An experimental study of the influence of atomizer dimensions and injection conditions on discharge coefficient and spray angle is presented. Simplex pressure-swirl nozzles atomizing heavy oil have been examined. Twenty nozzles of different geometries have been investigated, including orifice diameters down to 0.45 mm. Inviscid theory results or published correlations valid for larger atomizers do not seem to apply for those of smaller dimensions, for which viscous effects are thought to play a major role. This role is analyzed, and new correlations are proposed for discharge coefficient and spray cone angle.

INTRODUCTION

Pressure-swirl nozzles are commonplace in numerous engineering applications in which a liquid must be broken down into droplets, such as in combustion, drying, or agriculture. Their practical importance explains the considerable number of studies on this type of atomizer that can be found in the scientific literature since the 1940s. Most of them analyze experimentally the performance of the atomizers. Droplet size is often the main subject of the experimental investigations. Discharge coefficient, spray angle, liquid film thickness, or velocity coefficient are also parameters of interest.

Most of the current knowledge on the behavior of pressure-swirl nozzles is of an empirical nature. The complexity of the processes taking place from liquid injection to spray formation hampers the development of satisfactory predictive methodologies.

Drop size predictions would require the modeling of the liquid sheet breakup process, which remains to a large extent a poorly understood phenomenon. Pressure-swirl nozzles pose the additional difficulty of the the internal flow prediction. No attempt at complete modeling of this flow has been published. The most comprehensive work on the subject is that by Dumouchel et al. [1,2], who nevertheless neglect the modeling of the air core.

The most common approach uses inviscid theory analysis of the flow [3,4]. Under certain simplifying hypotheses, flow parameters at the exit orifice can be expressed as a function of atomizer geometry and, more specifically, of the atomizer constant $K$. Therefore, parameters such as discharge coefficient, spray angle, or liquid film thickness can be calculated.
However, the flow inside a pressure-swirl nozzle is characterized by high velocities and small dimensions. Consequently, viscous effects, which are neglected in the inviscid theory, may play a significant role. Taylor [5] studied the boundary layers formed near the wall of the swirl chamber and at the air core interface. He concludes that, under certain conditions, most of the liquid emerges through one of the boundary layers. A recent theoretical analysis [6] indicates that boundary-layer effects can range from dominant to negligible depending on the injection pressure. Therefore, the inviscid theory approach can lead to important errors.

Comparisons between theory and empirical correlations show the effect of viscosity. The formation of boundary layers may cause, among other things, the reduction of tangential momentum and, therefore, an increase in film thickness at the orifice. As a consequence, measured discharge coefficients are usually higher than those predicted theoretically, with some exceptions reported by Dombrowski and Hasson [7]. Apart from these considerations, published experiments tend to show that differences are not very important, and the predictions from the inviscid theory are usually accepted as reasonably good estimates [7,8].

The results of the present work display a significant disagreement with estimates from the theoretical analysis. The atomizers used were designed for an experimental study of heavy oil combustion. The design was conducted in accordance with inviscid flow theory and published correlations. The nozzles were expected to perform within certain ranges of discharge coefficient, cone angle, and drop size. However, in the first tests, flow rates more than twice the calculated ones were measured. Therefore, the atomizers had to be redesigned, reducing their dimensions. A systematic study of the influence of geometry and injection conditions on discharge coefficient $C_D$, cone angle $2\theta$, and drop size was conducted. An important departure of $C_D$ and $2\theta$ from the theory was observed, and is apparent in the results reported below.

In Section 2 the experimental facilities and measuring techniques are described. Section 3 presents the trends of the discharge coefficient $C_D$ as a function of test variables and compares the present measured data with available theoretical predictions and results from previous experimental studies, discussing possible explanations for the observed discrepancies. Spray cone-angle measurements, comparison with existing correlations, and a discussion of the influence of viscosity on this variable are included in Section 4. Tentative conclusions are drawn in Section 5.
2. EXPERIMENTAL FACILITIES

The test rig used in the present experiments was designed for the atomization of heavy oil using large-capacity pressure nozzles. A maximum injection pressure of 80 bar, oil temperatures up to 150°C, and a flow rate up to 700 liters/h can be reached. However, it was easily adapted to the conditions of the present study ($Q = 20–60$ liters/h, $\Delta P = 12–20$ bar). A detailed description of the facilities can be found in [9].

The atomizer is vertically oriented, injecting the liquid downward. The spray is discharged into an open quiescent environment. The cloud of droplets is collected by an extraction system placed under the atomizer.

The atomizers are simplex pressure-swirl nozzles and consist of three interchangeable parts:

- An orifice plate (Fig. 1), containing the conical swirl chamber and the exit orifice.
- Inlet ports (Fig. 2)—three rectangular tangential slots drive the liquid to the swirl chamber.
- An assembly cap (Fig. 3), which holds the orifice plate and inlet ports and attaches them to the barrel.

Several parts with different dimensions were manufactured, covering the following intervals:

- $D_o = 0.44–1.09$ mm
- $A_i = 0.6745–1.0096$ mm$^2$
- $K = 0.11–0.39$

A good surface finish turned out to be essential. Even microscopic imperfections caused deviation of the spray axis. The exact dimensions and the quality of the surfaces were checked with the aid of a microscope.

The test fluid was heavy oil customarily used in utility boilers. Its physical properties were determined as a function of temperature (Table 1). The oil temperatures were 100, 110, 120, and 135°C. The pressures selected for injection were 12, 14, 17, and 20 bar.

A total of 133 experimental runs were performed with different combinations of the variables $D_o$, $A_i$, $\Delta P$, and $T_{fo}$, corresponding to 20 atomizer geometries.

The spray angle was measured using low-speed photography. Plates 1 and 2 were
obtained for the same spray with two different exposure times. In Plate 1 the movement of the spray is frozen, showing the appearance and growth of disturbances on the liquid sheet and its final disintegration into drops. Plate 2 is an example of the photographs with exposure times of 1/60 s used to determine the spray cone angle. The exposure time is long enough to record the average location of the envelope of the spray. The reported angle corresponds to the tangent to the spray at an axial distance of about 3 mm from the orifice (nozzle geometry made it impossible to record the first millimeters). Nevertheless, angle variations are assumed to be negligible over that distance, and that value is taken as the maximum angle of the spray. Differences between angles measured on different days under the same experimental conditions do not exceed 4°.
MEASUREMENTS FOR SMALL PRESSURE-SWIRL NOZZLES

The discharge coefficient was calculated using the expression

\[ C_D = \frac{Q}{A_o (2 \Delta P \rho_0)^{0.5}} \]

The oil flow rate was measured with a positive displacement meter. The reading variations were less than 0.2 liter/h for repetitions of the same experiment, giving a repeatability better than 1% for the reported values of \( C_D \).
Plate 1 Photograph of the spray with an exposure time of 0.5 µs. Atomizer A-840a + P-50a; \( \Delta P = 12 \text{ bar}; T_{in} = 120^\circ \text{C} \).

Plate 2 Photograph of the spray with an exposure time of 1/60 s. Atomizer A-840a + P-50a; \( \Delta P = 12 \text{ bar}; T_{in} = 120^\circ \text{C} \).

3. DISCHARGE COEFFICIENT

The values of \( C_D \) as a function of the injection pressure are shown in Fig. 4 for several atomizers.

The atomizers are designated as \( A-x + P-y \), \( x \) and \( y \) indicating the total inlet ports section and orifice diameter, respectively. For instance, part A-840 has a nominal total ports section of 0.840 mm\(^2\), and plate P-80 has a nominal orifice diameter of 0.80 mm.

According to the inviscid theory, \( \Delta P \) should have no influence on the discharge coefficient. The curves in the graph are nearly horizontal, but they exhibit a slightly ascending slope. The reason for this increase could be ascribed to a reduction in relative head losses as the velocity increases. As a consequence of the small dimensions of the nozzle and the high viscosity of the liquid, the characteristics of the internal flow depend on the injection pressure in the range of the tests conducted. A higher pressure would be required to obtain values of \( C_D \) independent of \( \Delta P \) for these atomizers.

The variation of \( C_D \) with oil temperature is represented in Fig. 5. The evolution of \( C_D \) and \( \theta \) with temperature should be attributed to variations in viscosity, which changes over 250% within the temperature interval, and not to the density or surface tension, which change less than 6%. In fact, all the curves in Fig. 5 exhibit the maximum in \( C_D \) that is characteristic of pressure-swirl atomizers as the fluid viscosity decreases. At low
temperatures, the viscous friction prevents the formation of a central air core and the liquid exits as a full jet. The flow rate is a monotonically increasing function of temperature. As temperature increases, the tangential velocity of the liquid inside the swirl chamber causes the appearance of the air core, and the liquid emerges as an annular empty jet. The consequence is the reduction of the effective exit area for higher temperatures. Therefore, $C_D$ follows a decreasing trend with viscosity, as can be seen on the right-hand side of the curves in Fig. 5.

The changes in discharge coefficient with $A_t$ and $D_o$ are shown in Figs. 6 and 7. All the measurements of $C_D$ are displayed as a function of the atomizer constant in Fig. 8. The graph also contains the inviscid theory estimates for the same experimental conditions, as well as data points generated from the following published correlations:
Fig. 6 Effect of $D_o$ on $C_D$. Inlet ports A-630a. $T_{so} = 100^\circ$C.

Fig. 7 Effect of $A_i$ on $C_D$. Plate P-50a. $T_{so} = 100^\circ$C.

Jones [8]:

$$C_D = 0.45 \left( \frac{D_o \rho_i V}{\mu_i} \right)^{-0.02} \left( \frac{L_o}{D_o} \right)^{-0.03} \left( \frac{L_i}{D_i} \right)^{0.05} \left( \frac{A_i}{D_o D_i} \right)^{0.52} \left( \frac{D_i}{D_o} \right)^{0.23} \quad (1)$$

Rizk and Lefebvre [10]:

$$C_D = 0.35K^{0.5} \left( \frac{D_i}{D_o} \right)^{0.25} \quad (2)$$
Fig. 8 Comparison among present measurements of $C_D$, inviscid theory predictions, and available correlations.


$$C_D = 1 - \frac{2}{\pi} \arctan \left( 2.13 \left\{ \frac{(4/\pi)K + 1.2}{[(4/\pi)K + 1]^2 - 1} \right\} e^{-0.12(D_o/\sqrt{\lambda})} \right)$$

Despite the wide variety of experimental conditions, the results lie in a narrow band. This is an indication of the influence of $K$ on the flow characteristics, as predicted by the theory. However, discharge coefficients measured in this work are much greater than those estimated from previous correlations and from the theory.

Published experimental results for $C_D$ are usually larger than the theoretical estimates. The difference is traditionally explained by the reduction in tangential momentum caused by the viscous forces. The consequence is an increase of the liquid film thickness at the orifice and, therefore, of the effective exit cross section.

However, Fig. 8 indicates that departures from the theoretical conditions are much more important for the experiments reported in this work. When compared with the published correlations estimates, good agreement is observed only for the atomizers with the largest orifice diameters ($C_D < 0.32$ in Fig. 8). Larger differences appear as the orifice diameter becomes smaller. This change in behavior with variations in the scale of the atomizer is discussed next.

The application of multiple regression techniques to all the data points yields the following correlation:

$$C_D = 1.323 \times 10^{-3} K^{0.29} D_o^{-0.82} \Delta P^{0.03}$$

The variables are expressed in SI units. The quality of the fit is shown in Fig. 9.

As indicated previously, the trends of $C_D$ were observed to depend on the range of $D_o$ considered. For this reason, Eq. (4) does not represent the $C_D$ dependence accurately.
Should only the data points for orifice diameters smaller than 0.8 mm be included, the following correlation is obtained:

\[ C_D = 1.335 \times 10^{-2} K^{0.3} D_o^{-0.41} \Delta P^{0.07} \]  
(5)

While the remaining terms are almost identical in both expressions, Eqs. (4) and (5), the exponent of \( D_o \) is significantly different. The scatter of the data with respect to Eq. (5) is shown in Fig. 10. This graph also includes the data for atomizers with \( D_o > 0.8 \) mm, which did not contribute to the calculation of the fit. For \( D_o > 0.8 \) mm, Eq. (5) significantly overestimates the values of \( C_D \), with larger deviations for the smaller values of \( C_D \), i.e., the larger orifices.

Published correlations for orifice diameters ranging from around 1 mm [10] to 5 mm [8] show similar exponents, hence suggesting that all the atomizers in that scale interval display similar trends. However, the results reported here prove that this is not the case for smaller orifices. It seems logical to conclude, therefore, that the flow inside the atomizer exhibits different behavior depending on its size. The reason for these discrepancies is thought to be the dominant influence of viscous effects in the flow inside atomizers with smaller dimensions.

Viscosity, however, does not appear in the calculated correlations because \( C_D \) displays a maximum in the temperature interval investigated (see Fig. 5). Including viscosity as an additional variable in the correlations would therefore be meaningless. Cone angle correlations, on the other hand, will demonstrate the large influence of viscosity on the flow inside the atomizers.

4. SPRAY CONE ANGLE

Available studies do not allow one to establish a general trend of the influence of the injection pressure on the cone angle. Dodge and Biaglow [13] did not find any noticeable effect. De Corso and Kemeny [14] concluded that increases in \( \Delta P \) cause spray
contraction as a result of air entrainment, but have no influence on the angle at the exit of the atomizer. The measurements of Rizk and Lefebvre [15] and of Chen et al. [16] show a clear increase of the angle with $\Delta P$. The review work by Lefebvre [17] includes some plots of measurements of cone angle as a function of injection pressure showing a maximum. This diversity of trends suggests that the effect of $\Delta P$ is not always the same, but might depend on some other parameters, such as the atomizer exact geometry or dimensions.

Some examples of the variation of cone angle with injection pressure are shown in Fig. 11. An increase of $2\theta$ with $\Delta P$ is apparent, although the magnitude of this increment is not the same for all the cases.

A rise in the oil temperature results in an important increase in cone angle (Fig. 12). This trend is in agreement with previous studies [7,8,15]. However, the influence of viscosity is remarkably higher in the present work, as discussed in what follows.

As for $C_D$, a comparison is presented between measurements and predictions from the inviscid theory and from published expressions:


$$
2\theta_o = 180^\circ - 2 \arctan \left[ \frac{4}{\pi} K (1.37 + 26.9e^{-11.1(\sqrt{\rho_0/\rho_1})}) \right]
$$

Rizk and Lefebvre [15]:

$$
2\theta_o = 6K^{-0.15} \left( \frac{\Delta P D^2 \rho_1}{\mu^2} \right)^{0.11}
$$

The results for cone angle are much more scattered than those for $C_D$ due to the influence of injection pressure and, particularly, of the viscosity. Therefore, in order to
provide a clearer picture, the results are separated into four graphs (Figs. 13a, 13b, 13c, 13d), corresponding to the four oil temperatures. Although some dispersion is still apparent in the graphs, this strategy makes it possible to draw some tentative conclusions:

- Inviscid theory predictions produce higher values than those obtained from published correlations and the results of the present work.
- The expression proposed by Rizk and Lefebvre [15] provides good estimates for $K \geq 0.2$ and $T_{fo} = 100^\circ C$.
- For $K < 0.2$, i.e., plates with larger orifices, the discrepancy between measure-
MEASUREMENTS FOR SMALL PRESSURE-SWIRL NOZZLES

Fig. 13 Comparison among present measurements of spray cone angle, inviscid theory predictions, and available correlations: (a) $T_{jo} = 100^\circ$C; (b) $T_{jo} = 110^\circ$C; (c) $T_{jo} = 120^\circ$C; (d) $T_{jo} = 135^\circ$C.

The large differences between theory and experiments can also be explained by the reduction in the tangential component of the liquid velocity caused by the viscous friction. This conclusion is confirmed by the clear convergence of measurements and the theoretical curve as oil temperature increases.

The expression proposed by Rizk and Lefebvre [15] provides good estimates of the cone angle for $K \geq 0.2$ and $T_{jo} = 100^\circ$C. However, despite including viscosity, the increase of $2\theta$ is not followed by this correlation and, for $135^\circ$C, differences from the
present data are very important. Therefore, that expression cannot be considered to represent the behavior of the atomizers tested in this work.

The expression of Tanasawa and Kobayasi [11] includes only geometric parameters and cannot predict the effect of viscosity.

Multiple regression calculations for spray cone angle also showed that the exponent affecting the exit orifice diameter depends on the range of \( D_o \) over which calculations are made, as already observed for \( C_D \). The expression obtained when all the data points are considered is (in SI units)

\[
\theta = 16.156 K^{-0.39} D_o^{1.13} \mu_l^{-0.9} \Delta p^{0.39}
\]
Figure 14 shows the degree of agreement between the correlation and the measurements.

When the experimental points obtained for $D_o > 0.8$ mm are excluded, the best fit is given by

$$2\theta = 0.2197 K^{-0.39} D_o^{0.63} \mu_l^{-0.91} \Delta P^{0.42}$$  \hspace{1cm} (9)

Differences between measurements and estimates are smaller for this expression (Fig. 15). However, cone angle is underestimated for orifice diameters larger than those in the considered range.

With the exception of $D_o$, the powers affecting $K$, $\mu_l$, and $\Delta P$ remain remarkably constant in both equations. Therefore, the influence of these variables seems to be approximately the same over the range of atomizers used in the tests.

The powers in both correlations are much larger than those in the expression proposed by Rizk and Lefebvre [15]. The second term in Eq. (7) is the Reynolds number at the exit orifice, and it appears as $2\theta \sim Re_o^{0.22}$. If variables in Eqs. (8) and (9) are grouped in a similar way, it results in $2\theta \sim Re_o^{0.9}$. The important difference again suggests the decisive influence of viscous effects on the flow inside the atomizer for the experiments reported here when compared with previous results.

5. CONCLUSIONS

An extensive series of measurements of discharge coefficient and spray cone angle for pressure-swirl nozzles atomizing heavy oil have been presented. The influence of oil temperature, injection pressure, and nozzle geometry has been examined. The atomizer dimensions belong to a range not covered by the available open literature. The most significative findings are as follows.
Measurements of $C_D$ and $\theta_0$ display much higher deviations from the inviscid theory than reported for larger atomizers. The application of either theoretical estimations or published correlations to the design of small-size nozzles would result in very important errors.

Empirical correlations for discharge coefficient and spray cone angle have been obtained. The expressions derived when all the measurements are included [Eqs. (4) and (8)] are different from the equivalent ones when only results corresponding to the smaller exit orifices are considered [Eqs. (5) and (9)].

The observed differences in the behavior of small-size atomizers in relation to previous studies is attributed to the significant role of viscous effects. The large influence of viscosity is corroborated by the magnitude of its power in the spray cone angle correlations.

### REFERENCES


