Film Thickness Measurements in a Simplex Swirl Atomizer

M. Suyari* and A.H. Lefebvre†
Purdue University, West Lafayette, Indiana

The results of previous theoretical and experimental studies on the relationship between the liquid-film thickness produced at exit from pressure-swirl and airblast atomizers are reviewed. An electrical conductance method is used to measure the liquid-film thickness in the final orifice of a specially designed simplex atomizer when discharging water into air at normal atmospheric pressure. The results of these measurements are compared with various theoretical equations for predicting liquid-film thickness in this type of nozzle. Excellent agreement between theory and experiment is demonstrated for two equations, one of which is derived in this paper.

Nomenclature

A_a	= air core area, m^2
A_p	= total inlet ports area, m^2
A_0	= discharge orifice area, m^2
C_D	= discharge coefficient
d_p	= inlet port diameter, m
D_s	= swirl chamber diameter, m
d_0	= discharge orifice diameter, m
FN	= flow number, $[=\dot{m}/(\Delta P \rho_L)^{0.5}]$, m^2
$\dot{m}_L$	= liquid flow rate, kg/s
SMD	= Sauter mean diameter, m
t	= liquid-film thickness, m
X	$=A_a/A_0$
μ_L	= liquid viscosity, kg/ms
ρ_L	= liquid density, kg/m^3
θ	= spray cone half-angle, deg
ΔP	= total pressure drop across nozzle, Pa

Introduction

THE atomization process is of fundamental importance to the behavior of liquid fuel-fired combustion systems. Smaller drop sizes enhance the rate of fuel evaporation and yield useful performance improvements in terms of easier lightup, wider stability limits, higher combustion efficiency, and lower exhaust concentrations of carbon monoxide, unburned hydrocarbons, and smoke.[1,2]

In gas turbine engines, the atomization of a liquid fuel is most commonly carried out either by spreading the fuel into a thin liquid sheet and exposing it to high-velocity air, as in a prefilming airblast atomizer, or by pressurizing the fuel and forcing it through one or more small orifices. The most widely used forms of the pressure atomizer are the simplex and dual-orifice types, in which the liquid is fed into a swirl chamber through tangential inlet ports that give the liquid a high angular velocity, thereby creating an air-cored vortex. The outlet from the swirl chamber is the final orifice and the rotating liquid flows through this orifice under both axial and tangential forces to emerge from the atomizer in the form of a hollow conical sheet. The actual cone angle is determined by the relative magnitude of the tangential and axial components of velocity at the exit. Downstream of the atomizer, the liquid sheet rapidly disintegrates into ligaments and then drops.

Received April 11, 1986; revision submitted June 23, 1986.

*Visiting Scholar, School of Mechanical Engineering (on leave from Kobe Steel, Kobe, Japan).
†Reilly Professor of Combustion Engineering, School of Mechanical Engineering.

Influence of Film Thickness on Atomization

Despite the geometrical simplicity of the simplex swirl atomizer, the hydrodynamic processes leading to the formation of a conical liquid sheet and to the disintegration of this sheet into ligaments and drops are highly complex. Previous studies have revealed the basic mechanisms involved in the conversion within the swirl chamber of a finite number of discrete liquid jets into a thin conical sheet and have led to the formulation of quantitative relationships between the main atomizer dimensions and various flow parameters, such as discharge coefficient and initial spray cone angle.[3-11] However, much less is known about the factors that govern the thickness of the sheet, or film, at the plane of discharge from the nozzle, although it has long been recognized, for both pressure-swirl and airblast atomizers, that the thickness of the liquid film at the nozzle exit has a strong influence on the mean drop size of the spray.[12]

In an early paper on the design and performance of prefilming airblast atomizers, Lefebvre and Miller[13] stressed the importance of spreading the liquid into the thinnest possible sheet before subjecting it to airblast action, on the grounds that "any increase in the thickness of the liquid sheet flowing over the atomizing lip will tend to increase the thickness of the ligaments which, upon disintegration, will then yield drops of larger size."

In a detailed experimental study on the effects of air and liquid properties on the mean drop sizes produced by prefilming airblast atomizers, Rizkalla and Lefebvre[14] used dimensional analysis in conjunction with drop-size data to show that SMD $\alpha t^{0.5}$ for liquids of low viscosity and SMD $\alpha t^{0.575}$ for liquids of high viscosity.

The influence of atomizer scale on mean drop size was examined by El-Shanawany and Lefebvre.[15] They used three geometrically similar nozzles, manufactured to the same basic design as the Rizkalla-Lefebvre nozzle and having cross-sectional areas in the ratio of 1:4:16. Their experiments were confined mainly to water and kerosine, but they also used some specially prepared liquids of high viscosity.

From analysis of the experimental data, it was found that SMD $\alpha L_c{}^{0.43}$, where L_c is the characteristic dimension of the atomizer. Since for any given atomizer design, the thickness of the liquid sheet produced at the prefilmer lip is directly proportional to L_c, this finding could also be interpreted as SMD $\alpha t^{0.43}$, which is very consistent with the results of several theoretical and experimental studies on the influence of liquid-sheet thickness on the mean drop size. For example, the analysis of York et al.,[16] Hagerty and Shea,[17] and Dombrowski and Johns[18] all suggest that the mean drop diameter is proportional to the square root of the film thickness. In addition, the photographic studies of film disintegration made by Fraser et al.[19] show that, for sheets breaking down through the formation of unstable ligaments, the diameter of the latter depends mainly on the sheet thickness. More recently, Rizk and Lefebvre,[20] using a specially designed airblast system, succeeded in correlating the thicknesses of very thin flat sheets, subjected on both sides to coflowing high-velocity airstreams, to the mean drop sizes produced over a very wide range of conditions. They reported that SMD is proportional to the 0.4 power of the sheet thickness for low-viscosity liquids, but is slightly higher for liquids of high viscosity.

The results of the experiments described above on the influence of liquid-film thickness on mean drop size for prefilming airblast atomizers can be summarized as SMD αt^x, where x has a value between 0.4 and 0.43.

Much less information is available on the relationship between the liquid-film thickness and mean drop size of pressure-swirl atomizers. However, from analysis of published data, Simmons[21] concluded that the dependence of SMD on t for simplex nozzles approximates to SMD $\alpha t^{0.4}$. The close agreement between this exponent of 0.4 for pressure-swirl nozzles and the values of 0.4–0.43 for airblast atomizers suggests that, for both types of nozzle, some of the basic atomization processes must be essentially similar, if not the same.

In the following sections, various equations for predicting liquid-film thickness in the final orifice of pressure-swirl atomizers are reviewed and predictions of the film thickness based on these equations are compared with actual measured values.

Equations for Film Thickness

In their pioneer studies on the hydrodynamics of pressure-swirl atomizers, Giffen and Muraszew[22] considered the liquid flow to have a spiral motion as a result of an axial flow being superimposed on a free vortex. Since, at the axis of the vortex (where the radius is zero) the angular velocity would theoretically be infinite, this impossible condition is obviated by the formation of an air core concentric with the discharge orifice. Thus, the radial thickness of the annulus through which the fluid is discharged from the nozzle, i.e., the thickness of the liquid film in the final orifice, is directly related to area of the air core. Giffen and Muraszew's analysis of the flow conditions within a simplex nozzle, assuming a nonviscous fluid, led to the following relationship between atomizer dimensions and the size of the air core:

$$\left[\frac{A_p}{D_s d_0}\right]^2 = \frac{\pi^2}{32}\,\frac{(1-X)^3}{X^2} \tag{1}$$

where X is the ratio of the area of the air core to the area of the final discharge orifice.

After calculating X from Eq. (1), the corresponding value of liquid-film thickness t can be readily derived since, from geometrical considerations

$$X = (d_0 - 2t)^2/d_0^2 \tag{2}$$

Giffen and Muraszew[22] also derived the following equation for nozzle discharge coefficient:

$$C_D = 1.17\left[\frac{(1-X)^3}{1+X}\right]^{0.5} \tag{3}$$

Now according to Rizk and Lefebvre,[10] the discharge coefficient can also be expressed in terms of atomizer dimensions as

$$C_D = 0.35\,(A_p/D_s d_0)^{0.5}(D_s/d_0)^{0.25} \tag{4}$$

In Eqs. (3) and (4), it is of interest to note that the discharge coefficient is expressed solely in terms of the atomizer dimensions and is independent of the nozzle flow conditions. This is consistent with the early findings of Bird[23] and Gellales[24] who showed that for normal turbulent flow conditions C_D may be assumed approximately constant. Later work by Radcliffe[3] confirmed this result. His experiments encompassed a variety of pressure-swirl atomizers, using fluids that covered wide ranges of density and viscosity. He demonstrated the existence of a unique relationship between the discharge coefficient and the Reynolds number based on orifice diameter. At low Reynolds numbers, the effect of viscosity is to thicken the fluid film in the final orifice and thereby increase the discharge coefficient. However, for Reynolds numbers larger than 3000 (that is, over the normal working range), the discharge coefficient is practically independent of Reynolds number. Thus, for liquids of low viscosity, the convention is to disregard conditions at low Reynolds number and assume that any given atomizer has a constant discharge coefficient.

Combining Eqs. (3) and (4) yields another expression from which X and hence t can be derived from atomizer dimensions, namely,

$$0.09\left[\frac{A_p}{D_s d_0}\right]\left[\frac{D_s}{d_0}\right]^{0.5} = \frac{(1-X)^3}{1+X} \tag{5}$$

Simmons and Harding[25] derived the following expression for t:

$$t = 0.48\,\mathrm{FN}/(d_0\cos\theta) \tag{6a}$$

In this equation, the film thickness is expressed in micrometers, FN is the nozzle flow number in (lb/h)/(psi)$^{0.5}$ for a standard calibrating fluid (MIL-F-704II), d_0 is the

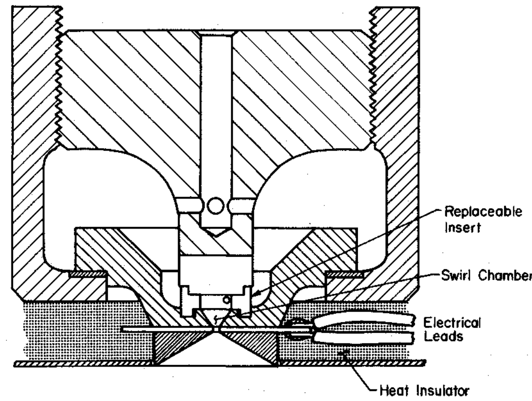

Fig. 1 Cross-sectional view of simplex swirl atomizer (scale 2:1).

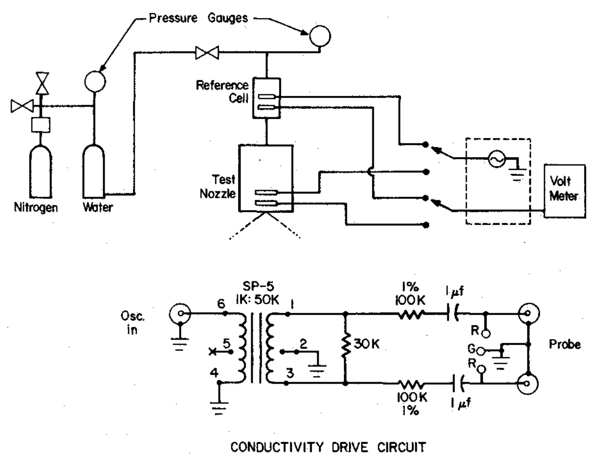

Fig. 2 Layout of apparatus and instrumentation.

discharge orifice diameter in inches, and θ is half the included spray angle in degrees.

In SI units, Eq. (6a) becomes

$$t = 0.00805\sqrt{\rho_L}\ \mathrm{FN}/(d_0 \cos\theta) \tag{6b}$$

A common feature of Eqs. (5) and (6) is that film thickness is independent of liquid viscosity and liquid injection pressure. This conclusion was questioned by Rizk and Lefebvre,[10] who used a theoretical approach to investigate the internal flow characteristics of pressure-swirl atomizers. In particular, they examined the effects of atomizer dimensions and operating conditions on spray cone angle, velocity coefficient, and the thickness of the annular liquid film formed at the discharge orifice. A general expression for film thickness was derived in terms of atomizer dimensions, liquid properties, and liquid injection pressure, as

$$t = 3.66\left[\frac{d_0 \mathrm{FN} \mu_L}{(\Delta P \rho_L)^{0.5}}\right]^{0.25} \tag{7}$$

Equation (7) provides useful guidance on the effects of atomizer characteristics and liquid-flow properties on film thickness and on the mean drop size of the ensuing spray. It is of interest to note that surface tension does not appear in Eq. (7) for film thickness, although, of course, it does play a major role in the subsequent breakup of the liquid sheet into ligaments and drops. The influence of liquid viscosity is clearly of major importance in the atomization process, because viscous forces impede atomization in two ways: by increasing the initial film thickness and by resisting the disintegration of the sheet into drops. Equation (7) shows that the effect of liquid density on film thickness is quite small ($t \alpha \rho_L^{-0.125}$). Thus, its influence on atomization quality should also be small; this is confirmed by the results of measurements of spray quality on pressure-swirl atomizers.[26]

By making the substitution

$$\mathrm{FN} = \dot{m}_L/(\Delta P \rho_L)^{0.5} \tag{8}$$

Eq. (7) may be rewritten as

$$t = 3.66\left[\frac{d_0 \dot{m}_L \mu_L}{\rho_L \Delta P}\right]^{0.25} \tag{9}$$

This equation indicates that the liquid-film thickness increases with increases in nozzle size, liquid flow rate, and liquid viscosity and diminishes with increase in liquid density and/or liquid injection pressure.

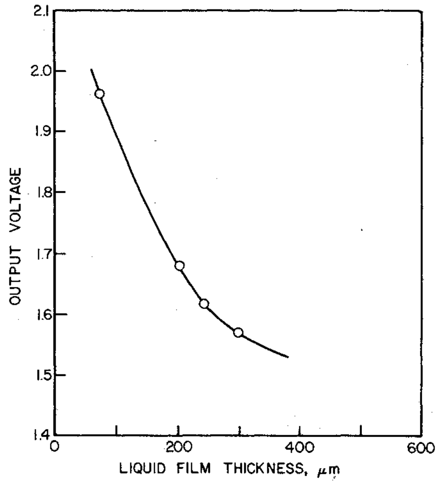

Fig. 3 Calibration curve: voltage vs film thickness.

Experimental

Accurate measurement of the liquid-film thickness is a problem of considerable practical importance in a number of areas. Many techniques have been developed for this type of measurement, but most are not suitable for in-situ measurements on pressure-swirl atomizers.

Kutty et al.[27] used a photographic technique to investigate the influence of liquid pressure differential on air core size. They measured the air core size by taking photographs with the camera pointing upstream through the nozzle outlet orifice. Illumination was achieved by fitting a transparent window at the rear of the swirl chamber. Air core diameters were measured from the negatives by enlarging them in a microfilm reader having a total magnification of 100.

Schmitt et al.[28] have devised an interesting and novel optical technique for determining liquid-film behavior at the tip of an airblast atomizer. Their method relies on the fluorescent emission from a liquid illuminated by a focused laser beam. Fluorescence can occur if the liquid is naturally fluorescent or if a suitable dye is dissolved in it. An argon laser produces an extended beam that is nearly constant in diameter through the liquid layer. Fluorescent emission from all points in this illuminated region is collected and imaged onto a pinhole in front of a photodetector. The detector output is linearly related to the length of the illuminated region that, in turn, is directly related to the thickness of the liquid film.

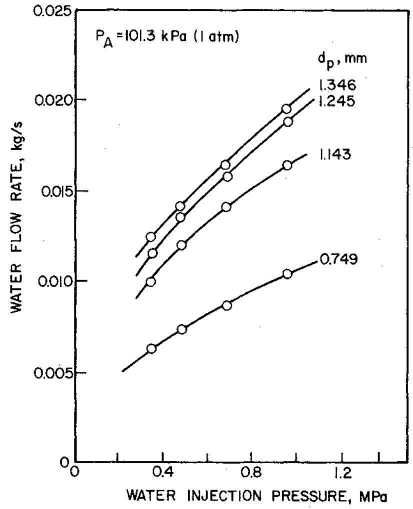

Fig. 4 Nozzle flow characteristics.

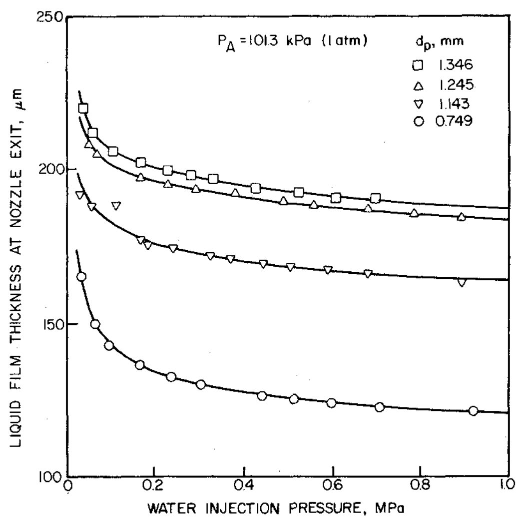

Fig. 5 Influence of water injection pressure and inlet port diameter on liquid-film thickness in final orifice.

This laser fluorescent technique could not be used in the present study due to the problem of optical access. Therefore, it was decided to use a method based on measurements of electrical conductance. The pressure-swirl atomizer designed specifically for this purpose is shown schematically in Fig. 1. The technique is to flow water through the atomizer and measure the electrical conductance between two electrodes located in the discharge orifice. Since the electrical conductivity of water is known, this measurement provides a direct indication of the average liquid-film thickness in the flow path between the two electrodes.

The electrodes employed are made from thin stainless steel sheets. They are separated from each other by a plastic disk of high electrical resistance and glued to the nozzle assembly with epoxy cement. An ac voltage of 10 kHz frequency and constant amplitude is applied to the electrodes. The main components of the electrical circuit shown in Fig. 2 are an oscillator, a noise reducer, and a digital voltmeter. The system is designed to supply a constant current to the electrodes over the entire range of test conditions. In consequence, the voltage drop across the electrodes varies with the film thickness. The output signal is read directly from a digital voltmeter.

A number of preliminary tests were conducted to investigate the effects of water purity and water temperature on the accuracy and consistency of the results obtained. Several different types of water were examined, including distilled and deionized, but clean tap water gave the best results in terms of minimum scatter and good reproducibility. Water temperature was found to be very important and extreme precautions were taken to ensure that it remained constant to within 1°C during any given test run. The conductivity of the water was monitored by a mounting another pair of stainless steel electrodes in a reference cell located in the water supply line and by checking the voltage reading across these electrodes at appropriate intervals, using the switching system illustrated in Fig. 2. By monitoring the electrical conductivity and, at the same time, exercising close control over water temperature, it is believed that the conductance method, as employed here, can provid reasonably accurate and consistent values of liquid-film thickness.

The system is calibrated by flowing water through the nozzle and measuring electrical conductance with a plastic rod of low electrical conductivity inserted along the axis of the nozzle discharge orifice. By repeating this measurement with rods of different diameter, the calibration curve shown in Fig. 3 could be drawn to relate voltmeter reading to film thickness.

In order to examine the effect of variations in nozzle geometry on liquid-film thickness, a number of inserts were produced to provide four different values of inlet port diameter, namely, 0.749, 1.143, 1.245, and 1.346 mm. The nozzle flow characteristics obtained with these four different port diameters are shown in Fig. 4. The results on liquid-film thickness obtained with these different nozzle geometries are shown in Fig. 5, in which the film thickness is plotted vs the water injection pressure differential for an ambient air pressure of 1 atm. The corresponding values of mean drop size, shown plotted in Fig. 6, were measured 15 cm downstream of the nozzle on a Malvern spray analyzer.[29]

This instrument uses the principle of Fraunhofer diffraction from the drops. A low-power visible laser transmitter produces a parallel monochromatic beam of light 9 mm in diameter at a wavelength of 0.6328 μm. The incident light is diffracted by the particles illuminated by the beam to give a stationary diffraction pattern regardless of particle movement. A Fourier transform lens focuses the diffraction pattern onto a multielement photoelectric detector, where the light energy received at any ring in the focal plane of the lens represents the sum of the contributions from individual drops of all sizes. It can be shown that, although any size of drop may diffract light to all radii, the energy distribution curve peaks at one particular radius. Finally, the light detector interfaces directly to a desk-top computer that reads the diffraction pattern and performs the calculations needed to determine the Sauter mean diameter of the spray.

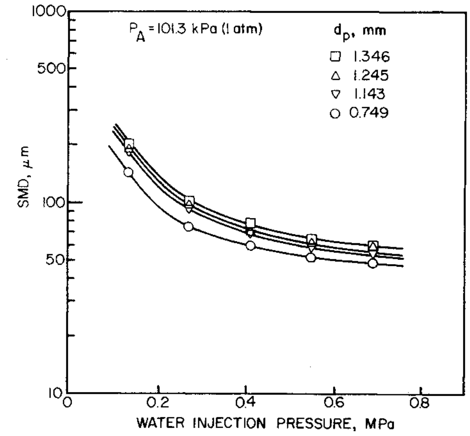

Fig. 6 Influence of water injection pressure and inlet port diameter on mean drop size.

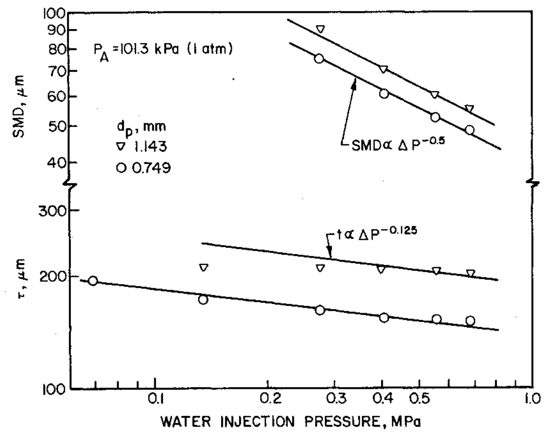

Fig. 7 Influence of nozzle pressure differential on liquid-film thickness and mean drop size.

Results for both mean drop size and film thickness, obtained with values of inlet port diameter of 1.143 and 0.749 mm, are plotted logarithmically in Fig. 7. The SMD data indicate that SMD $\alpha \Delta P^{-0.5}$, which is fully consistent with the results of previous workers (see, for example, Eq. 10.31 of Ref. 12). It is also of interest to note the fairly good agreement exhibited between the measured values of film thickness and the line drawn through these data with a slope of -0.125. This result clearly supports the validity of Eq. (7), according to which $t \alpha \Delta P^{-0.125}$.

Discussion

It is clearly of interest to compare the measured values of liquid-film thickness with the corresponding predicted values from Eqs. (1) and (5-7). This is done in Fig. 8 for conditions of normal atmospheric air pressure and a liquid pressure differential of 0.69 MPa (100 psi). This is the standard pressure differential used throughout most of the fuel nozzle industry for testing nozzles and for comparing the atomization performance of nozzles of different design. From inspection of Fig. 5, it is apparent that the curve of film thickness vΔP is fairly flat for pressure differentials of 0.69 MPa and higher, so that choosing any other value of ΔP (except the very low values that lie outside the range of practical interest because atomization quality is poor) would make little difference to the result.

Figure 8 demonstrates good agreement between the experimental data and values of t calculated using the simple in-

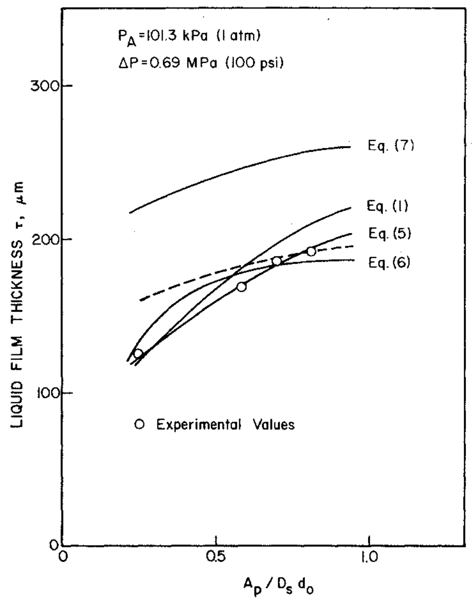

Fig. 8 Comparison of measured values of film thickness with theoretical predictions.

viscid relationship between atomizer dimensions and air core size provided by Giffen and Muraszew[22] [see Eq. (1)].

Equation (5), which was obtained by combining two equations for nozzle discharge coefficient, one derived by Giffen and Muraszew[22] and the other by Rizk and Lefebvre[10] to obtain a relationship between film thickness and atomizer dimensions, also demonstrates excellent agreement with the experimental data.

In order to use Simmons and Harding's equation for film thickness [Eq. (6)], the first requirement is to calculate the spray cone angle for each of the four nozzle geometries tested. This is readily accomplished using the well-known relationship between the spray cone angle and the ratio (A_p/D_sd_0) as first derived theoretically by Taylor,[4] and later modified to suit the experimental data obtained by Watson,[8] Giffen and Massey,[9] and Carlisle.[5] (For further information, see Ref. 12.) Predictions of film thickness based on Eq. (6) conform closely to the experimental data, as shown in Fig. 8.

The predictive capability of Eq. (7), due to Rizk and Lefebvre, is clearly much less satisfactory. This equation was derived from a theoretical analysis of the internal hydrodynamics of simplex nozzles[10] and the constant 3.66 was chosen to provide the best fit to the film thickness data of Kutty et al.[27] As discussed earlier, these workers measured the liquid-film thickness by taking photographs through the final discharge orifice. From considerations of the complex flow situation within a simplex nozzle, it would appear unlikely that the thickness of the liquid film remains perfectly constant and uniform throughout the final orifice, as this would necessitate either a very large number of liquid injection ports or a very long swirl chamber. As both of these requirements are precluded for practical reasons, it seems reasonable to expect that residual effects of the turbulence and flow disturbances created by the sudden expansion of the flow issuing from the inlet ports into the swirl chamber will be manifested as slight ripples or undulations in the liquid surface in the final orifice. Thus, whereas the conductance method as employed here measured the *average* film thickness in the film orifice, the photographic method of Kutty et al. measures the *maximum* thickness to be found anywhere within the orifice. This suggests that if Eqs. (7) and (9) are to represent the average film thickness within the final orifice, instead of the maximum film thickness, a lower value should be assigned to the constant in these equations. Reducing it from 3.66 to 2.7, to match the experimental values of film thickness obtained in the present investigation, gives the result indicated by the dashed line in Fig. 8. As would be expected, this effects a marked improvement in the predictive capability of Eq. (7), but the level of agreement between theory and experiment is still not as good as that obtained with Eq. (5).

Conclusions

1) Provided strict control is exercised over temperature and conductance to ensure constant values of the properties throughout the experiments, the electrical conductance method is considered very satisfactory for the measurement of liquid-film thickness within pressure swirl nozzles. The results obtained indicate that the liquid-film thickness in the final orifice of such atomizers varies with the nozzle pressure differential according to the relationship $t\alpha\Delta P^{-0.125}$. This finding confirms previous theoretical predictions.[10]

2) The best fit between the measured values of liquid film thickness and the various equations for calculating film thickness is provided by Eq. (5). This equation was obtained by combining the relationship derived by Giffen and Muraszew between nozzle discharge coefficient and air core size, with Rizk and Lefebvre's equation for calculating discharge coefficient in terms of nozzle dimensions. This combination provides a direct relationship between liquid-film thickness in the final discharge orifice and nozzle geometry.

3) Equation (6), due to Simmons and Harding, also provides an excellent fit to the experimental results.

Acknowledgment

The authors wish to thank Kobe Steel Ltd. of Kobe, Japan, for the leave of absence granted to M. Suyari. Financial support for this project was provided by a grant from the Parker Hannifin Corporation of Cleveland.

References

[1]Lefebvre, A.H., "Fuel Effects on Gas Turbine Combustion: Ignition, Stability, and Combustion Efficiency," *Transactions of ASME, Journal of Engineering for Gas Turbines and Power*, Vol. 107, Jan. 1985, pp. 24-37.

[2]Lefebvre, A.H., "Fuel Effects on Gas Turbine Combustion: Liner Temperature, Pattern Factor, and Pollutant Emissions," *Journal of Aircraft*, Vol. 21, Nov. 1984, pp. 887-898.

[3]Radcliffe, A., "The Performance of a Type of Swirl Atomizer," *Proceedings, Institution of Mechanical Engineers*, Vol. 169, 1955, pp. 93-106.

[4]Taylor, G.I., "The Boundary Layer in the Converging Nozzle of a Swirl Atomizer," *Quarterly Journal of Mechanics and Applied Mathematics*, Vol. 3, Pt. 2, 1950, pp. 129-139.

[5]Carlisle, D.R., "Communication on 'The Performance of a Type of Swirl Atomizer'," *Proceedings, Institution of Mechanical Engineers*, Vol. 169, 1955, pp. 101.

[6]Tipler, W. and Wilson, A.W., "Combustion in Gas Turbines, Paper B9," *Proceedings of Congress International des Machines a Combustion (CIMAC)*, Paris, 1959, pp. 897-927.

[7]Joyce, J.R., Shell Research Ltd., London, Rept. ICT 15, 1947.

[8]Watson, E.A., unpublished report, Joseph Lucas Ltd, London, 1947.

[9]Giffen, E. and Massey, B.S., The Motor Industry Research Association, England, Rept. 1950/5, 1950.

[10]Rizk, N.K. and Lefebvre, A.H., "Internal Flow Characteristics of Simplex Swirl Atomizers," *Journal of Propulsion and Power*, Vol. 1, May-June 1985, pp. 193-199.

[11]Rizk, N.K. and Lefebvre, A.H., "Prediction of Velocity Coefficient and Spray Cone Angle for Simplex Swirl Atomizers," *Proceedings of International Conference on Liquid Atomization and Spray Systems (ICLASS)*, 1985, Paper IV A/1.

[12]Lefebvre, A.H., *Gas Turbine Combustion*, McGraw Hill Book Co., New York, 1983.

[13]Lefebvre, A.H. and Miller, D., "The Development of an Air Blast Atomizer for Gas Turbine Application," College of Aeronautics, Cranfield, England, CoA-Rept.-AERO-193, 1966.

[14]Rizkalla, A. and Lefebvre, A.H., "The Influence of Air and Liquid Properties on Airblast Atomization," *Journal of Fluids Engineering*, Vol. 97, No. 3, 1975, pp. 316-320.

[15]El-Shanawany, M.S.M.R. and Lefebvre, A.H., "Airblast Atomization: The Effect of Linear Scale on Mean Drop Size," *Journal of Energy*, Vol. 4, July-Aug. 1980, pp. 184-189.

[16]York, J.L., Stubbs, H.E., and Tek, M.R., "The Mechanism of Disintegration of Liquid Sheets," *Transactions of ASME*, Vol. 75, No. 7, 1953, pp. 1279-1286.

[17]Hagerty, W.W. and Shea, J.F., "A Study of the Stability of Plane Fluid Sheets," *Journal of Applied Mechanics*, Vol. 22, 1955, pp. 509-514.

[18]Dombrowski, N. and Johns, W.R., "The Aerodynamic Instability and Disintegration of Viscous Liquid Sheets," *Chemical Engineering Science*, Vol. 18, 1963, pp. 203-214.

[19]Fraser, R.P, Dombrowski, N. and Routley, J.H., "The Atomization of a Liquid Sheet by an Impinging Air Stream," *Chemical Engineering Science*, Vol. 18, 1963, pp. 339-353.

[20]Rizk, N. and Lefebvre, A.H., "Influence of Liquid Film Thickness on Airblast Atomization," *Transactions of ASME, Journal of Engineering for Power*, Vol. 102, July 1980, pp. 706-710.

[21]Simmons, H.C., "The Prediction of Sauter Mean Diameter for Gas Turbine Fuel Nozzles of Different Types," *Transactions of ASME, Journal of Engineering for Power*, Vol. 102, No. 3, 1980, pp. 646-652.

[22]Giffen, E. and Muraszew, A., *The Atomization of Liquid Fuels*, Chapman & Hall Ltd., London 1953.

[23]Bird, A.L., "Some Characteristics of Nozzles and Sprays for Oil Engines," *Transactions of Second World Power Conference*, Berlin, Vol. 8, Sec. 29, No. 82, 1930, p. 260.

[24]Gellales, A.G., "Effect of Orifice Length/Diameter Ratio on Fuel Sprays for Compression Ignition Engines," NACA Rept. 402, 1931.

[25]Simmons, H.C. and Harding, C.F., "Some Effects of Using Water as a Test Fluid in Fuel Nozzle Spray Analysis," ASME Paper 80-GT-90, March 1980.

[26]Rizk, N.K. and Lefebvre, A.H., "Spray Characteristics of Simplex Swirl Atomizers," *Progress in Astronautics AIAA and Aeronautics: Dynamics of Flames and Reactive Systems*, edited by J.R. Bowen, N. Manson, A.K. Oppenheim, and R.I. Soloukhin, Vol. 95, 1984, pp. 563-580.

[27]Kutty, S.P., Narasimhan, M., and Narayanaswany, K., "Design and Prediction of Discharge Rate, Cone Angle, and Air Core Diameter of Swirl Chamber Atomizers," *Proceedings of 1st International Conference on Liquid Atomization and Spray Systems*, Fuel Society of Japan, Tokyo, Aug. 1978, pp. 93-100.

[28]Schmitt, R.L., Stevenson, W.H., and Simmons, H.C., "Optical Measurement of Liquid Film Thickness," *Proceedings of First International Congress on Application of Lasers and Electro-Optics*, 1982, pp. 31-35.

[29]Swithenbank, J., Beer, J.M., Abbott, D., and McCreath, C.G., "A Laser Diagnostic Technique for the Measurement of Droplet and Particle Size Distribution," AIAA Paper 76-69, Jan. 1976.