Immersion Sampling of Spray Droplets

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Nearly all processes involving sprays or aerosols are strongly affected by droplet size. The measurement of droplet size has therefore been attempted by numerous methods, including direct high-speed photography, light absorption or scattering, droplet cooling or freezing, and collection of droplets on coated slides or immersion cells. Although no method is entirely satisfactory, the immersion sampling technique has been successfully used both in research and industrial testing of atomizing devices. This method entails collection of dyed-water droplets in sampling cells containing solvent or a similar immersion fluid. Photomicrographs of the droplets are then obtained for manual or automatic counting.

Although immersion sampling has several recognized advantages, it is limited by the tendency of large, high-velocity droplets to shatter and by the failure of very small droplets to impact on the cell. Another problem is interference by the shutter used to expose the spray. To help overcome these limitations the mechanics of sampling hollow or solid-cone sprays was analyzed, and procedures were developed for selecting optimum cell and shutter configurations, sampling distance, and exposure time. Extension of the method to sprays comprised of two liquid streams and to sampling of oil droplets is also discussed.

The importance of droplet size in most spray processes is well recognized. Performance is strongly affected by the quality of atomization in such diverse applications as oil burning, combustion of turbojet and rocket fuels, aerosol dispersal, spray drying and cooling, dissemination of agricultural chemicals, and paint spraying.

Many interesting techniques have been developed for the measurement of droplet size (*1*). Unfortunately each method has its shortcomings. For example high-speed photography is an attractive direct method that avoids interference with the spray. However this method requires careful illumination, droplet velocity data to obtain the true size distribution, and considerable labor to sort the droplet images into various size groups. There is also difficulty in detecting very small droplets as well as those that are not in the exact plane of focus. Measurement of small droplets is also a problem with any freezing or cooling technique involving sieving. Conversely the cascade-impactor method is limited to analysis of small droplets. Light dispersion or absorption techniques, though rapid, are not capable of providing the entire droplet size distribution. When sampling sprays with coated slides or immersion cells extremely large droplets are subject to shattering, and some of the small droplets may bypass the sampler. On the other hand collection techniques are generally simple and rapid and permit droplet photographs of suitable quality for automatic scanning.

In the immersion sampling technique originated by Rupe (*2*) a 3% solution of nigrosine in water is sprayed into small cells filled with solvent. Because of the solvent's low density and immiscibility with water the droplets sink through the cell and remain suspended as practically perfect spheres, barely touching the bottom, as shown in Figure 1. After exposure to the spray the cells are completely filled with solvent and covered with glass to eliminate any meniscus effect. Glass cell bottoms permit photographing the collected droplets with light transmitted up through the sample. Photomicrographs at magnifications up to 50X are made on a high-contrast cut film (see Figure 2).

This method is attractive since it can be used to obtain droplet photographs that can be scanned automatically with an instrument such as that developed at the University of Wisconsin (*3*). This automatic droplet analyzer has not only contributed to basic atomizer research but has also served effectively as an industrial tool to evaluate many types of fuel injectors and commercial spray nozzles (*4*).

SAMPLING MECHANICS

Successful application of the immersion technique requires a thorough understanding of the sampling procedure. Significant results are not attainable unless the sample is representative and sufficiently large. At least 3,000 or 4,000 droplets should be sampled during each test to ensure good accuracy.

The droplet size distribution of the entire spray is also affected by the locations of the samples relative to the atomizer. For example in the hollow-cone circular spray pattern produced by a centrifugal pressure nozzle, droplets usually are coarser at the outside of the pattern that at the inside. Because of their greater mass and momentum the larger droplets are better able to resist the effects of gravity and induced air which tend to draw them toward the center (*5*). Accordingly it is necessary to sample across the entire pattern to obtain representative data. If small circular sampling cells are used, they should be positioned at the mid-points of several annular zones representing equal volumes of the total spray (*6*). These zones can be established from the flow distribution expressed as the cumulative percentage spray volume included within a given radial distance from the central nozzle axis. The droplet size distributions measured at each point must then be combined by adjusting the partial volumes of droplets collected in each zone to an equal basis. This method, though valid, requires flow distribution data, several individual droplet samples, and a subsequent calculation to obtain the size distribution for the complete spray.

More rapid analyses are possible with a single rectangular sampling cell that extends across the entire spray pattern (see Figure 3). A shutter hav-

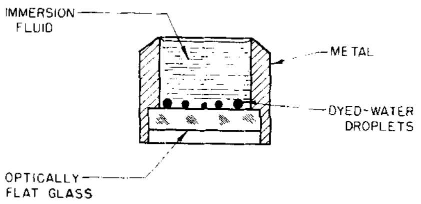

Fig. 1. Droplet sampling cell.

ing a sector-shaped aperture passes laterally above the cell, exposing it to an equal fraction of the spray at all distances from the nozzle axis. With this technique only one test is required to establish the droplet size distribution of a conical spray. It is assumed that the distribution is constant about the axis; otherwise samples should be taken along several radii. This sampling arrangement has been used at Delavan Manufacturing Company to evaluate several hundred nozzles. Depending on the width of the spray pattern, cells ranging between 2 and 20 in. in length have been employed. The shutter, activated by an air piston, may be moved across the cell at speeds up to about 25 in./sec. The shutter aperture is shielded by a stationary plate before and after exposure to the spray. Aperture inserts, varying in sector angle between 0.0086 and 0.0231 radians, have been used. Selection of aperture and shutter speed is dictated by the nozzle flow rate.

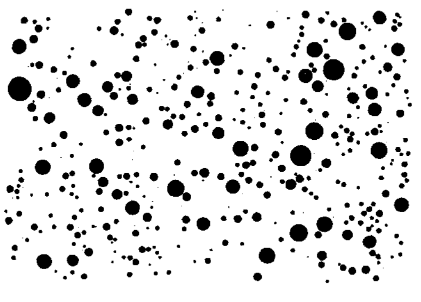

Fig. 2. Photomicrograph of collected dyed droplets.

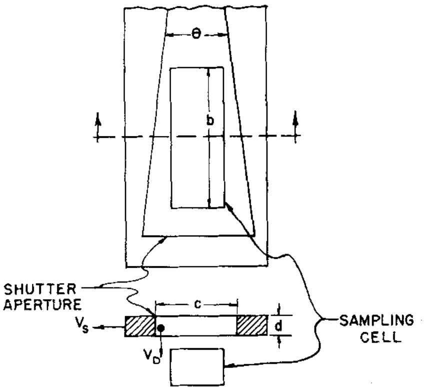

Fig. 3. Diagram of rectangular droplet sampling cell and shutter.

These variables determine the total number of collected droplets which may be calculated as follows:

$$N_D = \frac{(1.92 \times 10^{13})\, a\, \theta\, Q}{V_S D_V^3} \qquad (1)$$

This equation assumes that the flow density and degree of atomization are uniform around the nozzle axis. Since a cell ordinarily collects more droplets than are required for a representative sample, it is usually unnecessary to photograph the entire cell area. However exposures should be spaced at uniform intervals along the length of the cell. Cells having a width of at least 0.2 in. will accommodate two rows of frames giving 5- × 7-in. negatives at 50X magnification.

The suitability of samples for photographing and automatic counting depends not only on the number but also on the concentration of droplets in the cell. The fraction of cell area covered by droplets, denoted as the *droplet area fraction*, may be computed as follows:

Droplet area fraction

$$= \frac{(1.22 \times 10^{9})\, N_D D_A^2}{ab}$$

$$= \frac{(2.33 \times 10^{4})\, \theta\, Q}{b\, V_S D_{VA}} \qquad (2)$$

The concentration of droplets must be kept low enough to prevent appreciable coalescence in the cell. On the other hand enough droplets must be collected to provide a representative sample without requiring an excessive amount of photographic and analytic work. Good photomicrographs have been obtained with a droplet area fraction of about 0.05. When one uses this value as a criterion, compatible sampling conditions may be read from Figure 4. Although this may be used as a guide, selection of aperture size and shutter speed is largely determined by experience.

With reference to Figure 3, droplets entering the aperture may be considered as those whose centers lie between the upper edges of the aperture. The fraction of these droplets passing through the shutter without interference may be computed as follows:

Droplet clearance fraction

$$= \frac{(c - D) - d(V_S/V_D)}{c} \qquad (3)$$

It is evident from Equation (3) that interference is least severe for small, high-velocity droplets. Since large variations in droplet diameter and velocity normally exist in a spray, the actual clearance fraction is a composite value determined by the prevailing ranges of D and V_D. However a droplet clearance fraction of 0.95 was arbitrarily selected in developing Figure 5 which may be used as another guide in specifying suitable aperture dimensions and shutter speeds.

ERRORS AND LIMITATIONS

Some of the problems associated with immersion sampling of sprays have been discussed. A further source of error is the shattering of droplets as they strike the immersion fluid. Rupe (7), finding the critical impact velocity to be inversely proportional to droplet diameter, established the relationship shown in Figure 6 for the penetration of kerosene by water droplets. Thus, from the standpoint of critical impact velocity, large droplets are much more likely to shatter than small ones. This

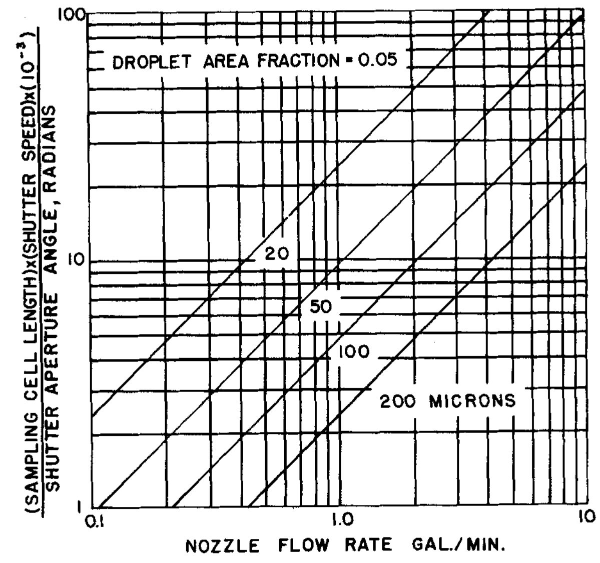

Fig. 4. Sampling conditions required for a droplet area fraction of 0.05.

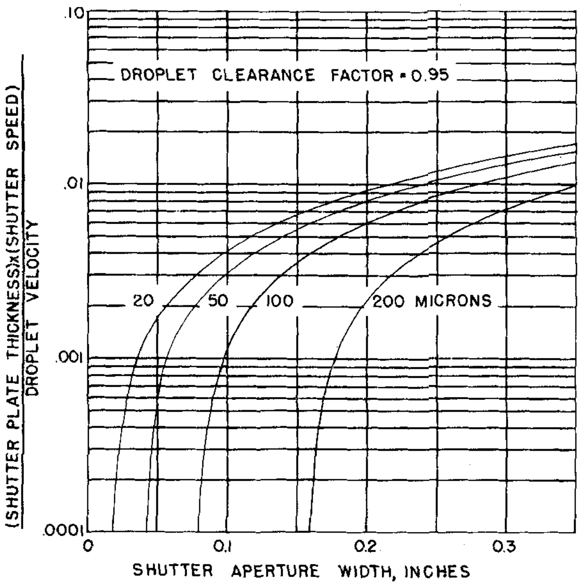

Fig. 5. Sampling conditions required for a droplet clearance fraction of 0.95.

tendency is compounded by the relatively low deceleration of the larger droplets after leaving the nozzle. This is illustrated in Figure 7 which is based on a correlation by Darnell and Marshall (*8*) relating droplet velocities in air to initial velocity, sampling distance and droplet diameter. For example a 400-μ droplet having an initial velocity of 100 ft./sec. would decelerate to nearly 25 ft./sec. within 5 in., whereas a 200-μ droplet would be reduced to about 6 ft./sec. With reference to Figure 6, breakup would be expected with the 400-μ droplet but not with the 200-μ droplet. For this reason aerosols and other finely atomized sprays may be sampled at much shorter distances than coarse sprays.

Although shattering is probably the most important factor, the measured droplet size distribution may also be affected by droplet coalescence between atomizer and immersion cell and by failure of some of the small droplets to impact on the cell. The latter error is difficult to predict since it requires a knowledge of the droplet and air flow patterns in the spray as well as the exact shape and orientation of the cell. These conditions are highly complex and almost impossible to determine precisely for any given test. Thus it can only be concluded that there is a danger of missing a substantial fraction of the smaller droplets through failure to impact. From a practical standpoint however many samples have been collected which contained thousands of droplets as small as 1 or 2 μ. In one test for example 60,000 droplets under 5 μ and 16,000 droplets between 5 and 10 μ were collected. This represented 98% of the total number of droplets in the spray.

To explore the limitations of immersion sampling this technique was employed to measure the droplet size distributions of two series of pressure nozzles having wide variations in flow rate. The same nozzles were then evaluated by a direct method involving high-speed spray photography (*9*). Double-exposure photos separated by a 22-μsec. interval were taken so that droplet velocities could be computed. It was thus possible to convert the spatial droplet size distribution measured from the high-speed photos to the temporal distribution obtained from the immersed samples. Table 1 lists the operating conditions, distribution data, and Sauter-mean diameters for each nozzle.

The oil-burner nozzles varied in flow between 0.7 and 36.5 gal./hr. at 100 lb./sq. in. gauge. As would be expected atomization became coarser at higher capacities. Agreement between the immersion sampling and photographic methods was fairly close at the two lower flow rates, but for the largest nozzle the Sauter-mean diameter determined by sampling was considerably smaller than that obtained photographically. Since neither method is entirely free from error, no positive conclusion can be drawn from this comparison. On the other hand it is suspected that some large droplets from the high flow nozzle may have shattered, resulting in the lower mean diameter reported.

A comparison of data for the smaller spray-drying nozzle shows that both analytical methods gave the same droplet diameter. However with the high-capacity nozzle the Sauter diameter measured by immersion sampling was again substantially less than that determined from high-speed photographs. The former method gave a maximum droplet size of approximately 400 μ. From Figure 7 one would predict a de-

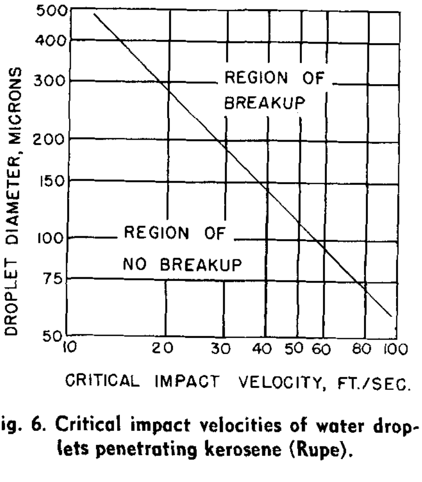

Fig. 6. Critical impact velocities of water droplets penetrating kerosene (Rupe).

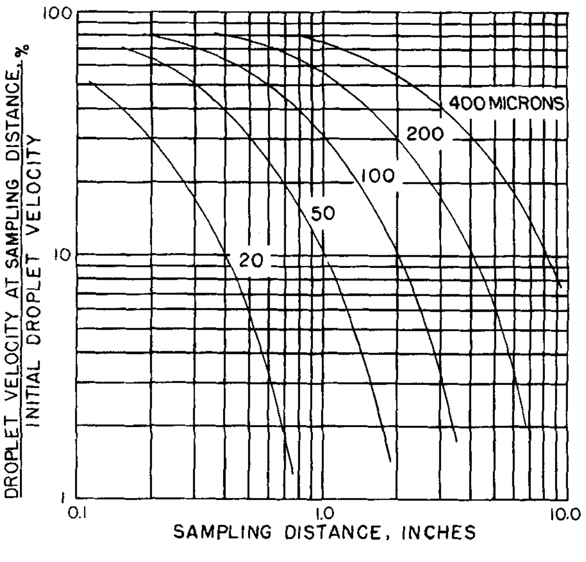

Fig. 7. Effect of droplet diameter and sampling distance on droplet velocity (Darnell and Marshall).

Table 1. Droplet Size Distribution Data for Representative Hollow-Cone Sprays

NOZZLE TYPE	OIL BURNER (Slotted Distributor)			SPRAY DRYING (Flat Swirl Chamber)	
Sampling pressure (psig)	100	100	100	300	300
Flow rate (gal./hr. water)	0.7	4.2	36.5	40.6	167.0
Orifice diameter (in.)	.009	.025	.082	.084	.094
Estimated axial spray velocity at orifice (ft./sec.)	90	79	72	102	167
Percentage of droplets in following size classes					
0 - 21.0 microns	62.2	30.7	41.2	56.6	67.7
21.0 - 42.0	18.7	28.0	24.5	20.8	20.9
42.0 - 63.0	10.5	21.3	14.6	10.6	6.9
63.0 - 84.0	5.7	9.8	7.5	5.4	2.4
84.0 - 105.0	2.3	4.3	4.8	3.3	1.1
105.0 - 126.0	0.5	3.0	2.6	1.6	0.4
126.0 - 147.0	0.1	1.5	1.5	0.9	0.2
147.0 - 167.9		0.8	1.5	0.4	0.2
167.9 - 188.9		0.4	0.8	0.3	0.1
188.9 - 209.9		0.1	0.3	0.1	0.0
209.9 - 230.9		0.1	0.2		0.1
230.9 - 251.9			0.3		
251.9 - 272.9			0.1		
272.9 - 293.9			0.1		
Sauter-mean droplet diameter (microns)					
Immersion sampling	65	94	131	92	86
High-speed photography	80	81	204	92	157

celeration from the estimated initial velocity of 167 ft./sec. to 10 ft./sec. within the 10-in. sampling distance. In accordance with Figures 6 and 7 a 450-μ or larger droplet would shatter on impact. This could well explain the absence of collected droplets above 400 μ for the high-capacity oil-burner and spray-drying nozzles and probably indicates a practical upper limit of 400 to 500 μ for the method.

It is evident that immersion sampling may be limited by large flow rates, high velocities, and large droplets. An increase in sampling distance is probably the best solution to these problems. However dense sprays are difficult to sample for several reasons. To avoid an overconcentration of droplets either a very rapid shutter or a narrow aperture must be used. However shutter interference is aggravated by both these conditions. Since a reduction in plate thickness would compensate for higher shutter speeds, a razor-edged aperture plate would be advantageous. Further improvement could be realized by utilizing a stationary aperture and a movable sampling cell, thereby eliminating the term $d(V_S/V_D)$ from Equation (3).

SPECIAL APPLICATIONS

The droplet sampler described earlier was designed to evaluate hollow and solid cone sprays which are used in most turbojet engines, oil burners, and industrial processes. There are however several important applications involving other types of spray patterns. Flat sprays for airless painting, metal descaling, and dissemination of agricultural chemicals are examples. In some instances irregular patterns are created by impinging jets or spray clusters. In these situations the geometry of the shutter and immersion cell would require modification to provide representative sampling of the particular spray configuration. This would usually entail flow-distribution data to help establish sampling locations.

An interesting application of the immersion sampling technique is the analysis of sprays comprised of two liquid streams. This would occur for example in impinging-jet injectors for rocket propellants (*10*) and in duplex and dual-orifice spray nozzles. In the latter devices, designed to cover wide flow ranges, the primary and secondary streams are metered independently within the nozzle but merge in a common spray. Thorough mixing of the primary and secondary liquid is desirable to produce fine atomization and efficient performance. This may be studied at least qualitatively by observing sampled droplets of the combined spray when dye has been added to only one of the streams. The extent of mixing may be estimated from the proportion of dye in each droplet.

The sampling technique described in this paper requires the collection of dyed water droplets in solvent or a similar immiscible hydrocarbon fluid. Because of the many spray applications involving heating oil or fuels for gas-turbines or rockets it would be desirable to sample these liquids directly. Oil sampling however requires an entirely different immersion fluid that is not only immiscible with oil but is of lower density. Moreover a dye is needed that will saturate the oil phase without coloring the immersion fluid. In a sponsored research program Battelle Memorial Institute surveyed numerous compounds and proposed dimethylamine borane as a possible immersion fluid when sampling droplets of JP-4 jet fuel (*11*). The borane compound has a density of about 0.69 g./cc. compared with 0.76 for JP-4 but is a crystalline solid up to 36°C. Since JP-4 is slightly soluble in the borane, the latter should first be saturated with jet fuel. In this condition the borane may be supercooled to room temperature for prolonged periods. Unfortunately the chemical is somewhat toxic and must be handled with caution.

Preliminary bench tests indicate that the collection of fuel droplets in dimethylamine borane may be feasible. However further development is necessary to find a suitable dye for the fuel and to produce samples comparable in quality to those obtainable with the water-solvent system.

NOTATION

a = width of sampling cell, in.
b = length of sampling cell, in.
c = shutter aperture width, in.
D = droplet diameter, in.
D_A = area-mean droplet diameter, μ
D_V = volume-mean droplet diameter, μ
D_{VA} = Sauter-mean droplet diameter, μ
d = thickness of shutter plate, in.
N_D = number of collected droplets per pass of shutter
Q = nozzle flow rate, gal./min.
V_D = droplet velocity, in./sec.
V_S = shutter speed, in./sec.
θ = shutter aperture angle, radians

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