d 50 and 200. Beyond x/d 350, it reaches the value of 0.1. The value found by Ricou and Spalding [27] was K = 0.32 for a gaseous jet. In the initial dense zone of the spray, the momentum transfer by drag forces between the liquid droplets and the gas is in the process of developing. This premixing or induction region between 50d and 350d results in delay of entrainment, compared to a gas jet.

Boëdec et al [26], measured the fluctuating components of velocity of different drop size classes. These velocity fluctuations provide information for the understanding of the momentum transfer between the droplets and the air. The profiles of the axial velocity fluctuations become similar at x/d beyond 400, which is consistent with the previously established origin of the fully-developed regime of the spray. The distance to achieve equilibrium is larger (600d), for the radial fluctuating velocity component $v^1$, and for the correlation of the axial and radial fluctuating velocity component $u^1v^1$ (shear stress), the distance to equilibrium is 500d. This conforms with the classic result for turbulent gas jets (Wygnanski and Fiedler [29]), who demonstrated that kinetic energy is first transformed from the mean motion to the axial longitudinal fluctuations before being redistributed by the pressure and velocity gradients between the radial components. In a spray, the situation is more complex. Energy is transferred from the liquid jet to the droplets and then to the gas. The gas also transfers energy to the droplets.

**Liquid Jets Injected into Air Cross-flow**

When a liquid jet is injected into a cross-flow of air, the cross-section of the liquid jet is strongly deformed by the distribution of static pressure on its surface; so that it assumes a crescent, or bow shape. Ligament formation at the tips of the crescent leads to a gradual erosion of the jet. Two different mechanisms of jet breakup have been identified—surface breakup and column breakup. The surface breakup mechanism is characterized by shear that causes striping of liquid from the surface of the jet. The column breakup mechanism's main feature is the appearance of waves on the windward surface of the liquid column, which are then amplified by aerodynamic forces and lead to the fracture of the liquid column in a wave trough. The breakup length measured in the direction of the airflow, is a constant multiple of nozzle diameter. For values of momentum flux ratio above 100, the dominant breakup mechanism is determined solely by the aerodynamic Weber number.

Penetration of the liquid jet into the cross-flow is governed primarily by the momentum flux ratio, downstream distance and nozzle diameter. Air velocity profiles, particularly boundary layers, also affect the penetration and atomization. The near-field penetration of the liquid jet needs to be separated from the far-field penetration of the spray after atomization. The lateral spreading of the spray in the near field has been found to be almost independent of the momentum flux ratio at a fixed distance from the nozzle.

Becker and Hassa [30], systematically studied the effects of the properties of the air flow and the momentum flux ratio on jet breakup, penetration, and lateral dispersion on global, as well as local, spray properties, at elevated ambient pressures for gas turbine applications. Time-resolved shadowgraphs of the jet breakup confirm that two basic breakup mechanisms can be discerned: For the column breakup mechanism, waves emerge and grow on the windward surface of the jet. Wave growth then causes the column to fracture in a wave trough, giving rise to the formation of ligaments, and, eventually, droplets. The onset of observable wave growth usually coincides with a fairly high degree of alignment of the jet with the direction of the air flow. The surface breakup mechanism, on the other hand, is characterized by a gradual erosion of the liquid column as ligaments and drops are stripped off from the sides of the jet. Surface breakup is favored at high momentum ratios. For a given value of momentum ratio, surface breakup dominates when the air flow has enough dynamic pressure--relative to surface tension forces--to atomize by shearing and stripping, i.e. at high values of aerodynamic Weber number. If, on the other hand, the kinetic energy of the air-flow is too low to overcome the surface tension forces of small surface perturbations, then jet breakup can only be brought about by aerodynamic amplification of instabilities of the liquid jet, following its alignment with the air flow. This configuration is similar to that of a liquid jet in a coaxial air flow. A preferred surface wavelength develops as a function of the parameters of the air flow and the liquid jet. Above a momentum ratio of 100, the breakup mechanism is a function of the aerodynamic Weber number only. In this domain, significant alignment of the jet with the air flow before the onset of atomization can be ruled out, so the momentum flux ratio ceases to be a governing parameter. It might be expected that at aerodynamic Weber numbers of the order of 1000, the kinetic energy of the air flow dominates over the surface energy of the air jet.

## X-Ray Measurements of Diesel Sprays

Laser optical techniques cannot be used to measure spray characteristics near the nozzle exit because multiple scattering from the large number of droplets in the dense spray region prevents light penetration. Yue et al [31], at the Argonne National Laboratory, USA, have used a synchrotron x-ray source that produces high-brilliance x-radiation for studying diesel sprays. The Advanced Photon Source Bending magnet source provides brilliant wide-band x-ray beams of the order of $10^{18}$ photons/s, with high mono-chromaticity. Multiple scattering is a negligible component in x-ray measurement. The x-ray measurements of Yue et al [31], are the first to provide quantitative information from the optically-dense region of a diesel spray.

The transient x-ray attenuation signal due to the fuel spray was measured by an avalanche photo-diode with a temporal resolution of 5ns. The output pulse voltage was proportional to the beam intensity. The entire spray sequence, beginning before the opening of the injector solenoid and ending after the spray passed through the beam, was captured.

The x-ray absorption technique determines the absolute mass and the mass distribution. The measurements showed that the radial mass distribution was Gaussian, and that the leading edge of the spray had the maximum fuel mass, compared to the bulk of the spray. Within the first 4mm from the nozzle, both the instantaneous mass, and the width of the spray leading edge increase with distance from the nozzle; this indicates a significant accumulation of fuel mass in the leading edge of the spray. In the bulk of the spray, the instantaneous mass decreases with distance away from the nozzle. The instantaneous mass increases with injection pressure over the range from 20 to 50 MPa.

The instantaneous mass in the leading edge of the spray is higher than in any other region of the spray. At all distances downstream, the maximum mass is located on the spray axis. When injection pressure is increased from 20 MPa to 80 MPa, the rate of fuel injection is increased for the same orifice geometry, and atomization is improved. The smaller fuel droplets lose their momentum more quickly than larger droplets, leading to accumulation of fuel mass in the spray plume. Bigger droplets have higher momentum and velocities than smaller droplets, causing bigger drops to accumulate in the leading edge of the spray.

The fuel volume fraction (FVF), distributions are Gaussian and symmetric about the spray axis. The maximum FVF of 78% occurs in the leading edge of the spray and decreases sharply beyond 4mm from the nozzle. The radius of the spray near the nozzle changes with time and increases sharply beyond 4mm from the nozzle. Except at the leading edge, the FVF in the spray never exceeds 50% during the entire spray duration. Beyond 4mm from the nozzle, the maximum FVF at the leading edge of the spray decrease sharply down to 26%. At 50 MPa injection pressure, the distance of 4-6mm from the nozzle is a region where the fuel mixture density and the width of the spray change sharply compared with other locations.

The measured mass fuel distributions in the diesel spray are considered to be highly reliable and more accurate than previously reported measurements or estimates. No evidence was found of an all-liquid core at, or near the nozzle exit. The measured fuel volume fraction in the bulk of the spray never exceeded 50% for injection pressures of 20 MPa and above. The Advanced Photon Source at Argonne National Laboratory is one of three third-generation synchrotron x-ray sources in the world. It produces high-brilliance x-radiations which are monochromatic. The transient x-ray attenuation signal--due to the fuel spray—was measured by an avalanche photodiode with a temporal resolution of 5 ns. The entire spray sequence was captured from before the opening of the injector solenoid until the end of the spray had passed through the x-ray beam.

Spray penetration illustrates spray behavior during the injection process. Hiroyasu et al [32], proposed a two-zone penetration model for the region near the nozzle. The x-ray measurements of Yue et al [31], show reasonable agreement with the predictions beyond 20mm from the nozzle. The following equation, modified from Hiroyasu's model, describes the experimental data: $S = C \cdot \Delta P^{m} t_{inj}^{n}$
Where S = spray penetration; $\Delta\rho$ is injection pressure drop; $t_{ing}$ is time after the start of injection, and the constants C, m, and n have the values 2.99, 1.1, and 1.33, respectively.

The measurements made by Yue et al [31] of spatial and temporal mass and density distribution in the dense spray region of diesel spray, using monochromatic x-ray absorption methods, are highly quantitative and time-resolved, with high spatial and temporal resolution. For injection pressures between 20 and 80 MPa, the region near the nozzle is composed of a liquid/gas mixture with liquid content not exceeding 77.5% in the leading edge of the spray; inside the bulk spray it is below 50%. A new quantitative, non-intrusive and time-resolved technique for diesel spray diagnoses in the region near the nozzle has been demonstrated. These results are complementary to variable-light measurements that yield reliable information about sprays far from the nozzle.

**Direct Injection Diesel and Spark Engines**

In small, high speed, direct-injection diesel engines, the liquid fuel is injected directly into a compact chamber at high speed and strikes the walls of the chamber. In direct-injection spark-ignition engines, fuel droplets may impact onto the combustion chamber walls and the piston crown. In port fuel-injection gasoline engines, a large portion of the fuel spray impinges on the walls of the port, or directly onto the intake valves.

The hydrodynamic and thermal characteristics of the post-impingement droplets are important issues in injection system design [33]. The following are of particular interest: (1) the total fuel mass, momentum and energy deposited on the wall, and (2) the fuel vapor distribution in the near-wall region. Liquid fuel on walls, which does not evaporate completely during combustion, can lead directly to enhanced levels of unburned hydrocarbon emissions. Fuel vapor near the walls can result in flame quenching as the flame approaches the cool walls of the chamber; this can result in an additional contribution to emissions. When a single droplet impinges on a solid surface, it first undergoes deformation and spreads out under the impingement-induced pressure gradients. This spreading flow may be stable or unstable, leading to different impingement regimes: stick, spread, rebound, splash. The spreading process is determined by a number of parameters characterizing the impingement conditions. These include the droplet diameter, velocity, incidence angle, temperature, viscosity, density, surface tension, as well as the solid surface temperature, roughness, liquid film thickness and gas boundary layer thickness. The most important dimensionless numbers are 1) droplet Weber number $We = \rho V^2 d / \sigma$ and the droplet Laplace number $La = \rho \sigma d / \mu^2$.

Droplets may bounce back elastically without energy loss. Droplets impinging on cold dry surfaces will tend to spread. Droplets on hot dry walls, with temperatures above the Leidenfrost temperature, will tend to rebound or break up.

Gasoline engines with port injection use pressures of around 3bar, which generate droplets of the order of 100 $\mu m$, whereas in high-speed direct-injection diesel engines, drop size is of the order of 20 $\mu m$. Regime transition conditions are determined by the wall conditions and the critical Weber number $We_c$. For dry walls, the transition from adhesion to splash is at $We_c$ =2630. For wetted walls, transition from stick to rebound is at $We_c$ =2; from rebound to spread, is at $We_c$ =20; and from spread to splash is at $We_c$ =1320 [33].

**Gas Turbine Engine Spray Combustion**

Driven by the goal of reducing the specific fuel consumption of aviation, as well as stationary gas turbine engines, the values of pressure and temperature at the inlet of gas turbine combustors have steadily increased. As a direct consequence, the emissions of

NOx have increased because the formation rates accelerate strongly with increasing pressure, and especially temperature. As the drive towards increased cycle efficiency increases, the need for the development of effective NOx reduction concepts has become more acute. One of several approaches is the creation of a lean homogenous fuel-air mixture, just upstream of the combustor inlet. If it is ensured that excess air is always present over the entire reaction zone, then the local temperature will be low enough to completely suppress the formation of thermal NOx, but high enough for stable and complete combustion of the fuel. The liquid fuel must be fully vaporized and mixed with the combustion air in a premix duct mounted at the combustor inlet. This concept is termed lean, premixed, pre-vaporized (LPP) combustion. It requires fine atomization and careful placement of the fuel, so that a high degree of mixing can be achieved before the onset of auto-ignition—i.e. within a few milliseconds. The plain jet in cross-flow configuration has regained interest as a candidate fuel injection system for LPP ducts because it is robust and versatile and unique among typical gas turbine fuel injectors in that it combines airblast atomization of the fuel with variable fuel placement.

**Agricultural Sprays**

The droplet size distribution of agricultural spray material influences the magnitude of evaporation, deposition, drift and application effectiveness. Droplet size information, in particular the volume fraction in the smaller droplet sizes--which are more prone to wind drift, and the larger droplet sizes—which are directed at the target, are critical to forest and agricultural applications, where specific levels of spray material must be deposited to achieve success and avoid excessive environmental contamination. The United States Department of Agriculture (USDA), Forest Service (FS), and other agencies and companies, conducted wind tunnel tests to determine droplet size distributions of pesticides and simulant spray materials, when applied through hydraulic and rotary atomizers over a period of 30 years. The experimental variables included liquid pressure and flow rate, air velocity and shear across the atomizers, physical properties (viscosity, density, and surface tension), and atmospheric conditions. [34].

Most measurements of droplet size in agricultural sprays have been made with the PMS (Particle Measurement Systems) instrument, which has a minimum droplet size resolution of $34\,\mu m$. The Spray Drift Task Force has made very detailed and comprehensive comparisons of measurements made with the PMS, compared to those made with the Malvern laser diffraction particle analyzer, which allows measurement of drop diameters down to $4\,\mu m$. SDTF field and modeling studies established that droplet sizes below $34\,\mu m$ are important for wind drift assessment and that the Malvern instrument is essential for measurement of small droplet size. Laser diffraction techniques (Malvern), use a “spatial” number-density-weighted sampling technique, whereas optical array probes (PMS), measure a “temporal” number—flux-weighted sampling technique. The Malvern and PMS produce different results if the spray does not contain droplets traveling at uniform speed at the sampling point The Malvern technique is completely non-intrusive, whereas the PMS instrument is inserted into the spray, causing a disturbance to the drop size and velocity field. Off-target drift in aerial application is due to small droplets that are generated, as well as larger droplets that evaporate to smaller sizes. Measurements made by the PMS need to be converted into Malvern-equivalent data.

When biological targets, such as weeds, are sprayed with biologically active materials, such as herbicides, surfactants are often used to increase the surface area coverage and promote uptake of the active ingredients. Additionally, liquid adjuvants are used to inhibit generation of small droplets that can be easily displaced by the wind. Long chain polymers are often used. Some polymer-based adjuvants significantly change the droplet size spectra of the sprayed formulations. Increase in volume of large droplets results in reduced coverage, while increase in volume of small droplets increases the spray drift. Addition of polymer material results in decreased volume of small droplets. The addition of polymers to emulsifiable concentrates increases the volume of large droplets. Use of polyethylene oxidize polymer can reduce liquid drag in the piping system, which can increase the distance of liquid traveling from fire hose nozzles by up to 50%. Solid particulates, injected as a slurry, with an appropriate size distribution of polymer particulates, will permit a continuous release of the drag-reducing polymer, in addition to decreasing the pressure supply requirements, compared to an aqueous mixture of polymer in solution.

In agricultural spraying, effective use of spray adjuvants, to alter liquid properties, can minimize spray drift, worker hazard and surface water contamination through irrigation or runoff. Uniform deposition of small, concentrated droplets can provide higher biological efficacy than large, dilute droplets. Improved spray technology has increased the ability to precisely dispense dose volumes on the order of micro-liters onto specific target locations. Dose applications within one centimeter are a completely new scale of accuracy and precision in chemical treatment. Spray applications can aim the initial deposit toward weed surfaces that are only slightly displaced from adjacent crop plants. A precise, post-emergent treatment system, coupled with an effective adjuvant may allow non-selective chemicals to be used for weed control. Non-selective herbicides are those which can kill the crop, as well as the target weeds. Adjuvants can significantly increase the physical transport of chemicals across a leafy surface after initial deposition. Surfactants have been found to improve droplet spread by factors up to 500.

Robotic machine vision pest control strategies have been used in fields of cotton and tomatoes [35]. Robotic systems allow centimeter scale application of herbicides using image based crop/weed discrimination systems to inspect the seed line from the vertical direction to locate and distinguish weeds from crops. A precision dosing system is used to simultaneously and exclusively apply any number of pest control agents to crop targets, weed targets, or combinations of the two.

Biological efficacy depends on precise target area coverage when micro-liter volumes are applied on a centimeter scale. Minimization of splashing to avoid phytotoxic damage to the adjacent crop is a critical constraint. The objectives of research are:

- To determine volume dose per pulse duration for a centimeter scale spot sprayer under different spray pressures, pulse durations of liquid jet emission, spray adjuvants, and orifice diameters.

- To estimate deposition area and centimeter-scale splashing using Kromekote TM cards for different adjuvant formulations and orifice-to-target distances.

- To establish liquid properties as a means for estimating application efficacy, spray adjuvant choice, and operational criteria.

Mosquito control is achieved by selecting the optimum size of droplets on adult mosquitoes, which is between 2 and 20 microns. Aerial spraying uses hydraulic nozzles with high pressure nozzle angles and air stream velocities for generation of small droplets. Wide fan angles and small orifice sizes are used. Rotary case and sleeve atomizers are also used. Good agreement has been found between droplet size spectra data measured in wind tunnels and on actual aircraft. The Spray Drift Task Force (SDTF), is a consortium of 39 agricultural chemical companies, investigating factors which affect pesticide drift for regulatory requirements. The American Society for Testing and Materials (ASTM), has set standards for sampling liquid sprays with laser diffraction techniques. Wind tunnel studies included air stream velocities, representing those encountered with rotary wings (80 mph), fixed wing piston engines (120 mph), and gas turbine engines (140-175 mph). Rotary atomizers were generated at rotation rates between 11,200 and 17,500 rpm. Flat fan nozzles were set $45^{o}$ forward into the air stream, and the rotary atomizers were oriented straight back from the air stream. Flat fan nozzle tests included spray pressures of 40 and 70 psi, with wind speeds of 145 and 175 mph. Rotary atomizer tests included liquid flow rates of 0.66 to 3.05 1/min and wind speeds of 80-175 mph.

Rotary cage atomizers produce finer sprays than the flat fan nozzles. Higher spray pressures, with flat fan nozzles, produce higher flow rates and finer sprays, with a given orifice diameter. With rotary cage atomizers, greater flow rates cause the sprays to become coarser. In flat fan nozzle atomization, liquid is discharged from the nozzle as a sheet, which breaks down into droplets. Atomization from rotary atomizers is by direct ligament and drop formation. For rotary cage atomizers, greater rotation rates produce finer sprays as the droplets are flung across the atomizer gauze with greater energy. Rotary cage and rotary screen atomizers provide the greatest potential for obtaining droplet sizes less than 25 microns, required for optimum control of adult mosquitoes, using aerial spraying [36]. The 20 and 30 micron porous high-density polyethylene screen rotary sleeve atomizers produced the most narrow droplet size spectra.

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