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Measurement of Droplet Sizes by the Diffraction Ring Method (Project MX-527) 44185

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Various techniques have been developed for measuring the droplet size distribution in sprays obtained by pressure injection of a liquid through an orifice or by air-stream atomization. An optical method, known as the corona or diffraction ring method, has found limited application to the study of droplet sizes in sprays. This method involves the use of the phenomenon of the diffraction of light around around a droplet or particle. The theory of the formation of diffraction rings and the experimental techniques used in applying this method are described. The results of the experiments indicate that for many typical sprays the droplet sizes vary so much that the method is not applicable. However, some hollow-cone injectors produce sprays which can be analyzed by this method. Typical results are given for an injector with water injected at various pressures. These values for the droplet size are compared with measurements made using the same injector by other methods.

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MEASUREMENT OF DROPLET SIZES BY THE DIFFRACTION RING METHOD

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I. INTRODUCTION AND SUMMARY

Various techniques have been developed for measuring the droplet size distribution in sprays obtained by pressure injection of a liquid through an orifice or by air-stream atomization. Perhaps the most widely used method consists of catching samples of the spray on coated slides or blotting paper or in oil-filled cells, and counting and measuring the individual droplets. This method involves a large amount of labor and time. Nevertheless, by its use not only a mean droplet size but also a size distribution curve can be obtained. Another method uses rotating cylinders of various diameters (Cf. Refs. 1 and 2). It is applicable only for measuring the size of airborne droplets moving at known velocities and makes use of known capturing coefficients for droplets of various sizes and for cylinders of various sizes. This method has found extensive application in the measurement of fog particles in airplane icing studies.

Other more indirect methods have been devised for obtaining a mean droplet size for sprays. Sauter (Cf. Ref. 3) developed a light absorption method for measuring the mean droplet radius for airborne sprays obtained in carburation of fuels. At this Laboratory the method has been applied to the study of sprays injected under pressure into a moving air stream (Cf. Ref. 4).

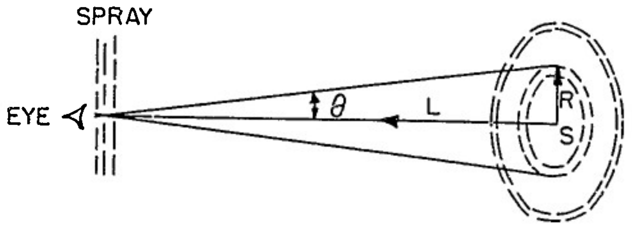
Another optical method that has found limited application to the study of droplet sizes in sprays makes use of the phenomenon of the diffraction of light around a droplet or particle. This is known as the corona or diffraction ring method. It is the purpose of this paper to present briefly the theory of the formation of diffraction rings and to describe the experimental techniques used in applying this method to the measurement of droplet sizes in sprays. The results of the experiments described indicate that for many typical liquid sprays the droplet sizes vary so much that the diffraction ring method is not applicable. However, some hollow-cone injectors produce sprays which can be analyzed by this method. Typical results are given for one such injector with water injected at various pressures. These values for the droplet size are compared with measurements obtained when using the same injector under somewhat similar conditions and measuring the mean droplet size by other methods.

II. THEORY OF LIGHT DIFFRACTION BY DROPLETS

Whenever a parallel beam of light of wavelength λ passes through an optical grating with a grating space equal to l, the beam will be diffracted through an angle θ such that

$$\sin \theta_n = \frac{n\lambda}{l} \tag{1}$$

where n is the order of diffraction. In this case a number of parallel regions of maximum and minimum light intensity will be formed. If the diffraction grating is replaced by a large number of small spherical droplets or solid particles of uniform size, the light will again be diffracted but rings or concentric regions of maximum and minimum intensity will be formed. In order that Equation (1) apply for the above conditions some modifications are necessary. If a point source of monochromatic light is observed through a spray consisting of small droplets of uniform size, diffraction rings will be seen around the light source S as shown in the sketch below. The



following expression gives the relation between θ_n, the angle subtended at the eye by the radius of the nth dark ring, the droplet diameter d, and the wavelength of the light (Cf. Refs. 5, 6, 7, and 8):

$$\sin \theta_n = \frac{(n+0.22)\,\lambda}{d} \tag{2}$$

Since the angle θ is very small, $\sin \theta_n$ can be replaced by $\tan \theta_n = R_n/L$ where R_n is the radius of the nth dark ring and L is the distance from the light source to the spray.

Equation (2) can then be written

$$d = \frac{(n+0.22)\,\lambda}{\sin \theta_n} = \frac{(n+0.22)\,\lambda\, L}{R_n} \tag{3}$$

If white light is used instead of monochromatic light, various colored rings will appear, and the analysis becomes more complicated.

III. DIFFRACTION RING METHOD

The diffraction ring method of measuring droplet sizes in sprays has the advantage that it is simple to use and does not disturb the spray pattern in any way as is the case when samples are removed. This method, however, has definite limitations. If the droplets are too large, the angle of diffraction will be so small that accurate measurements cannot be made. For droplets 0.4 mm in diameter θ would be only about 5′ of arc. If the droplet size approaches the wavelength of light, the diffraction rings disappear and the Tyndall effect appears. According to Mecke (Cf. Ref. 7) Equation (3) is valid only for values of $d > 0.008$ mm. If the droplet sizes in the spray vary too greatly, the discrete rings will disappear and only a bright halo will surround the light source.

Bock (Cf. Ref. 9) used this method to measure the size of the water droplets formed when a jet of steam was blown into free air. He measured droplet diameters ranging from 0.0034 to 0.0046 mm. Humphreys (Cf. Ref. 6) reported that cloud droplets commonly average about 0.005 mm, and Kuehn (Cf. Ref. 5) gave values somewhat larger than Humphreys' measurements. In sprays obtained by pressure injection, the size

of the droplets formed is frequently within the range for which the diffraction ring method should be applicable. Kuehn applied this method to sprays and found that when he observed a light source through various parts of the spray cone, a brightening effect occurred but nowhere was he able to detect the definite diffraction rings. He concluded that the droplet sizes in the sprays produced by pressure injection varied so widely that this optical method was not useful for making measurements.

At this Laboratory, attempts have been made to measure droplet sizes in sprays from solid-cone injectors using the diffraction method. It was found that no definite diffraction rings could be observed. However, when the experiments were repeated, using small hollow-cone injectors, the droplets were sufficiently small and uniform in size to permit the observation of very definite diffraction rings.

IV. EXPERIMENTAL PROCEDURE

The setup used at this Laboratory for the production and measurement of diffraction rings in liquid sprays consisted essentially of an injector, a pressurized reservoir, a point source of light, and a view camera.

Figure 1 shows a schematic diagram of this setup. The spray was produced by a Spraco J318D hollow-cone injector with an orifice 0.018 inch in diameter. The reservoir was pressurized from a nitrogen bottle through a pressure regulator. The spray receiving tank was vented at the bottom in order to reduce air turbulence around the spray cone.

The light source used for preliminary visual observations of the diffraction phenomenon was a 2-watt Western Union concentrated arc lamp. For photographic purposes a monochromatic light source was obtained by using a Wratten No. 62 green filter with a mercury arc lamp. In this way, light from the 5461 Å line of mercury was obtained. In order to obtain an approximate point source, the light from the mercury arc was concentrated, by means of a lens, upon a diaphragm containing a small circular hole 0.03 inch in diameter.

A 5x7-inch view camera with an 18-inch focal length Zeiss Tessar lens was used to photograph the diffraction rings. The camera and light source were interconnected so that whenever the camera was moved in order to photograph the diffraction pattern through various parts of the spray, the relation between camera and light source remained fixed. Several photographs could be obtained on the same negative by merely moving the film holder between successive exposures. The magnification of the camera was checked by photographing diffraction patterns obtained through diffraction gratings of known constants.

Visually as many as four or five orders of diffraction rings have been observed when viewing a monochromatic light source through a spray. The intensity of the outer rings was so low that they could not be photographed without overexposing the film by the inner rings. Figure 2 shows examples of photographs of diffraction rings. These were obtained through different sections of the same spray cone: (a) at a distance of 2 inches from the center, (b) at a distance of 3 inches from the center, and (c) at a distance of 4 inches from the center. All three were taken 7 inches downstream of the injector. It will be noted that the size of the rings increases as the center of the spray is approached, indicating that the droplet sizes decrease. At the very center of the cone no distinct rings could be observed. For each of these photographs the injection pressure was held at 100 psi. The photographs were made on Super XX film with an exposure time of 3 minutes.

Two methods were used to obtain the radius of the diffraction rings from the photographic negatives. The positions of maximum and minimum intensity were estimated on the negatives, and the radii of the rings obtained by the use of calipers. This method was rather highly subjective. A plot of the density variations along a diameter of the rings was then obtained with a Leeds and Northrup microdensitometer. Figure 3 shows these plots of the negative density as a function of the distance from the center of the rings. These microdensitometer curves were obtained from the photographic negatives corresponding to the photographs in Figure 2. The ordinate corresponding to the density is plotted on a logarithmic scale. The points A_1 correspond to the first dark ring and A_2 to the second dark ring. According to the microdensitometer record (Cf. Fig. 3), what appears to be a darker ring in Figure 2 is merely an abrupt change in the density, not really a region of minimum density in the original negative. Curve *b* of Figure 3 shows some indication of the existence of rings of minimum and maximum intensity. However, all the other records obtained were similar to curves *a* and *c* of Figure 3. The appearance of distinct dark and light rings in the photographs in Figure 2 is apparently due mainly to a visual response to an abrupt change in intensity. The diameters D_1 and D_2 of the first- and second-order diffraction rings, respectively, can be measured from the curves and the droplet size calculated from Equation (3). The values for D_2 were more difficult to determine than the values for D_1 from the microdensitometer records.

V. RESULTS OF DROPLET SIZE MEASUREMENTS

A number of quantitative data have been obtained using the photographic method and the same injector. Photographs were taken of the diffraction rings through the spray at points 1, 2, 3, 4, and 5 inches from the axis of the cone and 7 inches downstream of the injector. The injection pressure was kept constant at 100 psi. Then photographs were taken through a point 2 inches from the axis of the spray cone while varying the injection pressure from 50 to 175 psi. The negatives were measured by the microdensitometer and the corresponding droplet size was calculated. Table I summarizes the data obtained and the calculated values of the droplet diameter *d*: column 4, the radius of the first-order dark ring as measured by a caliper; columns 5 and 6, the radii of the first- and second-order dark rings, respectively, as obtained from the microdensitometer record; column 7, the droplet diameters obtained from the data in column 4; and columns 8 and 9, the droplet diameters obtained from the data in columns 5 and 6, respectively; column 10, values for the droplet diameters obtained by averaging the values in columns 7 and 8. It will be noted that the values obtained by estimating the various first-order dark rings and measuring them with calipers agree rather closely with those obtained by use of the microdensitometer. Since the second-order diffraction rings are indistinct, their diameters are uncertain. The values of *d* calculated from these diameters will also be uncertain.

In Figure 4 are plotted the droplet diameters as a function of the position in the spray cone. These data correspond to tests 30, 31, and 32 in Table I and to Figures 2 and 3. In Figure 5 is shown the relation between injection pressure and droplet size for a position 2 inches from the center of the spray cone.

VI. CONCLUSIONS

The values obtained for the droplet sizes by the diffraction ring method are consistent and reproducible. However, the sprays for which the values were obtained were not homogeneous. Thus the exact significance of the droplet diameter as obtained by this method is not clear; i.e., whether it is a mean* diameter or the diameter of the droplets representing the maximum in the distribution curves obtained when the number of droplets in a spray sample is plotted against the diameter.

Table I shows that for an injection pressure of 100 psi the droplet diameter 2 inches from the center of the spray and 7 inches downstream of the injector was found to be 81.7 μ by the diffraction ring method. A size distribution curve was obtained for the same injector under the conditions where the water spray was injected into an air stream in a 3-inch duct. The injection pressure was 100 psi and the air velocity 20 ft/sec. Samples of the spray were collected on small smoked slides passed rapidly across the duct, and the droplets were counted and measured. The samples were taken 8 inches downstream from the injector. The mean droplet diameter under these conditions was found to be 58 μ, and the maximum of the distribution curve occurred at about 34 μ. Figure 6 shows the distribution curves obtained by the above method. The mean droplet diameter obtained under the same conditions but measured by the light absorption method using a photometer was found to be about 55 μ. The values for the mean droplet diameter as obtained by the last two methods is a volume-to-surface area mean.

These results seem to indicate that the values obtained for the droplet sizes by the diffraction ring method do not agree very well with either those obtained for the mean droplet size by other methods or with the maximum in the distribution curve. This difficulty does not necessarily indicate that Equation (3) is incorrect but perhaps that it is restricted in its use to applications where the droplets are of fairly uniform size. It was not possible to test the diffraction ring method under such ideal conditions.

For the heterogeneous types of sprays obtained by pressure injection of liquids through an orifice, this method can be of definite value in obtaining a qualitative comparison of the droplet sizes for various injection conditions. When more data are available, perhaps some correlation can be found between the quantitative values for droplet sizes in sprays obtained by the diffraction ring method and those obtained by the use of the other methods.

*The term mean droplet diameter in a spray sample needs defining. A number of different definitions can be used depending upon the property of the spray in which one is interested. In combustion studies the ratio of the volume of the droplets to their surface area is an important property of a fuel spray. If the droplets in a sample of such a spray can be separated into a number of groups each containing i_r droplets of diameter d_r, the mean droplet diameter can be defined as $\Sigma(i_r d_r^3)/\Sigma(i_r d_r^2)$.

TABLE I

SUMMARY OF DATA FROM DROPLET SIZE MEASUREMENTS

1 Test No.	2 Distance from Center of Cone (in.)	3 Injection Pressure (psi)	4 Radius of First Dark Ring* (cm)	5 Radius of First Dark Ring** (cm)	6 Radius of Second Dark Ring** (cm)	7 Droplet Diameter* d_1 (μ)	8 Droplet Diameter** d_1 (μ)	9 Droplet Diameter** d_2 (μ)	10 Mean Droplet Diameter d_1 (μ)
30	4	100	1.22	1.23	2.15	93.8	93.0	97.0	93.4
31	3	100	1.32	1.29	2.29	86.8	87.5	91.0	87.1
32	2	100	1.38	1.42	2.55	83.0	80.5	82.0	81.7
34	2	50	1.23	1.23	2.24	93.0	93.0	93.0	93.0
35	2	75	1.33	1.33	2.45	86.0	86.0	85.0	86.0
36	2	125	1.48	1.47	2.65	77.2	78.0	78.6	77.6
37	2	175	1.56	1.57	2.96	73.3	73.0	70.4	73.1

*Measured from negative by calipers.

**Measured from negative by midrodensitometer.

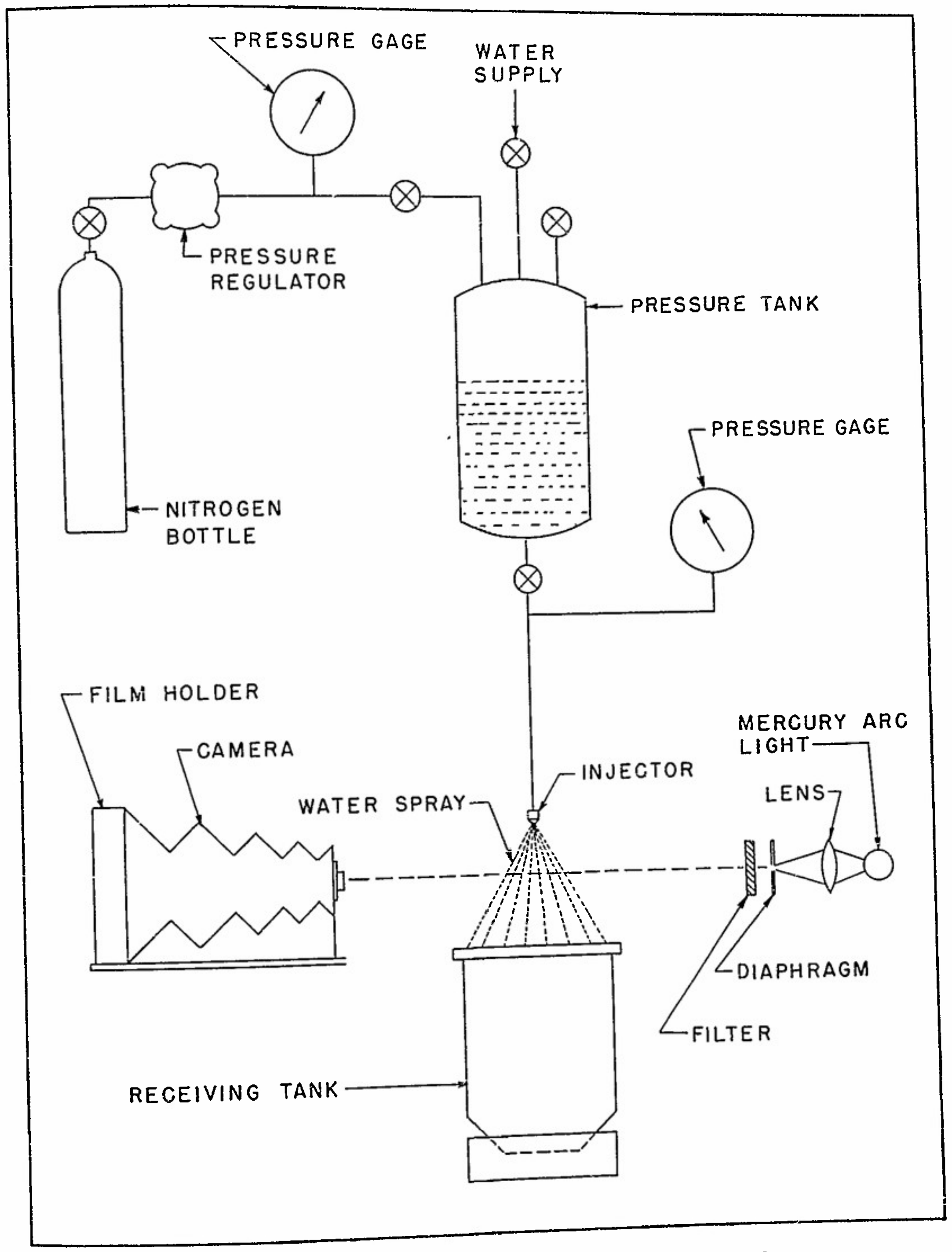


Figure 1. Laboratory Setup for Study of Droplet Sizes in Sprays by Diffraction Ring Method

TABLE I

SUMMARY OF DATA FROM DROPLET SIZE MEASUREMENTS

1 Test No.	2 Distance from Center of Cone (in.)	3 Injection Pressure (psi)	4 Radius of First Dark Ring* (cm)	5 Radius of First Dark Ring** (cm)	6 Radius of Second Dark Ring** (cm)	7 Droplet Diameter* d_1 (μ)	8 Droplet Diameter** d_1 (μ)	9 Droplet Diameter** d_2 (μ)	10 Mean Droplet Diameter d_1 (μ)
30	4	100	1.22	1.23	2.15	93.8	93.0	97.0	93.4
31	3	100	1.32	1.29	2.29	86.8	87.5	91.0	87.1
32	2	100	1.38	1.42	2.55	83.0	80.5	82.0	81.7
34	2	50	1.23	1.23	2.24	93.0	93.0	93.0	93.0
35	2	75	1.33	1.33	2.45	86.0	86.0	85.0	86.0
36	2	125	1.48	1.47	2.65	77.2	78.0	78.6	77.6
37	2	175	1.56	1.57	2.96	73.3	73.0	70.4	73.1

*Measured from negative by calipers.

**Measured from negative by midrodensitometer.

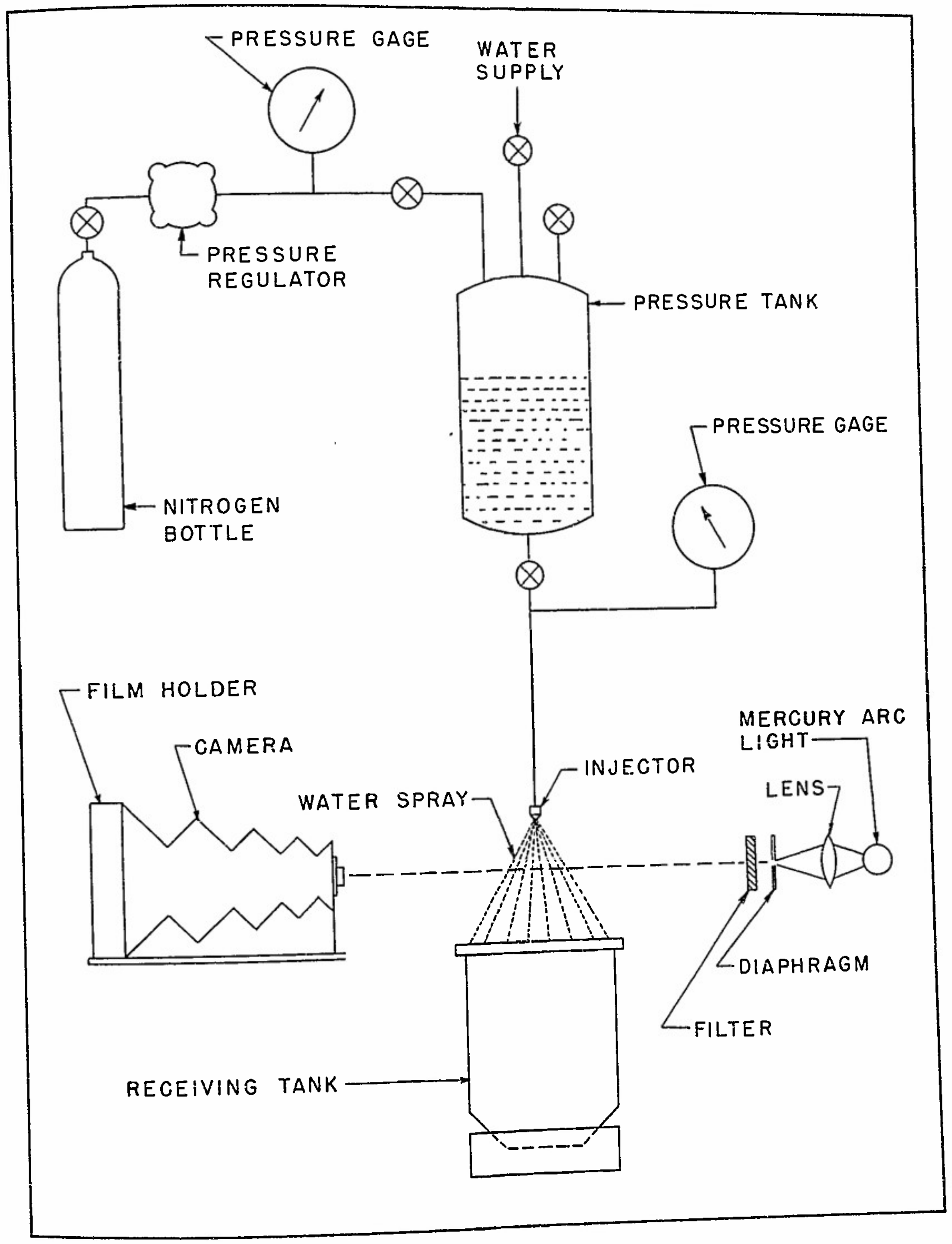


Figure 1. Laboratory Setup for Study of Droplet Sizes in Sprays by Diffraction Ring Method

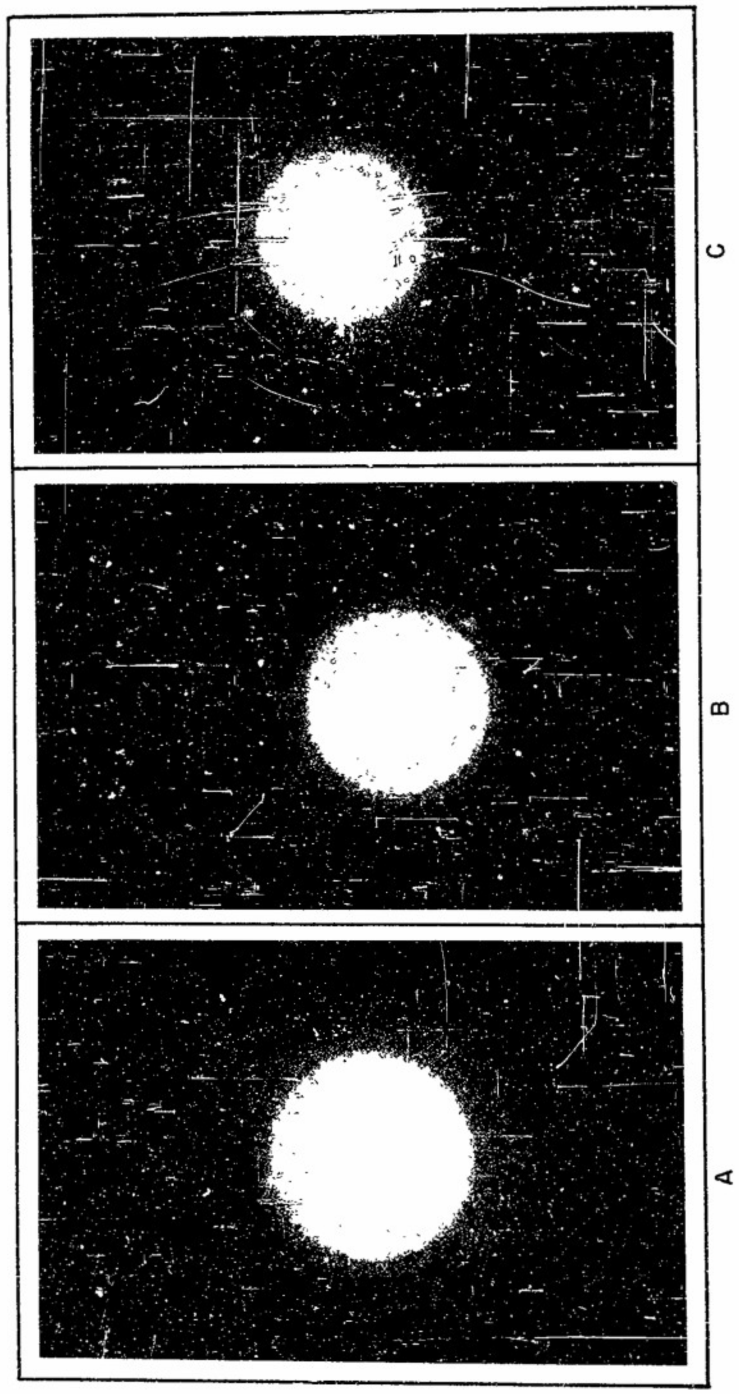


Figure 2. Diffraction Rings Obtained in Spray (Injection Pressure 100 psi)
A. Taken 2 Inches from Center of Spray
B. Taken 3 Inches from Center of Spray
C. Taken 4 Inches from Center of Spray

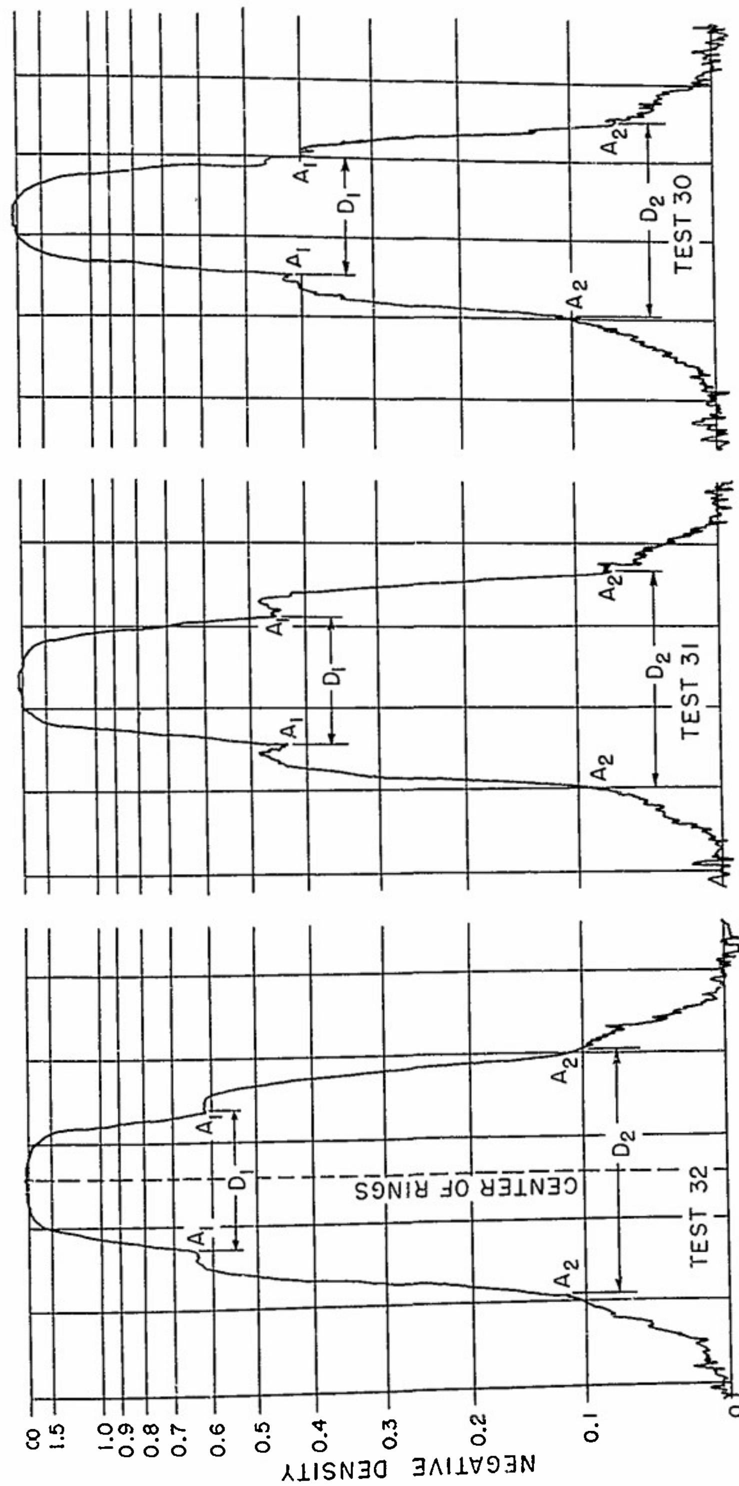


Figure 3. Densitometer Curves for Diffraction Rings of Figure 2

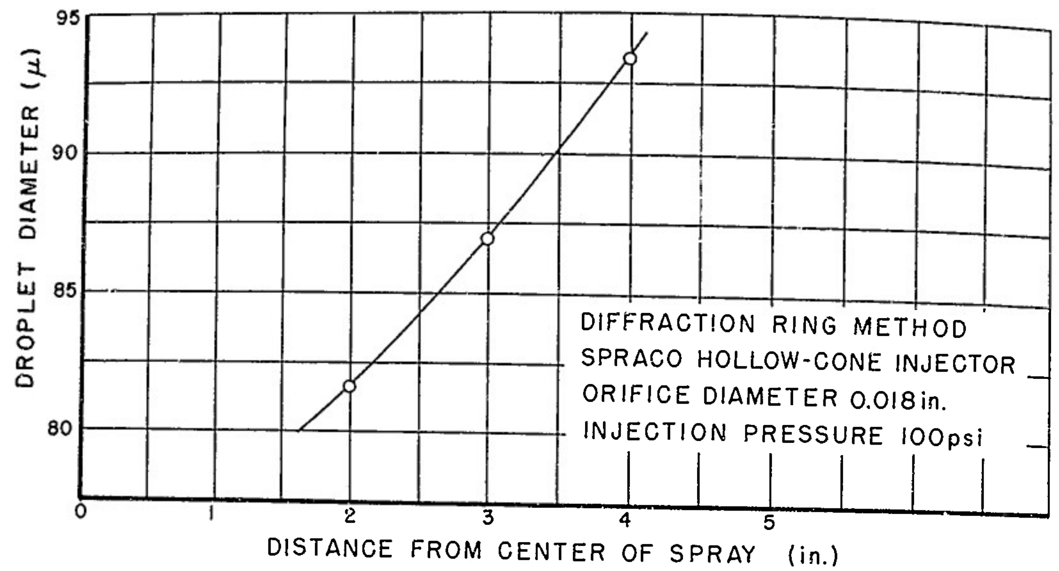


Figure 4. Droplet Diameter vs Position in Spray Cone

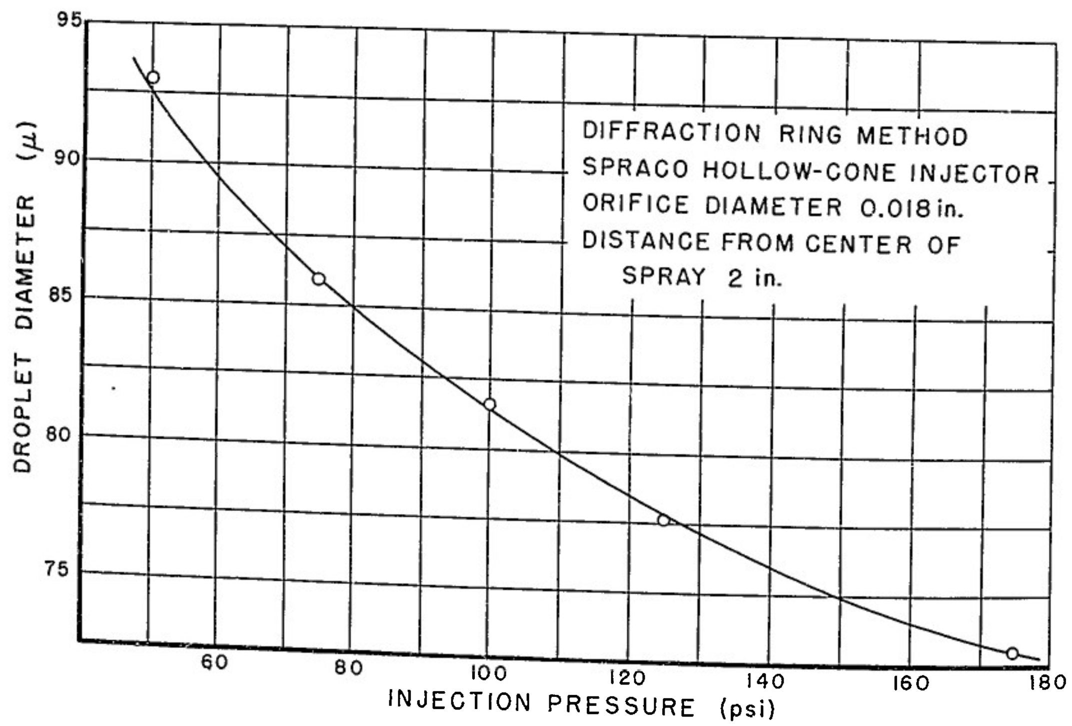


Figure 5. Droplet Diameter vs Injection Pressure

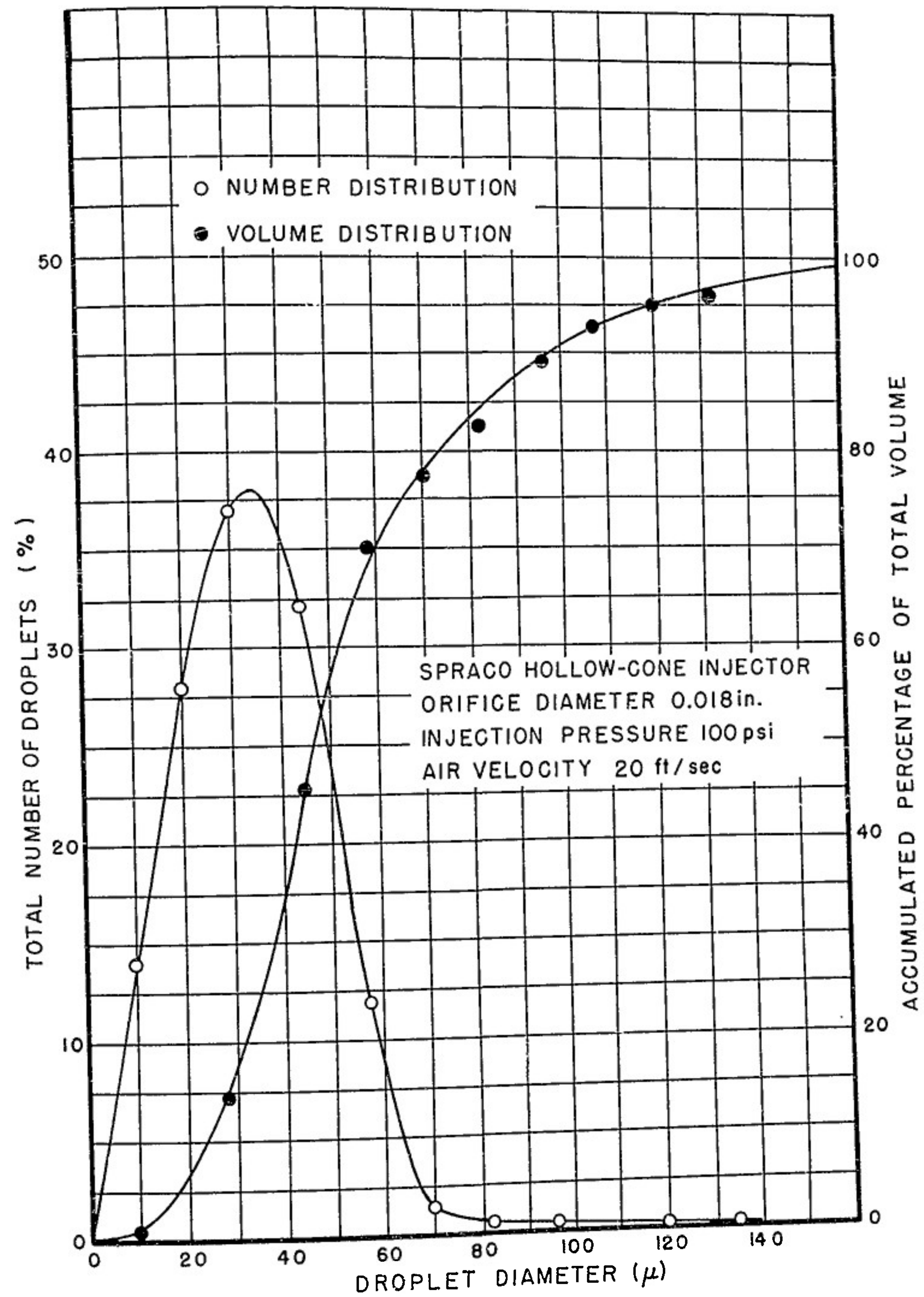


Figure 6. Distribution Curves for Spray Sample of Water Injected into Air Stream

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