Influence of Atomizer Design Features on Mean Drop Size

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Measurements of mean drop size, using the light-scattering technique, were carried out on eight different airblast atomizers. The liquids employed were water and kerosine. The test range included wide variations in atomizing air velocity, air pressure, and liquid and air flow rates, but the main objective was to examine the influence of scale and various design features on atomization performance. The results obtained show, for all types of airblast atomizer, that atomization quality is improved by increase in ambient air pressure, decrease in atomizer size, and by minimizing the angle of impact between the fuel jet and the high-velocity air stream.

Nomenclature

AFR = air/fuel ratio
D = exit diameter of air nozzle
L_c = characteristic dimension of atomizer
$\dot{m}_L$ = liquid flow rate
P_A = ambient air pressure
$\Delta P/P$ = pressure drop across atomizer
U_R = relative velocity between air and fuel
η = dynamic viscosity, kg/ms
ρ = density, kg/m^3
σ = surface tension, kg/s^2

Introduction

THE fuel injection process plays a major role in many key aspects of gas turbine performance. Furthermore, its influence seems likely to assume even greater importance in the future, since both aircraft and industrial engines will be called upon to burn a larger proportion of heavy distillate and synthetic fuels and, at the same time, satisfy fairly severe emissions regulations. Fuel injectors having multifuel capability will also be in increasing demand. To meet these changing needs the combustion engineer must be fully conversant with the capabilities and limitations of all the relevant fuel injection devices. In the present investigation attention is focused on airblast atomizers, since comparative studies have shown that they are superior to pressure atomizers and vaporizing systems in terms of lower pollutant emissions of nitric oxides and smoke.[1,2] They also provide a temperature distribution in the chamber efflux gases that is less susceptible to changes in combustor operating conditions and fuel type.

An essential feature of most of the airblast atomizers employed in gas turbine engines is the use of a prefilming surface to produce a thin, uniform sheet of liquid at the atomizing edge. To be fully effective, this system requires both sides of the liquid sheet to be exposed to the high-velocity air. This requirement introduces a complication in design, since it usually necessitates two separate airflows through the atomizer. For this reason the "plain-jet" airblast atomizer is sometimes preferred, in which the fuel is not transformed into a thin sheet but, instead, is injected into the airstream in the form of discrete jets. During the past few decades numerous experimental studies have been carried out on both types of airblast atomizer. The results of these investigations have been summarized elsewhere.[3] The primary purpose of the present work is to examine the effects of certain basic design features, such as scale and configuration, on atomization quality, for both plain-jet and prefilming types of airblast atomizer. This task is complicated by the fact that the concept of airblast atomization is so basically simple that the variety of potential nozzle configurations is almost infinite. Thus, in order to keep the scope of the work within reasonable bounds, it was decided to confine the number of atomizers investigated to two main categories: 1) those having certain design features which are considered basic to all present and future forms of airblast atomizer, and 2) those types which are currently installed in aircraft and industrial gas turbines. Even with this restriction the number of variables involved is still much larger than can be fully explored in a single investigation. However, it is hoped that the results presented herein will be of some interest and value to the combustion engineer.

Experimental

Most of the data reported here were obtained at Cranfield using air supplied from a fan at atmospheric pressure and room temperature. For the high-pressure tests the atomizer was mounted into a large cylindrical pressure vessel, as illustrated schematically in Fig. 1. A valve was fitted to this vessel which allowed tests to be conducted at pressures up to 1000 kPa. Air mass flow rates were measured using an orifice plate fitted with D and $D/2$ pressure tappings in accordance with British Standard (B.S.) 1042. The two main liquids employed were water ($\eta = 0.0010$, $\sigma = 0.0735$, $\rho = 1000$) and kerosine ($\eta = 0.00129$, $\sigma = 0.02767$, $\rho = 784$). Liquid flow rates were measured on precision flowmeters which had been calibrated previously for both water and kerosine at the flow rates employed.

Windows were fitted on diametrically opposite sides of the pressure vessel in order to provide optical access for measuring the Sauter mean diameter (SMD) of the fuel spray by the light-scattering technique, which is based on the forward scattering of a monochromatic beam of light resulting from its passage through a spray. This technique was first suggested by Dobbins et al.,[4] but was used here in its improved form, due to Lorenzetto.[5] Detailed information on the setting up procedures involved with the light-scattering technique are contained in Ref. 6.

Eight different atomizers were used in the investigation. Their basic design features and key dimensions are indicated in Fig. 2. Atomizers A and B represent the simplest form of

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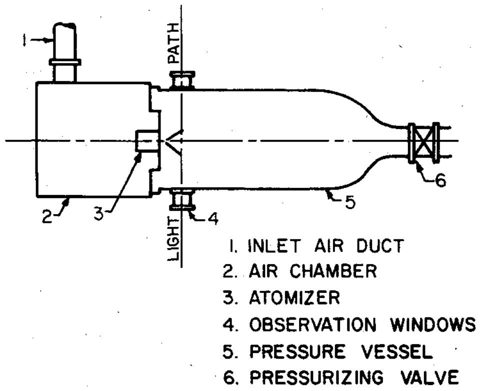

Fig. 1 Schematic diagram of test rig.

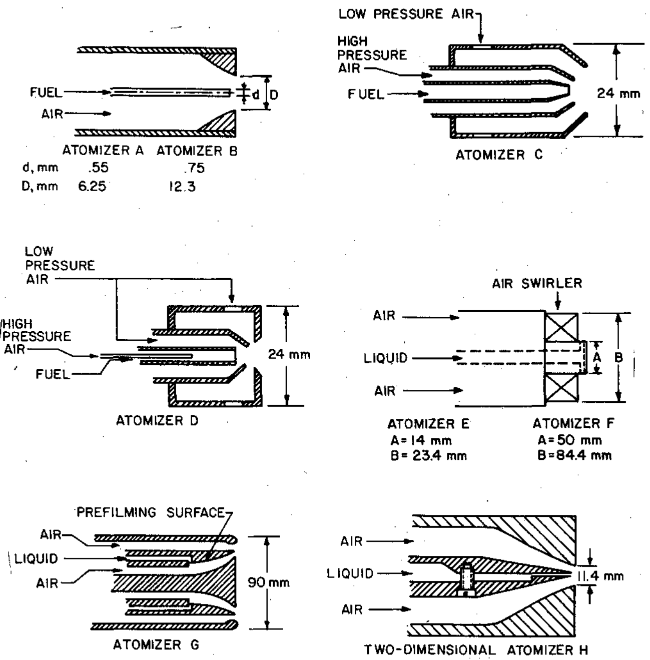

Fig. 2 Airblast atomizers used in test program.

plain-jet airblast atomizer, as first studied by Nukiyama and Tanasawa[7] and later by Lorenzetto and Lefebvre.[5] It comprises a round jet of liquid which is surrounded by a coaxial, coflowing airstream. The two atomizers A and B are geometrically similar, but one was made approximately twice the size of the other in order to investigate the effects of linear scale on mean drop size.

The basic difference between "airblast" and "air-assist" atomizers is that the former use large volumes of air flowing at relatively low velocity (usually $\not>100$ m/s), whereas the latter employ much higher air flow speeds (up to sonic velocity) to achieve good atomization with low air flow rates. The main drawback of the air-assist atomizer from a gas turbine viewpoint is that its use necessitates an external source of high-pressure air, which is clearly a major limitation for aircraft engines, although of less concern for industrial engines. Atomizers C and D are examples of a type of atomizer that can operate either as an airblast atomizer, or an air-assist atomizer, or in both modes simultaneously. With atomizer C the cylindrical stream of high-pressure air, and its surrounding, coflowing, annular sheet of low-pressure air, both impinge on the outer surface of the round liquid jet. However, with atomizer D the high-pressure air is injected directly into the fuel pipe at some distance upstream of the plane at which the fuel encounters the low-pressure air. Thus, atomizer D is essentially a plain-jet airblast atomizer in which

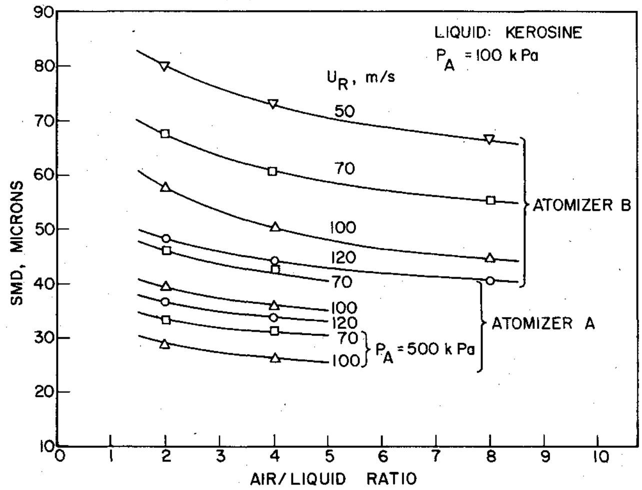

Fig. 3 Typical results obtained with atomizers A and B.

high-pressure air is used to achieve some degree of "pre-atomization" of the fuel.

Atomizers E and F represent a form of plain-jet atomizer that Jasuja[8,9] has studied in some detail. With this nozzle, the fuel flows through a number of radially-drilled holes, from which it emerges in the form of discrete jets which enter a swirling airstream. These jets then undergo in-flight disintegration without any further preparation.

Atomizer G is a prefilming airblast atomizer of the type that Lefebvre and colleagues have studied extensively at Cranfield.[10-14] In this design liquid flows through six equispaced tangential ports into a weir, from which it spills over the prefilming surface before being discharged at the atomizing lip. In order to subject both sides of the liquid to high-velocity air, two separate airflow paths are provided. One airstream flows through a central circular passage and is deflected radially outward by a pintle before striking the inner surface of the liquid sheet. The other airstream flows through an annular passage surrounding the main body of the atomizer. This passage has its minimum flow area in the plane of the atomizing lip in order to impart a high velocity to the air where it meets the outer surface of the liquid sheet.

Atomizer H is a "flat sheet" airblast atomizer that was designed by Rizk and Lefebvre[14] in order to investigate the effect of initial liquid film thickness on mean drop size. It is not a practical form of fuel nozzle, but it has considerable merit from a research viewpoint in that the initial liquid film thickness can be varied in a controlled manner and adjusted to any desired valve.

Results

Figure 3 shows some typical results obtained with atomizers A and B. In common with all previous studies, they demonstrate that atomization quality is improved by increases in ambient air pressure, atomizer air/fuel ratio, and air velocity. From these and many similar plots, it is found that mean drop size increases with linear scale according to the relationship

$$\mathrm{SMD} \alpha D^{0.5}$$

where D is the exit diameter of the air nozzle.

The results obtained with atomizers C and D are illustrated in Fig. 4. One striking feature of this figure is the marked superiority of atomizer C over atomizer D. At first sight this seems somewhat surprising in view of the fact that the two atomizers are identical in size and in fuel and air flow rates. However, with atomizer D the air strikes the fuel jet at a steep angle immediately it discharges from the fuel nozzle, whereas with atomizer C the air impacts the fuel jet some distance downstream of the discharge orifice, and at a much shallower

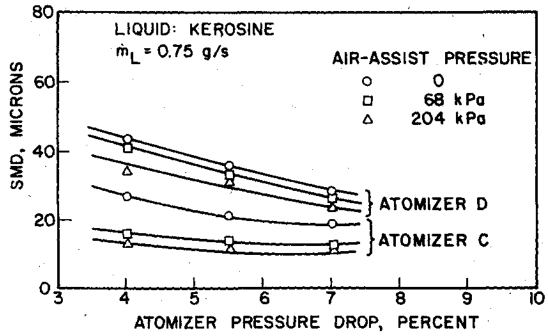

Fig. 4 Curves illustrating the beneficial effect of air-assist action on atomization quality.

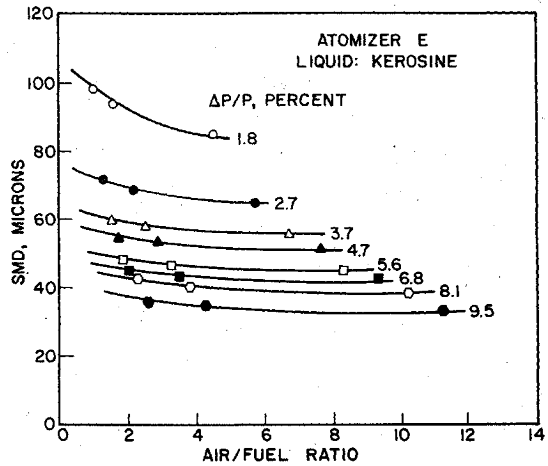

Fig. 5 Typical performance curves for transverse plain-jet airblast atomizer.

angle. It would appear, therefore, that in the design of plain-jet airblast atomizers it is advantageous to delay the exposure of the fuel jet to the high-velocity airstream until the processes of liquid jet instability and wave formation, which are the main factors governing the disintegration of the free jet, have attained some degree of completion.

Figure 4 also illustrates the beneficial effect of external high-pressure air (supplied in this instance from a high-pressure air bottle) on atomization quality. The enhanced air momentum provided by the "air-assist" air is clearly very effective in overcoming the consolidating forces exerted by surface tension and fuel viscosity.

The performance of the plain-jet atomizer E, in which the fuel is injected transversely across the air stream, is illustrated in Figs. 5 and 6 for kerosine and water, respectively. It may be noted that the water data exhibit higher values of SMD than the kerosine data due to the higher surface tension of water. In general, the results obtained with atomizer E confirm previous observations on the futility, from an atomization viewpoint, of increasing the air/liquid mass ratio above a value of around four to five.[6-14]

A comparison between the two plain-jet atomizers C and E, which are of comparable size, is presented in Figs. 7 and 8. For all test conditions it is observed that atomizer E is inferior to atomizer C. This is probably due to the fact, as discussed earlier, that with atomizer E the air impinges on the fuel jet immediately upon discharge from the orifice, and before the "natural" atomization of the free fuel jet has had a chance to develop, whereas with atomizer C the fuel jet is sheltered from the air stream in the initial portion of its trajectory. Figure 8 also demonstrates the improvement in atomization quality that accrues from decreasing atomizer size. Atomizers E and F are geometrically similar, but F is larger by a factor of 3.6. Analysis of the experimental data for this type of atomizer

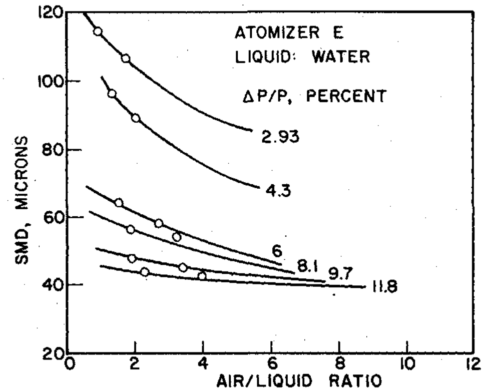

Fig. 6 Results obtained with transverse plain-jet atomizer for water.

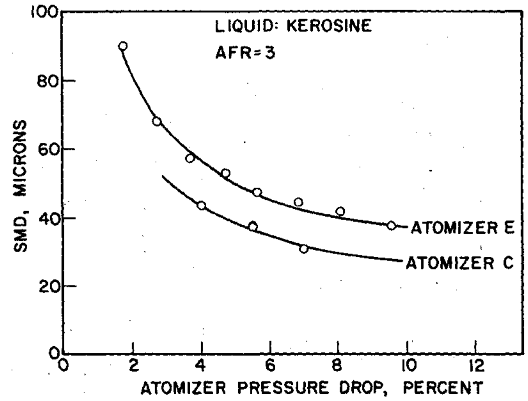

Fig. 7 Performance comparison of two plain-jet airblast atomizers.

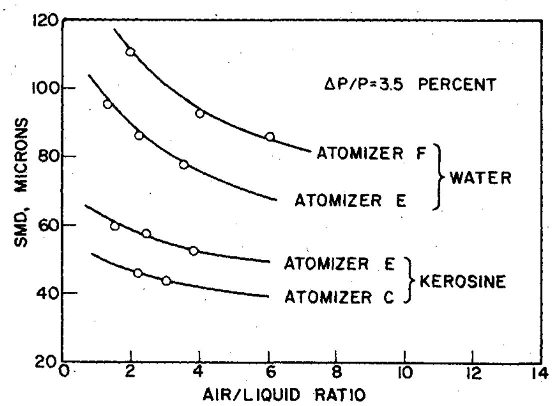

Fig. 8 Results on effect of atomizer scale (size) on atomization quality.

shows that

$$\mathrm{SMD} \alpha L_c^{0.2}$$

where L_c is the characteristic dimension of the atomizer. This exponent of 0.2 seems rather low in comparison to previously reported values of around 0.4 and 0.5 for "prefilming" and "coflowing plain-jet" airblast atomizers, respectively.[3] This low exponent may be due to the phenomenon discussed by Chin et al.,[15] whereby the fuel jet, regardless of its initial diameter, is flattened into a thin, fan-shaped, sheet by the transverse air flow, before disintegrating into ligaments and drops.

The influence of ambient air pressure on spray SMD is illustrated in Fig. 9. This figure shows results obtained with atomizer F when spraying water. Analysis of the data reveals

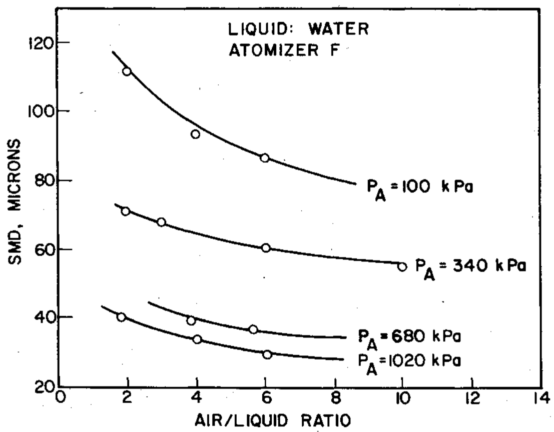

Fig. 9 Influence of ambient pressure on mean drop size.

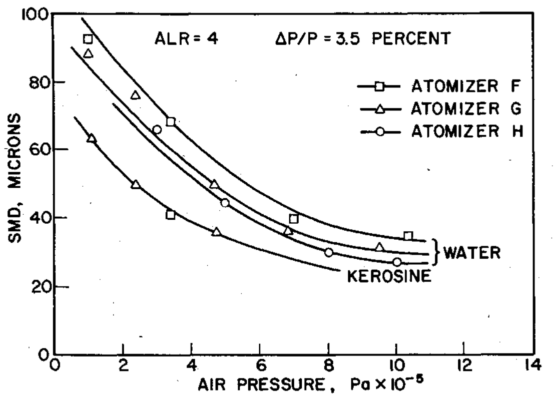

Fig. 10 Performance comparison of "plain-jet" and "prefilming" types of airblast atomizers.

that

$$SMD \alpha P_A^{-0.45}$$

which conforms exactly to the findings of Jasuja[9] for kerosine with the same type of atomizer.

Additional results on the effect of ambient pressure on spray SMD are provided in Fig. 10. This figure also illustrates the generally superior performance exhibited by the prefilming type of airblast atomizer over the plain-jet type. Best results were obtained with atomizer H, but this was to be expected since, with this design the initial film thickness can always be adjusted to provide any desired level of SMD. In fact, the only reason why this particular atomizer was included in the test program was to emphasize an important design requirement in all prefilming airblast atomizers, namely, that the initial liquid film thickness should be made as small as possible.

Conclusions

From a number of tests carried out on several plain-jet and prefilming types of airblast atomizer, the following conclusions are drawn.

1) For plain-jet airblast atomizers it appears advantageous to minimize the angle of impact between the liquid jet and the high-velocity airstream. Thus, the optimum arrangement appears to be one in which the liquid jet is surrounded by a coflowing, coaxial stream of air. It is also advantageous to shield the liquid jet from the atomizing air for a short distance downstream of the discharge orifice, in order to allow the natural jet instabilities to develop to an extent which greatly enhances the subsequent disintegration of the jet by the high-velocity air.

2) Small atomizers tend to yield small drop sizes. If $SMD \alpha L_c^x$, where L_c is a characteristic dimension of the atomizer, then for prefilming, coflowing plain-jet, and transverse plain-jet atomizers, appropriate values of x are 0.4, 0.5, and 0.2, respectively.

3) Increase in ambient air pressure reduces mean drop size. For airblast atomizers of the prefilming type, $SMD \alpha P_A^{-0.7}$. For plain-jet atomizers of the transverse type, $SMD \alpha P_A^{-0.45}$.

4) The results of this study generally reinforce previous observations in regard to the beneficial effect on atomization quality of increases in atomizer pressure drop ($\Delta P/P$), and in air/liquid ratio, up to a maximum value of around four to five.

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