PERFORMANCE OF VANED-DISK ATOMIZERS

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The problem of producing sprays of liquid droplets by atomization is finding increasing importance in chemical engineering processes. This is especially true for the process of spray drying, wherein one important method of producing sprays is by means of spinning disks. These atomizers produce liquid breakup by centrifugally accelerating a liquid to high velocity as it discharges from the disk periphery.

Spinning-, or centrifugal-disk, atomizers are built in a variety of designs, the simplest being a flat, smooth disk. More complicated designs may include concentric sets of vanes, two or three plates or cups separated by perforated bands, etc. Pictures and drawings of various types may be found in references *2* and *10*.

Although many designs of disk atomizers have been proposed for spray-drying applications, quantitative information on the performance characteristics of even the simplest type of atomizer is lacking. This paper is a report of an investigation of the performance characteristics of disk atomizers of the straight, radial-vaned type. The purpose of the investigation was to determine how the weight and drop-size distributions of water sprays were influenced by the diameter, speed, vane dimensions and number of the disk and by feed rate. High-speed photography was used in an effort to study the mechanism of atomization.

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PREVIOUS WORK

Weight Distribution. Some quantitative data on the weight distributions or trajectories of sprays from vaned-disk atomizers have been reported by Adler and Marshall(*2*) and Friedman et al.(*10*). The data of Adler and Marshall were in the form of complete weight distributions, sampling being done in a plane 3 ft. below the plane of the disk. Friedman et al. reported their data in terms of the distance to which 50% of the spray was thrown before dropping 10 in. Adler and Marshall found that at low feed rates and peripheral speeds the spray was thrown farther as either feed rate or peripheral speed was increased. At higher values of the variables the spray was affected only slightly by feed rate but decreased in distance thrown with increasing peripheral speed. Friedman et al. reported that the distance to which 50% of the spray was thrown increased continuously with both peripheral speed and feed rate over the range of variables studied.

Drop-Size Distribution. Limited data on drop-size distribution for vaned disks were reported by Adler and Marshall(*2*) and by Friedman et al. (*10*). Wallman and Blyth(*18*) reported drop-size data on spray-dried sodium silicate obtained from a pilot plant spray dryer with vaned-disk atomizers.

Adler and Marshall presented drop-size-distribution data for sprays of water from (1) smooth disks, (2) one straight, radial-vaned disk, and (3) several curved-vane disks at one feed rate and disk speed. The drop-size data appeared to plot linearly on arithmetic normal probability paper. No significant differences in the drop-size distributions among these disks were observed.

Friedman et al. studying the effects of disk speed, feed rate, disk diameter, and liquid properties on drop-size distribution found that drop size decreased as disk speed increased, but increased as feed rate increased. They did not definitely establish the effect of disk diameter on drop size. Their results were correlated in terms of the Sauter mean drop diameter as a function of the operating and liquid variables in dimensionless groups as follows:

$$\frac{\bar{x}_{vs}}{r} = 0.4\left(\frac{\Gamma}{Nr^2}\right)^{0.6}\left(\frac{\mu}{\Gamma}\right)^{0.2}\left(\frac{\sigma\rho L}{\Gamma^2}\right)^{0.1} \quad (1)$$

where x_{vs} is the Sauter mean diameter. The uniformity of the sprays obtained was reported in terms of the so-called Hatch dispersion coefficient defined as the ratio of x_{50} to $x_{15.87}$ where x_{50} is the mass or volume median diameter, and $x_{15.87}$ is the diameter which includes 15.87% of the mass or volume of the spray, and $x_{50} > x_{15.87}$. The Hatch dispersion coefficient, α, was correlated with $\bar{x}_{vs}$ as follows:

$$\alpha = 3.3\,(\bar{x}_{vs})^{0.1} \qquad (2)$$

This is based on only a twofold range of α. Friedman et al. also proposed a correlation for the maximum drop size, which had the same form as Equation (1) except that the coefficient 0.4 was replaced by 1.2; i.e., the maximum drop size was suggested to be three times the Sauter mean diameter.

Wallman and Blyth (*18*) studied the atomization from smooth and vaned disks by determining the particle-size distribution of spray-dried sodium silicate atomized with disk atomizers. They found particle size to decrease as centrifugal force was increased and proposed that centrifugal force, rather than peripheral speed, was the factor governing particle size. However, no correlation of drop-size distributions was proposed.

Mechanism of Atomization. The manner in which sprays are formed from a bulk of liquid has been the subject of numerous reports in the literature. The greatest amount of work on the mechanism of atomization has been done in connection with pressure nozzles (*4* to *9, 12, 13, 16*).

Since discussions of the mechanism of atomization by disks have been reviewed adequately by various investigators (*2, 3, 10, 11, 14,* and *19*), this subject will not be reviewed again here; however, the essential conclusions are presented below.

THEORETICAL CONSIDERATIONS

The practice of atomization by spinning disks is well ahead of both theory and the results of experimental studies. Theoretical predictions of drop-size distributions require a knowledge of the atomization mechanism involved. It is generally believed that three distinct factors influence the mechanism of atomization by spinning disks. Two of these involve liquid properties, and the third involves interaction with the atmosphere surrounding the atomizer.

One mechanism for spinning-disk atomization postulates that the liquid, by wetting the surface of the disk, is held to the disk by adhesion tension and flows to the disk periphery to form a torus (on smooth disks) which, because of the surface tension of the liquid, resists disintegration. Centrifugal force acting on the torus is opposed by the surface-tension force. When the centrifugal force becomes great enough (owing to either increased liquid mass or increased speed) to overcome the liquid-surface-tension force, liquid drops are torn from the torus and thrown from the disk periphery. As the liquid-feed rate increases, this mechanism goes through the regimes of direct drop formation, ligament formation, and finally film formation.

A second mechanism postulates that liquid traveling at a high velocity over the disk and along the vanes develops turbulence. At the disk periphery the liquid is discharged at high velocity and at the same time is released from the confinement of the vanes. The internal stresses in the liquid stream caused by the velocity fluctuations and turbulence produce disintegration of the liquid stream.

A third possible mechanism is that a high relative velocity between the liquid and the atmosphere creates friction, which contributes to the disintegration of the liquid.

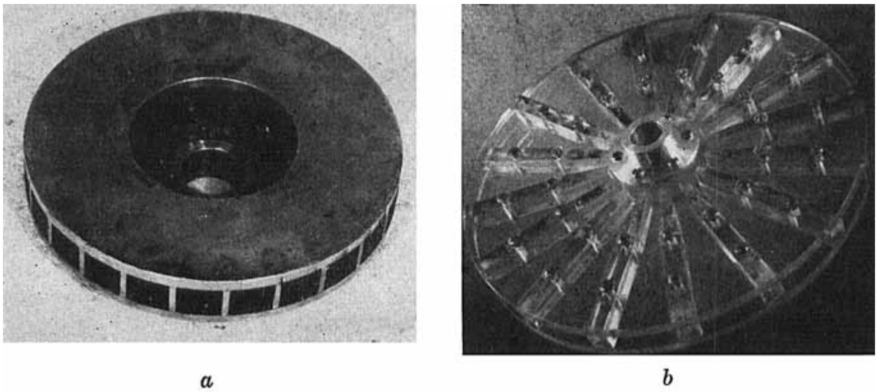


FIG. 1. VANED DISKS: (*a*) TYPICAL VANED-DISK USED IN STUDY; (*b*) LUCITE EXPERIMENTAL VANED DISK.

Although each of these mechanisms for atomization from spinning disks is possible, in the usual industrial range of operating conditions breakup probably is due to a combination of the mechanisms. It is also probable that the controlling mechanism may change with a change in the operating conditions.

In view of the complexities involved in predicting theoretically the performance characteristics of vaned-disk atomizers, this study was restricted to an empirical correlation of weight distributions and drop-size distributions as functions of operating and disk variables. The correlations were interpreted in the light of the foregoing suggested mechanisms.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Atomization Equipment. The twelve experimental disks used in this investigation were of a simple straight-vaned design as shown in Figure 1. The ranges of disk variables were as follows: (1) diameter, 2 to 8 in.; (2) number of vanes, 8 to 24; (3) vane height, 0.22 to 1.28 in.; and (4) vane length, 0.38 to 2.5 in. Table 1 gives the dimensions of all the disks studied.

TABLE 1.—DIMENSIONS OF EXPERIMENTAL DISKS

Disk	Diameter, in.	Vane Height, in.	Vane Length, in.	Number of vanes
V-1	3.75	0.375	0.375	24
V-2	5.0	0.375	1.00	24
V-3	8.0	0.312	2.50	24
V-4	5.0	0.656	1.00	24
V-5	5.0	1.281	1.00	24
V-6	8.0	0.375	2.50	24
V-7	5.0	0.375	0.625	24
V-8	5.0	0.375	1.625	24
V-9	5.0	0.375	1.00	20
V-10	5.0	0.375	1.00	16
V-11	5.0	0.375	1.00	8
V-12	2.0	0.219	0.50	24

The experimental disks were mounted on a vertical, belt-driven shaft, Figure 2, driven by a 3 hp., 3,450 rev./min. motor. Disk speed was varied by changing the ratios of the motor and disk pulley diameters. Disk speeds ranged between 700 and 10,000 rev./min. and were measured with a Strobotac.

The feed rate ranged from 5 to 60 lb./min. The water was fed uniformly to the disk through an annular distributor, the thickness of the annular ring being 1/32 in.

The atomization equipment was located in one corner of a 12- by 16-ft. room. All sampling was done in the sector-shaped area indicated in Figure 3.

Disk V-12 was operated at speeds of from 10,000 to 35,000 rev./min. by an air turbine mounted on a frame, as shown in Figure 4, and surrounded by a barricade. The capacity of this unit was less than 1 lb./min. of water.

Weight Distribution Determinations. The weight-sampling unit consisted of a sheet metal pan in the form of an 18° section taken from a circle of 10-ft. radius. The pan was divided into compartments by arcs at radial intervals of 1 ft., each compartment being provided with a drain. The pan was mounted horizontally 3 ft. below the disk with the apex of the section plumb with the disk shaft.

Weight-distribution data were obtained by collecting and measuring the amount of spray which entered each compartment during a timed interval. The total volume of liquid atomized during this time was obtained from a rotameter reading. For a uniform spray distribution, one twentieth of the total volume fell in the 18° section. Hence from the total volume and the volumes of spray falling in the sampling compartments up to 10 ft., the volume of spray thrown further than 10 ft. was estimated. From these volumes the distribution of the spray weight in the horizontal plane 3 ft. below the atomizer was established.

Drop-Size-Distribution Determinations. Spray-droplet samples were obtained by collection in sample cells by the method discussed by Rupe(*15*) and used by Adler and Marshall(*2*) and Tate and Marshall(*17*). In this method spray droplets fell into a sample cell filled with a fluid in which all droplets settled to a common plane. The collected group of drops in each sample cell was photomicrographed and the images were counted and classified. The sample cells were fitted with optically flat glass bottoms to permit the use of transmitted light for photography.

The immersion fluid employed in this investigation was Stoddard solvent. In order to obtain completely opaque images for photography, the water was dyed black with 3% nigrosine dye. The dyed water had essentially the same physical properties as water, except for a slightly lower surface tension.

The drop samples for a particular spray were obtained by positioning ten sample cells in the horizontal plane where the spray-weight distribution was determined. From data on the previously determined weight distribution for the spray, the sample cells were positioned in the center of areas each of which included 10% by weight of the spray. Thus the sample cells were positioned at radii which included 5,15,25 . . . 95 wt. % of the spray.

The sample cells were exposed to the spray by remote control. Each cell was enclosed in a narrow, shallow box with a sliding, slotted top which acted as a shutter. The operator, on a cat-walk above the spray, exposed the cell to the spray by pulling the shutter top with a fine string.

After the ten sample cells had been exposed, they were removed to be photographed. Ten photomicrographs at 35× were taken of each sample cell without duplication of area. The photomicrographs, on 5 by 7 film, generally averaged about 100 drops/negative, although as many as 1,500 or as few as 25 drops/negative were obtained in some instances, depending on the size and concentration of the drops in the cell.

The drop images on the negatives were counted and classified according to size by means of the scanning-type drop counter developed at the University of Wisconsin(*1*). With the aid of this counter the photomicrographs were analyzed at the rate of 150/day, and for this investigation, a total of 5,200 photomicrographs were scanned and 572,000 drops counted.

CALCULATION AND CORRELATION PROCEDURES

Weight Distribution. One hundred and seventeen weight-distribution experiments were made by the procedure described above. From each of these runs the cumulative volume, or weight percentages, of spray falling within radial increments of 1 ft. were established. These cumulative percentages were then plotted as the weight distribution for that run. Typical plots of this type may be observed in Figure 18 of reference *2*.

The variables influencing weight distribution were disk speed (1,500 to 9,800 rev./min.), feed rate (10 to 50 lb./min.), and the disk dimensions listed in Table 1. It was desired to correlate the data to show how these variables influenced the cumulative weight percentage of spray falling within any given spray radius, R.

It was decided that the most useful type of generalized weight-distribution correlation would be a cumulative distribution plot on either arithmetic- or log-probability coordinates with the nonprobability coordinate involving a grouping of the spray radius and variables, and the probability coordinate representing the cumulative weight percentage of spray included within the radial distance from the disk.

This correlation was made for the entire weight distribution obtained for each experimental run. The general procedure for correlating each variable was to plot values of spray radius, R, at cumulative percentages of 20, 40, 60, and 80 as a function of the particular variable under study. From such plots, R as a function of each variable was obtained, and these functional relations are shown in Figure 5*a* and *b*.

Drop-Size Distribution. The data from each drop-size-distribution run consisted of the number of drops counted in each of twenty equal-size classes (of 30 μ each) for each of ten samples taken from the spray produced during the run (*see* Table 6 of reference *10*a). The total number of drops at each sample point averaged 1,100 or the total counted in a run was about 11,000.

The attempt was made to present the drop-size data by an overall distribution which was representative of the entire spray from which the samples were taken.

Drop-size-distribution data may be based on the number, volume, or surface area of the drops in a spray, each basis being useful for a different purpose. It was felt that volume representation would probably be most useful, and hence the drop-size distribution on a volume basis was calculated for each of the ten droplet samples. Since the samples were representative of equal volume fractions of the spray, combination of the ten individual volume distributions into an overall distribution for the entire spray was merely a matter of averaging the individual sample distributions.

The variables to be correlated with drop-size distribution were disk speed (3,000 to 9,800 rev./min.), feed rate (20 to 50 lb./min.), and disk dimensions (Table 1). The method of correlation used differed from the usual method of correlating drop-size data in terms of a mean drop size and a standard deviation or dispersion coefficient [cf., Equation (1) and (2)]; rather, a generalized correlation for all points on the distribution curves was attempted. Thus the

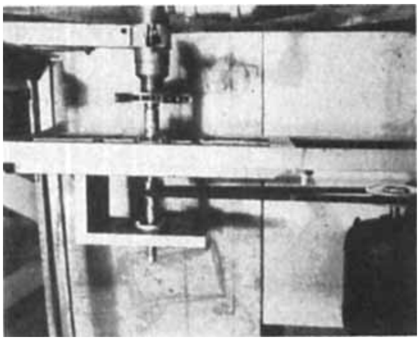


Fig. 2. Annular Feeding Device: Disk in Position, Motor, and Belt Drive.

effects of the pertinent variables on the drop diameter, x, at cumulative volume percentages of 20, 40, 60, and 80 were correlated and then grouped to form a general correlation (Figure 11a and b).

All the drop-size distributions were found to plot very nearly as straight lines on square root–normal probability coordinates. This type of distribution was first reported by Tate and Marshall (*17*) for pressure nozzles. Distinct curvature was observed for plots on either arithmetic- or log-normal probability coordinates.

EXPERIMENTAL RESULTS

Weight Distribution. The correlation of weight-distribution data showed that the weight distribution of sprays from vaned disks, expressed as R, the radial distance of travel of the spray, was related to the pertinent variables as follows:

For disk speed, N, in the range of 1,500 to 9,800 rev./min., $R \sim N^{-0.16}$

For feed rates, w, in the ranges of 10 to 50 lb./min., $R \sim w^{0.25}$

For disk diameters, D, from 3.75 to 8 in., $R \sim D^{0.21}$

For vane heights, b, from 0.376 to 1.28 in., $R \sim b^{-0.12}$

Increasing the number of vanes from 8 to 24 showed no significant variation of spray trajectory.

A variation of vane length from 0.375 to 1.63 in. revealed no definite trend in the weight-distribution data.

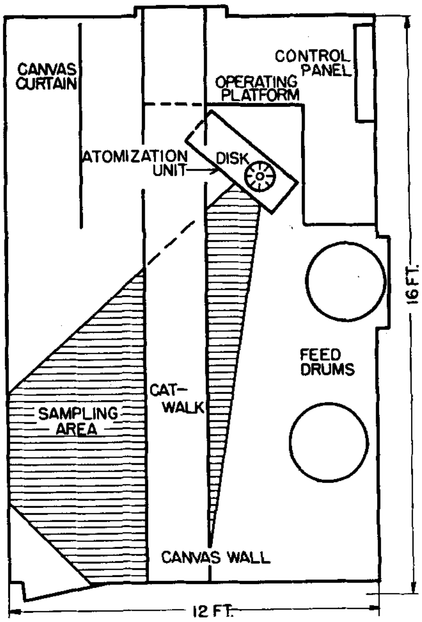


Fig. 3. Layout of Experimental Area.

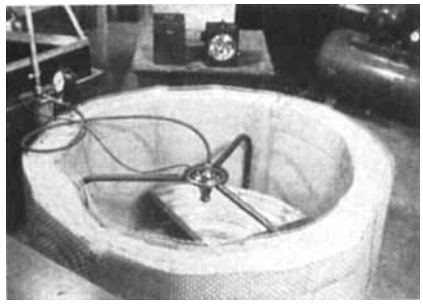


Fig. 4. Air-Driven 2-in.-Diam. Disk in Barricade.

On the basis of the foregoing relationships, a generalized graphical correlation involving disk speed, N, feed rate, w, and disk diameter, D, was developed by plotting the group $RN^{0.16} D^{-0.21} w^{-0.25}$ vs. the cumulative weight or volume percentage of the spray included in R on normal probability paper. This correlation is shown in Figure 5a and b. The data fell around a straight line having the constants $(RN^{0.16}\ D^{-0.21}\ w^{-0.25})_m = 7.7 =$ median value, $\sigma_w = 2.3 =$ standard deviation.

Figure 5a and b is based upon the following units for the ordinate values: $R =$ ft., $N =$ rev./min., $D =$ in., $w =$ lb./min.

Drop-Size Distribution. The drop-size-distribution data were obtained from fifty-two experimental

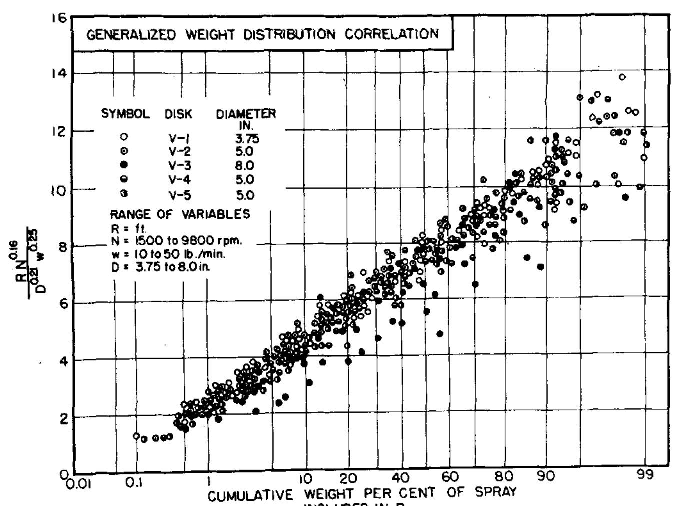


Fig. 5a.

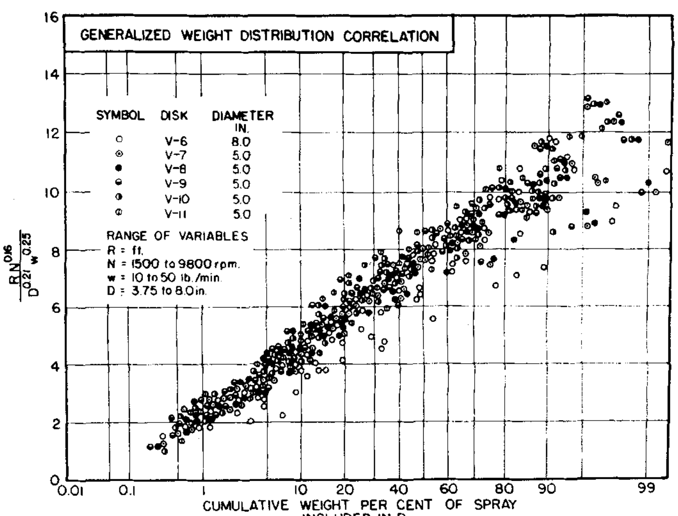


Fig. 5b.

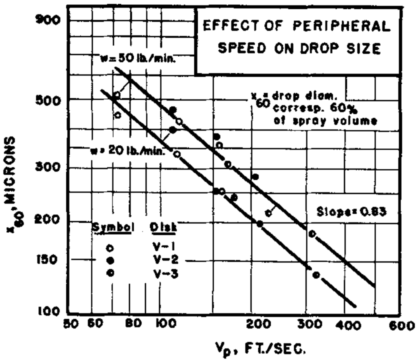


FIG. 6. TYPICAL PLOT OF EFFECT OF DISK PERIPHERAL SPEED ON DROP SIZE CORRESPONDING TO 60 CUMULATIVE PER CENT.

runs wherein about 572,000 drops were measured and counted. Analysis of the data showed that the variables affected the drop-size distribution of sprays produced by vaned disks as follows:

For a disk-speed range of 3,000 to 9,800 rev./min. drop size varied inversely with disk speed to the 0.82 power.

For disk diameters ranging from 3.75 to 8 in., drop size varied inversely with disk diameter to the 0.85 power.

The fact that disk speed and diameter had essentially the same effect on drop-size distributions suggested that the distributions were influenced by the peripheral speed of the disks. Figure 6 is a typical plot for two feed rates of drop size vs. peripheral speed for the peripheral-speed range of 50 to 300 ft./sec. The slope of the curves is –0.83.

For feed rates in the range of 20 to 50 lb./min., the drop size varied with feed rate to the 0.24 power. Figure 7 shows typical curves of the variation of drop size with feed rate. Drop diameters which include 20, 40, 60, and 80% by volume of the spray multiplied by $N^{0.82}$ are plotted vs. feed rate for three vaned disks of different diameters.

A variation of vane height from 0.375 to 1.28 in. showed that drop size varied with vane height to the –0.12 power.

Increasing the number of vanes from 8 to 20 showed that drop size varied with vane number to the –0.15 power.

Since vane height and number had essentially the same effect, it seemed reasonable to conclude that the drop-size distributions were probably influenced by the total wetted periphery for liquid discharge from the disk; however, the data on this effect scattered so much that a significant correlation cannot be proposed at this time. Therefore, the inclusion of wetted periphery in the general correlation of drop size must be regarded

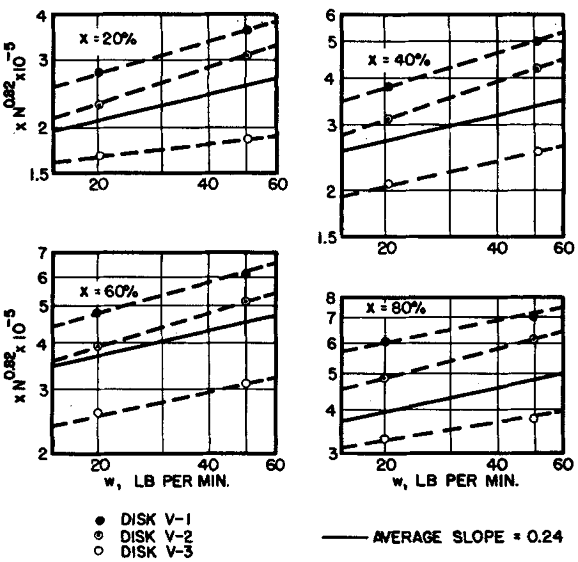


FIG. 7. TYPICAL PLOT OF EFFECT OF FEED RATE ON DROP SIZE AT VARIOUS CUMULATIVE PERCENTAGES.

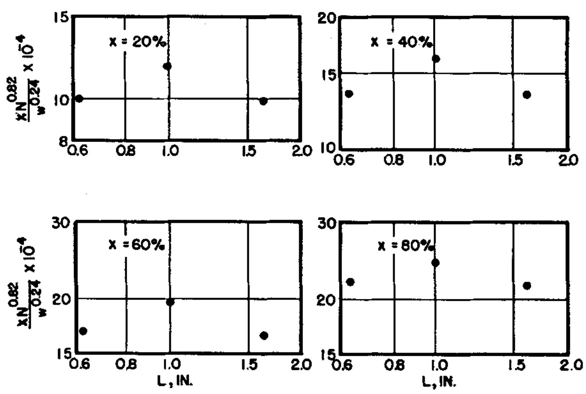


FIG. 8. EXAMPLE OF INCONCLUSIVE EFFECT OF VANE LENGTH ON DROP SIZE AT VARIOUS CUMULATIVE PERCENTAGES.

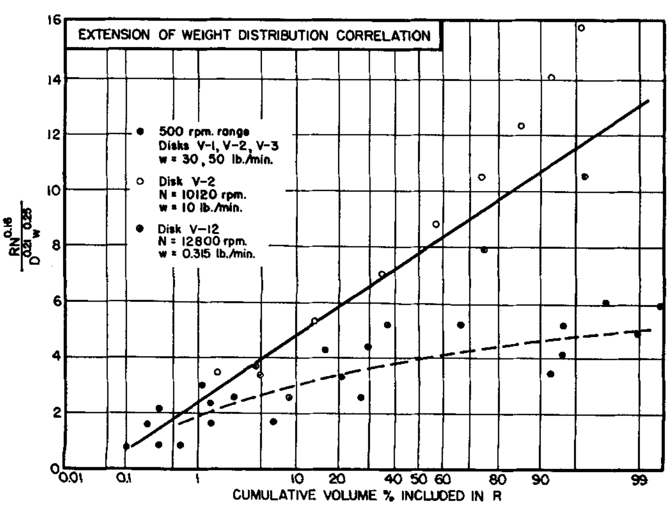


FIG. 9.

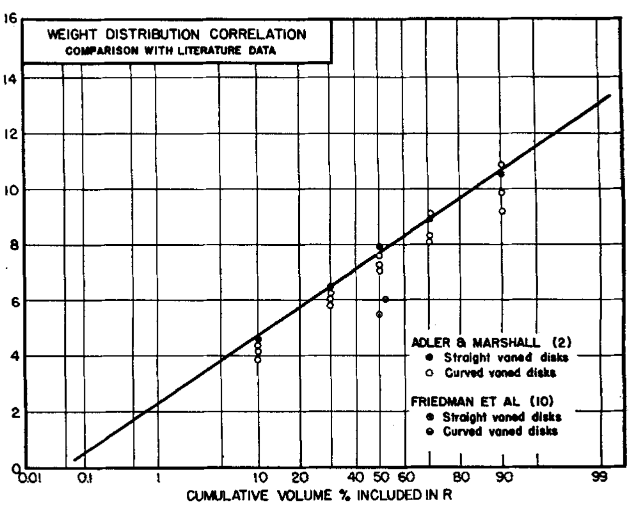


FIG. 10.

as tentative, but apparently, the effect is small.

Figure 8 shows typical plots of all the data on the effect of vane length on the drop size for a range of vane lengths from 0.376 to 1.63 in. The effect is inconclusive. Additional data involving a wider variation in vane length should be considered before a quantitative statement can be made concerning the effect of this variable on drop size.

The dimensional group of variables involving feed rate, w; peripheral speed, ND; and superficial total wetted periphery for liquid discharge, $L_p = nb$, was combined with drop diameter, x, to give the ordinate for a generalized drop-size-distribution correlation as follows:

$$y = x\,(ND)^{0.83}\,(nb)^{0.12}/w^{0.24} \quad (3)$$

The experimental data were combined into the dimensional group given by this equation and plotted on square root–normal probability coordinates as shown in Figure 11a and b. The data fell on a path about a straight line having constants

$$[x\,(ND)^{0.83}\,(nb)^{0.12}\,w^{-0.24}]_m = 92.5 \times 10^2$$
$$\sigma_v = 49.0 \times 10^2$$

where m refers to the median value.

The scale of the ordinate and the values of the constants for the straight line are based upon the following units for the variables: x = microns, ND = in./min., nb = in., w = lb./min.

DISCUSSION OF RESULTS

Weight Distribution. The generalized weight-distribution correlation (shown in Figure 5a and b) indicates how disk speed, feed rate, and disk diameter influence weight distribution or spray trajectory. The correlation is valid only in the ranges of the variables studied in this investigation. Data obtained for disk speeds as low as 500 rev./min. did not follow the correlation, as Figure 10 shows. This was due to the fact that the liquid did not atomize completely and tended to pour off the disk in continuous streams. Limited data for a 2-in.-diam. disk (V-12) rotating at about 13,000 rev./min. and fed at a rate of about 0.3 lb./min. also failed to agree with the correlation (Figure 9). However, the latter condition of fine atomization made collection of the spray very difficult.

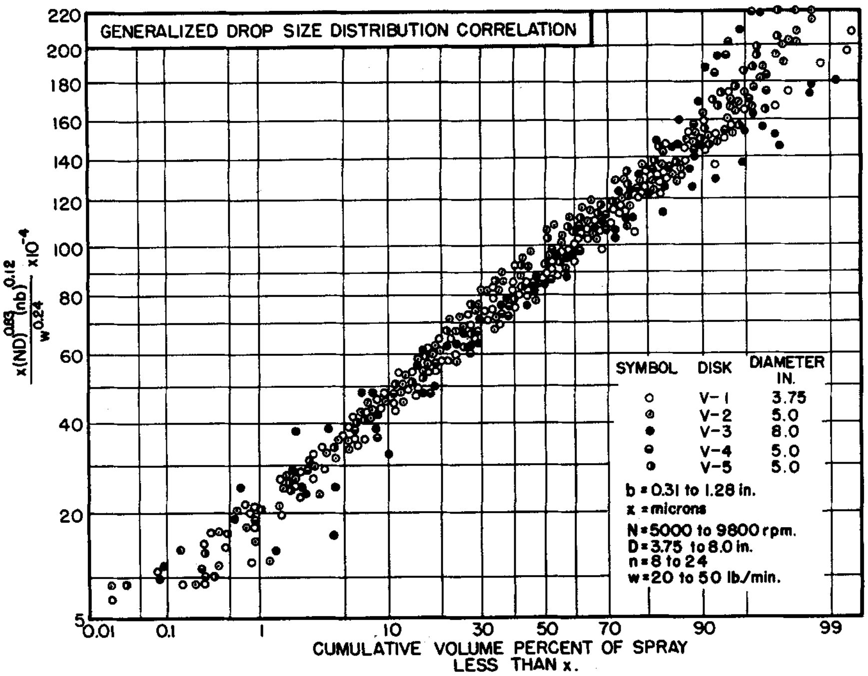


FIG. 11a.

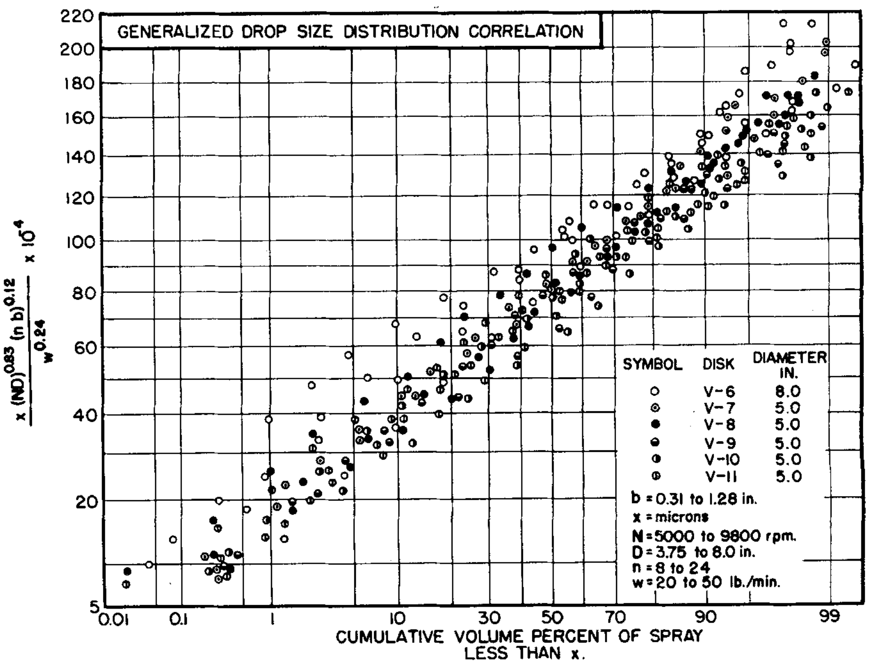


FIG. 11b.

The trajectory data of Adler and Marshall (*2*) and Friedman et al. (*10*) for straight- and curved-vaned disks were plotted in terms of the generalized correlation in Figure 11. The data of the former authors for the straight-vaned disk were fitted well by the correlation; the data for the curved-vaned disks were slightly low. The fact that Friedman et al. did their weight-distribution sampling in a plane 10 in. below the atomizer instead of 36 in., as in this study, may account in part for their data for the straight-vaned disk falling below the correlation of this study.

In the investigation by Friedman et al. of the influence of variables on weight distribution, it was found that spray trajectory varied directly with disk speed, feed rate, and disk diameter all to the 0.25 power. While their results agreed with the results of this study insofar as the effects of feed rate and disk diameter are concerned, there was no agreement on the effect of disk speed. There is no apparent reason for this disagreement. Offhand, it would seem logical that higher disk speeds also act to produce smaller drops, or a finer spray. Since small drops decelerate more rapidly than large ones, the spray trajectory should not increase with speed, but may even decrease, as found in this investigation (See also Figure 17 of reference *2*).

Because air currents and objects in the spray chamber were observed to cause billowing of the spray-air mass, it is believed that the absolute values of spray trajectory which can be predicted by the generalized weight-distribution correlation may be unique for the experimental setup used in this investigation. However, the correlation should prove useful in other disk-atomization setups using straight-vaned disks for prediction of how an established weight distribution should be influenced by disk speed, feed rate, and disk diameter.

One application of the weight-distribution correlation is the prediction of the required diameter of a spray tower to perform a given operation such as spray drying. In this connection, it is evident that the correlation of Figure 5*a* and *b* is conservative; i.e., presumably the spray from a disk in a spray dryer will not travel outward as far as this correlation would predict. This is true for two reasons: (1) the drops are undergoing drying with a reduction in density which reduces their distance of travel, and (2) downward air currents in the dryer would disturb the spray trajectory. As a conservative estimate, however, it is possible to write, on the basis of the correlation in Figure 5*a* and *b*, the following empirical expression for the radial distance to which 99% of the spray will travel:

$$R_{99} = \frac{12\, D^{0.21}\, w^{0.25}}{N^{0.16}} \qquad (4)$$

R_{99} is the radial distance in feet, which includes 99% of the mass of the spray.

A comparison of this equation with an existing installation is of interest. A spray dryer atomizing 80 lb./min. from an 8-in. disk operating at 10,000 rev./min. is performing satisfactorily in a 20-ft.-diam. chamber. These data substituted in Equation (4) predict a radius, R_{99}, of about 12.5 ft. or a 25-ft.-diam. chamber confirming the conclusion that Equation (4) is conservative for spray-dryer-diameter estimates.

Drop-Size Distribution. In Figure 11*a* and *b* are plotted the drop-size-distribution data for eleven experimental disks in the form of a generalized correlation. This correlation shows how disk peripheral speed, feed rate, and wetted periphery of the disk vanes affect the drop-size distributions of sprays produced by vaned-disk atomizers.

Extension of the correlation to higher disk speeds, lower feed rates and smaller disks was indicated as feasible from drop-size data on a 2-in.-diam. disk (V-12) at feed rates of less than 1 lb./min. and at speeds up to 32,500 rev./min. This is shown in Figure 12, where the drop-size data for these conditions have been plotted to compare with the general correlation of Figure 11*a* and *b*.

This generalized correlation can

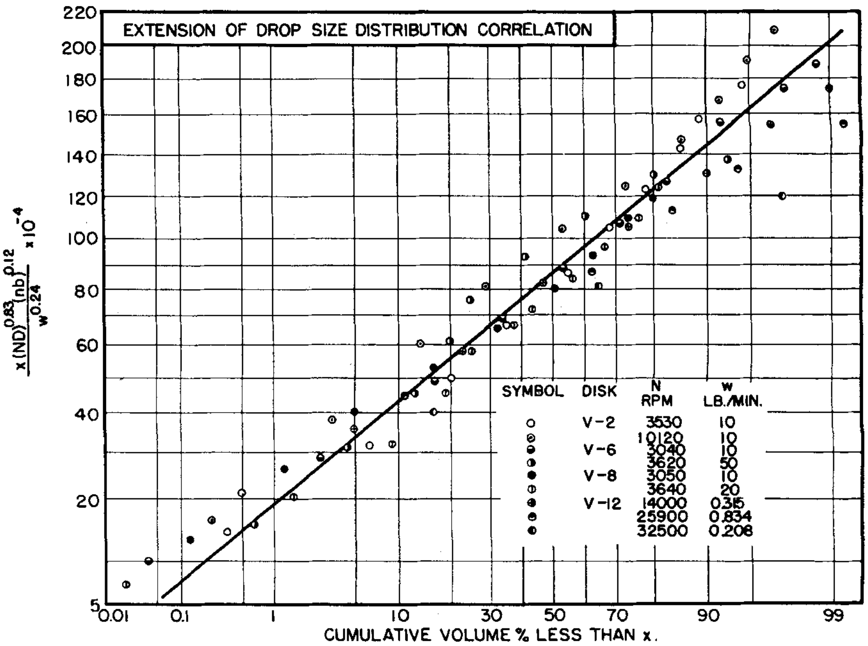


Fig. 12. Extension of Drop-Size Correlation to Higher Disk Speeds.

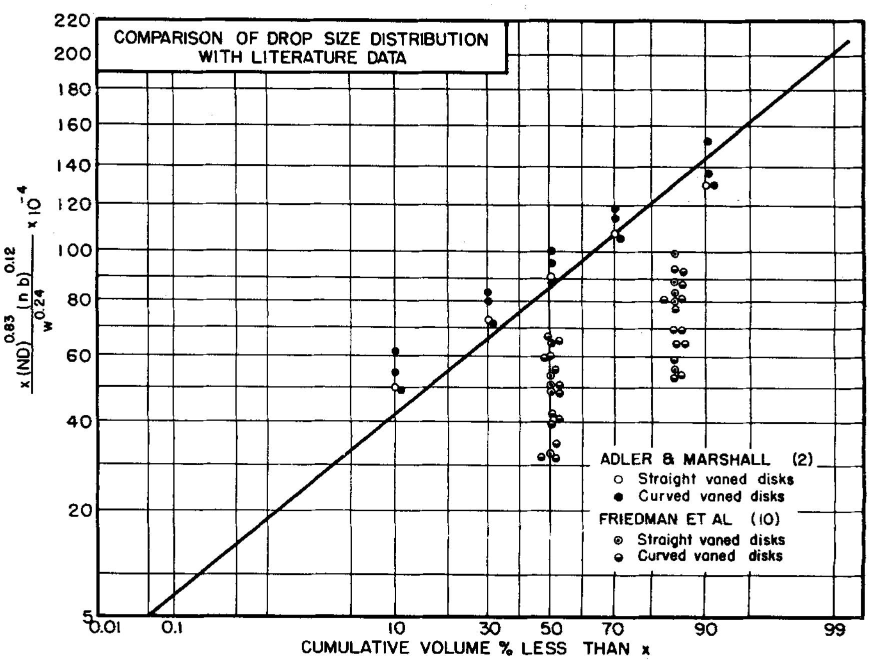


Fig. 13.

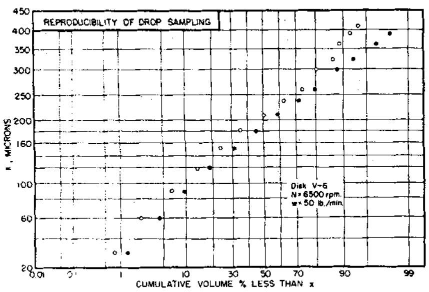


FIG. 14.

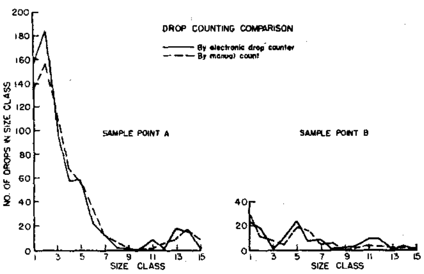


FIG. 15. COMPARISON BETWEEN DROP COUNTER AND MANUAL COUNTS.

be used within the experimental range to predict within 25% or better the drop-size distributions of sprays produced by straight-vaned disks. The correlation can also be used to determine trends in spray uniformity. The reciprocal of the difference between the drop diameter which included 84.12 volume % of the spray and that which included 50.0 volume % is a measure of spray uniformity. In terms of variables studied, uniformity may be expressed as

$$\delta = 2.04 \times 10^{-4} (\pi N D)^{0.83} (L_p)^{0.12}/w^{0.24} \qquad (5)$$

This relation shows that spray uniformity increases as peripheral speed increases, as total wetted periphery for discharge increases, and as feed rate decreases. These effects are all confirmed by experience.

Drop-size-distribution data for vaned-disk atomizers reported in the literature are meager. Only the data of Adler and Marshall (*2*) and Friedman et al. (*10*) were available for comparison with the generalized correlation. In order to determine the applicability of the correlation to the literature data, they were put in the form required by the dimensional group of Equation (3) and plotted in Figure 13.

The data supplied by Adler and Marshall for both straight- and curved-vaned disks compared well with the correlation; however, the data of Friedman et al. fell below the correlation of this study. This disagreement might be due to a number of causes, e.g., differences in drop-sampling procedures, differences in total numbers of drops counted, etc. It was believed that sufficient drops were counted in this study to ensure reliable trends of the data. Further, reproducibility of the data appeared acceptable, as Figure 14 indicates. Another factor lending confidence to the data of this study was the removal of the human error from the drop counting. The drop counter used and described in reference *1* gave consistently more reliable results than manual counting. This was checked many times. A typical comparison between a reliable manual count and the drop-counter count is shown in Figure 15.

The investigation of Friedman et al. (*10*) indicated that the effect of disk speed on drop size was in the same direction as found in this work, but to a smaller degree [cf. Equation (1)]. They reported that average drop size varied inversely with disk speed to the 0.6 power. They agreed as to direction and order of magnitude of feed rate, finding drop size to increase directly with feed rate to the 0.2 power. Because of insufficient data, they tentatively proposed that drop size varied inversely with disk diameter to the –0.2, a much smaller variation than found in this study.

In order to utilize better the drop-size-distribution correlation given in Figure 11*a* and *b*, perfomance charts (Figures 16 and 17) were prepared to show how the drop-size distribution varied with peripheral speed in one case and with feed rate in another. Figure 16 shows the drop-size distribution (volume basis) on a log-probability plot for disk peripheral speeds ranging from 50 to 300 ft./sec. These lines show how spray uniformity improves with disk speed. If plotted on square root–probability paper, the lines would be straight. A correction-factor curve for feed rate is given in the insert graph. A similar plot showing the variation of distribution with feed rate is given in Figure 17. Here a correction-factor curve for peripheral speed is included. The correction for wetted periphery is small but can be tentatively included for both charts on the basis that the drop size varies with $(nb)^{-0.12}$.

Atomization Mechanism. High-speed still and motion pictures were taken

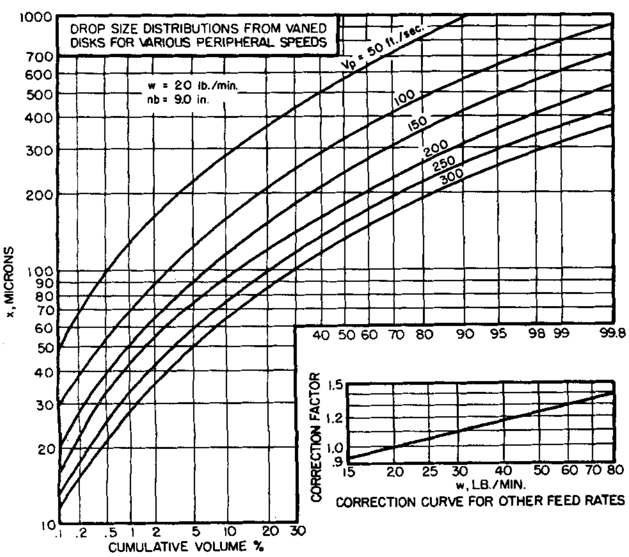


FIG. 16. PERFORMANCE CHART FOR ESTIMATING THE EFFECT OF PERIPHERAL SPEED ON DROP-SIZE DISTRIBUTION FROM VANED DISKS.

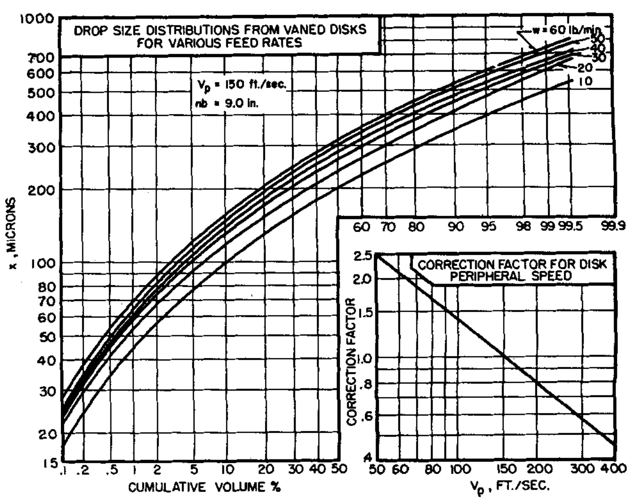


FIG. 17. PERFORMANCE CHART FOR ESTIMATING THE EFFECT OF FEED RATE ON DROP-SIZE DISTRIBUTION.

FIG. 18. HIGH-SPEED MOTION PICTURE FRAMES SHOWING COARSE LIGAMENTS FORMED AT LOW DISK SPEED; $N = 640$ REV./MIN., $w = 30$ LB./MIN.

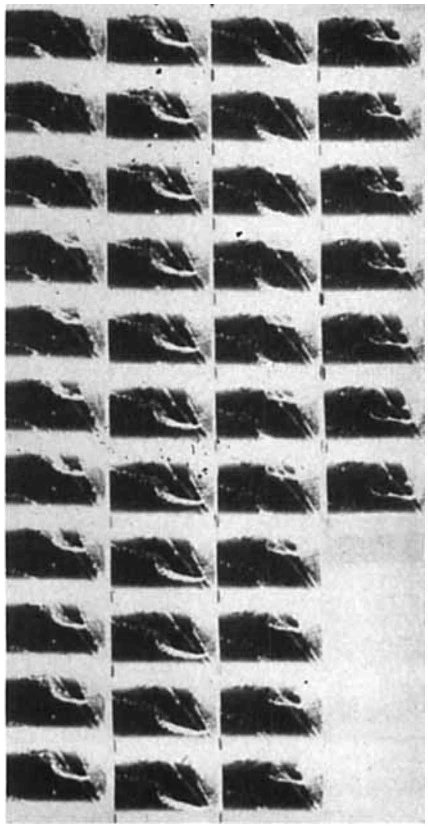


FIG. 19. HIGH-SPEED MOTION PICTURE FRAMES SHOWING FILM FORMATION FOLLOWED BY LIGAMENT FORMATION AND COLLAPSE; $N = 1{,}500$ REV./MIN., $w = 30$ LB./MIN.

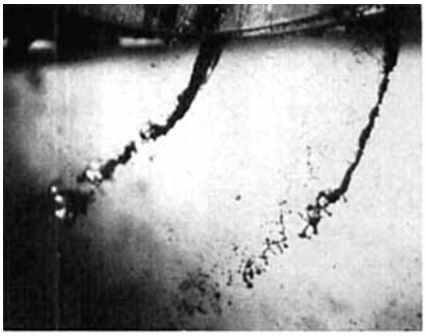
of the atomization action at the periphery of the vaned disks in an attempt to determine what mechanisms were influencing the spray formation. Because the action above 1,500 rev./min. was too rapid to be stopped by the high-speed motion picture camera, the motion pictures were confined to shots of the disks operating at speeds of 700 and 1,500 rev./min. However, high-speed still pictures were taken of the disks operating at 5,000 rev./min.

The atomization action appeared to change as disk speed was increased from 700 to 5,000 rev./min. At the low disk speeds liquid issued from the disk in heavy streams from each vane. Part of the liquid seemed to flow along the lower disk plate as well as along the surface of the vanes. The liquid discharged from each vane retained its stream-shaped identity for some distance beyond the disk, where it then broke up. The breakup occurred as the end of the stream spread out into a sheet which flapped like a flag. Heavy ligaments extended from this sheet and also trailed from the main stream between the sheeted end and the disk periphery. From the ligaments and from the sheet itself, irregular globs and drops of varied sizes were formed as shown in the high-speed movie frames of Figure 18.

At disk speeds of 1,500 rev./min., the liquid streams issuing from the disk vanes appeared to be thinner than those at lower speeds. Liquid flow along the lower disk plate was less noticeable. The end of the discharged stream was formed into a thinner, filmlike sheet from which ligaments were torn. At several intervals between the sheeted end of the stream and the disk periphery, eruptions occurred in the stream with the resultant formation of thin-walled, balloonlike films. These balloons were laced with heavier ribs of liquid and grew until they seemed to burst to form drops, as shown in the sequence of high-speed movie frames in Figure 19 and the high-speed still in Figure 20*a*.

High-speed still photographs of atomization at disk speeds of 5,000 rev./min. showed that, instead of solid streams of liquid emerging from disk vanes, the liquid appeared to disintegrate from a film almost as soon as it was discharged (Figure 20*b*). The liquid flowed along the vertical surface of the vanes and appeared to touch the surface of the lower disk plate only to the extent of the width of the film. Disintegration appeared to be the result of the collapse of short ligaments extending from the films. No formation of globs of liquid from the films was observed.

High-speed photography at a fixed disk speed showed that an increase in feed rate resulted in larger, less filmlike streams of



a

b

FIG. 20. HIGH-SPEED PHOTOGRAPHS OF VANED DISKS ATOMIZING DYED WATER.

liquid being discharged from each vane. The disintegration of such streams appeared to produce more globs of liquid and larger drops. An increase in vane height resulted in thinner, more filmlike streams of liquid being discharged from each vane. Such streams disintegrated to produce fewer large masses of liquid and smaller drops.

Analysis of the high-speed photographs indicated that the atomization mechanism was to a large extent governed by liquid velocity, increases in which resulted in finer atomization. It was also observed that the quantity of liquid discharged per unit length of discharge periphery influenced atomization. The smaller the quantity of liquid, the finer the atomization. On the basis of these two observations, it is believed that the liquid disintegration was largely the result of turbulence of the high-velocity liquid stream as it left the vanes. In this respect, the mechanism is similar to pressure-nozzle atomization. The friction created by the relative velocity of the liquid stream with the surrounding air probably had some effect on the breakup, but not a major one.

The atomization mechanism for liquid disintegration from vaned-disk atomizers is reflected in the generalized drop-size-distribution correlation, which stipulates that finer, more uniform sprays are produced by an increase in peripheral speed, i.e., increased liquid velocity, and by increased wetted periphery or by decreased feed rate, both factors contributing to the formation of thinner films of liquid.

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NOTATION

b = vane height
D = disk diameter
L_p = superficial disk wetted periphery for liquid discharge = nb
L = vane length
N = rotational speed of disk
n = number of vanes for a disk
r = disk radius
R = spray radius or trajectory
R_{99} = radial distance, including 99% of mass of spray.
V_p = disk peripheral speed, ft./sec.
w = liquid feed rate, lb./min.
x = drop diameter
x_{60} = drop diameter below which 60% of the mass of the spray lies.
x_{vs} = Sauter mean drop diameter
y = ordinate value on probability plots

Greek Letters

α = Hatch dispersion coefficient
δ = measure of uniformity
Γ = feed rate of liquid atomized based on wetted periphery, lb./(min.)(ft.)
σ = surface tension
σ_w = standard deviation for generalized weight-distribution correlation
σ_v = standard deviation for generalized drop size
μ = liquid viscosity
ρ = liquid density

Subscripts

m = median value

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