Atomization and Sprays

Arthur H. Lefebvre

Combustion: An International Series

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Arthur H. Lefebvre
Purdue University
West Lafayette, Indiana

江苏工业学院图书馆
藏书章

HEMISPHERE PUBLISHING CORPORATION
A member of the Taylor & Francis Group
New York Washington Philadelphia London

ATOMIZATION AND SPRAYS

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1 2 3 4 5 6 7 8 9 0 B C B C 8 9 8 7 6 5 4 3 2 1 0 9 8

This book was set in Times Roman by Edwards Brothers, Inc. The editors were Sandra Tamburrino and Mary Prescott.
Cover design by Sharon Martin DePass.
BookCrafters, Inc. was printer and binder.

Library of Congress Cataloging-in-Publication Data

Lefebvre, Arthur Henry, date
Atomization and sprays.

(Combustion)
Bibliography: p.
Includes index.
1. Spraying. 2. Atomization. I. Title. II. Series:
Combustion (Hemisphere Publishing Corporation)
TP156.S6L44 1989 660.2'961 88-30101
ISBN 0-89116-603-3
ISSN 1040-2756

PREFACE

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Arthur H. Lefebvre

CONTENTS

CHAPTER
ONE

GENERAL CONSIDERATIONS

INTRODUCTION

The transformation of bulk liquid into sprays and other physical dispersions of small particles in a gaseous atmosphere is of importance in several industrial processes and has many other applications in agriculture, meteorology, and medicine. Numerous spray devices have been developed, and they are generally designated as atomizers or nozzles. The process of atomization is one in which a liquid jet or sheet is disintegrated by the kinetic energy of the liquid itself, or by exposure to high-velocity air or gas, or as a result of mechanical energy applied externally through a rotating or vibrating device. Because of the random nature of the atomization process the resultant spray is usually characterized by a wide spectrum of drop sizes.

Natural sprays include waterfall mists, rains, and ocean sprays. In the home, sprays are produced by shower heads, garden hoses, and hair sprays. They are commonly used in applying agricultural chemicals to crops, paint spraying, spray drying of wet solids, food processing, cooling of nuclear cores, gas-liquid mass transfer applications, dispersing liquid fuels for combustion, and many other applications.

Combustion of liquid fuels in diesel engines, spark ignition engines, gas turbines, rocket engines, and industrial furnaces is dependent on effective atomization to increase the specific surface area of the fuel and thereby achieve high rates of mixing and evaporation. In most combustion systems, reduction in mean fuel drop size leads to higher volumetric heat release rates, easier lightup, a wider burning range, and lower exhaust concentrations of pollutant emissions [1–3]. In other applications, however, such as crop spraying, small droplets must be avoided because their settling velocity is low and, under certain meteorological conditions, they can drift too far downwind. Drop sizes are also important in spray drying and must be closely controlled to achieve the desired rates of heat and mass transfer.

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

ATOMIZATION

Sprays may be produced in various ways. There are several basic processes associated with all methods of atomization, such as the hydraulics of the flow within the atomizer, which governs the turbulence properties of the emerging liquid stream. The development of the jet or sheet and the growth of small disturbances, which eventually lead to disintegration into ligaments and then drops, are also of primary importance in determining the shape and penetration of the resulting spray as well as its detailed characteristics of number density, drop velocity, and drop size distributions as functions of time and space. All these characteristics are markedly affected by the internal geometry of the atomizer, the properties of the gaseous medium into which the liquid stream is discharged, and the physical properties of the liquid itself. Perhaps the simplest situation is the disintegration of a liquid jet issuing from a circular orifice, where the main velocity component lies in the axial direction and the jet is in laminar flow. In his classic study [4], Lord Rayleigh postulated the growth of small disturbances that eventually lead to breakup of the jet into drops having a diameter nearly twice that of the jet. A fully turbulent jet can break up without the application of any external force. Once the radial components of velocity are no longer confined by the orifice walls, they are restrained only by surface tension, and the jet disintegrates when the surface tension forces are overcome. The role of viscosity is to inhibit the growth of instabilities and generally delay the onset of disintegration. This causes atomization to occur farther downstream in regions of lower relative velocity; consequently, drop sizes are larger. In most cases, turbulence in the liquid, cavitation in the nozzle, and aerodynamic interaction with the surrounding air, which increases with air density, all contribute to atomization.

Many applications call for a conical or flat spray pattern to achieve the desired dispersion of drops for liquid-gas mixing. Conical sheets may be produced by

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

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

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

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

The difficulties in specifying drop size distributions in sprays have led to widespread use of various mean or median diameters. A median droplet diameter divides the spray into two equal parts by number, length, surface area, or volume [5]. Median diameters may be determined from cumulative distribution curves of the types shown in Fig. 3.6. In a typical spray the value of the median diameter, expressed in micrometers, will vary by a factor of about four depending on the median diameter selected for use. It is important therefore to decide which measure is the most suitable for a particular application. Some diameters are easier to visualize and comprehend, while others may appear in prediction equations that have been derived from theory or experiment. Some drop size measurement techniques yield a result in terms of one particular median diameter. In some cases a given median diameter is selected to emphasize some important characteristic, such as the total surface area in the spray. For liquid fuel-fired combustion systems and other applications involving heat and mass transfer to liquid drops, the Sauter mean diameter, which represents the ratio of the volume to the surface area of the spray, is often preferred. The mass median diameter, which is about 15 to 25% larger than the Sauter mean diameter, is also widely used. As Tate [5] has pointed out, the ratio of these two diameters is a measure of the spread of drop sizes in the spray.

ATOMIZERS

Sprays may be produced in various ways. Essentially, all that is needed is a high relative velocity between the liquid to be atomized and the surrounding air or gas. Some atomizers accomplish this by discharging the liquid at high velocity into a relatively slow-moving stream of air or gas. Notable examples include the various forms of pressure atomizers and also rotary atomizers, which eject the liquid at high velocity from the periphery of a rotating cup or disk. An alternative approach is to expose the relatively slow-moving liquid to a high-velocity airstream. The latter method is generally known as *twin-fluid, air-assist,* or *airblast* atomization.

Pressure Atomizers

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

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

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

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

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

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

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

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

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

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

Fan spray. Several different concepts are used to produce flat or fan-shaped sprays. The most popular type of nozzle is one in which the orifice is formed by the intersection of a V groove with a hemispheric cavity communicating with a cylindrical liquid inlet [5]. It produces a liquid sheet parallel to the major axis of the orifice, which disintegrates into a narrow elliptical spray.

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

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

Rotary Atomizers

One widely used type of rotary atomizer comprises a high-speed rotating disk with means for introducing liquid at its center. The liquid flows radially outward across the disk and is discharged at high velocity from its periphery. The disk may be smooth and flat or may have vanes or slots to guide the liquid to the periphery. At low flow rates, droplets form near the edge of the disk. At high flow rates, ligaments or sheets are generated at the edge and disintegrate into droplets. Small disks operating at high rotational speeds and low flow rates are capable of producing sprays in which drop sizes are fairly uniform. A 360° spray pattern is developed by rotating disks, which are usually installed in a cylindrical or conical chamber where an umbrellalike spray is created by downward gas currents [5].

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

Air-Assist Atomizers

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

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

Airblast Atomizers

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

Other Types

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

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

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

Sonic (whistle). Gas is accelerated within the device to sonic velocity and impinges on a plate or annular cavity (resonation chamber). The sound waves produced are reflected into the path of the incoming liquid [6]. The frequency of the sound waves is around 20 kHz, and this serves to disintegrate the liquid into small droplets ranging downward in size from 50 μm. The sonic and pneumatic effects are difficult to isolate from each other. Efforts have been made to design nozzles that operate above the audible frequency limit to reduce the nuisance of noise [7]. However, in some applications the attendant sound field may benefit the process (e.g., combustion) for which the resultant spray is required.

Windmill. Many aerial applications of pesticides require a narrow spectrum of drop sizes. Conventional rotary disk atomizers can provide such a spectrum but only when operating in the ligament mode at low flow rates. By making radial cuts at the periphery of a disk and twisting the tips of the segments, the disk can be converted into a windmill that will rotate rapidly when inserted into an airflow at aircraft flight speed. According to Spillmann and Sanderson [8], the disk windmill constitutes an ideal rotary atomizer for the aerial application of pesticides. It

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