Fuel Distributions from Pressure-Swirl Atomizers

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Measurements are made of the radial fuel distributions obtained with various types of pressure-swirl (simplex) atomizers, using a "patternator" which comprises 29 sampling tubes placed 4.5 deg apart on an arc of 10 cm. The patternator is mounted in a pressure vessel 10 cm below the fuel nozzle with the nozzle axis located at the center of curvature. The volume of fuel collected in each tube is proportional to the fuel flow at the sampling point. The results of tests performed over wide ranges of fuel injection pressure and ambient pressure show that spray angles diminish with increases in ambient gas pressure up to around 0.69 MPa (100 psia), above which they remain sensibly constant. Changes in the fuel injection pressure have differing effects on spray-cone angle depending on the ambient pressure. At normal atmospheric pressure an increase in fuel injection pressure causes the spray angle to first widen and then contract. At ambient pressures above around 2 atm the spray contracts continuously with increase in fuel injection pressure. Measurements of circumferential fuel distribution show that some nozzle designs possess a high degree of uniformity, while others exhibit significant deviations from the mean value.

Nomenclature

A_p = swirl-chamber inlet port area, m^2
D_s = swirl-chamber diameter, m
d_0 = discharge orifice diameter, m
P_A = ambient air pressure, MPa
ΔP_F = fuel injection pressure differential, MPa
ρ_A = air density, kg/m^3
ϕ_n = nominal spray angle, i.e., angle of spray silhouette measured at $\Delta P_F = 0.69$ MPa (100 psi) and $P_A = 0.101$ MPa (14.7 psia)
ϕ = equivalent spray angle, based on the angle between the centers of mass in the left- and right-hand lobes of the spray
ϕ_0 = equivalent spray angle measured at $\Delta P_F = 0.69$ MPa (100 psi) and $P_A = 0.101$ MPa (14.7 psia)

Introduction

AMONG all the various methods that have been devised for achieving liquid atomization, the pressure-swirl atomizer is probably the most widely used, having applications in broad areas of agricultural, chemical, and industrial engineering. Although plain-orifice atomizers have the virtue of simplicity, their narrow spray-cone angle (<10 deg) makes them impractical for use where a wide dispersion of droplets is required. Much wider cone angles are achieved in pressure-swirl atomizers, in which a swirling motion is imparted to the liquid so that, under the action of centrifugal force, it spreads out in the form of a hollow cone as soon as it leaves the orifice.

Most previous studies on the sprays produced by pressure-swirl atomizers have tended to concentrate on mean drop size (SMD) and drop-size distribution.[1-13] This is hardly surprising since mean drop size has been shown to strongly affect light-up performance, stability limits, idle combustion efficiency, and the emissions of unburned hydrocarbons and smoke.[2] With pressure-swirl atomizers the main soot-forming zone lies in the fuel-rich regions that are created inside the fuel spray just downstream of the nozzle. Clearly any feature that lowers the fuel concentration in this region will also reduce soot formation and smoke. Thus, a "hollow" spray, i.e., a spray in the form of a hollow cone of wide angle, with most of the drops concentrated at the periphery, will produce less soot than a "solid" spray in which the bulk of the drops are dispersed fairly evenly throughout the entire spray volume. It follows, therefore, that radial fuel distribution is a spray property of considerable significance. It should also be added that radial fuel distribution, or "equivalent spray angle," is important not only for its effects on soot formation and smoke but also because it has considerable influence on altitude relight performance and lean blowout limits. Generally it is found that reductions in spray-cone angle improve ignition performance and widen stability limits at the expense of increases in exhaust smoke concentrations. A major difficulty in the definition and measurement of cone angle is that the spray cone of a swirl atomizer has curved boundaries, due to the effects of air entrainment by the spray. To overcome this problem, the cone angle is often quoted as the angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at some specified distance from the atomizer face. A satisfactory method of measuring spray-cone angle is to project a silhouette of the spray onto a ground-glass screen at two or three magnifications. For simplex atomizers the spray-cone angle, as measured by this technique at normal room temperature and pressure, is governed mainly by the swirl-port area and the diameters of the swirl chamber and final orifice. Increases in the geometrical parameter $A_p/D_s d_0$ from 0.2 to 1.6 correspond to a reduction in spray-cone angle from 100 to 50 deg.

The effects of fuel-injection pressure and ambient pressure on spray angle for large-capacity simplex nozzles have been investigated by De Corso and Kemeny.[14] Their results show that, over a range of injection pressures from 1.7 to 2700 kPa and a range of gas pressures from 10 to 800 kPa, the spray-cone angle is an inverse function of $\Delta P_F e_A^{1.6}$. A similar study, carried out by Neya and Sato[15] on water sprayed into stagnant air, produced a similar result, namely, that spray contraction $\Delta\phi$ increases with $\Delta P_F e_A^{1.2}$. This "collapse" of spray-cone angle at high fuel flow rates and high ambient pressures is a primary cause of the soot formation and smoke associated with this type of nozzle.

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Table 1 Simplex atomizer characteristics

Simplex nozzle No.	Flow No., (lb/h)/$\sqrt{psi}$	Flow No., (kg/s)/$\sqrt{Pa - kg/m^3}$ $\times 10^6$	Nominal initial spray angle, ϕ_0, deg	Initial equivalent spray angle, ϕ_0, deg
1	1.134	0.0615	75	57
2	2.245	0.1218	82	66
3	1.43	0.078	90	65
4	1.43	0.078	30	27.5

Unfortunately, these studies were limited to ambient pressures below 1 MPa (10 atm). Moreover, little or no emphasis was placed on determining the circumferential distribution of fuel in the spray, although this clearly could have an important effect on many key aspects of combustion performance. For example, nonuniformities in circumferential fuel distribution could give rise to local pockets of fuel-weak mixture in which burning rates are low, thereby producing high concentrations of carbon monoxide and unburned hydrocarbons. By the same token, other regions of the spray in which the fuel concentration exceeds the mean value are characterized by high soot formation leading to excessive flame radiation and exhaust smoke. Irregularities in circumferential fuel distribution could also have an adverse effect on liner wall temperatures and combustor pattern factor.

A main objective of the present work is to extend the study on the influence of ambient pressure on radial fuel distribution and "equivalent" spray angle to higher levels of pressure that are more representative of modern gas turbines. Another objective is to examine the degree of uniformity of the circumferential fuel distribution exhibited by some typical commercial simplex nozzles.

To meet these goals a series of detailed measurements have been performed on four simplex nozzles that were selected to provide different values of flow number and spray-cone angle, as shown in Table 1.

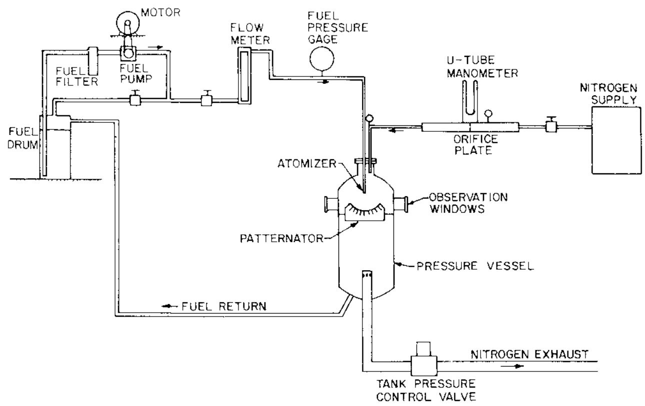

Fig. 1 Basic test facility.

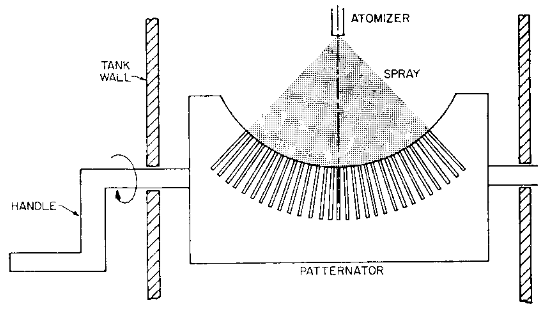

Fig. 2 Schematic diagram of patternator for measuring radial fuel distribution.

Experimental

The experimental facility employed in the measurement of fuel nozzle spray distributions is shown schematically in Fig. 1. It comprises a cylindrical pressure vessel designed to withstand pressures up to 2 MPa (20 atm). It is 120 cm long and 75 cm in diameter. Two Pyrex observation windows, 6.25 cm square, are fitted on opposite sides of the tank. Test nozzles are located centrally at the top of the cylinder and spray downward into the vessel which is pressurized to the desired level using gaseous nitrogen supplied from a large liquid-nitrogen storage evaporator system. Provision is made for each nozzle to be "clocked" on its axis at intervals of 22.5 deg in order to measure the circumferential distribution of fuel in the spray. Fuel is supplied to the nozzles from a centrifugal pump driven by an electric motor. The fuel flow rate is measured on a calibrated flowmeter.

The radial fuel distributions in the sprays are measured using a patternator supplied by the Parker-Hannifin Corporation of Cleveland, Ohio. The patternator is shown in Fig. 2. It is 1.27 cm wide and 31.75 cm long. The sampling tubes were formed by cutting slots into the opaque white plastic base over which a clear thin sheet of plastic is glued. The outer edges that form the openings to the tubes are filed to sharp edges so that each tube has a well-defined sampling area. The tubes are almost square in cross section, each tube having an area of 0.504 cm^2. There are a total of 29 sampling tubes, spaced 4.5 deg apart along a radius of curvature of 10 cm.

Before a spray sample is taken the patternator is inverted to drain away any fuel in the sampling tubes. The fuel flow rate is then adjusted until the nozzle is operating at the desired conditions. The patternator is rotated to the upright position, and the sampling tubes begin to fill. When one of the tubes is about three quarters full, the fuel supply is turned off and the patternator is rotated approximately 30 deg until a thin metal plate attached to the patternator blocks the fuel spray. This is necessary due to risk of fuel dribbling after the fuel pump is turned off.

Results

The volume of fuel in each tube is measured by visually locating the meniscus between lines scribed into the clear plastic of the patternator. Fuel distribution curves are made by plotting fuel volumes as the ordinate and corresponding angular location of the sampling tubes as the abscissa, as illustrated in Fig. 3. This type of plot is useful for determining how changes in the operating parameters affect the volume flow rate of fuel at individual locations in the spray. However, comparisons cannot be made between volume flow rates at different angular positions on the same curve. This is due to the fact that each sampling tube is the same size, so specific volumes are being measured. As the distance of the sampling tubes from the center of the spray increases, the proportion of the spray measured must diminish.

To overcome this problem each fuel volume is corrected using an "area weighting" factor. The "area weighting" factor is the total number of sampling tubes that would be needed to measure all of the fuel falling at a specified radial distance from the nozzle axis. The total amount of fuel in the spray is calculated by adding the corrected fuel volumes. The

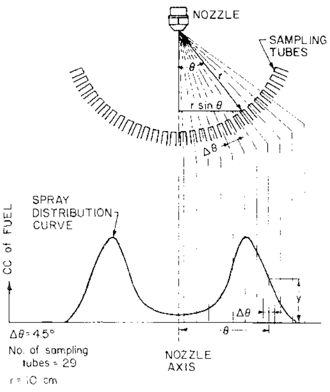

Fig. 3 Measurement of radial fuel distribution.

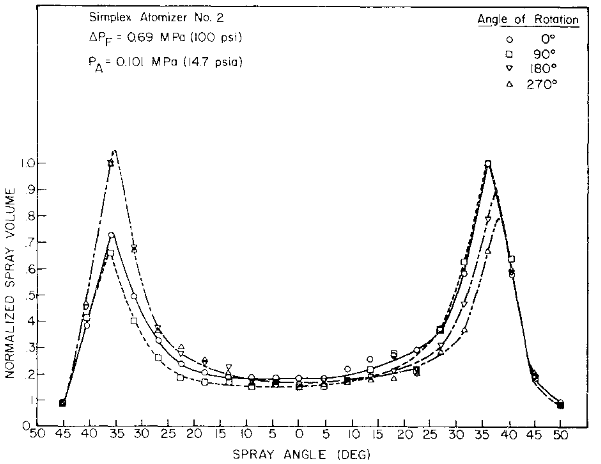

Fig. 4 Measurements of radial fuel distribution for $\Delta P_F = 0.69$ MPa and $P_A = 0.101$ MPa.

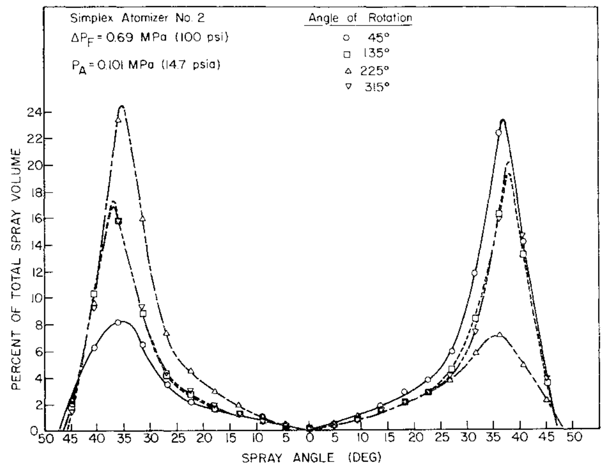

Fig. 5 Measurements of radial fuel distribution for $\Delta P_F = 0.69$ MPa and $P_A = 0.101$ MPa.

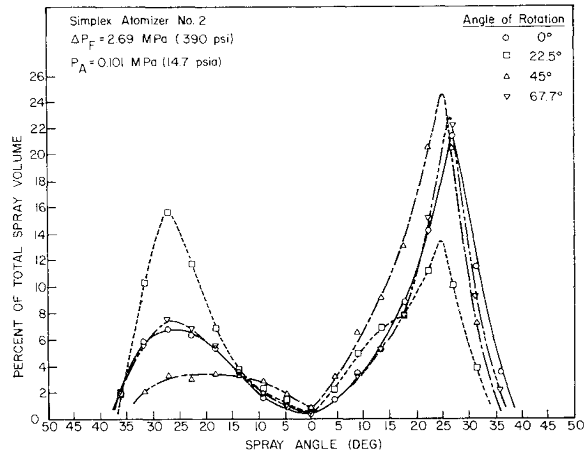

Fig. 6 Measurements of radial distribution for $\Delta P_F = 2.69$ MPa and $P_A = 0.101$ MPa.

percent of the total spray volume measured at each angular location is found by dividing the corrected volume by the total volume. A new fuel distribution curve can then be plotted which shows the relationship between volume flow rates at different angular locations.

In order to describe more succinctly the effect of changes in operating parameters on fuel distribution, the curves are reduced to a single numerical value called the "equivalent spray angle." The equivalent spray angle is the sum of two angles, $\phi = \phi_L + \phi_R$, which are calculated using the following equation:

$$\phi_L(\text{or } \phi_R) = \frac{\Sigma y\theta\Delta\theta\sin\theta}{\Sigma y\Delta\theta\sin\theta} = \frac{\Sigma y\theta\sin\theta}{\Sigma y\sin\theta}$$

L and R represent the left and right lobes of the fuel distribution curve respectively, θ is the angular location of the sampling tubes, $\Delta\theta$ the angle between the sampling tubes, and y the fuel volume measured at the corresponding tubes. The physical meaning of the equivalent spray angle is that ϕ_L (or ϕ_R) is the value of θ which corresponds to the position of the center of mass of a material system for the left-(or right-) hand lobe of the distribution curve.

For this study of spray characteristics it was decided to use the fuel of most relevance to turbojet engines, namely, standard aviation kerosine, having the following properties: density, 780 kg/m^3; surface tension, 0.0275 kg/s^2; and viscosity, 0.0013 kg/ms.

The simplex nozzles chosen included more than one manufacturer. For these nozzles it was found that spray quality, as expressed in terms of symmetry of radial fuel distribution and uniformity of circumferential fuel distribution, varied between different nozzles. These variations in performance are not caused by physical damage or errors in manufacture, but may be attributed directly to differences in nozzle design. The best nozzles exhibited excellent radial symmetry and circumferential fuel maldistributions of less than 10%. Other nozzles were less satisfactory, as illustrated in Figs. 4 and 5 in which eight radial fuel distributions obtained with No. 2 nozzle at normal atmospheric pressure are plotted at intervals of 45 deg to show both radial and circumferential fuel distributions. From inspection of these figures it is apparent that some nonuniformities are present. These maldistributions are also evident at other levels of fuel injection pressure and ambient gas pressure, as illustrated in Figs. 6 and 7. However, it is of interest to note that if a particular spray diameter is chosen along which the spray is reasonably symmetrical, it may not remain so with variations in fuel injection pressure.

The effect of fuel injection pressure on the equivalent spray angle is shown in Figs. 8 and 9. Figure 9 shows that starting from atmospheric pressure increases in fuel pressure cause the spray to widen and then contract. This phenomenon was also observed by Neya and Sato[15] but not by De Corso and Kemeny,[14] so presumably it is a function of nozzle design.

Following the initial increase in spray-cone angle (which occurs only with sprays injected into air at normal atmospheric pressure), further increases in fuel pressure cause the spray to contract continuously until a minimal spray angle is reached at which further increases in fuel injection pressure produce no discernible effect on spray angle.

Figures 10 and 11 show the influence of ambient gas pressure on equivalent spray angle. Initially, an increase in gas pressure above normal atmospheric pressure causes the spray to contract sharply. However, with continuing increases in gas pressure the rate of spray contraction decreases. Finally, a point is reached where further increases in ambient pressure have virtually no influence on the equivalent spray angle.

Discussion

The results obtained on the effects of fuel injection pressure and ambient gas pressure on equivalent spray angle are in close agreement with the findings of De Corso and Kemeny[14] over the range of test conditions covered in their experiments. This is demonstrated in Fig. 12 in which ϕ/ϕ_0 is shown plotted as a function of $\Delta P_F e_A^{1.6}$. [Note that ϕ is the measured equivalent spray angle, and ϕ_0 is the value of ϕ obtained at normal atmospheric pressure and a fuel injection pressure differential of 0.69 MPa (100 psi).] In Fig. 12 the results of the present investigation are superimposed on a curve which represents the average values of the ϕ/ϕ_0 points obtained by De Corso and Kemeny. The level of agreement between the two sets of data is clearly quite good. Although the data points for one nozzle lie well above the curve, it

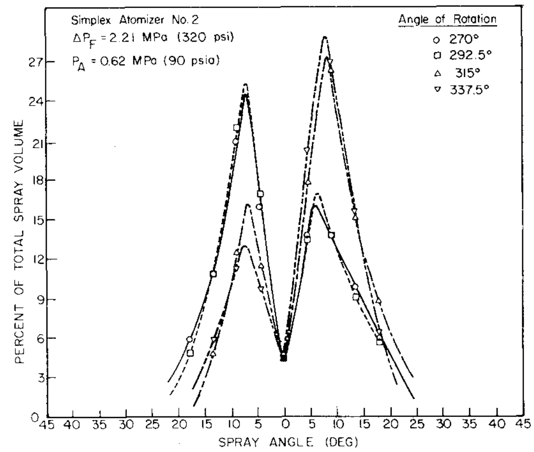

Fig. 7 Measurements of radial distribution for $\Delta P_F = 2.21$ MPa and $P_A = 0.61$ MPa.

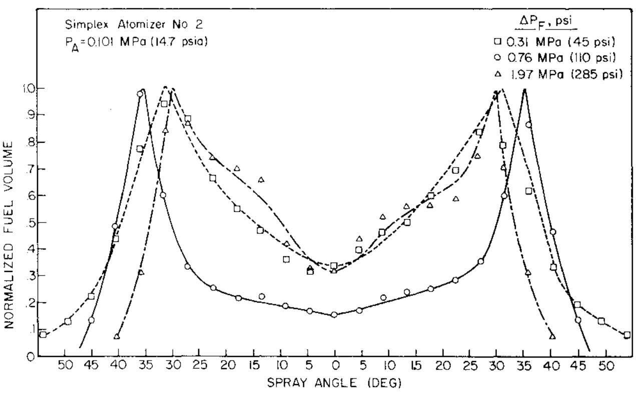

Fig. 8 Influence of fuel injection pressure on radial fuel distribution.

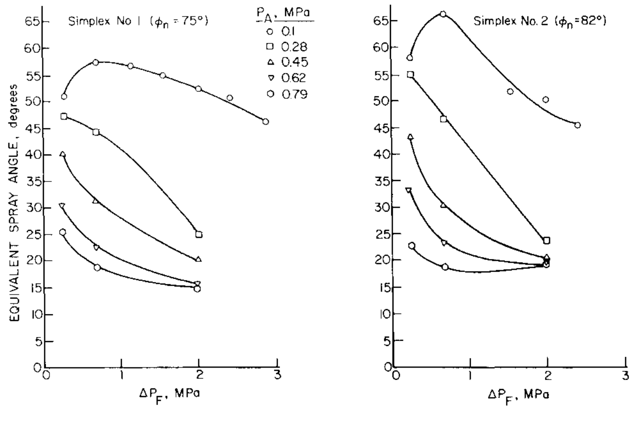

Fig. 9 Influence of full injection pressure on equivalent spray angle.

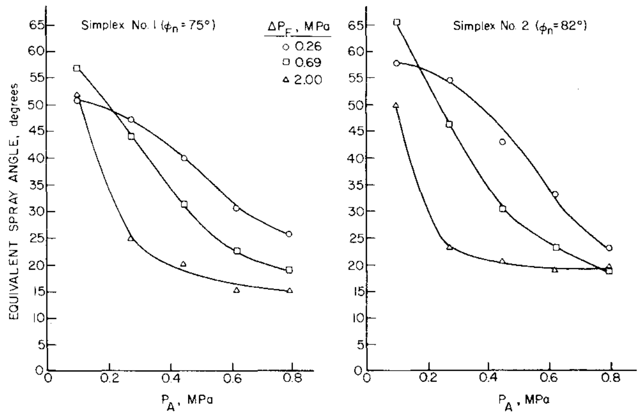

Fig. 10 Influence of ambient gas pressure on equivalent spray angle for simplex atomizers 1 and 2.

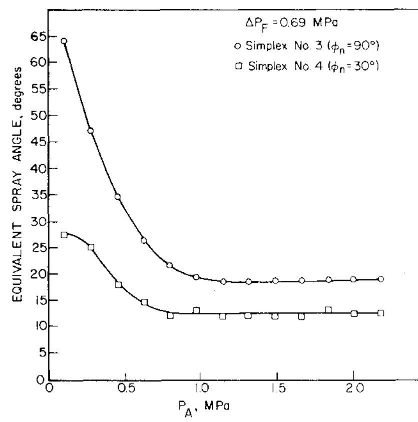

Fig. 11 Influence of ambient gas pressure on equivalent spray angle for simplex atomizer 3 and 4.

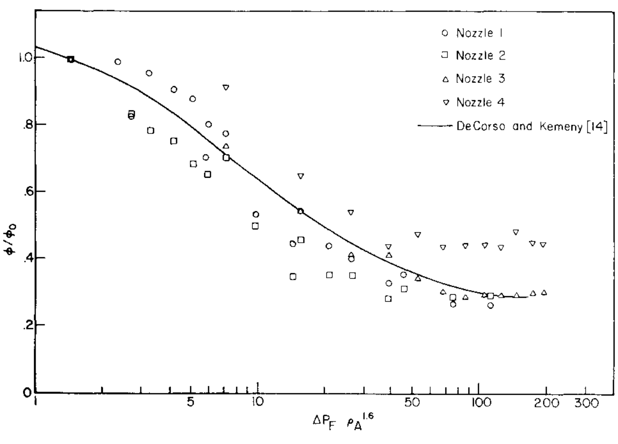

Fig. 12 Comparison of experimental data with results of Ref. 14.

should be noted that for this nozzle ϕ_0 is only 27 deg. Such a small cone angle is of little interest for gas turbine applications and is certainly outside the range of values of ϕ_0 employed in the experiments of De Corso and Kemeny. Thus, Fig. 12 should be regarded as constituting general confirmation of their findings.

According to De Corso and Kemeny,[14] the phenomenon of decreasing spray angle is caused by the aerodynamic effects due to the motion of the fuel spray through the ambient gas. The fuel emerging from the nozzle at high velocity entrains gas at the inner and outer surfaces of the spray "sheath." However, the gas supply to the inner portion of the spray sheath is limited by the enclosed volume in the sheath. The pressure difference resulting from this effect sets up airflows that produce droplet acceleration toward the nozzle axis, thereby reducing the effective spray angle. Clearly this pressure differential will increase with a reduction in spray angle due to shrinkage of the gas volume enclosed within the spray. However, with increasing gas pressure a condition eventually will be reached where the spray-cone angle is so small that any additional increases in gas pressure will produce no further reduction in ϕ. This is illustrated in Fig. 11, which shows that spray-cone angles remain constant at their minimum value at gas pressures above around 1 MPa.

The results of measurements of the circumferential fuel distributions produced by simplex atomizers show that significant maldistributions can occur with some nozzles over wide ranges of operating conditions. Clearly this could be of relevance to combustor design and performance, and also to the mathematical modeling of spray combustion where the normal procedure is to assume a symmetrical spray of uniform circumferential distribution. It is recommended that research be initiated to ascertain which geometrical design features of simplex nozzles are most determining to spray uniformity. This could lead to the establishment of simple procedures for achieving satisfactory spray uniformity—the kind that currently exists for securing any desired value of nominal spray-cone angle.

Acknowledgment

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