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SPRAY CHARACTERISTICS OF PLAIN-JET AIRBLAST ATOMIZERS

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ABSTRACT

The effects of air and liquid properties, and atomizer dimensions, on the spray characteristics of plain-jet airblast atomizers are examined. Mean drop size and drop-size distribution are measured using an improved form of light scattering technique. The test range includes wide variations in air velocity, air pressure, air/liquid ratio, and liquid viscosity.

The experimental data generally confirm the results of previous studies on prefilming types of airblast atomizers. They show that increases in air velocity, air pressure and air/liquid ratio all tend to produce a more uniform spray and a lower mean drop size. It is also observed that any change in air properties, liquid properties and atomizer geometry that lowers the mean drop size also produces a more uniform distribution of drop sizes in the spray.

NOMENCLATURE

A, B	constants in equations (1) and (2)
ALR	air/liquid ratio by mass
d_o	fuel nozzle diameter
L	atomizer dimension in equation (1)
L_c	characteristic dimension of atomizer
P	pressure
q	drop-size distribution parameter
SMD	Sauter mean diameter of drops in spray
U	velocity
v	volume (or mass) fraction of spray in drops of diameter less than x
x	drop diameter
$\bar{x}$	drop-size parameter
μ	liquid dynamic viscosity
ρ	liquid density
σ	surface tension

Subscripts

A	air
L	liquid
R	relative, air to fuel

INTRODUCTION

The merits of the airblast atomizer have led to its installation in a wide range of industrial and aircraft gas turbines. Most of the systems now in service are of the "prefilming" type, in which the fuel is first spread out into a thin, continuous sheet and then subjected to the atomizing action of high velocity air. In other designs the fuel is injected into the high velocity airstream in the form of one or more discrete jets. A drawback to the thin-sheet airblast atomizer is that it is fully effective only when both sides of the liquid sheet are exposed to the air. This requirement introduces a complication in design, since it usually means arranging for two separate air flows through the atomizer. For this reason the plain-jet type of airblast atomizer is sometimes preferred, in which the fuel is not transformed into a thin sheet, but instead is injected into the high velocity airstream in the form of discrete jets. Much less is known about the performance of this type of atomizer, since the only previous investigations of significance are those of Nukiyama and Tanasawa [1], Weiss and Worsham [2], Gretzinger and Marshall [3], Kim and Marshall [4], Lorenzetto and Lefebvre [5] and Jasuja [6]. Although these studies did much to elucidate the key factors involved in plain-jet airblast atomization the range of variables studied was incomplete. For example, almost all the experiments were conducted at normal atmospheric pressure. Jasuja's test program included measurements at higher levels of pressure, but no attempt was made to determine the distribution of drop sizes in the sprays.

The present investigation represents an attempt to remedy these deficiencies. In common with previous studies it covers fairly wide ranges of atomizing air velocity, fuel viscosity, air/fuel ratio and atomizer size. However, attention is focused on the effects of ambient pressure on mean drop size and drop-size distribution. Considerable importance is attached to the

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latter effect, since it is the drop-size distribution in a spray that determines its evaporation history. For example, sprays with a non-uniform drop-size distribution evaporate more rapidly in the initial phase than do uniform sprays of the same mean diameter [7, 8], due to the presence of a larger number of small drops. For gas turbine combustors therefore, a non-uniform spray has definite advantages in terms of wider burning limits and better ignition performance, especially at high altitudes where failure to relight is often due to an inadequate supply of fuel vapor in the spark zone. However, a non-uniform spray necessarily contains some larger drops [9] which take longer to evaporate. If the residence time in the combustion zone is insufficient to ensure complete evaporation and combustion of these large drops they will lower the level of combustion efficiency and raise the concentrations of carbon monoxide and unburned hydrocarbons in the exhaust gases. Another interesting feature of the evaporation history of fuel sprays is that the drop-size distribution changes during evaporation in such a way that the mean diameter of the remaining drops increases for moderately or highly non-uniform sprays, and decreases for more uniform sprays. This is again due to the existence of more small drops in the former case. From these and other considerations it is clearly of practical importance to acquire more knowledge on the drop-size distribution of sprays, and the manner and extent to which the drop-size distributions obtained with airblast atomizers are influenced by air properties, liquid properties and atomizer design features.

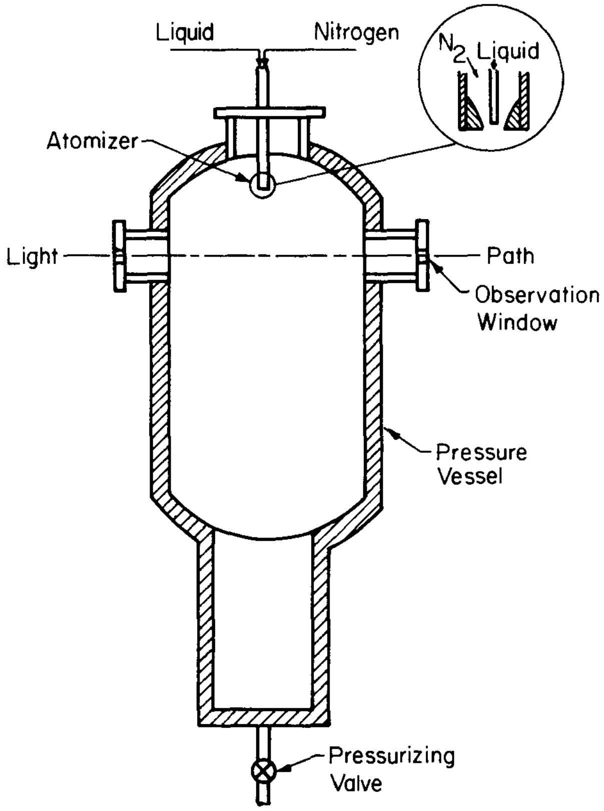

Fig. 1. Schematic Diagram of Test Rig

EXPERIMENTAL

The liquids selected for this study are:

Aviation kerosine; μ = 0.00129 kg/(ms), σ = 0.0275 kg/s^2, ρ = 780 kg/m^3

Gas oil; μ = 0.003 kg/(ms), σ = 0.0281 kg/s^2, ρ = 810 kg/m^3

Blended fuel; μ = 0.0183 kg/(ms), σ = 0.0285 kg/s^2, ρ = 840 kg/m^3

A cross-sectional schematic drawing of the plain-jet atomizer is shown in Fig. 1. Essentially it comprises a means for producing a round jet of liquid and surrounding this jet by a coaxial, coflowing stream of high velocity air. The apparatus for studying spray characteristics is also shown schematically in this figure. The main component is a cylindrical pressure vessel which is mounted on a stand with its axis in the vertical position. It is 120 cm long and 75 cm in diameter. The atomizer under test is located centrally at the top of the cylinder and sprays downward into the vessel which is pressurized to the desired level using gaseous nitrogen that is tapped from a large liquid nitrogen storage/evaporator system. Gaseous nitrogen from this same source also provides the atomizing 'air' for airblast atomizers. The reason for using nitrogen instead of air is to avoid the risk of explosion at high pressures. As the physical properties of nitrogen are very similar to those of air the results obtained with nitrogen are considered valid for systems using air.

After atomization the droplets fall downward into a collection tank at the bottom of the chamber, from whence the liquid is returned to the storage tank. Any fuel that is entrained into the nitrogen flowing out of the test chamber is also separated out and returned to the storage tank. The objective is partly to conserve fuel, especially those fuels of which only a limited supply is available, and also to avoid any pollution problems created by the escape of droplets or mists into the atmosphere.

Drop-sizes are measured using the light-scattering technique first proposed by Dobbins, Crocco and Glassman [10] and later developed at Cranfield [5]. It is based on a direct measurement of the scattered light intensity profile after the monochromatic light beam has passed through the spray. The SMD is obtained directly from measurement of intensity versus radius in the focal plane of the receiving lens. In practice, this is accomplished by measuring the traverse distance (r) between the optical axis and a point on the profile at which the light intensity is equal to one-tenth of the normalized intensity in the scattered profile. The SMD of the spray can then be determined using the relationship between r and SMD as derived by Roberts and Webb [11]. Recently, Rizk and Lefebvre [12] have used the method advocated by Swithenbank et al. [13] to extend the light-scattering technique to include measurements of drop-size distribution.

Tests were conducted using two geometrically similar atomizers, having fuel nozzle diameters of 0.55mm and 0.75mm, over the following ranges of test conditions.

Atomizing 'air' velocity	10 to 120 m/s
Ambient 'air' pressure	100 to 766 kPa
Air/liquid ratio	2 to 8
Fuel viscosity	0.0013 to 0.0183 kg/ms

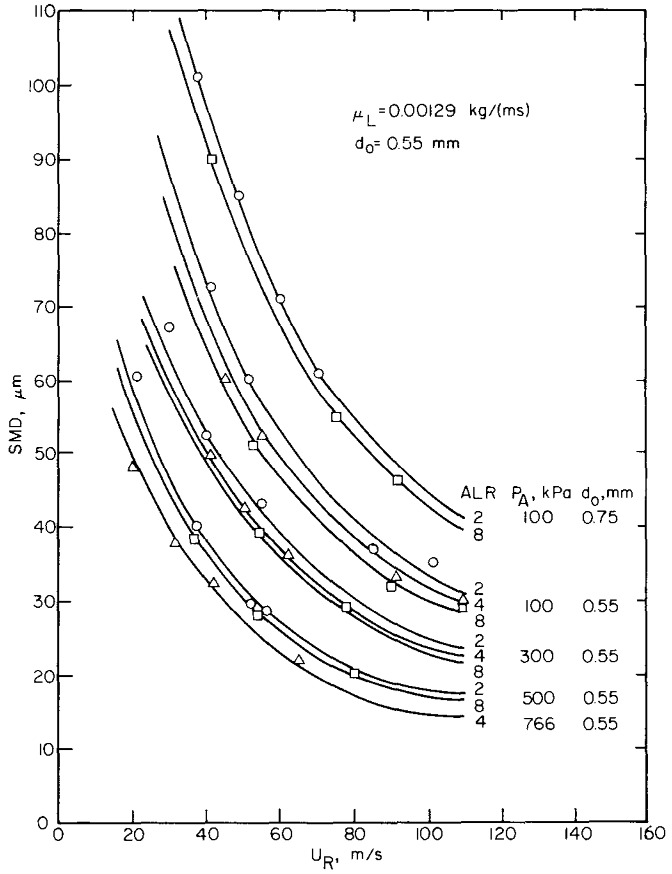

Fig. 2. Variation of mean drop size with air pressure, air/liquid ratio, and fuel nozzle diameter, for a low viscosity liquid.

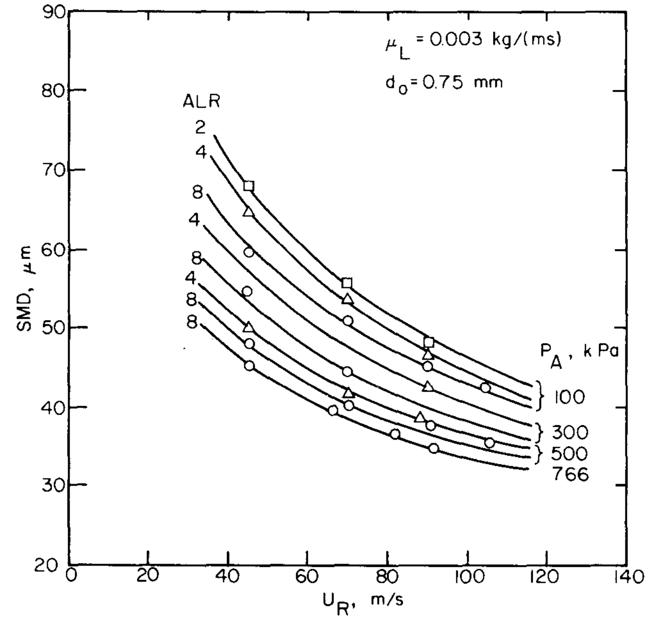

Fig. 3. Variation of mean drop size with air pressure and air/liquid ratio for a medium viscosity liquid.

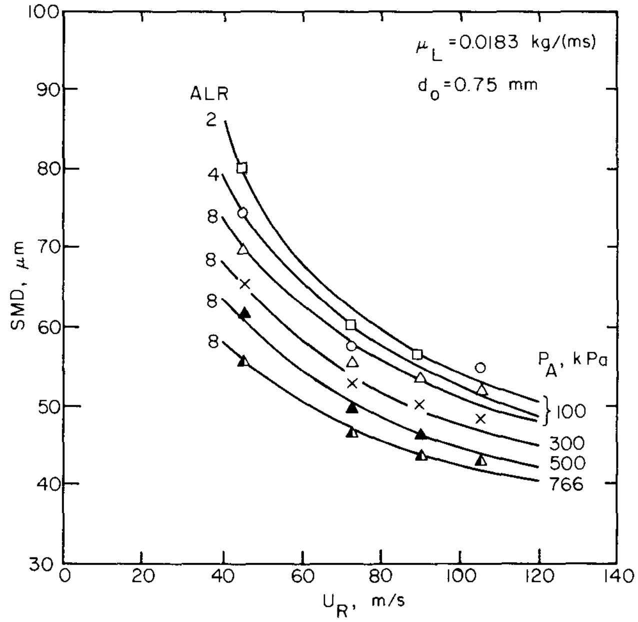

Fig. 4. Variation of mean drop size with air pressure and air/liquid ratio for a high viscosity liquid.

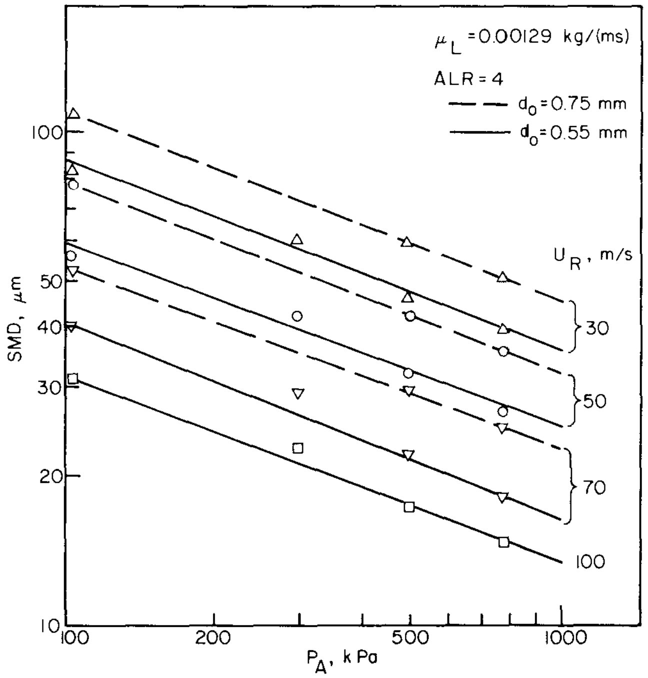

Fig. 5. Graphs illustrating the effect of ambient air pressure on mean drop size.

MEAN DROP SIZE

At the outset of the investigation it was anticipated that the effects of air and liquid properties on mean drop size would be very similar to previous findings in regard to general trends [1-6, 9, 12, 14], and this was confirmed by the experimental data. Some typical results are shown plotted in Figs. 2 to 5.

Figure 2 illustrates the effects of air velocity, air/liquid ratio, air pressure and atomizer dimensions on mean drop size. Similar data for liquids of higher viscosity are given in Figs. 3 and 4. These data show that SMD increases with increase in liquid viscosity and/or atomizer size, and decreases with increase in air/liquid ratio. SMD diminishes rapidly with increase in air velocity, according to the relationship SMD α $U_R^{-0.8}$. The influence of air pressure on SMD is less marked, in fact, SMD α $P_A^{-0.4}$. This relationship between SMD and P_A is illustrated more directly in Fig. 5.

It has been shown elsewhere [14] that the basic drop-size equation for airblast atomizers is

$$\frac{SMD}{L_c} = A\left[\frac{\sigma}{\rho_A U_A^2 L}\right]^{0.5}\left[1+\frac{1}{ALR}\right] + B\left[\frac{\mu_L^2}{\sigma \rho_L L}\right]^{0.5}\left[1+\frac{1}{ALR}\right] \qquad (1)$$

where A and B are constants whose values depend on atomizer design features and must be determined experimentally. L_c is a characteristic dimension that represents the scale of the atomizer. The term L represents the atomizer dimension at the point or surface where the liquid first contacts the air stream. For prefilming airblast atomizers L = D_p, the prefilmer lip diameter. For plain-jet atomizers L = d_o, which is also appropriate for the characteristic dimension, L_c. Substituting in equation (1) for L = L_c = d_o, gives

$$\frac{SMD}{d_o} = A\left[\frac{\sigma}{\rho_A U_A^2 d_o}\right]^{0.5}\left[1+\frac{1}{ALR}\right] + B\left[\frac{\mu_L^2}{\sigma \rho_L d_o}\right]^{0.5}\left[1+\frac{1}{ALR}\right] \qquad (2)$$

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, it is found that the ability of equation (2) to correlate SMD can be improved by reducing the exponent of the term $\sigma/\rho_A U_A^2 d_o$ from 0.5 to 0.4. Also, if relative velocity, U_R, is substituted for air velocity, U_A, then the diminished influence of air/liquid ratio on SMD should be accounted for by reducing the exponent of the term (1 + 1/ALR). These considerations lead to the following modified form of equation (2) which now includes the experimentally determined values of A and B.

$$\frac{SMD}{d_o} = 0.48\left[\frac{\sigma}{\rho_A U_R^2 d_o}\right]^{0.4}\left[1+\frac{1}{ALR}\right]^{0.4} + 0.15\left[\frac{\mu_L^2}{\sigma \rho_L d_o}\right]^{0.5}\left[1+\frac{1}{ALR}\right] \qquad (3)$$

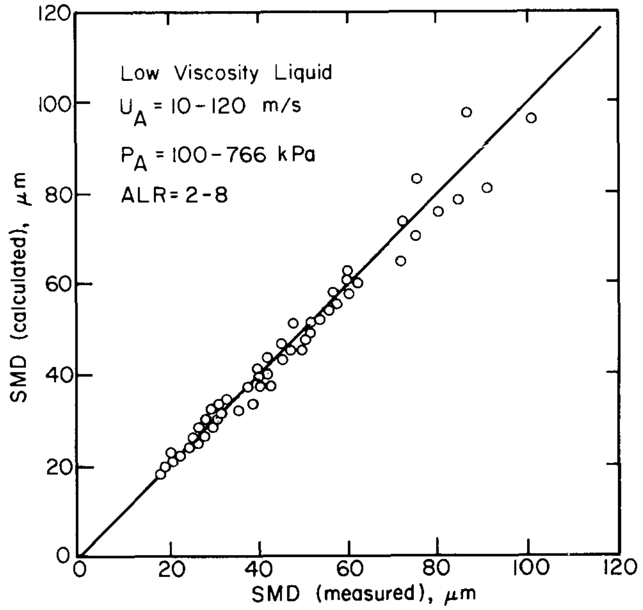

Fig. 6. Comparison of calculated and experimental values of mean drop size for low viscosity liquids.

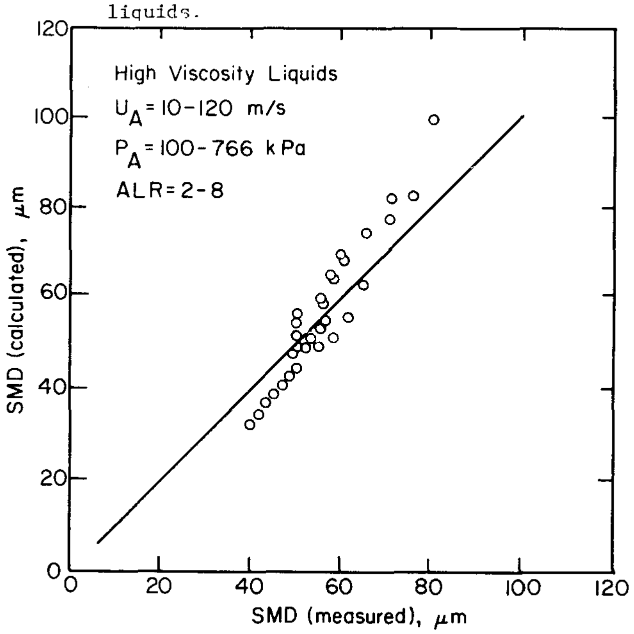

Fig. 7. Comparison of calculated and experimental values of mean drop size for high viscosity liquids.

Table 1. Summary of Data on Effect of Variables on Mean Drop Size for Liquids of Low Viscosity.

Investigators	Power dependence of mean drop size on				
	Air velocity U_A	Air density ρ_A	Liquid density ρ_L	Surface tension σ	Dimension d_o
Nukiyama and Tanasawa [1]	-1.0	0	-0.5	0.5	0
Weiss and Worsham [2]	-1.33	-0.30	-	-	0.16
Gretzinger and Marshall [3]	-0.40	-0.40	0	0	-
Kim and Marshall [4]	-1.14	-0.57	-0.16	0.41	-
Lorenzetto and Lefebvre [5]	-1.00	-0.30	-0.37	0.33	0
Jasuja [6]	-0.90	-0.45	0	0.45	0.55
Present Study	-0.80	-0.40	0	0.40	0.60
Ingebo [13]					
Theoretical	-0.67	-0.33	-0.17	0.17	0.5
Experimental	-0.75	-0.25	-0.25	0.25	0.5

The ability of equation (3) to correlate the values of SMD obtained experimentally is illustrated for low viscosity liquids in Fig. 6 and for high viscosity liquids in Fig. 7. An excellent correlation is demonstrated for low viscosity liquids. For liquids of high viscosity the correlation is inferior but still quite satisfactory. Comparison with the results obtained by other workers is hindered by the different methods adopted for presenting the data. However, a comparison is possible for liquids of low viscosity, as illustrated in Table 1. The values of the exponents for air pressure, air velocity, surface tension and liquid viscosity listed in this Table show appreciable differences, as might be expected in view of the different types of atomizer represented and the different methods used to measure mean drop size. However, there is a close similarity between the results of Jasuja [6] and those obtained in the present study. To some extent this may be due to the fact that both investigations employed the same light-scattering method for the measurement of mean drop size.

DROP-SIZE DISTRIBUTION

One of the most fundamental and important properties of a liquid spray is the frequency of occurrence of the various sizes of droplets, or the drop size distribution in the spray. It is also the property that is most difficult to predict theoretically and to determine experimentally. This is why so little information on drop-size distribution is available in the literature.

Several mathematical expressions have been derived to represent drop-size distribution. Usually they contain two independent parameters, one of which is a mean diameter of some kind and the other is a measure of the dispersion of the spray, or the deviation from the mean. The Rosin-Rammler expression [15] is perhaps the most widely used at the present time. Although developed originally for powders it has been applied with success to liquid drops. It can be expressed in the form

$$1 - v = \exp - (x/\bar{x})^q$$

where v is the volume fraction of the spray occurring in drops of diameter less than x, $\bar{x}$ is a size parameter, and q is a distribution parameter. The higher the value of q, the more uniform is the spray. Values of q were determined over the entire range of test conditions. Some typical results are shown in Figs. 8 and 9.

The beneficial effect of increasing relative velocity from 60 m/s to 96 m/s, and then to 110 m/s, at a constant air/liquid ratio, is shown in Fig. 8. The number of large drops in the spray diminishes rapidly with increase in air velocity. Figure 9 illustrates a significant shift in distribution toward lower drop sizes with reduction in d_o. In general, the results obtained on the influence of air and liquid properties

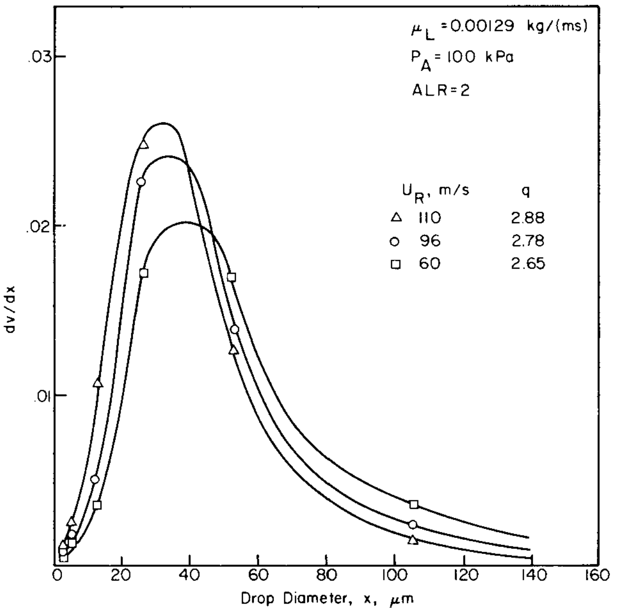

Fig. 8. Influence of air velocity on drop-size distribution.

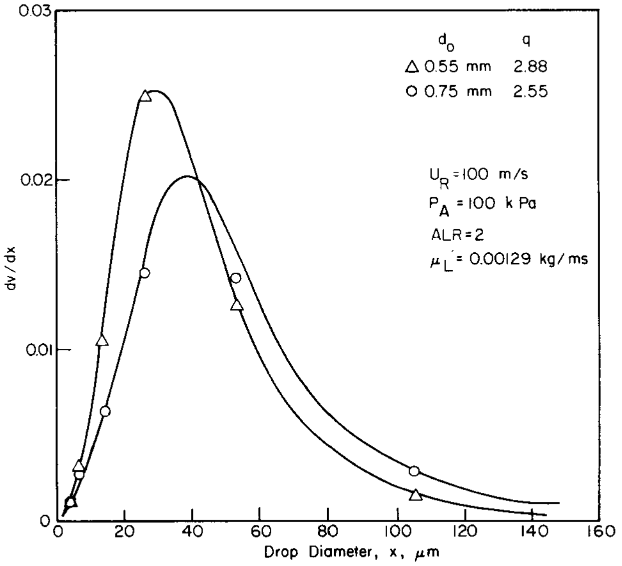

Fig. 9. Influence of liquid nozzle diameter on drop-size distribution.

on drop-size distribution in the present investigation, using a plain-jet airblast atomizer, are fully consistent with those obtained in a recent study conducted on a prefilming type of airblast atomizer [12]. Thus, it is found that any change in liquid properties, air properties, atomizer geometry and atomizer size that tends to produce a finer spray will also yield a higher value of q, i.e. a more uniform spray. This point is clearly brought out in Fig. 10 which shows that increases in air pressure, air velocity and air/liquid ratio all produce a more uniform drop size. However, increases in fuel viscosity and fuel nozzle diameter both result in coarser sprays.

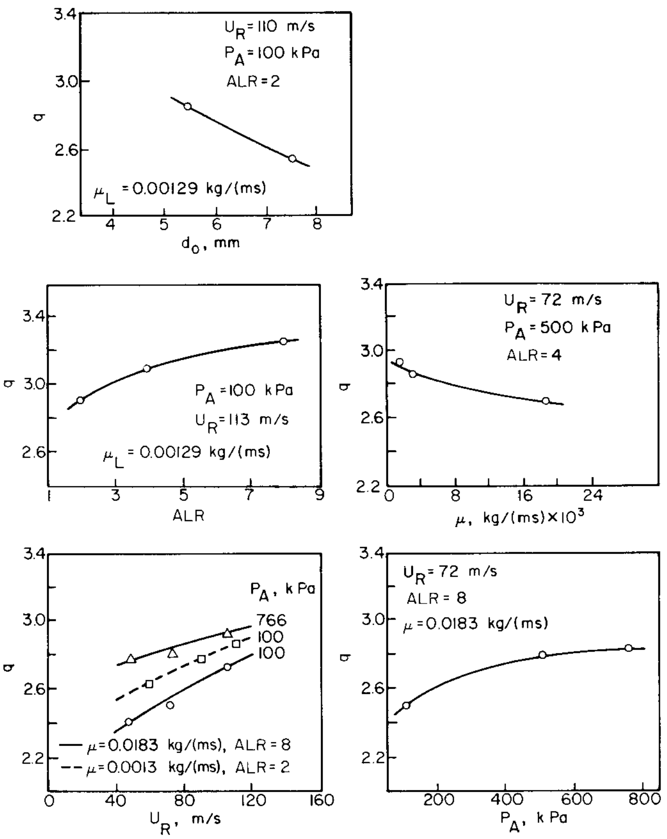

Fig. 10. Influence of liquid nozzle diameter, liquid viscosity, air pressure, air velocity and air/liquid ratio on drop-size distribution parameter, q.

CONCLUSIONS

From a series of measurements carried out on a coaxial, coflowing, plain-jet airblast atomizer it is found that the effects of the main air and liquid properties on mean drop size follow closely the trends observed previously with prefilming airblast atomizers, although the exponents of air pressure and velocity are slightly lower for the plain-jet type.

The experimental data collected in this study are correlated with good accuracy by the dimensionally-correct equation.

$$\frac{SMD}{d_o} = 0.48\left(\frac{\sigma}{\rho_A U_R^2 d_o}\right)^{0.4}\left(1+\frac{1}{ALR}\right)^{0.4} + 0.15\left(\frac{\mu_L^2}{\sigma \rho_L d_o}\right)^{0.5}\left(1+\frac{1}{ALR}\right)$$

The results also confirm previous findings for prefilming airblast atomizers in regard to the effects of air and liquid properties on drop-size distribution. The measurements show that any change in atomizer geometry, liquid properties or operating conditions that reduces the mean drop diameter will also increase the uniformity of drop sizes in the spray.

REFERENCES

1. Nukiyama, S. and Tanasawa, Y., "Experiments on Atomization of Liquids," Transactions of Society of Mechanical Engineers, Japan, 6 parts, English translation by the Dept. of National Defence, Canada, 1950, 1938-40.

2. Weiss, M. A. and Worsham, C. H., "Atomization in High Velocity Airstreams," ARS Journal, Vol. 29, No. 4, 1959, pp. 252-259.

3. Gretzinger, J. and Marshall, W. R., "Characteristic of Pneumatic Atomization," AIChE Journal, Vol. 7, No. 2, June 1961, pp. 312-318.

4. Kim, K. Y. and Marshall, W. R., "Drop-Size Distributions from Pneumatic Atomizers," AIChE Journal, Vol. 17, No. 3, 1971, pp. 575-584.

5. Lorenzetto, G. E. and Lefebvre, A. H., "Measurements of Drop Size on a Plain-Jet Airblast Atomizer," AIAA Journal, Vol. 15, No. 7, July 1977, pp. 1005-1010.

6. Jasuja, A. K., "Plain-Jet Airblast Atomization of Alternative Liquid Petroleum Fuels Under High Ambient Air Pressure Conditions," ASME Paper 82-GT-32, 1982.

7. Dickinson, D. R. and Marshall, W. R., "The Rates of Evaporation of Sprays," Journal of Am. Inst. Chem. Eng., Vol. 14, No. 4, July 1968, p. 541.

8. Chin, J. S., Durrett, R., and Lefebvre, A. H., "The Interdependence of Spray Characteristics and Evaporation History of Fuel Sprays in Stagnant Air," to be published.

9. Simmons, H. C., "The Correlation of Drop-Size Distribution in Fuel Nozzle Sprays," ASME Journal of Engineering for Power, Vol. 99, No. 3, July 1977, pp. 309-319.

10. Dobbins, R. A., Crocco, L., and Glassman, I., "Measurement of Mean Particle Sizes of Sprays from Diffractively Scattered Light," AIAA Journal, Vol. 1, No. 8, 1963, pp. 1882-1886.

11. Roberts, J. M. and Webb, M. J., "Measurement of Droplet Size for Wide Range Particle Distribution," AIAA Journal, Vol. 2, No. 3, 1964, pp. 583-585.

12. Rizk, N. K. and Lefebvre, A. H., "Influence of Airblast Atomizer Design Features on Mean Drop Size," Paper presented at AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, June 1982.

13. Swithenbank, J., Beer, J. M., Abbott, D., and McCreath, C. G., "A Laser Diagnostic Technique for the Measurement of Droplet and Particle Size Distribution." AIAA Paper 76-69, 14th Aerospace Sciences Meeting, Washington D.C., Jan. 26-28, 1976.

14. Lefebvre, A. H., "Airblast Atomization," Prog. Energy Combust. Sci., Vol. 6, 1980, pp. 233-261.

15. Rosin, P. and Rammler, E., "The Laws Governing the Fineness of Powdered Coal," Journal of the Institute of Fuel, Vol. 7, No. 31, October 1933, pp. 29-36.

16. Ingebo, R. D., "Capillary and Acceleration Wave Breakup of Liquid Jets in Axial-Flow Airstreams," NASA Technical Paper No. 1791, 1981.