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Effect of fluid properties and nozzle parameters on drop size distribution from fan spray nozzles

Louis Allen Liljedahl
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Effect of fluid properties and nozzle parameters on drop size distribution from fan spray nozzles

by

Louis Allen Liljedahl

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I. INTRODUCTION

As civilization has advanced, man has attempted various new means of improving the efficiency of his food production. This includes methods of controlling certain pests, which either compete with man for the consumption of the food he is growing, or compete with food plants and animals for nutrients and water. It is natural that man, long interested in alchemy and the mysterious effects of chemicals, would try to use chemicals for the control of these insects, weeds, and other organisms. As early as 1,000 B.C., Homer spoke of "the pest averting sulphur", and in the 18th century certain chemicals were recommended for preservation and fungus control (McNew, 1959). Routine use of pesticidal chemicals started shortly after the discovery of Bordeaux Mixture, by Millardette in the 1880's, for the control of downy mildew of grapes (Horsfall, 1956). These chemicals came to be used in increasing quantities, particularly in high value agricultural crops.

Use of chemicals for pest control in agriculture expanded rapidly after 1945. At that time, the phenoxy-alliphatic herbicides and the chlorinated hydrocarbon insecticides were introduced for general domestic and agricultural use. These chemicals were inexpensive, effective in very small dosages, and had low mammalian toxicity. The success and widespread adoption of these chemicals triggered a search which still continues for other chemicals which might have similar or other pesticidal properties. A large number of such chemicals have been found and produced commercially. In normal agricultural production today in the United States, a great amount of such chemicals are ordinarily used (Strickler and Hinson, 1962).
A. Loss of Control of Spray

Many of these pesticide chemicals are liquids, or can be emulsified or put into solution with inexpensive commercial solvents. In this form it is common to apply them to plants, animals, or the soil as a spray. Projected spray will, with relatively little special effort, produce a moderately uniform deposit upon rather irregular objects. This characteristic is exploited when paint is sprayed or pesticides are sprayed. However, sprays are not easy to control with a desirable degree of predictability. That is, only a portion of the sprayed material is deposited upon the intended target. The remainder is deposited some place where its presence is considered undesirable or wasted.

1. Effect of drift

The first type of lost material which became an object of concern was the undesirable deposit, called drift. Drift of a herbicide onto a crop which is sensitive to the chemical may kill the crop. Drift of other pesticides onto other crops for which there exist no legal tolerance for residues may result in the crop being unmarketable. Either type of drift may cause large economic damage, and cause individuals responsible for the drift in turn to be sued for compensation for the damage. Akesson and Yates (1961), for example, showed that even under good weather conditions, spraying upwind of a field of alfalfa hay closer than 600 feet with 1.5 lb/A of DDT would result in deposits of chemical on the hay which exceeded legal limits for marketing.
2. **Deposition efficiency**

Another type of lost material is the waste caused by poor deposition efficiency on the target. Bowen et al. (1952) measured the proportion of chemicals deposited on target plants by conventional spraying and dusting equipment. They found the deposit to be quite variable, but it was most frequently between 5 and 15 percent of the total amount used. Reeves et al. (1967) measured the proportion of spray deposited on simulated cotton plants, compared with alternative application methods using a rotary brush. They found the average proportion of chemical deposited on the simulated plants by spray to be 5.1 percent of the total used. Since large amounts of chemical are used in agricultural production each year and a major proportion of these chemicals are applied by spraying, this poor efficiency represents a considerable loss. Strickler and Hinson (1962) indicated that $462 million is spent annually for chemicals used in agricultural spraying. Stanton and Dominick (1963) reported that cost of spray materials alone represented 31 percent of the total cost of producing apples for fresh market in eastern United States.

3. **Atmospheric pollution**

Some of the spray becomes airborne for sufficient length of time to cause a health hazard, and this is another type of lost material which is of concern. Argauer et al. (1968) measured the deposit in the swath and the deposit up to one-half mile downwind resulting from sprays applied by aircraft at conventional rates (37 l/ha) and at an ultra low volume rate (2.4 l/ha). The amount of chemical recovered within one-half mile of the point of release by deposit on the ground averaged 52 percent of the
total, and in one test was 18 percent. The most plausible hypothesis to account for the remainder of the spray is that it still remained airborne. If this is so, the airborne spray must contain an appreciable fraction of droplets in the one to five micron diameter range, which are known to be respired into the lungs and be retained in the aveolar tracts, where the material is readily absorbed into the blood (Davies, 1961). Seven percent of the pesticide related occupational disease incidents reported by Kleinman et al. (1960) were respiratory illness, which indicates that airborne spray may be a health hazard. Thirty-three percent of the incidents reported by Kleinman et al. were classified as systemic poisoning, of which a portion may also have been caused by inhalation of spray.

To improve the control of spray by application equipment, exploitation of a number of forces known to affect small particles has been investigated by a number of workers. Aerodynamic forces, electrostatic forces, and thermal gradient forces have been applied to cause changes in the trajectories of spray droplets. Carleton et al. (1960) showed that the relative magnitudes of these forces are directly dependent upon the diameter of the droplet being subjected to the force. Normal spray from equipment currently in use has a widely variable distribution of droplet sizes. These distributions are log-normal in general form, and result in a 20-fold or greater range of droplet diameters from a single piece of application equipment. Because of the wide variation in droplet diameters present, even a careful application of these forces to conventional sprays will result in a wide variation in droplet trajectories, frustrating the attempt to improve the control of the spray. A more detailed review
of this problem by Courshee (1961) and Carleton et al. (1960) indicated a need for improved uniformity of spray droplet size before much progress could be expected in controlling droplet trajectories and the resulting deposition of spray.

B. Biological Effectiveness

In addition to the proposed value of more uniform spray for better control of pesticide spray deposition, a number of workers have reported evidence that pesticide application in certain droplet sizes may have a greater biological effect than when applied in another droplet size. Early work with modern insecticides by Yeomans et al. (1949) reported that the most effective diameter for DDT spray for control of mosquitoes was approximately 12 microns. Davis et al. (1956) tested fine, medium, and coarse sprays of DDT from aircraft for control of the spruce budworm. They reported highest mortality was obtained with the medium spray, which had a mass median diameter of approximately 150 microns. From probit analysis curves constructed with their experimental data, they estimated that 95 percent mortality could be achieved with a 50 percent reduction in the amount of pesticide used if the optimum droplet size spray was used for the application. The experiments of Davis et al. were done with sprays having a wide range of droplet sizes. Thus the droplet size distribution of all the sprays used overlapped to a considerable extent.

Hedden (1961) conducted an extensive series of experiments testing the effectiveness of disease control chemicals and insecticides on several vegetable crops using sprays having mass median droplet sizes from 100 microns to 500 microns. The results of these tests indicated that little
if any variation in control could be attributed to differences in droplet size of the sprays used. This experiment, like the work of Davis et al. (1956), used sprays having a wide range of droplet sizes and considerable overlap existed for the various size distributions used in the tests. This may have caused a loss of discrimination in the experiments.

Hartley and Brunskill (1958) conducted controlled laboratory experiments and showed that spray droplets in the range of 100 to 300 microns will bounce from the leaf surface of crop plants without retention if the surface tension of the droplet is high. Droplets smaller than 100 microns had 100 percent retention. Ennis and Williamson (1963) showed that the herbicidal activity of several chemicals increased as the droplet size decreased, when the volume of liquid used was low. Bengtsson (1964) conducted experiments on other crop and weed species with several herbicides and reported a similar effect of droplet size.

Workers investigating the use of ultra low volume spray methods have speculated that droplet size effect may be responsible for its increased effectiveness (Skoog et al., 1965). Himel and Moore (1967) inferred from particle size measurements made on insect larvae killed during actual field spraying operations that the bulk of insect deaths could be attributed to pesticide delivered as particles less than 50 microns in diameter. Burgoyne and Akesson (1968) and Kilpatrick (1967) reported that spray with a certain droplet size was most effective for control of mosquito larvae, but no supporting data were presented. Mount et al. (1968) reported the results of field experiments in which greatly reduced total dosage of pesticide produced satisfactory kill of mosquito adults.
when sprays of droplet size ranging from 6.4 to 10.8 micron diameter were used.

C. Recent Proposed Improvements

Since the suggestion by Carleton et al. (1960) and Courshee (1961) that more uniform droplet size might result in better controlled spray, a number of attempts have been made to produce more uniform spray by various means. Kirch et al. (1958) proposed that a spray liquid could be thickened by making it into an invert emulsion. Such an emulsion could have viscosities up to 10,000 centipoise. Kirch et al. distributed this material in the field using a spinning drum with nozzles or other orifices on its periphery. The resulting spray was quite coarse, having mean droplet sizes of several millimeters. It was claimed that a reduction in drift of the spray resulted. This was most likely due to the general increase in droplet size rather than increased uniformity.

Douglas (1968) proposed a design of a nozzle with a multiplicity of orifices on the periphery of a cylinder which oscillated radially approximately 0.4 radians. No data have been published on the uniformity of spray produced by such a device. The Dorman Sprayer Co. in Cambridge, England (National Institute of Agricultural Engineering, 1958) proposed that a hollow cone spray nozzle operated at 10 lbs per-square-inch would be a useful system for producing uniform spray droplets. Tests were conducted to show the lower proportion of spray droplets less than 100 micron diameter compared to a conventional fan spray nozzle.

Seymour and Byrd (1964) proposed a method of producing uniform spray
droplets by mixing a particulating material with the spray liquid (water). This material consists of a fine powder of uniform grain size of a hydrophyllic long-chain polymer. When mixed with water, this material absorbed water, producing small jelly-like, discrete particles. It was hypothesized that this jelly-like material, when forced through a conventional hydraulic nozzle, would break up into particles associated with the original dry polymer particles. If the polymer particles were approximately uniform in size when dry, the resulting jelly particles would also be approximately uniform in size, and if the correct amount of water were added, no free water between the particles would remain, so that no fine, secondary particles would be formed.

Roth (1966) proposed the use of Rayleigh break-up from small jets of liquid issuing from hypodermic tubing to obtain uniform droplets. Rayleigh break-up of liquids with moderate viscosity has satellite droplets associated with the major droplet formation. It was assumed that this spraying device did not produce completely uniform spray, since a certain fraction would consist of satellite drops. The uniformity of spray from such a device might still be better than from conventional hydraulic nozzles.

Walton and Prewett (1949) measured drop size distribution from spinning disc atomizers. Their results showed that the spinning disc atomizer was capable of producing relatively uniform droplets at low flow rates. There was evidence that some satellite droplets were produced. Burt et al. (1966) applied the spinning disc atomizer principle to agricultural work. They introduced an inwardly radial air flow over the
periphery of the disc to remove fine satellite drops. Thus only the principal droplet size left the spray device. Their particle size measurements indicate that a coefficient of variation of approximately 0.1 was obtainable by this method.

Sweet (1964) showed that a simple jet issuing from an orifice which was vibrating axially at approximately the same frequency as the Rayleigh break-up frequency on the emerging jet would produce a uniform droplet spray with no satellite drops. The device used for this work included use of a magnetostrictive transducer to drive a single orifice in a small metal block. This is too complicated and has insufficient capacity for a practical spraying device. If an inexpensive method were available for producing a multiplicity of such orifices, and a simpler method were used to drive the nozzles, it might be a practical spraying device.

Schridt (1967) proposed that uniform spray could be produced by means of a rapidly spinning porous toroid, through which a liquid would flow which would not wet the porous material. Under such circumstances, he reported that the device produced uniform spray. Even when liquids were used that did wet the porous material, spray was produced that was more uniform than that produced by most hydraulic nozzles.

The interest in producing more uniformly sized spray droplets suggests a need for data on the uniformity of droplet size produced now by common agricultural spray nozzles spraying ordinary Newtonian liquids. If work on uniformity of droplet size becomes extensive, simplified methods of measurement would also be useful.
II. OBJECTIVES

The overall objective of this study was to explore factors affecting the size and uniformity of spray droplets. Specific objectives were as follows:

1. To provide reference measurements on the size dispersion of spray from common agricultural spray nozzles to serve for comparison with performance of spray devices or systems which are claimed to produce more uniform spray.

2. To formulate the effect of fluid properties, spray nozzle parameters, and operating conditions on the mean and standard deviation of drop size in terms of dimensionless variables, and test the adequacy of this formulation with experimental measurements.

3. To formulate a simplified method of measuring size and uniformity of spray droplets, and test the adequacy of this formulation with experimental measurements.
III. LITERATURE REVIEW

A. Characterizing Droplet Size Distribution

The introduction has shown that spray droplets are not uniform in size, but rather have a distribution of sizes. The question now arises as to how to best characterize this distribution. The most fundamental approach would be to hypothesize a mathematical form for the distribution function which would fit the distribution data. Some method could then be developed to estimate the parameters of the distribution function.

A number of distribution functions for spray droplet sizes have been proposed, and discussed in earlier literature. Functions which have been discussed and used most frequently are:

a. Normal.
b. Rosin - Rammler
c. Nukiyama - Tanasawa.
d. Logarithmic - normal.
e. Square root normal.
f. Upper-limit logarithmic normal.

Various authors have used all of these functions for characterizing the distribution of drop sizes from various types of spray equipment. Mugele and Evans (1951) made a comparative examination of many distribution functions which had previously been used or proposed for spray drop size distributions. By comparing the goodness of fit of a number of such functions to experimental data, they concluded that the upper-limit logarithmic normal function best fitted most of the experimental data which they were able to examine. This function was written as:
\[ f(D) = \frac{\frac{D_m}{\sigma(D_m - D) \sqrt{2\pi}}}{\exp \left[ - \ln \left( \frac{D(D_m - D)}{\overline{D}(D_m - D)} \right) / 2\sigma^2 \right]} \] (1)

where \( D \) = droplet diameter, \( D_m \) = maximum drop diameter, \( \overline{D} \) = mean drop diameter, \( \sigma \) = a central tendency parameter, and \( f(D) \) = frequency of drops of diameter \( D \) produced or sampled during some time interval. This function seemed not only to fit experimental data well, but also met the objection that the logarithmic normal distribution function results in a small, but finite, probability for drops of an absurdly large size.

Although the literature contains numerous discussions of proposed frequency distribution functions for droplet sizes, practical use of these functions for characterizing drop size distribution has been rather limited. The parameters of these functions have less immediate meaning to the user than other descriptive measures which are independent of the distribution function. Also several of the functions are three parameter functions, requiring trial and error solutions.

In previous work on spray distributions, it has been more common to rely upon various descriptive measures, or statistics, to characterize the size distribution. The simplest descriptive measure of central tendency would be the arithmetic mean:

\[ D_n = \frac{\sum n_i D_i}{\sum n_i} \] (2)

where \( n_i \) is the frequency, and \( D_i \) is the mid-point, of the \( i \)th class.

\(^1\)Notation is defined when first used and summarized in Chapter VIII.
interval.

In spray research literature, the arithmetic mean is commonly referred to as the number mean, or unweighted mean. Spray research workers have been more often interested in the volume of spray contained in various droplet size classes, rather than the number of droplets in each size class. As a consequence, the most common measure of central tendency of spray drop size distribution is the volume median diameter, more frequently referred to as the mass median diameter. The use of this statistic has arisen primarily because of the ease of its calculation. The proportion of spray volume less than or included in each size class is computed, and then plotted against the upper limits of the size classes. The point at which the graph crosses the 50 percentile line is readily determined, and thus the volume median diameter determined graphically.

Volume mean diameter has also commonly been used as a measure of central tendency. There has existed in the literature, however, for some time, two different definitions of this expression. It is surprising that none of the authoritative works in this field (Herdan, 1960; Ranz, 1955; Marshall, 1954) discuss this discrepancy, or even recognize it. No attempt will be made to resolve the differing definitions, or develop a relationship between them. No simple relationship would likely exist because the definitions result from different concepts of the mean.

The volume mean diameter used most frequently in spray research in chemical and mechanical engineering literature is the result of an analogy with the simple arithmetic mean. It is defined as that diameter
of droplet which would result if the spray sample were divided into an equal number of uniformly sized droplets. That is:

\[ D_{VME} = \left( \frac{\sum n_i D_i^3}{\sum n_i} \right)^{1/3} \tag{3} \]

This mean will be referred to as the Mugele-Evans volume mean diameter.

The other volume mean results from finding the mean of the drop size volume distribution curve or histogram. Since the volume in each size class would be:

\[ V_i = n_i D_i^3 \tag{4} \]

\( V_i (D) \) becomes a distribution function itself. The mean of this distribution then results from the expression for the arithmetic mean of a distribution, that is:

\[ D_{VH} = \frac{\sum n_i D_i^4}{\sum n_i D_i^3} \tag{5} \]

This volume mean diameter will be referred to as the Herdan volume distribution mean diameter.

Because many drop size distributions are approximately normal with respect to the logarithm of the size, the logarithmic - normal distribution is frequently assumed and thus the logarithmic transformation is used. The mean computed from this transformation is known as the geometric mean. It can also be computed from the number distribution as well as the volume
distribution. These statistics are defined, respectively, as:

\[ D_{gn} = \exp \left[ \frac{\sum n_i (\ln D_i)}{\sum n_i} \right] \]  

(6)

and

\[ D_{gV} = \exp \left[ \frac{\sum n_i D_i^3 (\ln D_i)}{\sum n_i D_i^3} \right] \]  

(7)

Another measurement of central tendency commonly used in chemical and mechanical engineering processes is the Sauter mean diameter, which is defined as the diameter of droplet having the same ratio of volume to surface as the spray being measured. If a spray, or any dispersed medium, enters into any processes which involve heat and mass transfer through the surface, such as evaporation and drying, combustion or other chemical reaction, or even extraction processes, the Sauter mean diameter is appropriate for prediction of performance of the system. Mathematically, it is defined as:

\[ D_{Saut} = \frac{\sum n_i D_i^3}{\sum n_i D_i^2} \]  

(8)

Compared to the number of statistics used for representation of central tendency of drop size distribution of sprays, it has been a much less common practice to report measures of dispersion of such distributions. Because the median is frequently computed graphically, the inter-quartile range, the 0.1-0.9 decile range, and similar ranges are dispersion
statistics which have most often been reported, since the statistics could readily be obtained from the graphical process of computing the median.

Because the logarithmic normal distribution appears to fit many particulate materials, its application for this purpose has been discussed extensively by Aitchison and Brown (1957) and Herdan (1960). Duffle and Marshall (1953) studied the uniformity of spray drops resulting from the break-up of simple low speed jets, and used the geometric standard deviation to characterize the uniformity of the drops. Nelson and Stevens (1961) measured variability of spray droplet sizes in their experimental work. This variability was expressed in their work as the standard deviation of the square root transformed data.

B. Measurement of Droplet Size

Sampling of spray by collection of dyed spray on paper or card stock dates back at least to the work of Riley (1909). While Riley's work dealt principally with visual appraisal of mass distribution and droplet size, the same method was used for quantitative measurement of droplet size from the size of stains by Dorman (1952). Variations in this technique were later described by Davis and Elliot (1953), and Maksymiuk (1964). Middleton and Lowe (1967) report the use of clay coated thin layer chromatography plates for the same functional purpose. The coated cards are convenient to handle, can be used in the field as well as the laboratory, are relatively stable, and can be used in vertical as well as horizontal positions. When dyed spray drops deposit on such a card, the liquid is absorbed into the card forming a stain. The ratio of the stain
diameter to diameter of the drop causing the stain is termed the spread factor, and must be determined for each combination of spray liquid and card stock. This spread factor is often a function of the droplet size itself. Thus, to measure distribution of a wide range of droplet sizes requires determination of the spread factor for the same range of droplet sizes. The card stock material is usually a material used for commercial printing, and obtained from commercial sources. Some nonuniformity of the coating and calendaring of the card stock evidently exists, as an apparently inherent variation exists in the spread factor, even when droplet size is held constant. This variation introduces another source of variation into droplet size measurements, therefore making comparisons between tests less sensitive. The work by Middleton and Lowe using clay coated thin layer chromatography plates as a substitute for coated cards was intended to reduce this variation. Thin layer chromatography plates however, lack much of the convenience of handling which the coated cards have.

Castleman (1932) described the use of in-flight flash photography to study the formation of spray and measurement of droplet sizes. Dombrowski (1956) describes many of the details of this method of studying spray. This method was used by Ingebo (1956) more extensively than by any other worker. This method suffered from several limitations. The number of drops which can be sampled in any photograph is usually rather small if sufficient magnification is used to assure that small droplets are recorded. Large droplets are also less likely to be out of focus than small droplets, for any given depth of field of focus, resulting in a
biased sampling in favor of larger droplets. Furthermore, if the droplets are not all traveling the same velocity, as for example, in the case where spray may be accelerating due to aerodynamic drag, a bias is also introduced due to the difference between the distribution over space and the distribution over time. Ranz (1955) discussed this bias briefly, and showed that the distribution over time was related to the distribution over space, as follows:

\[ f(D) = \frac{v(D) f'(D)}{\int_{0}^{\infty} v(D) f'(D) \, dD} \]

where \( f'(D) \) = frequency of drops of diameter \( D \) sampled over some space while in motion, and \( v(D) \) is the velocity of drops of diameter \( D \) over the same space. In decelerating air flow where the velocity of particles decrease with size, this bias might tend to compensate for the bias due to differing image sharpness. Ingebo corrected for velocity distribution by use of double flash photography so that the \( v(D) \) was known. In-flight photography eliminates the need for spread factor measurements, and can be used in studying transient phenomena as well as studying drop-size in difficult situations, such as the work by Ingebo, where the size of burning droplets was measured.

Doble (1947) described a method of drop size determination which collected droplets in a shallow layer of castor oil above a layer of vaseline. Rupe (1949) modified this by use of a less viscous collecting fluid, naptha, in a flat bottom glass cell which was coated with silicone base material to make it hydrophobic. This method eliminated the need
for spread factor if the density of the spray liquid and the collecting liquid were close and rather large populations of droplets were to be sampled in a small area. It had a disadvantage that it was sensitive to contamination by dust and particles from other sources and it was restricted to sampling on a horizontal surface. It can only be used for study of sprays from relatively heavy liquids, since the spray liquid must be heavier than the collection liquid in a cell.

Joyce (1946) showed that freezing spray drops immediately after formation in a cold chamber would permit them to be sized with sieving equipment just as any other dry particulate material. This quickly provided weight distribution measurements. This method has been widely used by European workers studying petroleum fuel atomization. Hasson and Mizrahi (1961) have shown that there are circumstances when the frozen drops may introduce errors into the measurements. They attributed this error to recombination of a certain fraction of spray very close to the nozzle tip, which eliminates some fine spray and produces larger drops. If the drops are frozen before this natural recombination occurs, the measurement which results is not representative of that which occurs under normal circumstances.

C. Factors Affecting Droplet Size

Because the formation and use of liquid spray is involved in a number of industrial and chemical processes, an appreciable body of previous research exists describing various spray phenomena. The mechanism of spray formation and factors affecting the resultant droplet size have
received considerable attention. The desire to improve the efficiency of fuel burning devices and internal combustion engines stimulated interest in the atomization of hydrocarbon fuels, first with conventional Otto cycle engines, later in diesel engines and more recently in gas turbines and jet engines.

The spray nozzles used for hydrocarbon fuels are not very similar to those which are used for agricultural pesticides today. However, since such an extensive literature exists describing nozzles used for hydrocarbon fuel, a brief and abridged review of previous research may be of interest.

Among the earliest studies was that done by Scheubel (1927), who investigated the atomization occurring in carburetors. Scheubel took high speed photographs of water and alcohol being atomized and made droplet size measurements from these photographs. He then correlated the mean droplet size from these measurements with the surface tension, density, and viscosity of the liquid being atomized, and with the velocity of the air. Later, Ohnesorge (1936) studied the formation of spray from a simple jet. He determined that the breakup of the jet into spray passes successively through three different phases. He determined that the criteria for transition from one phase to the next was a function of a dimensionless term, which he denoted by \( Z = \frac{\mu}{\frac{1}{2} \sigma \varrho \, d} \), where \( \mu \) is the viscosity, \( \sigma \) is the surface tension, \( \varrho \) is the density, and \( d \) is the orifice diameter. Later we will show that this term is a simple product of the more conventional Reynolds number and Weber number.

Longwell (1943) conducted a rather extensive study of drop size
distribution from swirl chamber nozzles used for oil burners. The experiment was of a classical design and empirical correlations were obtained between mean drop size, cone angle, pressures over a ten-fold range, orifice diameters over a three-fold range, and viscosities over a ten-fold range.

Turner and Moulton (1953) studied the drop size distribution from two types of hollow cone spray nozzle spraying molten betanaphthol and molten benzoic acid. An appreciable range of surface tension and viscosity was thus obtained. Orifice diameters from 0.7 mm to 2.0 mm were used, with pressures from 2.2 to 9.0 kg/cm$^2$. Drop size statistics presented were the geometric mean and geometric standard deviation. Experimental results were presented in tabular form only, with no attempt to prepare a generalized equation.

Tate and Marshall (1953) studied the spray distribution, drop size distribution and capacity of centrifugal pressure nozzles over a range of pressures, orifice diameters, and spray cone angles. Mean drop size, the drop size uniformity, and the cone angle were correlated empirically with a tangential and axial velocity of the liquid as well as the orifice diameter. No comprehensive equation for prediction of drop size was given. Individual formulas and charts were presented on the effect of tangential velocity, axial velocity, viscosity, and orifice size on the mean droplet diameter. They also made limited observations on the uniformity of the drop size distribution.

Nelson and Stevens (1961) also studied the size distribution droplets from centrifugal nozzles spraying a wide variety of liquids. The drop
size was related to the liquid and nozzle diameter parameters by a plot of \( \frac{D}{d} \) against \( \frac{W}{R} \left( \tan \frac{\beta}{2} \right)^{1.2} \), where \( W = \frac{v^2 \rho}{\sigma} = \text{Weber number} \), \( R = \frac{v \rho}{\mu} = \text{Reynolds number} \), and \( \beta = \text{spray cone angle} \). They found that water spray values did not plot with data from other liquids but required a separate relationship. Nelson and Stevens also computed the standard deviation of drop sizes resulting from their experiments. By trial and error plotting of the data they found that the standard deviation of the square root transformed data, \( s_{sr} \), could be related to fluid properties and operating conditions by a plot of the variable \( s_{sr} \frac{W}{d^{1/2}} \) against \( W R^{1/2} \). They also studied the effect of spray angle, \( \theta \), and found that it was negligible.

At first glance it would seem that the work on drop size distribution from hollow cone spray nozzles might be used to predict similar relationships for the flat fan spray nozzles more commonly used in agricultural work. A hollow cone nozzle spreads the liquid into a sheet of decreasing thickness in the same manner as the fan on a fan spray nozzle, and this rate of spreading by a fan spray nozzle of angle \( \theta \) would be equal to a conical spray nozzle of angle \( \beta \) by the relationship \( \theta = 2 \pi \beta \). However, while the flow exterior to the nozzle has some similarity, as has just been mentioned, the flow inside the nozzle is considerably different, with the result that even simple phenomena, such as discharge, cannot be predicted with similar equations for hollow cone nozzles and fan spray nozzles. This is due in large part to the presence of the air core in the hollow cone nozzle, and the tangential entrance of the liquid into the nozzle. It has been shown that all liquid leaving hollow cone
nozzles must flow through a boundary layer which extends from the back of the nozzle to the orifice. As a result, there is an appreciable range in which an increase in viscosity causes an increase in the discharge coefficient of a hollow cone nozzle, because of the thickening of the boundary layer and consequent decrease in the size of the air core.

Less work has been done on the flat fan nozzle used in agriculture. Dorman (1952) measured the drop size produced by flat fan nozzles over a range of orifice diameters and pressures using kerosene and water. He estimated mean drop size by measuring the size of the largest drop and assuming a constant ratio between the maximum drop size and a mean drop size. He related mean drop size to operating conditions in fluid properties by means of a simplified dimensional analysis which yielded the relationship

\[ D_{\text{saut}} = 4.4 \left( \frac{Q}{\theta} \right)^{1/3} \sigma^{1/3} \rho^{1/6} \rho^{1/2} \] (10)

in consistent units, where the coefficient 4.4 was obtained experimentally.

Fraser and Eisenklam (1956) published a survey of much previous research on liquid atomization. In this publication they also included previous unpublished data and empirical correlations on the relationship of droplet size to fluid properties and operating conditions. Two expressions were presented which were claimed to have good agreement with experimental data. These were:

\[ D_{\text{saut}} = 160 \left( \frac{\sigma}{p} \right)^{0.25} \left( \frac{\varphi}{\theta} \right)^{0.37} \rho^{0.065} k_Q^{0.98} \]
and

\[ \log_{10} D_{\text{saut}} = 1.823 + \frac{4.42}{p} + 0.0203 F \]

where \( F \) = the flow number (imperial gallons per hour divided by the square root of pressure, \( \text{lb/in.}^2 \)), \( K_Q \) = the discharge coefficient of the nozzle, \( \sigma \) = surface tension, dynes/cm, \( \theta \) = spray angle in radians, \( p \) = pressure, \( \text{lb/in.}^2 \), and \( \rho \) = liquid density, gm/cm\(^3\).

Fraser et al. (1957) measured drop size of hydrocarbon fuel spray produced by flat fan nozzles. From these data Fraser et al. proposed an empirical equation for predicting the Sauter mean diameter:

\[ D_{\text{saut}} = 181 \left( \frac{F \, \sigma \, \theta \rho}{\theta p} \right)^{1/3} \]  

(11)

Meyer (1965) measured the droplet size distribution from large flat fan spray nozzles, having equivalent orifice diameters of about 5 to 6 mm, operating at 0.3 to 0.4 kg/cm\(^2\) pressure. No functional relationship between droplet size and operating conditions was attempted, but the results of measurements were tabulated.

Hedden (1961) conducted a series of measurements of drop size from a flat fan spray nozzle at pressures ranging from 1.4 to 18 kg/cm\(^2\). For a particular spray nozzle he found a good fit of experimental data with the following relationship:

\[ D_{\text{MM}} = a - b \log p \]

where \( D_{\text{MM}} \) = mass median diameter and \( a \) and \( b \) are empirical constants. Hedden did not present the statistics on the uniformity of this spray but
did present tabular illustrations of the range of droplet sizes produced by spray nozzles, and emphasized the great difference between the arithmetic mean and the mass median diameter for the samples which he took.

Tate and Janasen (1966) measured the drop size distribution from a number of types of agricultural spray nozzles, including the flat fan spray type. The mass median diameter of the spray was tabulated for spray nozzles of different capacities operating at differing pressures, predominantly at 2.8 kg/cm². No generalized prediction for drop size was attempted, although the results of the tests were compared with Hedden's data and Fraser's equation. No data on the uniformity of the droplet size were presented.
IV. EXPERIMENTAL PROCEDURE

The previous research studies on drop size distribution from flat fan spray nozzles have one or more of the following shortcomings:

1. The work was conducted with oil base materials. Because Nelson and Stevens (1961) showed that water appeared to perform differently than sprays from all other liquids, it may be unsafe to extrapolate data collected from oil base materials to water sprays, which are predominantly used in agriculture.

2. The relationship between drop size distribution and liquid properties and operating conditions was not formulated in dimensionless terms.

3. Data on the uniformity of the drop size distribution are not presented.

4. Experiments were not conducted over a wide range of operating conditions, e.g., nozzle size and liquid pressure.

The general plan for the experimental work to be conducted in this study, then, was to conduct experiments and collect data in such a way that the deficiencies of previous research were avoided. That is:

1. A wide range, ten-fold or greater, of operating conditions would be covered, including pressure, nozzle capacity, and fan spray angle.

2. A description of the results would be formulated in dimensionless terms, to permit maximum generalization from the data.

3. The experiments would be conducted with water and water base materials.
4. Sufficient data would be collected that the variability of the drop size distribution could be measured, and statistics on dispersion could be computed.

To conduct such experiments, a series of liquids, consisting of various mixtures of water and glycerol, were sprayed from a number of specimens of flat fan spray nozzles obtained from commercial manufacturers. The spray produced was sampled in such a way that counting and sizing of the droplets could be performed on automatic sizing and counting equipment. A wide variety of statistics were computed from these data and compared for their value in characterizing the drop size distribution.

A. Dimensional Analysis

The previous studies by Dorman (1952) and Fraser and Eisenklam (1956) with flat fan nozzles indicated that the surface tension was the fluid property which most strongly affected the spray formation process, and consequently, the resulting droplet size. Both studies, however, also indicated that the density of the spray fluid may have some effect. Neither of these studies seem to indicate the viscosity of the fluid affected the mean droplet size, at least over the range of viscosities which were studied. However, in work with centrifugal nozzles, Nelson and Stevens (1961) found the fluid viscosity affected the mean drop size. Furthermore, much recent agricultural work, such as that by Kirch et al. (1958) has implied that greater uniformity of spray droplet size should be achieved by increasing the viscosity of the spray fluid used. Consequently, it seems reasonable to include the fluid viscosity as a variable which
may affect drop size distribution in some manner.

The only operating condition for a flat fan spray nozzle which one can readily change is the pressure. Although Dorman (1952) used the discharge rate of the nozzle as the operating variable, he also included the pressure. Because the discharge rate is affected by both the orifice area and the pressure, this does not logically seem to be an independent variable. In this work we will consider the pressure as the principal operating variable.

The capacity of spray nozzles is varied by changing the orifice area. As a first approximation, at least, if fluid properties and pressures are equal, orifices of equal cross-sectional area will have equal discharge.

To form a flat fan spray, such nozzles often use a conical converging fluid flow, emerging into the surrounding atmosphere through a more or less elliptically shaped orifice. The exact manner in which this orifice is generated to provide a desired angle of spray while maintaining uniformity of flow across the fan is a proprietary art. Approximately, the orifice is generated by the intersection of a simple wedge with a right cone. The boundary of the resulting orifice is described by two inclined elliptical arcs. Proprietary art is involved in modification of the wedge to have a somewhat hyperbolic section and/or modifications of the cone to resemble a paraboloid of revolution or hyperboloid of revolution. Figure 1 shows specimens of such nozzles.

It can be seen from Figure 2 that a series of orifices of differing size can be generated by the intersection of the cone and wedge, depending upon the depth of intersection. However, for orifices of equal area,
Figure 1. Specimens of typical commercial flat fan nozzles, manufactured by Delavan Manufacturing Co., West Des Moines, Iowa (left), and Spraying Systems Co., Bellwood, Illinois (right)
Figure 2. Typical generation of orifice for fan spray nozzle
spray of different fan angle may be generated by varying both the wedge angle and the cone angle. Both the wedge angle and cone angle, as well as departures from the wedge and cone shape, are part of the proprietary art. For the purpose of this investigation it was decided to use nominal spray angle as the spray nozzle variable which described the divergence of flow of the spray nozzle, combining the effect of the more basic nozzle parameters of generating wedge angle and cone angle. The nominal spray angle is defined as the angle of spray produced by a spray nozzle at 40 pounds per square inch. The actual spray angle may vary with the pressure, so is not actually a nozzle design parameter.

Consequently, in this study we will assume that the design of a flat fan spray nozzle is adequately represented by two parameters, the projected area of the orifice, and the nominal spray angle.

At any particular operating condition, a spray nozzle will produce a certain continuous distribution of droplet sizes. In this study, we will characterize this distribution by two statistics; that is, we will characterize the distribution by a statistic measuring central tendency, a mean, and a statistic measuring dispersion, a standard deviation. Many forms of these statistics have appeared in prior literature. Our examination of this literature has not led us to any overwhelming evidence that one form is superior to the others which have also been used. Therefore, in this study the arithmetic mean, $D_n$, the volume mean diameter, $D_{VME}$, the volume distribution mean diameter, $D_{VH}$, the geometric mean of the number distribution, $D_{gN}$, and the geometric mean of the volume distribution, $D_{gV}$, will all be computed from the data.
Although it will not be used in the formulation of hypothesis, the Sauter mean diameter will also be computed for all distributions measured so that the data can be compared with the results of other workers who have used it.

As a measure of dispersion, the standard deviation of the droplet distribution will be computed:

\[ s_N = \left[ \frac{\sum n_i (D_i - D_N)^2}{\sum n_i} \right]^{1/2} \]  \hspace{1cm} (12)

The standard deviation of the volume distribution will also be computed, defined as:

\[ s_{VH} = \left[ \frac{\sum n_i D_i^3 (D_i - D_{VH})^2}{\sum n_i D_i^3} \right]^{1/2} \]  \hspace{1cm} (13)

The geometric standard deviation will also be computed, defined as:

\[ s_{gN} = \left[ \frac{\sum n_i (\ln D_i - \ln D_{gN})^2}{\sum n_i} \right]^{1/2} \]  \hspace{1cm} (14)

The geometric standard deviation of the volume distribution will be computed, defined as:

\[ s_{gV} = \left[ \frac{\sum n_i D_i^3 (\ln D_i - \ln D_{gV})^2}{\sum n_i D_i^3} \right]^{1/2} \]  \hspace{1cm} (15)

The common fitting of the logarithmic normal distribution to spray
data implies that the dispersion of the drop size distribution may be proportional to the mean of the distribution. In order to compare the relative uniformity of coarse and fine sprays, the coefficient of variation will be computed as the measure of the relative uniformity of all sprays. This will be done for both the number distribution and the volume distribution of the spray. The coefficient of variation is a dimensionless variable. The geometric standard deviations are also dimensionless variables, and have been shown by Aitchison and Brown (1957) to be related to the coefficient of variation.

The previous literature and the above discussion lead to the following hypothesis:

**HYPOTHESIS:** If the resulting drop diameter distribution from a flat fan spray nozzle is characterized by a mean diameter, $\overline{D}$, which may stand for $D_n$, $D_{VH}$, $D_{ME}$, $D_{gN}$, or $D_{gV}$, and a coefficient of variation, $c$, which may stand for $s_n/D_n$, $s_{VH}/D_{VH}$, $s_{gN}$, or $s_{gV}$, then

$$\overline{D} = F(p, \rho, \sigma, \mu, A, \theta)$$  \hspace{1cm} (16)

and

$$c = G(p, \rho, \sigma, \mu, A, \theta)$$  \hspace{1cm} (17)

These relationships can be formulated in dimensionless terms by accepted procedures. Generally, this would yield

$$\Pi_1 = f(\Pi_2, \Pi_3, \Pi_4)$$  \hspace{1cm} (18)

$$\Pi_1' = g(\Pi_2, \Pi_3, \Pi_4)$$  \hspace{1cm} (19)
where \( \Pi_1 = \frac{D}{A^{1/2}} \), \( \Pi_2 = c \), \( \Pi_2 = A^{1/2} p/\sigma \), \( \Pi_3 = A^{1/2} p^{1/2} \rho^{1/2}/\mu \), and \( \Pi_4 = \theta \).

Substitution of these terms would yield

\[
\frac{D}{A^{1/2}} = f \left( A^{1/2} \frac{p}{\sigma}, A^{1/2} \frac{p^{1/2} \rho^{1/2}}{\mu}, \theta \right) \tag{18a}
\]

\[
c = g \left( A^{1/2} \frac{p}{\sigma}, A^{1/2} \frac{p^{1/2} \rho^{1/2}}{\mu}, \theta \right) \tag{19a}
\]

Relationships of other dimensionless terms might be used instead.

Any such dimensionless terms would be, in turn, products of the terms listed above. Our choice of the products used is justified only by the long usage and the prior literature on fluid mechanics, the expression \( A^{1/2} p/\sigma \) being related to the Weber number, and the expression \( A^{1/2} p^{1/2} \rho^{1/2}/\mu \) being related to the Reynolds number.

The work of many previous workers can be cast in the form shown above by appropriate algebraic manipulation in order to compare data. For example, Dorman (1952) showed that his data yielded:

\[
D_{\text{saut}} = 4.4 (Q/\theta)^{1/3} \sigma^{1/3} p^{1/6} \rho^{-1/2}
\]

For flow through a nozzle we know that

\[
Q = K_f A \left( 2p/\rho \right)^{1/2}
\]

Where \( K_f \) is the flow coefficient for the nozzle under the given operating conditions. Thus, rewriting

\[
D_{\text{saut}} = 4.4 \left[ Q^2 \theta^{-2} \sigma^2 p \rho^{-3} \right]^{1/6}
\]

substituting
\[ D_{\text{saut}} = 4.4 K_f^{1/3} 2^{1/6} \left[ A^2 \theta^{-2} \sigma^2 \rho^{-2} \right]^{1/6} \]
dividing by \( A^{1/2} \)

\[ \frac{D_{\text{saut}}}{A^{1/2}} = 4.95 K_f^{1/3} \left( \frac{A^{1/2} \rho}{\sigma} \right)^{-1/3} \theta^{-1/3} \]  
(20)

which is a functional relationship of the form derived by dimensional analysis above.

No such manipulation would be possible on either of the equations presented by Fraser and Eisenklam (1956), as they are both dimensionally inconsistent. Similar arrangement of the equation from Fraser et al. (1957) (Equation 11) yields

\[ \frac{D_{\text{saut}}}{A^{1/2}} = 2.5 K_f^{1/3} \left( \frac{A^{1/2} \rho}{\sigma} \right)^{-1/3} \theta^{-1/3} \]  
(21)

No explanation can be given for the obvious discrepancy between this and the result from rearrangement of Dorman's equation (Equation 20).

B. Experimental Design

Where several independent dimensionless terms exist and the experiments are done in the classical way, with tests performed at several levels of each dimensioned variable, the results usually do not yield values of dimensionless variables at distinct levels. Consequently, it is difficult to fit any type of prediction equation to the results other than a simple straight line regression equation.

Experiments could be designed in the space defined by the independent dimensionless variables, and derive from this design the values required
for dimensioned variables to satisfy the experimental design. Such an approach was used in this study.

It was recognized that the hypothesis constitutes a response surface of the dependent dimensionless term \( \Pi_1 = \frac{D}{A^{1/2}} \) as a function of the independent dimensionless terms \( \Pi_2 = \frac{p A^{1/2}}{\sigma}, \Pi_3 = \frac{p A^{1/2}}{\rho \mu}, \text{and} \ Pi_4 = \theta \).

To enable us more carefully to fit a functional relationship to the experimental data to be obtained, it would be convenient if experiments were conducted in such a way that the resulting independent dimensionless variables formed an orthogonal array, preferably incremented in some consistent fashion, as illustrated in Figure 3.

The first step was to explore how a plane defined by the variables \( p \) and \( A \), when \( \sigma, \mu, \text{and} \ \rho \) were held constant by using a single liquid, mapped onto the plane defined by \( \Pi_2 \) and \( \Pi_3 \). Figure 4 shows the locus experimental conditions of a series of tests conducted with a nozzle of fixed orifice but varying pressure. Figure 5 shows the locus of points described with a constant pressure but varying orifice size. Figure 6 shows the result of a classical experiment where both orifice size and pressure were varied systematically using a single fluid.

Several things become evident from inspection of this mapping. First, a considerable area of the plane can be covered with a single fluid by varying the nozzle size and pressure. It is still limited, however, as the range of practical pressure is restricted from approximately 0.5 kg/cm\(^2\) to about 15 kg/cm\(^2\) and the range of practical nozzle sizes is 0.1 mm\(^2\) to about 1 mm\(^2\).
Figure 3. Diagram of ideal response surface and orthogonal array of experimental conditions for dimensionless variables.
Figure 4. Locus of tests with single liquid and orifice size

\[ \Pi_3 = \left( \frac{A}{D} \frac{p}{ho} \right)^{1/2} \]

\[ \Pi_2 = \frac{A^{1/2} p}{\sigma} \]

1 dyne/cm pressure

Figure 5. Locus of tests with single liquid and constant pressure

\[ \Pi_3 = \left( \frac{A}{D} \frac{p}{ho} \right)^{1/2} \]

\[ \Pi_2 = \frac{A^{1/2} p}{\sigma} \]

.1 mm² orifice area

.31
Secondly, even in this relatively simple experiment some orthogonal comparisons exist. That is, a curve in Figure 6 through F-G compares varying $\Pi_3$ at constant $\Pi_2$. So does a curve through C-D or I-J. Similarly, a curve through C-E-G or F-H-J compares the effect of varying $\Pi_2$ at constant $\Pi_3$.

Furthermore, if a liquid were available having the same surface tension but 1.78 greater viscosity, the immediately adjoining area in the $\Pi_2-\Pi_3$ plane could be covered by a similar series of experiments, as shown in Figure 7. The restriction of equal surface tension is not strictly necessary. By adjusting the sizes of nozzles and operating pressures, a series of experiments could be performed extending over a wider range of $\Pi_3$ while still maintaining constant $\Pi_2$ and also extending over a wider range of $\Pi_2$ at constant $\Pi_3$. If it were possible to conduct the same series of tests with additional liquids having progressively greater viscosity, correct choice of pressure and nozzle size could result in a considerable extension of tests at either constant $\Pi_2$ or constant $\Pi_3$.

Such experiments could be conducted most conveniently with mixtures of two liquids having surface tension and density values which are not greatly different. Water and glycerol have such properties, and as a consequence, mixtures of these liquids can be prepared which have widely varying viscosity with relatively little variation in density and surface tension. Since water exhibits a relatively small change of surface tension and density with changes of temperature, while the viscosity changes considerably, tests could be extended to higher values of $\Pi_3$ by conducting tests with heated water.
Figure 6. Locus of dimensionless independent variables in a classical experiment

Figure 7. Result of repeating experiment with liquid having greater viscosity and equal surface tension
Based upon this general line of reasoning, the following basic experimental design was developed. Specimens of commercial flat fan spray nozzles were flow rated and specimens selectively chosen such that specimens were available which had orifice areas in the ratios $1, \sqrt{10}$, and 10. These nozzles were operated with water heated to two different temperatures, plus various mixtures of water and glycerol at $20^\circ C$ such that viscosities of the liquids used were logarithmically equal spaced in ratios of 1.78 which requires four different fluids to cover a ten-fold range of viscosities. The experiments are shown on the $\Pi_2-\Pi_3$ plane on Figure 8. The points at tests number 9, 16, 40, 47, 54, and 15 encompass the conditions under which the bulk of agricultural spray operations is now conducted. To gain a better understanding of the effect of surface tension and viscosity, tests were extended in a more or less orthogonal fashion, but over wider increments of $\Pi_2$ and $\Pi_3$, to the area encompassed by experiments number 3, 2, 1, 51, 34, 48, 65, 66, 64, 49, 61, 33, 14 and 68.

To compare the results of experiments with different liquids conducted at identical conditions of $\Pi_2$ and $\Pi_3$, experiments 15, 16, 19, were performed for comparison with tests number 30, 21, and 20, as shown in Figure 9.

To obtain an estimate of the variance in measurements of drop size distribution, experiments 17 and 18 were performed as replicates of experiment 16 and experiments 22 and 23 were performed as replicates of experiment 21.

All of the tests described above in the basic experimental design
Figure 8. Locus of dimensionless independent variables in basic experimental design
Figure 9. Tests conducted having identical condition of dimensionless independent variables but using liquids with different properties

Figure 10. Locus of tests conducted with different nominal spray angle nozzles
were conducted with nozzles having a spray angle of approximately 65°. In order to test the effect of spray angle, the additional series of tests number 9, 11, 4, 6, 27, 28, 57, 58, 59, and 60 were conducted with nozzles having a nominal angle of 40° and 80°. Additional tests number 26 and 29 were conducted with nozzles having nominal spray angles of 15° and 110°. These test conditions are shown on a $\Pi_2-\Pi_3$ plot in Figure 10.

The conditions describing all planned experiments are shown in Table 1.

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<th>Nozzle used</th>
<th>Pressure used lb/in.²</th>
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<th>Nozzle used</th>
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<td>Surface tension dyne/cm</td>
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</table>
C. Control and Measurement of Variables

The size of nozzle orifices was controlled by measuring the flow rate of a number of commercial spray nozzles at 40 lbs per sq in., the pressure at which manufacturers frequently specify the discharge to be equal to the nominal rating. From the collection of nozzles which were measured in this way, specimens were chosen which showed, as closely as possible, flow rates in the ratio of $1, \sqrt{10}$, and 10. Three closely matched specimens were chosen of both the largest and the smallest nozzle sizes.

Nominal spray angles were measured by photographing the spray fan when operating at 40 lbs per sq in., and measuring the flow in degrees with a protractor from the photograph. This angle was then converted to radians. Measurement of the spray angle was somewhat subjective, and may have been subject to as much as two degrees of error.

The pressure in the fluid was measured 0.3 cm behind the spray orifice with a commercial bourdon tube pressure gage. The two lower pressures were measured with a 0 - 30 lbs/in.$^2$ gage of $\pm 2$ percent accuracy. This gage was checked against a 0 - 60 lb/in.$^2$, $\pm 1$ percent accuracy gage, and found to be accurate within the limits of reading precision at the two pressures used. The two higher pressures were measured on 0 - 150 lb/in.$^2$, 5 percent accuracy, and 0 - 300 lbs/in.$^2$, $\pm 5$ percent accuracy gages. No calibration source was available for these two gages, and they were used uncalibrated.

The viscosities of all liquid spray were measured with Ostwald-Fenske viscometers, a capillary tube type viscometer which measures the time for a metered amount of liquid to flow through a capillary tube under gravity.
The viscometers were purchased uncalibrated and were calibrated using distilled water at 20°C. The glycerine solutions were prepared by estimating the proportion of glycerine required to produce the desired viscosity from tabulated values of viscosity for aqueous glycerol solutions given in Handbook of Chemistry and Physics (1959). Three measurements of the viscosity were then made with the Ostwald-Fenske apparatus, and additional water or glycerol was added to bring the viscosity closer to the value desired. After additional mixing, the viscosity was again measured, and the process repeated until the viscosity measured was within three decimal place accuracy of the value desired. The tests were conducted in air-conditioned rooms maintained at 20°C. The temperature of the spray liquid was also measured immediately before pouring it into the spray tank of the experimental apparatus. The control of the temperature of heated water used in several of the experiments was maintained by heating it to approximately 5°C higher than the temperature desired for the test, pouring the liquid into the spray tank, applying a small amount of pressure, and then closing the outlet valve to fill the piping with hot water. Water was then left in the apparatus to heat the spray tank and piping. The hot water was then run out of the spray tank through the nozzle piping with the nozzle removed, reheated quickly to 5° above the desired temperature again, and poured into the spray tank and the piping line filled as before. After the water had remained in the tank for several minutes it was run out through the nozzle piping with the nozzle removed and the temperature of the liquid measured. This process was repeated until the temperature of the liquid leaving the spray piping was
exactly the temperature desired. At that point, the liquid was re-heated to one degree above the desired temperature, poured into the tank, and the experiment run immediately. The spray tank was insulated with two inches of fiberglass batt insulation, and the piping leading to the spray nozzle was insulated with one inch of fiberglass wraps. No temperature control system was used in the spray tank and the piping to the nozzle. Thus the temperature at the nozzle could have varied $\pm 1^\circ C$.

The surface tension of the liquid was measured with a double bubble surface tensiometer calibrated with reagent grade benzene. Accuracy of this equipment is affected somewhat by the care with which the airflow is adjusted. For this reason it may not be as accurate as the ring type method for pure liquids. However, since it measures the surface tension on new rapidly forming surface, it is less affected by surface active agents, and therefore more representative of the surface tension acting during the spray formation process. For this reason, perhaps, the surface tension measurements shown for the spray liquid, which contains a 2 percent solution of nigrosine dye, is higher than reported by other workers using dyed water, as, for example, Rupe (1949). The density of the spray liquid was not measured, as precision equipment for this purpose was not available. Values used were taken from tabulated data in the Handbook of Chemistry and Physics (1959).

To measure the area of nozzle orifices, the orifices were photographed at 2X magnification on fine grain film, and the resulting negatives were enlarged to approximately 20X. The area of the orifice image on the print was then measured with a planimeter, and the exact magnification of the
photographic print was measured by comparison with microscopic measurement of the orifice diameter.

D. Collection of Spray Samples

Spray formed by the nozzles was collected using a procedure similar to that described by Rupe (1949). Flat bottom petri dishes were coated on the inner bottom and sides to make the glass surface hydrophobic. This prevents collected spray drops from spreading on the surface. The interior of two dishes was wiped with a small cotton swab wetted with dimethyldichlorosilane, two drops of water were placed in one of the dishes and the other dish placed face to face with it, and taped together with vapor proof plastic adhesive tape. The interiors of the dishes were then exposed by this method, to the vapor of dimethyldichlorosilane and water for approximately 48 hours, after which the tape seal was removed, and the dishes rinsed with water, methanol, and again with water. This is an adaptation of a procedure suggested by Howard and Martin (1950) to confer hydrophobic properties on diatomaceous earth column support materials used for gas chromatography. Glass surfaces treated in this way were found to be more consistently hydrophobic than when treated by other methods which have been proposed, such as with the solutions of silicone resins (Tate and Marshall, 1953). The hydrophobic surface thus formed was stable and not easily damaged, except by high pH detergents.

The dishes were filled to a depth of 3 - 4 mm with Stoddard solvent, a commercial naptha. Five such dishes were placed in a symmetric linear array directly under the spray nozzle and centered in the spray deposit pattern. The 15°, 40°, 65°, and 80° fan angle nozzles were located 50 cm
above the dishes. The 110° fan angle nozzle was located 30 cm above the dishes. The dishes were separated from the spray nozzle by a continuous movable rubber membrane containing a 2 cm wide slot perpendicular to the direction of travel of the membrane. Movement of the membrane thus acted as a shutter to permit a portion of the spray to fall into the dishes. The shutter was moved by hand, by pulling it with a small cord. An attempt was made, when operating the shutter, to move it at a speed proportional to the discharge rate of the nozzle. This was approximately 0.5 ft/sec for small nozzles increasing to approximately 2 ft/sec for the large nozzles. This range of speeds, however, was still not sufficient to provide a uniform deposit of spray, as some samples had to be discarded because of too heavy deposits. Figure 11 shows one dish in position under the shutter. The nozzle to be tested is also visible in the photograph.

To insure that the sample of spray was taken from the center of the pattern, prior to each experiment a sheet of white paper was laid over the shutter and the nozzle operated momentarily to observe the location of the pattern over the shutter.

After many experiments had been conducted with this apparatus, it was observed that the small water droplets were shrinking in size rather quickly after their collection in the naptha. Figure 12 shows the size of spray droplets collected in 20°C Stoddard solvent as a function of time elapsed after collection. This phenomena, although discussed by Fraser and Eisenklam (1956), does not appear to have been discussed by other workers who have used the Rupe cell. This decrease in size is attributed to the small, but sufficient, solubility of the water in naptha. Because
Table 2. Nozzles used for experiments

<table>
<thead>
<tr>
<th>Specimen designation</th>
<th>Working designation</th>
<th>Nominal fan angle</th>
<th>Projected orifice area $mm^2$</th>
<th>Discharge of water at 40 psi ml/sec</th>
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<tr>
<td>B</td>
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<td>J</td>
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Table 3. Liquids used for experiments

<table>
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<tr>
<th>Liquid designation</th>
<th>Material used</th>
<th>Viscosity</th>
<th>Surface tension</th>
<th>Density $\text{gm/cm}^3$</th>
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<td>B</td>
<td>98% water, 2% nigrosine at 48°C</td>
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<td>0.9889</td>
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<td>C</td>
<td>98% water, 2% nigrosine at 20°C</td>
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<td>D</td>
<td>98% water, 2% nigrosine at 4°C</td>
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<td>0.9999</td>
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<td>E</td>
<td>23.8% glycerol, 74.8% water, 2% nigrosine at 20°C</td>
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<td>72</td>
<td>1.0566</td>
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<tr>
<td>F</td>
<td>40.0% glycerol, 58.0% water, 2% nigrosine at 20°C</td>
<td>0.0316</td>
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<td>1.0995</td>
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<tr>
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<td>55.5% glycerol, 42.5% water, 2% nigrosine at 20°C</td>
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<td>1.1715</td>
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it was felt that this phenomena would introduce a bias into the measurement technique, a search was made for liquids which have appreciably less solubility for water than naptha. A number of liquids were investigated, including silicone oils, but none were found.

Presaturation of the naptha with water prior to its use in the Rupe cell was found to have no practical effect in reducing the rate of spray
Figure 11. Interior of spray collection chamber. Shroud in front of dishes is pushed up to show position of dishes under the shutter.
Figure 12. Effect of spray dissolution on apparent droplet size
dissolution. Apparently, the surface energy of the spray droplets was so great that water still dissolved in the naptha. The next procedure investigated was to lower the temperature of the naptha. This caused as much as a five-fold reduction in the rate of spray dissolution. If the naptha were chilled below the dewpoint of the surrounding air, atmospheric moisture would condense on the surface of the liquid, causing a haze on the surface which interfered with subsequent photography. This water haze also frequently coalesced to form large, undyed water drops, which would sink to the bottom of the cell to be photographed with the dyed spray. The undyed drops frequently resulted in a ring-shaped image when photographed, and when counted with the automatic scanning equipment caused erroneous measurements to be made.

The procedure which was finally followed was to conduct tests when the absolute humidity of the air was low, and chill the naptha to a few degrees above the dewpoint. In this way, the length of time available for photography of the sample was increased approximately four-fold.

The spray nozzles, shutter, and collection apparatus were enclosed in a tight chamber to control the environment surrounding spray. The chamber contains a plenum at the top into which air is carried by a small centrifugal blower. The partition between the plenum and the rest of the chamber is perforated to serve as a diffuser for the air, which moves vertically downward and leaves by a pipe at the center of the bottom. This pipe in turn leads to a vertical pipe, the top of which leads to a filter box and the bottom of which contains a 3 mm hole to permit liquid spray to drain from the pipe. A diagram of the
chamber is shown in Figure 13, and a photograph is shown in Figure 14. The vertical velocity of the air in the chamber is approximately 1 ft/sec; this was maintained during the test to prevent accumulation of fine spray in the chamber, which would then result in a bias in the sampling of the spray.

E. Measurement of Spray Samples

After the dishes were exposed to the spray, the spray was turned off and the droplets allowed to settle to the bottom of the dish for about 15 seconds. The dish was then transferred to a flat stone block, which was suspended by three ribbons extending approximately 20 cm above it, as shown in Figure 15. The purpose of this block and its suspension, which constituted a pendulum, were to permit the dishes to be carried freely without the jiggling inherent in hand carrying of light objects. A typical sample is shown in Figure 16.

The dish was then transferred from the block to the light stand for photographing. Photographs of the spray samples were taken on 35 mm Kodalith Ortho No. 3 film. The camera used was a conventional single lens reflex 35 mm camera. A bellows was used to permit extension of the lens to permit a 2X magnification of the object on the film. The magnification was measured by focusing the camera on the scale of a vernier caliper. The size of the image at the film plane was measured on the ground glass using the dividers. The extension of the lens was then adjusted until an exact 2X magnification was achieved. The photographic apparatus used is shown in Figure 17.
Figure 13. Diagram of spray collection apparatus
Figure 14. General view of spray collection apparatus, showing, from left to right, the nitrogen supply, insulated spray liquid tank, spray chamber, and filter box for effluent air
Figure 15. Method of carrying spray collected in dish of naptha on a pendulum block

Figure 16. Typical sample of spray collected in dish of naptha
Figure 17. Apparatus used for photographing spray samples
The lens used was a 55 mm macro lens available from the camera manufacturer. A number of experiments were photographed at first using the general purpose lens provided with a camera mounted in a reverse position on Kodak high contrast high resolution film. When such films were scanned on the automatic counting equipment, however, it was found that the contrast and the resolution of this film was not sufficient to record droplets of 20 microns or smaller. These experiments were then repeated using the higher resolution film and lens.

The procedure suggested by Rupe (1949), and later used by Tate and Marshall (1953) involved filling the collecting cell (dish) to the brim with additional Stoddard solvent after the droplets had been collected, and covering the cell with an optically flat glass while being photographed. This procedure is time consuming, and the delay caused by filling the cell permits considerable dissolution of the water droplets into the solvent. To permit faster photography, the dishes were photographed uncovered, through the free liquid surface. Vibrations of the building caused small gravity waves to exist frequently on this surface, causing the image to move. The Kodalith Ortho No. 3 film has a low light sensitivity (ASA rating = 2.0) so that considerable light was required for adequate exposure of film. To prevent blurring of images by the surface waves, lighting was provided by two high intensity photographic strobe lights directed into a box painted with flat white paint. This lighting, in addition to being of high intensity and brief duration, also provides a very flat lighting when used in such a box, with resulting satisfactorily uniform illumination over the image.
Because dyed spray drops, even though they may appear to the eye to be quite dark, will transmit some light, photographs of very small spray drops may not register on high contrast film if overexposed. The lithographic type film used in this work has a very low latitude for exposure. As a result, it was found that exposure must be closely controlled to preserve drop registration and size on the films. Figures 18 and 19 show the effect of changes in several photographic variables on the resulting measurements obtained.

Similar care and control was necessary in the development of film. The film was developed in Kodalith Ortho developer for 2-1/2 minutes at 20°C. The temperature of the developer could not be permitted to vary more than ±0.5°C, nor could the development time vary more than 5 seconds without variations in the size of image recorded on the film.

Using one roll of film, five photographs were taken of each of the five sample dishes, or a total of 25 photographs for each experiment. Another photograph was taken of the experiment number and other experimental conditions on one frame of the film to provide a permanently attached record to prevent confusion of films. A diagram of the system for photographing the sample is shown in Figure 20.

An exception to this system was made for samples taken from experiments with 15° and 40° fan angle nozzles. In such cases, the sampling system was as shown in Figure 21 and 22, respectively.

The size of the droplet images on film were then counted in different size classes using a flying spot scanner. The general principles of operation of this scanner have been described by Mansberg (1964).
Figure 18. Effect of varying film exposure on droplet size measurements

Figure 19. Effect accuracy of focus on droplet size measurements
Figure 20. Sampling system on 65°, 80°, and 110° fan angle nozzles
Figure 21. Sampling system used on 10° fan angle nozzles
Figure 22. Sampling system used on 40° fan angle nozzles
general, this instrument can be set to count the number of circular images on film which are greater than 20k microns diameter, where \( k = 1, 2, 3 \ldots, 1,000 \). Because such a wide choice of size classifications was possible, it was necessary to choose a practical set of classifications for this study. Because of the general logarithmic normal distribution of spray, a set of size classifications was chosen which increased in increment as the classification size increased. The classifications chosen are listed in Table 4. As a 2X drop to film image magnification took place during photography, the spray droplet size classifications are equal to one-half of the classifications listed in Table 4. The

| Table 4. Upper limits of film image size classifications, microns |
|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 20                     | 140                    | 320                    | 640                    | 1280                   | 2560                   | 4960                   | 9840                   |
| 40                     | 160                    | 360                    | 720                    | 1440                   | 2880                   | 5520                   | 11040                  |
| 60                     | 180                    | 400                    | 800                    | 1600                   | 3200                   | 6080                   | 12160                  |
| 80                     | 200                    | 460                    | 920                    | 1840                   | 3600                   | 6720                   | 13440                  |
| 100                    | 240                    | 520                    | 1040                   | 2080                   | 4000                   | 7360                   | 14720                  |
| 120                    | 280                    | 580                    | 1160                   | 2320                   | 4480                   | 8000                   | 16000                  |

counts made with the flying spot scanner were punched onto machine tabulating cards by an on-line card punch while the counts were made, so that reduction of data could be made with automatic data processing equipment.

A computer program was then written which caused the computer to read the data recorded on these cards, sum the data from all photographs for
each experiment, and subtract counts in sequence to provide the number
distribution as a function of the size of classifications used. The
program further caused the computation of the statistics given in
Equation 2, 3, 5, 6, 7, 8, 12, 13, 14, and 15. The computer program for
these calculations is shown in Appendix A. Appendix B describes the
testing procedure used for this program. The program further printed
out the drop size distribution for each experiment and the statistics
computed for each experiment. The distribution data for each experiment
is shown in Appendix C. The resulting distribution data and statistics
were also punched onto tabulating cards suitable for further computation
or machine plotting.

F. Simplified Measurement Techniques

A further objective of our work was to develop a method for measuring
droplet size and variability which would circumvent the usual size
classification process used in most particle sizing operations. It was
believed that such a system might save time for future researchers
measuring droplet sizes and computing descriptive statistics.

The motivation for pursuing this objective results from the problem
faced by research workers involved in collecting low density droplet
samples which are counted and measured with flying spot scanner equipment.
Each photograph may show only a few droplets. If such samples are scanned
with flying spot scanning equipment, the length of time required to scan
each sample is fixed. To obtain accurate estimates of drop size statis-
tics, a certain minimum number of drops must be counted, which requires
many photographs to be scanned. This requires an excessive amount of time for counting and sizing of such samples on automatic counting equipment. This time could be greatly reduced if counts and calculations based upon size classifications were unnecessary.

One such approach is described by the following line of reasoning. Say that a sample of circles exists on the surface, having varying diameters, \( D \), having a frequency distribution, \( f(D) \). The first moment of the distribution about the origin \( D = 0 \) is defined as

\[
\mu^1 = \sum D f(D)
\]  

(22)

likewise the second moment is

\[
\mu^2 = \sum D^2 f(D)
\]  

(23)

By definition the mean of \( f(D) \) is \( \mu = \mu^1 \) and it can be shown that \( \mu^2 = \mu^2 + \sigma^2 \), where \( \sigma^2 \) is the variance of \( f(D) \).

From a sample of \( n \) circles, the sum of diameters, \( L \), is

\[
L = n \sum D f(D)
\]  

(24)

and the sum of the areas of the circles, \( A_s \), would be

\[
A_s = n \sum \left(D^2 \pi/4\right) f(D)
\]  

(25)

equating integrals yields the simplified mean, \( D_{the} \)

\[
D_{the} = \mu = L/n
\]  

(26)

and equating the other corresponding integrals yields
\[
\frac{4 A_s}{n \pi} = \mu^2 + \sigma^2 \tag{27}
\]

or

\[
\sigma^2 = \frac{4 A_s}{n \pi} - \frac{L^2}{n^2} \tag{28}
\]

and we will write

\[
s_{\text{the}} = \sigma = \left[ \frac{4 A_s}{n \pi} - \frac{L^2}{n^2} \right]^{1/2} \tag{29}
\]

We see from this that it may be possible to get a measure of the mean and variance of \( F(D) \) directly from measures of \( A_s, L, \) and \( n \), without measuring the drop distribution in discrete size classes, and that this can be done without any assumption, or knowledge, of the form of the size distribution, \( F(D) \).

Fortunately, estimates of \( A_s, L, \) and \( n \) can be obtained quickly from photographic films of drop samples using the flying spot particle counter. This can be seen by inspection of Figure 23, a schematic diagram of the mode of operation of the flying spot particle counter. As the cathode ray tube image scans the \( i \)th particle, it is evident that the sum of the diameters is approximately

\[
L = \sum_{i=1}^{n} D_i = \delta r n_{\text{ch}} \tag{30}
\]

and the sum of the areas is approximately

\[
A_s = \sum_{i=1}^{n} A(D_i) = \delta r \delta p n_p \tag{31}
\]
Figure 23. Schematic diagram of geometric relationship between raster lines, clock pulses, and droplet images on film being scanned in the flying spot particle counter.
where \( n_{ch} \) = total number of chords intercepted, \( n_p \) = total number of pulses in the intercepted chords, \( \delta_r \) = the spacing of the scan lines in the cathode ray tube raster, and \( \delta_p \) = the spacing, on the raster line, of the clock pulses used to measure chord length.

To determine if these relationships actually hold in practice, \( n_{ch} \) and \( n_p \) were measured for all samples of spray droplets taken in this study. A section of the computer program shown in Appendix A computed \( A_s \) and \( L \) using Equations 30 and 31, also computed the mean and variance of the sample using Equations 26 and 29.
V. RESULTS

The principal statistics computed from the measurements taken with the flying spot counter are tabulated in Appendix D and E. As indicated on the table, certain planned experiments could not be conducted because spray would not form under the conditions established for the experiment. Several other experiments were unproductive because the samples taken from the experiments contained too great a droplet population to be accurately counted with the flying spot counter. Some such experiments were repeated, yielding films of samples which were successfully counted. Finally, data are also included on several tests which are replicates of tests in the basic experimental plan.

These data were, in turn, used for computing various dimensionless ratios $\frac{D}{A^{1/2}}$, as well as the other independent dimensionless variables in Equation 18, using the computer program listed in Appendix F. In order to understand this program, it should be borne in mind that the data for operating conditions for each experiment were read in the units which were measured during the experiment. Thus, pressure was read in lb/in.$^2$, and nominal nozzle angle was measured in degrees, while the remaining operating variables were measured in standard gm-cm-sec metric units. The data from this program were intended to be used for computer plotting of results. The program used for plotting on the local computer would not accommodate logarithmic scales having values less than one.
Consequently, all values of $\overline{D}/A^{1/2}$ were multiplied by 1,000 during this computation.

A. Dispersion Statistics

The results of the experiments are presented in dimensionless form in Appendix H and I. This is the first point at which one is able to see some measures of the relative uniformity of droplet sizes. The coefficient of variation ranges from approximately 0.56 to 1.09, the volume weighted coefficient of variation ranges from 0.45 to 1.53, the geometric standard deviation ranges from 0.44 to 1.12, and the volume weighted geometric standard deviation ranges from 0.34 to 0.72. The relationship among these statistics, and their relationship to operating conditions is discussed later, but the general values are pointed out here, as they constitute a reference against which other spray devices, intended for the production of uniform spray, must be compared.

B. Effect of Design and Operating Variables

Values of $\overline{D}/A^{1/2}$ were plotted as functions of $p A^{1/2}/\sigma$ and $p^{1/2} \rho^{1/2} A^{1/2}/\mu$. An example of such a plot is shown in Figure 24. A distinct dependence upon $p A^{1/2}/\sigma$ is evident from this plot, but no clear dependence upon $p^{1/2} \rho^{1/2} A^{1/2}/\mu$ can be discerned, either by inspection or by regression analysis. However, further inspection of the data and the resulting graphs indicated that distinctly different results were obtained with the three different sizes of nozzles used for the
Figure 24. $D_n/A^{1/2}$ as a function of $p A^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $p^{1/2} A^{1/2} p^{1/2}/\mu$. 
experiments. Consequently $D/A^{1/2}$ was further plotted as a function of $p A^{1/2}/\sigma$ and the nozzle sizes. The results of these plots are shown in Figures 25 through 29. The effect of orifice size appears to exist even though values of $p^{1/2} \rho^{1/2} A^{1/2}/\mu$ are equal. That is, the effect of orifice size cannot be accounted for by variations in $p^{1/2} \rho^{1/2} A^{1/2}/\mu$.

No fully satisfactory explanation can be advanced for this effect of orifice size. No other variable has been previously reported which might account for such a large difference in results of experiments conducted under identical conditions of $p A^{1/2}/\sigma$ and $p^{1/2} \rho^{1/2} A^{1/2}/\mu$. For example, the density in this variable changed little and seem unlikely to have caused such a large effect. Conversely, the liquid was forced through the nozzle in all experiments by gas pressure in the spray liquid container. Liquid issuing from the nozzle at high pressures may have had a greater amount of dissolved nitrogen which would come out of solution, forming bubbles, as the liquid pressure dropped going through the orifice. However, this result would have caused the curve for small nozzles to lie below the curve for large nozzles, which is the opposite of that represented by the experimental data.

It is possible that biases introduced by the spray collection and sampling process might have produced such a result. Deposition of the finer spray onto the surface of the collecting liquid by inertial impaction would be less than that of the coarser spray (which is produced by the largest nozzles). This would produce a sample from fine spray which is coarser than the true population. Likewise, dissolution of the spray droplets into the collecting liquids would produce a sample mean larger than that of the original population. Both of these biases, however, have
Figure 25. $D_n/A^{1/2}$ as a function of $pA^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of A.
Figure 26. $\frac{d_{\text{VME}}}{A^{1/2}}$ as a function of $p \frac{A^{1/2}}{\sigma}$ for 65° nominal fan angle nozzles, at differing levels of A.
Figure 27. $D_{VH}/A^{1/2}$ as a function of $p A^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $A$. 
Figure 28. $D_{MM}/\lambda^{1/2}$ as a function of $p A^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $\lambda$. 
Figure 29. $D_{gn}/A^{1/2}$ as a function of $p A^{1/2}/\sigma$ for $65^\circ$ nominal fan angle nozzles, at differing levels of $A$. 

\[ p A^{1/2}/\sigma \]
been present to some extent in the collecting and sampling methods used by previous investigators, who have not reported such a distinct effect of nozzle size.

It is also possible that the lack of exact geometric similarity between large and small nozzles may be sufficient to yield different results. Figures 30 and 31 show enlargements made from the photomicrographs of nozzle orifices which were used to measure orifice cross-sectional areas. It appears that the small orifice is somewhat more rounded on the ends of the oval opening than is the case with the larger orifice. The sharp corners at the end of the larger orifice may produce a small segment of thinner liquid sheet, which breaks up into fine spray, which is lacking in the case of the smaller nozzle. Again, however, such differences, although unreported, are likely to have existed in the nozzles in previously reported research, where the effect on droplet size was missing.

Although one would wish to present the results of these experiments in completely dimensionless form, this cannot be done at the present. Attribution of the different results among different size nozzles to any of the effects discussed above is still speculative, as no measures of the variables involved were made.

Figures 32 and 33 show the additional effect of nominal spray fan angle on droplet size. Values of the arithmetic mean, $D_n$, are not affected by $\theta$, while there is a definite effect upon the volume mean, $D_{\text{VH}}$. This is somewhat surprising at first, but $D_{\text{VH}}$ is the integral of quite a different function than $D_n$. 
Figure 30. 20X magnification photograph of 0.09 mm$^2$ nozzle orifice

Figure 31. 20X magnification photograph of 0.92 mm$^2$ nozzle orifice
Figure 32. \( \frac{D_n}{A^{1/2}} \) as a function of \( \Theta \) at differing levels of \( p A^{1/2}/\sigma \).
Figure 33. $D_{VH}/A^{1/2}$ as a function of $\theta$ at differing levels of $pA^{1/2}/\sigma$. 

The diagram shows data points and a trend line for $D_{VH}/A^{1/2}$ plotted against the nominal fan spray angle, expressed in radians. The data points are differentiated by the value of $n_2$, with symbols indicating $n_2 = 800$, $n_2 = 2600$, and $n_2 = 8000$, respectively.
From the indications given by the previous graphs, one can propose a form for Equation 18. Because considerable scatter exists in all of the plots of dimensionless variables, any extensive work in fitting an explicit mathematical form to the data would probably be misleading at this point. Although the work by Dorman (1952) shown in Equation 20 as well as that of Fraser et al. (1957) shown in Equation 21 both indicated a simple inverse power relationship, these data appear to show a leveling out in the value of $\bar{D}/A^{1/2}$ at $p A^{1/2}/\sigma = 2600$. This suggests a relationship of the form:

$$\Pi = C_1 \Pi_4 C_2 \left(1 - C_3 \Pi_2^3\right) A^5$$  \hspace{1cm} (32)

or

$$\bar{D}/A^{1/2} = C_1 \theta_4 \left(1 - C_3 \left(p A^{1/2}/\sigma\right)^{C_4}\right) A^5$$  \hspace{1cm} (33)

This can be systematically fitted to the experimental data by establishing a dummy variable $\Pi_1 A^{-C_5} C_2 - C_1$. The value of $C_1$, $C_2$ and $C_5$ can be visually estimated from the graphs, after which $C_3$ and $C_4$ can be solved directly by regression. Better values of $C_1$, $C_2$, and $C_5$ can then be obtained by trial and error to minimize variance from the data, or by an optimum search technique in the space of $C_1$, $C_2$, $C_3$, $C_4$, and $C_5$ to minimize $\chi^2$.

Using this procedure yields the relationships:

$$D_n/A^{1/2} = 0.109 A^{-0.38} \left(1 + 13.77(p A^{1/2}/\sigma)^{-0.33}\right)$$  \hspace{1cm} (34)
Likewise plots of coefficients of variation for constant nominal fan angle are plotted as functions of \( p \frac{A^{1/2}}{\sigma} \) and \( p^{1/2} A^{1/2} \frac{\rho^{1/2}}{\mu} \) in Figures 34 and 35. From inspection it was seen from similar plots that the geometric standard deviations \( s_g \) and \( s_v \) were not related to the coefficients of variation, although theoretically they should be if the distributions are logarithmic normal (Aitchison and Brown, 1957). The absence of such relationship in the statistics computed in this study implies that there was a poor fit of the distribution data to the log normal function.

Figures 36 and 37 show the coefficient of variation of the number and volume distribution as a function of \( p^{1/2} A^{1/2} \frac{\rho^{1/2}}{\mu} \) at various levels of \( p A^{1/2}/\sigma \). Figures 38 and 39 also indicate the effect, at constant levels of \( p^{1/2} A^{1/2} \frac{\rho^{1/2}}{\mu} \), of varying fan angle. Nothing on these plots would suggest a functional relationship more complex than simple powers of \( p A^{1/2}/\sigma \), \( p^{1/2} A^{1/2} \frac{\rho^{1/2}}{\mu} \), and \( \theta \).

Thus, the specific form of Equation 19 would be:

\[
\frac{s_N}{D_N} = 0.323 (p A^{1/2}/\sigma)^{0.047} (p^{1/2} A^{1/2} \frac{\rho^{1/2}}{\mu})^{0.06} \theta^{-0.136} \quad (36)
\]

\[
\frac{s_{\text{VH}}}{D_{\text{VH}}} = 0.062 (p A^{1/2}/\sigma)^{0.124} (p^{1/2} A^{1/2} \frac{\rho^{1/2}}{\mu})^{0.185} \theta^{-0.146} \quad (37)
\]
Figure 34. $\frac{s_N}{D_N}$ as a function of $p \frac{A^{1/2}}{\sigma}$ for 65° nominal fan angle nozzles, at differing levels of $p^{1/2} A^{1/2} D^{1/2} / \mu$. 
Figure 35. $s_{\text{VH}}/D_{\text{VH}}$ as a function of $p A^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $p^{1/2}A^{1/2}p^{1/2}/\mu$.
Figure 36. $s_N/D_N$ as a function of $p^{1/2}A^{1/2}a^{1/2}/\mu$ for 65° nominal fan angle nozzles, at differing levels of $p a^{1/2}/\sigma$
Figure 37. $s_{VH}/D_{VH}$ as a function of $p^{1/2}A^{1/2} \rho^{1/2}/\mu$ for 65° nominal fan angle nozzles, at differing levels of $p A^{1/2}/\sigma$. 
Figure 38. $s_N/D_N$ as a function of $\Theta$ at differing levels of\n\[ \rho^{1/2}, A^{1/2}, \rho^{1/2}/\mu \]
Figure 39. $s_{vH}/v_{H}$ as a function of $\theta$ at differing levels of $\Pi_3$. 

$\sqrt[2]{\frac{1}{2}} \frac{1}{2} \frac{1}{2} \frac{1}{2}$
C. Simplified Measurement Technique

To determine the value of simplified statistics based on summed drop diameter and summed drop areas, estimates of the statistics derived from classified data were plotted against the simplified statistics. The plots for mean diameters are shown in Figures 40 through 46. The unweighted statistics, that is, $D_n$ and $D_{gn}$, appear to be predicted more accurately by this simplified statistic than do the volume weighted statistics. This is understandable, since the volume weighted statistics reflect other properties of the distribution, being related to higher moments of the distribution.

Close inspection of the data seems to reveal that the accuracy of prediction might be related to the size of the samples used for the measurements. To determine if this was so, the ratio $D_n/D_{n+}$ was computed for each test and plotted as a function of the number of droplets used in the test in Figure 47. This shows such an effect does exist, and that the best relationship between the statistics based on classified data and those based upon the simplified measurements likely exist for a droplet sample of about 2,500 drops. This would only be plausible if the effect were, in fact, due to the crowding, or lack of it, of the samples on the film which was counted. Since 25 samples were usually taken, this would indicate the best drop density per frame would be approximately 100 drops. Higher numbers of droplets per frame result in portions of some drops intercepting the margins of the counting area. Such cases will tend to distort the relationship between the two statistics, since the simplified statistic is based on the assumption of circular images.
Figure 40. Correlation of $D_n$ and $D_{the}$.
Figure 41. Correlation of $D_{vme}$ and $D_{the}$
Figure 42. Correlation of $D_{VH}$ and $D_{the}$
Figure 43. Correlation of volume median diameter and $D_{\text{the}}$. 
Figure 44. Correlation of $D_{gN}$ and $D_{\text{the}}$.
Figure 45. Correlation of $D_{gV}$ and $D_{the}$.
Figure 46. Correlation of $D_{Saut}$ and $D_{the}$
Figures 49 and 50 show the relationship between standard deviations from classified data and that from the simplified measurements, for unweighted and volume weighted data, respectively. There is a good relationship with the unweighted distribution, but the statistics from the simplified measurements would be of little value in predicting the standard deviation of volume weighted classified data.

Figure 48 shows the ratio $S_n/S$ as a function of the number of droplets in the sample. Clearly there is no significant effect.
Figure 47. Prediction of classified count statistics from simplified measurement statistics, as affected by number of droplets counted on 25 frames.

Figure 48. Prediction of classified count statistics from simplified measurement statistics, as affected by number of droplets counted on 25 frames.
Figure 49. Correlation of $s_N$ and $s_{the}$
Figure 50. Correlation of $s_{VH}$ and $s_{the}$.
VI. DISCUSSION

A. Uniformity of Droplet Size

It has been commonly assumed that the dispersion of spray droplet size is approximately proportional to the mean of the distribution. This assumption was derived from frequent observations that drop sizes approximately followed a logarithmic normal distribution, and that the geometric standard deviation of such distributions did not vary greatly. Since it can be shown that the coefficient of variation of a log normal distribution is a function only of the geometric standard deviation of the distribution, if this does not vary much, then the coefficient of variation will also not vary much.

Although the droplet distributions in this study did not appear to fit log normal models very well, the data from the study did confirm the common assumption that the coefficient of variation does not vary widely in spray from a fan spray nozzle.

The lowest coefficient of variation computed from the data was 0.55. While it is nearly half of the largest value of this statistic computed, it still represents a highly nonuniform distribution. Thus, no spray measurements obtained from any of these tests of fan spray nozzles could be considered to be very uniform.

Furthermore, Equation 18a gives little basis for expectation that more uniform spray could be obtained from this type of nozzle by extending design and operating conditions in directions that reduce variation. This is because the exponents in the function in Equations 36 and 37 are so
small. Only the fan angle, \( \theta \), has an appreciable effect, but this cannot be increased very much beyond 1.8 radians without a radical change in the basic design of such nozzles. The effect of fan angle, however, does imply that hollow cone nozzles might produce more uniform spray than the fan spray nozzle, since the "fan angle" of the hollow cone might effectively be \( 2\pi \), or nearly 6 times greater than the fan angles used most commonly in the true fan nozzles. In view of this prospect, attempts to produce spray of much more uniform droplet size, e.g., with coefficient of variation less than 0.1, should be directed to development of new nozzles rather than expect that a change in the fluid properties or that some modification of conventional fan nozzles such as used in these experiments might yield these results.

B. Formulation of Results

Equations 34, 35, 36, and 37, and the data upon which they are based, cover a wider range of conditions than any previously known study of fan spray nozzles. There is appreciable scatter between the data and the fitted equations, however, and it is disappointing that the mean droplet statistics could not be represented by dimensionless variables.

It is not possible to compare these data with previous work in dimensionless form, except for the work by Dorman (1952). Even this is not directly comparable, as the mean used by Dorman was the Sauter mean diameter, which was not computed in the form of a dimensionless equation in this study. Comparison of the exponents of the power terms in Equations 20, 34, and 35 shows much similarity, however. Conversely, Dorman's
equation is plotted on Figure 29. This shows that Dorman's equation is consistent with the data collected in this study, but would fit progressively more poorly at high values of $p \frac{A^{1/2}}{\sigma}$. Dorman's data exhibited considerably less scatter than the data in this study; however, he used only two liquids, used a narrower range of pressures, and used measurements of maximum drop size to compute the mean sizes reported, based upon a correlation which he established between maximum drop size observable and the Sauter mean diameter.

It is instructive to see how Equations 34 and 35 simplify at lower values of $p \frac{A^{1/2}}{\sigma}$. Dropping the first term in brackets yields, after some rearrangement:

$$D_N^* = (\sigma/p)^{0.33} A^{-0.05}$$

$$D_{\text{VH}}^* = (\sigma/p)^{0.4} e^{-0.33} A^{0.05}$$

These results predict a remarkably small influence of orifice size on the resulting droplet size. It follows that orifice size can be chosen to meet discharge requirements, after which the droplet size can be controlled by changing the pressure and the surface tension.

On the other hand, at sufficiently high values of $p \frac{A^{1/2}}{\sigma}$, if the second term in the brackets is dropped to estimate the right hand asymptote, one obtains $D_N^* \sim A^{0.25}$ and $D_{\text{VH}}^* \sim A^{0.12}$. Predicting drop size in this range, however, would involve extrapolating Equations 34 and 35 beyond the range of experimental data on which they are based.
C. Simplified Measurement Method

The ability to predict the arithmetic mean and standard deviation, shown in Chapter V, Section C, may be of considerable use in expediting droplet size measurement in situations where low droplet sample densities would otherwise reduce the value of automatic droplet sizing equipment. The apparent dependency of accuracy of size prediction on low sample densities will not affect the practical use of this method, as this condition is exactly the condition when the method is most likely to be used. Biological scientists who have become accustomed to use of volume weighted statistics, such as the mass median diameter, may be reluctant to use this simplified method, since it cannot be used to predict accurately any of the volume weighted statistics.
VII. SUMMARY

The objectives of this study were to obtain better measurements of central tendency and dispersion in drop sizes produced by agricultural fan spray nozzles, and to relate these measures to the operating conditions and nozzle design parameters. To attain these objectives, a series of controlled experiments were conducted in the laboratory.

The experiments were conducted at combinations of several levels of orifice size, liquid pressure, nominal fan angle, and liquid viscosity. An attempt was made to choose combinations of values of these conditions in such a way that orthogonal arrays of the dimensionless independent variables would result. Seven statistics indicating central tendency and four statistics indicating dispersion of the drop size distribution were computed for each experiment.

All mean drop sizes were influenced most strongly by nozzle size, operating pressure, and nominal fan angle. The manner in which these variables affected mean drop size also implied through dimensional analysis, that surface tension was equally as influential, although it did not vary greatly during these experiments. The small influence of $A^{1/2} \rho^{1/2} \rho^{1/2}/\mu$ implied that the spray liquid viscosity had less effect, at least to 17.8 centipoise, which was the highest value used.

In contrast, nominal fan angle, viscosity, surface tension, and pressure were more nearly equal in influencing dispersion measures computed from the data, such as coefficient of variation and geometric standard deviation.

A simplified method of estimating the mean and standard deviation of
a sample of spray drops was derived. Statistics based on these simplified measurements were compared with statistics derived from the same spray droplet samples by counts in size classifications. The simplified statistics were found to be mostly related to statistics from classified data which had not been weighted. This relationship also appeared to be affected by the population density of the droplet samples from which the measurements were taken.

It was also found that the effect of orifice size could not be fully accounted for in the descriptive equations containing only the dimensionless variables $\sqrt{d/A}$, $\frac{1}{\sigma}$, $\frac{1}{\mu}$ and $\frac{1}{\mu}$, $\frac{1}{\sigma}$. The influence of other variables and biases in the collection and sampling procedure were suggested as possible reasons for this effect. Insufficient evidence was available to attribute this effect to any of the causes suggested. A considerable portion of variation in the drop size statistics which were computed was not accounted for by the descriptive equation derived to fit the experimental data. This fit was about the same as for one previously reported study on spray droplet size, and poorer than that shown by a second author.
VIII. CONCLUSIONS

The following conclusions were drawn from this study:

1. The coefficient of variation of spray droplet sizes produced by these nozzles varied from 0.56 to 1.09, and the influence of operating conditions and nozzle design parameters was best described by the expressions

\[ s_N / D_N = 0.323 (p A^{1/2}/\sigma) 0.047 (p^{1/2} A^{1/2} \rho^{1/2} / \mu)^{0.06} \theta^{-0.136} \]  

\[ s_{VH} / D_{VH} = 0.062 (p A^{1/2}/\sigma) 0.124 (p^{1/2} A^{1/2} \rho^{1/2} / \mu)^{0.185} \theta^{-0.416} \]  

where \( s_N \) is the standard deviation of the drop size distribution, \( D_N \) is the arithmetic mean, \( s_{VH} \) is the standard deviation of the volume weighted drop size distribution, \( D_{VH} \) is the mean of the volume weighted drop size distribution, \( p \) is the pressure at which the nozzle is operated, \( A \) is the cross sectional area of the nozzle orifice in square millimeters, \( \sigma \) is the liquid surface tension, \( \rho \) is the liquid density, \( \mu \) is the liquid viscosity, and \( \theta \) is the nominal fan angle for the nozzle.

2. The geometric standard deviation, resulting from logarithmic transformation of the distribution data, was not as predictable as ordinary coefficient of variation statistics.

3. The mean drop size produced by fan spray nozzles was described by the expressions
\[ D_N/A^{1/2} = 0.109 A^{-0.38} (1 + 13.77(p A^{1/2}/\sigma)^{-0.33}) \]  \hspace{1cm} (34)

\[ D_{VH}/A^{1/2} = 0.298 A^{-0.33} A^{-0.25} (1+80.9(p A^{1/2}/\sigma)^{-0.4}) \]  \hspace{1cm} (35)

The experimental data exhibited considerable deviation from this expression. The effect of orifice size could not be accounted for completely by dimensionless variables included in the hypothesis proposed at the beginning of the study.

4. A simplified method for computing mean and standard deviation of droplet diameters based upon the sum of droplet diameters and the sum of droplet cross sectional areas was useful in predicting statistics computed by classification and counting, if such statistics were not weighted by volume or some other function.

5. The poor relationship of parameters of a log normal distribution, based on log transformation of the experimental data, to other statistics computed directly implied that the drop size distribution data was not sufficiently well fitted by a log normal model that meaningful parameters for such a model could be estimated from the data.
IX. REFERENCES


Wilson, J. D., O. K. Hedden, and J. P. Sleesman. 1963. Spray droplet size as related to disease and insect control on row crops. Ohio Agricultural Experiment Station Research Bulletin 945.

X. NOTATION USED

It will be noted that the letters $G$ and $U$ are both used to denote two entirely different quantities, a practice which is usually avoided. However, the usages shown are well established in the fields of statistics and fluid mechanics. Since the different usages appear in entirely separate equations, we do not believe it should be misleading.

$A = \text{cross sectional area of orifice.}$

$A_s = \text{cross sectional area of droplet images on film.}$

$c = \text{general term for coefficient of variation.}$

$D = \text{droplet diameter.}$

$\bar{D} = \text{general term for droplet mean, such as } D_n, D_{VH}, D_{VME}, D_{gN}, \text{ or } D_{gV}, \text{ listed below.}$

$D_{gN} = \text{geometric number mean diameter, defined in Equation 6.}$

$D_{gV} = \text{geometric volume mean diameter, defined in Equation 7.}$

$D_{mm} = \text{mass, or volume, median diameter, defined as the size of droplet such that half of the volume of spray is contained in droplets which are smaller than this size.}$

$D_n = \text{number mean diameter, defined in Equation 2.}$

$D_{VME} = \text{volume mean diameter attributed to Mugele and Evans (1951), defined in Equation 3.}$

$D_{VH} = \text{volume mean diameter attributed to Herdan (1960), defined in Equation 5.}$

$D_{Saut} = \text{Sauter mean diameter, defined in Equation 8.}$

$D_{the} = \text{number mean diameter computed from simplified measurements, defined in Equation 26.}$
\( d \) = orifice diameter.

\( D_m \) = maximum droplet size in a droplet population.

\( f \) = frequency function notation for frequency of droplet size sampled over a unit time

\( f' \) = function notation for frequency of droplet size sampled over a unit of space.

\( i \) = index value for discrete counts.

\( L \) = sum of droplet diameters in a sample.

\( n_{ch} \) = number of chords intercepted.

\( n_p \) = number of pulses in intercepted chords.

\( p \) = pressure drop of liquid through nozzle orifice.

\( Q \) = volumetric discharge of nozzle.

\( R \) = Reynolds number, \( \nu d \rho / \mu \).

\( s \) = standard deviation.

\( s_N \) = number standard deviation, defined in Equation 12.

\( s_{VH} \) = volume standard deviation, defined in Equation 13.

\( s_{gN} \) = geometric standard deviation of the number distribution, defined in Equation 14.

\( s_{gV} \) = geometric standard deviation of the volume distribution, defined in Equation 15.

\( W \) = Weber number, \( \nu^2 d \rho / \sigma \).

\( \beta \) = cone half angle of hollow cone nozzle, radians.

\( \delta_p \) = spacing of clock pulses on raster line.

\( \delta_r \) = spacing of scan lines in cathode ray tube raster.

\( \mu \) = parametric mean of a population distribution.

\( \mu \) = absolute viscosity.
H = any valid dimensionless product of variables.
σ = surface tension.
σ² = variance of a population distribution.
ρ = density.
θ = nominal angle of fan spray nozzle
Sr = square root standard deviation.
v = liquid eflux velocity from orifice.
χ² = goodness of fit statistic.
XI. ACKNOWLEDGEMENTS

The author would like to express his appreciation to:

The Agricultural Research Service, United States Department of Agriculture for providing the facilities and support for this study.

Dr. W. F. Buchele for serving as major professor and for guidance in this study, particularly for provocative discussion during the planning of the study.

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Delavan Manufacturing Company, West Des Moines, Iowa, and Spraying Systems Company, Bellwood, Illinois, for supplying specimens of nozzles used in the study.

His wife, Joan, and children, for deferring many domestic amenities to permit completion of this study.
XII. APPENDIX A. COMPUTER PROGRAM FOR DATA REDUCTION
LILJEDAHNL SPRAY DROP SIZE ANALYSIS

THIS PROGRAM IS DESIGNED TO COMPUTE VARIOUS STATISTICS FROM
SPRAY DROP SIZE MEASUREMENTS, PARTICULARLY, MEASUREMENTS
RECORDED ON PUNCHEO CARDS FROM THE WOOSTER PARTICLE COUNTER.
THE OUTPUT CONSISTS OF A SELF EXPLANATORY LISTING (FORMATS
(101 - 104), PLUS CARDS SUITABLE FOR MACHINE PLOTTING OR FURTHER
COMPUTATION.

INPUT PARAMETERS ARE -- N = TEST IDENTIFICATION NUMBER,
F_MAG = DROP TO FILM SPOT MAGNIFICATION, ICHEK = A DUMMY VARIABLE
USED FOR AN IDENTITY CHECK TO DETERMINE IF DATA CARDS MIGHT
BE OUT OF ORDER AND IF 'NEW SIZE CLASSIFICATIONS APPLY TO THE
NEXT DATA SET, AND K(I) = SIZE CLASSIFICATIONS SET ON THE
WOOSTER COUNTER WHEN MAKING COUNTS.

INPUT DATA CONSISTS OF -- NCUMR(I) = NUMBER OF SPOTS LARGER THAN
K(I) COUNTED BY THE WOOSTER COUNTER.

OUTPUT DATA CONSISTS OF -- A(I) = CENTER OF DROP SIZE CLASS,
K(I) = LOWER LIMIT OF DROP SIZE CLASS, M(I) = UPPER LIMIT OF
DROP SIZE CLASS, NO(I) = NUMBER OF DROPS IN CLASS, PN(I) =
PROPORTION OF NUMBER OF DROPS IN CLASS, PV(I) = PROPORTION
OF SPRAY VOLUME IN CLASS, SPN(I) = INTEGRAL OF PN(I), AND
SPN(I) = INTEGRAL OF PV(I).
OUTPUT STATISTICS CONSIST OF -- ON THE MEAN DROPLET DIAMETER
COMPUTED FROM INTERCEPT MEASUREMENTS, SDTH = STANDARD
DEV DEVIATION OF DROPLET SIZE COMPUTED FROM INTERCEPT MEASUREMENTS,
DMN = MEAN DIAMETER COMPUTED FROM COUNTS, SDN = STANDARD
DEV DEVIATION OF DROPLET SIZE COMPUTED FROM COUNTS, VMN = VOLUME MEAN
DIAMETER, VLD = VOLUME WEIGHTED MEAN DIAMETER, SDV = VOLUME
WEIGHTED STANDARD DEVIATION, DMV = MASS MEAN DIAMETER.
XN = GEOMETRIC MEAN DIAMETER, XSD = GEOMETRIC STANDARD
DEV DEVIATION, ZM = GEOMETRIC VOLUME WEIGHTED MEAN DIAMETER.
ZSD = GEOMETRIC VOLUME WEIGHTED STANDARD DEVIATION, AND
DSD = SAUTER MEAN DIAMETER.

DIMENSION M(42), ND(42), PV(42), NCUM(42), K(43), SPV(42)
DIMENSION X(42), PN(42), V(42), NCUMR(42), A(42), SPN(42)

FOR EACH TEST WE READ IN THE TEST NUMBER, THE NUMBER OF FRAMES
COUNTED (TO CONTROL CARD READING), AND A DUMMY VARIABLE CALLED
ICHEK WHICH WE SET EQUAL TO 1111 IF NEW CLASS SIZES ARE TO BE
USED, 5555 IF THE CLASS SIZES FROM THE PREVIOUS TEST ARE VALID
FOR THIS ONE, AND 9999 AT THE END OF DATA. ANY OTHER NUMBER WILL
CAUSE THE PROGRAM TO BRANCH TO PRINT A MESSAGE "CARDS OUT OF
ORDER" AND STOP. THE SPOT MAGNIFICATION IS ALSO READ IN.

1 READ(5,98) N, NREP, ICHEK, EMAG
   IF (ICHEK = 5555) 2,5,997
2 IF (ICHEK = 1111) 999, 3,68
3 READ(5,98) NCLAS, (K(I), I=1,43)
DO 4 I = 1,4
4 K(I) = (FLOAT(K(I))) / FMAG
DO 5 I = 1,5
M(I) = K(I+1)
5 A(I) = (FLOAT(K(I)) + K(I+1))/2.
DO 7 I = 1,42
SPN(I) =
SPM(I) =
NCUMR(I) = 0
7 NCUM(I) =
IK = -1
ONTHF = 0
SOTHE = 0
L =
NA = 0
C C C
C C C
C C C
C C C
C C C
C C C
C C C
C
C READ IN DATA FROM WINTER COUNTER, AND SUM DATA FROM ALL FRAMES.
C
C DO 9 J = 1, NREP
READ(5,16) NAR, LR, (NCUMP(I), I = 1, NCLAS)
DO 9 9 I = 1, NCLAS
9 NCUM(I) = NCUM(I) + NCUMR(I)
NA = NA + NAR
C C C
C C C
C C C
C C C
C C C
C C C
C C C
C L = L + LR
DO 12 I = 1, NCLAS
ND(I) = NCUM(I) - NCUM(I+1)
IF(ND(I))L = -1, L = I
IM(I) =<
IF (NCUM(I) ) 13, 13, 12
CONTINUE
IMAX = 1-1

COMPUTE MEAN AND STD DEVIATION FROM INTERCEPT DATA.

GN = NCUM(I)
AN = NA
ML = L
AR = 197.8*AN/(FMAG*FMAG)  
SUML = 19.78*AL/FMAG  
SSTHE = SUML/ON  
SSTHE = (4.*AP)/(CN*3.1415926)-(SUML*SUML)/(ON*ON)  
SDTHE = SQRT(SSTHE)

COMPUTE NUMBER AND VOLUME DISTRIBUTION, AREA AND VOLUME TOTALS,  
AND THE SAUTER MEAN AND VOLUME MEAN DIAMETER (MUEGGE-EVANS).

AT =  
VT =  
XM =  
YM =  
OM =  
VLD =  
SSN =  
SSV =  
SSW =  
SSX =  
SSZ =  
I = 1, NMAX
PN(I) = NO(I)/ON
AT = AT + NO(I)*A(I)*A(I)
V(I) = NO(I)*A(I)*A(I)*A(I)
VT = VT + V(I)

14 IF (I 16,16,17)
15 I = 1, NMAX
16 PV(I) = V(I)/VT

C INTEGRATE THE DISTRIBUTIONS ABOVE AND FIND MASS MEDIAN DIAMETER.
C
SPN(I) = PN(I)
SPV(I) = PV(I)
DO 2, I = 2, NMAX
SPN(I) = SPN(I-1) + PN(I)
SPV(I) = SPV(I-1) + PV(I)
IF (IK) 16,16,2
16 IF (SPV(I) - .5/2^17,18
17 DMM = M(I)
GO TO 19
18 DMM = M(I-1)+(M(I-M(I-1))/(SPV(I)-SPV(I-1)))
19 IK = IK + 2
2. CONTINUE
WRITE(6,111)

C COMPUTE MEAN AND STD DEV OF THE NUMBER AND VOLUME DISTRIBUTIONS.
C
DO 21 I = 1, NMAX
SSN = SSN + PN(I) * A(I) * A(I)
DMN = DMN + PN(I) * A(I)
SSV = SSV + PV(I) * A(I) * A(I)
VID = VID + PV(I) * A(I)

PUNCH CARDS ON DISTRIBUTION DATA.
WRITE(4,139) N, A(I), NH(I), PN(I), PV(I), SPN(I), SPV(I)

PRINT OUT DISTRIBUTION DATA.
21 WRITE(6,133) K(I), M(I), N(I), PN(I), PV(I), SPN(I), SPV(I)

TAKE LOGARITHMS OF CLASS MIDPOINTS AND COMPUTE GEOMETRIC MEAN
AND STANDARD DEVIATION OF BOTH NUMBER AND VOLUME DISTRIBUTIONS.

DO 22 I = 1, NMAX
X(I) = ALOG (A(I))
ZM = ZM + PV(I) * X(I)
XM = XM + PN(I) * X(I)
SSZ = SSZ + PV(I) * X(I) * X(I)
?? SSX = SSX + PN(I) * X(I) * X(I)
SSX = SSX - XM * XM
SSZ = SSZ - ZM * ZM
XSD = SORT (SSX)
ZSD = SORT (SSZ)
XM = EXP (XM)
ZX = EXP (2M)
SSN = SSN - (DMN)*(DMN)
SDN = SORT (SSN)
SSV = SSV - (VLO)*(VLO)
SOV = SORT (SSV)

PRINT OUT DISTRIBUTION STATISTICS.

WRITE (4, 1, 9) NCUM(1), LNTHE, SDTHE, DMN, SDN, VMU, VLQ, SOV, OMM, XM, XSD,
C ZM, ZSD, OSAUT

PUNCH CARDS ON DISTRIBUTION STATISTICS.

WRITE (4, 1, 9) NCUM(1), LNTHE, SDTHE, DMN, SDN, VMU, VLQ, SOV, OMM, XM, XSD,
C ZM, ZSD, OSAUT

END OF COMPUTATIONS FOR ONE EXPERIMENT. LOOP BACK TO DATA LEADER.

GO TO 1
997 IF (ICKEK = 999) 999, 999999
998 WRITE (6, 11)
999 STOP
91 FORMAT (12, 3X, I2, 13X, I4, 5X, F5.2)
99 FORMAT (5X, 12, 1X, 18I4/(2,14))
11 FORMAT (4X, 15, 16I4/(4X, 15, 15, 16I4))
111 FORMAT (IH1, 15X, 'TEST NUMBER', I4, T32) -- DISTRIBUTION DATA,
C 113,'DROP', 'T21,'NUMBER', 'T23,'PORTION'.
C */T13,'CLASS', 'T21,'DROPS', 'T29,'DROPS'.
C */T38,'VOLUME', 'T47,'IN AND 'T59,'IN AND'.
C */T13,'MICRONS', 'T21,'IN', 'T39,'IN', 'T47,'FLOW', 'T54,'FLOW'.
C */T21,'CLASS', 'T29,'CLASS', 'T38,'CLASS', 'T47,'CLASS', 'T56,'CLASS'./
13 FORMAT (1X,14,15,15,4X,6F4.4,3X,6F4.4,3X,6F4.4)
14 FORMAT (1H1////////18X,11HTEST NUMBER,13H,17,13H DROP SAMPLE."
C /18X,32HCOMPUTED DISTRIBUTION STATISTICS.//
C /16X,31HMEAN DIAMETER FROM INTERCEPTS =, F6.1,8H MICRONS/
C /16X,36HSTANDARD DEVIATION FROM INTERCEPTS =, F6.1,8H MICRONS/
C /16X,27HMEAN DIAMETER FROM COUNTS =, F6.1,8H MICRONS/
C /16X,32HSTANDARD DEVIATION FROM COUNTS =, F6.1,8H MICRONS/
C /16X,28HVOLUME MEAN (MUGUEL-EVANS) =, F6.1,8H MICRONS/
C /16X,29HVOLUME MEAN (HERDON) =, F6.1,8H MICRONS/
C /16X,27HVOLUME STANDARD DEVIATION =, F6.1,8H MICRONS/
C /16X,22HMEDIAN DIAMETER =, F6.1,8H MICRONS/
C /15X,32HGEOMETRIC NUMBER MEAN DIAMETER =, F6.1,8H MICRONS/
C /16X,29HGEOMETRIC NUMBER STD. DEV. =, F6.4/
C /16X,32HGEOMETRIC VOLUME MEAN DIAMETER =, F6.1,8H MICRONS/
C /16X,29HGEOMETRIC VOLUME STD. DEV. =, F6.4/
C /16X,22HSAUTER MEAN DIAMETER =, F6.1,8H MICRONS)
12A FORMAT (1H1,0H1,12X,1F5.3,1X,1F5.3,1X,1F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3)
11 FORMAT (1H1////////24HINPUT CARDS OUT OF ORDER )
END
XIII. APPENDIX B. SYNTHETIC DISTRIBUTION FOR PROGRAM TESTING

In order to debug the data reduction program and test if for accuracy, a synthetic distribution was made up and reduced by hand calculation to permit comparison with results from the computer. The distribution used was as follows:

<table>
<thead>
<tr>
<th>Drop size, microns</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>150</td>
<td>1</td>
</tr>
<tr>
<td>250</td>
<td>1</td>
</tr>
<tr>
<td>350</td>
<td>1</td>
</tr>
<tr>
<td>450</td>
<td>1</td>
</tr>
</tbody>
</table>

This could be a sample from a uniform distribution, from which the actual parameters could be computed. In this case, \( \mu = 2504 \) and \( \sigma = 141\mu \). Likewise the parameters could be computed for such a distribution if it were volume weighted, in which case one would have \( v(D) = \frac{4 \times 10^{-8}}{625} D^3 \), for which \( \mu_v = 400\mu \) and \( \sigma_v = 81.64\mu \).

The output from the data reduction program is given on the following page. In all cases the computer output agreed with hand calculated values within the limits of calculation precision used. The discrepancy between the computed values and parameters referred to above is caused by classification effects.
<table>
<thead>
<tr>
<th>DROP NUMBER</th>
<th>PORTION</th>
<th>PORTION VOLUME IN AND BELOW CLASS</th>
<th>SUM OF PORTION VOLUME IN AND BELOW CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DROP SIZE</td>
<td>OF DROPS</td>
<td>OF DROPS VOLUME IN AND BELOW CLASS</td>
<td>SUM OF DROPS VOLUME IN AND BELOW CLASS</td>
</tr>
<tr>
<td>MICRONS IN</td>
<td>CLASS DRPS</td>
<td>CLASS DRPS VOLUME IN AND BELOW CLASS</td>
<td>CLASS DRPS VOLUME IN AND BELOW CLASS</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>0.2000</td>
<td>0.0008</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>0.2000</td>
<td>0.2200</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
<td>0.2000</td>
<td>0.4200</td>
</tr>
<tr>
<td>300</td>
<td>400</td>
<td>0.2000</td>
<td>0.6200</td>
</tr>
<tr>
<td>400</td>
<td>500</td>
<td>0.2000</td>
<td>0.8200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2000</td>
<td>1.0000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
TEST NUMBER 0, 5 DROP SAMPLE.

COMPUTED DISTRIBUTION STATISTICS

MEAN DIAMETER FROM INTERCEPTS = 249.2 MICRONS
STANDARD DEVIATION FROM INTERCEPTS = 142.8 MICRONS
MEAN DIAMETER FROM COUNTS = 250.0 MICRONS
STANDARD DEVIATION FROM COUNTS = 141.4 MICRONS
VOLUME MEAN (HUGOLE-EVANS) = 312.9 MICRONS
VOLUME MEAN (HERDAN) = 394.7 MICRONS
VOLUME STANDARD DEVIATION = 77.5 MICRONS
MASS MEDIAN DIAMETER = 416.0 MICRONS
GEOMETRIC NUMBER MEAN DIAMETER = 196.8 MICRONS
GEOMETRIC NUMBER STD. DEV. = 0.7777
GEOMETRIC VOLUME MEAN DIAMETER = 384.9 MICRONS
GEOMETRIC VOLUME STD. DEV. = 0.2430
SAUTER MEAN DIAMETER = 371.2 MICRONS
<table>
<thead>
<tr>
<th>CLASS</th>
<th>1.000</th>
<th>1.645</th>
<th>1.818</th>
<th>2.000</th>
<th>4.000</th>
<th>7.200</th>
<th>9.000</th>
<th>12.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2.064</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>9.590</td>
<td>7.000</td>
<td>7.000</td>
<td>7.000</td>
<td>7.000</td>
<td>7.000</td>
<td>7.000</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Test Number 4 -- Distribution Data**

XI\(^{v}\): Appendix C: Experimental Drop Plot, Size Distribution Data

136
TEST NUMBER 5 -- DISTRIBUTION DATA

<table>
<thead>
<tr>
<th>DROP SIZE OF CLASS, MICRONS</th>
<th>DROP NUMBER OF DROPS</th>
<th>PORTION OF DROPS</th>
<th>SUM OF PORTION OF VOLUME IN AND BELOW CLASS</th>
<th>SUM OF VOLUME IN AND BELOW CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 10</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>10 20</td>
<td>546</td>
<td>0.0387</td>
<td>0.0000</td>
<td>0.0387</td>
</tr>
<tr>
<td>20 30</td>
<td>1022</td>
<td>0.0724</td>
<td>0.0001</td>
<td>0.1111</td>
</tr>
<tr>
<td>30 40</td>
<td>1068</td>
<td>0.0757</td>
<td>0.0003</td>
<td>0.1868</td>
</tr>
<tr>
<td>40 50</td>
<td>962</td>
<td>0.0682</td>
<td>0.0006</td>
<td>0.2550</td>
</tr>
<tr>
<td>50 60</td>
<td>873</td>
<td>0.0619</td>
<td>0.0010</td>
<td>0.3169</td>
</tr>
<tr>
<td>60 70</td>
<td>875</td>
<td>0.0620</td>
<td>0.0017</td>
<td>0.3789</td>
</tr>
<tr>
<td>70 80</td>
<td>779</td>
<td>0.0552</td>
<td>0.0023</td>
<td>0.4341</td>
</tr>
<tr>
<td>80 90</td>
<td>1442</td>
<td>0.1022</td>
<td>0.0062</td>
<td>0.5363</td>
</tr>
<tr>
<td>90 100</td>
<td>661</td>
<td>0.0468</td>
<td>0.0040</td>
<td>0.5831</td>
</tr>
<tr>
<td>100 120</td>
<td>1101</td>
<td>0.0780</td>
<td>0.0102</td>
<td>0.6612</td>
</tr>
<tr>
<td>120 140</td>
<td>927</td>
<td>0.0657</td>
<td>0.0142</td>
<td>0.7269</td>
</tr>
<tr>
<td>140 160</td>
<td>638</td>
<td>0.0452</td>
<td>0.0150</td>
<td>0.7721</td>
</tr>
<tr>
<td>160 180</td>
<td>479</td>
<td>0.0339</td>
<td>0.0164</td>
<td>0.8060</td>
</tr>
<tr>
<td>180 200</td>
<td>581</td>
<td>0.0412</td>
<td>0.0278</td>
<td>0.8472</td>
</tr>
<tr>
<td>200 230</td>
<td>484</td>
<td>0.0343</td>
<td>0.0336</td>
<td>0.8815</td>
</tr>
<tr>
<td>230 260</td>
<td>335</td>
<td>0.0237</td>
<td>0.0344</td>
<td>0.9052</td>
</tr>
<tr>
<td>260 290</td>
<td>251</td>
<td>0.0178</td>
<td>0.0365</td>
<td>0.9230</td>
</tr>
<tr>
<td>290 320</td>
<td>269</td>
<td>0.0191</td>
<td>0.0533</td>
<td>0.9421</td>
</tr>
<tr>
<td>320 360</td>
<td>150</td>
<td>0.0106</td>
<td>0.0412</td>
<td>0.9527</td>
</tr>
<tr>
<td>360 400</td>
<td>261</td>
<td>0.0185</td>
<td>0.1001</td>
<td>0.9712</td>
</tr>
<tr>
<td>400 460</td>
<td>138</td>
<td>0.0098</td>
<td>0.0767</td>
<td>0.9810</td>
</tr>
<tr>
<td>460 520</td>
<td>120</td>
<td>0.0085</td>
<td>0.0986</td>
<td>0.9895</td>
</tr>
<tr>
<td>520 580</td>
<td>54</td>
<td>0.0038</td>
<td>0.0628</td>
<td>0.9933</td>
</tr>
<tr>
<td>580 640</td>
<td>60</td>
<td>0.0043</td>
<td>0.0952</td>
<td>0.9976</td>
</tr>
<tr>
<td>640 720</td>
<td>33</td>
<td>0.0023</td>
<td>0.0725</td>
<td>0.9999</td>
</tr>
<tr>
<td>720 800</td>
<td>23</td>
<td>0.0016</td>
<td>0.0705</td>
<td>1.0016</td>
</tr>
<tr>
<td>800 920</td>
<td>12</td>
<td>0.0009</td>
<td>0.0533</td>
<td>1.0024</td>
</tr>
<tr>
<td>920 1040</td>
<td>2</td>
<td>0.0001</td>
<td>0.0132</td>
<td>1.0025</td>
</tr>
<tr>
<td>1040 1160</td>
<td>3</td>
<td>0.0002</td>
<td>0.0279</td>
<td>1.0028</td>
</tr>
<tr>
<td>1160 1280</td>
<td>1</td>
<td>0.0001</td>
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XVII. APPENDIX F. COMPUTER PROGRAM FOR CALCULATION OF
DIMENSIONLESS VARIABLES
This program computes mean-drop/orifice ratios, Weber No., Reynolds No., and flow angle from data read in in statements 1 and 2.

\[
\theta_{LT} = (6,1) \cdot 3
\]

1 \text{ read } (5,1:9) N, \text{ THE, DMN, VMD, VLD, DMM, XM, ZM, DSAUT}

\text{IF} (N = 90) \text{ ?} 5,4

2 \text{ read } (5,1:11) N, P, A, \text{ THE, VI}, \text{ S, SURET, DENS}

\text{IF} (N1 = N) \text{ ?} 4,3,4

\text{A} = (A \times 1.5) \times 1.06

\text{VMD} = \text{ THE} / A

\text{VMD} = \text{ VMD} / A

\text{VLD} = \text{ VLD} / A

\text{DMM} = \text{ DMM} / A

\text{XM} = \text{ XM} / A

\text{ZM} = \text{ ZM} / A

\text{DSAUT} = \text{ DSAUT} / A

\text{THE} = \text{ THE} / 57.2

\text{P} = 6.726 \times P

\text{A} = \text{ A} \times \text{ P} / \text{ SURET}

\text{P} = \text{ \text{ A} \times (\text{ P} \times \text{ DENS})} \times \text{ \text{ P} / \text{ SURET}}

\text{P} = \text{ \text{ P} \times \text{ SURET}}

\text{VMD} = \text{ \text{ VMD} \times 1.06}

\text{VMD} = \text{ \text{ VMD} \times 1.06}

\text{VLD} = \text{ \text{ VLD} \times 1.06}

\text{DMM} = \text{ \text{ DMM} \times 1.06}

\text{XM} = \text{ \text{ XM} \times 1.06}

\text{ZM} = \text{ \text{ ZM} \times 1.06}

\text{DSAUT} = \text{ \text{ DSAUT} \times 1.06}

\text{THE} = \text{ \text{ THE} \times 1.06}

\text{THE} = \text{ \text{ THE} \times 1.06}
This program computes coefficient of variation, Weber No., Reynolds No., and fan angle from data read in in statements 1 and 2.

READ (5,1;9) N,ONTHE, SCOTHE, CN, SDN, VLN, SDV, XSD, ZSD
IF(N = 99) 2, 5, 4
READ (5,11;) N1, P, A, THETA, VIS, SURFT, DENS
IF (N1 = N) 4, 3, 4
N = (A**P) * 0.1
CVN = SDN/ONN
CVV = SDV/VLN
CVTHE = SCOTHE/ONTHE
THLT1 = THETA/57.3
P = 68726.8
R = (A*(P*DENS)**0.5)/VIS
U = A*P/SURFT
WRITE (6,112) N, R, W, THETA, CVTHE, CVN, CVV, XSD, ZSD
ONTHE = ONTHE**1.000
CVV = CVV * 1.000
CVTHE = CVTHE * 1.000
CVN = CVN * 1.000
XSD = XSD * 1.000
ZSD = ZSD * 1.000
THETA = THETA*1.000
WRITE (6,111)
GO TO 1
4 WRITE (6,111)
5 STOP

FORMAT (1H1, 45X, 14HTABULATED RESULTS //
C T52, ' CVV', T61, ' XSD', T73, ' ZSD')/1
11 FORMAT (12, 3X, F6.1, 7X, 6.4, 5X, F5.1, 15X, F6.4, 8X, F4.1, 4X, F5.3)
11 FORMAT (18HCAP'S OUT OF ORDER)
11 FORMAT (1X, 12, F4.0, F7.4, 1X, 9F9.4)
11 FORMAT (12, F7.0, 8.0, 9F7.1)
END
XVIII. APPENDIX G. CENTRAL TENDENCY STATISTICS IN DIMENSIONLESS FORM
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XX. APPENDIX I. PRELIMINARY PLOTS OF $\frac{D}{A^{1/2}}$ AGAINST $p^{1/2}/\sigma$

AT VARYING LEVELS OF $p^{1/2}A^{1/2}\rho^{1/2}/\mu$
Figure 51. $D_{VME}/\Lambda^{1/2}$ as a function of $p\Lambda^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $p^{1/2}/\Lambda^{1/2}\rho^{1/2}/\mu$. 
Figure 52. $D_{\text{VH}}/A^{1/2}$ as a function of $p A^{1/2}/\sigma$ for $65^\circ$ nominal fan angle nozzles, at different levels of $p^{1/2}A^{1/2}/\nu$. 
Figure 53. $D_{tm}/\sqrt{\alpha}$ as a function of $p^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $p^{1/2}A^{1/2}\rho^{1/2}/\mu$
Figure 54. $D_{gN}/A^{1/2}$ as a function of $p A^{1/2}/\sigma$ for 65° nominal fan angle nozzles, at differing levels of $p^{1/2} A^{1/2} \rho^{1/2}/\mu$.