Spray Characteristics of Spill-Return Atomizers

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The spray characteristics of three spill-return atomizers are studied by inserting each nozzle into a cylindrical vessel which is pressurized to the desired level using gaseous nitrogen supplied from a large liquid nitrogen storage/evaporation system. The nozzle under test is located centrally at the top of the cylinder and sprays downward into the vessel. Two diametrically opposite windows are fitted to the cylinder which allow mean drop sizes in the spray to be measured using a light-scattering technique. The apparatus is used to study the effects of spill fuel fraction, fuel-injection pressure, ambient gas pressure, and nozzle flow number on mean drop size. The results show that the influence of spill fuel fraction on spray quality is small. They also indicate that spray quality may improve or decline with increases in ambient gas pressure depending on the initial spray angle. If this is larger than around 75 deg, spray quality improves with increases in gas pressure. For initial spray angles smaller than around 65 deg spray quality declines with increase in gas pressure. The extent to which a change in fuel injection pressure affects mean drop size is also found to depend on initial spray angle. An explanation for these phenomena is provided. Measurements to determine the influence of nozzle flow number (FN) on mean drop size (SMD) show that SMD $\propto$ FN$^{0.25}$.

Nomenclature

FN	= nozzle flow number
FN_1	= flow number based on SI units (kg/s)/(Pa. kg/m^3)$^{0.5}$
FN_2	= flow number in conventional units (lb/hr)/(psi)$^{0.5}$
$\dot{m}_{F_{spill}}$	= spill fuel flow rate, kg/s
$\dot{m}_{F_{total}}$	= total fuel flow rate to nozzle, kg/s
P_A	= ambient air pressure, Pa
ΔP_F	= fuel-injection pressure differential, Pa
μ	= fuel viscosity, kg/ms
ρ	= fuel density, kg/m^3
σ	= surface tension, kg/s^2

Introduction

THE spill-return or spill atomizer is basically a simplex swirl atomizer with one important difference: the rear wall of the swirl chamber, instead of being solid, contains a passage through which fuel can be "spilled" away from the atomizer, as shown in Fig. 1. Its basic features have been described by Joyce[1] and Carey.[2] Fuel is supplied to the swirl chamber at high pressure and high flow rate. The fraction of fuel injected into the combustion zone is varied and controlled by a valve located in the spill-return line. As the fuel demand decreases with an increase in altitude or a reduction in engine speed, more fuel is spilled away from the swirl chamber, leaving less to pass through the atomizing orifice. The spill atomizer's constant use of a relatively high pressure means that even at extremely low fuel flows there is adequate swirl to provide efficient atomization of the fuel. According to Carey,[2] satisfactory atomization can be achieved even when the fuel flow rate is as low as 1% of its maximum value and, in general, the tendency is for atomization quality to improve as the fuel flow is reduced.

A most useful characteristic of the spill-return atomizer is the wide range of fuel flows over which atomization quality is high. Joyce[1] has stated that a flow range of 20 to 1 can be attained by spill control alone, using a constant supply pressure. If pressure is also varied over a range of 25 to 1, then a flow range of 100 to 1 can be readily achieved. Other attractive features include an absence of moving parts and, because the flow passages are designed to handle large flows, freedom from blockage by contaminants in the fuel.

A disadvantage of the spill-return atomizer is its alleged large variation in spray angle with changes in fuel flow rate. Other disadvantages are: 1) problems of metering the fuel are more complicated than with other types of atomizers, and 2) a larger-capacity pump is needed to handle the large recirculating flows. For these reasons, interest in the spill-return atomizer has declined in recent years. However, if the aromatic content of gas-turbine fuels continues to increase, serious problems could arise due to blockage, by gum formation, of the fine passages of conventional pressure atomizers. The spill atomizer, having no small passages, is virtually free of this defect. This fact and its excellent atomizing capability make it attractive for use with the various alternative fuels now being actively considered for gas-turbine applications, most of which have high aromaticity, high viscosity, and low volatility.

Experimental

The apparatus for studying spray characteristics is shown schematically in Fig. 1. The main component is a cylindrical pressure vessel mounted on a stand with its axis in the vertical position. It is 120 cm long and 75 cm in dia. 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. 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. The droplets produced by atomization gravitate into a collection tank at the bottom of the chamber, from which the fuel is returned to the storage tank. The objective is to conserve fuel and to avoid potential pollution arising from the escape of fuel droplets into the atmosphere.

Two extra nitrogen lines are connected to the tank. One line is used to protect the windows from any contamination by fuel drops or mist, while the other line is connected to a manifold located at the top of the tank which provides a gentle down-

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draft of nitrogen through a large number of holes. By this means the problem of droplet recirculation is kept to a minimum.

Spray characteristics are measured using an extended form of light-scattering technique whereby the light-intensity profile generated by a monochromatic beam of light is analyzed after passage through the spray to determine both mean drop size (SMD) and drop-size distribution.[3,4] This technique has been very widely used [Refs. 3-7] and is considered to be among the most accurate available. However, it is important not to attempt measurements of mean drop size and drop-size distribution too close to the nozzle for the following reason. Although all the drops leave the nozzle with approximately the same velocity, because of air resistance the smaller drops tend to lose momentum faster than the larger drops. This may lead to overpresentation of the fine drops in the sampling volume. Further away from the nozzle, where all the drops are moving at roughly the same velocity as the downdraft of nitrogen, the measurements indicate larger values of SMD which are more representative of the actual spray.

The fuel chosen for this study is a light aviation kerosine. Its physical properties relevant to atomization are:

$$\mu = 0.00129 \text{ kg/ms},\ \sigma = 0.0275 \text{ kg/s}^2,\ \rho = 780 \text{ kg/m}^3$$

A cross-sectional schematic drawing of the type of simplex swirl atomizer employed in this study is shown in Fig. 1. Three geometrically similar atomizers were used, having flow numbers (FN) of 0.076×10^{-6}, 0.114×10^{-6}, and 0.152×10^{-6}, where flow number is defined as

$$FN_I = \frac{\text{fuel flow rate, kg/s}}{[(\text{fuel pressure drop, Pa})(\text{fuel density, kg/m}^3)]^{1/2}} \quad (1)$$

This definition of flow number, in SI units, defines the effective flow area of the nozzle in m^2. In the past the most widely used definition of flow number has been

$$FN_2 = \frac{\text{fuel flow rate, lb/hr}}{(\text{fuel pressure drop, psi})^{1/2}} \quad (2)$$

It can readily be shown that

$$FN_2 = 0.66\times10^6 \times \sqrt{\rho_F} \times FN_I \quad (3)$$

In the following text, flow numbers will be quoted in SI units with FN_2 shown alongside in brackets.

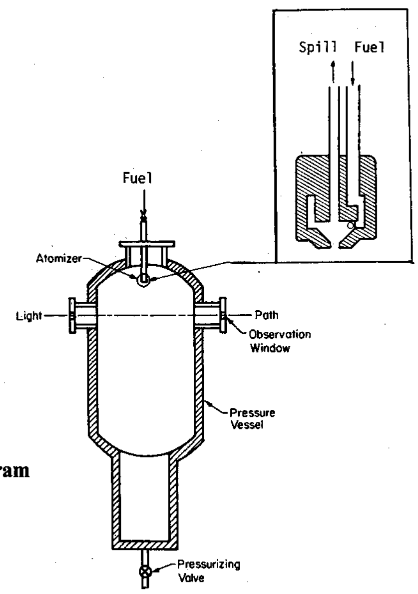

Fig. 1 Schematic diagram of test rig.

Results

The results obtained on the influence of spill fuel flow on mean drop size are illustrated in Figs. 2-4. Figures 2 and 3 show plots of SMD vs the fraction of spill fuel for several different values of fuel-injection pressure. The ambient air pressures in Figs. 2 and 3 are 100 kPa and 300 kPa, respectively. It is clear from these figures that the effect of spill fuel on mean drop size is quite small. Similar results are shown in Fig. 4 in

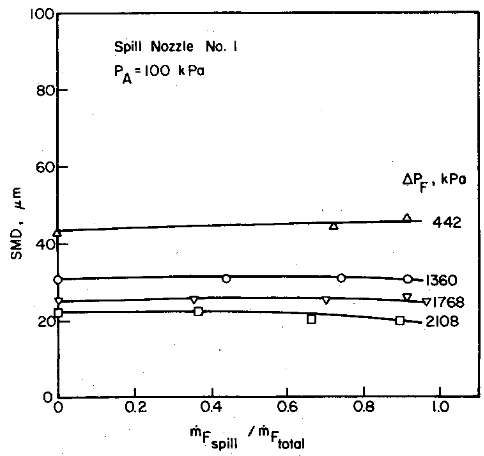

Fig. 2 Influence of spill fuel fraction on mean drop size for nozzle 1 at different fuel-injection pressures.

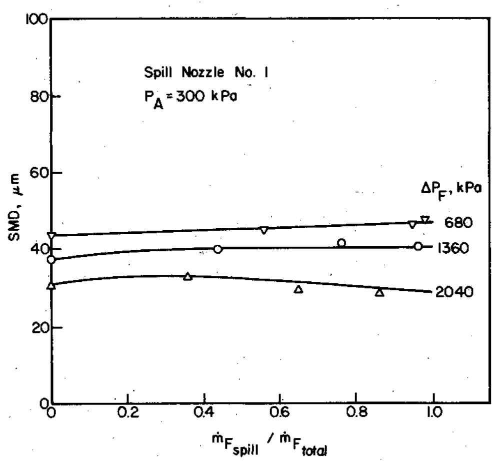

Fig. 3 Influence of spill fuel fraction on mean drop size for nozzle 1 at higher ambient air pressures.

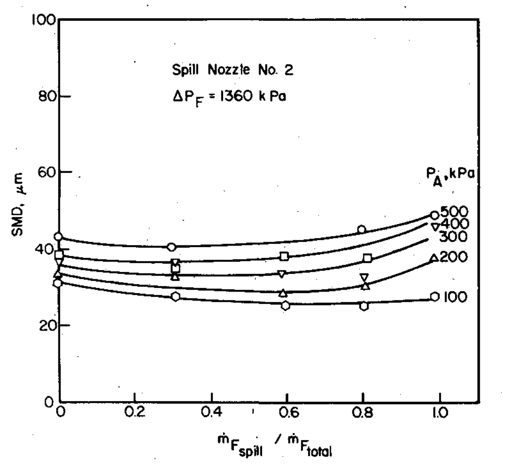

Fig. 4 Influence of spill fuel fraction on mean drop size for nozzle 2 at various levels of ambient air pressure.

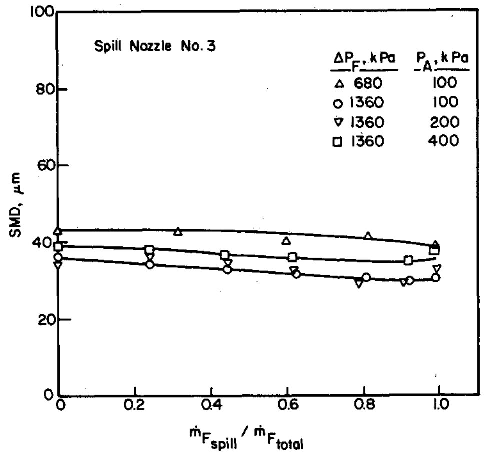

Fig. 5 Influence of spill fuel fraction on mean drop size for nozzle 3 at various levels of ambient air pressure.

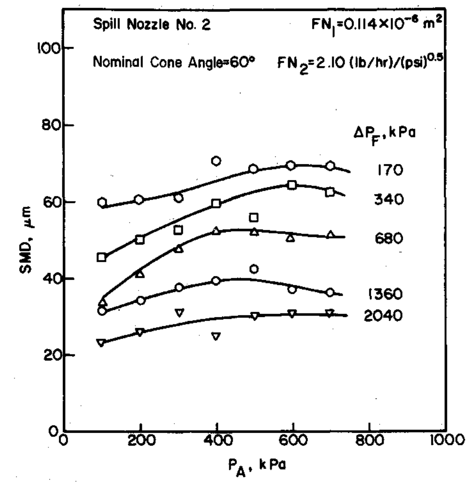

Fig. 7 Influence of air pressure and fuel-injection pressure on mean drop size for nozzle 2.

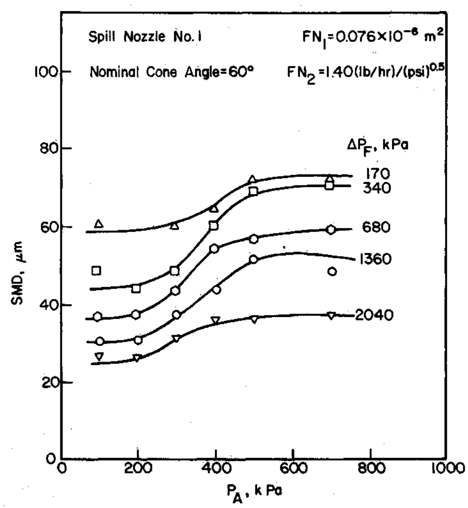

Fig. 6 Influence of air pressure and fuel-injection pressure on mean drop size for nozzle 1.

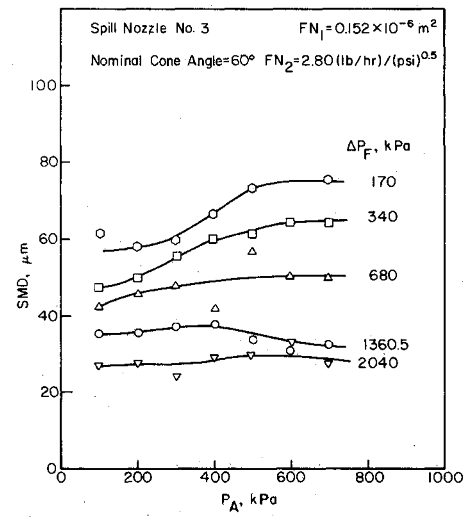

Fig. 8 Influence of air pressure and fuel-injection pressure on mean drop size for nozzle 3.

which measured values of SMD are plotted against spill fuel fraction for several values of ambient air pressure. The influence of spill fuel fraction on SMD is again small, but inspection of the figure shows that SMD decreases slightly with increasing fuel spill at low air pressures, around normal atmospheric, and increases slightly with increasing fuel spill at higher air pressures. The data obtained for nozzle 3 on the effect of spill fuel on SMD at various levels of ambient air pressure and fuel-injection pressure are shown in Fig. 5. The results confirm those obtained with the other two nozzles in showing that, provided the fuel-injection pressure is maintained constant, the mean drop size is sensibly independent of spill fuel fraction.

The influence of ambient air pressure on mean drop size is shown in Figs. 6, 7, and 8, and nozzles, 1, 2, and 3, respectively. All the data used to construct these figures were obtained with the spill line closed, but similar plots for finite spill fractions exhibit very similar results. The most striking feature of these figures is that for all nozzles, and all levels of fuel-injection pressure, the spray quality declines with increases in ambient air pressure. This result is in marked contrast to the authors' previous findings for simplex nozzles,[8] which showed that SMD declines as the ambient air pressure is increased. Further investigation revealed that the reason for this anomaly lies in the exceptionally small spray cone angle of the three spill nozzles tested, which was 60 deg in all cases. Measurements of spray cone angle at various levels of air pressure showed that spray angle contracts sharply with increase in ambient air pressure. This is illustrated for nozzle 1 in Fig. 9, which is also representative of the results obtained with the other two nozzles.

Contraction of the spray angle reduces the volume of air that interacts with the spray. In consequence the aerodynamic drag forces created by the spray induce a more rapid acceleration of this smaller air mass in the direction of spray motion, thereby reducing the relative velocity between the fuel drops and the air surrounding these drops. As mean drop size is inversely proportional to this relative velocity, the effect of a reduction in spray angle is to increase mean drop size. Thus an increase in ambient air pressure has two opposing effects on SMD. Contraction of the spray angle tends to increase the mean drop size as discussed above. However, at higher air pressures the more densely packed air molecules greatly accelerate the processes whereby the liquid sheet emerging from the nozzle disintegrates into drops, thereby producing smaller drops. Which of these two opposing influences is most dominant in any given situation depends on the "nominal" cone angle of the spray. If the nominal cone angle, i.e., the cone angle of the spray silhouette as measured for a fuel-injection pressure of 0.69 MPa (100 psi) and an ambient air pressure of 0.101 MPa (14.7 psia), is wide—say, 75 deg or larger—the effect of increasing air density will outweigh that of reduced

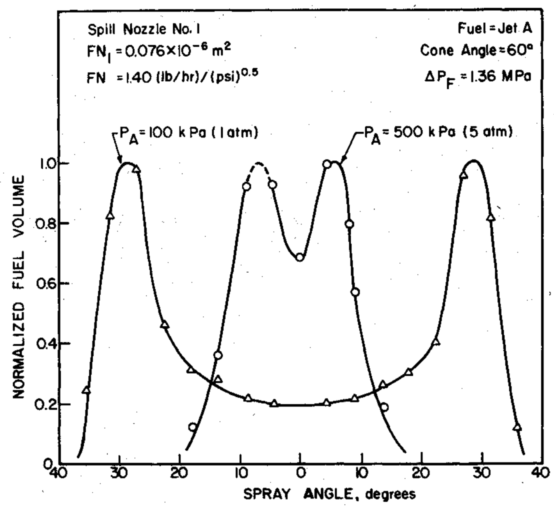

Fig. 9 Effect of ambient air pressure on radial fuel distribution.

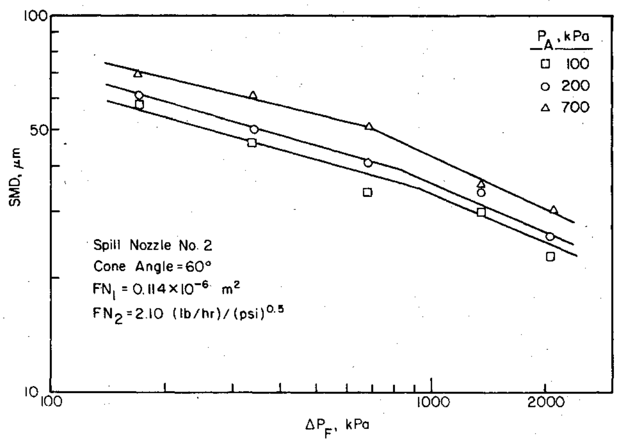

Fig. 10 Logarithmic plot of mean drop size vs fuel-injection pressure for nozzle 2.

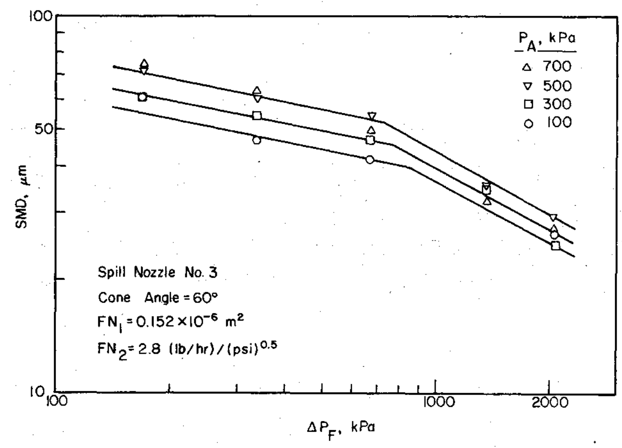

Fig. 11 Logarithmic plot of mean drop size vs fuel-injection pressure for nozzle 3.

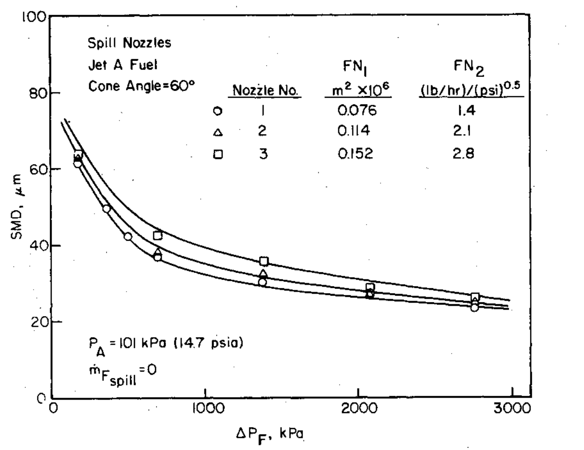

Fig. 12 Effects of nozzle flow number and fuel-injection pressure on mean drop size.

spray angle and the net result will be a decrease in mean drop size.[8] However, if the initial spray angle is small—say, less than around 65 deg—the further reduction in spray angle brought about by an increase in ambient air pressure, as illustrated in Fig. 9, leads to an increase in mean drop size. As stated above, this increase in SMD is caused partly by the reduction in the mass of air that interacts with the spray, and also by the decrease in relative velocity between the fuel drops and the surrounding air.

Figures 10 and 11, which contain logarithmic plots of SMD vs ΔP_F for nozzles 2 and 3, respectively, show that in the relationship SMD $\propto \Delta P_F^{-x}$, the value of x is not constant but is higher at higher levels of fuel-injection pressure. For values of ΔP_F below around 0.8 MPa (8 atm), $x \simeq 0.25$; for higher values of ΔP_F, $x \simeq 0.5$. This agrees exactly with the result obtained in a previous study on simplex nozzles.[8]

An explanation for the sudden change in the slopes of the curves of $\ln$ SMD vs $\ln \Delta P_F$, as shown in Figs. 10 and 11, may be found in the spray contraction that occurs with increases in ΔP_F or P_A. It is well known that increases in fuel-injection pressure improve atomization quality, but initially this reduction in SMD is partly offset by the spray contraction that accompanies an increase in ΔP_F and that tends to impair atomization, as discussed above. However, as shown by Ortman and Lefebvre,[9] above a certain value of ΔP_F, which depends on the initial spray angle, the spray contraction ceases and thereafter the spray angle remains constant and sensibly independent of ΔP_F. Beyond this critical value of ΔP_F, the spray continues to receive the beneficial effect on atomization of increasing ΔP_F but is no longer subjected to the adverse effect of atomization caused by a reduction in spray angle. Thus logarithmic plots of SMD vs ΔP_F are characterized by a shallow slope, i.e., a low value of x, when ΔP_F is low, and a steeper slope and a higher value of x, when ΔP_F is high.

Ortman and Lefebvre[9] also demonstrated that the effect of increasing ambient air pressure on spray angle is exactly the same as increasing ΔP_F. The spray angle first contracts and then stabilizes at a constant narrow angle. Since for wide-angle sprays (>75 deg) an increase in P_A acts exactly like an increase in ΔP_F in improving atomization quality, one would expect that logarithmic plots of SMD against P_A should exhibit the same characteristics as the plots described above for $\ln$ SMD vs $\ln \Delta P_F$, namely, a shallow slope at low values of P_A where the spray angle is contracting, and a steeper slope at the higher values of P_A where the spray angle is constant. This, in fact, is precisely the result obtained by Rizk and Lefebvre.[8]

The influence of nozzle flow number on mean drop size is illustrated in Fig. 12. Analysis of the data contained in the figure reveals that SMD $\propto$ FN$^{0.25}$ which also agrees exactly with the findings of Ref. 8.

Conclusions

From analysis of the experimental data obtained in the present investigation, along with similar results from recent studies on simplex atomizers, the following conclusions are drawn:

1) Provided the fuel-injection pressure is maintained constant, the influence of spill fuel fraction on mean drop size is quite small.

2) Whether or not spray quality declines or improves with increase in ambient air pressure depends upon the relative magnitude of two opposing forces, of which one, increasing air density, tends to improve atomization, while the other, which is caused by the decline in spray angle that accompanies an increase in ambient air pressure, tends to impair atomization. For fuel nozzles designed for high spray angles (>75 deg) the beneficial effect of an increase in air density outweighs the adverse effect of a lower spray angle, and atomization quality thus improves with increase in ambient air pressure. However, for fuel nozzles of low initial spray angle (<75 deg) the opposite is true and spray quality declines with increase in air pressure.

3) The dependence of mean drop size on fuel-injection pressure can be expressed by the relationship SMD $\propto \Delta P_F^{-0.25}$ for values of ΔP_F below around 0.8 MPa (8 atm) and by SMD $\propto \Delta P_F^{-0.5}$ at higher levels of fuel-injection pressure.

4) Increases in fuel-injection pressure lead to reductions in spray angle. However, if ΔP_F is increased continuously, a minimum spray angle is eventually reached beyond which any further increase in ΔP_F has no influence on spray angle. This critical value of ΔP_F, at which the spray angle attains its miminum value, corresponds to the point on a plot of $\ln$ SMD vs $\ln \Delta P_F$ at which the slope changes from -0.25 to -0.5.

5) The influence of nozzle flow number on mean drop size conforms to the relationship SMD $\propto$ FN$^{0.25}$. This finding confirms the results of recent studies on the spray characteristics of simplex swirl atomizers.

Acknowledgments

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