

Formation and Characterization of Simulated Small Droplet Icing Clouds

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FORMATION AND CHARACTERIZATION OF SIMULATED SMALL DROPLET ICING CLOUDS

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Abstract

Two pneumatic two-fluid atomizers operating at high liquid and gas pressures produced water sprays that simulated small droplet clouds for use in studying icing effects on aircraft performance. To measure the volume median diameter, MVD or $D_{V,5}$, of small droplet water sprays, a scattered-light scanning instrument was developed. Drop size data agreed fairly well with calculated values at water and nitrogen pressures of 60 and 20 psig, respectively, and at water and nitrogen pressures of 250 and 100 psig, respectively, but not very well at intermediate values of water and nitrogen pressure. MVD data were correlated with D_0 , W_n , and W_w , i.e., orifice diameter, nitrogen, and water flowrate, respectively, to give the expression for MVD in microns:

$$MVD = 48 D_0^{0.2} W_w^{0.4} W_n^{-0.8}$$

for values of $MVD > 8 \mu m$, since MVD is influenced by the loss of vaporizing small drops. Values of D_0 , W_w , and W_n are in centimeters and grams/second, respectively. Also, exponents for the Rosin-Rammler and Nukiyama-Tanasawa drop size distribution expressions, N_r and N_n , respectively, were obtained with the Scattered-Light Scanner and correlated to give the relationship: $N_r = 2.8 N_n^{0.45}$.

Introduction

In applying atomization techniques to the study of icing clouds, there is considerable demand for spray nozzles capable of producing small droplets with volume median drop diameters, MVD, below $10 \mu m$. Also, drop sizing instruments are needed that are capable of accurately measuring high density clouds with values of MVD below $10 \mu m$. In the present investigation, a spray nozzle was used at high fluid pressures to produce sprays with values of MVD considerably below $10 \mu m$. Also in this study an improved version of the Scanning Radiometer drop size measuring instrument that is now called the Scattered Light Scanner was developed at the NASA Lewis Research Center.

In previous wind tunnel studies¹ various instruments were tested for agreement in measuring values of MVD for icing clouds produced by atomizers in the NASA Lewis Icing Research Tunnel. As a result it was found that a given laser instrument did give good reproducibility of measured values of MVD. However, there was considerable disagreement noted between different instruments although they were of the same model and were calibrated with the same technique and standards. This indicated the need for additional testing and comparison of various drop sizing instruments for application to wind tunnel testing. It also demonstrated the need for a more basic understanding of the atomization process and especially the need for knowing how the

interaction of hydrodynamic and aerodynamic forces on liquid surface forces will control the breakup of liquid jets and sheets.

Once a spray nozzle is selected for wind-tunnel icing tests, it is necessary to specify very precisely the nozzle operating conditions in order to consistently produce small-droplet icing clouds. This investigation was undertaken to determine how closely flow rates of nitrogen and water had to be controlled to obtain good reproducibility of both MVD and SMD, as well as the drop size distribution parameters. Under certain unfavorable conditions, multimodal drop size distributions are produced instead of the desired single mode Nukiyama-Tanasawa or Rosin-Rammler type of distribution.

In the present study of liquid jet atomization, the effects of fluid dynamic forces on the MVD, $D_{V,5}$, and SMD, D_{32} , were measured in the regimes of both capillary-wave and acceleration-wave breakup. The water sprays were formed in a low velocity airstream of 5 m/sec, and the effect of water and nitrogen gas flow rates on MVD and SMD were investigated at a liquid and gas pressure range of 15 to 1000 psig and at a distance of 25 cm downstream of the atomizer.

Nomenclature

MVD	volume median drop diameter, $D_{V,5}$, μm
N_n	exponent for Nukiyama-Tanasawa expression
N_r	exponent for Rosin-Rammler expression
P	fluid static pressure, psig
SMD	Sauter mean diameter, D_{32} , μm
w	weight flow of fluid, lb/sec or g/sec

Subscripts

n	nitrogen gas
o	zero gas flow
w	water

Apparatus and Procedure

The atmospheric pressure test section and the scattered light scanner optical path are shown in Fig. 1. Airflow was drawn from the laboratory supply system at ambient temperature (293 K) and exhausted to the atmosphere while airflow rate in the test section was determined with an orifice and controlled by opening an air flow control valve and setting the air velocity at 5 m/sec. The test section is 1 m in length with an inside diameter of 0.24 m.

Two pneumatic two-fluid atomizers were used to produce clouds of small diameter water droplets. They were operated over water and nitrogen gas pressure ranges of 15 to 1000 psig, respectively, as shown in Fig. 2. The atomizer injected water sprays in the airflow at the test section center line 5 cm upstream of the duct exit and 25 cm from the center line of the 7.5 cm-diameter laser beam as shown in Fig. 1. A detailed diagram of the atomizer is shown in Fig 3.

Water at 293 K as determined with an I.C. thermocouple was axially injected in the airstream by gradually opening a waterflow control valve until the desired flow rate was obtained as indicated by a turbine flowmeter. Nitrogen gas was then turned on and weight flowrate was measured with a sharp edge orifice.

When air, nitrogen, and water flowrates were set, volume median and Sauter mean diameters as well as drop size distribution parameters were determined with the scattered-light scanner. Its optical system shown in Fig. 2 consisted of a 1-mW helium-neon laser, a 0.003-cm-diameter aperture, a 7.5-cm-diameter collimating lens, a 10-cm-diameter converging lens, a 5-cm-diameter collecting lens, a scanning disk with a 0.05-cm slit, a timing light, and a photomultiplier detector. A more complete description of the scattered-light scanner, the mean drop diameter range, and the method of determining mean particle diameter are discussed in Refs. 2 and 3.

Experimental Results

The dynamic force of an assist nitrogen gas flow and the hydrodynamic force of the liquid flow was used to atomize water jets and produce clouds of relatively small droplets in low velocity airstreams as shown in Fig. 1. The volume median drop diameter, MVD, the Sauter mean diameter, SMD, and exponents for the Rosin-Rammler and Nukiyama-Tanasawa drop size distribution expressions were determined to characterize the water sprays.

Correlation of MVD With Parameter $P_W - P_N$

MVD data obtained with the scattered-light scanner are plotted against the difference between water and air pressures, $P_W - P_N$, as shown in Fig. 4. Also shown in this figure is a comparison of the MVD data with values calculated according to Eqs. (A-2) and (A-3) given in Ref. 1. At low water and nitrogen pressures, i.e., $P_N = 20$ and $P_W - P_N = 40$ psig, the experimental and calculated values of MVD agree fairly well but the effect of $P_W - P_N$ on MVD was found to be considerably less than that predicted by the equations in Ref. 1. Also, at high nitrogen pressures of 100 or 200 psig the agreement was fairly good with values of $P_W - P_N$ in the order of 150 psig. The MVD data were obtained at a distance of 25 cm downstream of the atomizer and the results were undoubtedly markedly influenced by the evaporation and dispersion of small droplets prior to sampling the spray at the location of the scattered-light scanner. To check the effect of vaporization on MVD, the diameter of droplets that would be completely vaporized were calculated from the vaporization rate expressions given in Ref. 4 and the results are shown in Fig. 5. From this plot it is evident that the loss of small droplets due to evaporation and dispersion would tend to make the

measurements of MVD too large and they should be corrected for these effects. To make such a correction based on experimental data, the spray should be sampled at several locations downstream which was not attempted in the present study.

Water Flowrate Correlation With Water and Nitrogen Pressures

The variation of nitrogen pressure, P_N , with water pressure, P_W , at zero and constant water flowrate, W_W , is shown in Figs. 6(a) and 6(b) for the two atomizers used in this study. The data show that values of P_N were considerably above those of P_W at zero and constant water flowrates and also that a general expression relating water and nitrogen pressures to water flowrate may be written as follows:

$$P_W = P_{W,0} + 0.74 P_N \quad (1a)$$

for the large atomizer with orifice diameter $D_0 = 0.064$ cm and

$$P_W = P_{W,0} + 0.45 P_N \quad (1b)$$

for the small atomizer with $D_0 = 0.038$ cm, where $P_{W,0}$ is the water pressure when nitrogen gas pressure, P_N , is zero. For this condition, $P_N = 0$, water flow rate, W_W , is plotted against $P_{W,0}$ as shown in Fig. 7 and the following expressions are obtained:

$$W_W = 0.0090 P_{W,0}^{0.5} \quad (2a)$$

and

$$W_W = 0.005 P_{W,0}^{0.5} \quad (2b)$$

for the large and small flowrate atomizers, respectively.

Substituting Eqs. (2a) and (2b) into Eqs. (1a) and (1b), respectively gives the following expressions:

$$W_W = 0.0090 (P_W - 0.74 P_N)^{0.5} \quad (3a)$$

and

$$W_W = 0.0050 (P_W - 0.45 P_N)^{0.5} \quad (3b)$$

for the large and small flowrate atomizers, respectively. Generally it is expected that $W_W \sim (P_W - P_N)^{0.5}$ and that $W_W = 0$, when $P_N = P_W$. However, in this study P_N was not measured inside the atomizer tube and was assumed approximately 74 percent of the measured values of P_N as given in Eq. (3a). Therefore, an attempt was made to correlate MVD with W_W instead of with the parameter $P_W - P_N$.

Correlation of MVD With Flowrates, W_N and W_W

Since liquid jet atomization can be controlled by either hydrodynamic or aerodynamic forces that are functions of W_W and W_N , respectively, it may be assumed that:

$$MVD = f(W_N^a, \text{ and } W_W^b) \quad (4)$$

where a and b are experimentally determined exponents.

In Fig. 8, MVD is plotted against nitrogen flowrate, W_n , at constant values of water flowrate, W_w . This plot shows that:

$$\text{MVD} \sim W_n^{-0.8} \quad (5)$$

for values of MVD $> 8 \mu\text{m}$. For MVD's less than $8 \mu\text{m}$, it appears that the scattered-light scanner may not be sensitive enough to measure them accurately. Also, judging from the calculations shown in Fig. 5, it is apparent that the disappearance of $6 \mu\text{m}$ diameter drops or less due to vaporization can also explain the slope dropping off at values of $W_n > 10^{-2} \text{ lb/sec}$.

From cross plots such as that shown in Fig. 9, the following relationship is obtained:

$$\text{MVD} \sim W_w^{0.4}, \text{ and } D_0^{0.2} \quad (6)$$

Thus, from the relationships given in Eqs. (5) and (6) it is found that:

$$\text{MVD} = 48 D_0^{0.2} W_w^{0.4} W_n^{-0.8} \quad (7)$$

for values of MVD from 8 to $80 \mu\text{m}$, W_w from 3.16 to 12.5 g/sec, and W_n from 0.91 to 9.1 g/sec.

Correlation of Drop Size Distribution Characteristics

To further characterize the sprays, Rosin-Rammler and Nukiyama-Tanasawa drop size distribution exponents N_r and N_n , respectively, were obtained with the scattered-light scanner. A plot of the data is shown in Fig. 10 and the following relation between N_r and N_n was obtained:

$$N_r = 2.8 N_n^{0.45} \quad (9)$$

From the data plotted in Fig. 11 and from a cross plot of this figure, the following relations are obtained:

$$\text{MVD/SMD} = 2.52 N_r^{-0.75} W_w^{0.06} \quad (10)$$

and in terms of N_n

$$\text{MVD/SMD} = 1.17 N_n^{-0.35} W_w^{0.06} \quad (11)$$

Combining Eqs. (10) and (11) yields Eq. (9). Also, it was noted that as drop size was reduced values of MVD/SMD approached unity and the spray appeared to have a more narrow drop size distribution.

Concluding Remarks

Pneumatic two-fluid atomizers operating at high fluid pressures produced small droplet clouds and the drop size measuring instrument or scattered-light scanner developed in this investigation gave MVD measurements of water sprays as small as $5 \mu\text{m}$. However, due to the effects of evaporation and dispersion on the spray sample, only values of MVD $> 8 \mu\text{m}$ were correlated with operating variables to give the expression:

$$\text{MVD} = 48 D_0^{0.2} W_w^{0.4} W_n^{-0.8}$$

over the ranges, $D_0 = 0.038$ to 0.064 cm , $W_w = 3.16$ to 12.5 g/sec , and $W_n = 0.91$ to 9.1 g/sec . Exponents N_r and N_n for the Rosin-Rammler and Nukiyama-Tanasawa expressions gave the following correlation: $N_r = 2.8 N_n^{0.45}$ and they were related to the ratio MVD/SMD as follows:

$$\text{MVD/SMD} = 2.52 N_r^{-0.75} W_w^{0.06}$$

and

$$\text{MVD/SMD} = 1.17 N_n^{-0.35} W_w^{0.06}$$

where W_w is given in grams/second. Droplet vaporization rate calculations indicated that droplets initially having diameters in the order of 6 m or less were completely vaporized in a distance of 25 cm with a liquid jet velocity of 9.8 m/sec . Hence, it was assumed that the very small droplets were lost from that portion of the spray being sampled due to their vaporization and dispersion, especially at low liquid injection velocities.

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4. Ingebo, R.D.: Vaporization Rates and Heat-Transfer Coefficients for Pure Liquid Drops. NACA TN-2368, 1951.

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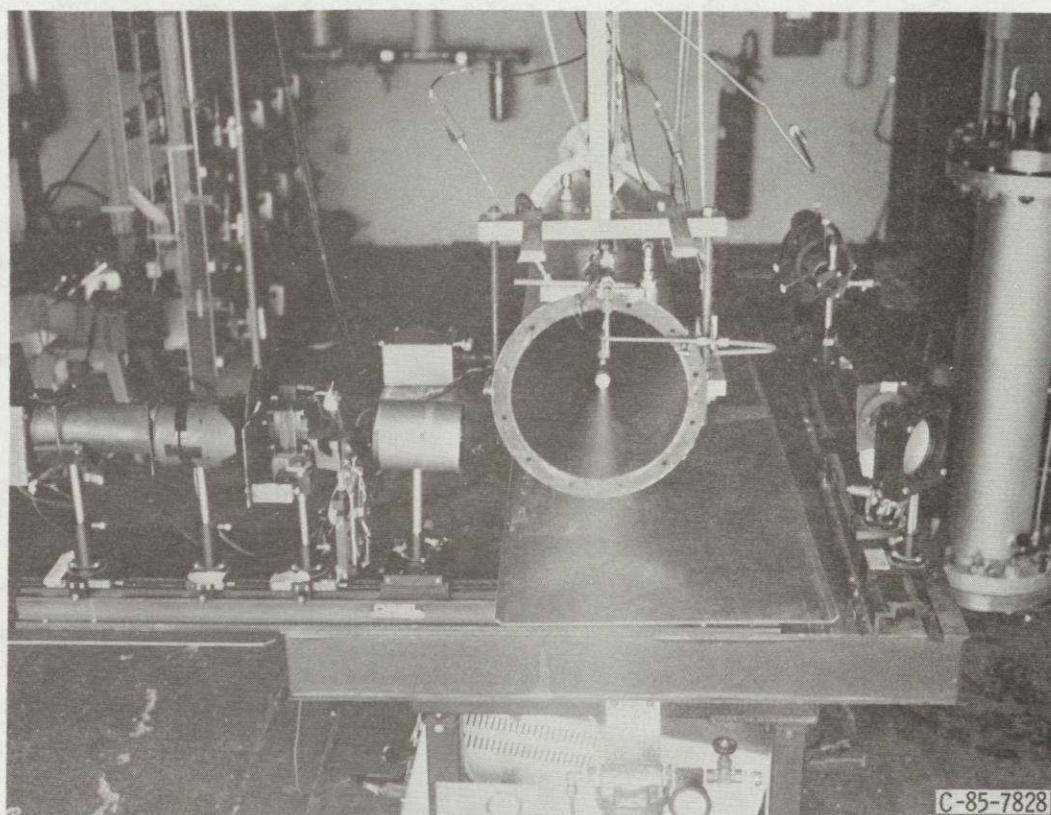


Figure 1. - Apparatus and auxilliary equipment.

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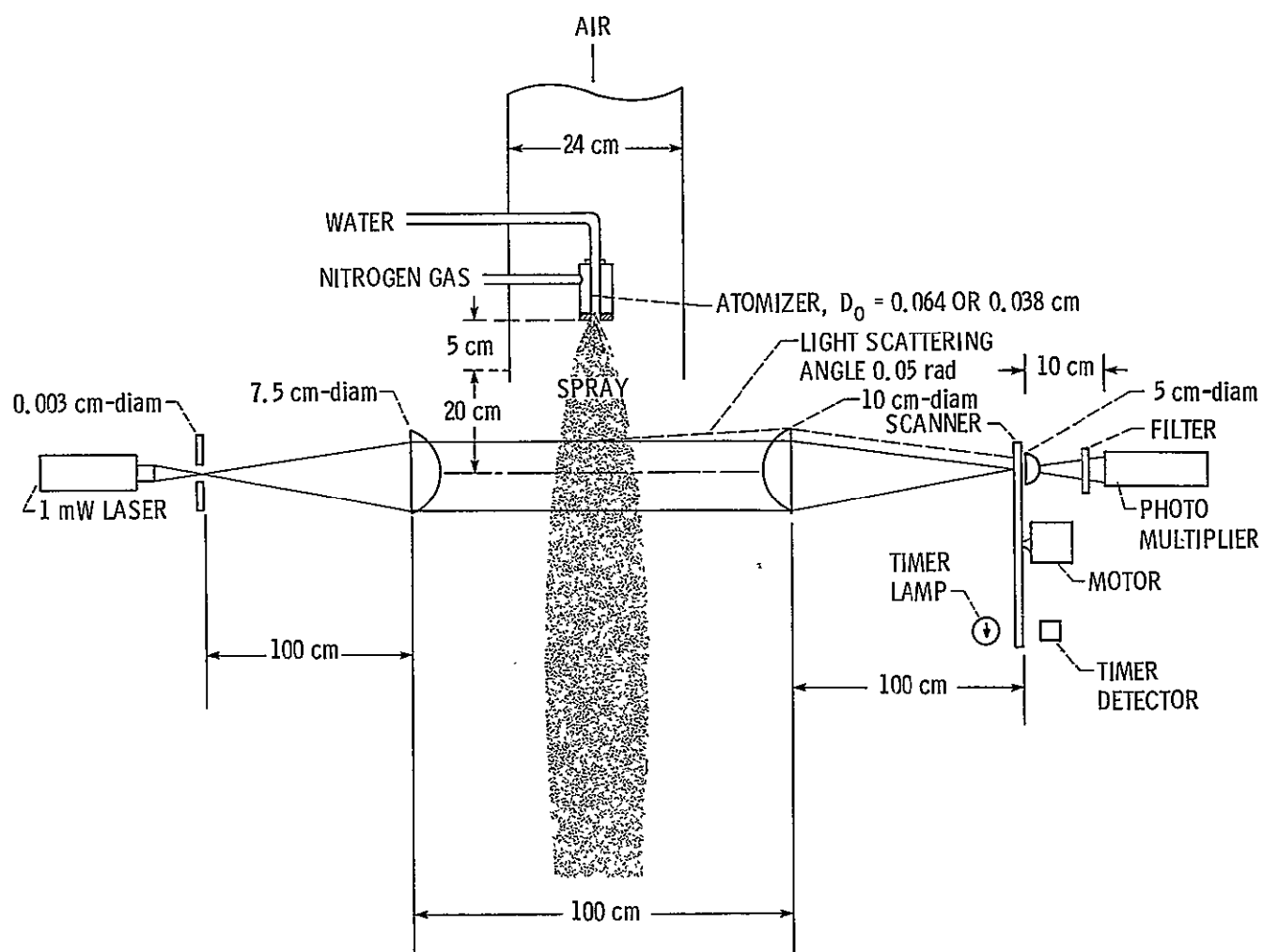


Figure 2. - Atmospheric pressure test section and optical path of scattered-light scanner.

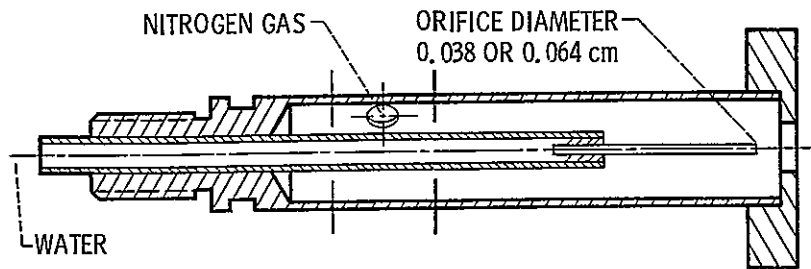


Figure 3. - Diagram of pneumatic two-fluid atomizer.

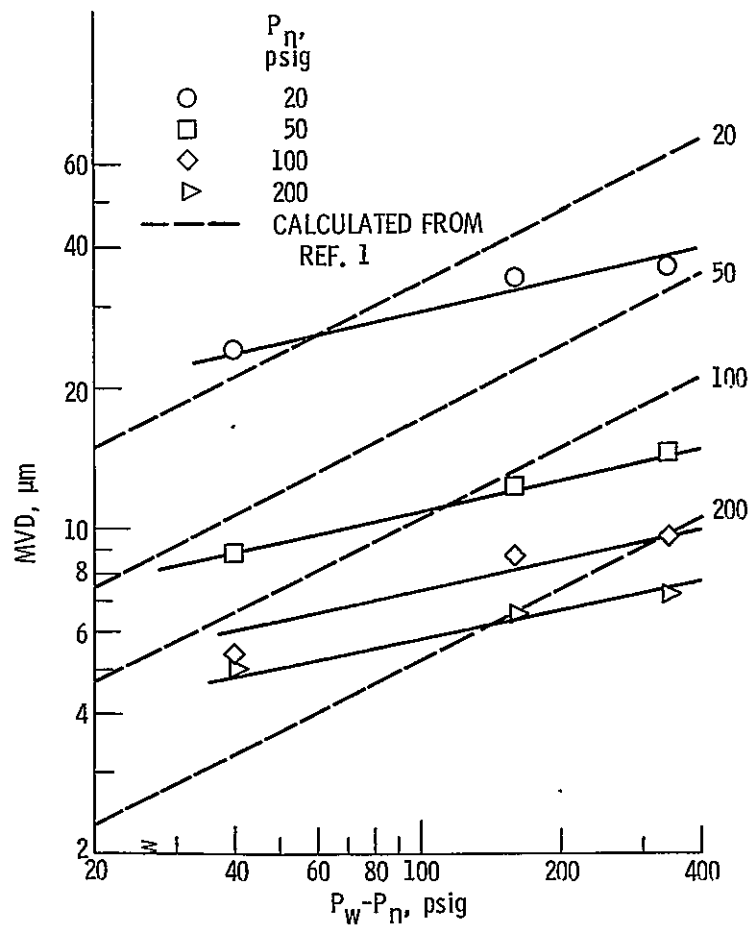


Figure 4. - Variation of MVD with parameter $P_w - P_n$.

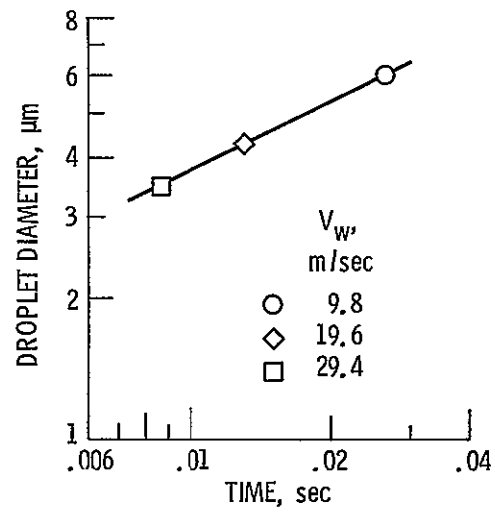


Figure 5. - Variation of diameter of completely vaporized droplet with vaporization time, for three liquid jet velocities. Calculated from ref. 4.

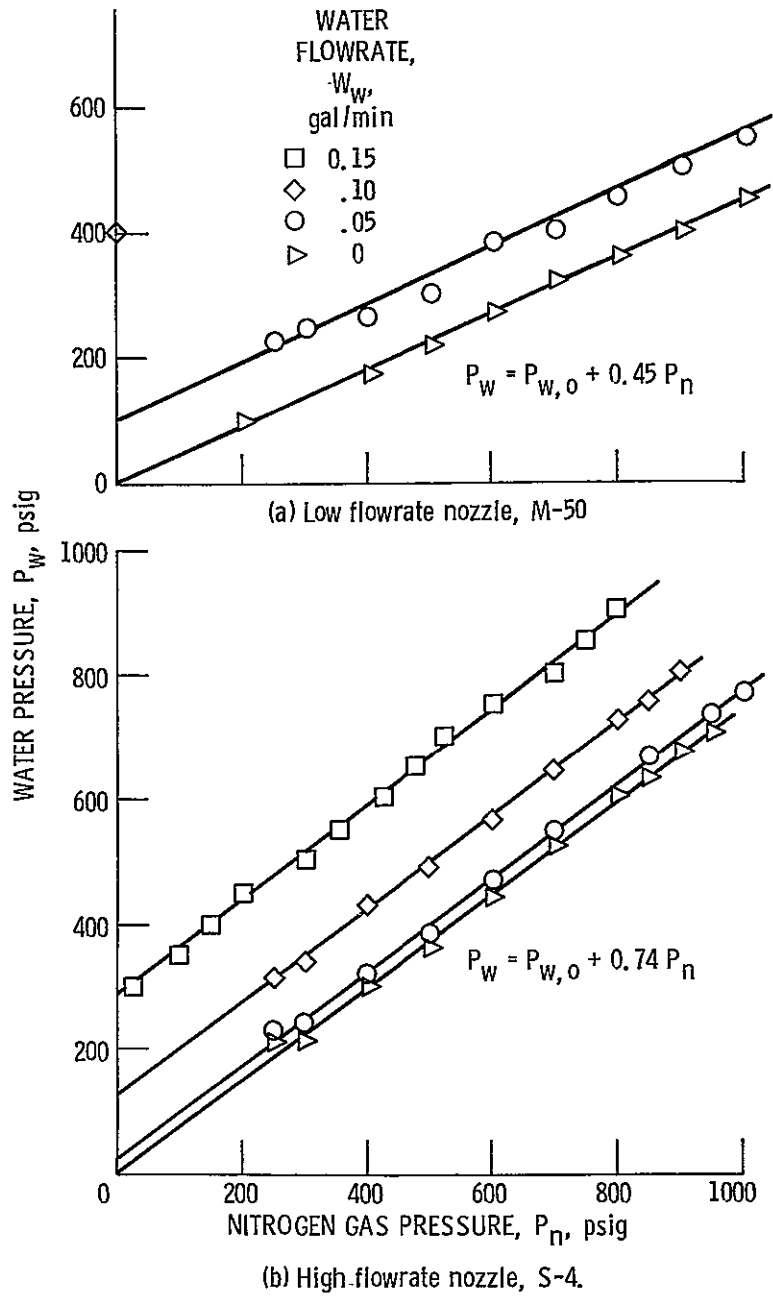


Figure 6. - Variation of water and nitrogen gas pressures at zero and constant water flowrates.

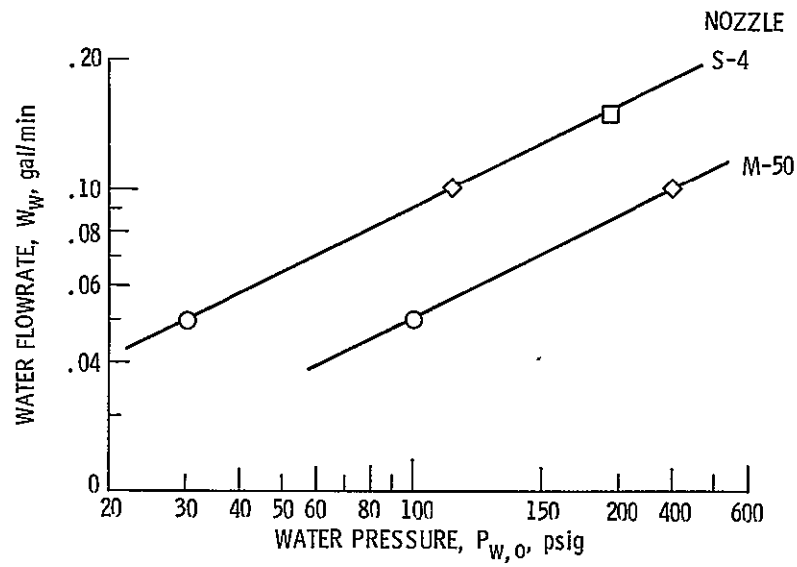


Figure 7. - Variation of water flowrate with pressure at zero nitrogen gasflow, $P_n = 0$.

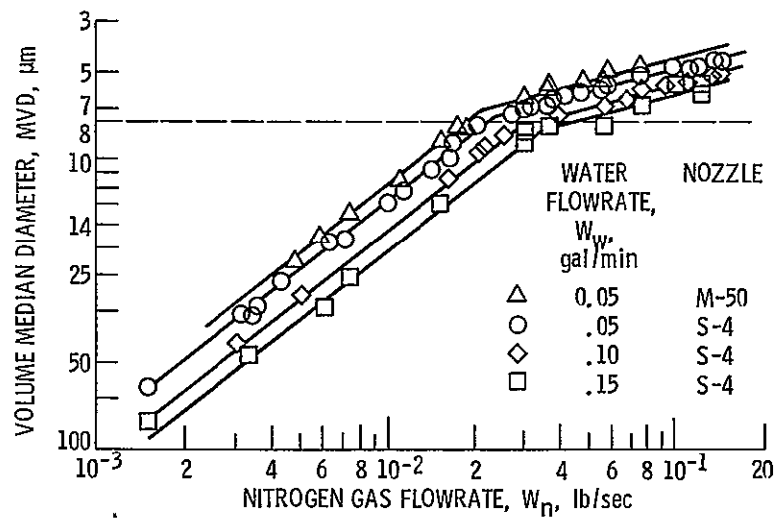
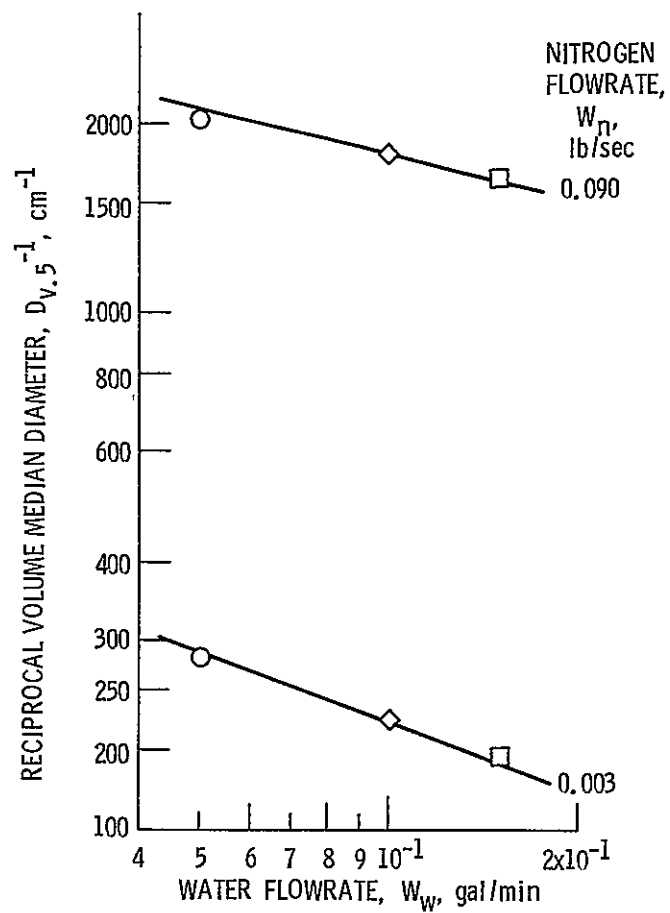


Figure 8. - Correlation of volume median drop diameter with nitrogen gas flowrate.



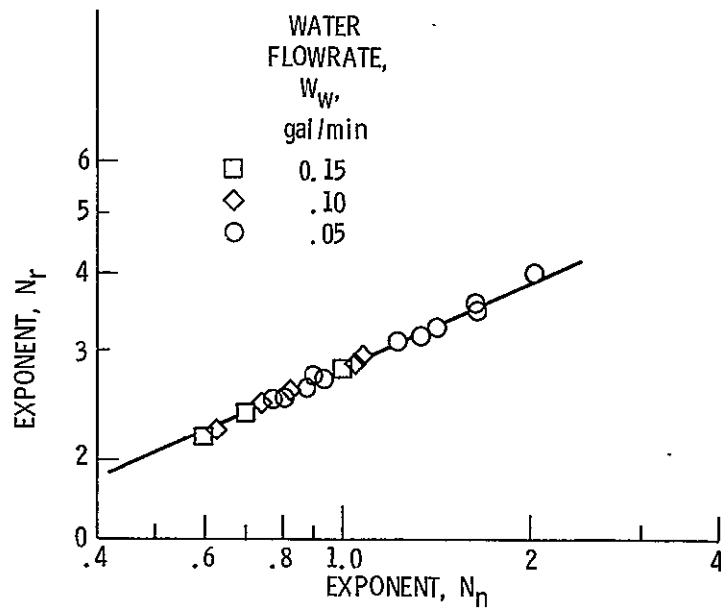


Figure 10. - Correlation of Rosin-Rammler and Nukiyama-Tanasawa exponents N_r and N_n , respectively.

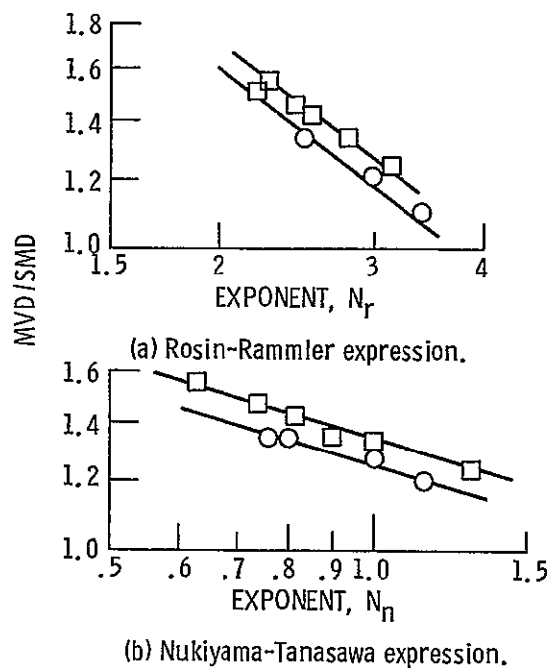


Figure 11. - Correlation of ratio $D_{v,5}/D_{32}$ with exponents N_r and N_n for Rosin-Rammler and Nukiyama-Tanasawa expressions, respectively.

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