Measurements of Drop Size on a Plain-Jet Airblast Atomizer

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Measurements of the mean drop size (Sauter mean diameter) produced by a plain-jet airblast atomizer were carried out using the well-established light-scattering technique. Specially prepared liquids were employed to distinguish between the separate effects on SMD of viscosity, surface tension, and density. Atomizing air velocities of up to 180 m/s were used in order to cover the range of interest for the gas turbine. The effect of atomizer size on SMD was studied using several geometrically similar systems in which the fuel injection orifices varied between 0.397 and 1.588 mm in diameter. The results of the investigation generally confirmed those obtained in previous studies in regard to the effects of liquid properties, air velocity, and air/liquid ratio on atomization quality. The effect of fuel orifice diameter D was found to be quite small, except for liquids of high viscosity, where SMD varied roughly in proportion with $D^{0.5}$. Analysis of the experimental data revealed that under comparable operating conditions the performance of the plain-jet airblast atomizer is inferior to that of the widely used thin-sheet airblast atomizer.

Nomenclature

SMD = Sauter mean diameter
V = velocity
V_r = relative velocity (air minus liquid)
W = mass flow rate
μ = viscosity
σ = surface tension
ρ = density
D = diameter of fuel injection orifice

Subscripts

a = air
ℓ = liquid

Introduction

THE advantages of airblast atomizers over pressure atomizers, especially in their application to gas turbines of high pressure ratio, are now well-established. Compared with conventional pressure atomizers of the "duple" or "dual-orifice" type, airblast atomizers require lower fuel pressures and produce a finer spray. Moreover, because the fuel drops are thoroughly mixed with the atomizing air as it enters the primary zone, the ensuing combustion process is characterized by very low soot formation and a blue flame of low luminosity, resulting in relatively cool liner walls and a minimum of exhaust smoke. A further asset of the airblast atomizer is that it provides a sensibly constant fuel distribution over the entire range of fuel flows. This offers an important practical advantage in that the temperature distribution in the chamber efflux gases, which determines turbine blade life at high pressures, may be predicted adequately from temperature surveys carried out at lower and more convenient levels of pressure.

The merits of the airblast atomizer have led in recent years to its installation in a wide range of industrial and aircraft engines. Most of the systems now in service are of the so-called "thin-sheet" 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. The characteristics of this type of atomizer have been studied in detail by Rizkalla and Lefebvre.[1,2]

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 investigation of significance was that reported by Nukiyama and Tanasawa[3] about 40 years ago. Although this pioneer work did much to elucidate the key factors involved in airblast atomization, the range of variables covered was fairly narrow. Therefore it was considered appropriate to initiate a further detailed study of the plain-jet airblast atomizer, using a specially designed system in which all of the relevant parameters, i.e., liquid properties, liquid/air ratio, air velocity, and atomizer dimensions; could be varied independently and examined for their separate effects on spray quality.

Experimental

A cross-sectional drawing of the atomizer employed 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. In order to determine the effects of scale, four brass liquid injectors were manufactured with orifice diameters of 0.397, 0.794, 1.19, and 1.588 mm. In order to separate the effects of liquid flow rates from those of air/liquid ratio, ten air nozzles were produced, having throat diameters between 5.84 and 25.4 mm.

All of the experimental data were obtained using air supplied from a fan at atmospheric pressure and room temperature. Air mass flow was measured by the orifice plate method, whereas liquid flow rates were metered on calibrated precision flowmeters.

Drop sizes were measured using the well-established light scattering technique. The optical system employed is fully described in Ref. 4. It was basically the same equipment as

Presented as Paper 76-679 at the AIAA/SAE 12th Propulsion Conference, Palo Alto, Calif., July 26-29, 1976; submitted Jan. 13, 1977; revision received April 8, 1977.

Index categories: Airbreathing Propulsion; Combustion and Combustor Designs; Combustion Stability, Ignition, and Detonation.

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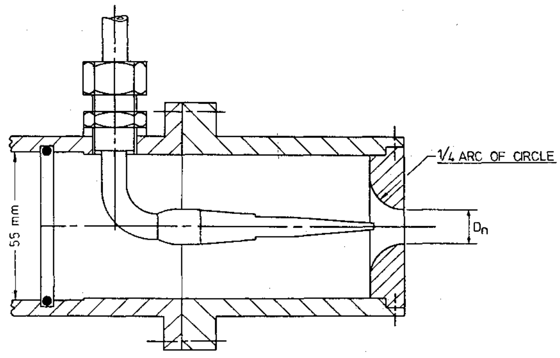

Fig. 1 Plain-jet airblast atomizer.

that used in previous studies of airblast atomization,[1,2] except that various improvements had been made, notably in the light source, which enabled the SMD of the spray to be measured accurately down to values of around 20μ microns.

Results

The two main liquids employed in the investigation were water ($\mu = 0.0010$ kg/ms, $\sigma = 0.0735$ N/m, $\rho = 1000$ kg/m^3) and kerosine ($\mu = 0.00129$ kg/ms, $\sigma = 0.02767$ N/m, $\rho = 784$ kg/m^3). In order to examine the separate effects on SMD of variations in liquid viscosity, surface tension, and density, a number of liquid solutions were prepared in which two of these physical properties were maintained substantially constant, while the third property was varied over a wide range. Standard laboratory techniques were used to measure viscosity, surface tension, and density. The results of measurements carried out on all liquids at a temperature of 20°C are presented in Table 1.

The results obtained from all previous studies on liquid atomization show that any increase in viscosity always increases the mean drop size. Normally this is attributed to viscosity forces, which tend to oppose the disintegration of liquids into drops and to resist any further break-up of drops already formed. The adverse effect of viscosity on spray quality was confirmed in the present experiments, as illustrated in Fig. 2. In this figure, SMD is shown plotted against absolute viscosity for a constant liquid flow rate of 1.5 g/sec and at various levels of air velocity ranging from 70 to 140 m/sec. Figure 2 also demonstrates the beneficial effect of an increase in air velocity in reducing SMD. However, it should be borne in mind that these results were obtained with a single air nozzle, so that any increase in air velocity was also accompanied by a corresponding increase in air/liquid ratio. Thus the effect of velocity on SMD is not quite so pronounced as the curves in Fig. 2 might suggest.

Surface tension forces also affect atomization adversely by opposing any distortion of the liquid surface. This effect is shown in Fig. 3, where mean drop sizes are observed to increase with increase in surface tension. Also of interest in this figure is that the influence of surface tension diminishes at the higher levels of air velocity.

In a previous study of airblast atomization,[1] using a thin-sheet type of atomizer, it was found that SMD increased with liquid density up to a value of around 1500 kg/m^3, above which any further increase in density caused SMD to decline. In the present study, however, atomization quality was always improved by an increase in liquid density, as shown in Fig. 4. Incidentally, the "flattening out" of the right-hand part of the curves in this figure may be attributed to the exceptionally high value of surface tension of the liquid used to obtain the highest density point (see Table 1). Had it been more consistent in this respect with the other liquids used in this series of tests, then it is considered that Fig. 4 would have demonstrated a continuing decline of SMD with increase in liquid density.

Table 1 Test results at 20°C

1 Solution of the synthetic hydrocarbon polymer, Hyvis Polybutene No. 0.5 in kerosine to obtain a wide range of viscosity.

Level Tested	Solution	μ (kg/ms)	σ(N/m)	ρ(kg/m³)
1	Pure Kerosine	0.00129	0.0277	784
2	30% Hyvis 05	0.00287	0.0287	800
3	40% " "	0.00429	0.0288	809
4	50% " "	0.00604	0.0289	812
5	60% " "	0.00979	0.0292	819
6	70% " "	0.01701	0.0301	823
7	80% " "	0.03380	0.0302	828
8	85% " "	0.04410	0.0303	830
9	90% " "	0.07654	0.0305	833
10	95% " "	0.12392	0.0307	838
	100% " "	0.21856	0.0310	840

2 Mixtures of sec-Butyl Alcohol (Butan-2-ol) with water to obtain different values of surface tension.

Level Tested	Solution	μ (kg/ms)	σ(N/m)	ρ(kg/m³)
1	Pure Water	0.00100	0.0735	1,000
2	1.48% Butan-2-ol	0.00113	0.0559	990
3	2.44% "	0.00113	0.0519	988
4	3.85% "	0.00115	0.0465	986
5	6.98% "	0.00127	0.0395	983
6	11.11% "	0.00140	0.0340	980
7	16.67% "	0.00171	0.0291	978
8	25.93% "	0.0o234	0.0268	968
	100.00% "	0.00347	0.0242	807

3 Dibrono-ethane (ethylene dibromide) diluted with methylated spirit to obtain a wide range of density.

Level Tested	Solution	μ (kg/ms)	σ(N/m)	ρ(kg/m³)
	Pure Methylated Spirit	0.00153	0.0262	812
1	9.09% Dibromo-ethane	0.0154	0.0299	933
2	13.04% "	0.00155	0.0303	978
3	16167% "	0.00155	0.0307	1,031
4	23.08% "	0.00156	0.0311	1,123
5	28.57% "	0.00157	0.0316	1,213
6	37.50% "	0.00157	0.0320	1,315
7	44.44% "	0.00158	0.0324	1,430
8	50.00% "	0.00159	0.0328	1,503
9	54.00% "	0.00160	0.0333	1,634
10	60.00% "	0.00160	0.0337	1,830
	100.00% "	0.00173	0.0420	2,180

Another characteristic of interest which was not observed with thin-sheet airblast atomizers was an independent effect of liquid flow rate on SMD. In order to determine this effect, a series of tests was carried out in which all four fuel-injectors were used in conjunction with nine different air nozzles. By this means it was possible to run tests on both water and kerosine in which the relative air velocity and AFR were maintained constant, while the liquid flow rate was varied over a very wide range. The results obtained for kerosine are presented in Fig. 5; they show that an increase in liquid flow rate raises SMD. This figure also illustrates the beneficial effect of an increase in air/liquid flow ratio in reducing SMD, especially for low values of air/liquid ratio. This same point is high-lighted in Fig. 6, which is based on data obtained from a special series of tests in which several air nozzles of different diameter were used in order to fully isolate the effects of air/liquid ratio from the other parameters controlling SMD. Figure 6 shows the measured values for water, but very similar results, at generally lower levels of SMD, were obtained for kerosine. All of the plots of SMD vs air/liquid ratio exhibit the same characteristics as the corresponding curves for thin-sheet atomizers.[2] Thus, in Fig. 6, it is observed that atomization quality starts to decline when the air/liquid ratio falls below about four, and deteriorates quite rapidly at air/liquid ratios below about two. The figure also shows that

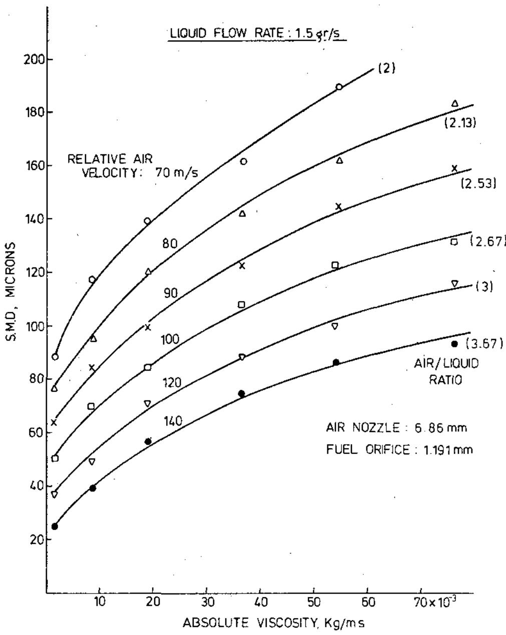

Fig. 2 Variation of mean drop size with liquid viscosity for a constant liquid flow rate.

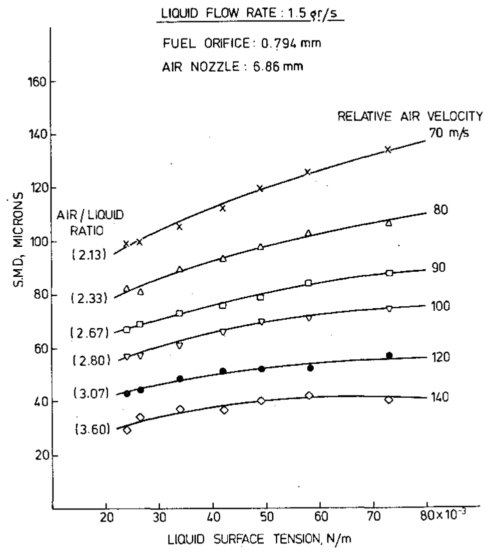

Fig. 3 Variation of mean drop size with liquid surface tension for a constant liquid flow rate.

above an air/liquid ratio of about five, only very marginal reductions in SMD are gained by the use of more air in atomization. It would appear, therefore, that for both thin-sheet and plain-jet atomizers the optimum air/liquid ratio for design purposes is between three and four. At low air/liquid ratios, the amount of atomizing air is insufficient to overcome the viscous and surface tension forces, which act together to oppose drop formation, whereas at high air/liquid ratios, some of the air is too remote from the fuel jet to play an active part in the atomization process. Figure 6 also illustrates that, except at the lowest air/liquid ratios, a deficiency of air may always be compensated by an increase in air velocity.

Of all the various factors influencing SMD, air velocity is undoubtedly the most important. This is very clear from inspection of Figs. 2-4 and 6; but the precise effects of velocity cannot be assessed from these figures, because any change in air velocity also incurred a change in some other parameter known to affect SMD. In order to ascertain the genuine effect of air velocity on SMD, a number of tests were conducted on both water and kerosine in which increase in air velocity was

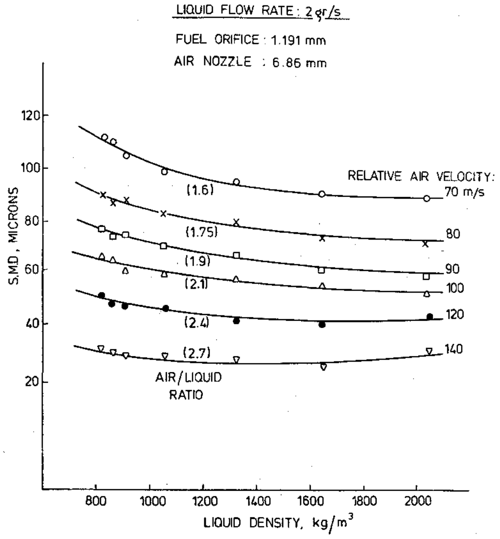

Fig. 4 Variation of mean drop size with liquid density for a constant flow rate.

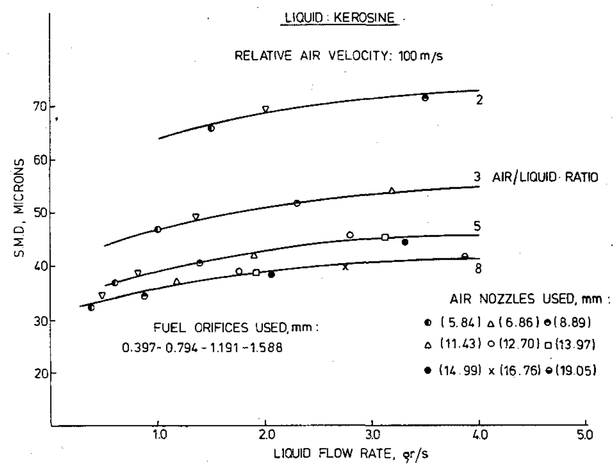

Fig. 5 Influence of liquid flow rate on SMD.

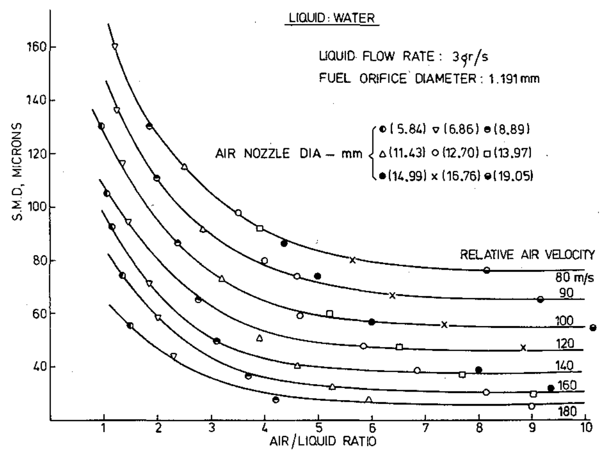

Fig. 6 Influence of air/liquid ratio on SMD.

always achieved by fitting a smaller air nozzle, thereby maintaining a constant air/liquid ratio. The results for kerosine, at a constant air/liquid ratio of three, are shown in Fig. 7, in which the four different lines correspond to four different values of liquid flow rate. A point to note in this figure is that SMD is plotted as a function of the relative velocity between the air and the liquid, since this is considered to be most relevant to the atomization process. However, as

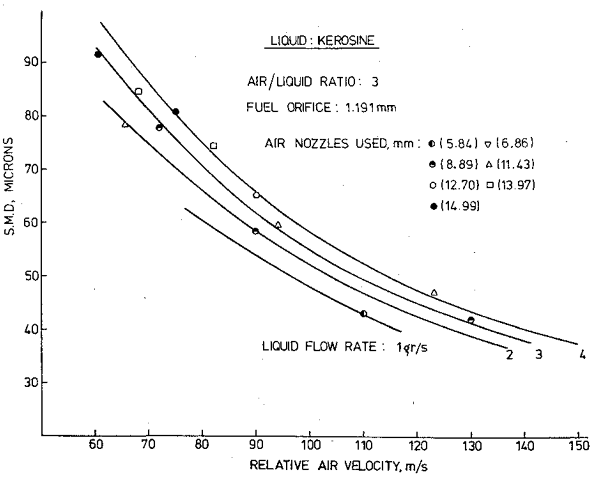

Fig. 7 Influence of air velocity on mean drop size.

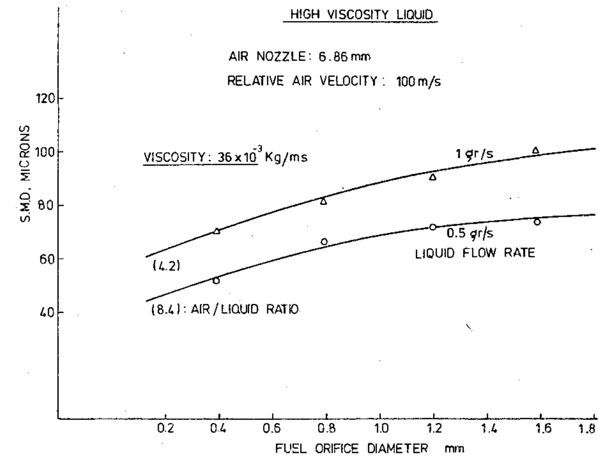

Fig. 9 Influence of fuel orifice diameter on SMD for liquids of high viscosity.

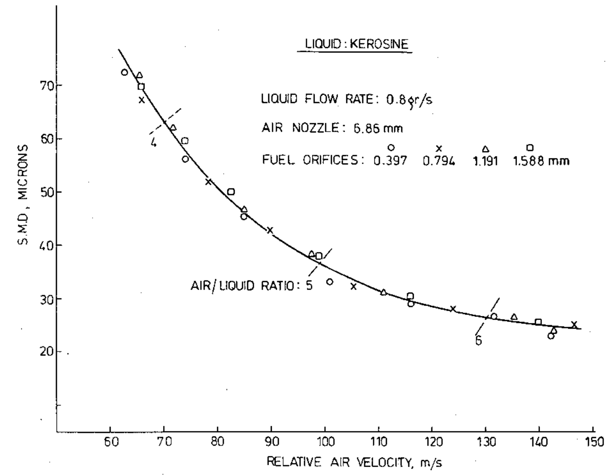

Fig. 8 Graph illustrating independence of SMD on fuel orifice diameter for kerosine.

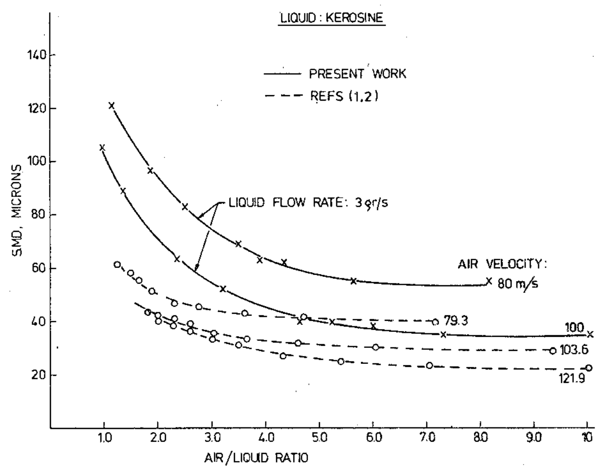

Fig. 10 Comparison of atomizing performance of plain-jet and thin-sheet airblast atomizers.

the liquid velocity rarely exceeded a few meters per second, the difference between the relative velocity and the absolute air velocity always was quite small.

Examination of Fig. 7 reveals that, for kerosine, SMD is roughly inversely proportional to velocity. This result underlines the importance in airblast atomizer design of arranging for the fuel jet or sheet to be exposed to the highest possible air velocity consistent with the available pressure drop.

The effect of variation in fuel orifice diameter on atomization quality is illustrated in Figs. 8 and 9. All tests were conducted with a 6.85-mm air nozzle in conjunction with all four fuel injectors. The results obtained with kerosine are plotted in Fig. 8 as SMD vs relative air velocity, and it is interesting to note that all of the experimental points fall on a single curve, regardless of fuel orifice diameter. The implication of this result is that atomizer size, per se, has no effect on mean drop size. However, further tests carried out on a liquid of much higher viscosity ($\mu = 0.036$ kg/ms) demonstrated a much larger dependence of spray quality on fuel orifice diameter (in fact, SMD $\propto D^{0.5}$). The results of these tests for two different liquid flow rates are plotted in Fig. 9.

Since both thin-sheet and plain-jet airblast atomizers are employed on modern gas turbines, it is of interest to comapre the atomizing performance of these two types. This is readily accomplished by plotting some of the measured values of SMD from the present investigation alongside the experimental data obtained by Rizkalla and Lefebvre[1,2] under comparable operating conditions. The results of such a comparison are presented in Figs. 10 and 11. It is clear from these figures that the plain-jet atomizer performs less satisfactorily than the thin-sheet atomizer, especially under the adverse conditions of low air/liquid ratio and/or low air velocity.

Correlation of Experimental Data

The following expression for SMD was derived from analysis of the experimental data:

$$\mathrm{SMD} = 0.95 \left[\frac{(\sigma_\ell W_\ell)^{0.33}}{V_r \rho_\ell^{0.37} \rho_a^{0.30}} \right] \left[1 + \frac{W_\ell}{W_a} \right]^{1.70}$$

$$0.13\, \mu_\ell \left[\frac{D}{\sigma_\ell\, \rho_\ell} \right]^{0.5} \left[1 + \frac{W_\ell}{W_a} \right]^{1+70} \qquad (1)$$

It is accurate to within ±8% over the following range of air and liquid properties: liquid viscosity—0.001 to 0.076 kg/msec, liquid surface tension—0.026 to 0.076 N/m; liquid density—794 to 2,180 kg/m^3; air velocity—70 to 180 m/sec; air/liquid mass ratio—1 to 16. The preceding expression for SMD is dimensionally correct, and therefore may be used with any consistent set of units. A noteworthy point is that it contains an air density term. This was included to satisfy the requirements of nondimensionality, although, in fact, all tests were carried out under conditions of constant air density.

In view of the widespread use of the Nukiyama and Tanasawa equation for the mean drop size produced by plain-jet airblast atomizers, it is clearly of interest to compare the

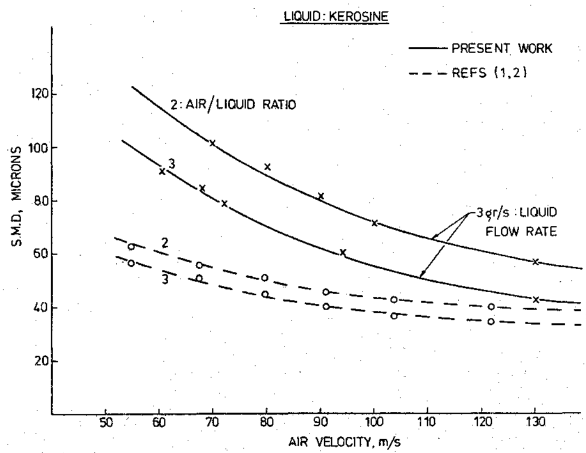

Fig. 11 Comparison of atomizing performance of plain-jet and thin-sheet airblast atomizers.

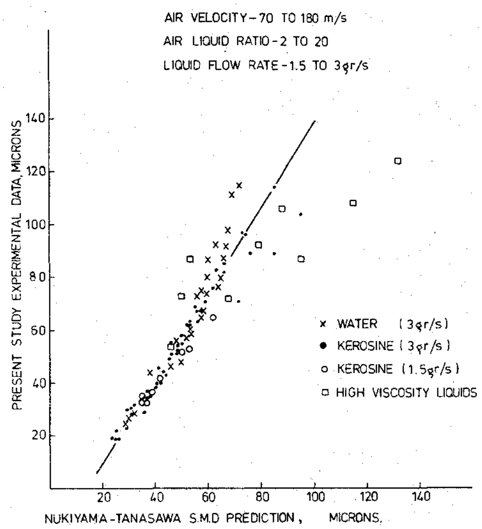

Fig. 12 Comparison of experimental data on SMD with predicted values from Nukiyama and Tanasawa.[3].

predictions of this equation with the experimental data obtained during the present investigation. The result of such a comparison is illustrated in Fig. 12. From inspection of this figure, it is apparent that good agreement is obtained for SMD's around 40μ. At higher and lower levels of SMD, the predicted values of SMD tend to fall respectively below and above the experimental points. Equation (1) exhibits better agreement with the experimental data, because it predicts a more pronounced effect of air velocity on SMD, than does the corresponding expression for SMD derived by Nukiyama and Tanasawa.

Conclusions

From analysis of experimental data obtained on the performance of plain-jet airblast atomizers tested over a wide range of liquid properties and flow conditions, the following conclusions were drawn:

1) The mean drop size of the liquid spray increases with increase in liquid viscosity and surface tension and decreases with increase in liquid density.

2) Atomization quality is improved by an increase in air/liquid ratio and by a reduction in liquid flow rate.

3) For liquids of low viscosity, e.g., water or kerosine, the air/liquid ratio should ideally exceed a value of three. However, little improvement in atomization quality is gained by raising the air/liquid ratio above a value of about five.

4) Atomization is improved by an increase in air velocity. For liquids of low viscosity, the mean drop size is inversely proportional to air velocity. This conclusion thus confirms the results of previous work on airblast atomization.[1,2]

5) For liquids of low viscosity, the size of the fuel injection orifice has virtually no effect on drop size, but for liquids of high viscosity, atomization quality is improved by a reduction in fuel jet diameter.

6) The experimental data on mean drop size correlate satisfactorily with the dimensionally correct equation:

$$\mathrm{SMD} = 0.95 \left[\frac{(\sigma_\ell W_\ell)^{0.33}}{V_r \rho_\ell^{0.37} \rho_a^{0.30}} \right] \left[1 + \frac{W_\ell}{W_a} \right]^{1.70} + 0.13\, \mu_\ell \left[\frac{D}{\sigma_\ell \rho_\ell} \right]^{0.5} \left[1 + \frac{W_\ell}{W_a} \right]^{1.70}$$

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