Mean Drop Sizes from Pressure-Swirl Nozzles

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A study of the factors governing the atomization process in pressure-swirl nozzles is presented. Extensive measurements of mean drop size are conducted on six simplex nozzles of different sizes and spray-cone angles. The liquids employed are water, diesel oil, and several blends of diesel oil with polybutene. These liquids provide a range of viscosity from 3 to 18×10^{-6} m^2/s (3–18 cs), and a range of surface tension from 0.027 to 0.0734 kg/s^2 (27–73.4 dyne/cm). The results are used to substantiate an equation for mean drop size derived from basic considerations of the hydrodynamic and aerodynamic processes that govern the atomization processes in pressure-swirl nozzles. A very satisfactory correlation is demonstrated between predictions based on this equation and the actual measured values of mean drop size.

Nomenclature

A,B = constants, Eq. (16)
A_a = air core area, m^2
A_o = discharge orifice area, m^2
A_p = swirl chamber port area, m^2
D_s = swirl chamber diameter, m
d_o = liquid orifice diameter, m
$\dot{m}$ = mass flow rate, kg/s
P = pressure, Pa
ΔP = pressure differential, Pa
Re = Reynolds number
SMD = Sauter mean diameter, m
t = film thickness in final orifice, m
t_s = liquid sheet thickness after exit from nozzle, m
U = velocity, m/s
We = Weber number
X = A_a/A_o
θ = spray cone half-angle, deg
μ = dynamic viscosity, kg/ms
ν = kinematic viscosity, m^2/s
ρ = density, kg/m^3
σ = surface tension, kg/s^2

Subscripts

A = air
F = fuel
L = liquid
R = air relative to liquid

Introduction

MANY processes within the combustion, agricultural, and chemical engineering industries rely on the rapid dispersion of liquids into a gaseous medium. For example, the hydrocarbon fuels used in combustion systems are normally of relatively low volatility, and could not generate vapor in the amounts required for easy ignition and efficient combustion without the very large increase in surface area provided by atomization.

A widely used form of atomizer is the pressure-swirl nozzle which, for most applications, is designed to produce a hollow-cone spray. Its advantages include simplicity of construction, reliability, good atomization, and low pumping power requirements. In this nozzle, the liquid is fed into a swirl chamber through a number of helical or tangential passages that impart to the liquid a high angular velocity which creates an air-cored vortex. The liquid then emerges through the final orifice with both tangential and axial components, thereby producing a hollow conical sheet which rapidly disintegrates into ligaments and then drops.

Due to its wide range of applications, the pressure-swirl atomizer has attracted the attention of many research workers and has been the subject of considerable theoretical and experimental studies. However, despite these efforts, our knowledge of pressure-swirl atomization is still unsatisfactory. The physics is not well understood, the available data and correlations are of questionable validity, and there is little agreement between previous workers as to the exact relationships between liquid properties, nozzle dimensions, and mean drop size. This unsatisfactory situation is due to several causes: the great complexity of the atomization process; differences in the design, size, and operating conditions of the nozzles tested; and the inaccuracies and limitations associated with drop-size measurement techniques.

The advent of laser diagnostics has led to serveral new techniques for line-of-sight and local point measurements in sprays. One of the most convenient and reliable instruments for examining the global characteristics of sprays is the Malvern particle analyzer. This instrument is based on the Fraunhofer diffraction theory of a collimated laser beam scattered by moving drops. The widespread use of this instrument has led to significant improvements in drop-size measurements. However, Hirleman et al.[1] and Dodge[2] have exposed some of the limitations of the instrument while several workers have indicated that the variation in mean drop size and size distribution can be strongly influenced by the effects of drop acceleration and deceleration.[3,4]

The Combustion Laboratory at Purdue University is engaged in a comprehensive research program on the spray characteristics of pressure-swirl nozzles. It is hoped that by using the best available instrumentation and exercising very precaution to ensure its operation at conditions of maximum precision the designer and user of pressure-swirl nozzles will be provided with reliable experimental data on the effects of variations in liquid properties, geometric parameters, and operational variables, on mean drop size and drop-size distribution. The work reported here represents the first stage of this program, and is devoted to the influence of liquid properties on mean drop size.

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Previous Work

Most previous work has concentrated on small-scale pressure-swirl atomizers of the type used in aircraft gas turbines, the only exception of note being the comprehensive experimental study carried out by Jones[5] on pressure-swirl nozzles of the large size used in electrical power generation. In these various studies, emphasis has been placed on the variation of drop size with liquid properties and operating conditions. The liquid properties of relevance to atomization are density, surface tension, and viscosity. However, extensive measurements carried out on both pressure-swirl and airblast atomizers have shown that, for the range of densities of most practical interest, the influence of this property on drop size is quite small. Thus, the liquid properties of prime importance to atomization are surface tension and viscosity.

Due to the highly complex nature of the atomization process most workers have tended to resort to various empirical correlation formulas, of which the most popular is

$$\mathrm{SMD} \propto \sigma^a \nu^b \dot{m}_L^c \Delta P_L^d \tag{1}$$

The reported values of a, b, c, and d have some features in common, but overall they display sufficient disparity to preclude any possibility of a universal correlation.

One of the earliest and most widely quoted expressions is that of Radcliffe[6]:

$$\mathrm{SMD} = 7.3\sigma^{0.6}\nu_L^{0.2}\dot{m}_L^{0.25}(\Delta P_L)^{-0.4} \tag{2}$$

This equation was derived from analysis of experimental data obtained by Needham,[7] Joyce,[8] and Turner and Moulton.[9] Subsequent work by Jasuja[10] yielded the expression

$$\mathrm{SMD} = 4.4\sigma^{0.6}\nu_L^{0.16}\dot{m}_L^{0.22}(\Delta P_L)^{-0.43} \tag{3}$$

However, the variation of surface tension in these experiments was very small and was accompanied by wide variations in viscosity. Thus the exponent of 0.6 has no special significance in Eqs. (2) and (3).

Simmons and Harding[11] studied the difference in atomizing performance between water and kerosine for six simplex fuel nozzles. These two liquids had virtually the same viscosity and a 30% difference in density, but the surface tension was higher by a factor of 3 for water. Thus, according to Simmons and Harding, any significant differences in SMD could be attributed to differences in surface tension rather than density. For the important practical case of Weber number less than unity, it was found that $a = 0.19$.

Recent tests by Kennedy[12] on simplex nozzles featuring much higher flow numbers demonstrated a far stronger dependence of SMD on surface tension. In fact, if Kennedy's data are replotted as log SMD vs log σ, the slope of the resulting graph indicates that $\mathrm{SMD} \propto \sigma^a$, where a has a value of at least 1.5. Kennedy attributes this, and other differences between his results and those of other workers, to the larger Weber numbers resulting from his use of nozzles of exceptionally high flow number. According to Kennedy, "for Weber numbers greater than 10, a different atomization process occurs, i.e., shear-type breakup, which results in much finer atomization than predicted by previously reported correlations." However, Jones,[5] using large industrial nozzles of much higher flow number than those employed by Kennedy, obtained an exponent for surface tension of $a = 0.25$. This value is fairly close to the experimental finding of Simmons and Harding, and is identical to the value derived by Lefebvre[13] from dimensional analysis of published data on SMD.

Published data on the effect of viscosity on mean drop size are usually expressed in the form

$$\mathrm{SMD} \propto \mu_L^b \tag{4}$$

Values for b of 0.16, 0.20, 0.118, 0.16, 0.06, and 0.215 have been reported by Jasuja,[10] Radcliffe,[6] Dodge and Biaglow,[14] Jones,[5] Simmons,[15] and Knight,[16] respectively.

This wide disparity in the published results on the effects of surface tension and viscosity on mean drop size, coupled with the lack of any reliable expression for drop-size correlation, highlights the need for further experimental and analytical work in this area. This need has grown appreciably in recent years due to the development of new models for spray combustion and the growing obligation of combustion engineers to burn more efficiently; and with lower pollutant emissions, fuels are of gradually diminishing quality.

Experiment

The apparatus for studying spray characteristics comprises a cylindrical pressure vessel mounted on a stand with its axis in the vertical position. It is 120 cm long and 75 cm in diameter. 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 tapped from a large liquid nitrogen storage/evaporator system. The reason for using nitrogen instead of air is to avoid the risk of explosion. Since 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 whence the liquid is either disposed of or returned to the storage tank.

In addition to the nitrogen supply for tank pressurization, two extra nitrogen lines are connected to the tank. One line is used to protect the windows from any contamination by liquid drops or mist, and the other is connected to a manifold located at the top of the tank which provides a gentle downdraft of nitrogen through a very large number of small holes. By this means, the problem of droplet recirculation is kept to a minimum.

Mean drop sizes are measured using a Malvern particle-size analyzer. This instrument is based on the Fraunhofer diffraction theory of a collimated laser beam scattered by moving drops. The principle of operation of the Malvern analyzer is reviewed in Refs. 17 and 18, and the accuracy and limitations of the instrument are discussed in Refs. 1–4.

The need to avoid making drop-size measurements close to the nozzle has been stressed by Wittig et al.[3] The rapid deceleration of the smallest drops in the spray in this region gives rise to readings of SMD appreciably lower than the true value. Chin et al.[4] recommend a downstream distance of around 25 cm as being the ideal plane at which to make drop-size measurements. However, their calculations take no account of evaporation. To minimize errors arising from this effect, it is desirable to keep the distance between the nozzle and the plane of measurement as short as possible. For the liquids employed in these experiments, it was estimated that 15 cm would be the best downstream distance; this value was used throughout the test program.

All measurements were taken with the laser beam passing through the centerline of the spray. The problems involved with such measurements have been discussed by various workers, including Dodge[2] and Chin et al.[4] Centerline measurements are generally preferred because they encompass both the smaller drops in the core of the spray as well as the larger drops at the spray periphery.

The liquids selected for this study are: diesel oil (DF-2): $\mu = 0.00261$ kg/ms, $\sigma = 0.027$ kg/s^2, $\rho = 860$ kg/m^3; and water: $\mu = 0.001$ kg/ms, $\sigma = 0.0734$ kg/s^2, $\rho = 1000$kg/m^3.

These liquids were chosen to provide a wide variation in surface tension. Initially, it was planned to use a light kerosine instead of diesel oil to achieve a sensibly common viscosity for both liquids. However, preliminary measurements with the lighter and more volatile fuel soon revealed significant errors due to evaporation. It was decided, therefore, to use a less volatile liquid (DF-2) and to "correct" for its higher viscosity when making comparisons with water to assess the influence of surface tension on SMD.

The effect of variation in liquid viscosity on mean drop size is examined by blending the diesel oil in varying concentrations with a commercially available polybutene (Amoco L-100) to produce a range of viscosities from 3 to 18×10^{-6} m^2/s (3–18 cs). This wide range of viscosity is accompanied by only slight variations in surface tension.

The atomizers selected for this study are simplex pressure-swirl nozzles manufactured by the Delavan Corporation. This company manufactures aircraft nozzles to precise standards, but also supplies a range of mass-produced nozzles at a cheap price. The latter generally provide excellent atomization, but their radial and circumferential liquid distribution is sometimes poor. However, by measuring these spray characteristics on a large number of nozzles, it is usually possible to find some which combine good atomization with acceptable spray symmetry, free from any streaks or voids.

The six simplex nozzles employed herein all produce a hollow-cone spray. Three of the nozzles have a nominal cone angle of 90 deg, and nozzle numbers (*NN*) of 2, 4, and 8. The corresponding flow numbers in SI units are 6.25, 12.5, and 25×10^{-8}, while in conventional units [lb/h/(psi)$^{0.5}$], the three flow numbers are 1.14, 2.28, and 4.56. The other three nozzles have the same three flow numbers, but their nominal cone angle is 60 deg.

The reason for choosing these values of flow number was partly to cover the range of interest to the designers of primary nozzles for aircraft gas turbines, and also to minimize the problem of laser beam obscuration that arises with nozzles of high flow rate. The Malvern instrument provides a direct indication of beam obscuration, and for all of the measurements reported here it was always at an acceptably low value. Even so, the correction formula devised by Dodge and Cerwin[19] was applied as a routine procedure in all cases to eliminate any possibility of errors arising from this source.

Results

During the course of this investigation, a large amount of experimental data was acquired for both mean drop size (SMD) and drop-size distribution. However, the latter are not included due to the need to keep the length of this paper within reasonable bounds. Some typical results for mean drop size are contained in Figs. 1–11.

Figure 1 illustrates for water the relative importance to atomization of liquid flow rate, nozzle flow number, and liquid pressure differential. Figure 2 shows similar data, with the spray-cone angle reduced from 90 to 60 deg. Comparison of Figs. 1 and 2 clearly illustrates the deleterious effect on atomization quality of reduction in spray-cone angle. Figures 3 and 4 show similar data for DF-2. They demonstrate the same basic features, including the beneficial effects on atomization of increases in cone angle and injection pressure, and decrease in flow number. Charts of the type drawn in Figs. 1–4 are useful from a designer's viewpoint because they can be used to determine the optimum conbination of flow number and fuel injection pressure to provide any given value of SMD for any stipulated liquid flow rate.

Additional data for water and DF-2 are presented in Figs. 5 and 6. Also shown are so-called "corrected" values of SMD for DF-2. These values represent what would have been measured if DF-2 had the same viscosity as water. These values were obtained by multiplying the measured values of SMD for DF-2 by the factor $(\mu_{water}/\mu_{DF\text{-}2})^{0.17}$, the exponent 0.17 being an average of the values 0.16, 0.20, 0.118, 0.16, and 0.215, as reported by Jasuja,[10] Radcliffe,[6] Dodge and Biaglow,[14] Jones,[5] and Knight,[16] respectively. The purpose of this exercise was to determine the influence of surface tension on SMD. Thus, in Figs. 5 and 6, the higher SMD values exhibited by water, in comparison with "corrected" DF-2, are due entirely to the higher surface tension of water.

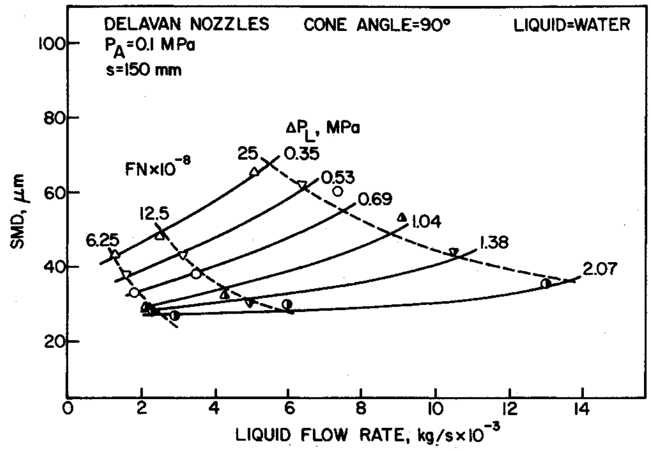

Fig. 1 Relationship between SMD, flow number, and injection pressure for water. Spray cone angle = 90 deg.

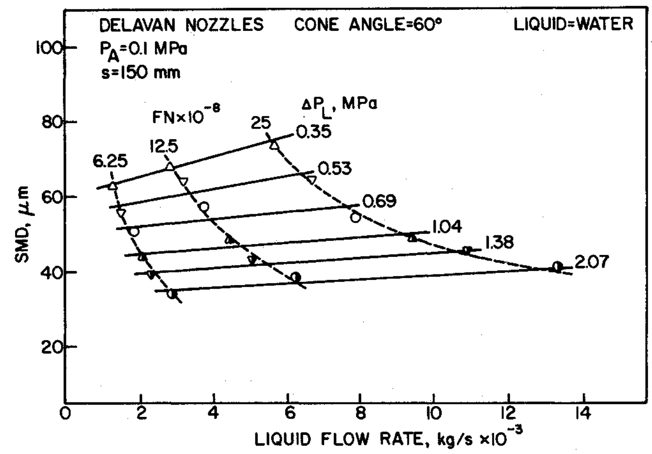

Fig. 2 Relationship between SMD, flow number, and injection pressure for water. Spray cone angle = 60 deg.

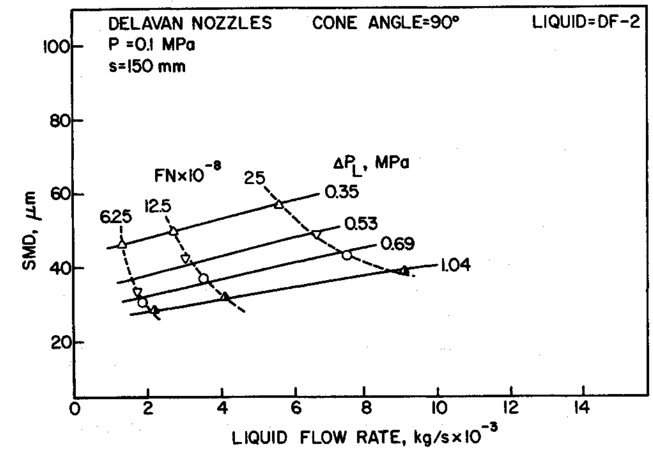

Fig. 3 Relationship between SMD, flow number, and injection pressure for DF-2. Spray cone angle = 90 deg.

Figure 7 illustrates the effects of liquid pressure differential and nozzle flow number on mean drop sizes for DF-2, while Fig. 8 shows similar results for a liquid of higher viscosity. These, and all subsequent figures, are plotted in logarithmic form to facilitate data analysis. The "slopes" indicated in these and other figures denote the exponent z in the expression SMD α ΔP_L^z. Comparison of Figs. 7 and 8 reveals that the effect of a reduction in nozzle flow number, which is always

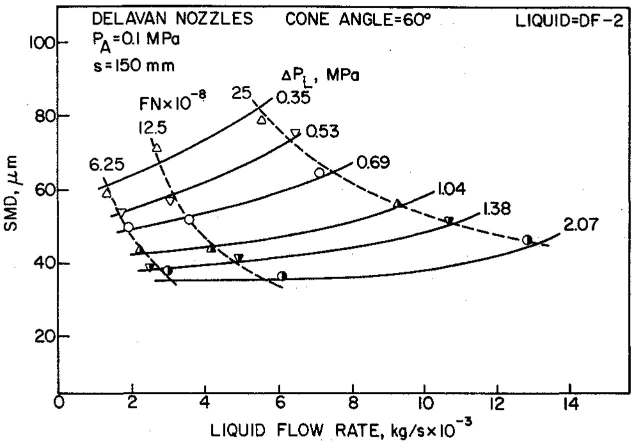

Fig. 4 **Relationship between SMD, flow number, and injection pressure for DF-2. Spray cone angle = 60 deg.**

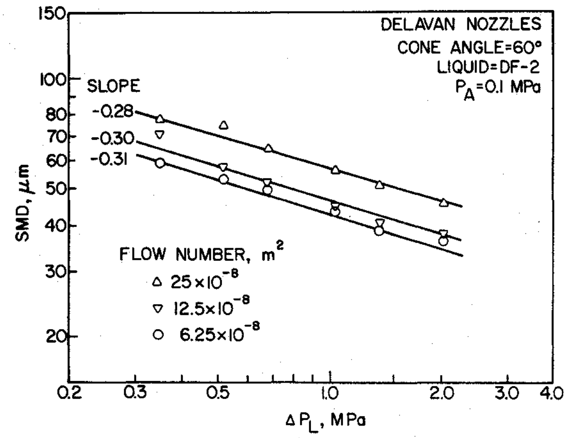

Fig. 7 **Influence of flow number on SMD for low-viscosity liquid.**

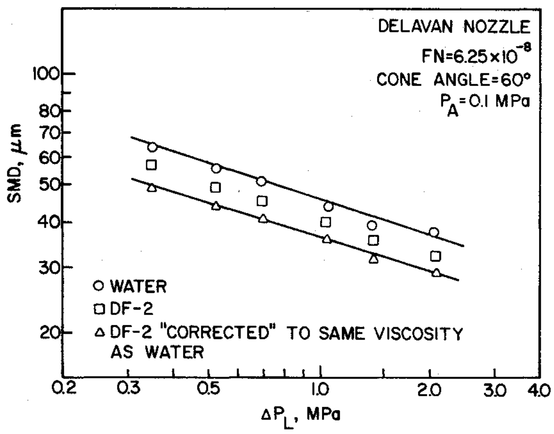

Fig. 5 **Influence of surface tension on mean drop size.**

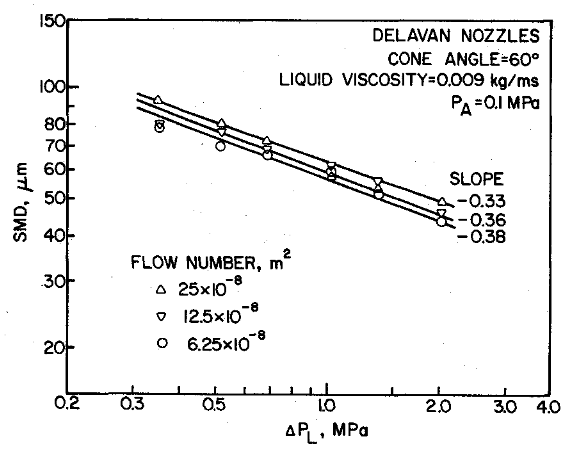

Fig. 8 **Influence of flow number on SMD for high-viscosity liquid.**

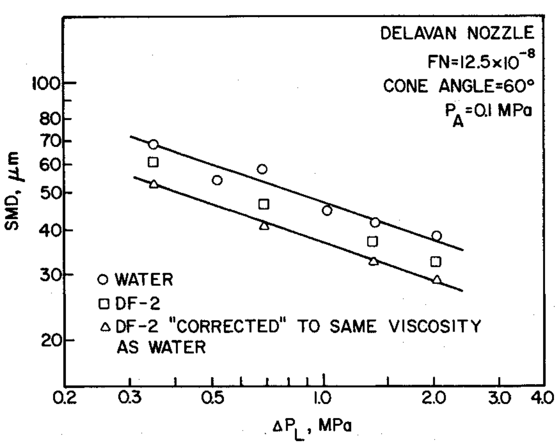

Fig. 6 **Influence of surface tension on mean drop size.**

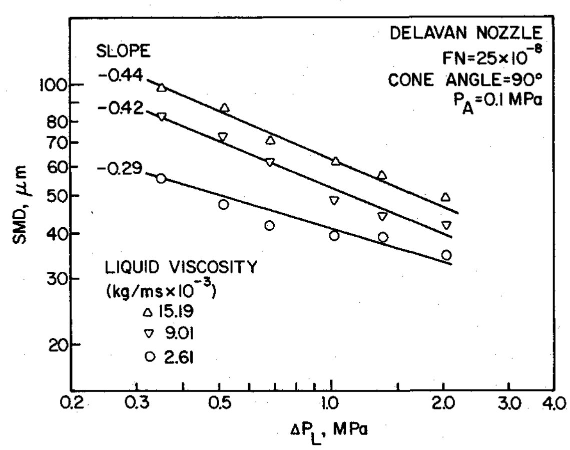

Fig. 9 **Influence of viscosity on SMD for a 90-deg cone angle.**

conducive to better atomization, is appreciably less for the liquid of higher viscosity.

Figures 9 and 10 serve to confirm the well-known adverse effect of increase in liquid viscosity on atomization quality. Of more interest, perhaps, is the demonstration that viscosity has less effect on SMD for nozzles of lower spray-cone angle. Also worthy of note is that the slopes of the lines representing log SMD vs log ΔP_L are slightly steeper for the wider cone angle.

The influence of liquid viscosity on SMD is shown more directly in Fig. 11, which illustrates the adverse effects of increases in viscosity and flow number on mean drop size. Of special interest in this figure is that the dependence of SMD on viscosity diminishes with an increase in flow number. This effect, and many others previously noted, cannot be explained on the basis of existing equations and correlations for mean drop size. Clearly, any new or proposed form of equation for mean drop size must not only account for the well-known and well-documented features of pressure-swirl atomization, such as the beneficial effect on atomization of increase in pressure differential, or reduction in liquid viscosity, but must also serve to explain the various apparent anomalies that careful measurements often reveal, some of which have been observed in this study.

Data Analysis

Owing to the complexity of the various physical phenomena involved in pressure-swirl nozzles, the study of atomization has been pursued principally by empirical methods, yielding correlations for mean drop size of the form of Eq. (1).

Quite apart from the fact that it is clearly unreasonable to expect a single-term parameter to describe adequately the complex fluid-dynamic processes involved in atomization, further objections to this type of formula can be made on purely practical grounds. For example, it takes no account of spray-cone angle, which is known to affect mean drop size. Furthermore, it implies that a nonviscous liquid would yield a spray of infinitely small drops, which seems highly unlikely from both theoretical and practical considerations.

In an attempt to alleviate this situation, Lefebvre[20] has proposed an alternative form of equation for the mean drop sizes produced by pressure-swirl atomizers. This equation is not the result of a mathematical treatment of the subject, but is based on considerations of the physical processes involved in pressure-swirl atomization. Its derivation has been described elsewhere[20] but, as this report is not generally available, the underlying arguments on which it is based are reiterated below.

Although several different mechanisms have been proposed to describe the atomization process,[21-24] it is generally agreed that the disintegration of a liquid jet or sheet issuing from a nozzle is not caused solely by aerodynamic forces, but must be the result, at least in part, of turbulence or other disruptive forces within the liquid itself. These disturbances within the flow have a strong influence on sheet disintegration, especially in the first stage of atomization. Subsequently, and to some extent simultaneously, the relative velocity between the liquid and the surrounding gas plays an important role in atomization through its influence on the development of waves on the initially smooth surface, and the production of unstable ligaments. Any increase in this relative velocity causes a reduction in the size of the ligaments, so that when they disintegrate much smaller drops are produced.

As the process of atomization in pressure-swirl nozzles is highly complex, it is convenient to subdivide it into two main stages. The first stage represents the generation of surface instabilities due to the combined effects of hydrodynamic and aerodynamic forces. The second stage is the conversion of surface protuberances into ligaments and then drops. It is recognized that this subdivision of the total atomization process into two separate and distinct stages represents a gross oversimplification of the mechanisms involved. However, it allows the formulation of an equation for SMD as

$$SMD = SMD_1 + SMD_2 \tag{5}$$

Here, SMD_1 represents the first stage of the atomization process. Its magnitude depends partly on Reynolds number, which provides a measure of the disruptive forces present within the liquid sheet. These forces are enhanced by increases in liquid velocity and sheet thickness, and are diminished by an increase in liquid viscosity. SMD_1 is also influenced by

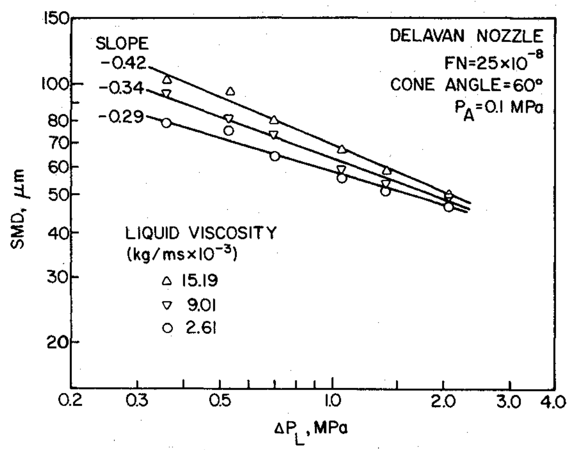

Fig. 10 Influence of viscosity on SMD for a 60-deg cone angle.

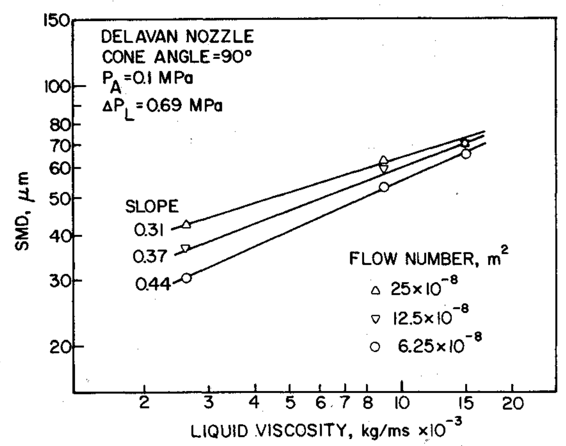

Fig. 11 Influence of viscosity on SMD for various flow numbers.

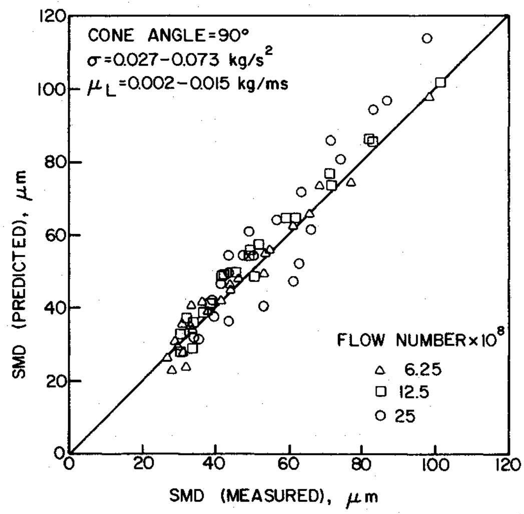

Fig. 12 Correlation of experimental data with Eq. (16) for a 90-deg cone angle.

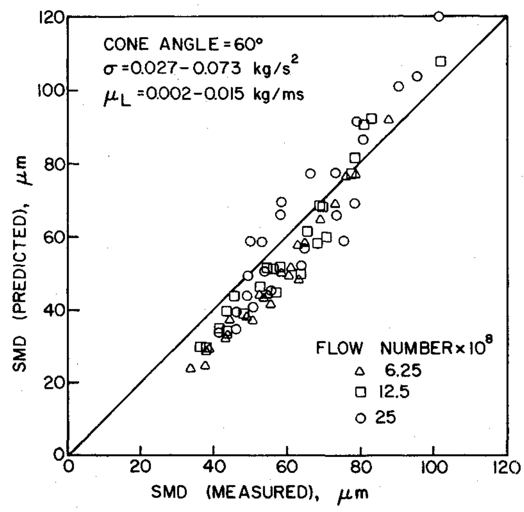

Fig. 13 Correlation of experimental data with Eq. (16) for a 60-deg cone angle.

Weber number, which governs the development of capillary waves (ripples) on the liquid surface. The rate of growth of these perturbations into projections large enough to break off and form ligaments is dependent on the ratio of the aerodynamic forces at the liquid/air interface to the consolidating surface tension forces in the liquid, i.e., on Weber number.

It appears, therefore, that a suitable form for SMD_1 might be one that combines both Reynolds and Weber numbers into a single parameter. Analysis of the experimental data leads to the following expression for SMD_1 (Ref. 20):

$$\frac{SMD_1}{t_s} \propto (Re \times \sqrt{We})^{-x} \tag{6}$$

where

$$Re = \frac{\rho_L U_L t_s}{\mu_L}$$

$$We = \rho_A U_R^2 t_s / \sigma$$

and t_s is the initial sheet thickness at nozzle exit.

It is important not to confuse SMD_1 with the "Z" or Ohnesorge number,[24] which is denoted as $\sqrt{We/Re}$, and represents the *ratio* of surface tension to viscous forces operating on the liquid. In contrast, SMD_1 is intended to represent the manner in which suface tension and viscous forces *act together* in opposing the disruptive actions of the hydrodynamic and aerodynamic momentum forces.[20]

For both pressure and airblast nozzles, the relative velocity between the liquid and the surrounding gas has a profound effect on atomization. It generates the projections on the liquid surface that are an essential prerequisite to atomization, and also furnishes the energy needed to convert these projections into ligaments and then drops. However, another important factor in atomization, as discussed previously, is the contribution made to sheet or jet disintegration by the instabilities created within the liquid itself, and which are very dependent on liquid velocity. In airblast atomization, where high-velocity air impacts on a slow-moving liquid, the only factor promoting atomization is the relative velocity between the air and the liquid. This relative velocity between air and liquid is also vitally important in pressure atomization but, by achieving this relative velocity through liquid motion, instead of air motion, an important advantage is gained in that the liquid now makes an additional and independent contribution to its own disintegration; an effect that is either absent or negligibly small in airblast and air-assist atomization.

These arguments highlight the special importance of velocity in pressure atomization. The velocity at which the liquid is discharged from the nozzle has two separate effects on atomization. One important effect, which is dependent on the *absolute* velocity U_L, is in generating the turbulence and instabilities within the bulk liquid that contribute to the first stage of the atomization process. The other effect, which depends on the *relative* velocity U_R, is in promoting the atomization mechanisms that occur on the liquid surface, and in the adjacent ambient gas. This means that Reynolds number, which relates to the bulk liquid, should be based on U_L, while Weber number, which is associated with events occurring through the action of the surrounding gas on the liquid surface, should be based on U_R.

Dividing $\sqrt{We}$ by Re to produce the Z number has the effect of eliminating velocity from both We and Re. This severely curtails its useful application to pressure atomization, where velocity is of paramount importance. In contrast, *multiplying* $\sqrt{We}$ by Re not only enhances the role of velocity, but also provides a more accurate description of how SMD is affected by changes in liquid properties, as well as nozzle size and geometry.[20]

From simple geometrical considerations, the initial thickness of the liquid sheet, t_s, after it is discharged from the nozzle, can be related to the film thickness within the final orifice, t, by the following equation:

$$t_s = t\cos\theta \tag{7}$$

where θ is half the spray-cone angle.

According to Suyari and Lefebvre,[25] the most accurate equation for film thickness t is

$$\frac{(1-X)^3}{1+X} = 0.09\left[\frac{A_p}{D_s d_o}\right]\left[\frac{D_s}{d_o}\right]^{0.5} \tag{8}$$

where

$$X = (d_o - 2t)^2 / d_o^2 \tag{9}$$

Substituting for t_s from Eqs. 7–9 into Eq. (6), along with the appropriate terms for Re and We, gives

$$SMD_1 \propto \left(\frac{\sigma^{0.5}\mu_L}{\rho_A^{0.5}\rho_L U_R U_L}\right)^x (t\cos\theta)^{1-1.5x} \tag{10}$$

For the normal case of a nozzle spraying fluid into stagnant or slow-moving air, $U_R \simeq U_L$, and Eq. (10) simplifies to

$$SMD_1 \propto \left(\frac{\sigma^{0.5}\mu_L}{\rho_A^{0.5}\Delta P_L}\right)^x (t\cos\theta)^{1-1.5x} \tag{11}$$

SMD_2 represents the final stage of the atomization process, in which the high relative velocity induced at the liquid/air interface by the rapidly evolving conical sheet causes the surface protuberances generated in the first stage to become detached and break down into ligaments and then drops. This final disintegration is also opposed by surface tension forces, but Reynolds number is no longer relevant. Thus, we have

$$\frac{SMD_2}{t_s} \propto We^{-y} \propto \left(\frac{\sigma}{\rho_A U_R^2 t_s}\right)^y \tag{12}$$

Substituting for t_s, using Eqs. (7–9) converts Eq. (12) into

$$SMD_2 \propto \left(\frac{\sigma}{\rho_A U_R^2}\right)^y (t\cos\theta)^{1-y} \tag{13}$$

or, since $U_R \simeq U_L$, and $\Delta P_L = 0.5\rho_L U_L^2$,

$$SMD_2 \propto \left(\frac{\sigma\rho_L}{\rho_A \Delta P_L}\right)^y (t\cos\theta)^{1-y} \tag{14}$$

Eq. (5) thus becomes

$$SMD = A\left(\frac{\sigma^{0.5}\mu_L}{\rho_A^{0.5}\Delta P_L}\right)^x (t\cos\theta)^{1-1.5x} + B\left(\frac{\sigma\rho_L}{\rho_A\Delta P_L}\right)^y (t\cos\theta)^{1-y} \tag{15}$$

where A and B are constants whose values depend on nozzle design.

Analysis of the experimental data acquired in this investigation indicates appropriate values for x and y of 0.5 and 0.25, respectively. For the Delavan nozzles employed in this study, it is found that values for A and B of 4.52 and 0.39, respectively, provide good correlation of the data, as illustrated in Figs. 12 and 13. Substituting these values of x, y, A, and B

into Eq. (15) gives

$$\mathrm{SMD}=4.52\left(\frac{\theta\mu_L^2}{\rho_A\Delta P_L^2}\right)^{0.25}(t\cos\theta)^{0.25}$$
$$+0.39\left(\frac{\rho_L}{\rho_A\Delta P_L}\right)^{0.25}(t\cos\theta)^{0.75} \tag{16}$$

Inspection of this equation reveals several important features of pressure-swirl atomization, which may be listed as follows:

1) Increase in spray-cone angle reduces mean drop size. This result is fully consistent with the experimental data shown in Figs. 1 and 2 for water, in Figs. 3 and 4 for diesel oil, and in Figs. 9 and 10 for special liquids of high viscosity. In all three sets of figures, the comparison is made between spray angles of 60 and 90 deg, respectively.

Equation (16) also suggests that an increase in spray angle should cause a stronger dependence of SMD on viscosity and pressure differential, ΔP_L. It does this by causing SMD_2 to decline more than SMD_1, thereby increasing the relative importance of the contribution made by SMD_1 to the overall mean drop size. Both these effects are validated by the data shown in Figs. 9 and 10. Comparison of these two figures shows that widening the spray-cone angle improves atomization quality and increases the dependence of SMD on both viscosity and liquid injection pressure. Also worthy of note in these figures is that the exponent of ΔP_L increases with increase in viscosity. This again stems directly from the added importance imparted to SMD_1 by increasing the liquid viscosity.

2) Equation (16) indicates a surface tension exponent of 0.25. This agrees exactly with the findings of Jones,[5] and is fairly close to Simmons and Harding's[11] value of 0.19. The data shown in Figs. 5 and 6 for water ($\sigma=0.0734$ kg/s^2) and "corrected" DF-2 ($\sigma=0.027$ kg/s^2) also suggest a surface tension exponent of 0.25.

3) As liquid density appears only in SMD_2, its influence on mean drop size should generally be quite small, depending on the contribution of SMD_2 to SMD. As the density of commercial hydrocarbon fuels is normally confined to within 760–900 kg/m,^{3} in practice, changes in fuel type are not usually accompanied by large changes in density. This fact, combined with the small dependence of SMD on ρ_L indicated in Eq. (16), implies that for most practical purposes the influence of density can usually be neglected when considering the effect of a change in fuel type on SMD.

4) From analysis of published data on simplex nozzles, Simmons[15] concluded that the dependence of SMD on film thickness t approximates to SMD $\propto t^{0.5}$. This exponent of 0.4 lies between the values of 0.75 and 0.25 given in Eq. (16) for nonviscous and high-viscosity liquids, respectively.

As t is directly proportional to flow number [see Eq. (5) of Ref. 11] Eq. (16) shows that the impact of a change in flow number on SMD should be less for liquids of high viscosity. This prediction is borne out by the experimental data plotted in Figs. 7 and 8 for liquid viscosities of 0.0026 and 0.0091 kg/ms, respectively.

These same figures also show a stronger dependence of SMD on injection pressure for the higher viscosity liquid. This also is consistent with Eq. (16), which indicates exponents for ΔP_L varying from -0.25 for nonviscous liquids to -0.5 for liquids of high viscosity.

5) The influence of viscosity on mean drop size is demonstrated directly in Fig. 11. This figure illustrates the diminishing effect of flow number on SMD with increase in viscosity as discussed previously, and also shows that SMD becomes less dependent on viscosity with increase in flow number, as predicted by Eq. (16).

Conclusions

From extensive measurements of mean drop diameter in the sprays produced by six simplex atomizers of different size and spray-cone angle, it is shown that atomization quality deteriorates with increases in surface tension, liquid viscosity, and nozzle flow number, and is improved by increases in spray cone angle, ambient gas density, and injection pressure differential.

The experimental data on mean drop size are found to be fully consistent with Eq. (16), which can be used to predict the manner and extent to which mean drop size is influenced by changes in liquid properties, and in nozzle size and geometry. For example, it shows that SMD is proportional to $(\sigma/\rho_A)^{0.25}$. It also indicates that SMD is diminished by an increase in spray-cone angle.

A further conclusion to be drawn from Eq. (16) is that the impact on SMD of changes in nozzle dimensions and operating conditions will vary depending on the level of liquid viscosity. From inspection of the equation it is evident that, for liquids of high viscosity, SMD will be more dependent on injection pressure differential ΔP_L and less dependent on nozzle flow number (via t) and spray-cone angle, than liquids of low viscosity.

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