

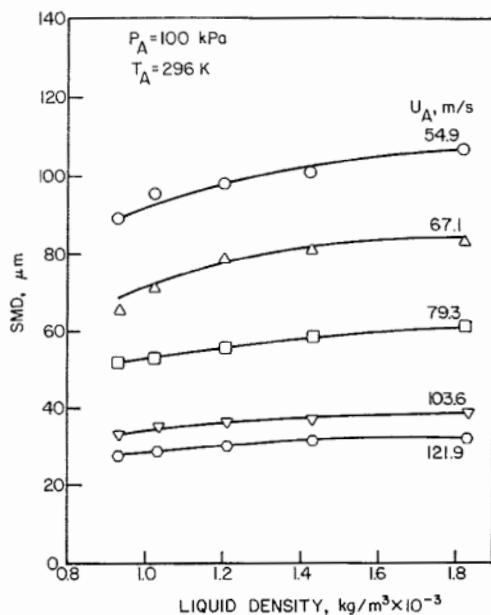


Figure 6.37 Variation in mean drop size with liquid density for a prefilming airblast atomizer (Rizkalla and Lefebvre [77]).

$$\text{SMD} = 3.33 \times 10^{-3} \frac{(\sigma \rho_L D_p)^{0.5}}{\rho_A U_A} \left(1 + \frac{1}{\text{ALR}} \right) + 13.0 \times 10^{-3} \left(\frac{\mu_L^2}{\sigma \rho_L} \right)^{0.425} D_p^{0.575} \left(1 + \frac{1}{\text{ALR}} \right)^2 \quad (6.57)$$

where L_c , the characteristic dimension of the atomizer, is set equal to D_p .

For liquids of low viscosity, such as water and kerosine, the first term pre-

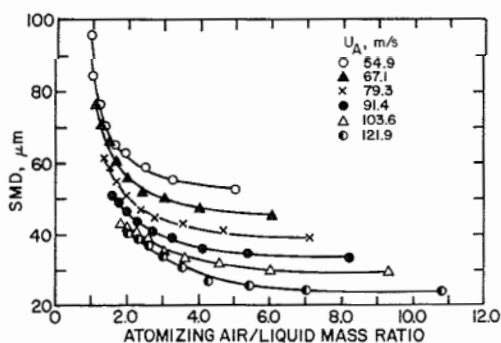


Figure 6.38 Variation of mean drop size with air/liquid ratio for a prefilming airblast atomizer (Rizkalla and Lefebvre [77]).

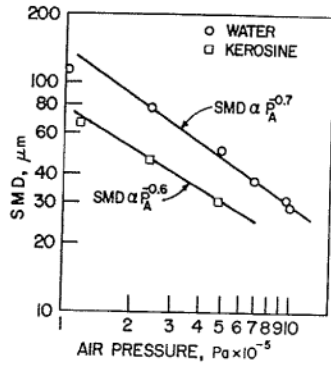


Figure 6.39 Variation of mean drop size with ambient air pressure for a prefilming airblast atomizer (Rizkalla and Lefebvre [77]).

dominates; the SMD thus increases with increases in liquid surface tension, liquid density, and atomizer dimensions and decreases with increases in air velocity, air/liquid ratio, and air density. For liquids of high viscosity the second term acquires greater significance; in consequence, the SMD becomes less sensitive to variations in air velocity and density.

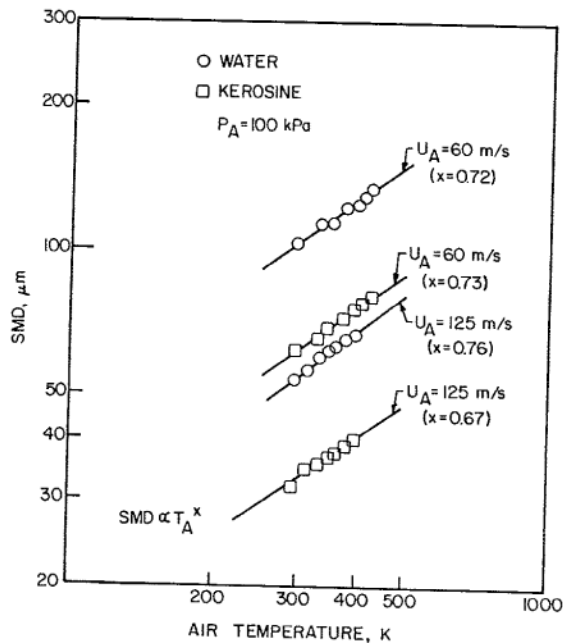


Figure 6.40 Variation of mean drop size with air temperature for a prefilming airblast atomizer (Rizkalla and Lefebvre [77]).

In view of the growing interest in “alternative” fuels for gas turbines, Jasuja [15] carried out an experimental study of the airblast atomization characteristics of kerosine, gas oil, and various blends of gas oil with residual fuel oil. He used the airblast nozzle developed by Bryan et al. [81], as illustrated in Fig. 6.41, and measured mean drop sizes by the light-scattering technique. The experimental data correlated well with the equation

$$\text{SMD} = 10^{-3} \left(1 + \frac{1}{\text{ALR}} \right)^{0.5} \left[\frac{(\sigma \rho_L)^{0.5}}{\rho_A U_A} + 0.06 \left(\frac{\mu_L^2}{\sigma \rho_A} \right)^{0.425} \right] \quad (6.58)$$

This equation is very similar to Eq. (6.57), except for the absence of a term representing the atomizer dimensions and a somewhat lower dependence of the SMD on air/liquid ratio.

The effect of atomizer scale on mean drop size was examined by El-Shanawany and Lefebvre [82]. They used three geometrically similar nozzles having cross-sectional areas in the ratio of 1:4:16. The basic atomizer design was almost identical to that used by Rizkalla and Lefebvre [77], shown in Fig. 6.34, except for some modifications to the inner airflow passage to ensure that its cross-sectional area diminished gradually and continuously toward the atomizing lip. These changes eliminated any possibility of airflow separation within the passage and encouraged the liquid film to adhere to the prefilming surface until it reached the atomizing lip.

El-Shanawany and Lefebvre's experiments were mainly confined to water and kerosine, but some specially prepared liquids of high viscosity were also used. Mean drop sizes were measured by the light-scattering technique in its improved form, as developed by Lorenzetto [75]. Their results for water, obtained over a

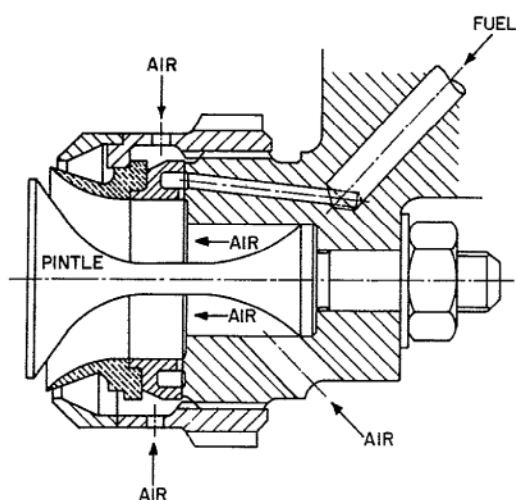


Figure 6.41 Bryan, Godbole, and Norster's atomizer [81].

wide range of air velocities with all three nozzles, are shown in Fig. 6.42. They demonstrate that $SMD \propto L_c^{0.43}$. From an analysis of all the experimental data, El-Shanawany and Lefebvre [82] concluded that the mean drop sizes produced by prefilming airblast atomizers could be correlated by the following dimensionally correct equation:

$$\frac{SMD}{D_h} = \left(1 + \frac{1}{ALR}\right) \left[0.33 \left(\frac{\sigma}{\rho_A U_A^2 D_p} \right)^{0.6} \left(\frac{\rho_L}{\rho_A} \right)^{0.1} + 0.068 \left(\frac{\mu_L^2}{\rho_L \sigma D_p} \right)^{0.5} \right] \quad (6.59)$$

Wittig and colleagues [83] have also examined the spray characteristics of a prefilming type of airblast atomizer in which the liquid sheet is injected into the outer airstream. Their results are generally consistent with those obtained for other types of prefilming airblast atomizers.

Miscellaneous Types

Several important studies of airblast atomization have been carried out on nozzle designs or nozzle configurations that do not fit neatly into either of the two main categories of plain-jet or prefilming systems. For example, Ingebo and Foster [84] used a plain-jet type of airblast atomizer, featuring cross-current air injection, to examine the breakup of isooctane, JP 5, benzene, carbon tetrachloride, and water. These workers derived an empirical relationship to correlate their experimental data, which they expressed in the following form:

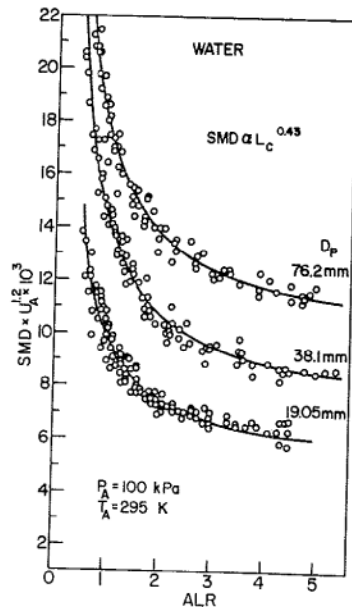


Figure 6.42 Effect of linear scale on mean drop size for water (El-Shanawany and Lefebvre [82]).

$$\frac{\text{SMD}}{d_o} = 5.0(\text{We Re})^{-0.25} \quad (6.60)$$

Substituting for We and Re gives

$$\text{SMD} = 5.0 \left(\frac{\sigma \mu_L d_o^2}{\rho_A U_R^3 \rho_L} \right)^{0.25} \quad (6.61)$$

According to Ingebo [85], the above equations are valid for $\text{We Re} < 10^6$. For $\text{We Re} > 10^6$ Ingebo recommends the following expression for mean drop size:

$$\frac{\text{SMD}}{d_o} = 37(\text{We Re})^{-0.4} \quad (6.62)$$

or

$$\text{SMD} = 37 \left(\frac{\sigma \mu_L d_o^{0.5}}{\rho_A U_R^3 \rho_L} \right)^{0.4} \quad (6.63)$$

Only water jets were used in deriving these dimensionally correct empirical expressions.

Equations (6.60)–(6.63) are highly relevant to the design of various air-breathing propulsion engines, such as ramjets and turbojet afterburners. These engines commonly employ radial fuel injection from plain-orifice atomizers into high-velocity, cross-flowing streams of air or gas.

In situations where transverse penetration of fuel into the gas stream is unnecessary or undesirable, a splash-plate type injector is generally preferred. With this device a round fuel jet is arranged to impinge at the center of a small plate. As the fuel flows over the edge of the plate, it is atomized by the high-velocity gas stream in which it is immersed. Essentially, the device functions as a simple prefilming airblast atomizer.

Ingebo [86] has studied the atomizing performance of this type of injector for air pressures ranging from 0.10 to 2.1 MPa (1 to 20 atm). His tests were confined to water, for which the effects of liquid velocity and air properties on mean drop size conformed to the relationship

$$\text{SMD} = (2.67 \times 10^4 U_L P_A^{-0.33} + 4.11 \times 10^6 \rho_A U_A P_A^{-0.75})^{-1} \quad (6.64)$$

Weiss and Worsham [87] investigated both cross-stream and costream injection of liquid jets into high-velocity air. Their experiments covered ranges of air velocity from 60 to 300 m/s, orifice diameters from 1.2 to 4.8 mm, liquid viscosities from 0.0032 to 0.0113 kg/m s, and air densities from 0.74 to 4.2 kg/m³. The most important factor controlling the mean drop size was found to be the relative velocity between the air and the liquid. They argued that the drop size distribution in a spray depends on the range of excitable wavelengths on the surface of a liquid sheet, the shorter-wavelength limit being due to viscous damping, while the longer wavelengths are limited by inertia effects. Based on these as-

sumptions, they concluded that

$$\text{SMD} \propto \left(\frac{U_L^{0.08} d_o^{0.16} \mu_L^{0.34}}{\rho_A^{0.30} U_R^{1.33}} \right) \quad (6.65)$$

Their experimental data confirmed the dependence predicted for air velocity but gave slightly different indices for the effects of liquid properties.

Gretzinger and Marshall [88] studied the characteristics of mean drop size and drop size distribution for two different designs of airblast atomizer. One was a "converging" nozzle of the type employed by Nukiyama and Tanasawa [68], in which the liquid is first brought into contact with the atomizing airstream at the throat of an air nozzle. The other, described as an "impingement" nozzle, consisted of a central circular air tube surrounded by an annular liquid duct. An impinger, mounted on a rod centered in the air tube, permitted adjustment of the airflow pattern and produced corresponding changes in the spray cone angle. Three orifices of 2.4, 2.8, and 3.2 mm diameter were employed.

Sprays of aqueous solutions of black dye were first dried and then collected in mineral oil and counted using a light microscope. The experiments covered a liquid flow range from 2 to 17 liters/h. Over the range of drop diameters from 5 to 30 μm , their experimental data were correlated by the equation

$$\text{MMD} = 2.6 \times 10^{-3} \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{0.4} \left(\frac{\mu_A}{\rho_A U_A L} \right)^{0.4} \quad (6.66)$$

for the convergent nozzle and

$$\text{MMD} = 1.22 \times 10^{-4} \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{0.6} \left(\frac{\mu_A}{\rho_A U_A L} \right)^{0.15} \quad (6.67)$$

for the impingement nozzle, where L is the diameter of the wetted periphery between the air and liquid streams.

The results of this investigation generally confirmed previous findings in regard to the beneficial effects of increases in air/liquid mass ratio, air velocity, and air density on atomization quality. However, Gretzinger and Marshall [88] emphasized that discretion should be exercised in applying their correlations to other nozzle types, especially for fluids whose physical properties are dissimilar to those used in their tests.

An interesting feature of Eqs. (6.66) and (6.67) is that they contain an air viscosity term, although the effect of air viscosity on mean drop size was not studied directly. More surprising, perhaps, is the result that increase in nozzle size reduces the mean drop size. This was interpreted to mean that a longer wetted perimeter creates a thinner liquid film and hence a finer spray.

Kim and Marshall [89] used an airblast nozzle of versatile design that provided two different configurations for the atomizing airflow. In one form, the atomizing air converged and expanded through an annulus around a liquid nozzle. In the alternative form, a secondary air nozzle was inserted axially in the liquid nozzle as shown in Fig. 6.43. Thus, an annular liquid sheet was produced between

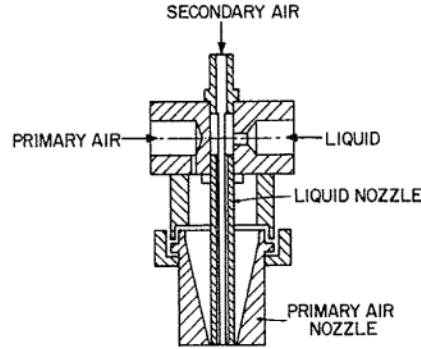


Figure 6.43 Kim and Marshall's atomizer [89].

two airstreams, an arrangement that previous work by Lefebvre and Miller [80] had shown to be very successful in producing fine sprays. Drop size measurements were carried out on melts of wax mixtures over a range of liquid viscosity of 0.001 to 0.050 kg/m s, relative air velocity of 75 to 393 m/s, air/liquid mass flow ratio of 0.06 to 40, liquid density of 800 to 960 kg/m³, and air density of 0.93 to 2.4 kg/m³.

For the convergent single airblast nozzle, it was found that

$$\begin{aligned} \text{MMD} = 5.36 \times 10^{-3} \frac{\sigma_L^{0.41} \mu_L^{0.32}}{(\rho_A U_R^2)^{0.57} A^{0.36} \rho_L^{0.16}} \\ + 3.44 \times 10^{-3} \left(\frac{\mu_L^2}{\rho_L \sigma} \right)^{0.17} \left(\frac{\dot{m}_A}{\dot{m}_L} \right)^m \frac{1}{U_R^{0.54}} \end{aligned} \quad (6.68)$$

where A is the flow area of the atomizing airstream in square meters and

$$m = \begin{cases} -1 & \text{for } \dot{m}_A/\dot{m}_L < 3 \\ -0.5 & \text{for } \dot{m}_A/\dot{m}_L > 3 \end{cases}$$

For the double concentric airblast atomizer, it was found that

$$\text{MMD} = 2.62 \frac{\sigma_L^{0.41} \mu_L^{0.32}}{(\rho_A U_R^2)^{0.72} \rho_L^{0.16}} + 1.06 \times 10^{-3} \left(\frac{\mu_L}{\rho_L \sigma} \right)^{0.17} \left(\frac{\dot{m}_A}{\dot{m}_L} \right)^m \frac{1}{U_R^{0.54}} \quad (6.69)$$

Kim and Marshall [89] concluded that the important operating variables in airblast atomization are the ALR and the dynamic force $\rho_A U_R^2$. Increasing either (or both) reduces the mean drop size. The recommended operating range for the ALR is from 0.1 to 10. Below the lower limit the atomization deteriorates, while above the upper limit air energy is wasted. It should be noted that these operating limits of ALR are far wider than those indicated by the various Cranfield studies [77, 80, 82], all of which demonstrated a marked deterioration in atomization quality at air/liquid ratios below 2.0.

It is of interest to note that the atomizer with concentric double air nozzles,

i.e., the arrangement in which the liquid sheet is entrained between two air-streams, yields only a slight improvement in atomization quality over the single air nozzle. Thus, the superior performance of the former type, as observed by Lefebvre and Miller [80], was not confirmed in these experiments.

Fraser et al. [90] studied the spray characteristics of an airblast system in which a spinning cup produced flat circular liquid sheets of sensibly uniform thickness. Disintegration of the liquid sheet was accomplished by a high-velocity airstream that flowed through an annular gap located axially symmetrically to the cup. They compared their experimental data with those of other workers and reported that prefilming atomizers are superior to plain-jet atomizers in producing finer sprays and that the controlled production of thin liquid sheets is a prerequisite to fine atomization. Their correlation for drop size data was derived as

$$\text{SMD} = 6 \times 10^{-6} + 0.019 \left[\frac{\sigma^{0.5} \nu_r^{0.21}}{\rho_A^{0.5} (aD_L + a^2)^{0.25}} \right] \times \left[1 + 0.065 \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{1.5} \right] \left[\frac{Q_L}{U_p^2 (0.5U_r^2 - U_r + 1)} \right]^{0.5} \quad (6.70)$$

where ν_r = kinematic viscosity ratio relative to water

a = radial distance from cup lip, m

D_L = diameter of cup at lip, m

U_p = cup peripheral velocity, m/s

U_r = air/liquid velocity ratio = U_A/U_p

Fraser et al. also concluded that the air/liquid mass ratio has little effect on SMD for values exceeding 1.5. This is appreciably lower than the values of between 4 and 5 reported in subsequent investigations [77, 80, 82].

Many expressions for correlating and predicting the mean drop sizes of airblast atomizers have been proposed. Those believed to be the most significant are listed in Tables 6.9, 6.10, and 6.11 for plain-jet, prefilming, and other types of nozzles.

Effect of Variables on Mean Drop Size

The main factors influencing the mean drop size of the spray are liquid properties, air properties, and atomizer geometry.

Liquid properties. The liquid properties of importance in airblast atomization are viscosity, surface tension, and density. The adverse effect on spray quality of an increase in viscosity is demonstrated in Fig. 6.35, in which the SMD is plotted against viscosity for various levels of air velocity at a constant liquid flow rate of 15 g/s. The influence of surface tension on the SMD is illustrated in Fig. 6.36, which also shows the adverse effect of an increase in liquid flow rate on atomization quality.

Table 6.9 Drop size equations for plain-jet airblast atomizers

Investigators	Equations	Remarks
Nukiyama and Tanasawa [68]	$\text{SMD} = 0.585 \left(\frac{\sigma}{\rho_L U_R^2} \right)^{0.5} + 53 \left(\frac{\mu_L^2}{\sigma \rho_L} \right)^{0.225} \left(\frac{Q_L}{Q_A} \right)^{1.5}$	No effect of nozzle dimensions or air density
Lorenzetto and Lefebvre [75]	$\begin{aligned} \text{SMD} = 0.95 \left[\frac{(\sigma \dot{m}_L)^{0.33}}{\rho_L^{0.37} \rho_A^{0.30} U_R} \right] \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)^{1.70} \\ + 0.13 \left(\frac{\mu_L^2 d_o}{\sigma \rho_L} \right)^{0.5} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)^{1.70} \end{aligned}$	For low-viscosity liquids SMD is independent of initial jet diameter d_o
Jasuja [78]	$\begin{aligned} \text{SMD} = 0.022 \left(\frac{\sigma}{\rho_A U_R^2} \right)^{0.45} \left(1 + \frac{1}{\text{ALR}} \right)^{0.5} \\ + 0.00143 \left(\frac{\mu_L^2}{\sigma \rho_L} \right)^{0.4} \left(1 + \frac{1}{\text{ALR}} \right)^{0.8} \end{aligned}$	For cross-current breakup
Rizk and Lefebvre [79]	$\begin{aligned} \text{SMD} = 0.48 d_o \left(\frac{\sigma}{\rho_A U_R^2 d_o} \right)^{0.4} \left(1 + \frac{1}{\text{ALR}} \right)^{0.4} \\ + 0.15 d_o \left(\frac{\mu_L^2}{\sigma \rho_L d_o} \right)^{0.5} \left(1 + \frac{1}{\text{ALR}} \right) \end{aligned}$	Coflowing air and liquids

Liquid density affects drop size in a fairly complex manner. For example, with prefilming atomizers, the distance to which the coherent liquid sheet extends downstream of the atomizing lip increases with density, so that ligament formation occurs under conditions of lower relative velocity between the air and the liquid. Moreover, for any given flow rate, an increase in liquid density produces a more compact spray that is less exposed to the atomizing action of the high-velocity air. These two effects combine to increase the mean drop size. However, an increase in liquid density can also improve atomization by reducing the thickness of the sheet produced at the atomizing lip of prefilming systems ($t \propto \rho_L^{-0.4}$) and by increasing the relative velocity U_R for plain-jet nozzles. The net effect of these conflicting factors is that the influence of liquid density on SMD is fairly small, as illustrated in Fig. 6.37.

Air properties. Of all the various factors influencing mean drop size, air velocity is undoubtedly the most important. This is very clear from inspection of Figs. 6.35, 6.37, and 6.38. For low-viscosity liquids, the SMD is roughly inversely proportional to the air velocity. This underlines the importance, in airblast atomizer design, of arranging for the liquid to be exposed to the highest possible air velocity consistent with the available pressure drop.

The effects of air pressure and temperature on mean drop size are illustrated

Table 6.10 Drop size equations for prefilming airblast atomizers

Investigators	Equation	Remarks
Rizkalla and Lefebvre [77]	$\text{SMD} = 3.33 \times 10^{-3} \frac{(\sigma \rho_L t)^{0.5}}{\rho_A U_A} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right) + 13.0 \times 10^{-3} \left(\frac{\mu_L^2}{\sigma \rho_L} \right)^{0.425} t^{0.575} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)^2$	L_c equated to t
Jasuja [15]	$\text{SMD} = 10^{-3} \frac{(\sigma \rho_L)^{0.5}}{\rho_A U_A} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)^{0.5} + 0.6 \times 10^{-4} \left(\frac{\mu_L^2}{\sigma \rho_A} \right)^{0.425} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)^{0.5}$	No effect of nozzle dimensions
Lefebvre [91]	$\frac{\text{SMD}}{L_c} = A \left(\frac{\sigma}{\rho_A U_A^2 D_p} \right)^{0.5} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right) + B \left(\frac{\mu_L^2}{\sigma \rho_L D_p} \right)^{0.5} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)$	"Basic" equation for prefilming airblast atomizers L_c = characteristic dimensions D_p = prefilmer diameter A, B = constants whose values depend on atomizer design
El-Shanawany and Lefebvre [82]	$\frac{\text{SMD}}{D_h} = \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right) \left[0.33 \left(\frac{\sigma}{\rho_A U_A^2 D_p} \right)^{0.6} \left(\frac{\rho_L}{\rho_A} \right)^{0.1} + 0.068 \left(\frac{\mu_L^2}{\sigma \rho_L D_p} \right)^{0.5} \right]$	L_c equated to D_h
Fraser et al. [90]	$\text{SMD} = 6 \times 10^{-6} + 0.019 \left[\frac{\sigma^{0.5} \nu_r^{0.21}}{\rho_A^{0.5} (a D_L + a^2)^{0.25}} \right] \left[1 + 0.065 \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{1.5} \right] \left[\frac{Q_L}{U_p^2 (0.5 U_r^2 - U_r + 1)} \right]^{0.5}$	a = radial distance from cup lip U_p = cup peripheral velocity U_r = air/liquid velocity ratio

in Figs. 6.39 and 6.40, respectively, for kerosine and water. These results, taken together, strongly suggest that for prefilming atomizers the SMD is proportional to air density to the -0.6 power.

For prefilming atomizers the SMD increases with an increase in atomizer scale (size) according to the relationship $\text{SMD} \propto L_c^{0.4}$.

Analysis of Drop Size Relationships

From inspection of all the experimental data on prefilming airblast atomizers, some general conclusions concerning the effects of air and liquid properties on mean drop size can be drawn. For liquids of low viscosity, such as water and kerosine, the main factors governing the SMD are surface tension, air density,

Table 6.11 Drop size equations for miscellaneous airblast atomizers

Investigators	Equation	Remarks
Gretzinger and Marshall [88]	$\text{MMD} = 2.6 \times 10^{-3} \left(\frac{\mu_A}{\rho_A U_A L} \right)^{0.4} \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{0.4}$	L = diameter of wetted periphery Drop size independent of liquid viscosity but dependent on air viscosity
Ingebo and Foster [84]	$\text{SMD} = 5.0 \left(\frac{\sigma \mu_L d_o^2}{\rho_A U_R^3 \rho_L} \right)^{0.25}$	For cross-current breakup
Kim and Marshall [89]	$\text{MMD} = 5.36 \times 10^{-3} \left[\frac{\sigma^{0.41} \mu_L^{0.32}}{(\rho_A U_R^2)^{0.57} A^{0.36} \rho_L^{0.16}} \right] + 3.44 \times 10^{-3} \left(\frac{\mu_L^2}{\sigma \rho_L} \right)^{0.17} \left(\frac{\dot{m}_A}{\dot{m}_L} \right)^m \frac{1}{U_R^{0.54}}$	A = flow area of atomizing airstream $m = -1$ at $\dot{m}_A/\dot{m}_L < 3$ $m = -0.5$ at $\dot{m}_A/\dot{m}_L > 3$
Weiss and Worsham [87]	$\text{SMD} \propto \left(\frac{U_L^{0.08} d_o^{0.16} \mu_L^{0.34}}{\rho_A^{0.30} U_R^{1.33}} \right)$	Cross-stream and costream injection
Ingebo [86]	$\text{SMD} = (2.67 \times 10^4 U_L P_A^{-0.33} + 4.11 \times 10^6 \rho_A U_A P_A^{-0.75})^{-1}$	Splash plate injector

and air velocity; for liquids of high viscosity the effects of air properties are less significant, and the SMD becomes more dependent on the liquid properties, especially viscosity.

The fact that viscosity has an effect quite separate from that of air velocity, as observed experimentally by Nukiyama and Tanasawa [68], Kim and Marshall [89], Lefebvre et al. [77, 80, 82], and Jasuja [15], suggests a form of equation in which the SMD is expressed as the sum of two terms, one dominated by air velocity and air density and the other by liquid viscosity. For prefilming types of atomizer, it can be shown [91] that

$$\frac{\text{SMD}}{L_c} = \left[A' \left(\frac{\sigma}{\rho_A U_A^2 D_p} \right)^{0.5} + B' \left(\frac{\mu_L^2}{\sigma \rho_L D_p} \right)^{0.5} \right] \left(1 + \frac{1}{\text{ALR}} \right) \quad (6.71)$$

where A' and B' are constants whose value depends on the atomizer design and must be determined experimentally.

Equation (6.71) is the "basic" equation for the mean drop size of the prefilming airblast atomizer. It shows that the SMD is proportional to the characteristic dimension L_c , which represents the linear scale of the atomizer. Equation (6.71) also shows that mean drop size is inversely proportional to the square root of the prefilmer lip diameter D_p . This is not surprising; if other parameters are kept constant, an increase in D_p will reduce the liquid film thickness at the atomizing lip and hence the SMD. The implication of this result for atomizer design is clear—for any given atomizer size (i.e., for any given value of L_c), the ratio D_p/L_c should be made as large as possible.

In practice, some secondary factors, such as liquid stream Reynolds number and airstream Mach number, affect the atomization process in a manner that is not yet fully understood. Thus, the ability of Eq. (6.71) to predict mean drop diameters can be improved by raising the exponent of the term $\sigma_L/\rho_A U_A^2 D_p$ from 0.5 to 0.6. Moreover, high-speed photographs of the atomization process have shown that for prefilming atomizers the effect of an increase in ρ_L/ρ_A is to extend the distance downstream of the atomizing lip at which sheet disintegration occurs, so that it takes place in a region of lower relative velocity [92]. Analysis of the experimental data shows that this effect may be accommodated by introducing into Eq. (6.71) the dimensionless term $(\rho_L/\rho_A)^{0.1}$. With these modifications Eq. (6.71) becomes

$$\frac{\text{SMD}}{L_c} = A \left(\frac{\sigma}{\rho_A U_A^2 D_p} \right)^{0.6} \left(\frac{\rho_L}{\rho_A} \right)^{0.1} \left(1 + \frac{1}{\text{ALR}} \right) + B \left(\frac{\mu_L^2}{\sigma \rho_L D_p} \right)^{0.5} \left(1 + \frac{1}{\text{ALR}} \right) \quad (6.72)$$

A logical choice for the characteristic dimension L_c is the hydraulic mean diameter of the atomizer air duct at its exit plane (see Fig. 6.34). Equating L_c to D_h and substituting into Eq. (6.72) the values of A and B derived from the experimental data of reference [82] yields Eq. (6.59).

Summary of Main Points

From the experimental data obtained by many workers on many different types of airblast atomizer, the following conclusions are drawn:

1. The mean drop size of the spray increases with increasing liquid viscosity and surface tension and with decreasing air/liquid ratio. Ideally, the air/liquid mass ratio should exceed 3, but little improvement in atomization quality is gained by raising this ratio above a value of about 5.
2. Liquid density appears to have little effect on the mean drop size. For prefilming nozzles, the mean drop size increases slightly with an increase in liquid density; for plain-jet nozzles, the opposite effect is observed.
3. The air properties of importance in airblast atomization are density and velocity. In general, the mean drop size is roughly inversely proportional to air velocity. The effect of air density may be expressed as $\text{SMD} \propto \rho_A^{-n}$, where n is about 0.3 for plain-jet atomizers and between 0.6 and 0.7 for prefilming types.
4. For plain-jet nozzles, the initial liquid jet diameter has little effect on mean drop size for liquids of low viscosity, but for high-viscosity liquids the atomization quality deteriorates with increasing jet size.
5. For prefilming atomizers, the mean drop size increases with increasing atomizer scale (size) according to the relationship $\text{SMD} \propto L_c^{0.4}$.
6. For any given size of prefilming atomizer (i.e., for any fixed value of L_c), the finest atomization is obtained by making the prefilmer lip diameter D_p as large as possible. This is because an increase in D_p reduces the liquid film thickness t , which in turn reduces the mean drop size ($\text{SMD} \propto t^{0.4}$).

7. Minimum drop sizes are obtained by using atomizers designed to provide maximum physical contact between the air and the liquid. With prefilming systems the best atomization is obtained by producing the thinnest possible liquid sheet of uniform thickness. It is also important to ensure that the liquid sheet formed at the atomizing lip is subjected to high-velocity air on both sides. This not only provides the finest atomization but also eliminates droplet deposition on adjacent solid surfaces.

8. The performance of prefilming atomizers is superior to that of plain-jet types, especially under adverse conditions of low air/liquid ratio and/or low air velocity.

9. At least two different mechanisms are involved in airblast atomization, and the relative importance of each depends mainly on the liquid viscosity. When a low-viscosity liquid is injected into a low-velocity airstream, waves are produced on the liquid surface; this surface becomes unstable and disintegrates into fragments. The fragments then contract into ligaments, which in turn break down into drops. With increased air velocity, the liquid sheet disintegrates earlier, so ligaments are formed nearer the lip. These ligaments tend to be thinner and shorter and disintegrate into smaller drops. With liquids of high viscosity, the wavy-surface mechanism is no longer present. Instead, the liquid is drawn out from the atomizing lip in the form of long ligaments. When atomization occurs, it does so well downstream of the atomizing lip in regions of relatively low velocity. In consequence, drop sizes tend to be larger.

The effects of the major variables on mean drop size are summarized for low-viscosity liquids in Table 6.8.

EFFERVESCENT ATOMIZER

Some of the results of drop size measurements made by Lefebvre et al. [93] for the type of atomizer shown in Fig. 4.49 are illustrated in Fig. 6.44. This figure shows mean drop size plotted against gas/liquid ratio by mass (GLR) for four values of liquid injection pressure ΔP_L , namely 34.5, 138, 345, and 690 kPa. The corresponding pressures in English units are 5, 20, 50, and 100 psi. The atomization quality demonstrated in this figure is clearly quite high. Even at a water pressure of only 138 kPa (20 psi), mean drop sizes of less than 50 μm are obtained at a GLR of 0.04, i.e., when using only 1 part by mass of nitrogen for every 25 parts of water. Figure 6.44 also shows, as would be expected, that increases in gas flow rate and/or liquid injection pressure lead to significant improvements in atomization quality.

If we now consider the flow of gas through the injector orifice, for continuity we have

$$\dot{m}_G = \rho_G A_G U_G \quad (6.73)$$

where A_G is the average cross-sectional area occupied by the gas flow and U_G is the mean gas velocity through the injection orifice.

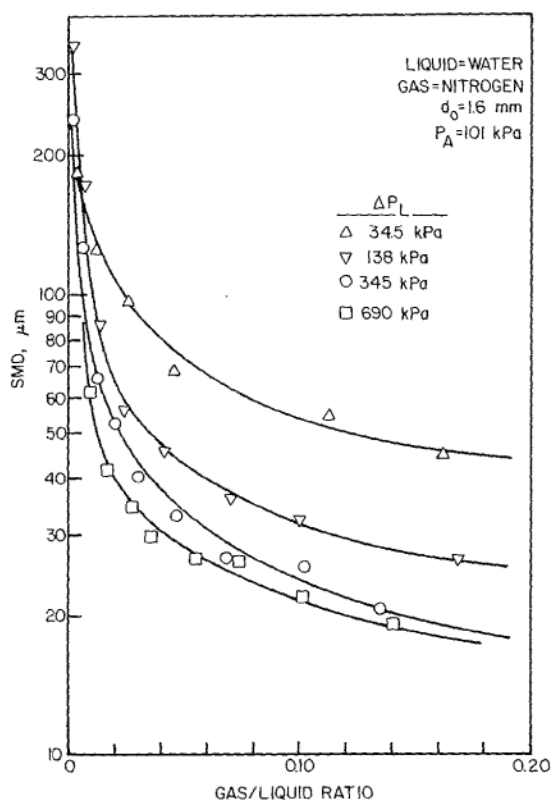


Figure 6.44 Influence of gas/liquid ratio and injection pressure on SMD for $d_o = 1.6$ mm [93].

From the above equation it follows that, for a constant gas flow rate, a reduction in ρ_G must lead to an increase in A_G or U_G , or both. Increase in gas flow area is beneficial to atomization because it reduces the area available for the liquid flow; i.e., it squeezes the liquid into thinner films and ligaments as it flows through the injector orifice. Increase in gas velocity is also beneficial to atomization because it accelerates the flow of liquid through the injector orifice, causing it to be discharged at a higher velocity. Thus, when operating at high injection pressures, atomization quality is high for two reasons. One is the high pressure drop across the exit orifice. This represents the atomization that would have been achieved in the absence of any injected gas. The second reason stems from the beneficial effects of the injected gas (1) in squeezing the liquid into fine ligaments as it flows through the injector orifice and (2) in "exploding" downstream of the nozzle exit to shatter these ligaments into small drops. With decrease in injection pressure, the "natural" atomization, i.e., the atomization that occurs solely as the result of the pressure drop across the nozzle, is impaired, but this is compensated in a large measure by the relatively bigger role played by the gas, which expands

in volume with reduction in pressure, leading to increases in the number of gas bubbles in the flow. Both these effects are conducive to better atomization.

If all the gas bubbles flowing through the discharge orifice are the same size, then from simple geometric considerations it can be shown that the average minimum thickness between adjacent gas bubbles is given by

$$t_{\min} = d_G \left\{ \left[\frac{\pi}{6} \left(1 + \frac{\rho_G}{\rho_L \text{GLR}} \right) \right]^{1/3} - 1 \right\} \quad (6.74)$$

where d_G is the average diameter of the gas bubbles, GLR is the gas/liquid ratio by mass, and ρ_G and ρ_L are the gas and liquid densities, respectively. Equation (6.74) indicates that $t_{\min}$ is directly proportional to the average diameter of the gas bubbles, which suggests that better atomization could be achieved by generating smaller bubbles. Equation (6.74) also suggests that increase in GLR should improve atomization quality, a result that is very evident in Fig. 6.44. Another interesting feature of Eq. (6.74) is that it does not include a term to represent the injector orifice diameter. This is fully supported by the results shown in Fig. 6.45, which demonstrate that SMD is virtually independent of injector orifice diameter. From a practical viewpoint, this is a most useful characteristic, because hitherto the general tendency has been to associate small drop sizes with small nozzle dimensions. From a combustion standpoint it is clearly most advantageous to have

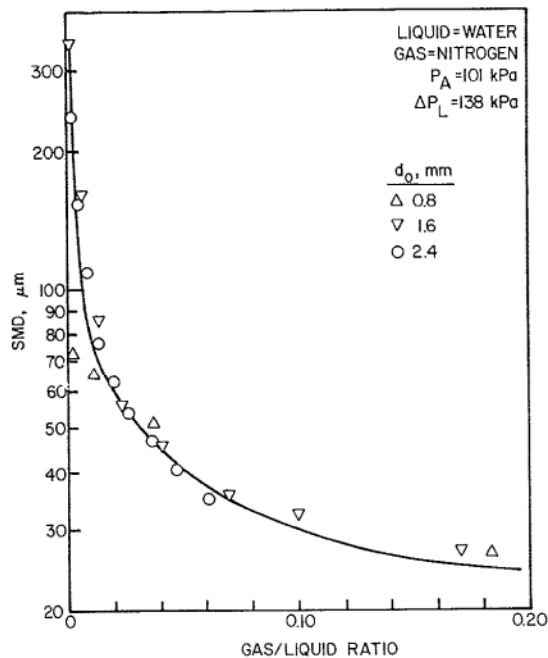


Figure 6.45 Influence of injector orifice diameter on SMD for an injection pressure of 138 kPa [93].

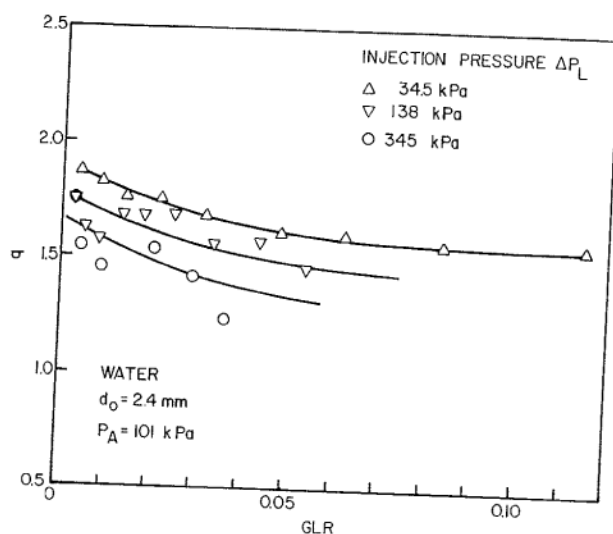


Figure 6.46 Influence of gas/liquid ratio and injection pressure on drop size distribution parameter [93].

a fuel nozzle that can provide good atomization at low fuel injection pressures, while still employing flow passages that are so large in cross section that problems of plugging by contaminants in the fuel are greatly alleviated.

Measured values of the Rosin-Rammler drop size distribution parameter q (see Chapter 3) for a 2.4-mm-diameter discharge orifice are shown in Fig. 6.46. They indicate that any change that tends to impair atomization quality, i.e., produce a larger value of SMD, also yields a more monodisperse spray.

ELECTROSTATIC ATOMIZERS

Very few measurements of the drop sizes produced in electrostatic atomization appear to have been made. A search of the literature revealed only the following expression for SMD, due to Mori et al. [94]:

$$\text{SMD} = 5.39 d_o \bar{E}^{-0.255} \bar{Q}^{0.277} \text{Re}^{-0.124} \quad (6.75)$$

where d_o = outer diameter of liquid supply tube

$$\bar{E} = \epsilon E^2 d_o / \sigma$$

ϵ = dielectric constant

E = intensity of electric field

$$\bar{Q} = \rho_L Q^2 d_o^3 / \sigma$$

Q = liquid flow rate

$$\text{Re} = Q / \mu_L d_o$$

ULTRASONIC ATOMIZERS

The drop formation mechanism for this type of atomizer was originally attributed to the creation and subsequent collapse of cavities caused by the intense sound wave. However, more recent opinion favors a capillary wave theory based on the observation that the mean drop size produced from thin layers of liquid on an ultrasonically excited plate is proportional to the capillary wavelength on the liquid surface. This implies that the mean drop size should be related to the ripple wavelength, which in turn is controlled by the vibration frequency. The results of experiments tend to support this hypothesis. For example, Lang [95] found that

$$D = 0.34\lambda = 0.34\left(\frac{8\pi}{\rho_L F}\right) \quad (6.76)$$

which is in close agreement with Lobdell's theoretical value of 0.36λ obtained from considerations of drop formation from high-amplitude capillary waves [96].

Another capillary wave theory was developed by Peskin and Raco [97] in terms of Taylor instability. They found that the atomization process is governed by several nondimensional parameters. Figure 6.47 gives the drop size in terms of transducer amplitude a , frequency ω_0 , liquid film thickness t , surface tension, and density. The drop size is seen to be a function of frequency and film thickness. For films of large thickness, their analytical result reduces to

$$D = \left(\frac{4\pi^3 \sigma}{\rho_L \omega_0^2}\right)^{1/3} \quad (6.77)$$

The ranges of drop sizes obtained by various workers are summarized in Table 6.12 from Lee et al. [98]. The operating frequency used in these studies varied from 10 to 2000 kHz.

Mochida [99] has studied a horn type of ultrasonic atomizer, operating at a frequency of 26 kHz, at flow rates up to 50 liters/h. Using distilled water and solutions of water with methanol and glycerin to obtain suitable variations in the

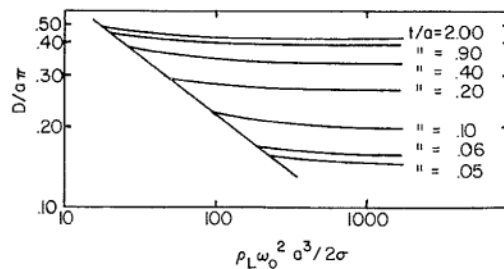


Figure 6.47 Relationship between dimensionless groups in ultrasonic atomization (*Peskin and Raco [97]*).

Table 6.12 Range of drop sizes covered by various studies employing an ultrasonic atomizer

Investigators	Drop size (μm)			
	1	10	100	1000
Wilcox and Tate [100]				
Crawford [101]				
Antonevich [102]				
Lang [95]				
Bisa et al. [103]				
McCubbin [104]				
Topp [105]				
Muromstev and Nenashev [106]				

Source: Lee et al. [98].

Table 6.13 Ability of ultrasonic nozzles to atomize various liquid classes

Easy	Medium difficulty	Very difficult or impossible
Water	Oil-based paints and coatings	Heavy hydrocarbons (unless heated)
Soluble water solutions	Medium-weight oils	Certain long-chain polymer solutions, e.g., tablet coating
Light hydrocarbons	Coal slurries	High solids content latex paints and coatings
Light oils	Most emulsions	Latex adhesives
Organic solvents		Ceramic slurries
Short-chain polymer solutions		

Source: Berger [107].

liquid properties that influence atomization, he obtained the following empirical equation for SMD:

$$\text{SMD} = 0.158 \left(\frac{\sigma}{\rho_L} \right)^{0.354} \mu_L^{0.303} Q_L^{0.139} \quad (6.78)$$

Further information on the performance of ultrasonic atomizers is contained in references [99] to [107]. The degree of difficulty involved in the atomization of various classes of liquids is indicated in Table 6.13.

NOMENCLATURE

A_o	discharge orifice area, m^2
A_p	total inlet ports area, m^2

A_s	swirl chamber area, m^2
ALR	air/liquid mass ratio
D	drop diameter, m
D_h	hydraulic mean diameter of air exit duct, m
D_p	prefilmer diameter, m
D_s	swirl chamber diameter, m
d	disk diameter, m
d_o	discharge orifice diameter, m
F	charging factor
FN	flow number $[=\dot{m}_L/(\Delta P_L \rho_L)^{0.5}]$, m^2
L_c	characteristic dimension of airblast atomizer, m
L_s	length of swirl chamber, m
MMD	mass median diameter, m
$\dot{m}$	flow rate, kg/s
N	rotational speed, rps
P	pressure, Pa
ΔP_L	injection pressure differential across nozzle, Pa
Q	volumetric flow rate, m^3/s
R	disk radius, m
Re	Reynolds number
Re_L	Reynolds number based on liquid properties $(=U_L \rho_L d_o / \mu_L)$
SMD	Sauter mean diameter, m
s	downstream distance of measuring plane from nozzle
T	temperature, K
t	film thickness in final orifice, m
t_s	initial sheet thickness at nozzle exit, m
U	velocity, m/s
We	Weber number
We_L	Weber number based on liquid properties $(=\rho_L U_L^2 d_o / \sigma)$
ω	rotational speed, radians/s
λ	wavelength, m
μ	dynamic viscosity, kg/m s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, kg/s^2

Subscripts

A	air
L	liquid
R	air relative to liquid

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DROP SIZING METHODS

INTRODUCTION

The problem of measuring the size of very small particles has been encountered in many branches of engineering science, and many different methods have been employed with varying degrees of success. However, special difficulties arise in the application of these methods to the measurement of drop sizes in a spray and are well known to those who have attempted such measurements. These difficulties include (1) the very large number of drops in a spray, (2) the high and varying velocity of the drops, (3) the wide range of drop sizes encountered in most practical sprays (the ratio of the largest to the smallest drop diameter often exceeds 100:1), and (4) the changes in drop size with time through evaporation and coalescence. All these factors must be considered when choosing a drop size measuring technique for any given application.

Drop sizing techniques for sprays should ideally have the following characteristics.

1. Create no disturbance to the atomization process or spray pattern. Caution is required when using intrusive devices to measure drop sizes in a flowing airstream since small drops generally follow streamlines whereas large drops tend to migrate across streamlines. This phenomenon can cause a size bias in the measurements.
2. Have a size range capability of at least 10, although a factor closer to 30 is desirable in some applications. Generally, probe methods such as the hot-wire technique have a size range from 1 to 600 μm and imaging techniques a size range above about 5 μm .

3. Have the ability to measure both spatial and temporal distributions. The latter is generally preferred, but many important optical techniques provide only spatial distributions. Conversion from one type of distribution to the other is possible if drop velocity data are also available.
4. Where appropriate, provide large representative samples. To achieve a reasonably accurate measurement of size distribution, the sample should contain at least 5000 drops.
5. Tolerate wide variations in the liquid and ambient gas properties. Many combustion systems operate at elevated pressures and temperatures. Successful development of mathematical models for fuel evaporation and combustion at these arduous conditions is heavily dependent on accurate and reliable spray diagnostics.
6. Provide rapid means of sampling and counting. Automated data acquisition and processing is needed to accumulate results within seconds. When the number density (drops/cm³) is required, the system must be fast enough to measure and record every drop passing through the probe volume. The data management system should be able to reproduce promptly the drop size distribution in histogram form along with the various mean diameters and standard deviations.

As it is virtually impossible to fulfill all these criteria in a single instrument, the capabilities and limitations of the various available measuring techniques must be recognized.

Drop Sizing Methods

The various methods employed in drop size measurement may be grouped conveniently into three broad categories—mechanical, electrical, and optical—as outlined below. The third category includes optical systems that have been developed in recent years and are finding an increasing range of applications. Some of these instruments have the capability of measuring drop velocity and number density as well as size distribution.

1. Mechanical
 - a. Drop collection on slides or in cells
 - b. Molten-wax and frozen-drop techniques
 - c. Cascade impactors
2. Electrical
 - a. Charged-wire and hot-wire techniques
3. Optical
 - a. Imaging—photography, holography
 - b. Nonimaging—single-particle counters, light scattering, Malvern particle analyzer

The growing importance of spray diagnostics, especially in the combustion area, has prompted several instrument manufacturers to intensify their research

and development activities to satisfy this expanding market. In this chapter no attempt is made to encompass all the techniques of relevance or potential application to the measurement of size distributions in sprays. Instead, attention is focused on three main categories: methods that have been widely used in the past, those still in widespread use, and methods that appear to have exceptional promise for enhanced diagnostic capabilities in the future.

Excellent reviews of drop size measuring techniques have been provided by Chigier [1,2], Bachalo [3], Ferrenberg [4], Hirleman [5], and Jones [6].

FACTORS INFLUENCING DROP SIZE MEASUREMENT

All measuring techniques, whether simple or sophisticated, are susceptible to various errors and ambiguities, the nature and importance of which depend on the particular method employed. However, a number of potential sources of error in drop size measurement are common to almost all methods. They include the method of sampling (spatial or temporal), sample size, drop saturation, drop evaporation, drop coalescence, and sampling location. In the design of instruments for drop size measurement every effort is made to minimize these types of errors, but the fact remains that all techniques are subject to errors and inaccuracies associated with the basic assumptions employed, their manner of use, and the quantity of data obtained.

Spatial and Temporal Sampling

Two types of sampling are employed to determine drop size distribution. One is *spatial sampling*, which describes the observation or measurement of drops contained within a volume during such short intervals of time that the contents of the volume do not change during any single observation. Examples of spatial sampling are single-flash, high-speed photography and laser holography. Any sum of such photographs would also constitute spatial sampling. The second type is *temporal sampling*, which describes the observation or measurement of drops that pass through a fixed area during a specific time interval, with each drop individually counted. Temporal distributions are generally produced by collection techniques and by optical instruments which are capable of sensing individual drops. Under certain circumstances, samples may be obtained that are neither spatial nor temporal, an example being the collection of drops on a slide that is moving, so that drops settle on the slide in addition to the drops collected by the motion of the slide through the swept volume.

If all the drops in a spray travel at the same velocity, the results obtained by spatial and temporal sampling are identical. If not, the spatial drop size distribution may be converted into the temporal distribution by multiplying the number of drops of a given velocity by that velocity.

With pressure atomizers, the smaller drops in the spray usually decelerate more rapidly than the larger drops, which leads to a high concentration of small

drops just downstream of the atomizer. Thus, spatial sampling in this region yields mean diameters smaller than those indicated by temporal sampling [7,8]. Farther downstream, where all the drops are moving at the same velocity, the results obtained by both methods should be the same.

The relative merits of spatial and temporal sampling are often debated. It is sometimes argued that spatial sampling is incorrect because it gives results that do not correspond to the spectrum of drop sizes actually discharged by the atomizer during a given time interval. However, as Tate [9] has pointed out, neither method is basically inferior to the other. In practice, which method is best depends on the application. For example, when herbicides are sprayed on the ground, temporal sampling would be the most informative. However, spatial sampling might be advantageous in combustion applications, where ignition and burning rates are dependent on the instantaneous droplet population within a given volume or zone [9].

Sample Size

Although a spray contains a far larger proportion of small drops than large ones, it is the relatively few large drops that predominate in determining the average drop diameter of the spray. Thus if a sample of drops is to be truly representative of the spray as a whole, it is vitally important that the large drops be included. As Lewis et al. [10] have pointed out, the presence or absence of one large drop in a sample of 1000 drops may affect the average diameter of the sample by as much as 100%.

To achieve a reasonably accurate estimate of spray quality, it is necessary to measure about 5500 drops. The accuracy of the mean diameter obtained for various sample sizes, as estimated by Bowen and Davies [11] for 95% confidence limits, is shown in Table 9.1.

Drop Saturation

This occurs when the drop flux or population exceeds the capability of the sizing instrument or method. The problem is most evident when drops are collected on coated slides or in immiscible solvents. If the sample is too large, the probability of error due to overlapping of drops (or their impressions) is high.

Table 9.1 Influence of sample size on accuracy of drop size measurements [11]

No. drops in sample	Accuracy (%)
500	± 17
1,500	± 10
5,500	± 5
35,000	± 2

Saturation is also encountered in optical systems [9]. Certain instruments are designed to sense one particle at a time. The presence of more than one particle in the optical path will be recorded as a single drop of large apparent diameter unless the instrument is capable of recognizing and rejecting coincident particles. Saturation is also a problem when dense sprays are studied using high-speed photographic or video imaging techniques.

Drop Evaporation

As the lifetime of small drops is extremely short, evaporation effect are very important in the measurement of fine sprays. Whether evaporation leads to an increase or decrease in mean drop size depends on the initial drop size distribution. For a monodisperse spray, evaporation always reduces the mean drop size, but if the spray contains a wide range of drop sizes initially, then evaporation may produce an increase in mass median diameter (MMD). The effects of evaporation on mean drop size have been discussed by Chin et al. [12]. The changes in MMD with evaporation time for different initial values of the Rosin-Rammler size distribution parameter q are shown in Fig. 9.1 for a kerosine (JP 5) fuel spray evaporating in air at a temperature of 2000 K and pressure of 2 MPa. It is apparent in this figure that MMD generally increases with evaporation time, the change of MMD being more significant for sprays having smaller q_0 values. For values of q_0 higher than 4, Fig. 9.1 indicates that MMD declines as evaporation proceeds.

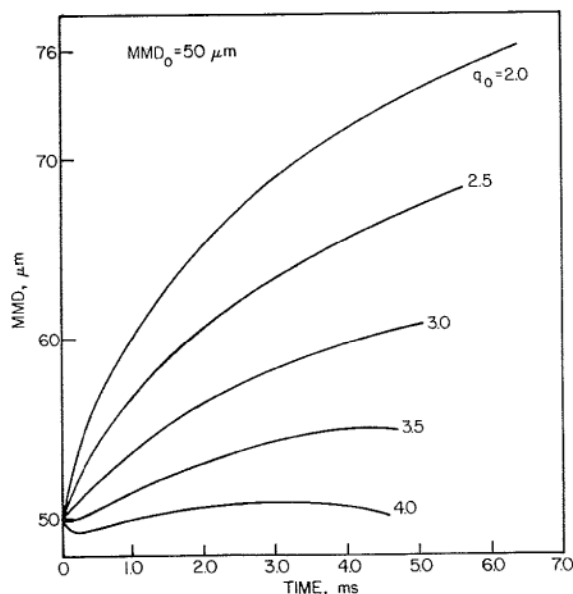


Figure 9.1 Change of mass median diameter with evaporation time for different values of q_0 . Fuel = JP 5, $P_A = 2000$ kPa, $T_A = 2000$ K (Chin et al. [12]).

Drop Coalescence

The collision of drops sometimes results in drop coalescence. Whether or not the collision of two drops leads to coalescence depends on the diameter of the drops, their relative velocity, and the collision angle [13]. It also depends on the number density of the spray and the time available for collisions. Thus coalescence is most likely to occur in dense sprays when sampled at large distances from the atomizer.

Sampling Location

With some measuring techniques it is possible to sample the entire spray or, at least, a representative portion of it. In other methods the data are drawn from a very small volume, typically around 1 mm³. With such methods the acquisition of sufficient data to characterize the total spray could prove tedious and time-consuming.

Most pressure-swirl atomizers produce a hollow-cone spray in which the largest drops, due to their higher inertia, are located at the outer periphery. In fan sprays also, the largest drops are usually found at the outer edges of the spray pattern. For such sprays local measurements of drop size distribution could clearly be misleading, but it should also be noted that even instruments that measure a line-of-sight average through the complete spray (for example, those that sample drops contained within a volume defined by the intersection of a laser beam and the spray) are not immune to errors from this source.

For low ambient temperatures, where the effects of fuel evaporation may be regarded as negligibly small, Chin et al. [8] have shown that when a liquid is injected from a pressure atomizer into a coflowing airstream, the values of mean drop size and drop size distribution, as measured by light-scattering techniques in the region downstream of the atomizer, may be appreciably different from the true values that would be measured in a plane fairly close to the nozzle where the atomization process is just complete. Unfortunately, in practice, this plane is very difficult to determine with any degree of precision, since it is very dependent on nozzle design features as well as liquid flow rate, injection pressure, and ambient air properties.

Generally it is found that a more uniform spray (higher q) or a higher initial MMD will exhibit less variation of MMD with changing axial location. Where drop acceleration or deceleration is present, the effect on spray measurement is to increase or decrease, respectively, the measured value of MMD. Far downstream of the nozzle, the distance depending on the air velocity and initial MMD, all the drops attain a sensibly uniform velocity, regardless of size, so the measured MMD again approaches the initial value.

These findings suggest that measurements of nozzle spray characteristics in a flowing airstream should ideally be carried out well downstream of the nozzle (200 to 300 mm), using air at low temperature (<300 K) in conjunction with liquids of low volatility.

The problems outlined above with pressure atomizers are far less pronounced

with airblast atomizers, partly because of the turbulent mixing of droplets and air but mainly because the airborne drops are transported radially by the flowing air to an extent that prohibits the formation of steep drop size gradients. However, errors arising from the combined effects of coalescence and evaporation still apply to this type of atomizer.

In general, the spray patterns produced by most practical atomizers are so complex that fairly precise measurements of drop size distributions can be obtained only if accurate and reliable instrumentation and data reduction procedures are combined with a sound appreciation of their useful limits of application. As emphasized by Tate [9], the ability to recognize and challenge questionable data is especially important. Thus, experience and judgment are valuable attributes for those who measure drop sizes and use the information in the design and application of atomizing systems.

MECHANICAL METHODS

These usually involve the capture of a sample of the spray on a solid surface or in a cell containing a special liquid. The drops are then observed, or photographed, with the aid of a microscope. The method is fairly simple and has many variations.

Collection of Drops on Slides

With this technique a solid surface, usually a glass slide, is covered with a suitable coating, which must be of very fine grain structure to make distinct the impressions created by very small drops [9,14]. A very fine surface may be obtained by burning a kerosine-soaked wick under the glass to produce a thin coating of soot, or by burning a magnesium ribbon to deposit a thin layer of magnesium oxide. With such coatings, drop sizes down to 3 μm in diameter can be observed and measured [15].

After the slide is exposed to the spray, the sizes of the drop impressions are measured, sometimes by means of a microscope fitted with a traversing scale, but more usually with a Quantimet image analyzer computer. These sizes are then converted to actual drop sizes using a correction factor derived by May [15].

More recently, Elkotb et al. [16] used soot-coated slides to measure both the radial and overall drop size distributions in a spray. The sampling apparatus consists of a small-diameter cylinder with 10 holes of 5 mm diameter at different radial distances; the soot-coated glass slide is mounted on an axle fitted inside the cylinder and can be rotated around the cylinder axis by a wheel. The apparatus is placed a distance of 60 mm from the atomizer.

Sprays injected from the atomizer and passing through the holes on the rim of the apparatus leave impressions on the soot layer deposited on the glass slide. The impressions on the slide are photographed under a microscope with a total magnification of 350. Each group of impressions represents part of the spray at

a radial distance equal to that of the hole responsible for these impressions. The diameters of the impressions are measured with a scale graduated down to 0.5 μm , and the drops that have the same diameter are counted and classified into size intervals of 10- μm width. The number and diameters of the impressions obtained for each radius of the spray define the spatial and total size distributions.

One problem associated with slides is that of determining what fraction of the slide area should be covered by drops. If too many drops are collected, the probability of error due to overlap is high and drop counting becomes tedious. On the other hand, if too few drops are collected, the sample may not be representative of the spray. From the standpoint of ease of measurement and counting, 0.2% coverage is satisfactory, but a coverage as high as 1.0% can be tolerated before the problem of drop overlap becomes significant.

Other important considerations are drop evaporation and collection efficiency. The lifetime of small drops is extremely short. For example, a water drop that is 10 μm in diameter has a lifetime of about 1 s in a 90% relative humidity atmosphere [17]. Thus, evaporation effects are very significant in the measurement of fine sprays. Collection efficiency is especially important with airblast atomizers, owing to the flow field created around the collecting surface. The large drops have enough inertia to hit the surface, but the small drops tend to follow the streamlines. For these reasons, drop size data for airblast atomizers obtained by direct drop collection tend to indicate larger than actual sizes.

Yet another problem that arises with the collection of drops on coated slides is the determination of the correction factor by which the diameter of the flattened drop must be multiplied to obtain the original diameter of the spherical volume. Its value depends on liquid properties, notably surface tension, and on the nature of the coating employed. For example, with oil drops the correction factor is around 0.5 for a clean glass surface and 0.86 for a magnesium-coated slide [18].

Most of the work using the impression method was performed more than 20 years ago, and the technique has now been largely supplanted by photographic and optical methods.

Collection of Drops in Cells

An improvement on the coated-slide technique is one in which the drops are caught on a target where they are held suspended while they are counted and measured. Hausser and Strobl [19] were among the first investigators to use as the target microscope slides coated with a special liquid in which the drop would not dissolve but would remain stable and suspended. An alternative approach is to collect the drops in a cell containing a suitable immersion liquid. This method has three advantages over collection on a slide: (1) the drops remain almost perfectly spherical, provided the density of the immersion liquid is only slightly less than that of the sprayed liquid, (2) evaporation is prevented, and (3) provided no splitting of the drop occurs on hitting the immersion liquid, the true sizes of the drops are obtained and can be measured directly. The method cannot be applied satisfactorily to coarse sprays due to the risk of disintegration of the largest drops on

impact with the immersion liquid. The problem of drop breakup can be alleviated to some extent by choosing immersion liquids of low viscosity and surface tension. Such liquids facilitate the penetration of the liquid surface by the drops. The drops then settle to the bottom of the cell, where they remain suspended and stable for an appreciable time, provided, of course, the immersion liquid is absolutely immiscible with the sprayed liquid.

Another problem with the immersion sampling method is that of drop coalescence. According to Karasawa and Kurabayashi [20], this phenomenon is often overlooked because the occurrence of coalescence is difficult to detect. The remedy is the same as that for drop breakup mentioned above, namely to use an immersion liquid of low viscosity [20]. Rupe [21] used this method in his investigation of sprays. The liquids employed were water and water-alcohol mixtures, and the immersion liquids were Stoddard solvent and white kerosine. The Delavan Corporation in the United States has also used this technique extensively to accumulate considerable data on drop size distributions in sprays [22]. The experimental procedures employed follow closely those of Rupe. Dyed water is sprayed into a cell filled with Stoddard solvent. The cell is located beneath an air-operated shutter, whose speed is adjusted to obtain a representative number of drops. After settling at the bottom of the cell, the drops are photographed at high magnification (usually $50\times$). The magnified drop images are then processed and the final computer printouts show the number of sampled drops and the spray volume associated with each size class. The computer also determines mean and median drop diameters as well as parameters indicating the uniformity of the distribution [22].

Molten Wax Technique

Joyce [23] developed this technique to a high state of perfection during the period 1940 to 1946. The basic idea is that paraffin wax, when heated to a suitable temperature above its melting point, has physical properties close to those of aviation kerosine (density, 780 kg/m^3 ; surface tension, 0.027 kg/s^2 ; kinematic viscosity, $1.5 \times 10^{-6}\text{ m}^2/\text{s}$). The molten wax is injected into the atmosphere of a large pressure vessel, where the drops rapidly cool and solidify. The sample is then subjected to a sieving operation in which the wax drops are separated into size groups. Each size group is weighed to obtain the volume (or mass) fraction in each size range. Thus the cumulative volume distribution and mass median diameter are measured directly without the large expenditure of time and personnel associated with the sizing and counting of multitudinous individual drops. Furthermore, the number of drops in a sample runs into millions, so clearly the technique does not suffer from a sample size that is too small to be statistically accurate.

One serious disadvantage of the hot wax technique is the limited choice of materials that can be used conveniently. If the properties of any given liquid are different from those of the simulant, it is necessary to establish the effects of these properties (notably surface tension and viscosity) on the atomization process. Other drawbacks of the method are the practical problems associated with preheating

the wax and the errors incurred because of changes in the physical properties of the wax droplet as it rapidly cools after leaving the atomizer, so that the processes of formation and secondary recombination may not be accurately reproduced. For this reason the air near the nozzle, i.e., in the region where the key atomization processes are taking place, should be heated to the same temperature as the molten wax.

Drop Freezing Techniques

A natural extension of the molten wax technique is to solidify the drops by freezing as soon as they emerge from the nozzle. In an early investigation, Longwell [24] developed a technique for collecting the liquid drops from a fuel spray into a stream of flowing fluid at room temperature. The fluid carrying the drops was then fed into an alcohol bath kept at approximately the temperature of dry ice, which was cold enough to freeze the drops into solid spheres. The drops were then sieved while still frozen to separate them into different size groups.

In the early 1950s Taylor and Harmon [25] froze water drops by collecting them in a hexane pan, packed around with dry ice and containing hexane at -20°C . Their method was dependent on the time taken for the drops to fall through hexane. The drops froze during their descent through the fluid and came to rest on a shutter. When the sample had all settled, the shutter was opened and the time for the drops to fall another 30 cm was measured. After traveling the 30 cm, the drops landed on a scale pan. The variation of scale pan weight with time could then be converted to equivalent drop diameters, the time taken for the fall being a function of the density difference between the drops and the supporting liquid, the liquid viscosity, the depth of fall, and the drop diameter squared. The process was, however, a very lengthy one, with $5\text{-}\mu\text{m}$ drops taking up to 27 h to fall, $100\text{-}\mu\text{m}$ drops taking 4 min.

In 1957 Choudhury et al. [26] described a method for freezing the entire spray in a bath of liquid nitrogen. The atomizer was mounted with its discharge nozzle pointing downward at a height of approximately 0.4 m above the liquid-nitrogen surface. After sufficient drops had been collected, the liquid nitrogen was decanted off and the frozen drops were passed through a series of screens ranging in size from 53 to $5660\text{ }\mu\text{m}$. It was found that to avoid any agglomeration of drops on the liquid-nitrogen surface, the density of the liquid being atomized should exceed 1200 kg/m^3 . Thus, the method is unsuitable for kerosine, fuel oils, and water, which clearly represents a serious disadvantage—especially coupled with a minimum measurable drop size of $53\text{ }\mu\text{m}$.

Various refinements to the nitrogen-freezing technique have been made by Nelson and Stevens [27], Street and Danaford [28], Rao [18], and Kurabayashi et al. [29]. Rao's method employs a specially designed isokinetic probe that is mounted with its inlet facing the atomizer. Gaseous or liquid nitrogen is conveyed to the tip of the probe and injected into the incoming spray through a narrow annular slot. The nitrogen, at a temperature of around 140 K, rapidly freezes the drops, which are then collected in a nitrogen-cooled Perspex pot and photographed

through a microscope. The final prints, showing the drops enlarged by a factor of 50 or more, are subsequently analyzed to determine the number and sizes of the drops in the sample. The method is simple, elegant, and convenient, but it still involves a correction factor to account for the change in drop size that occurs during freezing. A typical frozen drops photograph is shown in Fig. 9.2.

Cascade Impactors

This method is based on the principle that a large drop moving at high velocity will, because of its momentum, hit an obstacle placed in its path, whereas small



Figure 9.2 Typical photograph of frozen drops.

drops traveling below certain velocities will follow the airflow around the obstacle.

A single-stage impactor is shown in Fig. 9.3. A sample of the spray under investigation is drawn through a nozzle, where it encounters a slide. The slide is usually coated with a mixture of carbon and magnesium oxide to retain the drops. The large drops hit the slide, whereas the smaller drops follow the airstream around the slide. As the velocity of the jet containing the drops is increased by decreasing the area of the nozzle through which the stream flows, smaller drops will hit the slide by virtue of their increased momentum. May [30] has designed a four-stage cascade impactor in which the four jets are made progressively smaller, so that the speed and therefore the efficiency of impaction of drops increases from slide to slide when air is drawn through at a steady rate. Deposition of liquid on the walls of the first orifice becomes a problem for drop sizes larger than $50\text{ }\mu\text{m}$, so the greatest efficiency of sampling is achieved in the size range from 1.5 to $50\text{ }\mu\text{m}$ in diameter. To improve the sampling of larger drops, the dimensions of the impactor should be increased.

One advantage of the cascade impactor is that isokinetic sampling can be used to avoid discrimination against either very large or very small drops in the spray. Another advantage is that, after calibration, the quantity of liquid associated with each drop size range, collected in each stage of the cascade impactor, can readily be assessed by gravimetric or chemical means. In theory, any number of stages may be used to provide the desired drop size groupings.

The cascade impactor clearly lacks the sophistication of modern optical methods, but it can be made mechanically strong to withstand the rigors of routine handling. Moreover, it can operate satisfactorily under quite arduous conditions; for example, it has been used in flight tests to measure drop size distributions in clouds [14].

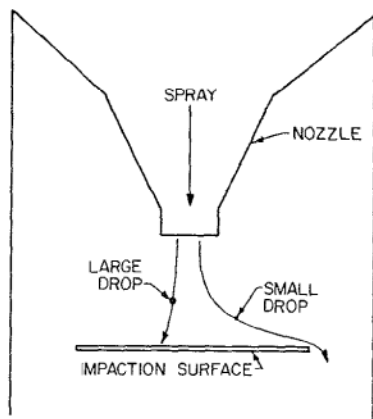


Figure 9.3 Schematic diagram illustrating principle of cascade impactor.

ELECTRICAL METHODS

Electrical methods generally rely on the detection and analysis of electronic pulses produced by drops for calculating size distributions.

Wicks-Dukler Technique

The method proposed by Wicks and Dukler [31] is based on the counting of pulses produced by drops momentarily bridging the gap between two sharp needles across which there is a potential difference. By adjusting the width of this gap, frequency counts can be obtained in terms of gap size and then converted into drop size distributions.

Some of the problems that can arise with this type of instrument have been described by Jones [6]. It has been found that the apparent resistance of a drop bridging the gap is a function of both drop velocity and the depth of immersion of the needles into the drop. Unless a very sensitive detection and counting system is employed, a large proportion of the pulses will be below the threshold that has to be set to avoid counting pulses due to noise. This could lead to large errors in drop size distribution [6]. Furthermore, changes in drop velocities will have the same effect on count rate as changes in drop sizes, so that apparent changes in size distribution could occur when, in fact, only drop velocities have changed. Despite these limitations, the system might find useful application for certain types of spray, bearing in mind its ease of operation. Comparison with a proven drop sizing method would be necessary to establish its useful operating range and to identify and quantify the principal sources of error.

Charged Wire Technique

This technique operates on the principle that when a drop impinges on an electrically charged wire it removes an amount of charge that depends on its size. This allows drop sizes to be obtained by converting the charge transfer into a measurable voltage pulse.

According to Gardiner [32], the limitations of the charged wire probe appear to depend on a combination of the electrical conductivity of the liquid and the flux of drops. Liquids of low conductivity produce pulses of long duration, which increases the probability of counting errors due to successive impingements being superimposed on each other. This problem appears to limit the useful application of this technique to dilute sprays of high-conductivity liquids.

Hot Wire Technique

When a liquid drop becomes attached to a heated wire it causes local cooling of the wire as it evaporates. This phenomenon can be used to obtain the sizes and concentrations of liquid drops present in a gas stream. Essentially, the device

employed is a constant-temperature hot wire anemometer. When no drops are present, the electrical resistance of the wire is high and sensibly uniform along its length. When a drop attaches to the wire, local cooling by the drop reduces the resistance in proportion to the drop size. This reduction in resistance is manifested as a voltage drop across the wire supports. The constant-current electrical energy supplied to the wire subsequently evaporates the drop, leaving the device ready to receive another drop. The entire process takes place within a time of 2 ms, depending on the drop size [33].

Mahler and Magnus [33] have described the operating principles and calibration procedures of a commercial hot wire instrument in some detail. Under the right conditions it can yield accurate measurements of Sauter mean diameter, mass mean diameter, volume flow rate, and liquid concentration. Although it is an intrusive technique, the platinum wire employed is only 5 μm in diameter and 1 mm long and causes very little disturbance to the flow. However, when measuring large drops the device can operate only at flow velocities below around 10 m/s because of drop shattering on the wire [3]. Moreover, the technique cannot be used for liquids that leave a residue on the wire, as this affects the calibration.

For a more complete account of the hot wire technique and other electrical methods for drop size measurements, reference should be made to the review by Jones [6].

OPTICAL METHODS

Optical methods can be broadly divided into *imaging* and *nonimaging* types. The former, including flash photography and holography, are limited in practice to drop sizes larger than 5 μm . Imaging methods have the advantage of allowing the drops to be "seen" as they exist at the point and time where knowledge of their size is required. Another advantage is that errors that might arise from coalescence or evaporation of drops after sampling are eliminated [14].

Nonimaging methods can be subdivided into two classes—those that count and size individual drops, one at a time, and those that measure a large number of drops simultaneously. For accurate results it is important to know both drop size and velocity, and some nonimaging instruments can provide both sets of information.

A variety of optical methods have been employed for spray analysis. Each method has its own advantages and limitations, but they all have the important attribute of allowing size measurements to be made without the insertion of a physical probe into the spray.

High-Speed Photography

At present, photography is one of the most accurate and least expensive techniques for the measurement of drop sizes and velocities in sprays. Usually it involves taking a photograph with a light pulse of sufficient intensity and sufficiently short

duration to produce a sharp image and then counting and sizing the images on the processed film. Much of the development work in the application of photography to spray analysis was carried out by Dombrowski and co-workers [34–36] and by Chigier and co-workers at Sheffield University [37–40].

Mercury vapor lamps, electrical sparks, flash lights, and laser pulses are generally used to create a high-intensity light source of short duration. Flash light sources have time durations of the order of 1 μ s, while lasers have pulse durations of the order of nanoseconds.

According to Jones [6], photography is probably the only technique with the potential to provide drop size information from the dense, fast-moving sprays of interest in power generation. However, the method is not without problems, of which the most difficult is analysis of the photographic images, which always entails at least some degree of human involvement. Manual sizing is tedious and time-consuming and invariably subject to operator fatigue and bias. Automatic image analyzers, such as the Quantimet, also call for considerable judgment on the part of the operator, who must ultimately decide which drops are in focus. With high-density sprays, the drop images may become very closely spaced on the negative, or even overlapping, which detracts appreciably from the accuracy of automatic image analysis. Increase in magnification at the imaging stage tends to alleviate this problem and also reduces the minimum drop size that the Quantimet can reliably measure. However, these improvements can be realized only by forfeiting depth of field [6].

A calibration procedure for determining the effective depth of field has been described by Chigier [40]. Particles of known size, deposited on a glass slide, are traversed across the region of focus of the camera and photographs are taken at regular intervals. Particle images are determined by measuring each particular diameter at two different light intensity levels. The average of these measurements is related to the particle diameter, and the difference between the diameters is a measure of the thickness of the blurred “halo” at the edge of the particle. By this means the effective depth of field is determined for each particular optical system and particle size.

High-speed photography can also be used to obtain information on drop velocities. If two light pulses are generated in rapid succession, a double image is obtained of a single drop on the photographic plate, from which the velocity of the drop can be determined by measuring the distance traveled by the drop and dividing it by the time interval between the two pulses. The direction of movement of the drop can also be directly determined from the photograph as an angle of flight with respect to the central axis of the spray. The method provides instantaneous measurements for individual drops, and from a series of such measurements time-average and space-average quantities can be determined as well as standard deviations. Measurement techniques based on this principle have been used successfully by many workers including De Corso and Kemeny [41], Mellor et al. [38], and Chigier [40].

High-magnification double-pulse laser photography has the capability for measuring simultaneously both drop sizes and velocities. It cannot normally be

used in regions close to the atomizer where drops are traveling at speeds in excess of 100 m/s, but particles down to 5 μm in diameter have been photographed when moving at speeds of 30 m/s [1].

TV Image Scanning Spray Analyzer

The data-processing problems associated with photographic methods are alleviated to a great extent by the TV analyzer developed by the Parker-Hannifin Corporation [42]. This instrument has been used to study in detail the spray characteristics of large numbers of pressure-swirl and airblast atomizers. It uses a 0.5- μs flash to photograph the drops contained within a small frame of dimensions 1.5×2.0 mm, approximately 1 mm in depth. The resolution of the system is within 4 μm . The rate of photography is 15 frames/s. A complete test takes about 20 min and encompasses more than 14,000 drops. The instrument is considered precise in the SMD range from 80 to 200 μm . The term "precise" in this context is intended to imply a repeatability of $\pm 6\%$.

Holography

Although holographic techniques have much in common with high-speed photography, they have the advantage of allowing a sizable region to be captured rather than the limited depth of field afforded by photographic methods. The application of holographic techniques to spray systems has been described by Chigier [2], Jones [6], MacLoughlin and Walsh [43], Murakami and Ishikawa [44], and Thompson [45].

With this method a sample volume of moving drops is illuminated with a coherent beam of light in the form of a short pulse. The measurement volume is a cylinder with length equal to the total width of the spray at the particular axial station and with diameter equal to that of the laser beam. As the duration of the laser pulse is extremely short (20 ns), the drops contained within the measurement volume are effectively "frozen." The resulting hologram provides a complete three-dimensional image of the spray in which drops as small as 15 μm are clearly visible. The hologram can then be illuminated with a coherent beam of light to produce a stationary image of all the drops at their correct relative locations in space. Thus, the holographic method is essentially a two-step imaging process that captures in permanent form the size and location of a moving system of drops and then produces a stationary three-dimensional image of all the drops contained within the sample volume.

One advantage of the holographic technique is that it produces a recorded image that can be studied later at leisure. Another asset is that, in principle, it requires no calibration. The accuracy of the method is fundamentally set by the wavelength of light; hence, in theory, about 2- μm resolution can be obtained. The main drawback of the method is that its application is limited to dilute sprays [6]. A typical laser holographic system is illustrated in Fig. 9.4.

A laser holographic system for the study of sprays has been developed at the

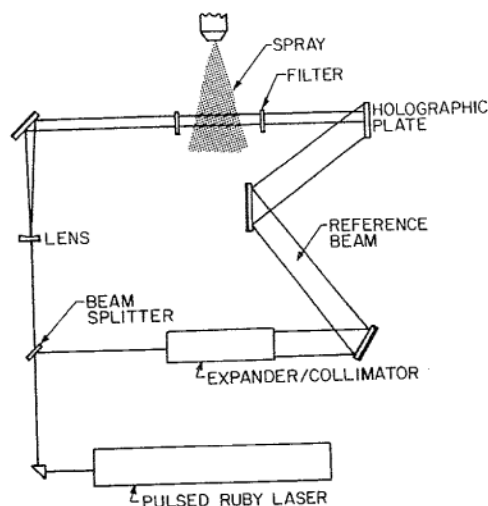


Figure 9.4 Schematic diagram of laser holographic system.

Marchwood Engineering Laboratories in England [6]. Holographic techniques are also being used for spray analysis at the United Technology Research Center in East Hartford, Connecticut [46].

At the Kyushu University in Fukuoka, Japan, Murakami and Ishikawa [44] have developed a technique employing two pulse lasers of different wavelengths so that two holograms are recorded on two different films separated by a suitable time interval. The displacements of moving particles (i.e., particle velocities) are measured on a superimposed picture of these two films.

Single-Particle Counters

As their name implies, single-particle counters measure individual particles or drops that pass through a focused laser beam. Because a single-particle counter can see only one drop at a time, the size of the *measurement* or *probe* volume sets the limitation on the drop number densities in which these counters will operate accurately. In practice, the measurement volume is controlled by the diameter of the focused beam, the f number of the receiver lens and its angle to the transmitted beam, and the aperture of the photodetector [3].

Although, in the past, single-particle counters were limited to fairly dilute sprays, the more recent use of large off-axis angles of light scatter detection has allowed these instruments to be used in relatively dense sprays [47]. They are now restricted to sprays with number densities similar to those to which the Fraunhofer diffraction method is restricted. It should be noted that single-particle counters are limited by high particle number densities and beam extinction, whereas diffraction instruments are limited by low number densities and by extinction in high

number density environments. Since beam extinction is dependent on the optical path length and number density, in particle fields larger than around 100 mm both methods are limited by beam extinction.

Single-particle counters have considerable potential for obtaining both size and velocity distributions directly. These distributions are based on measurements of individual drops and do not require the use of distribution functions. They also have the capability to perform the measurements nonintrusively with high spatial resolution over a large size range.

Light-scattering interferometry. With the advent of the laser Doppler velocimeter (LDV), interest in simultaneous particle sizing with the system soon arose. This was due to the realization that particles were needed that could follow the flow to be measured. These considerations and other principles and practice of laser anemometry are outlined in the book by Durst et al. [48]. Farmer [49,50] investigated the possibility of particle sizing using the visibility of the Doppler burst signal. The analysis of Farmer, although not entirely rigorous, was accurate given the appropriate conditions on the optical parameters. Perhaps the greatest limitation of the technique was the requirement of using on-axis forward- or back-scattered light detection. This resulted in an excessively large sample volume and the detection of particles that passed outside the region of complete overlap of the two laser beams. In addition, the size range of the method was limited to a factor of 10 or less. Other efforts by Chigier and co-workers ([51], for example) sought to combine the measurement of the scattered light intensity with the LDV to obtain simultaneous particle size and velocity measurements. Because near-forward light scatter detection was used, this method was also limited to very dilute particle fields. It was not until Bachalo [47] derived the theoretical analysis for dual-beam light scattering at large off-axis angles that the method of light-scattering interferometry appeared to be a viable means for spray diagnostics.

Beginning with the approach of Farmer, the measurement of drop size and velocity is based on the observation of the light scattered by drops passing through the crossover region of two intersecting laser beams. In practice, a single laser beam is split into two coherent beams of equal intensity and parallel polarization, which are made to cross as illustrated in Fig. 9.5. Drops passing through the intersection of the two beams scatter light that produces information from which the drop velocity U is calculated as

$$U = \frac{\lambda f_D}{2 \sin(\theta/2)} \quad (9.1)$$

where λ is the wavelength of laser light, f_D the Doppler frequency, and $\theta/2$ the laser beam intersection half-angle.

Size information is contained in the relative modulation (visibility) of the scattered signal. The term visibility may be understood by reference to Fig. 9.6. It was defined by Michelson as

$$\text{Visibility} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (9.2)$$

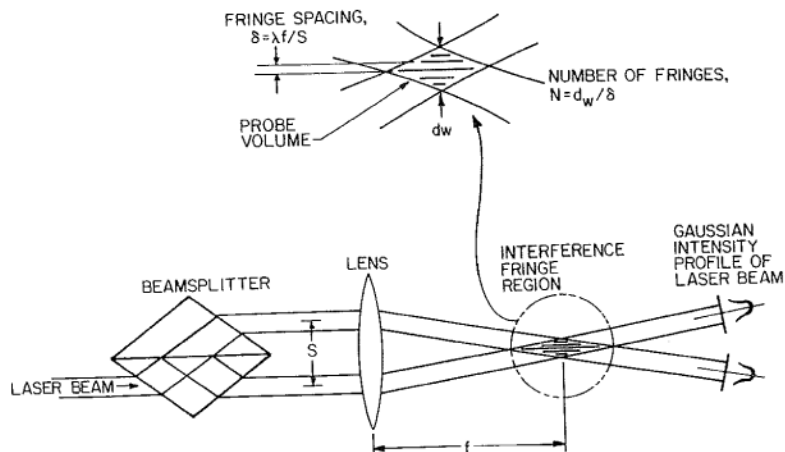


Figure 9.5 Drop sizing interferometer optics (Mularz *et al.* [55]).

where $I_{\max}$ and $I_{\min}$ are as shown in Fig. 9.6. The phenomena may be viewed in two ways. In Fig. 9.7 the fringe model is used to show how, as particles increase in size relative to the fringe spacing, they scatter light from more than one fringe at a time to reduce the signal modulation, or visibility. A more rigorous description considers the superposition of the light scattered from each beam separately which then interferes. In the near-forward direction, and for particles much larger than the light wavelength, this scattered light may be described by Fraunhofer diffraction theory or more accurately, for spherical particles of arbitrary size, by the Lorenz-Mie theory. The relative overlap of the forward-scattered light intensities then determines the relative visibility of the scattered interference fringe pattern. For example, larger particles scatter light that is more narrowly distributed in the forward direction, hence producing less intensity overlap for a given beam intersection angle. Based on the scalar diffraction theory and the derivation of Farmer, the relationship between drop size and visibility can be expressed as

$$\text{Visibility} = \frac{2J_1(\pi D/\delta)}{\pi D/\delta} \quad (9.3)$$

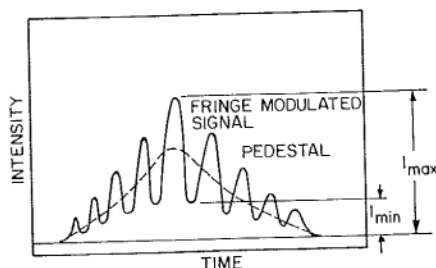


Figure 9.6 Doppler burst signal and pedestal components.

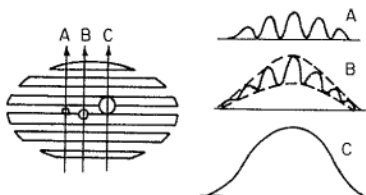


Figure 9.7 Effect of particle size on signal modulation.

where D is the drop diameter, J_1 a first-order Bessel function of the first kind, and δ the interference fringe spacing. This equation shows the functional relationship between the dimensionless parameter D/δ and the signal visibility, which allows a maximum measurement range of about 10:1.

In the implementation by Farmer using the on-axis light scatter detection mode, the visibility sizing method is suitable only for drops with diameters smaller than the fringe spacing. This forces the use of rather large beam diameters. Also, if the fringe spacing is increased to measure drop sizes around, say, 200 μm , the beam diameter must be approximately 10 times that diameter and the beam intersection angle must be made very small. For sprays containing a broad range of drop sizes, the excessively large sample volume will no longer leave an adequate probability that only one particle will reside in the sample volume at any one time, which leads to particle coincidence errors.

Large off-axis light scatter detection. The need to measure large drops on the order of 100 μm in diameter suggested a reevaluation of the light-scattering mechanism used. Bachalo [47] considered the light scattered by reflection and refraction as a more reliable means of sizing large spherical particles. These light-scattering components require the use of large off-axis detection, which, of course, is one of the advantages sought for handling high number density environments. The sample volume is thus reduced in size by as much as two to three orders of magnitude. Bachalo's analysis showed how the phase shift of the light scattered by refraction or reflection could be related to the particle diameter. For example, for light scattered by refraction in the off-axis forward direction, the scattering angle θ and phase shift ϕ are given as

$$\theta = 2\tau - 2\tau' \quad (9.4)$$

$$\phi = \frac{2\pi D}{\lambda} (\sin \tau - m \sin \tau') \quad (9.5)$$

where τ is the incidence angle of a ray with a surface tangent, τ' is the refracted angle of the transmitted ray given by Snell's law, and m is the drop index of refraction. Note that τ and τ' are fixed by the receiver aperture, so the phase shift ϕ is directly proportional to the drop diameter D . With dual-beam light scattering, the phase shift manifests as an interference fringe pattern with a spatial frequency that is inversely proportional to the drop diameter.

To avoid the detection of light scattered by diffraction and to detect light scattered predominantly by the mechanism of refraction, an angle 30° off the forward optical axis and orthogonal to the plane of the two beams is used. For this optical arrangement, the required focused beam diameters and length of the sample volume are significantly reduced and more precisely defined by the off-axis detection. Using refracted or reflected light, good sensitivity to drops in the size range from 5 to 3000 μm can be obtained using optical configurations allowing discrete measurement steps. However, the dynamic size range for any one optical configuration is still limited to less than 10:1.

A drop sizing interferometer incorporating a laser velocimeter and an interferometer system with off-axis collection has been described by Bachalo et al. [52] and is available commercially through Spectron Development Labs (Costa Mesa, Calif.) The system is shown schematically in Fig. 9.8. It comprises two essential units, the transmitter and the receiver. The transmitter optics define the fringe spacing (determined by the intersection angle of the laser beams) and the position of the probe volume. The receiving optics collect the light scattered from drops moving through the probe volume. In the system shown in Fig. 9.8 the collection angle θ is 30° from the forward direction. A collecting lens is used to image the probe volume on the photomultiplier's aperture or pinhole, where the drop signals are registered. The electronic components consist of a visibility processor that is used to process the input signals, which consist of Doppler signals superimposed on Gaussian pedestals as illustrated in Fig. 9.6. The processor separates the Doppler component from the pedestal component, integrates the areas under the respective signals, and divides the result to produce the signal visibility measurement. The drop size is determined from the signal visibility, i.e., the magnitude of the ratio between the Doppler and the pedestal components, and the velocity is determined from the Doppler frequency.

The visibility technique can provide accurate drop size measurements only if

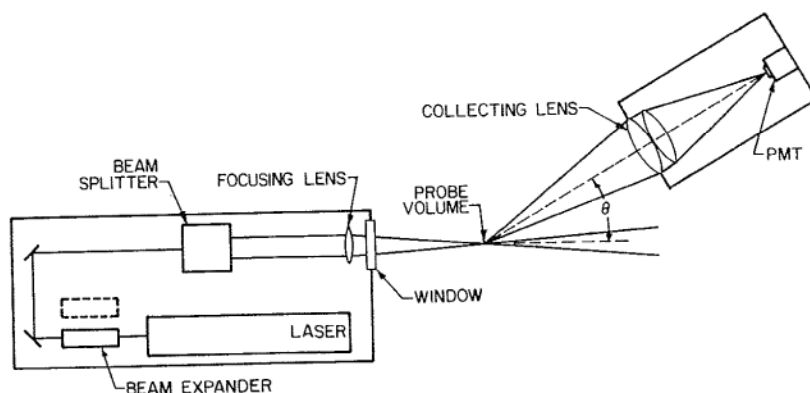


Figure 9.8 Schematic diagram of optical arrangement for drop sizing interferometer with off-axis collection.

the fringe visibility (or contrast) is known. In dense sprays, drops interacting with the transmitted beam upstream of the probe volume can randomly disrupt the conditions necessary for perfect fringe contrast at the probe volume. (These conditions include highly coherent beams, equal beam intensities, and complete beam overlap at the crossover.) The result is reduction in fringe visibility, which causes the measured drop size to exceed the actual drop size. It is also possible for the visibility to increase due to masking of the signal from out-of-focus drops by the pinhole or by the visibility processor's response to a signal with a high rise [53].

Spectron has now extended the capability of their drop sizing interferometer to include the amplitude of the scattered light in addition to the visibility [54]. The signal from each drop yields both parameters, and their cross-correlation can be used to select the right signals.

A correlation between the measured size of the drop and the amount of scattered light (Mie theory) is used to eliminate signals that indicate the wrong size. This *intensity validation* (IV) technique is based on the fact that drops that produce a certain visibility must have a given size, and consequently they must scatter light with a given intensity. In this manner, limits are fixed for every measured visibility [55].

Two of the main problems are solved by this technique. First, drops with erroneous visibility (due to beam blockage that causes a disturbed probe volume) will scatter light with an intensity lower than that pertaining to their apparent size. Second, drops crossing the probe volume at the point of less intensity (the tail of the Gaussian intensity profile) will have the right visibility but will scatter light with different intensity. The IV technique sets limits for the probe volume and rejects invalid signals by establishing limits on the intensity of the pedestal.

An advantage of this system is that it obviates the need for a direct calibration of intensity by an automated setting of the voltage to the photomultiplier. This added capability has resulted in a significant improvement in instrument accuracy, especially for measurements in dense sprays [3]. The disadvantage of this approach is that it rejects a very large number of samples, which greatly increases the sampling time.

Phase/Doppler particle analyzer. The theoretical description by Bachalo [47] of dual-beam light scattering showed that, at off-axis angles, the spatial frequency of the scattered interference fringe pattern is inversely related to the drop diameter. Limitations of the visibility method for measuring the spatial frequency suggested the development of other methods of measuring the fringe pattern. Since it is well known that the temporal frequency is a function of the beam intersection angle, the light wavelength, and the velocity of the drop, a method for simultaneously measuring both spatial and temporal frequencies was sought. Bachalo then derived a method (U.S. Patent No. 4,540,283) using pairs of detectors at fixed spacings in the image of the interference or fringe pattern. The approach has several advantages: the measurements are relatively unaffected by the random beam attenuations provided the signal-to-noise ratio is sufficient, the instrument response is linear over the entire working range, and it has a potentially large size dynamic

range. The dynamic range is limited only by the detector response and signal-to-noise ratio. An example of the instrument response function for monodisperse drops is shown in Fig. 9.9.

The method has been developed into a phase/Doppler particle analyzer by Aerometrics, Inc. (Mountain View, Calif.). The instrument is similar to a conventional dual-beam laser Doppler velocimeter except that three detectors are used in the receiver. The optical arrangement is shown schematically in Fig. 9.10. A standard system consists of a 10-mW HeNe laser light source followed by a combination beam expander and diffraction grating to split the beam. The diffraction grating is rotated at precisely controlled rates to provide frequency shifting for measurements in complex sprays. The receiver consists of a 108-mm-diameter $f/5$ lens located at 30° to the plane of the transmitted beams. Three detectors are employed to eliminate measurement ambiguity, add redundant measurements to improve reliability, and provide high sensitivity over a large size range. Their juxtaposition is such that Doppler burst signals are produced by each detector but with a relative phase shift. This phase shift is linearly related to the drop size. Signals from the photodetectors are amplified and transferred to the signal processor. Data acquisition and transfer to computer memory requires $20\ \mu\text{s}$ per drop. Histograms of drop size and velocity distributions can be displayed on a video monitor in essentially real time. At the completion of the data acquisition, the various mean sizes, mass flux, number density, and mean and rms velocity are determined.

The overall measurement size range of the instrument is from 0.5 to $3000\ \mu\text{m}$, provided the drops remain spherical. A size range of 105 may be covered at a single optical setting. The dynamic range is a factor of 35, which is limited by signal level and signal-to-noise considerations. Extensive testing of the method has been carried out, sometimes in high-density environments [56, 57].

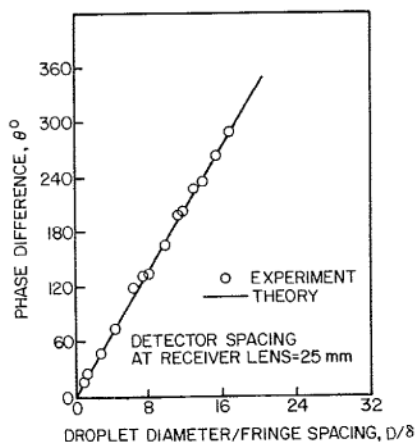


Figure 9.9 Plot of phase shift versus nondimensional drop size; comparison of theory and experiment (Bachalo and Houser [56]).

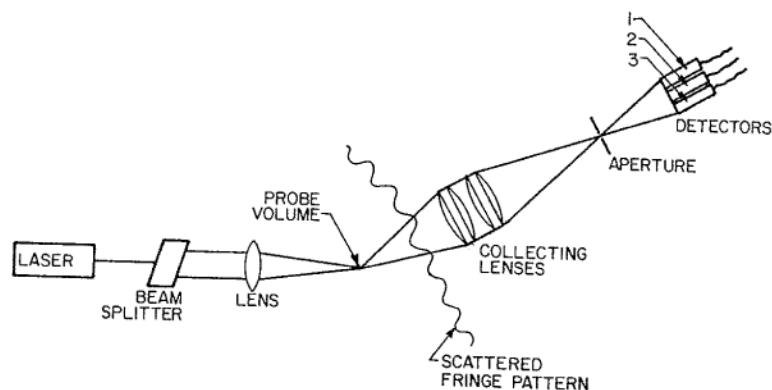


Figure 9.10 Schematic of the phase/Doppler particle analyzer.

Intensity deconvolution technique. In addition to interferometric techniques, single-particle counting can also be accomplished by measuring the *absolute intensity* of light scattered by particles traversing a single focused laser beam. The PCSV instrument manufactured by Insittec (San Ramon, Calif.) makes use of an intensity deconvolution technique to measure particle size, concentration, and velocity (Fig. 9.11). The principle of operation is explained in publications by Holve and co-workers [58–62]. Basically, this instrument measures the absolute intensity of light scattered by drops or solid particles passing through the sample volume of a single focused HeNe laser beam. The sample volume is defined by the intersection of the laser beam and the detector optics. A photomultiplier in the receiver measures the absolute intensity of light scattered by each particle passing through the sample volume. Since the sample volume has a nonuniform light intensity distribution, the intensity of the scattered light signals depends on both drop size and drop trajectory. The potential ambiguity in drop size and concentration measurements is resolved using a deconvolution algorithm. This solution

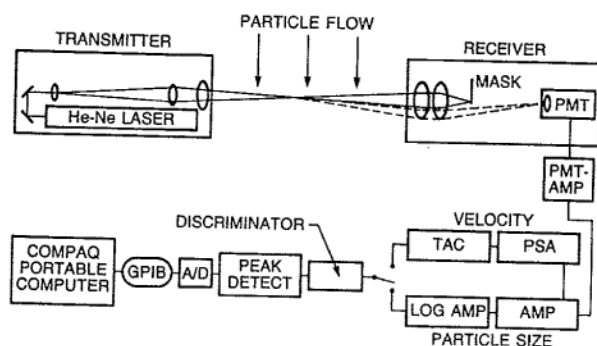


Figure 9.11 Schematic diagram of particle counter-size velocimeter (PCSV).

has two requirements: (1) the absolute scattered light intensity of a large number of drops must be measured (a process that typically requires less than 1 min) and (2) the sample volume intensity distribution must be known.

Knowing the sample volume intensity distribution, the count spectrum of scattered light intensities can be *deconvoluted* to yield the absolute drop concentration as a function of drop size, hence the name *intensity deconvolution* technique. Although the physics of the two measurement techniques is entirely different, the solution strategy of the intensity deconvolution technique is analogous to that of the Malvern particle sizer.

An important asset of the intensity deconvolution method is its ability to make measurements of drops, slurries, and solid particles. Since this measurement technique analyzes light scattered in the near-forward direction, the scatters may be spherical or irregular in shape. Use of an interference filter allows particle measurements to be made in combustion conditions. The overall measurement size range is 0.2 to 200 μm . The optical configuration of a typical instrument allows measurements from 0.3 to 100 μm . Particle velocities up to 200 m/s are determined using a transit timing technique [62]. Rapid signal processing (40–150 kHz) permits on-line data analysis.

Other miscellaneous techniques. Several other techniques have been proposed for simultaneous measurements of velocity and drop size in sprays. Work at Sheffield University by Yule et al. [51] has led to the development of a drop sizing technique based on laser velocimetry. Rather than measure signal modulation, they measure the peak mean value of the Doppler signal for drops larger than the fringe spacing. Their analysis shows a linear relationship between pedestal peak amplitude (Fig. 9.6) and drop diameter for drops between 30 and 300 μm in diameter. Good agreement was found between drop size distributions measured in sprays with their laser velocimeter and size distributions measured by collecting the drops on a slide and using an image analysis computer.

TSI Inc. (St. Paul, Minn.) has developed a visibility module for use in conjunction with a TSI laser anemometer system that provides simultaneous measurement of velocity, visibility, and pedestal amplitude. It operates in conjunction with a TSI LDV signal processor. The system has a large input Doppler frequency range from 1 kHz to 2 MHz with high data rates up to 50 kHz [2]. As the system is still relatively new, insufficient operational experience has been gained to allow performance comparisons to be made with the more established instruments.

Light-Scattering Technique

The optical properties of a medium are characterized by its refractive index, and as long as this is uniform, light will pass through the medium undeflected. Whenever there are discrete variations in the refractive index due to the presence of particles, part of the radiation will be scattered in all directions while the other part is transmitted unperturbed. In drop size analysis, provided the number of drops under observation is large enough to ensure that a representative sample is

obtained, the properties of the scattered light can be used to indicate the drop size distribution. The formulation of a theory for the scattering properties of particles of arbitrary size and arbitrary refractive index occurring in polydispersions of finite optical depth was first derived by Dobbins et al. [63]. For a polydisperse system, the radiant intensity $I(\theta)$ scattered at a small angle θ from the forward direction due to an incident planar wave of irradiance E_0 can be written as

$$\frac{I(\theta)}{E_0} = \frac{D^2}{16} \left\{ \alpha^2 \left[\frac{2J_1(\alpha\theta)}{\alpha\theta} \right]^2 + \left[\frac{4m^2}{(m^2 - 1)(m + 1)} \right]^2 + 1 \right\} \quad (9.6)$$

where E_0 = incident irradiance

$I(\theta)$ = radiant intensity

θ = scattering angle

α = size number $\pi d/\lambda$, where λ is the wavelength of incident light

m = refractive index

J_1 = Bessel function of first kind of order unity

The three terms inside the braces in Eq. (9.6) represent, respectively, the Fraunhofer diffraction, the optical scattering due to refraction of the centrally transmitted ray, and the optical scattering due to incident rays. Equation (9.6) requires that (1) the incident radiation is planar and monochromatic, (2) the forward angle θ is small, (3) the particle size number α and phase shift $2\alpha(m - 1)$ are large, and (4) the distance between particle and observer is large compared to D^2/λ .

If a polydispersion of particles is present, the integrated intensity of all particles is found by summing over all diameters. The expression for the intensity of scattering due to polydispersion is normalized by dividing by the intensity of diffractively scattered light in the forward direction, $\theta = 0$. It is then found that the second and third terms in Eq. (9.6) are small and can be ignored. The normalized integrated intensity of forward-scattered light, $I(\theta)$, due to a polydispersion of relatively large particles is given as

$$I(\theta) = \frac{\int_0^\infty \left[\frac{2J_1(\alpha\theta)}{\alpha\theta} \right]^2 N_r(D) D^4 dD}{\int_0^\infty N_r(D) D^4 dD} \quad (9.7)$$

where $N_r(D)$ is defined in such a way that the integral of $N_r(D)$ over a given diameter interval represents the probability of occurrence of particles within the specified interval.

Equation (9.7) represents a relationship between the angular distribution of scattered light and the particle size distribution. The basic problem then becomes one of evaluating the particle size distribution from an experimentally determined angular distribution of scattered light, $I(\theta)$. Dobbins et al. [63] and Roberts and Webb [64] have demonstrated that, for a number of drop size distribution functions with varying size parameters, a unique illumination profile (or scattered light

distribution) of $I(\theta)$ is obtained when plotted against an abscissa of $\pi D_{32}\theta/\lambda$, as shown in Fig. 9.12. Thus, the experimental determination of $I(\theta)$ versus θ does permit an evaluation of D_{32} (SMD).

The original optical system employed by Dobbins et al. [63] is shown in Fig. 9.13. The advent of laser technology allowed various improvements to be made, and a more recent version, due to Lorenzetto [65], is shown schematically in Fig. 9.14. The light source is a 5-mW HeNe laser operating at wavelength of 6328 Å. The laser beam is spatially filtered to pass only the fundamental laser mode. An expanding telescope is used to produce a highly collimated beam, which is then "chopped" by a rotating perforated disk to reduce the stray light and increase the sensitivity of the system.

The parallel light beam is diffracted through the spray under investigation and focused by a receiver of 600 mm focal length onto a circular aperture 20 μm in diameter. The light then enters a photomultiplier tube that is located at the focal plane of the receiving lens and is arranged to traverse horizontally in a direction at right angles to the optical axis. The signals from both the photomultiplier tube

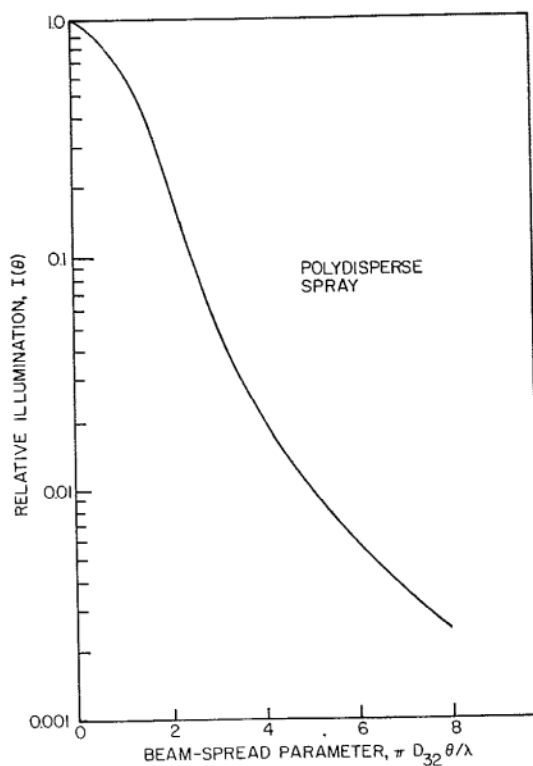


Figure 9.12 Mean theoretical illumination profile for mean drop size D_{32} with sizes distributed according to the upper-limit distribution function (Dobbins et al. [63]).

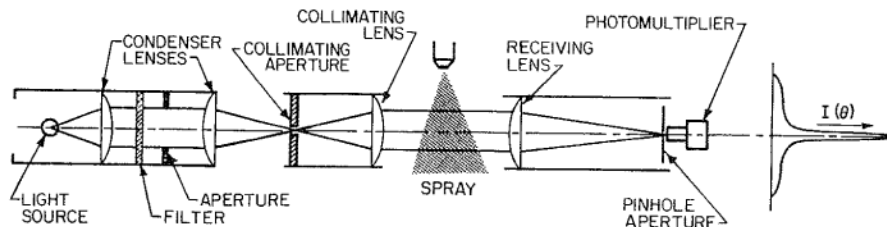


Figure 9.13 Schematic drawing of the light-scattering system used by Dobbins et al. [63].

and a position transducer are fed simultaneously into an X-Y plotter to obtain the light intensity profile. Typical plots for sprays produced by a prefilming type of airblast atomizer are given in Fig. 9.15, while Fig. 9.16 shows the normalized light intensity profiles. The SMD is determined by measuring the radial distance from the optical axis to a point on the curve at which the light intensity is one-tenth of its maximum value [64]. The SMD is then read off the curve drawn in Fig. 9.17, which is based on a relationship between the relative light intensity and the scattered angle, as determined by Roberts and Webb [64].

Lefebvre and co-workers have carried out an extensive series of measurements using this technique [66–70]. The good agreement found between their results and other independent measurements indicates the practical usefulness of the method. However, all methods have certain limitations, and this is no exception. One obvious drawback is a size limitation, which is evident in Fig. 9.17. The intensity

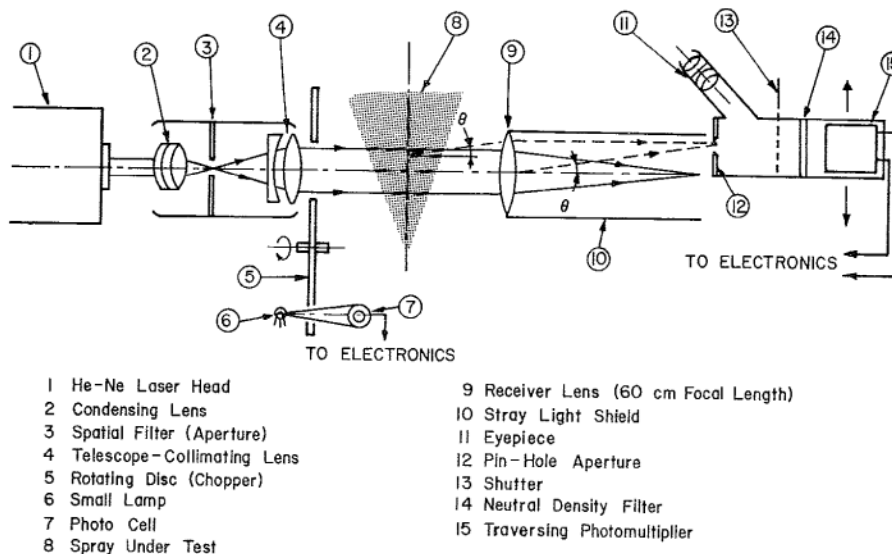


Figure 9.14 Lorenzetto's improved light scattering system [65].

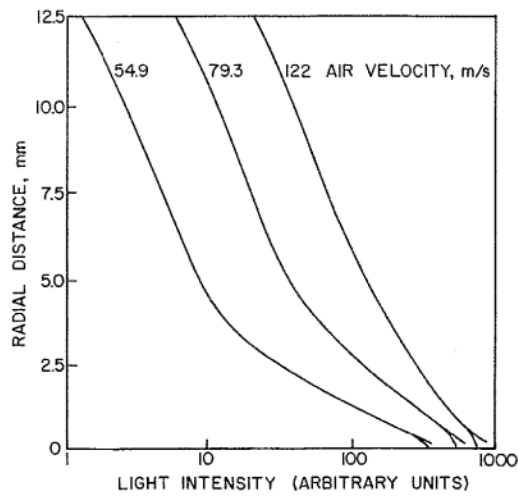


Figure 9.15 Data obtained with an airblast atomizer illustrating effect of air velocity on light intensity distributions (Rizk and Lefebvre [71]).

variation is weak for small particles, resulting in a lower size limit of about $10\text{ }\mu\text{m}$ in practice. For large particles the light intensity is concentrated near the axis, and it is difficult to obtain accuracy for particles with diameters larger than around $250\text{ }\mu\text{m}$. Another problem with this method is that some ambiguity exists con-

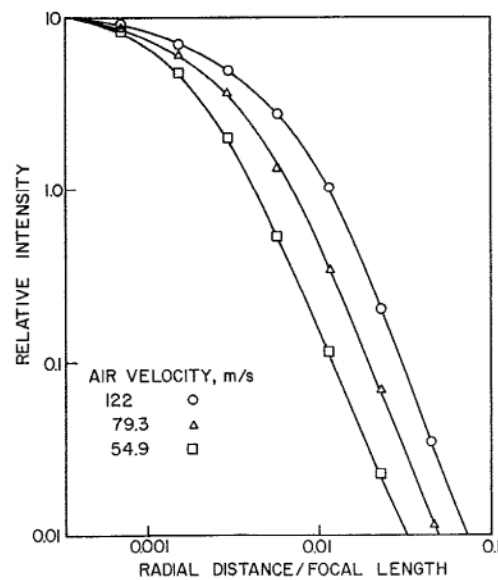


Figure 9.16 Variation of relative intensity with radial distance (Rizk and Lefebvre [71]).

cerning the maximum light intensity at the optical axis (I_0) due to the strong on-axis peak from the unscattered beam. Thus I_0 must be determined from extrapolation, as shown in Fig. 9.15. The resulting error proves to be rather small.

To date, the Dobbins technique has been confined mainly to the measurement of SMD. It has generally been considered difficult to obtain drop size distributions from measurements of light intensity, since the scattered light profile lacks the sensitivity needed to determine the shape parameters uniquely [63]. To overcome this limitation, Rizk and Lefebvre [71] have evolved a technique whereby the light intensity plots used to determine SMD can also provide the basic information needed to estimate the complete drop size distribution. The method employs the theory developed by Swithenbank et al. [72], which is based on the scattered energy distribution rather than the intensity distribution. Fortunately, it is quite straightforward to convert plots of light intensity into distributions of light energy. The light intensity at any given radial distance has only to be multiplied by this distance and then replotted. The energy distributions shown in Fig. 9.18 were obtained in this manner from the light intensity profiles plotted in Fig. 9.16.

In comparison with the Malvern particle sizer, as described below, the Dobbins technique has the advantages of simplicity and lower cost. It also has the advantage of recording the light intensity profile for inspection so that results that are clearly spurious can be discarded. However, it lacks the speed, convenience, and data-storing capacity of the Malvern instrument.

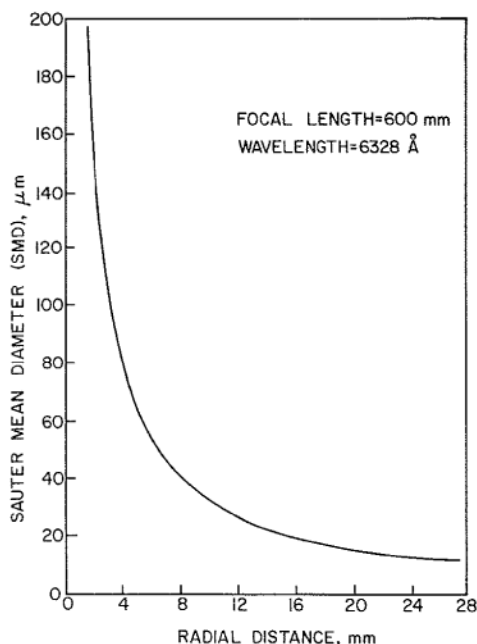


Figure 9.17 Variation of SMD with radial distance (Rizk and Lefebvre [71]).

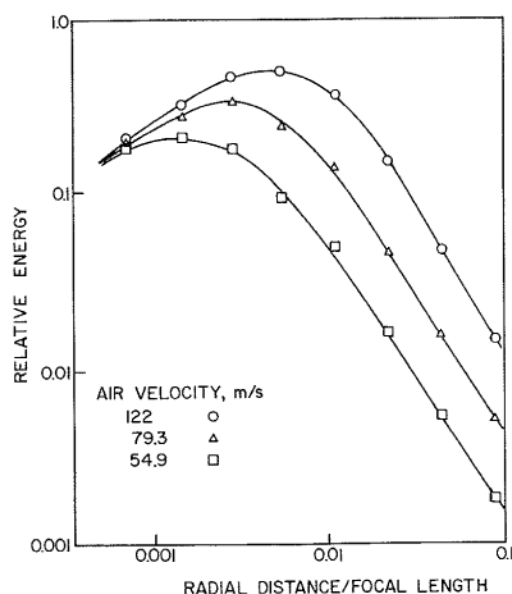


Figure 9.18 Influence of atomizing air velocity on light energy distribution (*Rizk and Lefebvre [71]*).

Malvern Particle Sizer

Although many nonintrusive techniques have been developed for the measurement of drop size distribution, the most widely used is the Malvern particle sizer. For a rapid measurement of the global (ensemble) characteristics of a spray, this is currently one of the most effective, simple, and reliable methods that is commercially available. It is easy to use, and very little knowledge of its basic principles is required for operation. For applications where it is adequate to characterize a spray solely in terms of its SMD and an exponent in a size distribution equation, the Malvern system with its associated microcomputer yields computer printouts of the desired information. The instrument owes its initial development to Swithenbank et al. [72] but is now manufactured and distributed by Malvern Instruments Ltd. (Malvern, England, and Framingham, Mass.).

The technology employed is based on the Fraunhofer diffraction of a parallel beam of monochromatic light by a moving drop. The optical system is shown schematically in Fig. 9.19. When a parallel beam of light interacts with a drop, a diffraction pattern is formed in which some of the light is diffracted by an amount depending on the size of the drop. The diffraction pattern produced when the spray is monodisperse is of Fraunhofer form; i.e., it consists of a series of alternate light and dark concentric rings, the spacing of which depends on the drop diameter. However, for the more commonly encountered polydisperse sprays, a number of these Fraunhofer patterns are produced, each by a different group of drop sizes. This results in a series of overlapping diffraction rings, each of which

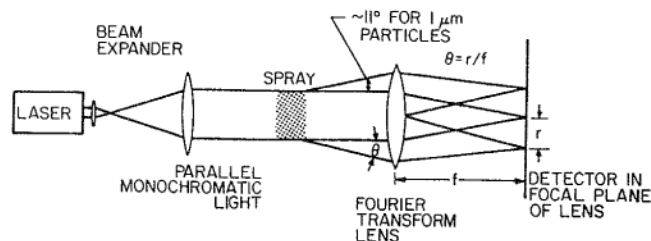


Figure 9.19 Optical arrangement employed in Malvern particle sizer.

is associated with a characteristic drop size range, depending on the focal length of the Fourier transform receiver lens. This lens focuses the diffraction pattern onto a multielement photodetector that measures the light energy distribution. The photodetector comprises 31 semicircular photosensitive rings surrounding a central circle. Each ring is therefore most sensitive to a particular small range of drop sizes. The output of the photodetector is multiplexed through an analog-to-digital converter. Interpretation of the measured light energy distribution as a drop size distribution is then carried out by a computer, which provides an instant display of the measured distribution. Thus, a major advantage of the system is the speed at which data can be both accumulated and analyzed, allowing complete (ensemble) characterization of an atomizer over its entire operating range within a few hours. Another important attribute is that the diffraction pattern generated by drops is independent of the position of the drop in the light beam. This allows measurements of size distribution to be made with the drops moving at any speed.

Experience has shown that good alignment of the Malvern optical system is essential for accurate measurement. The correct focal length of lenses should be chosen according to the drop size range to be measured. Each detector/lens combination employed gives approximately a 100-to-1 drop size range; a 63-mm lens gives a drop size range from 1.2 to $118\ \mu\text{m}$, a 100-mm lens from 2 to $197\ \mu\text{m}$, and a 300-mm lens from 5.8 to $564\ \mu\text{m}$. Other lenses are available having focal lengths of 600, 800, and 1000 mm for use with coarser sprays. It is also important to align the laser beam so that it is perpendicular to the spray axis at a suitable distance downstream from the atomizer.

Developments in computer software have produced a number of user-selectable features (Malvern Instruments Ltd.). Data sets may be stored in any one of 32 RAM memory blocks. Mass storage of data is available on magnetic tape or disks. The data may be analyzed in terms of a histogram with 15 size classes or presented in the format of normal, lognormal, Rosin-Rammler, or model-independent modes. When the Rosin-Rammler function is used, attention must be paid to the log error reading, which represents the closeness of the data fit to the indicated values of SMD and q (see Chapter 3). If the log error exceeds 4.5 it may be desirable to check the data against other drop size distribution models or use the model-independent mode.

Accuracy of Malvern Particle Sizer

In view of its widespread usage and unique capabilities, it is important for the user to fully appreciate the limitations on the Malvern instrument's accuracy and repeatability. For example, the Fraunhofer diffraction theory on which the instrument relies applies only to drops whose diameter is much larger than the wavelength of the incident light. This means that inaccuracies may be incurred when measuring drop sizes below 5 μm using a 300-mm receiver lens. It is also important to remember that the instrument is capable of measuring drop sizes only in a certain range. By a proper choice of lens, most practical sprays can be analyzed without difficulty. However, the indicated histogram of drop sizes should always exhibit a definite peak. Where no peak is evident, it may mean that a significant number of drops lie outside the range of measurement capability, so the instrument cannot interpret properly the observed scattering pattern.

Other problems that have arisen with the Malvern particle sizer include variations in detector sensitivity, multiple scattering, vignetting, and beam steering. How and to what extent these problems influence data accuracy are discussed below.

Variations in detector responsivity. One of the earliest doubts expressed about the accuracy of the Malvern system arose from a reported lack of consistency between results obtained at different laboratories in tests carried out on the same atomizer. The interpretation of such discrepancies between different Malvern instruments in their application to sprays that are ostensibly the same is complicated by the numerous possible reasons for the observed differences. These reasons include actual differences in the spray, even when using the same atomizer at nominally the same flow conditions, errors in the instrumentation used to measure nozzle pressures and flow rates, and failure to align the instrument properly. However, according to Dodge [73], the major cause of inconsistencies between different Malvern instruments is an inherent limitation on the accuracy of the photodiode detectors. These detectors are assumed to have a uniform responsivity to the incident light energy but, in fact, the responsivity of different detectors in the same set can vary appreciably, and these variations are not repeatable between different detector assemblies.

To overcome this problem, Dodge [73] devised a method that involves the separate calibration of each detector ring. Each detector is exposed to several different light levels to determine its response factor $F = C/R$, where C is a normalization constant that is different for each light level and R is the responsivity. The value of F determined from this procedure is then entered into the Malvern computer program to replace the existing response factor. The latter factor, termed LA in the Malvern 2200 user's manual, was determined using a procedure similar to that followed by Dodge, but the values actually employed for calibration purposes are the same for all instruments and were calculated by averaging the results obtained from a few detector assemblies. The values of F determined by the Malvern company range from 0.551 for the first (innermost) detector, through 0.848

for the fifteenth (central) detector, to 0.996 for the thirtieth (outermost) detector. The corresponding values of F as determined by Dodge [73] were 0.288, 0.746, and 0.996, respectively. Thus, significant improvements in accuracy can be achieved by using Dodge's calibration procedure.

It is the author's understanding that Malvern Instruments Ltd. now uses an undescribed procedure similar to that of Dodge for the calibration of current production particle analyzers.

Multiple scattering. When spray densities are high, light that is scattered by a drop may be scattered by a second drop before reaching the detector. Since the theory for laser diffraction-based instruments assumes scattering from a single drop, this multiple scattering introduces errors in the computed size distribution.

When measuring drop sizes in a spray, the Malvern instrument indicates the extinction or percentage of the light removed from the original direction. As Dodge [74] has emphasized, extinction (sometimes called obscuration) is of primary importance since it is directly dependent on the cross section of the drops present in the beam and is a major indicator of the extent to which the measurements are being affected by multiple scattering. The density of the spray is not a good parameter because extinction can vary over a wide range for a given density, depending on the size distribution and optical path length in the spray. The major consequence of multiple scattering is distortion of the diffraction pattern toward larger angles and a wider angle range. When the distorted data are processed, they cause the indicated drop sizes to be broader in distribution and smaller in average size than the actual distribution. The problem becomes significant when more than 50% of the incident light is scattered by the drops. However, measurements can still be performed in dense sprays where the extinction is as high as 95%, provided a correction is applied to the results.

Dodge [74] examined this problem experimentally and developed an empirical correction scheme. This was followed by more extensive theoretical efforts that led to new correction techniques that are more generally applicable, as discussed below.

Felton et al. [75] have developed a theoretical model of multiple light scattering whereby the light path is divided into a sequence of slices of equal extinction and the effect of multiple scattering on the diffraction pattern is evaluated. Predictions based on this model were compared with experimental results obtained using dense suspensions of glass beads, and excellent agreement was obtained. The influence of multiple scattering was found to depend on size distribution parameters, and a set of correction equations was derived for both Rosin-Rammler and lognormal distributions. For a Rosin-Rammler distribution, the relevant correction factors are

$$C_x = \frac{\bar{X}_0}{\bar{X}} \quad (9.8)$$

and

$$C_q = \frac{q_0}{q} \quad (9.9)$$

where X and q are the actual measured values with high extinction, and X_0 and q_0 are the corresponding calculated values for low extinction. The parameters X and q are defined in Chapter 3. They represent, respectively, the characteristic diameter and size distribution functions in the Rosin-Rammler expression, Eq. (3.14).

The following expressions were derived for C_X and C_q :

$$C_X = 1.0 + [0.036 + 0.4947(EX)^{8.997}]q_{\text{dens}}^{1.9-3.437(EX)} \quad (9.10)$$

$$C_q = 1.0 + [0.035 + 0.1099(EX)^{8.65}]q_{\text{dens}}^{0.35+1.45(EX)} \quad (9.11)$$

where EX is the extinction and q_{dens} is the Rosin-Rammler distribution parameter as measured for the dense spray.

The results of applying these correction factors to Dodge's [74] experimental data are shown in Fig. 9.20, in which SMD is plotted against light extinction. The corrected values are clearly much closer to the true values than the raw data, but it is also apparent that at the highest extinction levels some differences between theory and experiment still exist.

Hamadi and Swithenbank [76] recently extended the procedure of Felton et al. for the correction of multiple scattering to include any type of drop size distribution, including bi- and trimodal size distributions.

Vignetting. When taking measurements in sprays, it is necessary to limit the maximum distance between the spray and the receiving optics. This maximum distance depends on the focal length and diameter of the receiver lens. Exceeding this distance results in vignetting of the signal on the outer detector rings, thereby skewing the measured size distribution toward the larger diameters. Dodge [73] has discussed this problem and provided the following expression for calculating the maximum allowable distance x :

$$x = f \left(\frac{D_1 - D_b}{D_d} \right) \quad (9.12)$$

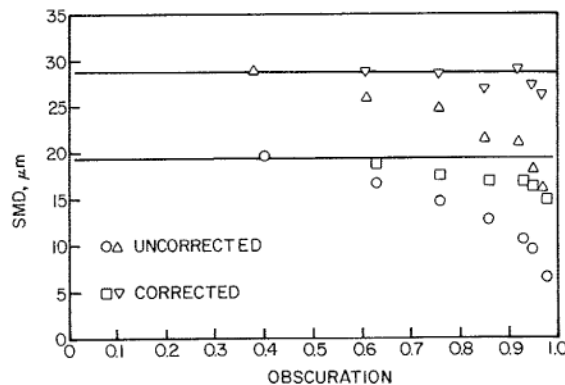


Figure 9.20 Dodge's results [74], with and without the correction of Felton et al. [75] for multiple scattering.

where f = lens focal length

D_l = lens diameter

D_b = laser beam diameter

D_d = detector diameter (twice the distance from center to outermost edge of detectors)

Dodge [73] has given specific results for the Malvern system using the three standard lenses. With the standard instrument it is difficult to exceed x with the 300-mm lens, but with the 100-mm lens the spray should be within 120 mm of the lens, and with the 63-mm lens it should be within 55 mm.

Wild and Swithenbank [77] have also studied the problem of vignetting and developed a theory that can be used to correct for vignetting errors. Their method has been validated by comparison with computational and practical vignetting experiments. It can be applied wherever the particle field is homogeneous and is of large extent or low concentration.

Beam steering. Problems can arise with light-scattering techniques in their application to sprays in a high-temperature environment. Even with no spray present, thermal gradients in the hot air refract the laser beam in a random high-frequency pattern (called *beam steering*), resulting in a spurious reading on the innermost detectors. When the spray is present, additional thermal and concentration gradients are created that result in the first few detectors receiving abnormally large signals. Unfortunately, the problem cannot be solved merely by subtracting out the background when no spray is present.

Dodge and Cerwin [78] have suggested that, as the 15 detector pairs of the Malvern analyzer form an overdetermined data set, if only the two or three innermost detectors are involved, their contribution can be ignored by appropriate changes in the computer software. However, if the spray contains many large drops that scatter light onto the inner detector channels, it is not possible to ignore these channels and still arrive at a reasonable drop size distribution. In practice, a subjective judgment must be made on how many channels contain spurious data. Usually this is fairly straightforward if the drops in the spray are small enough so that the peak detector signal is located well outside the region of the disturbed channels.

Dodge and Cerwin [78] recommend three checks for verifying that the corrected light distribution is a reasonable one. First, the corrected light distribution should show a smooth transition between the outer channels that were used to compute the drop size distribution and the inner channels in which the recorded data have been replaced by the new computed light pattern that best fits the overall pattern. Second, there should be at least four or five good detector signals to the left of the peak of the light distribution. When the perturbed detector signals approach the peak of the light distribution, this technique becomes invalid. Third, the log error as indicated by the Malvern should not exceed 5.0.

The errors and uncertainties associated with this correction technique must obviously increase with the number of detector signals that have to be ignored. Best results are obtained with finely atomized sprays for which the light intensity

signal reaches a maximum in the outer half of the detector channels. Examples illustrating the use of this correction technique have been provided by Dodge and Cerwin [78].

As a footnote to the subject of potential errors and inconsistencies with the Malvern instrument, Jackson and Samuelson [53] have drawn attention to significant differences in the data depending on whether Rosin-Rammler or model-independent distribution is used to process the data. They clearly favor the model-independent mode, but the study carried out by Dodge et al. [79] indicates no particular advantage for this approach.

Intensity Ratio Method

When a light beam is passed through a spray the drops scatter light in all directions. For drops larger than around $2\text{ }\mu\text{m}$, the relative intensity of the light scattered in the forward direction can be calculated as a function of angle by using diffraction theory.

This smooth variation of scattered intensity with angle in the forward direction led Hodgkinson [80] to suggest a simple means of particle sizing based on the ratio of measured light intensity at two different angles. An instrument based on this idea was developed and used by Gravatt [81]. The method has the advantage of being fairly insensitive to refractive index, but its drop size range is limited to below $5\text{ }\mu\text{m}$. Larger drops call for accurate measurements at very small angles, where interference with the direct unscattered beam becomes significant [81, 82].

The single intensity ratio method as outlined above is prone to serious error if the drop size distribution is broad. Hirleman and Wittig [83] proposed a multiple ratio system based on different wavelengths and/or different pairs of scattering angles to minimize these errors. The multiple ratio system actually used by Hirleman [84] has four angles, but clearly the system becomes less practical as the number of angles increases.

A ratioing processor has been developed by Spectron [85] and is shown schematically in Fig. 9.21. An annular mask pair is incorporated in the collection optics, so light scattered at two angles (5° and 2.5°) in the near-forward direction is observed. The ratio of the two measurements is a function of particle size, the lower limit on size being around $0.3\text{ }\mu\text{m}$.

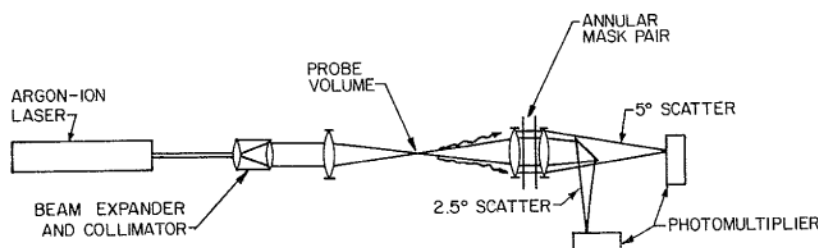


Figure 9.21 Intensity ratio system for particle sizing (Wuerer et al. [85]).

Calibration Techniques

Most of the optical methods employed in drop size measurement require calibration of some kind. The calibration techniques in common use have been reviewed by Hirleman [86].

Highly monodisperse polystyrene microspheres (available from Duke Scientific Co., Palo Alto, Calif.) sprayed from a dilute liquid suspension and subsequently dried can be used for the calibration of particle sizing instruments up to a maximum particle diameter of around 5 μm . For larger particle sizes, polystyrene or glass spheres must be used in liquid suspensions. As glass spheres have broader size distributions than polystyrene, sieve or sedimentation techniques are used to produce well-defined size groups. Glass microspheres can also be attached to microscope slides or rotating glass disks and placed in the instrument sample volume [51]. Problems that arise with these techniques include gravitational settling and wall deposition, which are size-dependent phenomena, the need for a sample cell and flow system, and interference with the scattering process by the glass slide used to support the calibration spheres [86].

Vibrating-orifice techniques are sometimes used to generate a stream or cloud of nearly monodisperse drops in sizes ranging from 10 to 150 μm in diameter [87]. Spinning disk generators have also been used to generate relatively small drops. These mechanical techniques are useful for calibrating single-particle optical counters, but they cannot generate sprays containing the broad spectrum of drop sizes needed for the calibration of ensemble scattering instruments [86].

The fact that in the near-forward direction the scattering properties of drops, pinholes, and opaque disks of the same diameter are equivalent allows precisely formed circular pinholes to be used for the calibration of drop sizing instruments that operate as single-particle counters [58]. This approach also has limited utility for ensemble scattering instruments.

All the calibration methods described above have limited applicability to the calibration and performance verification of diffraction-based drop sizers. In one sense it might be argued that such instruments do not require calibration because the diffraction angles and intensities of scattered light are defined rigorously in the Mie scattering theory. If the scattering measurements are restricted to small angles (forward diffraction) and the particle diameters are much larger than the wavelength of the radiation, the particle properties are unimportant and the scattering intensities are dependent only on the diameters of the scatterers. Thus, measurements of the intensity of scattered light as a function of angle may be used to determine drop sizes without any need to calibrate the instrument. This is the principle used in the Malvern and similar particle sizers, which, in theory, require no calibration. In practice, however, potential sources of error do exist, as discussed by Dodge [73, 74].

A calibration technique developed by Hirleman [86] has some significant advantages over other methods, especially for laser/optical instruments based on forward light scatter (diffraction) or imaging. The technique employs reticles that provide a two-dimensional sample array of typically 10,000 circular disks of chrome film photoetched on a glass substrate. These disks (simulated droplets) are ran-

domly positioned in a circular sample area 8 mm in diameter. Typically, 23 discrete diameters with one to several thousand replications of each discrete size are used to approximate a specific particle size distribution. Reticles can be used in series to simulate multimodal distributions, and the number of potential array configurations appears to be virtually unlimited. Measurement accuracy for drops larger than 10 μm is around $\pm 1 \mu\text{m}$ [86].

The manufacturer of the reticles (Laser Electro-Optics) supplies a predicted light-scattering intensity distribution relative to the detector sizes of the Malvern instrument. This can be entered into the Malvern computer as ideal measured data and the corresponding values computed for X and q in the Rosin-Rammler distribution parameter [Eq. (3.14)].

CONCLUDING REMARKS

It is clear that no single drop sizing method is completely satisfactory. Many useful techniques have been developed, each with its own advantages and limitations.

Mechanical methods have the virtues of simplicity and low cost. Their main problem lies in the extraction and collection of representative spray samples.

Of the various electrical methods discussed, the hot-wire technique appears to be the most useful. However, the device can operate only at relatively low velocities ($<10 \text{ m/s}$) due to the risk of drop breakup on impact with the wire. There is also some question about the measurement of liquids that could leave a residue on the wire.

Imaging systems allow the spray to be "seen," but a major difficulty is the determination of the size of the viewing volume to be assigned to given drop sizes. For ensemble measurements the light diffraction methods of Dobbins and Swithenbank have much to commend them. The latter, in the form of the Malvern particle sizer, is now in widespread use as a general-purpose tool for spray analysis. Of the remaining optical methods discussed, the advanced laser light scatter interferometry techniques show considerable promise for obtaining simultaneous drop size measurements and drop velocity data in the dense sprays produced by most practical atomizers.

Dodge [88] has recently compared the performance of 17 drop size measuring instruments including six different types. Ten instruments were compared on one type of spray and eleven on another, with some instruments being used on both types. The results indicated systematic differences in instrument performance beyond what could be attributed to problems in spray reproducibility. Differences in average drop size were as large as a factor of five. However, good to excellent agreement was obtained between observations for some types of instrument.

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