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FINAL REPORT

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A STUDY OF VIBRATING-CAPILLARY ATOMIZERS

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I. SUMMARY

A vibrating atomizer produces liquid droplets by creating instability in a liquid jet through the agency of the vibration. Under proper control, the liquid jet will disintegrate into a stream of uniform size droplets. The jet is produced by forcing the liquid through either a small tube (capillary) or orifice. Single tubes or orifices produce aerosol at a limited rate. Multiple capillary tubes are difficult to vibrate in unison in order to produce dense uniform-size aerosols. On the other hand, spinnerettes, or orifice plates with multiple, small, uniform holes in them, are capable of producing aerosols of high concentration because the vibration can be applied equally. The uniformity of the droplets produced in this manner strictly depends on the uniformity of the holes in the plate. A metal screen with square holes 5 μ on a side, for example, showed much promise for producing uniform droplets of high concentration. However, should one of the holes not be identical with the others or should some of the holes become partially blocked, the resulting droplets will not be uniform. Further investigation is needed to improve the quality of orifice plates, particularly those with extremely small holes.

Photography of the droplet stream immediately after formation was found to be the most satisfactory method for determining droplet sizes. This method avoided the problems of evaporation and distortion that are present in other techniques. Due to a limited depth of focus, only one jet could be examined at one time, however, with the apparatus employed.

The liquid jets produced by small orifices were found in this study to have the same diameter as the orifices, i.e., the coefficients of contraction were essentially unity. Two droplets were formed under proper

regulation during each cycle of vibration of an orifice. The diameters of the droplets so formed varied directly as the one-third power of the liquid flow rate and inversely as the one-third power of the vibration frequency.

II. INTRODUCTION

A. Statement of the Problem

The ready availability of uniform liquid droplets would be of value in research into light scattering, nucleation, coalescence, and precipitation, as well as in certain respiratory-ailment treatments. Unfortunately, readily available atomizers produce a range of droplet sizes. Two types of atomizers, the spinning disk[1] and vibrating capillary[2], produce fairly uniform droplets, however. The spinning disk device is complex and requires elaborate control. Vibrating-capillary atomizers have very low output and produce relatively large droplets. The object of this project was, therefore, to increase the output and improve the uniformity of droplets from a vibrating-type atomizer.

B. Background of the Problem

Ennis and James[3] first produced uniform droplet by means of a fine, glass capillary. A steady flow of air across the capillary picked off the droplets when each attained a certain size, forming a stream of uniform droplets. The droplets produced by this device were relatively large. Smaller capillaries and orifices were used by other investigators, and droplets down to 30 microns in diameter are reported[4, 5, 6] to have been produced.

When a liquid is forced through a capillary tube or an orifice with sufficient velocity, it forms a jet that decomposes into a sequence of droplets of various sizes. Under certain conditions of mechanical vibration, the jet will break into uniform-size droplets. The size can be adjusted somewhat by altering the liquid velocity and the characteristics of the vibration. Ryley and Wood[4] produced uniform water droplets by vibrating a hypodermic needle. The initial tests were limited to a narrow range of vibrations and produced comparatively large water droplets. Mason, Jayaratne, and Woods[6] employed a similar design but utilized a different control system. The needle tip was modified by inserting a smaller steel tube inside it to produce smaller droplets. Lindblad and Schneider[7] used a piezoelectric transducer to produce the vibration of the jet. Charged droplets were produced by placing a cylindrical,charging electrode beneath the capillary tip.

Woffinden[5] used an orifice to produce small, uniform droplets by vibrating an orifice at high frequencies, the droplets being produced for the purpose of studying their coalescence. The orifice was made by soldering a tungsten wire into a small hole in a brass disc and then withdrawing the wire. The orifice had to be replaced frequently.

III. THEORETICAL DEVELOPMENTS

The phenomenum of atomization of liquid jets is extremely complicated. The mechanism differs depending on the conditions, and usually more than one mechanism is involved at one time. Complete analysis of some systems is impossible because breakup and coalescence of droplets occur repeatedly.

Study of the breakup of inviscid liquid jets was initiated by Lord Rayleigh[8] in 1878. Breakup was considered a result of the instability of the jet. Basset[9] took account of the viscosity of the liquid and solved the general Navier-Stokes equation of hydrodynamic flow. Weber[10] attributed the basic cause of disruption to the surface tension of the liquid, and, using this assumption, derived equations for the breakup time and distance. Joyce[11] suggested three controlling factors: mechanical, operational, and the liquid properties. Theoretical predictions, at best, are good only when the assumptions are met.

A. Lord Rayleigh's Theory

If a jet of inviscid and incompressible liquid disintegrates into droplets because of instability arising from capillary or surface tension forces, the surface of the cylindrical jet at any time t is of the form[8, 12]

$$r = R + H \cos Kx \tag{1}$$

where r is the variable radius of the jet, R the original radius of the jet, H the amplitude of displacement, K the spatial frequency coefficient equal to $2\pi/\lambda$, and x the length along the axis. The average surface area, $\overline{S}$, and volume, $\overline{V}$, per unit length along the axis of the jet can be expressed, respectively, as

$$\bar{S} = 2\pi R + \pi R K^2 H^2/2 \qquad (2)$$

and

$$\bar{V} = \pi R^2 + \pi H^2/2 \qquad (3)$$

Letting $\bar{S}_o$ and R_o be the surface area per unit length and the radius of the undisturbed jet, respectively, there can be written

$$\bar{S}_o = 2\pi R_o = 2\pi R + \pi H^2/2R \qquad (4)$$

Thus the difference between the average surface area and the surface area per unit distance along the axis is

$$\bar{S} - \bar{S}_o = \frac{\pi H^2}{2R} (K^2 R^2 - 1) \qquad (5)$$

The jet is stable for $KR > 1$. Letting σ be the surface tension, a jet is unstable when the potential energy E per unit length along the axis is

$$E = - \sigma \left(\frac{\pi H^2}{2R}\right)\left(1 - K^2 R^2\right) \qquad (6)$$

The kinetic energy of motion can thus be calculated from the potential energy E. The velocity potential, Φ, satisfies the Laplace equation and can be written for an invicid and incompressible fluid as

$$\Phi = A\, J_o\,(iKr) \cos Kx \qquad (7)$$

where J_o is the Bessel function of zero order. The coefficient A can be determined by the outward normal velocity at the surface of the liquid cylinder which is $\left(\frac{dH}{dt}\right)$ cos Kx, according to equation 1. Here t denotes the time. Hence

$$A = \frac{\frac{dH}{dt}}{iKRJ_o'(iKR)} \tag{8}$$

where J_o' is the derivative of J_o with respect to iKR. The kinetic energy per unit distance along the axis of the unstable jet is found to be

$$T = \frac{1}{2}\rho \int_0^1 2\pi R\Phi\left(\frac{d\Phi}{dr}\right)_{r=R} dx$$

or

$$T = \frac{1}{2}\rho\, \pi R^2 \cdot \frac{J_o(iKR)\left(\frac{dH}{dt}\right)^2}{iKR\ J_o'(iKR)} \tag{9}$$

where ρ is the density of the fluid.

If it is now assumed that the disturbance amplitude H varies as $e^{\mu^2 t}$, by Lagrange's method there is obtained:

$$\mu^2 = \frac{\sigma}{\rho R^3} \cdot \frac{(1-K^2R^2)\ iKR\ J_o'(iKR)}{J_o(iKR)} \tag{10}$$

The value of μ^2 represents the degree of instability of the liquid jet. Expanding equation 10 and differentiating μ^2 with respect to KR, the maximum value of μ^2 is found to be at $K^2R^2 = 0.4858$. Thus the corresponding value of λ is given by

$$\lambda = 4.508\ (2R) \tag{11}$$

This means that the jet, if from an imcompressible and inviscid fluid, will disintegrate most rapidly when the ratio of the wavelength of the disturbance to the diameter of the jet is 4.508. In this case, the diameter of the droplet, d, which is formed by a cylinder of liquid disintegrating in lengths λ will be

$$d = 1.87\ (2R) \tag{12}$$

Therefore, according to Lord Rayleigh's analysis, the droplet diameter is equal to 1.87 times the diameter of the jet at the point of maximum disturbance.

B. Analysis for Viscous Liquids

Many other investigators, following Lord Rayleigh's lead, have examined the behavior of liquid jets. Basset[9] studied jet instability by giving greatest consideration to the viscosity of the liquid and the influence of the surrounding air. The details are covered by Schneider[13]. Agreement is general on the following: greater liquid viscosity tends to produce stability; the surrounding air tends to produce instability; and the surface tension of the liquid causes stability or instability depending on whether the ratio of the wavelength of the disturbance to the circumference of the jet is less than or greater than unity. The equations derived by Besset are complex and appear to be impracticable.

Haenlein[14] made pictures with high-speed, spark photography showing the characteristics of jet disintegration. For viscous liquids such as castor oil, it was found that the ratio of $\lambda/2R$ was between 30 and 40, or much higher than the value of 4.508 for inviscid liquid as predicted by Lord Rayleigh. Also the disintegration length was found to be proportional to the velocity. The process of drop formation in the presence of air was thus interpreted as being similar to the wind blowing over a body of water. The air velocity increases over the wave crests and decreases over the troughs. This creates a pressure difference on the wave surface and leads to jet disintegration. The influence of the surrounding gas is much less important, however, for a jet of low velocity.

The cause was attributed by Weber[10] to the surface tension of the liquid, and, on this basis, the approximate equation

$$\mu^2 + \mu \frac{3\eta K^2}{\rho} = \frac{\sigma}{2\rho R^3} [K^2R^2(1-K^2R^2)] \tag{13}$$

was obtained for liquids with a viscosity of η.

For an inviscid liquid, the maximum value of μ was predicted to be

$$\mu_{max} = \sqrt{\frac{\sigma}{8\rho R^3}} \tag{14}$$

and the corresponding value of λ to be

$$\lambda = \pi \sqrt{2} (2R) = 4.44 (2R) \tag{15}$$

this latter value being very close to 4.508 (2R) as obtained by Lord Rayleigh.

For a fluid with a viscosity η, Weber obtained the breakdown time t_b and breakdown L_b to be described, respectively, by

$$t_b = \left[\left(\frac{8\rho}{\sigma}\right)^{1/2} R^{3/2} + \frac{6\eta R}{\sigma}\right] \ln \frac{R}{H} \tag{16}$$

and

$$L_b = \left[\left(\frac{8\rho}{\sigma}\right)^{1/2} R^{3/2} + \frac{6\eta R}{\sigma}\right] v \ln \frac{R}{H} \tag{17}$$

where v is the jet velocity.

The presence of air surrounding the jet creates a significant resistance as the relative velocity between the two phases becomes large. Castleman[15] proposed that disturbances on the liquid surface are thus caught up and drawn out as a fine ligament. The ligament is cut off by the rapid growth of any indentation, and the detached mass then forms a drop. Putman and his co-investigators[12] attributed the differences of opinion concerning the physical mechanism of atomization by Haenlein and by Castleman to the respective methods of producing the sprays. Both analyses have experimental evidence to support them.

Atomization is itself a simple process, but in theory it is complicated. No single theory covers all the phenomena.

C. Disintegration and Coalescence of Liquid Droplets

A liquid droplet is not stable when subjected to shear in a gas stream. Lane[16] studied this phenomena by photographic means using liquid drops injected into an air stream or subjected to a sudden air blast. The pictures showed that at high velocities the air blew the drop into the form of a hollow bag with a circular rim that ultimately bursted into fine droplets. Tovbin, Panasynk, and Oleinik[17] studied the critical size of disintegrating drops of water, aqueous solutions, and organic solvents. The method employed was to place a drop on the tip of a needle and then insert the needle in the air stream. Unfortunately, the air velocity was varied only over a relatively narrow range, but the effects of the surface tension of the liquid and the critical size for disintegration were well investigated.

Theoretical analysis suggests that the critical radius for a disintegrating liquid drop is proportional to Weber's number, expressed as

$$r_c = c\left(\frac{\sigma}{\rho_g v^2}\right) \tag{18}$$

where ρ_g is the density of the gas medium and c is a constant. The constant c was reported by Levich[18] to be 2.3 on theoretical grounds. This does not agree with measured values. Toubin, Panasyuk, and Oleinik[17] reported an average value of c to be 4.28, and Putnam, et al.,[12] reported it to be 5.48. These values were determined in steady air streams; values from 2.25 to 5.07 have been reported for transient-blast conditions.[12, 16] There are no data on droplets as small as usually found in atomization. In general, droplets formed by viscous or high-surface-tension liquids are more stable than those formed from non-viscous and low-surface-tension liquids.

Collision of droplets may occur through the mechanism of eddy diffusivity and through differences in droplet velocities. It is very doubtful that all colliding droplets actually coalesce. Mason, Jayaratne, and Woods[6] found that two interacting streams of drops coalesce to produce a new stream containing larger drops. But they also found that one-hundred-micron radius drops make on the average three successive bounces on a plane water surface before coalescence. Coalescence of droplets depends not only on the liquid properties and the droplet size, but also on the angle of collision and the relative velocity of impact. Large droplets injected into still air travel farther and faster than small ones. So in a cloud of various size droplets the larger ones catch up with the small ones and combine into still larger drops. Sometimes the wake produced by a droplet behind itself will allow another droplet immediately following to catch up with the first and then collide with it. Therefore, the droplet ultimately created by atomization may not be the droplets initially produced as a result of jet breakup.

D. Evaporation of Liquid Droplets

In order to obtain droplets of the desired size in an experiment at any given time not immediately after the breakup, an adjustment for evaporation is necessary. The evaporation rate of drops depends on their volatility, their velocity relative to that of the surrounding gas, and the degree of saturation of their vapor in the surrounding atmosphere. Frössling[19] initiated study of this situation by following the method for treating the velocity boundary layer about a rotating sphere immersed in a moving medium. If the droplet temperature can be assumed always the same as that of the gas, an approximate equation for the total evaporation rate over a sphere can be expressed as

$$\frac{dm}{dt} = -2\pi D \frac{M(P_d - P_a)d}{R\,T}\left\{1 + [\Psi(Sc)]\,(Re)^{1/2}\right\} \tag{19}$$

where m is the mass of the droplet, D the diffusion coefficient, d the diameter of the droplet, R the gas constant, P_a the partial pressure of the droplet liquid in the ambient gas, and P_d the droplet vapor pressure, which can be expressed by[20]

$$\log\left(\frac{P_d}{P_f}\right) = \frac{4\,\sigma\,M}{2.303\,\rho\,RT\,d} \tag{20}$$

where P_f is the vapor pressure of a flat surface of the liquid. Both of the above equations assume the ideal gas law applicable.

Frössling evaluated Ψ (Sc) experimentally to be 0.276 $Sc^{1/3}$. If diffusion is the sole mechanism of vapor migration or the droplet is stationary, then Re = 0, and equation 19 becomes

$$\frac{dm}{dt} = -2\pi D \frac{M(P_d - P_a)d}{R\,T} \tag{21}$$

The assumption that the droplet temperature is the same as the ambient temperature will not be true for very volatile materials. Heat transfer rate then becomes important in the evaporation process. Ranz[21] has shown that the heat transfer coefficient for the case of a moving drop is of the form

$$Nu = Nu' \, [Re, (Re, Pr)] \tag{22}$$

where the dimensionless term Nu is $h_c d/k$, the term Nu' is $k_G M_m d P_f / D_V \rho$, and the term Pr is $C_p \mu/k$, and where h_c is the average heat-transfer coefficient by convection and conduction per unit area of interface per unit temperature difference across the transfer path, k is the thermal conductivity, k_G is the coefficient of mass-transfer analogous to h_c, M_m is the average molecular weight of the gas mixture in the transfer path, P_f is the average partial pressure of the nondiffusing component (usually a log-mean value), and D_v is the diffusivity of the vapor in the transfer path.

Considering a droplet stationary relative to the gas and considering a density gradient exists across the transport path, Ranz[21] has shown that

$$Nu' = 2.0 + k_1 \, Sc^{1/3} \, Gr^{1/4} \tag{23}$$

and

$$Nu = 2.0 + k_2 \, Pr^{1/3} \, Gr^{1/4} \tag{24}$$

where the Grashof group, Gr, is equal to $d^3 \rho^2 \, g \, \beta \, \Delta \, T/\mu^2$, if Δ T is the temperature drop cross the film and β is the thermal coefficient of expansion of the gas phase. These equations can be applied to natural convection.

For a simple case of heat conduction and molecular diffusion, Ranz[21] also showed that

$$Nu' = 2.0 + k_1 \, Sc^{1/3} \, Re^{1/2} \tag{25}$$

and

$$Nu = 2.0 + k_2 \, Pr^{1/3} \, Re^{1/2} \tag{26}$$

and these equations can be applied to forced convection conditions for low volatility materials. The value of k_1 in equation 25 usually has a value between 0.55 and 0.60[22].

The rate of evaporization can be evaluated by

$$\frac{dm}{dt} = - \pi D \frac{M(P_d - P_a)d}{R \, T_d} \, Nu' \tag{27}$$

where T_d is the absolute temperature of the droplet.

IV. EXPERIMENTAL WORK

At initiation, the experimental program envisioned a study of single capillary atomization that would be expanded into multi-capillary systems as experience and knowledge were accumulated. The work did not develop as planned. Single capillary systems were studied, but multi-capillary devices were quickly found to be impractical because multiple capillaries could not be vibrated in unison, i.e., they could not be made to have identical resonant frequencies. The study then shifted to single orifices and to multi-orifice systems that could be vibrated with the same frequency because all openings were in the same piece of metal. The mass to be vibrated was greater, however, and more energy was required. This posed a serious problem, particularly since high frequency is required to create small droplets.

The several systems are described in detail in subsequent sections.

A. Capillary Atomizers

Hypodermic needles were utilized in the first actual tests, but it was soon evident that smaller capillary tubing was desirable. A supply of tubes having internal diameters down to 25 μ -- the smallest obtainable -- was purchased from the Superior Tube Co., Norristown, Pa. These tubes were employed thereafter in tests with capillaries.

1. Single-Capillary Types

The experimental apparatus consisted of a pressure tank, Millipore filter and holder (Millipore Corporation, Bedford, Mass.), flow meter, and the capillary tube. To vibrate the capillary a Hewlett-Packard, Model 201C, audio signal generator was used to drive the voice coil of a speaker which was attached to the mount holding the capillary tube. To eliminate some of the noise, the paper portion of the diaphragm was removed from the speaker. Several modes of vibration were tried. These included vibrating straight capillary tubes perpendicular and parallel to the horizontal and an L-shaped, or bent, capillary tube. This latter tube was vibrated at the resonant frequency of the fixed side of the "L", and the mechanical connection to the speaker was made half way between the fixed end and the 90° bend. It was found that best results were obtained when the capillary was mounted horizontal and vibrated perpendicular to the axis of the capillary, including the bend. Usable frequencies were very limited. The foundamental frequency of the capillary tube, and sometimes an overtone, could be employed. By vibrating in this manner, two drops per cycle were generated. The capillaries tested were 300, 90, and 25 μ in diameter.

In most cases the droplets produced followed two main paths, diverging by approximately 20°. The angular spread was a function of the amplitude of the vibration. By varying parameters such as the flow rate it was possible to break the jet into more than two streams of droplets. These conditions were unstable and subject to erratic change without the operator touching the controls, however.

Approximately monosize droplets were produced when the jet divided into only two streams. The droplets were relatively large. Estimates of their size were obtained by collecting the droplets on smoked, glass slides and examining microscopically the craters left after the droplets evaporated.

2. Multiple-Capillary Type

To increase the number of droplets that could be produced in a given time, apparatus were constructed having 10 capillary tubes mounted in one base. The same power supply, the same driver, and the same liquid filtering system were employed as for the single capillary tube. Irregularities in the wall thickness of the capillary tubes and the consequent inability to make all capillaries have exactly the same liquid flow rate caused the fundamental frequency of each to be different. Hence, the total assembly could not be vibrated so as to produce monosize, or even approximately monosize, droplets. Multi-capillary systems thus were soon found to be impractical; their use was abandoned.

Out of the multiple, capillary-tube experiments, however, came the first orifices. One of the mounting methods involved casting a block of epoxy resin with one end of a number of 135-μ diameter capillary tubes in it. After being discarded for use as a capillary system, this block was milled flat on both sides, and mounted in a holder so that water pressure could be applied from one side while it was vibrated. Again the same liquid-filtering system, audio power supply, and driving coil were employed. The sprays were not of uniform size due to differences in the inside diameter of the tubes and the inability to finish the ends of the tubes so that they were sharp-edged, but the results were good enough to suggest other orifice plates should be tested.

B. Orifice Atomizers

Spinnerettes are orifice plates having up to several hundred individual openings through them that are employed industrially in the production of nylon, rayon, and other synthetic fibers. One of these was obtained having 100 openings 75 μ in diameter, another with 10 openings of 27 μ diameter, and another with one opening of 20 μ in diameter. These spinnerettes were produced by J. Bishop & Co., Malvern, Pa. Additionally single-hole orifice plates were purchased from the Ealing Corp., Cambridge, Mass., having hole diameters of 203, 100, 90, 53, 25, 9.4 and 5.5 μ. The larger-hole orifices could be used at audible frequencies, but the smaller ones necessitated use of higher than audible frequencies.

1. Audible Frequency Systems

a. Single-Orifice. The equipment employed with the capillary tubes was modified to produce more power output. A 100-watt amplifier was used in conjunction with a 60-watt, speaker-driver unit. To couple the mechanical energy from the driver to the spinnerette a piece of thin stainless steel was spun to the shape of the diaphram of the driver unit. A metal piece threaded on one end was then silver soldered at the other to the center of the spun stainless steel piece. The stainless steel piece was fastened with epoxy resin in place of the original diaphram, and, finally, the spinnerette holder was bolted to the diaphram. An additional liquid filter was added to the system to prevent the spinnerette from plugging with debris from the liquid. Figure 1 is a schematic diagram of the system while Figure 2 presents two views of the system.

The first experiments were not too successful for reasons that are not clear. However, when a Schmidt triggering circuit along with biasing control was added to the output of the signal generator to produce more nearly a square-wave vibration, the droplets produced became almost monosize.

The main disadvantage to this system arose because the amplifier could not exactly follow the square-wave signal, and, if the amplifier was not adjusted properly, two or more drops would be produced in a half cycle instead of one cycle. When this situation prevailed the two droplets produced in each half cycle would often coagulate so that actually only one droplet each half cycle was produced. Figure 3 is a good example. It was a larger droplet as

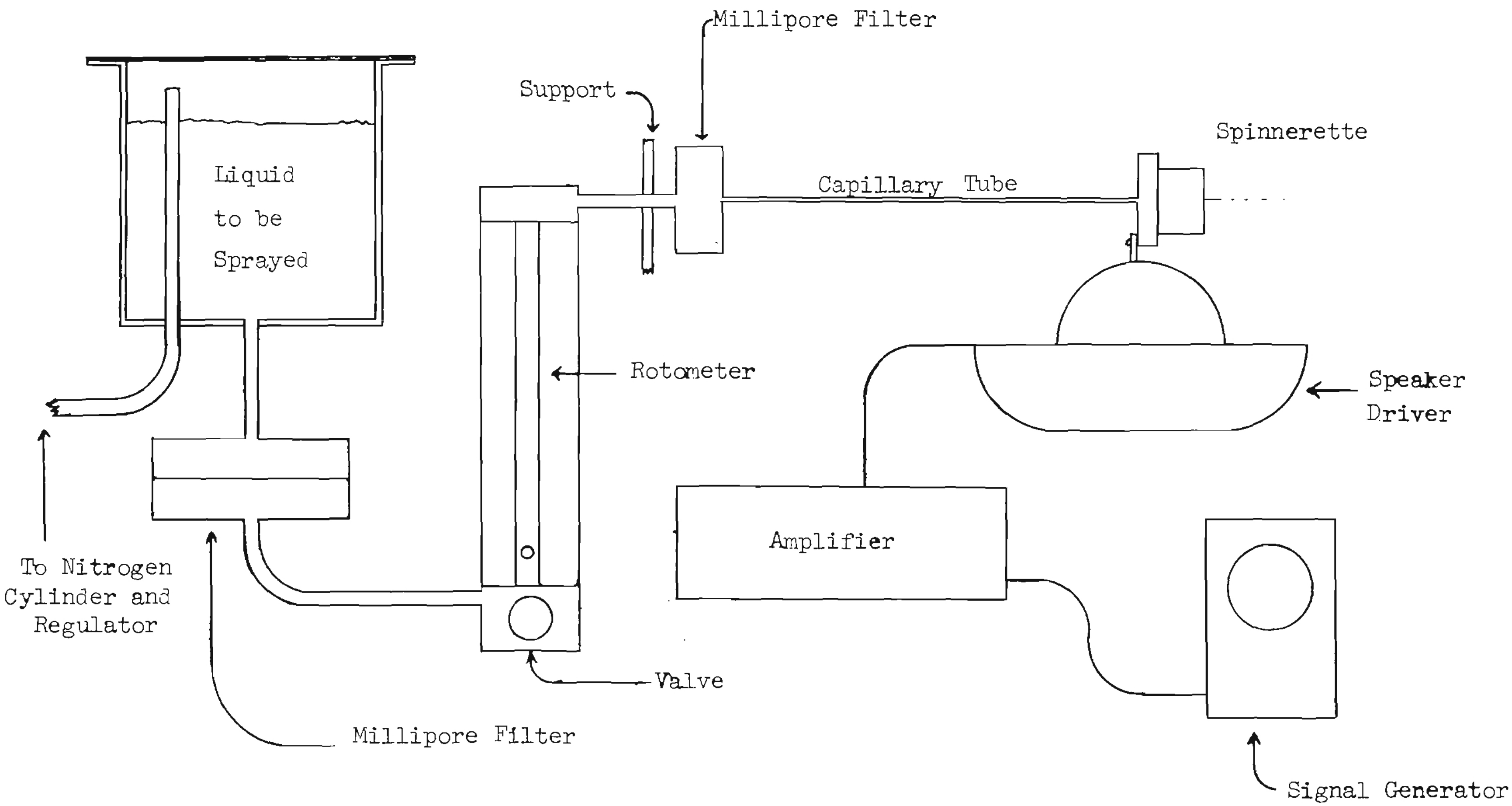


Figure 1 . Audio Atomizer Apparatus

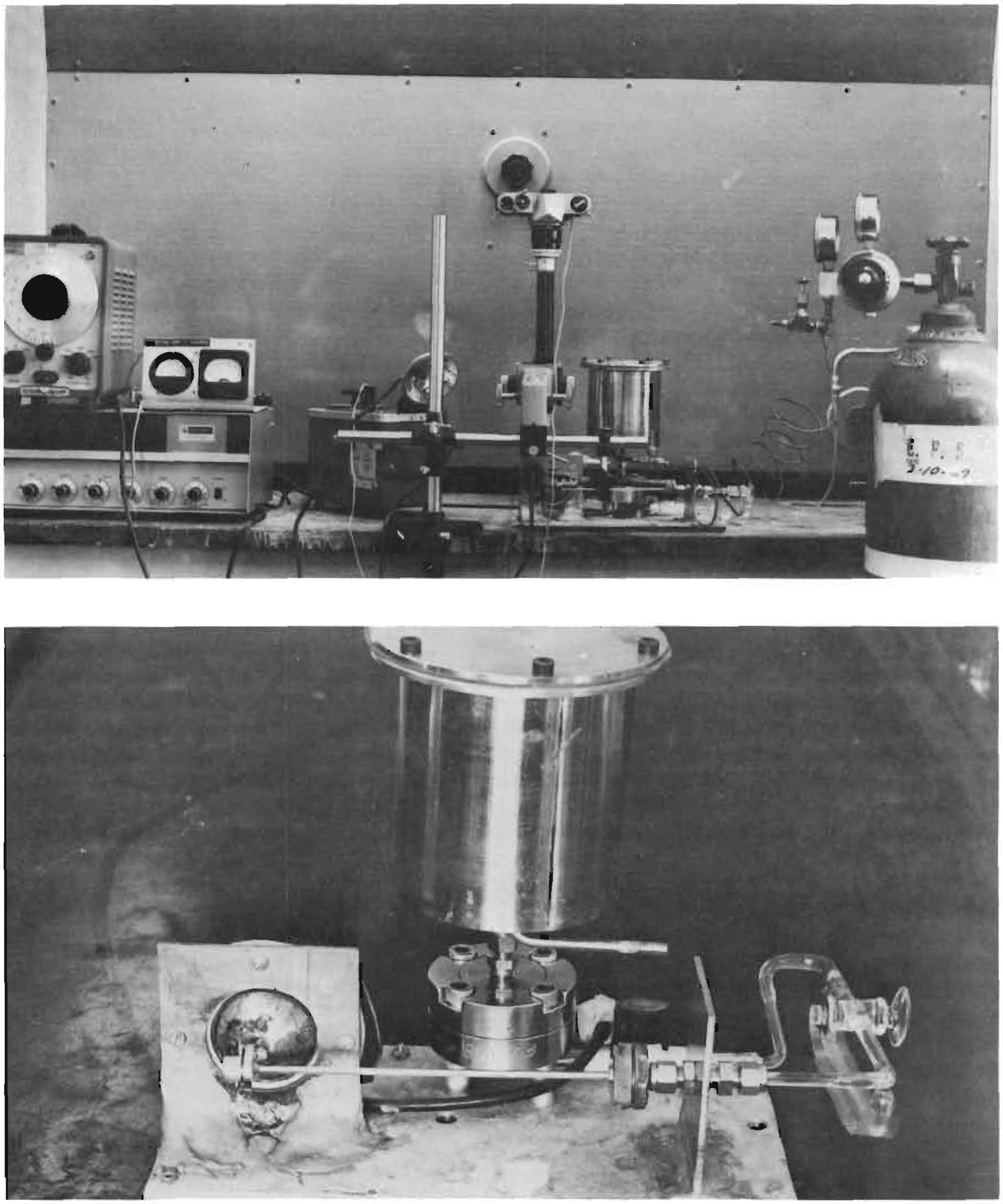


Figure 2. Photographs of the Audio Atomizer Employing a Single Orifice. The top photograph is an overall view and the bottom shows a closeup of the orifice holder and flow meter.

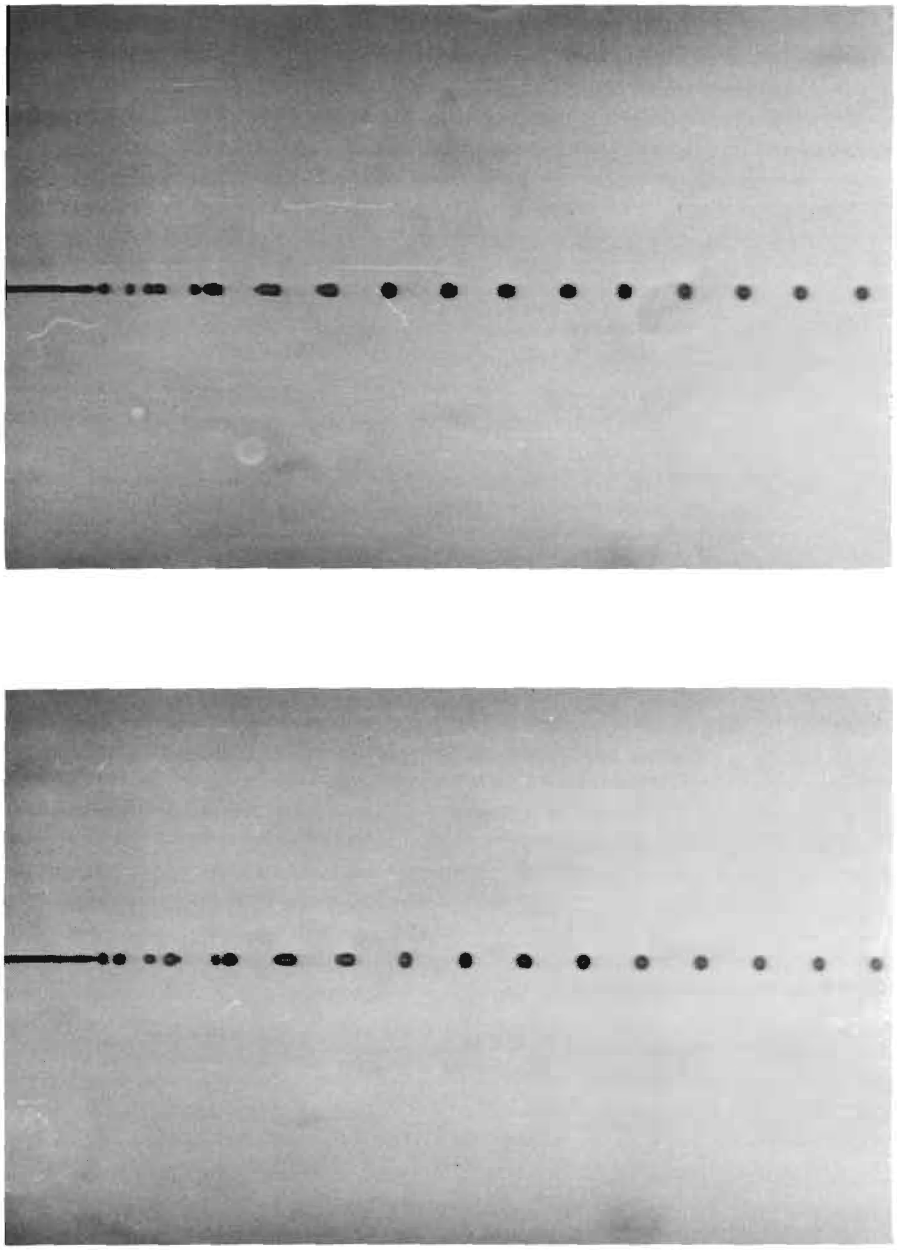


Figure 3. Photographs Showing the Absence of Contraction in Jets but Showing Droplet Coagulation.

a result.

b. Multiple-Orifice. The spinnerette with ten holes each 27 μ in diameter was next mounted in the same apparatus that held the spinnerette with the single orifice. Difficulties arose now in trying to keep all orifices completely open at all times. A completely plugged orifice will not alter the distribution of droplet sizes. However, a partially plugged orifice will, and this proved not to be an uncommon happening.

c. Methods of Spray Analysis. Several techniques were employed in the attempts to analyze for droplet size. Since small droplets of volatile liquids evaporate rapidly, the liquids employed included molten materials and solutions of low volatility. Direct photography immediately after droplet creation was used with the more volatile liquids.

The attempts to spray a molten material utilized phenol. Only moderate success was achieved. All the equipment had to be kept hot and the spray had to be cooled before collection. Also the phenol droplets sometimes, upon cooling, became supercooled and did not solidify until they hit the wall of the vessel in which they were to be collected.

Fair success was achieved using a nitrocellulose solution. The resulting solid particles were wrinkled on the outside and hollow on the inside, however, as may be seen from Figure 4. Accurate size data could not be accumulated by this method. An aqueous solution of sodium chloride was also tried, but this caused corrosion of the apparatus, and particles of the corrosion products plugged the orifices with great frequency.

The most success was attained with photography. Several different methods were tried, but the clearest pictures were obtained by placing the remote bulb of a General Radio Company, Model 1538A, Strobotac directly

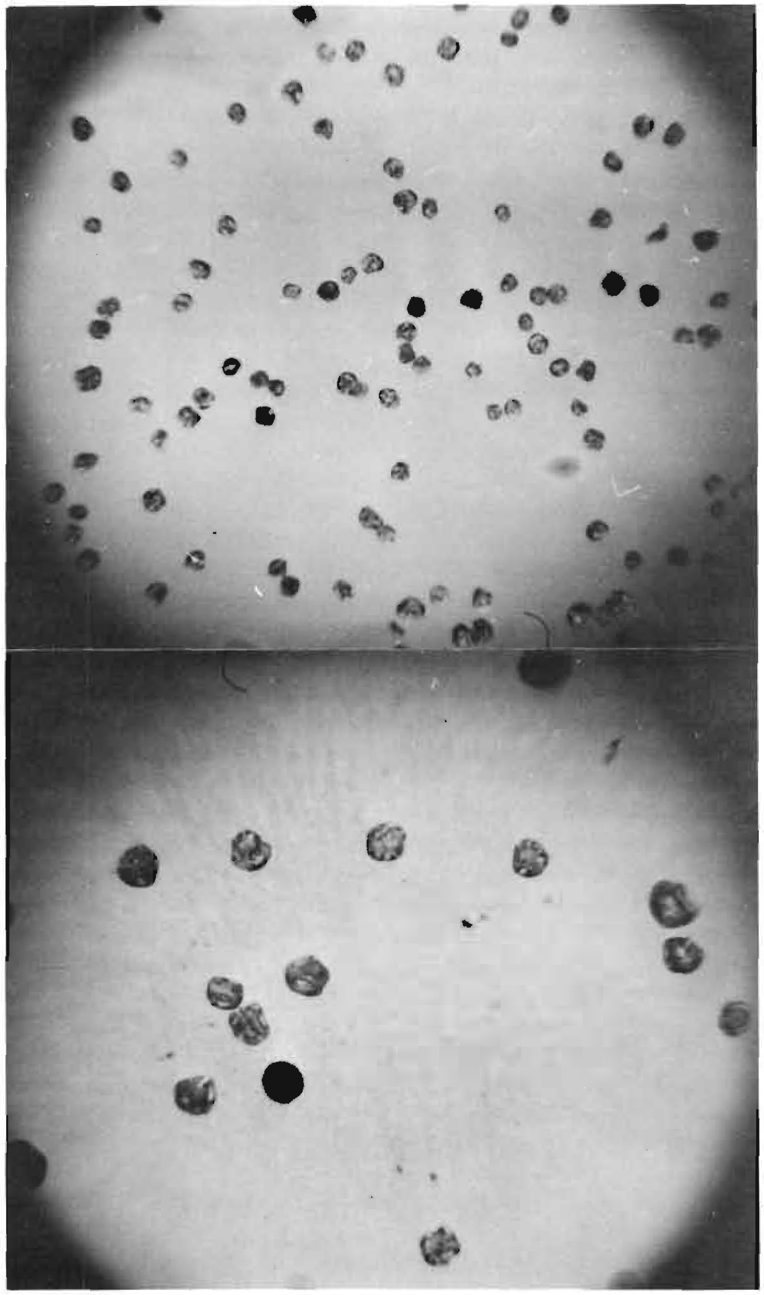


Figure 4. Photographs of Dried Nitrocellulose

opposite the jet stream to be photographed. Pictures were then taken through a Vickers Instruments Inc. surgical microscope. With this arrangement the lighted area was small but very bright and the duration of the flash needed was less than one microsecond. The particular microscope used had a working distance of approximately four inches which was much greater than is usually the case.

Pictures taken by this arrangement resulted in black appearing droplets against a white background. Other arrangements, such as side lighting, gave white appearing droplets on a black background. In addition, it was extremely difficult to illuminate the whole drop with one flash in a side-lighting system, and most of the droplets on the pictures looked like half moons. Any lighting angle other than directly opposite the microscope suffered from lack of intensity. When the droplets were photographed with the jet directly between the strobe lamp and camera, those droplets in focus have the immage of the lamp in their center. This was important, since droplets slightly out of focus may appear either larger or smaller than they are actually.

Any liquid, even though it might be volatile, could be examined by the photographic technique. As a result,pure water and silicone liquids were used for most of the subsequent tests, and most of the pictures were taken near the orifice so that evaporation was negligible.

Photographs of droplets from the multiple-orifice system were difficult to interpret. Observations through the microscope using the strobe lamp indicated that each jet stream behaved just as the single jet, i.e., that each orifice produced essentially monosize droplets. It appeared that when two jets created by identical orifices broke in the same fashion, the droplet size was the same. While this was evident to be the case, it was not photographically established, because the size of the droplets as they appeared on photographs was a function of the goodness of focus of the microscope and difficulties arose in trying to focus on two jets at the same time.

d. Analysis of Data. Uniform droplets were obtained at audible frequencies using a spinnerette with a single orifice 20 μ in diameter. Two droplets were produced from the liquid jet during each cycle of the vibration.

If two droplets are produced in each cycle, then the volume of each droplet V_d can be expressed by

$$V_d = \frac{\pi R^2 v}{2f} \tag{28}$$

where R and v are the radius and velocity of the liquid jet, respectively, and f the frequency of the vibration.

The volume of a droplet can be written as

$$V_d = \frac{4\pi a^3}{3} \tag{29}$$

where a is the radius of the droplet. The liquid velocity v can be written as

$$v = \frac{Q}{\pi R^2} \tag{30}$$

where Q is the flow rate of the liquid. Thus the radius of the droplet can be expressed as

$$a = \left(\frac{3R^2v}{8f}\right)^{1/3} = \left(\frac{3Q}{8\pi f}\right)^{1/3} \tag{31}$$

Taking the logarithm of both sides of equation 31, there is obtained

$$\ln a = \ln \left(\frac{3Q}{8\pi}\right)^{1/3} - \frac{1}{3} \ln f \tag{32}$$

Data are given in Figures 5 and 6 for a jet of water at a flow rate of 0.0028 cc/sec while Figures 7 and 8 show data taken with Dow Corning, Series 200, silicone liquid having a viscosity of 1 centistoke. The flow rate for the silicone was 0.0023 cc/sec.

Using equation 32 and the data for water

$$\ln a = \ln 0.696 - 1/3 \ln f \tag{33}$$

or

$$a = 0.0696 \ f^{-1/3} \tag{34}$$

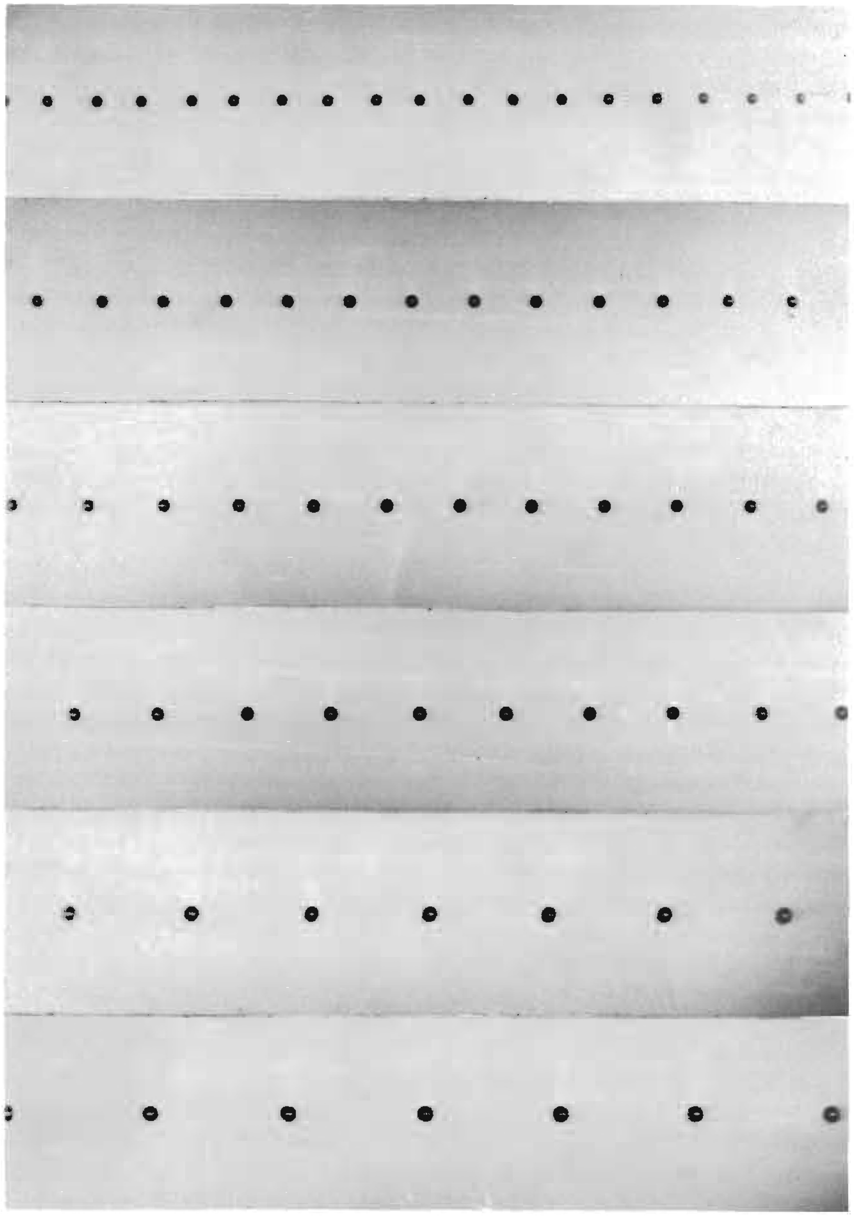
For the silicone, equation 31 becomes

$$a = 0.0650 \ f^{-1/3} \tag{35}$$

Results corresponding to these equations are plotted on Figures 6 and 8.

2. Ultrasonic Frequency Systems

Since very small droplets were desired, methods were sought that could produce them. Smaller holes and higher frequencies, of course, offered the means to solution. One way to impose the desired frequency on the jet was to modulate the pressure upstream of the orifice by placing a transducer behind it. One droplet per cycle should be generated by this



1 mm.

Figure 5. Single-Flash Photographs of a 20-μ Diameter Jet of Water at a Flow Rate of 0.17 cm^3/min Being Vibrated at Various Frequencies. The frequencies are, from top to bottom, 20,000; 15,000; 13,000; 11,000; 8,000 and 7,000 cps.

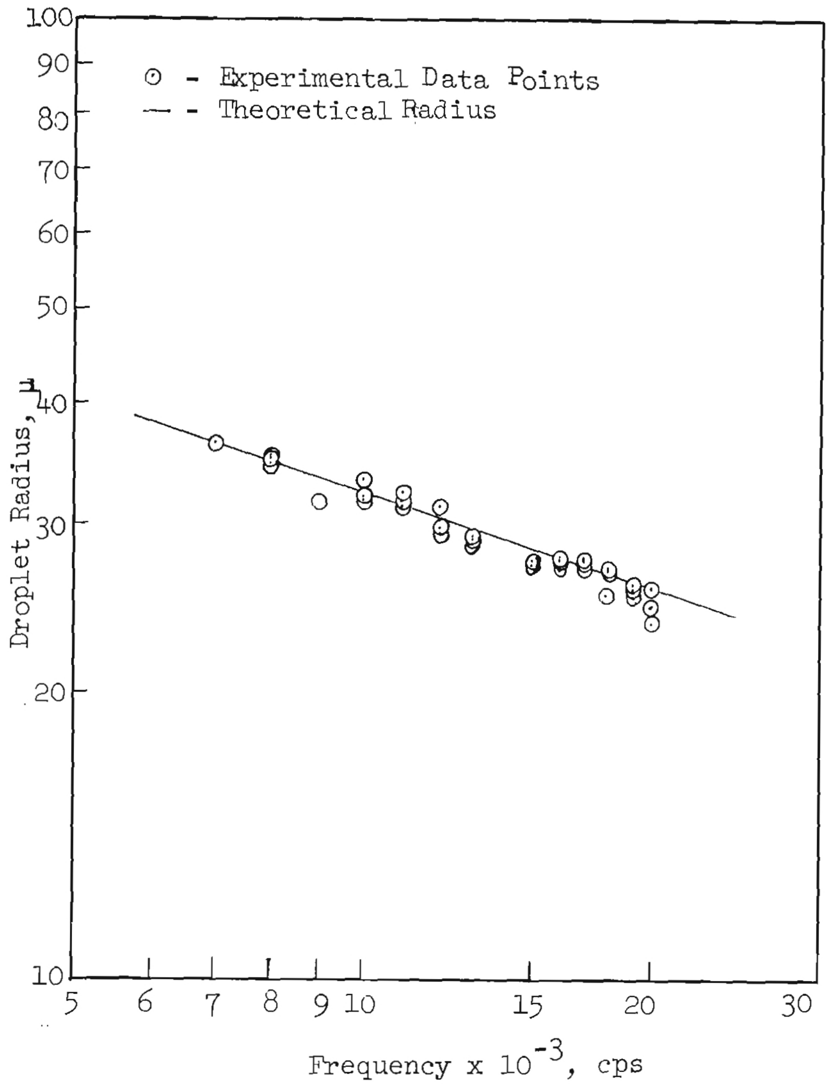


Figure 6 . Droplet Radius as a Function of Vibration Frequency as Produced with Water Flowing Through a 20-μ Diameter Orifice at a Rate of 0.17 cm^3/min.

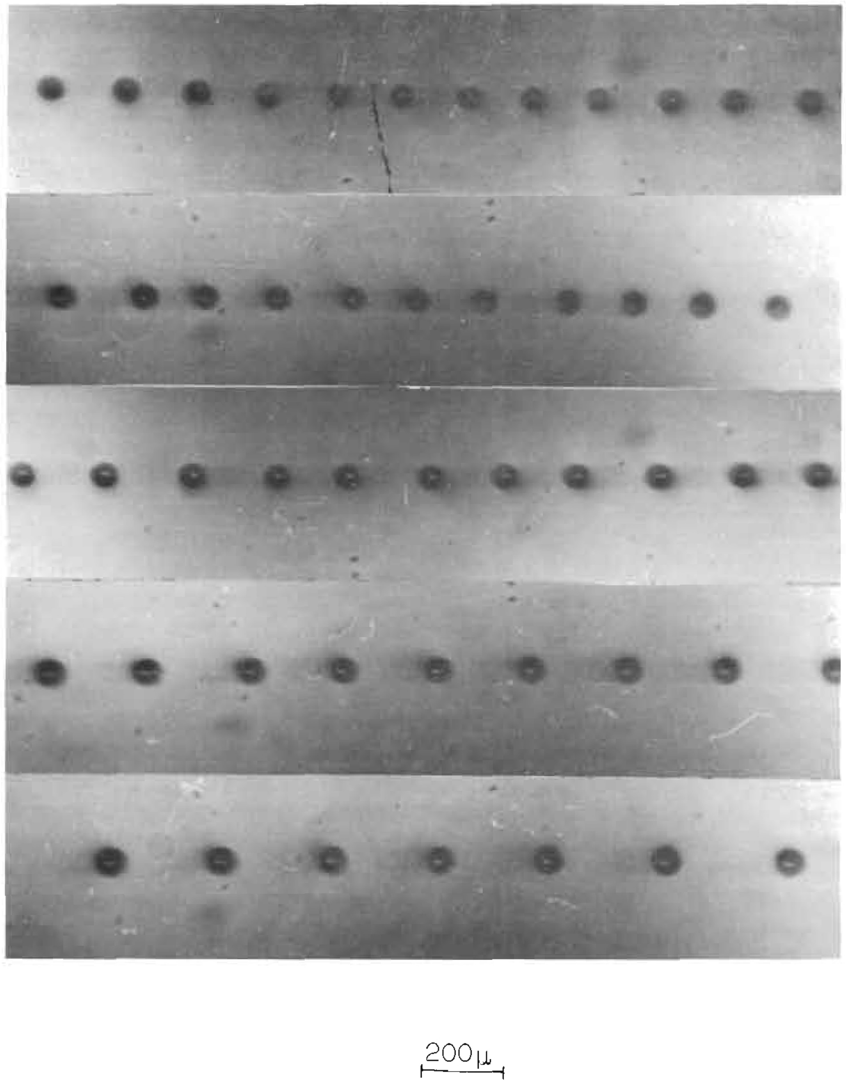


Figure 7. Single-Flash Photographs of a 20-μ Diameter Jet of Dow Corning Silicone Oil (viscosity, 1 centistoke) at a Flow Rate of 0.138 cm^3/min Being Vibrated at Various Frequencies. The frequencies are, from top to bottom, 20,000; 19,000; 17,000; 14,000 and 12,000 cps.

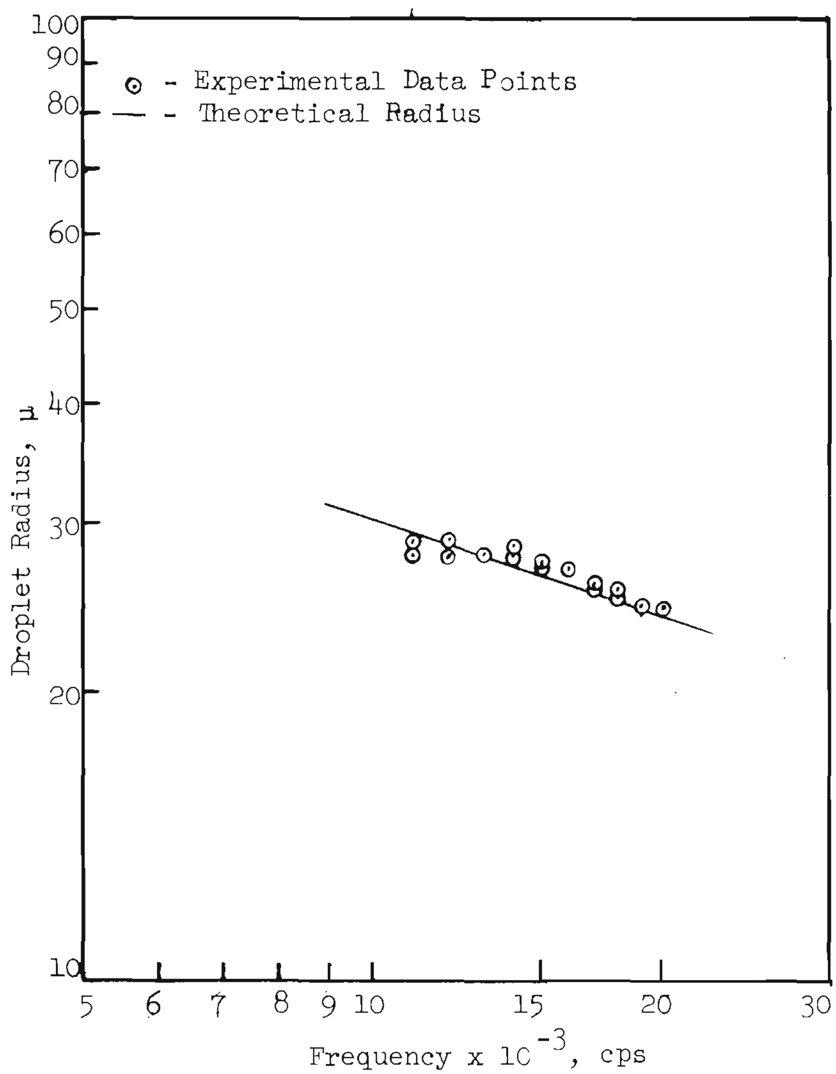


Figure 8. Droplet Radius as a Function of Vibration Frequency as Produced with Dow Corning Silicone Oil (viscosity, 1 centistoke) Flowing Through a 20-μ Diameter Orifice at a Rate of 0.138 cm^3/min.

arrangement.

a. Single Orifice. The basic apparatus consisted of a stainless steel cylinder within which was fitted a piston holding the transducer. Ahead of the piston and transducer was located the orifice plate which served also to seal one end of the cylinder. In order to have no pressure across the transducer, the system was arranged so that equal pressure was applied on both its sides. The liquid to be atomized was fed between the transducer and the orifice and air pressure was applied behind it. Cooling water was circulated within the resonant cavity, because, without cooling, the system temperature rose rapidly. The arrangement is shown schematically in Figure 9. The transducer had a resonant frequency of 1.24×10^6 cycles per second. The transducer was curved and so positioned that the energy from it would be focused at the orifice.

The precision pinhole orifice plates from the Ealing Corporation were first employed to study jet breakup at ultrasonic frequencies. These orifices, being in very thin plates, were mounted with heavier and larger orifice plates in front of them to provide support. In this way they were made to withstand the atomization pressure.

The system operated as expected, i.e., a very fine jet was produced, and when the ultrasonic energy was applied the jet broke into a fine spray. However, the plates eroded rapidily and extra holes even developed.

Due to the short lifetime of these orifices no data were collected with them and the droplet sizes they produced are not known.

b. Multiple Orifices. Screens made by the Buckbee Mears Co. of St. Paul, Minnesota, were employed as multiple orifices. Primarily, screens with square 5- and 10-μ openings were of main interest, since,

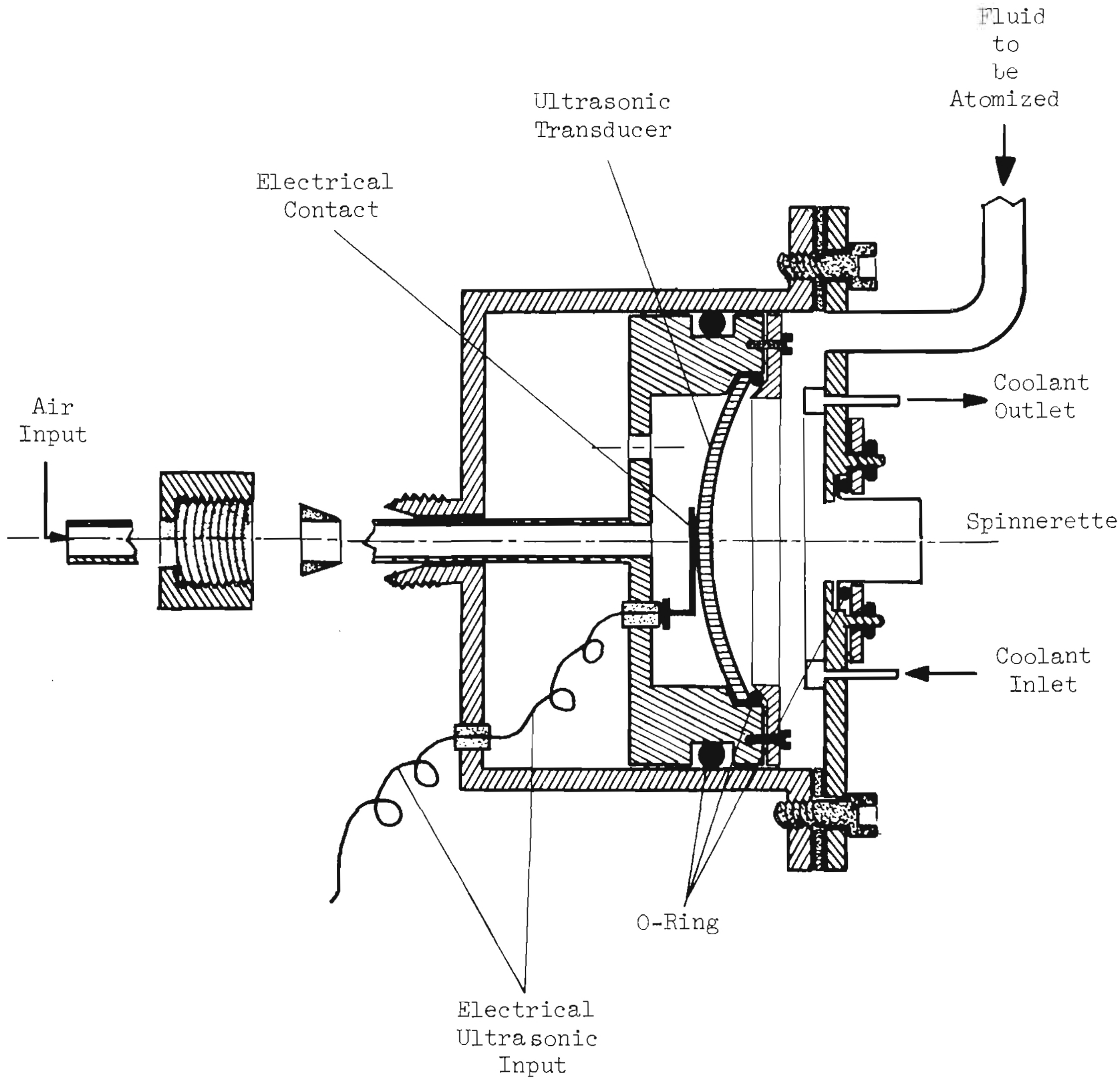


Figure 9 . Ultrasonic Atomizer

according to equation 31, 9- to 20-μ droplets should be produced with them if driven at the frequency of maximum power. This fundamental frequency of maximum output was 1.24 megacycles. The pressure and, therefore, the flow rate were varied in these experiments. The arrangement is shown in Figure 10.

Photography was used to analyze the droplet size from this apparatus. Because there were many orifices, only a few of the droplet could be in focus at one time, and to distinguish between those that were and those that were not became the problem. The photographs showed droplets apparently ranging from 10 to 60 μ in diameter, and, as long as a certain minimum pressure was applied to sustain the jets, any increase in pressure up to 100 lb/in^2 made no detectable difference in the size of the droplets.

3. Coefficient of Contraction.

The diameter of a jet issuing from an orifice does not in general, coincide with that of the orifice. Usually it becomes smaller at a diameter or two downstream from the orifice. This is due to the fact that the direction from which the flow enters the orifice is not entirely perpendicular to the cross-section of the opening. The phenomenon is called contraction. The section at which the jet becomes paralled is called the *vena contracta*. The coefficient of contraction is the ratio of the cross-sectional area of the jet to that of the orifice; it usually falls between one-half and unity for sharp-edge orifices. For a tapered or thick orifice, the change of direction of the streamlines is more or less completed within the orifice itself. The jet produced by this type of orifice usually has essentially the same cross-sectional area as the orifice.

In the study of the breakup of a liquid jet, the size of the jet is of primary interest. A series of pictures was taken at, and near, the

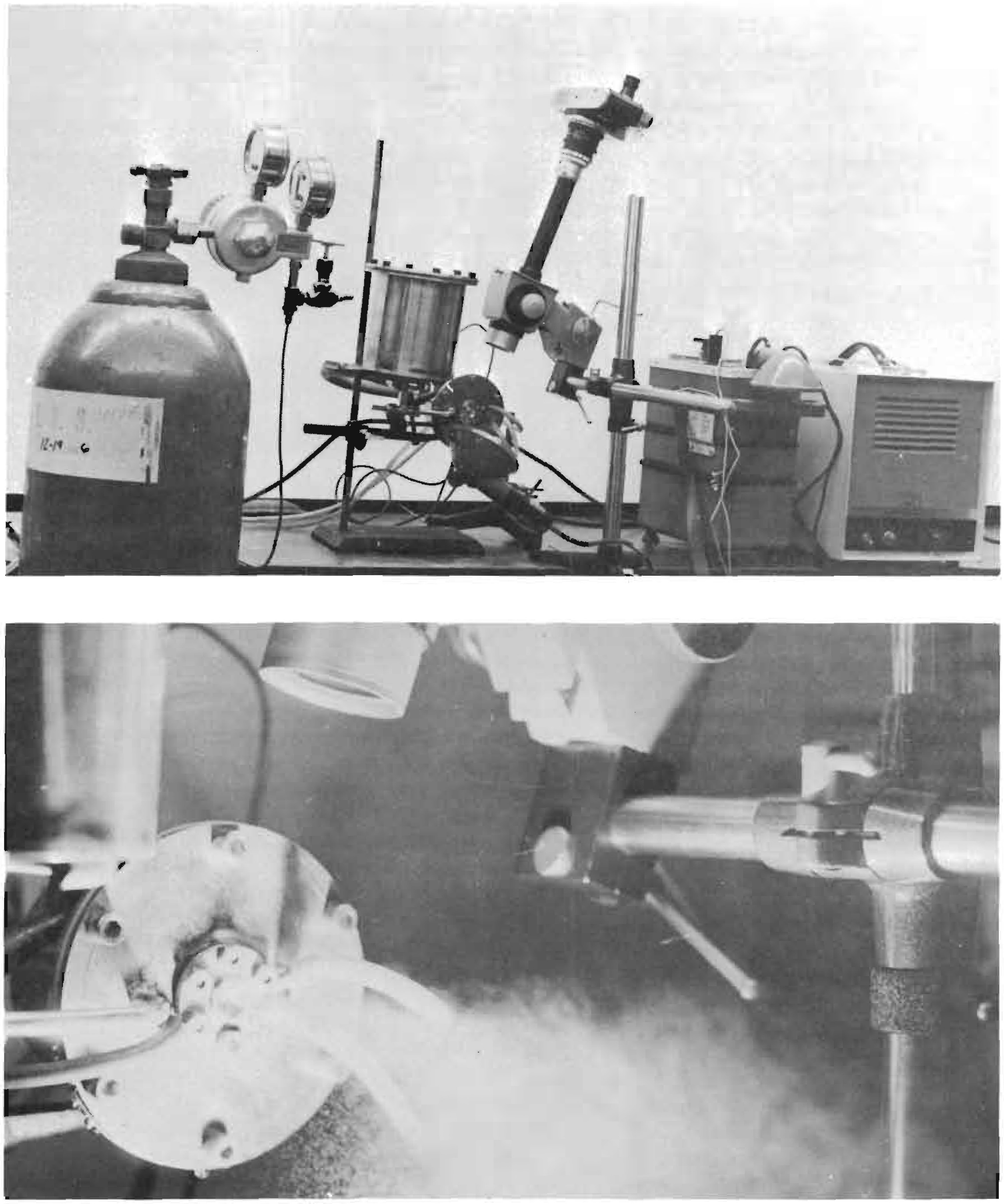


Figure 10. Photographs of the Ultrasonic Atomizer with Multiple Orifices. The top photograph is an overall view and the buttom shows a closeup of the orifice while a cloud is being generated.

orifices of this study at various pressures. All the jets produced were found to have the same dimension as the orifice within the accuracy of the measurements. In other words, the coefficient of contraction was unity for all the situations investigated. A typical jet stream is shown in Figure 3.

4. Effect of Pressure on Volume Flow Rate

The volumetric flow rate Q of a liquid through an orifice can be expressed by

$$Q = k \sqrt{\Delta p} \tag{36}$$

where k is a function of the characteristics of the system and the fluid properties and Δp is the pressure loss. The value of k is constant for a particular fluid flowing through a particular orifice. In the systems investigated here, Δp should be the difference between the system pressure and atmospheric pressure. Equation 36 can be rewritten as

$$\ln Q = \ln k + \frac{1}{2} \ln (\Delta p) \tag{37}$$

The experimental measurements of volumetric flow rate for water and the silicone liquid were plotted against differential pressures as shown in Figure 11. The slope of the lines are one-half in agreement with prediction. The value of k is 0.040 $cm^3 in/(min\ lb^{1/2})$ for the water and 0.049 $cm^3 in/(min\ lb^{1/2})$ for silicone oil. The units of Q are cm^3/min for convenience of calculation and p is in lb_f/in^2 for convenience of reading from a pressure gauge.

Thus equation 37 becomes

$$Q = 0.040 \sqrt{\Delta p} \quad \text{for water} \tag{38}$$

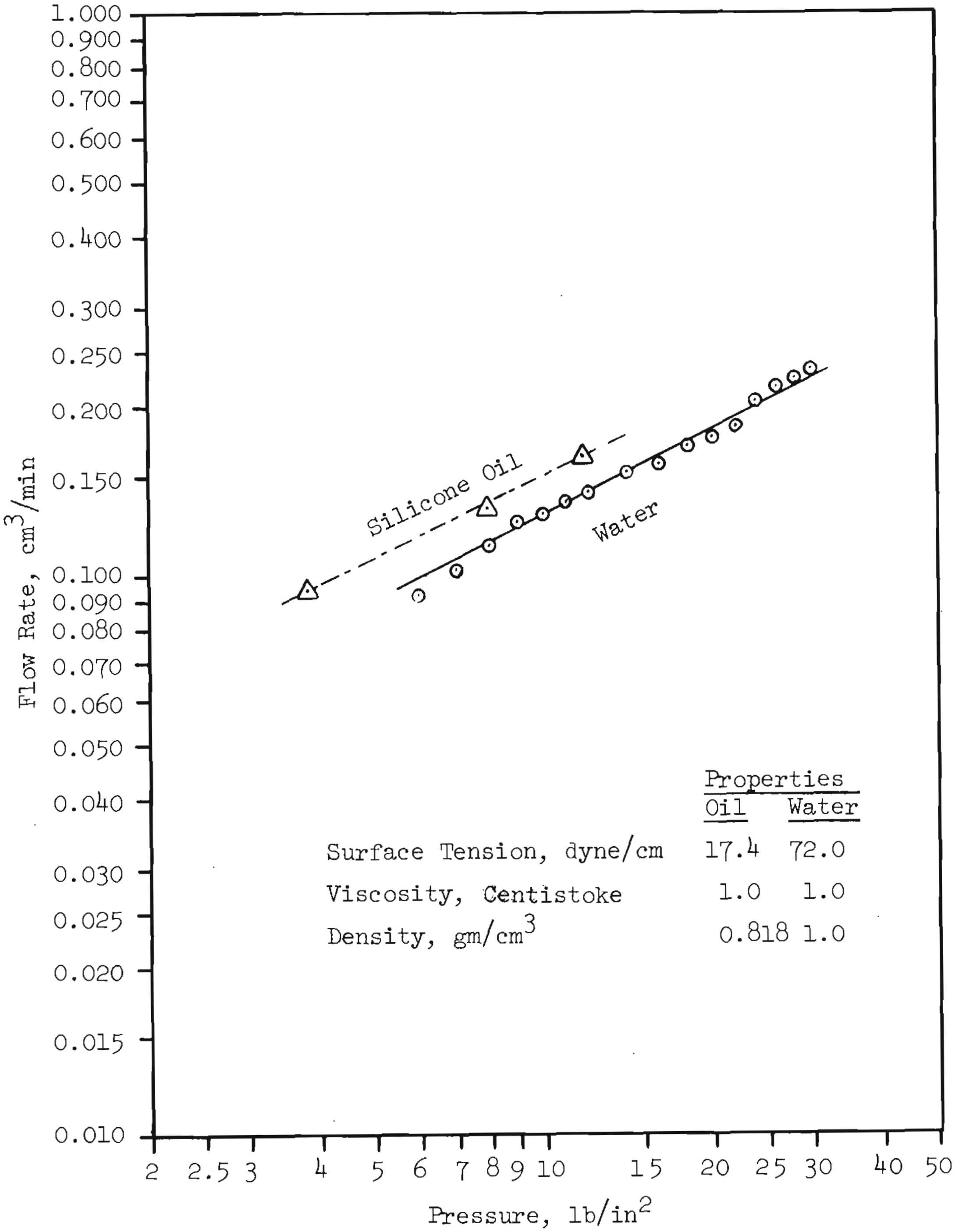


Figure 11. Flow Rate as a Function of Pressure for a 20μ Diameter Orifice.

and

$$Q = 0.049 \sqrt{\Delta p} \quad \text{for silicone oil} \tag{39}$$

The difference in the values of k for water and silicone oil is attributable mainly to their unequal surface tensions. The water has a greater surface tension (72 dyne/cm) than silicone oil (17.4 dyne/cm), so it required a higher pressure to achieve the same flow rate. Both liquids have the same viscosity -- 1 centistoke.

V. DISCUSSION OF RESULTS

The investigation was beset by two recurring problems throughout -- the tendency of the small openings to become blocked, or partially blocked, and the lack of a really satisfactory system of droplet size measurement.

Despite the use of stainless steel wherever possible, the careful polishing and cleaning of internal surfaces, and the careful filtering of the liquids to be atomized, debris repeatedly interrupted tests by blocking the capillary tubes and orifices. The problem arose when the vibration was initiated, for jets could be maintained without vibration almost indefinitely. With vibration, orifice plugging usually began in a minute or so. Apparently the vibration dislodged bits of matter that had not been removed previously.

Photography of the droplets immediately after formation proved to be most satisfactory for determining droplet sizes. The method avoided the problems of evaporation and distortion by collection on solid surfaces, but the desired sharpness of focus and depth of field could not be attained simultaneously. This meant that only one jet of a multijet system could be examined at one time.

Despite experimental problems, vibrating, capillary-type atomizers were confirmed to be good producers of monosize droplets. Vibrating multiple capillaries were found not to be satisfactory producers of uniform droplets due to slight differences in the size and thickness of the capillary tubes that caused them to have different resonant frequencies. Orifices were found to offer many advantages. Besides being available and having greater uniformity, they require less liquid pressure. Small capillary tubes are also more difficult to produce than simple orifice plates.

Small orifices were found to give coefficients of contraction of essentially unity. The flow rate of liquid through them was proportional to the square root of pressure, so, once a single calibrating factor is obtained, a desired flow rate can be achieved easily by adjusting the pressure on an orifice. Monosize droplets could be produced when the power and frequency were adjusted properly, provided the diameter of the orifice was between one-half and one-fourth the diameter of the droplet desired. The diameter of the droplets produced under best conditions varied inversely as the one-third power of the frequency.

Under some conditions, smaller droplets were observed that are called satellites. Satellites were produced from fine ligaments of liquid that originally connected two droplets but became detached, forming a smaller droplet. Sometimes the satellites collided with others to form bigger droplets. Under certain conditions, the droplet stream ultimately contained essentially uniform droplets even though satellites were produced. This happened when all the satellites coagulated in the same manner. Usually this kind of coagulation occurred rapidily, estimates were within one ten-thousandth of a second after satellite formation. Coagulation was due to the differences in momentum between the satellite droplets and the regular droplets and to the unequal drag of the air on them. When two droplets collide and combine into one, the combination oscillates with diminishing intensity between an oblate spheroid and a prolate spheroid, the frequency varying with size and the surface tension of the liquid.

Strong indications were found that multiple-orifice atomizers would produce dense aerosols containing uniform droplets, provided all orifice diameters were identical.

VI. CONCLUSIONS

The following statements summarize the conclusions of this investigation:

1. Capillary-type atomizers are good for producing monosize droplets only in single units. Multiple capillary units are extremely difficult to operate in unison.
2. Small-orifice, vibrated atomizers also produce uniform size droplets. When the orifices are identical and all within one plate, multiple orifices can be made to produce dense aerosol of essentially monosize droplets.
3. When uniform droplets are produced by vibrating atomizers, they will have diameters ranging from two to four times the diameter of the capillary tube or orifice.
4. Uniform droplet production is optimized when the frequency of vibration f, the flow rate Q, and droplet diameter d are related by $d = \left(\frac{3Q}{\pi f}\right)^{1/3}$.
5. The flow rate of a liquid through a small orifice is proportional to the square root of the pressure. Thus, the size of the droplets, the frequency of vibration, and the pressure are related by $d = k\left(\frac{\Delta p}{f^2}\right)^{1/6}$, where k is a proportionality constant.

VII. RECOMMENDATIONS

Multiple-orifice atomizers are much more satisfactory producers of uniform-droplet clouds than are multiple-capillary systems. The orifices must be of one size, and, to produce small droplets, must be very small themselves. Producing such orifices in plates of sufficient rigidity is a problem not yet satisfactorily solved for droplets to be created reliably below about 20 μ in diameter. Future work should concentrate first on developing techniques to produce multiple-orifice plates with orifices in the 5-μ diameter range. Boring such holes by laser techniques should, perhaps, be explored.

The interrelationships of liquid viscosity, surface tension, and density and jet breakup are also not entirely resolved. Additional study should be given to this aspect of atomization.

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