Airblast Atomization at Conditions of Low Air Velocity

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Spray quality is determined by a series of measurements of drop size distribution and mean drop size. The atomizer employed is a two-dimensional design, producing a flat liquid sheet of variable thickness sandwiched between two coflowing nitrogen gas streams. The range of test conditions is chosen to simulate those typically found in a gas turbine combustor during startup, when air velocities are low. Four different liquids—tap water, heating oil, aviation kerosine (Jet-A), and a high-viscosity mixture of glycerine and distilled water—are used to investigate the effects of liquid physical properties on atomization quality. The results generally confirm those obtained in previous studies in regard to the effects of relative velocity, air/liquid mass flow ratio, and liquid physical properties on Sauter mean diameter. However, the significant dependence of mean drop size on initial liquid film thickness reported by other investigators is not observed in this study. Also, the results suggest the existence of a threshold of relative velocity below which atomization of the liquid sheet is not possible. As the relative velocity is reduced, the Sauter mean diameter eventually reaches a maximum value, and any further reduction in relative velocity results in the loss of the spray.

Introduction

IN gas turbine applications, one of the most common nozzle types is the prefilming airblast atomizer. Fuel at low pressure flows through the nozzle and onto a prefilming surface via several tangential ports. The swirling fuel flows over the surface to form a thin, continuous, annular liquid sheet at the atomizing edge. Interaction with high-velocity air on both sides of the sheet results in atomization of the liquid. Vanes located in the airstreams promote swirl, which enhances the disruption of the liquid sheet and improves mixing of the air and fuel drops.

Extensive research on airblast atomization has yielded considerable information on the effects of variations in liquid properties, air properties, and atomizer design features on the drop size distributions produced in the spray. In general, for prefilming airblast atomizers, spray quality can be improved by increasing the air velocity, air density, and air/liquid mass flow ratio and by decreasing the liquid viscosity, surface tension, and atomizer size. This general statement is embodied quantitatively in the various semiempirical equations which have been developed to relate the spray Sauter mean diameter (SMD) to the above-mentioned atomizer operating parameters.[1]

The measurement of SMD for prefilming airblast atomizers obtained by Lefebvre and co-workers (see, for example, Refs. 2–5) and Jasuja[6,7] are in the velocity range from 55 to 150 m/s, corresponding to pressure drops across the atomizer from 2 to 12% of inlet air pressure. This range is of practical importance for gas turbine applications because combustor liner pressure drops are typically between 2 and 5%. Under certain engine operating conditions, however, the pressure drop across the liner may be considerably less than the nominal design value corresponding to steady-state operation. A good example is when the engine is being cranked over during starting. This "off-design" condition presents a special problem with prefilming airblast atomizers, because the velocity of the air flowing through the atomizer is insufficient to shatter the liquid into a fine spray. Consequently, poor startup performance is sometimes exhibited by this type of atomizer and is one of its major drawbacks.

The present investigation was undertaken in an attempt to alleviate this problem and to obtain a better understanding of the process of prefilming airblast atomization under conditions of reduced air velocity, an area which so far has remained largely unexplored. Attention is also given to the possibility of improving atomization quality by reducing the initial thickness of the fuel sheet created on the prefilming surface as a means of compensating for a reduction in atomizing air velocity.

Experimental

The experimental rig is shown schematically in Fig. 1. The main component is a cylindrical pressure tank, which is mounted on a stand with its axis vertical. The atomizer is located centrally at the top of the tank and sprays downward. The tank is fitted with several pairs of diametrically opposed

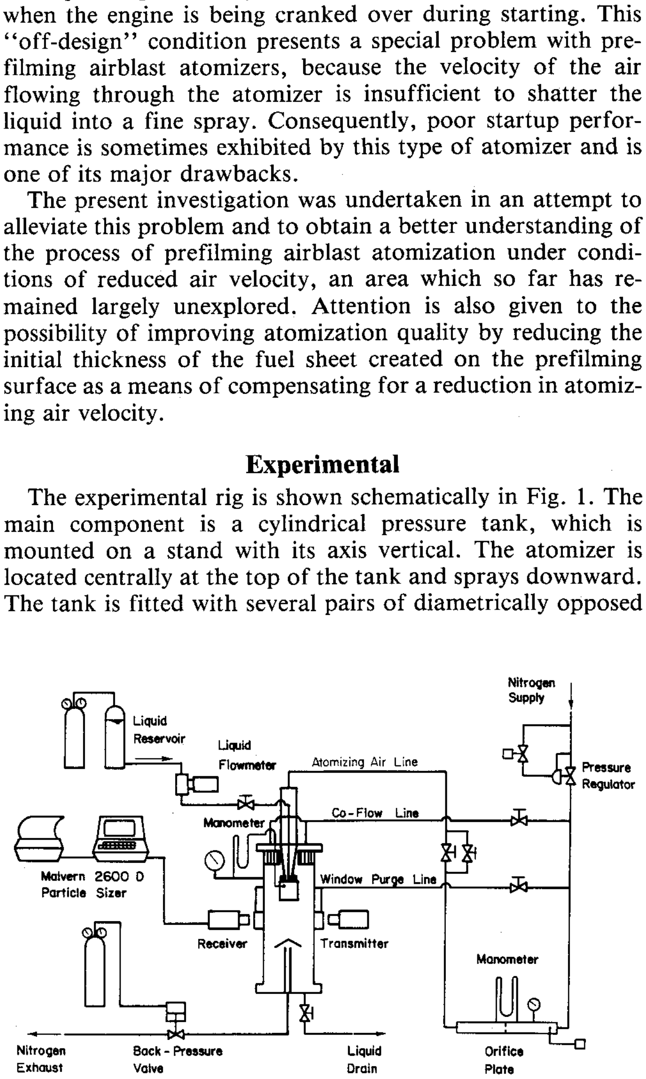

Fig. 1 Layout of apparatus and instrumentation.

Received Oct. 15, 1988; presented as Paper 89-0217 at the AIAA 27th Aerospace Sciences Meeting, Reno, NV, Jan. 9–12, 1989; revision received Oct. 15, 1989.

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quartz windows to allow optical access at several distances downstream of the atomizers.

Atomization is achieved using nitrogen gas instead of air to avoid the risk of explosion within the tank. 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. Hence, elsewhere in this paper, the atomizing medium will be referred to as air.

In addition to the air supply line for atomization, two other air lines are fitted to the tank. One line supplies air to protect the windows from contamination by drops and mist, while the other line is connected to a manifold and flow straightener at the top of the tank and provides a uniform downdraft of low velocity coflowing air. By this means, the problem of droplet recirculation within the tank is kept to a minimum.

The flows of air to the atomizer, flow straightener, and windows are controlled using ball valves. In addition, fine control of the atomizer airflow is achieved by means of a needle valve located in parallel with the ball valve.

Liquid is supplied to the atomizer by means of a pressurized reservoir. The free surface in the reservoir is pressurized with nitrogen, and the rate of the resulting liquid flow is measured with either a Fluidyne Model 214 or a Brooks Model 1110 rotameter, depending on the type of liquid being sprayed.

Four different liquids are employed to determine the effects of liquid physical properties on atomization quality—tap water, heating oil, aviation kerosine (Jet-A), and a high viscosity mixture of glycerine and distilled water (68% glycerine by mass). The liquid properties listed in Table 1 were measured at a temperature of 298 K. Wide ranges of surface tension and viscosity are considered; the surface tension is approximately 2½ times that of the Jet-A fuel, and the viscosity of the glycerine-water mixture is approximately 13 times that of water.

The airblast atomizer used in this study is illustrated in Fig. 2. It is a two-dimensional design; the primary objective is to produce a thin liquid sheet that is flat and consequently easier to measure and control. This is accomplished by flowing the liquid into a variable-width slot from which it issues along the axis of the atomizer into the intersection of two airstreams. The atomizer closely resembles the design successfully employed by Rizk and Lefebvre[3] in a previous study on the influence of liquid film thickness on drop size distributions.

The atomizer is made of three major components: two air/liquid control assemblies, designated in Fig. 2 by the numbers 1 and 2 and a top plate assembly. Fluid-tight seals are established between adjacent surfaces of the three components by thin rubber gaskets, and the atomizing edge is made sharp to provide maximum physical contact between the air and the liquid at the atomizer exit.

Table 1 Test liquids and their properties

Liquid	Surface tension, N/m	Viscosity, kg/ms	Density, kg/m^3
Water	0.0746	0.00104	998
Heating oil	0.0307	0.00275	852
Jet-A kerosine	0.0285	0.00151	804
Glycerine-water	0.0705	0.01360	1170

Table 2 Experimental test conditions

Parameter	Conditions
T_A and T_L, K	298
P_A, MPa	0.101
$\Delta P/P_A$, %	2.0, 1.5, 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1
$\dot{m}_L$, g/s	10, 15, 20, 25
t, μm	102, 203, 305
Liquids	Water, heating oil, Jet-A, glycerine-water mixture

The initial thickness of the liquid sheet is assumed to be equal to the width of the slot from which the liquid emerges. By turning two cap screws located along the sides of the atomizer, the separation between the two control assemblies can be varied and hence also the width of the slot and the thickness of the liquid sheet. Owing to the compressible nature of the rubber gasket material, a wide range of values of initial liquid film thickness is possible. The slot width is set and frequently checked using accurate feeler gauges.

Air enters the atomizer through two rectangular channels located on the top plate. Each of these channels contains a single coarse mesh screen and a single fine mesh screen to enhance the uniformity of the incoming flow. At the atomizing edge, the velocities of the air in both exit slots are equal and are calculated from the Bernoulli equation by measuring the pressure drop across the atomizer with a U-tube water manometer. The velocity calculations are verified by inserting a total-pressure probe in the exit flow.

Drop size distributions are measured with a Malvern Model 2600D particle sizer fitted with a 300-mm lens. In analyzing the experimental data, the Rosin-Rammler expression

$$1 - Q = \exp - (D/X)^q \tag{1}$$

is chosen to describe the drop size distribution, where Q is the fraction of the total volume contained in drops of diameter less than D, and X and q are constants. By applying the Rosin-Rammler relationship to sprays, it is possible to describe the drop size distribution in terms of the two parameters X and q. The exponent q provides a measure of the spread of drop sizes. The higher the value of q, the more uniform is the spray. If q is infinite, the drops in the spray are all the same size. For most sprays the value of q lies between 1.5 and 4. It is perhaps worthy of note that the values of q recorded in this test program showed no significant trends with variations in liquid properties, sheet thickness, and relative velocity. Over the entire range of test conditions, the value of q varied between 1.6 and 2.0, thus indicating a fairly broad range of drop sizes in the spray.

From the distribution parameters X and q, the SMD of the spray can be obtained for an infinite size range directly from the expression

$$\mathrm{SMD} = \frac{X}{\Gamma\,(1 - 1/q)} \tag{2}$$

where Γ is the gamma function.

To avoid any effects resulting from the edges of the liquid sheet, the axis of the laser beam is located in the center of, and normal to, the sheet. Also, because of the wide spray angle, measurements are made fairly close to the exit face of the atomizer (a downstream distance of 5 cm is employed) to avoid the direct impingement of drops on the quartz windows. In addition, all experimental drop size results are corrected for laser beam obscuration using the empirical correction scheme developed by Dodge.[8]

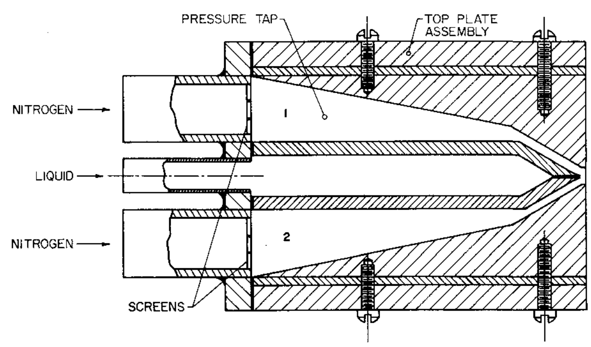

Fig. 2 Cross-sectional view of two-dimensional airblast atomizer.

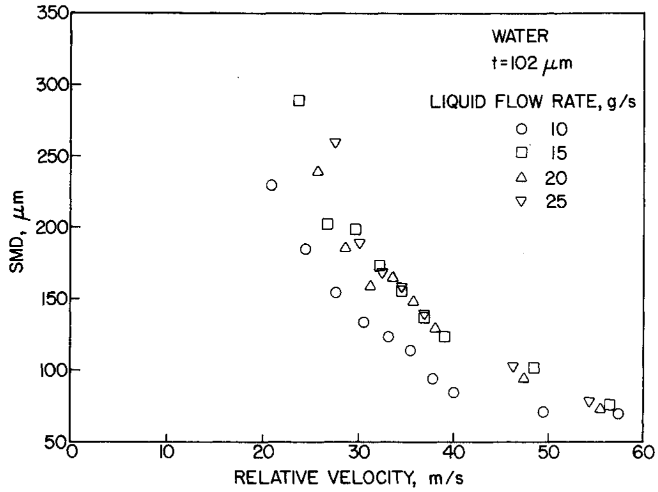

Fig. 3 Influence of relative velocity and liquid flow rate on mean drop size.

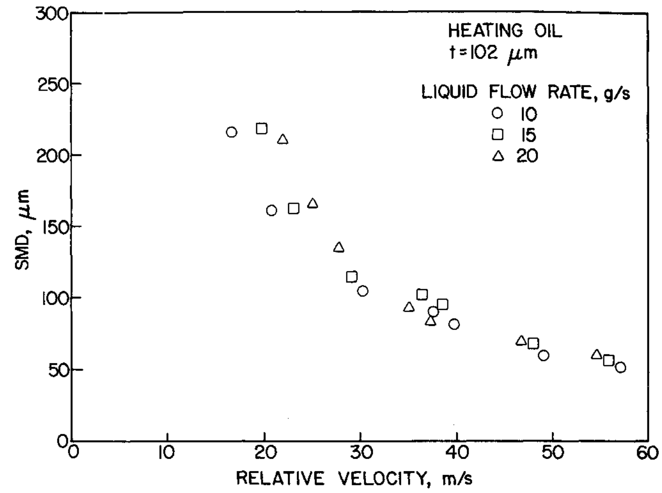

Fig. 5 Influence of relative velocity and liquid flow rate on mean drop size.

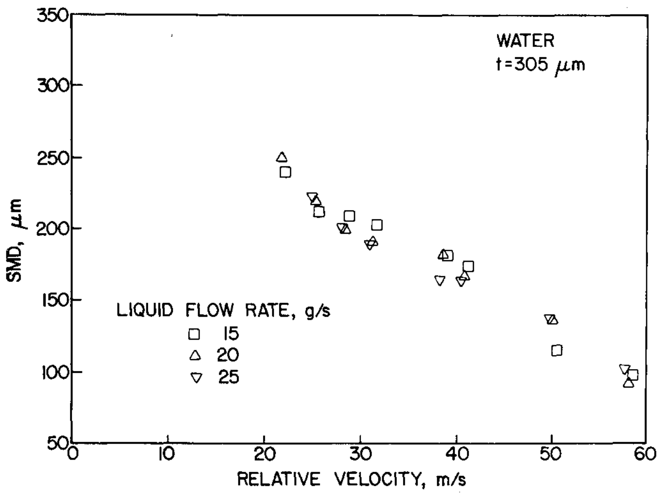

Fig. 4 Influence of relative velocity and liquid flow rate on mean drop size.

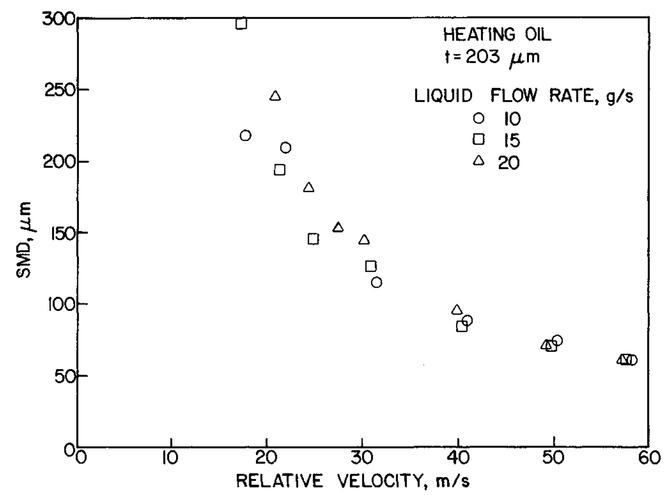

Fig. 6 Influence of relative velocity and liquid flow rate on mean drop size.

Results

The results of this investigation show the individual effects of relative velocity, air/liquid mass ratio, initial liquid film thickness, and liquid physical properties on spray mean drop size. The range of conditions considered is summarized in Table 2. The bulk of the experimental data was obtained using water, but the three additional liquids listed in Table 1 afforded an opportunity to study the separate effects of liquid viscosity and surface tension on mean drop size.

During preliminary tests, two interesting observations were made regarding the limiting test conditions for the flat-sheet atomizer. First, in the absence of any atomizing airflow, the production of a well established liquid sheet at the atomizing edge was found to be a necessary prerequisite if repeatable drop size measurements were to be obtained. For the smallest initial liquid film thickness (102 μm), a well-defined liquid sheet was obtained only when the liquid mass flow rate exceeded approximately 8 g/s. If the mass flow rate was reduced below this value, the sheet contracted under the influence of surface tension and liquid dripped from the atomizing edge, resulting in inconsistent measurements. For the largest film thickness (305 μm), a liquid mass flow rate greater than approximately 13 g/s was necessary to form a well defined sheet at the atomizing edge. The phenomenon placed a lower limit on the range of possible liquid mass flow rates that could be considered for each film thickness.

Second, for any given liquid mass flow rate and initial liquid film thickness, gradual reduction in atomizing air velocity eventually led to a condition at which normal atomization no longer occurred. Instead the liquid sheet disintegrated into fairly coarse drops well downstream of the nozzle. This condition was verified before each measurement by visually inspecting the spray. In the figures described below, the lowest relative velocity where a measurement of mean drop size was obtained is very close to a minimum value below which a spray is no longer attainable. For water, the minimum relative velocity required for atomization is around 20 m/s, whereas for heating oil, which has a much lower surface tension, atomization is possible at relative velocities as low as 16 m/s.

The effect of relative velocity U_R on the SMD for water at different liquid mass flow rates and two initial liquid film thicknesses is shown in Figs. 3 and 4. For all test conditions, it is observed that as the relative velocity decreases, the SMD increases due to the lessening aerodynamic shear forces acting on the liquid sheet. For liquids of low viscosity, the results indicate that SMD α $U_R^{-0.90}$. Inspection of Figs. 3 and 4 reveals the sensitivity of mean drop size to changes in the mass flow rate of the liquid. In most cases, the results demonstrate that an increase in SMD is associated with an increase in liquid mass flow rate for a given air velocity and initial liquid film thickness. This is because the air/liquid mass flow ratio decreases as the liquid mass flow rate is increased. Consequently, the amount of air momentum per unit mass of liquid is reduced and is no longer sufficient to fracture the liquid stream to the same degree.

Some of the results obtained using heating oil are shown in Figs. 5 and 6. It is again observed that a decrease in relative velocity is accompanied by an increase in the SMD for all three liquid mass flow rates, regardless of initial liquid film thicknesses. The magnitudes of the SMD, however, are different from those of water for the same operating conditions due to the differences in surface tension and viscosity.

Figure 7 illustrates the effect of air/liquid mass flow ratio on SMD for different air velocities and a constant initial liquid film thickness. The fraction of air momentum per unit mass of liquid increases as the air/liquid mass flow ratio increases for a given air velocity. As a result, the liquid sheet is more effectively atomized, and the SMD decreases.

The most interesting and surprising aspect of this investigation concerns the observed effect of initial liquid film thickness on mean drop size. Figures 8 through 10 show the influence of initial film thickness on SMD at different air velocities for three different liquid mass flow rates. The results generally indicate that, for any given air velocity and liquid flow rate, an increase in liquid film thickness produces only a slight increase in SMD. This result is somewhat at variance with the classical theories of sheet disintegration, all of which lead to a direct relationship between the mean diameter of the drops in a spray and the thickness of the liquid sheet from which they are formed. According to the mechanism of drop formation proposed by Fraser et al.,[9] the diameter of ligaments formed from fragments breaking off the sheet edge is dependent on the sheet thickness; a thicker sheet produces ligaments of greater diameter. Since the size of the drops resulting from a collapsing ligament is proportional to the diameter of the ligament, a thicker sheet results in larger drops. This finding has been generally supported by the results of experimental research. For example, the studies of El-Shanawany and Lefebvre[2] and Rizk and Lefebvre[3] both gave the result that mean drop size is proportional to the initial sheet thickness raised to the power 0.4.

However, other mechanisms for sheet disintegration can be postulated, which lead to a much lower dependence of mean drop size on initial sheet thickness, especially for liquids of low viscosity. For example, aerodynamic instabilities created on the *surface* of a liquid sheet by virtue of its interaction with the surrounding air may cause the surface to become wavy and to break up into ligaments and then drops. The diameters of the drops formed in this manner will depend primarily on the ratio of the consolidating surface tension force to the disruptive aerodynamic force ($\rho_A U_R^2$), i.e., on reciprocal Weber number and on sheet thickness only to the extent that this dimension influences the sheet Reynolds number. As the sheet thickness is gradually diminished by the continuous removal of liquid from its surface, it eventually becomes comparable in magnitude to the amplitude of the surface waves. At this point the sheet itself becomes unstable and breaks down into ligaments and drops according to the classical wavy sheet mechanism.[9]

A key feature of the proposed "wavy surface" mechanism is that the sizes of the drops produced are largely independent of the initial sheet thickness and are governed mainly by liquid properties, notably surface tension and air momentum. This is precisely the result obtained in the present experiments. However, although this mechanism appears to provide a plausible explanation for the observed lack of sensitivity of mean drop size to initial sheet thickness, it is one that would seem to be

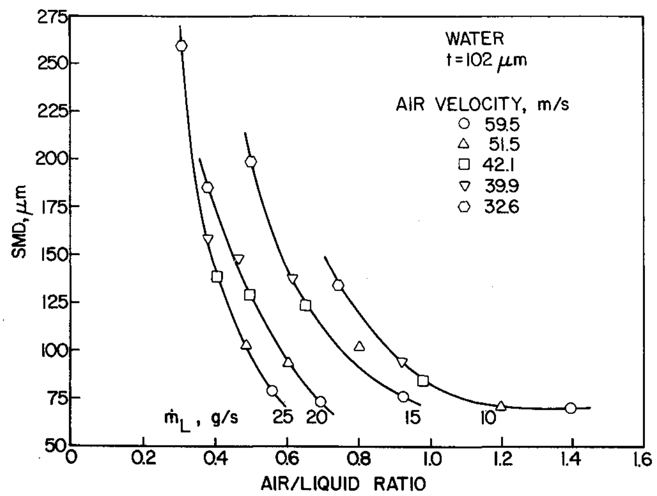

Fig. 7 Influence of air/liquid ratio on mean drop size.

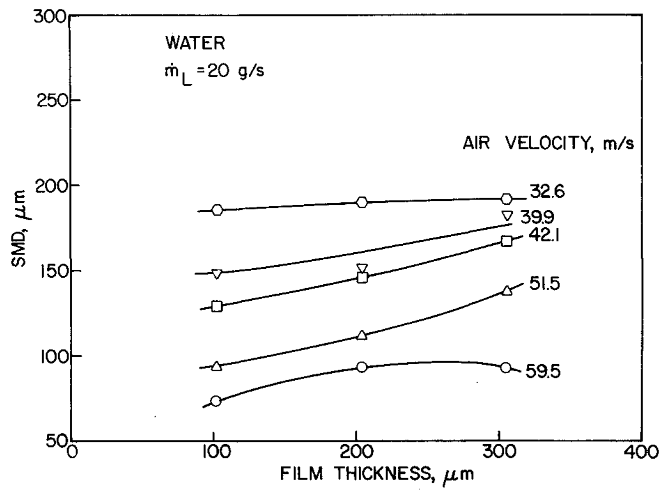

Fig. 9 Effect of film thickness on mean drop size ($\dot{m}_L = 20$ g/s).

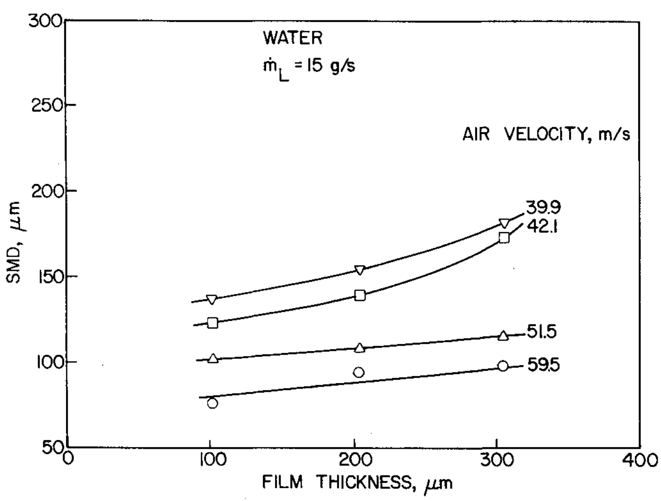

Fig. 8 Effect of film thickness on mean drop size ($\dot{m}_L = 15$ g/s).

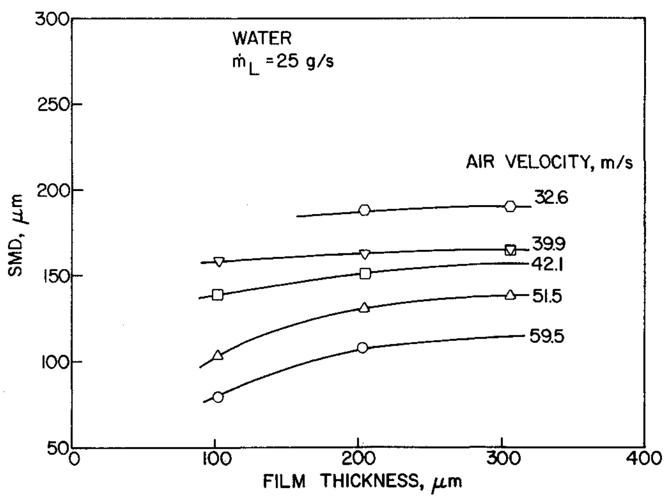

Fig. 10 Effect of film thickness on mean drop size ($\dot{m}_L = 25$ g/s).

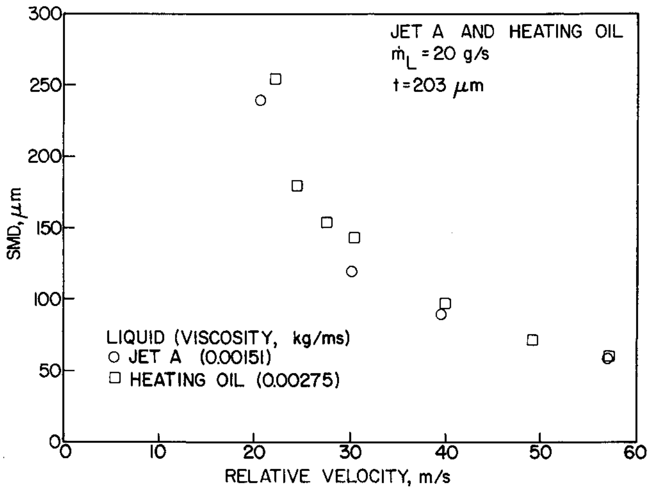

Fig. 11 Influence of viscosity on mean drop size.

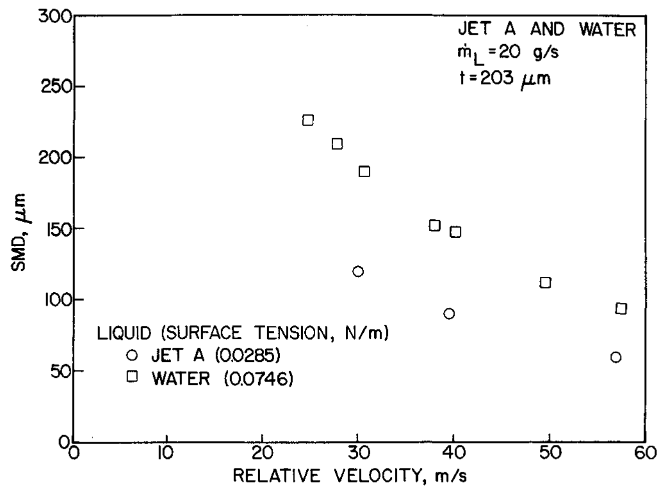

Fig. 13 Influence of surface tension on mean drop size.

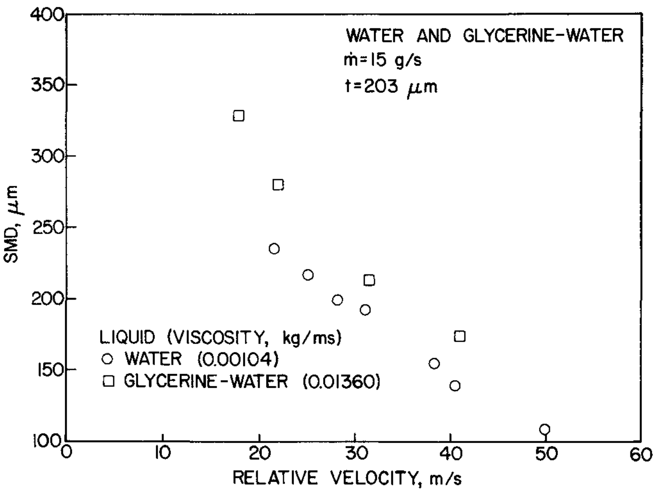

Fig. 12 Influence of viscosity on mean drop size.

more appropriate for liquid sheets of much greater thickness than those employed in the present experiments.

An alternative, and more likely explanation for the results obtained, lies in the angle at which the two airstreams impinged on the liquid sheet. Examination of the atomizer employed in the study of Rizk and Lefebvre[3] reveals that the airstreams emerged almost parallel to the liquid sheet. Thus the interaction between the air and the liquid was one where only shearing forces acted on the liquid. With the atomizer design employed in this investigation, the two airstreams strike the liquid sheet at an angle of 30 deg (see Fig. 2). Consequently, there is a component of air momentum normal to the sheet that was not present in the study by Rizk and Lefebvre. It is believed, therefore, that during this investigation, the liquid sheet was being "extruded" between the two colliding airstreams before breakup occurred, thus, effectively altering the thickness of the sheet and in some cases removing all traces of the initial sheet thickness before the onset of breakup. As a result, a generally neutral dependence on film thickness was observed.

Support for this notion is provided in the results obtained by Lorenzetto and Lefebvre,[10] who used a plain-jet airblast atomizer to examine the effects of air and liquid properties on mean drop size. These workers reported that for liquids of low viscosity, the SMD was completely independent of the initial diameter of the liquid jet. Inspection of the cross-sectional drawing of their atomizer[10] shows that the shape of the air passage is such that the atomizing air also strikes the liquid jet at an appreciable angle, thereby extruding the jet to an extent that greatly reduces the dependence of mean drop size on initial jet diameter.

The effects of liquid physical properties (i.e., surface tension and viscosity) are illustrated in Figs. 11–13. To separate and present the independent effects of surface tension and viscosity, results are compared for liquids which are similar in one property, but differ markedly in the other. For example, by comparing the results obtained using Jet-A with those obtained with water (two liquids having similar viscosities, but differing surface tensions), the increase in SMD associated with an increase in liquid surface tension can be seen. Since surface tension is a measure of the consolidating forces which oppose the distortion and irregularity of the liquid surface which precedes liquid breakup, any increase in this property lessens the ability of the atomizing air to reduce the liquid to small drops, and a coarser spray results.

Figures 11 and 12 both show the independent influence of liquid viscosity on mean drop size for liquids having similar levels of surface tension. An increase in SMD due to increasing viscosity is clearly revealed. Since liquid viscosity forces enhance the dampening of disturbances in the liquid, they oppose breakup and result in a coarser spray. The adverse effect of an increase in surface tension on atomization quality is illustrated in Fig. 13.

An analysis of the drop size data showed that the dependence of mean drop size on liquid viscosity μ_L and surface tension σ conformed to the relationship SMD α $\mu_L^{0.09}$ $\sigma^{0.45}$. This finding is consistent with the results obtained from previous studies on prefilming airblast atomization, all of which showed only a slight dependence of mean drop size on liquid viscosity.

Conclusions

1) The results generally confirm those obtained by other investigators in regard to the beneficial effect on spray quality of increasing air velocity and air/liquid mass flow ratio and decreasing liquid surface tension and viscosity.

2) A substantial deterioration in spray quality is observed as the relative velocity approaches zero. The SMD increases to a maximum value at some critical value of relative velocity, and any further reduction in velocity results in the loss of the spray. This behavior suggests the existence of a threshold of relative velocity below which atomization is not possible for a given set of conditions.

3) The dependence of the SMD on initial liquid film thickness is weak for the atomizer employed in this investigation; this is especially true at higher air velocities. This is attributed to the airstreams impinging on the liquid sheet at a 30-deg angle and extruding the sheet between the two colliding

streams, thereby largely nullifying the influence of the initial sheet thickness.

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