DROP SIZE MEASUREMENTS IN HEAVY OIL SPRAYS FROM PRESSURE-SWIRL NOZZLES

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The performance of pressure-swirl nozzles atomizing heavy oil is examined using laser diffractionmetry. Errors due to multiple scattering in dense sprays are avoided by the specific arrangement of the laser-diffraction particle size analyzer adopted in the present work. A parametric study of the influence of injection conditions and nozzle internal dimensions on mean drop size has been conducted, and empirical correlations are proposed. The results display significant differences with respect to previous studies, which are considered to be related to the small dimensions of the atomizers tested (orifice diameters down to 0.45 mm). The relevant role of viscous effects on the flow inside small-size nozzles is thought to be the factor responsible for their different behavior.

INTRODUCTION

Fuel injection in industrial boilers and furnaces and in internal combustion engines is one of the main areas of application of liquid atomization. The spray characteristics are a key factor for the performance of those systems, as they determine the spatial distribution of fuel and the distance required for its evaporation. That is especially true for low-volatility fuels such as heavy oil, where unburned carbon emissions depend largely on spray drop size [1, 2]. Hence, a precise knowledge of the behavior of the atomizers can provide valuable help for the optimization of combustion systems.

In particular, pressure-swirl nozzles are widely used in combustion and many other engineering areas; the investigation of their performance has been the objective of a large number of studies during the last half-century. However, due to the complexity of the phenomena involved, no satisfactory predictive methodologies have been developed, and most of the available knowledge comes from empirical research work.

A detailed modeling of the flow inside the atomizer would be required in order to determine the conditions of the liquid sheet at the exit orifice. The lack of those results has traditionally been replaced by simplified models based on inviscid flow theory. The method described in [3, 4] has been used since the 1950s to obtain estimates of discharge coefficient, spray angle, and liquid film thickness. A slightly more sophisticated approach is the one recently proposed by Yule et al. [5], which makes some of the original assumptions unnecessary. In all the cases, flow parameters at the exit orifice can be expressed as a function of the internal dimensions of the atomizer.
A number of empirical correlations relating those parameters with the nozzle geometry, liquid properties, and operating conditions have been obtained from experimental studies. The estimates for discharge coefficient and spray cone angle obtained using inviscid theory display in many cases a reasonable agreement with the results from those studies [6, 7]. However, a previous study [8] demonstrates that both the theoretical expressions and the commonly used empirical correlations for $C_D$ and $\theta$ fail to predict the performance of small-size atomizers, where viscous effects play a dominant role. Therefore, even though they constitute a valuable design tool for most of the range of interest, those expressions are not of universal applicability and can be considered strictly valid only for the conditions in which they were obtained.

An even more complex problem is the subsequent disintegration of the conical liquid sheet issuing from the atomizer. The breakup of the sheet into threads and their final disintegration to form drops are poorly understood phenomena. Different theories on the mechanisms involved are still being investigated. Some early studies [9, 10] were devoted to the analysis of the growth of sinusoidal and dilational waves on the liquid sheet as a consequence of the interaction between surface tension forces and the relative motion of the liquid with respect to the surrounding air. More recently, some studies [11—13] have shown the appearance of a cellular structure on the sheet due to the formation of both streamwise and spanwise ligaments, which is attributed mainly to the vorticity dynamics in the liquid and in the air. Lozano et al. [13] suggest that vorticity present within the bulk of the liquid resulting from the large velocity gradients inside the nozzle can also play a very relevant role in the disintegration process.

For the specific case of pressure-swirl nozzles, Taylor [9] postulates the appearance of disturbances in the issuing conical sheet as a consequence of the nature of the flow inside the atomizer. For example, a lack of symmetry in the liquid supply through the tangential channels or air core oscillations would lead to nonuniformities in the liquid sheet thickness. The measurements of Dombrowki and Tahir [14] demonstrate the presence of significant fluctuations in the liquid film thickness at the exit orifice, and that they are related to disturbances originating along the surface of the air core. Those results suggest that the nature of the internal flow should also be taken into account in the analysis of the disintegration process in pressure-swirl atomizers.

<table>
<thead>
<tr>
<th>NOMENCLATURE</th>
<th></th>
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<tbody>
<tr>
<td>$A_i$</td>
<td>total inlet slots area</td>
</tr>
<tr>
<td>$A_e$</td>
<td>exit orifice area</td>
</tr>
<tr>
<td>$C_D$</td>
<td>discharge coefficient</td>
</tr>
<tr>
<td>$D_s$</td>
<td>swirl chamber diameter</td>
</tr>
<tr>
<td>$D_e$</td>
<td>exit orifice diameter</td>
</tr>
<tr>
<td>$D_{10}, D_{50}, D_{90}$</td>
<td>drop diameters under which 10%, 50%, and 90%, respectively, of the liquid volume is atomized</td>
</tr>
<tr>
<td>$e_i$</td>
<td>liquid film thickness at the exit orifice</td>
</tr>
<tr>
<td>$K$</td>
<td>atomizer constant $=$ $A_e/D_e$</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>injection pressure</td>
</tr>
</tbody>
</table>
Experimental studies are still the only reliable source of knowledge of the drop size distribution in sprays. A variety of empirical correlations have been developed to express mean drop size as a function of the experimental parameters. Some of them are mentioned later in this article. A comparison among the available correlations shows significant variability. That is not surprising if the wide differences in experimental conditions and atomizer designs are taken into consideration. In particular, since the characteristics of the flow at the exit orifice for small nozzles display rather different behavior with respect to other studies [8], the same difference should be reflected regarding drop size. That assertion has been corroborated in the present work, where the spray drop size obtained with small atomizers, as well as its sensitivity to different variables, have been analyzed.

The experimental facilities used in this work are described in the following section, where special attention is given to the arrangement adopted for the laser diffractometer. Then we provide a characterization of the sprays, based on photographs and measurements of drop size distribution at different points of the spray. A parametric study of the influence of oil injection pressure and temperature and of the nozzle geometry on mean drop size is presented next. Empirical correlations have been developed and are compared with previously published results. The final section summarizes the main results and offers some tentative conclusions.

EXPERIMENTAL FACILITIES

Atomization Rig

The experiments are conducted in an atomization rig that provides accurate control of the operating conditions and allows detailed study of the spray. The atomizer is vertically oriented, injecting the liquid downward. The spray is discharged into an open, quiescent environment. This configuration avoids possible disturbances of the flow by the influence of gravity or the presence of walls, and provides unrestricted optical access. The oil spray is collected by an extraction system placed under the atomizer, so that undesirable recirculation of drops is avoided. The system is adjusted by means of specific drop-size data checks in order to avoid influencing the spray structure through excessive suction velocity. An inertial separator eliminates the liquid drops before they reach the exhaust fan.

Drop size distributions are measured by laser diffractometry, using a Malvern 2600 particle size analyzer. The location of the point where the laser beam crosses the spray can be adjusted in two directions. The laser diffractometer is mounted on a traversing system that allows horizontal displacements at both sides of the spray axis, whereas the axial coordinate can be controlled by the vertical position of the atomizer.

The heavy-oil feeding system was designed for the test of large-capacity pressure nozzles (injection pressure up to 80 bar, flow rate up to 700 liters/h). Slight modifications allow accurate control in the range of conditions of the present study ($\Delta P = 12–20$ bar, $Q = 20–60$ liters/h).

Simplex pressure-swirl nozzles with different geometries have been tested. The atomizers consist of three interchangeable parts:

1. The orifice plate (Fig. 1) contains the conical swirl chamber and the exit orifice.
2. Three rectangular tangential slots (Fig. 2) drive the liquid to the swirl chamber.

This part also includes a central orifice for the measure of pressure at the axis of the chamber.
3. The assembly cap (Fig. 3) holds the orifice plate and inlet ports and attaches them to the barrel.

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

- \( D_o = 0.44\text{--}1.09 \text{ mm} \)
- \( A_f = 0.6745\text{--}1.0096 \text{ mm}^2 \)
- \( K = 0.11\text{--}0.39 \)

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. A good surface finish along the oil paths turned out to be essential, specially at the exit orifice. Even microscopic imperfections caused deviation of the spray axis. The exact dimensions (which are not exactly the same as the nominal values) 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).

Drop size measurements were performed in 105 runs for different combinations of the variables \( D_o, A_f, \Delta P \), and \( T_{so} \), covering 20 atomizer geometries. The oil temperatures were 100, 110, 120, and 135°C. The pressures selected for injection were 12, 14, 17, and 20 bar. Both parameters are measured by transducers installed at the inlet of the oil barrel.

### Setup for the Laser Diffractometer

The arrangement adopted for the Malvern 2600 in the present experiments is represented in Fig. 4 and explained in what follows.

A 600-mm lens was selected, providing a measuring range between 11.6 and 1128 \( \mu \text{m} \). A shorter focal length could seem desirable in order to improve the resolution for smaller sizes (e.g., the range for a 300-mm lens is 5.8--564.0 \( \mu \text{m} \)). However, the volume of liquid under 11.6 \( \mu \text{m} \) was typically 0.5%, exceeding 1% in very few cases, and there are some reasons that support this choice. In the first place, it allows a long distance between
the detector and the spray, which minimizes the risk of oil deposition on the lens surface. According to the expression given in [15], a maximum length of 944 mm is possible for the parameters of the equipment used in the present tests. A distance of 660 mm between the lens and the spray centerline was selected. The same configuration using a 300-mm length would have caused vignetting error, i.e., the biasing of the measured distributions toward larger sizes due to the loss of a fraction of the signal from the smaller drops [15].

On the other hand, the largest-size band (523.2–1128 µm) was not considered in the calculations. An abnormally high volume fraction was detected in that interval, whereas the percentage for the previous bands was much lower as a consequence of a sharp decay in the distribution. That was attributed to the beam steering effect reported in [16, 17], which causes the deviation of the laser beam due to changes in refraction index along its path. As a consequence, the unscattered light can impinge on the detectors located close to the center, causing the device to read an erroneous proportion of large drops. In the present work, variations of the refraction index can be produced by the high temperature of the oil, which could result in temperature and/or fuel vapor gradients within the volume of the spray. Had a 300-mm lens been used, this effect would have invalidated the results in the interval 261.4–564 µm, where significant levels were in many cases detected.

As indicated in Fig. 4, two tubes are assembled to the frontal lenses of the detector and the laser source, respectively, in order to keep them free from oil deposition. A forced air stream prevents the drops from entering into each tube. A compressed air line with a disengager provides a clean and dry air flow, so that interferences with the laser beam are avoided. Since the tube on the detector is far away from the spray, it is not expected to cause any flow disturbance. Nevertheless, some comparisons were performed with and without the tube/air stream on the detector in order to check possible
influences of both elements. The root mean square of the differences in mean drop size was 3.4%, which is better than the repeatability of the results, and confirms that their influence is negligible.

Another difficulty that had to be faced in the present experiments was the appearance of multiple scattering due to the high concentration of drops in the spray. This effect has been reported in a number of works [17—19] and is described briefly here. Drop sizing by laser diffractometry is based on the light-scattering pattern produced by a spherical particle under certain hypotheses (Fraunhofer scattering). The algorithms for a cloud of particles assume that the energy scattered by each individual drop reaches the detector undisturbed by the rest of the drops. Should this not be the case, multiple scattering takes place and the algorithm is no longer valid, as the results would be biased toward the smaller sizes. Obviously, multiple scattering always occurs when the laser beam goes through a spray. However, its consequences are negligible if the number of drops within the measuring

Table 1  Physical Properties of Heavy Oil

<table>
<thead>
<tr>
<th>( T_w (^\circ C) )</th>
<th>( \rho_w (kg/m^3) )</th>
<th>( \mu_s (Pas) )</th>
<th>( \sigma_s (N/m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>983</td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>977</td>
<td>0.735</td>
<td>0.0337</td>
</tr>
<tr>
<td>40</td>
<td>979</td>
<td>0.354</td>
<td>0.0323</td>
</tr>
<tr>
<td>50</td>
<td>966</td>
<td>0.222</td>
<td>0.0316</td>
</tr>
<tr>
<td>60</td>
<td>959.5</td>
<td>0.126</td>
<td>0.0309</td>
</tr>
<tr>
<td>70</td>
<td>951</td>
<td>0.080</td>
<td>0.0302</td>
</tr>
<tr>
<td>80</td>
<td>0.046</td>
<td>0.0325</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>0.033</td>
<td>0.0289</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.025</td>
<td>0.0285</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>0.019</td>
<td>0.0278</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>
The error is considered to become significant when the obscuration is higher than 0.3, i.e., when over 50% of the laser beam deviates from its original trajectory before reaching the detector. The first tests in the present work displayed obscurations in the range 0.2—0.7. Therefore, in some cases the results could be biased due to multiple scattering.

Different solutions have been adopted in previous works in order to avoid measurement errors in dense sprays. References [18, 19] propose some corrections on the angular energy distribution measured by the detector which take into account the influence of multiple scattering. Dodge and Biaglow [17] developed empirical correlations that provide the real Rosin-Rammler parameters as a function of the measured values and the obscuration. The expressions were obtained by comparing the drop size distribution in a spray with the results when a number of sprays identical to that one are aligned so that obscuration can be varied.

In the present study the obscuration was kept below 0.5 by including in the measuring volume only a radius of the spray instead of a full diameter. Obscuration can be expressed as [19] \( Ob = 1 - e^{-tL} \), where \( t \) is the particle field turbidity (related to the concentration and scattering properties of the particles [19]) and \( L \) is the length of the measuring volume (i.e., a diameter in a round spray). If the laser beam goes only through a radius \((L/2)\), the new obscuration is given by \( Ob' = 1 - (1 - Ob)^{0.5} \). For instance, for \( Ob = 0.7 \), the new obscuration is only \( Ob' = 0.45 \).

Figure 4 shows the arrangement used for the measurement over a half-spray. The function of the tube on the laser source is, besides the protection of the optics, acting as a "light guide" that conveys the beam undisturbed up to the spray axis.

The main uncertainties in the proposed configuration come from the possible disturbances that the tube and the issuing air stream can induce on the spray. A series of tests were conducted for the assessment of that source of error. Measurements at the same point were
performed with and without the light guide and its associated air flow. In the second case, the laser beam crosses a full diameter of the spray. That was repeated for a variety of experimental conditions and measuring locations in order to cover a wide range of obscuration levels. Figure 5 displays the results in terms of the relative change in Sauter mean diameter (SMD).

When the obscuration is below 0.5, the influence of multiple scattering is expected to be negligible and the measurements over a radius and over a diameter should yield the same results. Figure 5 shows that the differences in that range are between -3% and 8%, with an average overestimation of SMD of the order of 4% due to the presence of the light guide. For higher obscurations, the measured SMD for a spray radius are higher than those obtained over a full diameter. The difference reaches 26% for an obscuration of 0.7. These results are in agreement with the estimates of the bias due to multiple scattering reported by Felton et al. [18], and are an indication of the severe errors that can be produced.

The use of the light guide was demonstrated to be an effective way to eliminate that error source, as it allows us to perform all the measurements with obscurations lower than 0.5. The proposed arrangement is expected to give a slight overestimation in mean drop size (around 4%). That could be a consequence of drop coalescence due to impingement on the tip of the tube or to the disturbance of the flow by the air stream coming out of the light guide. There is also the possibility that the bias due to multiple scattering is not completely negligible at obscurations in the range 0.3–0.5, and that drop size measurements over a full diameter are slightly underestimated.

As in the case of the detector lens, an air flow through the tube has to be maintained in order to prevent oil deposition on the optical elements. In the case of the laser source, the air stream also turns out to be essential for obtaining reliable measurements. Without air coming out of the light guide, a cloud of droplets can be seen inside the tube, as indicated by a visible scattering of the laser beam. Those drops are also included in the measuring volume and influence the results, as some tests demonstrated. The results under some

![Figure 5](image-url)
conditions were: SMD = 48.6 µm, Ob = 0.28. After the air supply was switched off, the values changed to SMD = 38.3 µm, Ob = 0.39. The increase in obscuration confirms the inclusion of a higher number of drops in the measuring volume. The mean drop size decreases because, as could be expected, the smaller droplets are preferentially entrained into the recirculating flow created inside the tube. Therefore, an air flow must be maintained through the light guide. The flow rate is adjusted by a needle valve at the minimum level where no droplets can be seen inside the tube. As a result, no visible disturbances are noticed in the spray. The measurements presented in Fig. 5 are performed under those conditions, and demonstrate that the influence of the air flow, if any, is very small.

A similar arrangement has been used previously [20, 21]. In those cases, the light guide was not aligned with the spray axis, but its tip was located some distance behind the center (12 mm in [20], 10 mm in [21]), so that the laser beam spanned more than a half-diameter. A forced air flow through the tube was not used in [20, 21].

Drop Size Parameters

Among the available functions, the Malvern-instrumen model-independent algorithm was selected to represent drop size distributions. It includes 15 parameters corresponding to the same number of size bands. Comparisons with the Rosin-Rammler function shows that the model-independent algorithm provides the best fits.

The results of the experiments are analyzed in terms of the Sauter mean diameter (SMD), but some values of volume mean diameter (VMD) are also reported. The parameter known as Span (Δ) is used as an indicator of the width of the distribution.

No definite criterion has been found about the most representative region of the spray in order to characterize its fineness by a single measurement. Some works report measurements taken at a long axial distance from the nozzle [6, 22], while the nearest possible location has been selected in other cases [17, 23]. However, the measurement location can influence the results, because mean drop size displays significant changes with axial distance and the curves are not always parallel. In some cases, the analyses based on the SMD obtained at two different axial locations can lead to opposite conclusions.

In the present study, the average SMD of the spray, SMD, is used. For each run, at least six measurements are performed along the spray axis, at distances from the nozzle between 3.5 and 25 cm. An average drop size distribution is obtained by numerically integrating the six individual distributions along the axial coordinate. SMD is then calculated from this averaged distribution. This parameter is an estimate of the SMD that would be obtained if the measuring volume is an axial section of the spray extending from an axial distance of 3.5 cm to 25 cm. SMD allows a global characterization of the spray, and its use eliminates the uncertainties due to variations in the axial evolution of the drop size distribution for different cases. An additional benefit is that this averaging procedure reduces the effect of any random error associated to the measurement process.

An analysis similar to the one presented here for SMD has also been performed for the minimum SMD detected along the axis in each test. Comparisons between the parameters display similar trends, with a slightly higher consistency when using SMD. Repeatability of the results of drop size has been studied from over 100 measurements performed on different days. The root mean square (rms) of differences is 6.2% for single-point SMD values, with a maximum variation of 11.1%. The rms for SMD is 5.3%, while the maximum difference is 9.3%. 
CHARACTERIZATION OF THE SPRAYS

Visualization of the Spray

A light source providing a 0.5-µs pulse allows us to freeze the spray motion completely and to record a sharp image of the sheet breakup region. Plates 1–5 show a sequence of the evolution as the injection pressure increases (the 25.5-mm nozzle diameter provides a reference for the actual dimensions of the spray).

- At very low pressures, the liquid emerges as a round jet, in which swirling motion is not noticeable.
- Plate 1 (DP = 5 bar). The tangential velocity of the liquid at the exit orifice becomes higher, and the jet looks like a "twisting ribbon." Downstream, the liquid accumulates in thick rims, due to surface tension forces, that are joined by a thin membrane. Some ripples appear and grow on the rims, which finally disintegrate, showing the typical aspect of the Rayleigh breakup regime.
- Plate 2 (DP = 8 bar). The ribbon becomes wider and forms three edges, probably corresponding to the three tangential slots. Again, thin membranes are surrounded by thick rims. At some distance, two different disturbances appear. The rims ripple and break, and the contraction due to surface tension forces causes those discontinuities to pierce the membrane. On the other hand, waves created on the sheet grow rapidly and break it into filaments. The photograph suggests that the second mechanism is mainly responsible for the final disintegration.
- Plate 3 (DP = 15.5 bar). At some injection pressure the tangential velocity at the exit orifice is high enough to create the air core, and the oil emerges as a conical sheet. The initial expansion is attenuated and, finally, the sheet converges again due to the surface tension forces (bubble or onion stage). The sheet displays a smooth surface until, at the final part, the first waves appear and grow rapidly, leading to the disintegration into filaments and large drops.
- Plate 4 (DP = 16.5 bar). An increase in injection pressure results in a higher sheet velocity caused by the rise in flow rate and by the smaller film thickness. Perturbations appear earlier on the bubble surface, and disintegration takes place before it converges (tulip stage). Plate 4 shows the presence of nearly sinusoidal waves, which break the sheet into ribbons around one wavelength in width.
- Plate 5 (DP = 20 bar). At high injection pressures the breakup region suddenly moves back close to the nozzle and the smooth, tulip shape is no longer visible. This photograph shows the typical aspect of the sprays studied in the present work. The scale of the perturbations is much smaller, resulting in an irregular appearance. The intermediate stage of filament formation is again visible, but the final cloud is much more uniform and consists of smaller drops than those in Plate 4.

The sequence described was observed only at oil temperatures below 100°C. For higher temperatures, the stages were visible during the first instants of atomization, after a period without oil injection through the nozzle. Afterwards the breakup region suddenly changed, and disintegration started at short distances from the nozzle. These observations suggest that the formation of a smooth conical sheet is possible (under the present operating conditions) only when the oil viscosity is high enough to damp and delay the growth of the liquid sheet disturbances.
Plates 1–5 Spray photographs at different injection pressures with an exposure time of 0.5 μs. Atomizer A-630b + P-30a; $T_m = 93.5^\circ$C. (1) $\Delta p = 5$ bar; (2) $\Delta p = 8$ bar; (3) $\Delta p = 15.5$ bar; (4) $\Delta p = 16.5$ bar; (5) $\Delta p = 20$ bar.
Depending on the operating conditions, significant changes in the length of the sheet before disintegration into drops were detected. For example, increases in pressure or temperature result in reductions of the breakup length, as well as of the scale of the ripples that can be observed on the sheet.

Drop Size Measurements

The spatial variation of drop size distribution within the spray can be appreciated from Figs. 6–11. The associated experimental conditions are:

- Atomizer: A-630b + P-55b
- $DP = 17$ bar
- $T_{fo} = 100^\circ C$

The appearance of the spray in that case can be seen in Plates 6 and 7, showing the sheet breakup region (exposure time = 0.5 $\mu$s) and the spray as the eye can see it (1/60 s), respectively.

Figure 6 represents the volume fraction of drops in 15 size bands at three axial locations. The distribution becomes narrower as the spray moves downstream. The fraction of large drops displays a steep reduction between 3.5 and 11.5 cm and diminishes more slowly up to $x = 25$ cm. The proportion of smaller drops decreases gradually, and at $x = 25$ cm the first four bands are almost empty.

The axial profiles for the parameters of the distribution are represented in Fig. 7. The curve for VMD shows a sharp decrease in the first centimeters as a consequence of the reduction at the coarse end of the distribution. Downstream it levels off and displays a slight increase, due to the lower proportion of small drops. SMD is less sensitive to changes in the proportion of large drops, and it is nearly constant at points close to the atomizer, increasing beyond 7 cm with the axial distance. The values of $\Delta$ show a monotonic decrease due to the reduced fractions at both ends of the distribution.

Figure 8 represents the radial evolution of the three drop size parameters. Since laser diffractometry is a line-of-sight technique, the results obtained with the laser beam crossing at different distances off the axis are not the actual radial profiles. The values at a certain radial distance include the contributions of the layers of the spray located at larger radii. The real profile could be obtained by performing a tomographic deconvolution over those measurements [24, 25]. Nevertheless, the present results are useful for a qualitative characterization of the spray structure.

The drop size distribution becomes narrower as the distance from the axis increases. The evolution is more pronounced for the proportion of the finer ranges, which show a continuous decrease; at $r = 3.5$ cm the fraction of drops under 47 $\mu$m is very small.
Plate 6 Spray photograph with an exposure time of 0.5 μs. Atomizer A-630b + P-55b; ΔP = 17 bar; $T_m = 110^\circ$C.

Plate 7 Spray photograph with an exposure time of 1/60 s. Atomizer A-630b + P-55b; ΔP = 17 bar; $T_m = 110^\circ$C.
Fig. 6  Axial evolution of drop size distribution \((r = 0)\). Atomizer A-630b + P-55b; \(\Delta P = 17\) bar; \(T_m = 100^\circ C\).

Fig. 7  Axial evolution of drop size parameters \((r = 0)\). Atomizer A-630b + P-55b; \(\Delta P = 17\) bar; \(T_m = 100^\circ C\).
Fig. 8 Radial evolution of drop size distribution (x = 11.5 cm). Atomizer A-630b + P-55b; ∆P = 17 bar; T₀ = 100°C.

Figures 9, 10, and 11 represent the spatial distribution of SMD, VMD, and Δ. Those graphs have been built from 101 measurements at different locations. The flat zones at the corners indicate approximately the limits of the spray. Over most of the spray, both VMD and SMD increase with the radial distance. Some exceptions are the most peripheral regions and the points close to the nozzle. At x = 3.5 cm, VMD displays the opposite trend, while the radial profile for SMD is nearly flat. The highest values of span are located along the spray axis, and they continuously decrease toward the outer points.

Those results reveal significant inhomogeneities in the spray. Several causes can be enumerated:

- Interactions with the surrounding air
- Secondary atomization of the initial drops
- Collision and coalescence
- Evaporation
- Effects associated to the measuring technique
- Selective centrifugation due to vortical structures

The spray motion induces an air flow by nonslip condition that can have different consequences [26, 27]:

- Contraction of the spray. The decrease of spray cone angle with axial distance can be observed, for example, in Plate 7.
Transport of drops toward the center of the spray by aerodynamic drag, contributing to filling the inner region with drops that initially follow trajectories contained in an approximately conical surface. The finer drops are more easily dragged and, hence, the nucleus of the spray is characterized by smaller drop sizes than the outer regions. This effect explains the observed evolutions in Figs. 8, 9, and 10. For example, at $x = 11.5$ cm, $r = 3.5$ cm, there is a very low level of drops under 47 mm (Fig. 8), indicating that most of the drops deviate toward the axis (where, in fact, higher proportions are measured) before reaching this point. The low values of D at the outer points (Fig. 11) are a consequence of this aerodynamic selection, which almost eliminates a part of the distribution.

The drops generated from the sheet disintegration can be again subdivided by interaction with the air (secondary atomization). This process would ideally occur until the critical diameter is reached [28, 29] and would cause a progressive disappearance of the coarser tail of the distribution. That type of evolution can be observed in Fig. 6, especially along the first few centimeters. The occurrence of secondary atomization is supported by the fact that the highest proportion of drops in the range 225.6–523.2 μm was obtained at $x = 3.5$ cm. If spatial redistribution were the only effect responsible, similar percentages should be observed downstream at the peripheric points. Since that is not corroborated by the measurements, some of the large drops are expected to be broken into smaller ones. In
Plate 6, the liquid filaments disappear at about $x = 2.5$ cm; and at $x = 3.5$ cm, some coarse drops are still visible. Therefore, it is not unlikely that secondary atomization is still relevant over that distance. A slight decrease in the fraction of large drops was detected downstream, which could be ascribed to the same phenomenon.

Another effect that can modify the structure of the spray is drop coalescence. Collisions between drops can be caused by turbulent fluctuations in the air velocity (and, therefore, of the drops) and by the differences in the velocity of drops (both in module and direction), due to the action of aerodynamic forces. This phenomenon has been proposed in a number of works [20, 21, 23, 27] to explain the observed evolutions. However, no experimental evidence of its relevance has been found. Drop coalescence would result in an increase in mean size and a narrowing of the distribution [23]. Since those changes are observed in Fig. 6, coalescence effects could also explain the reduction in the proportion of fine drops at long axial distances in the present work.

Some studies in which the spray is injected in an atmosphere at high temperature demonstrate the influence of evaporation on the evolution of drop sizes [17, 30]. Its consequences are not thought to be relevant in the present experiments, due to the use of air at room temperature and to the high boiling point of the heavy oil.

Finally, the reported measurements can be affected by the peculiarities of the measuring technique. First, the laser diffractometer performs a spatial averaging, instead of a temporal averaging. Therefore, the measured distribution depends not only on the number
of drops generated with a certain size, but also on their velocity. As discussed previously, aerodynamic drag causes velocity differences among drops of different size. This effect could be reduced to some extent by using a co-flowing air stream, as it would create a more uniform velocity field inside the spray. Chin et al. [31] analyzed the consequences of drop velocity variations on the measurements by laser diffractometry; they concluded that, as the spray moves downstream, this effect should initially cause an artificial increase in the fraction of fine drops, which is afterwards reduced until it again approaches the real value. In the present work a decrease at both tails of the distribution has been detected, and the type of averaging alone cannot explain the observed evolution.

On the other hand, the measuring volume is not exactly a representative sample of the spray, as discussed in [32]. However, a different explanation is proposed here. Figure 12 represents a schematic of the area covered by the laser beam as it traverses a spray with a round cross section for two different diameters. The intersection consists of elements A1 and A2. The circular sector A1 is a representative sample of the spray, but in element A2 the inner regions are overweighted. The sum of both areas causes the measurements to be biased toward the drop size distributions around the axis. In the present experiments, this means that the drop size is underestimated. As can be easily deduced from Fig. 12, the shape of triangle A2 is closer to a circular sector as the spray cross section decreases. As a consequence, the bias toward smaller mean sizes caused by this effect increases with axial distance. However, that effect cannot explain the reported axial evolutions, as they display an opposite trend.
In summary, the observed spray structure is the result of many different effects. The influence of air entrainment, secondary atomization, and possible coalescence of drops can explain the spatial evolution of drop size distributions. The peculiarities of the measuring technique are expected to affect the results to some extent, but they cannot alone be responsible for the reported variations.

**INFLUENCE OF ATOMIZATION CONDITIONS ON DROP SIZE**

**Injection Pressure**

Liquid injection pressure is a key factor in the characteristics of sprays from pressure-swirl nozzles, as it largely determines the conditions at the exit orifice. A rise in pressure results in a significant increase in the spray cone angle for the atomizers tested and, since discharge coefficient is almost unaffected, flow rate increases as a square-root law of \( \Delta P \) [8]. The results also show a large influence on drop size.

Figure 13 represents the spatial distribution of SMD, within the spray for \( \Delta P = 14 \) bar. A fair spray symmetry is again observed, except for the radial profile measured at \( x = 25 \) cm. It can be compared to Fig. 9, which was obtained at \( \Delta P = 17 \) bar and keeping constant the rest of conditions. The increase in the oil injection pressure (Fig. 9 versus Fig. 13) displays the following effects:

- SMD decreases over the whole spray.
- Maximum values are located at larger radial distances, due to the wider spray angle.
- Differences between SMD at the center and at peripheral points within a cross section are smaller.

Axial profiles of SMD measured along a spray radius are shown in Fig. 14. Again, the beneficial effect of higher \( \Delta P \) on the fineness of the spray is evident. It can be noticed that the axial location of the minimum SMD increases for lower \( \Delta P \). This could be explained by a longer region where secondary atomization is relevant, and is consistent with the observed increase in the breakup length of the liquid sheet as \( \Delta P \) is reduced.

![Fig. 12 Cross section of measuring volume for two different spray diameters.](image)
Fig. 13 Spatial variation of SMD within the spray (line-of-sight measurements).
Atomizer A-630b + P-55b; $\Delta P = 14$ bar; $T_{in} = 100^\circ C$.

Fig. 14 Axial evolution of SMD at different injection pressures. Atomizer A-630b + P-55b; $T_{in} = 135^\circ C$. 
Figures 15 and 16 represent the evolution of the average SMD of the spray (SMD) with injection pressure under different conditions. The curves in Fig. 16 remain approximately parallel. However, Fig. 15 displays some changes in the slopes for different diameters of the exit orifice. This effect has been observed in many other cases, indicating that the degree of influence of ΔP on SMD can also depend on other experimental variables. A quantification of the influence of ΔP on SMD is given in a subsequent section in the form of empirical correlations.

The improvement of atomization at higher injection pressures is usually explained by the increase in liquid exit velocity and, hence, in the forces leading to the disintegration of the sheet. Another reason may be the reduction in sheet thickness, which varies approximately as (ΔP)^1/2, as proposed in [33].

Oil Temperature

The variation of oil temperature between 100 and 135°C causes a large reduction in its viscosity (around 250%), but only minor changes in density (6%) and surface tension (2.5%). Therefore, the influence of temperature on the spray characteristics can only be ascribed to variations in the heavy oil viscosity.

For the atomizers used in the present work, the spray cone angle increases with oil temperature approximately as μ^1/8 [8]. Flow rate is only slightly sensitive to that parameter, as discharge coefficients display a maximum within the temperature range covered in the tests.

The effects on the spatial distribution of SMD of a rise in oil temperature from 100 to 110 °C can be observed by comparing Figs. 13 and 17. The differences are very similar to those associated with an increase in the injection pressure. Figure 18 represents axial
Fig. 16 Influence of ΔP on SMD. Plate P-55b.

Fig. 17 Spatial variation of SMD within the spray (line-of-sight measurements). Atomizer A-630b + P-55b; ΔP = 14 bar; $T_{in} = 110^\circ$C.
profiles of SMD obtained at four different oil temperatures. Figure 19 is an example of the observed evolution of SMD and shows the significant influence of the oil temperature.

Increased oil viscosity can have an influence on the atomization through different mechanisms:

- Viscous dissipation causes head losses and, hence, the liquid velocity at the nozzle exit decreases.
- The tangential velocity inside the swirl chamber is reduced, resulting in a thicker liquid sheet.
- The growth of disturbances on the surface of the sheet, which is the mechanism responsible for its disintegration, is damped.

All those phenomena can explain, in an intuitive way, the coarser spray obtained at low oil temperatures. Among the available literature, the only study providing some more detailed data is [14], in which the influence of viscosity on sheet velocity and on film thickness fluctuations at the exit orifice is analyzed. Their results confirm that exit velocity decreases with viscosity, and the authors also find that the sheet appears more disturbed at the exit for higher-viscosity liquids. An interesting conclusion is that, for a given exit velocity, the SMD is not affected by the value of viscosity. That is explained by the opposite effect that an increase of viscosity has on the disintegration process, by damping the growth of disturbances and by producing a more distorted sheet at the exit orifice. As a consequence, knowledge of the exit velocity would provide a means to estimate mean drop size independent of the liquid viscosity.

![Fig. 18 Axial evolution of SMD at different oil temperatures. Atomizer A-630b + P-55b; ΔP = 12 bare.](image.png)
Geometry of the Nozzle

Some examples of the variation of SMD with changes in the internal dimensions of the atomizers are shown in Figs. 20–23. Figure 20 displays a decrease in SMD when a small exit orifice is used. The observed trends are not completely confirmed in Fig. 21. Above \( D_o = 0.65 \) mm, all the curves show an increase in SMD with \( D_o \). For smaller diameters, the dominant feature is that apparent in Fig. 20. A more detailed discussion on the influence of \( D_o \) is given in the next section. The evolution of SMD with the cross section of the tangential slots is presented in Figs. 22 and 23. In general, the mean drop size decreases for high values of \( A_r \). However, curves in Figs. 20–23 are not exactly parallel, suggesting that changes of injection pressure lead to SMD variations, the magnitude of which also depends on the exact geometry of the nozzle.

Empirical Correlations

Different expressions have been considered for the empirical correlations developed in the present work. In a first stage, dimensionally consistent equations including all the relevant adimensional parameters (\( K \), Reynolds and Weber numbers, etc.) were used. Functional forms tested include the traditional expression (product of powers of the parameters) as well as the one proposed by Wang and Lefebvre [22]. All these attempts led to very poor fits, which can be improved only if some independent variables (e.g., oil viscosity or orifice diameter) are artificially added to the expression. Therefore, it was finally decided to develop correlations involving only the independent parameters that have been varied in the tests. As a consequence, the expressions are not dimensionally consistent, but they represent the experimental results accurately. Discharge coefficient and spray
angle are not included in the correlations, as they are dependent parameters and their inclusion would mask the influence of the independent variables on SMD. Empirical correlations for $C_o$ and $2\theta$ have also been developed for the present tests and are reported elsewhere [8].
Fig. 22  Influence of $A_i$ on $\overline{SMD}$. Plate P-55b; $T_m = 110^\circ$C.

Fig. 23  Influence of $A_i$ on $\overline{SMD}$. Plate P-55b; $T_m = 120^\circ$C.
Figures 13–19 demonstrate a strong dependence of spray mean drop size on injection temperature and pressure. On the other hand, the effects of nozzle internal dimensions of the atomizer are not so well defined. Hence, it seems convenient to calculate an expression relating SMD solely to injection conditions. The application of multiple regression techniques yields the correlation (in SI units):

$$\text{SMD} = 22.35 \mu^0.59 \Delta P^{-0.74}$$

Equation (1) indicates that the influences of viscosity and pressure in the present experiments are remarkably higher than those suggested by empirical correlations proposed in previous works. The exponents affecting viscosity are in the range 0.118–0.25 [6, 14, 17, 34–37], and those for $\Delta P$ fall between $-0.275$ and $-0.5$ [6, 14, 34–38]. The causes for these differences are considered to be related to the small scale of the atomizers tested in the present case. For example, in the available literature the orifice diameters are larger than 1 mm, whereas they range from 0.45 to 1.1 mm in the present work.

Figure 24 presents a comparison between the measurements and the results of the fit. Measurements of discharge coefficient and spray angle show that the commonly used correlations are not valid for nozzles with $D_o < 0.8$ mm and the present liquid viscosity levels [8]. Should empirical correlations for spray angle be expressed in terms of the Reynolds number at the exit orifice, its exponent is 0.9, which is about four times the value commonly found for larger nozzles. This significant difference demonstrates that the flow at the exit is controlled largely by viscous effects. As a consequence, the tangential velocity is lower and liquid film thickness larger than expected from the inviscid theory standpoint or from similarity scaling of results corresponding to large nozzles.

**Fig. 24** Scatter of measurement data points of SMD with respect to Eq. (1).
A different correlation can be obtained if the internal dimensions are included in the expression (in SI units), namely,

\[
\text{SMD} = 0.436\mu_{ij}^{0.55} \Delta P^{-0.74} D_o^{-0.03} A_i^{-0.24}
\]

(2)

The degree of agreement with the measurements is shown in Fig. 25. Even though Eq. (2) contains more terms than Eq. (1), only a slight improvement is observed. This is probably due to the fact that the variations of SMD with A_i and, especially, with D_o do not display clearly defined trends.

Figures 20 and 21 suggest an idea already raised when analyzing the results of C_o and 20 [8]: The influence of the orifice diameter on the results depends on the range considered for D_o. Whereas the slopes are positive for D_o > 0.65 mm, the opposite trend is observed in most cases for D_o < 0.65 mm. Therefore, Eq. (2) represents only a mathematical averaging of the curves for both ranges and does not reproduce the single features of any of them.

When the results corresponding to Plates P-80 and P-110 are not included in the calculations, an expression is obtained that is valid only for D_o < 0.67 mm (in SI units):

\[
\text{SMD} = 9.21 \times 10^{-3}\mu_{ij}^{0.56} \Delta P^{-0.74} D_o^{-0.59} A_i^{-0.23}
\]

(3)

Figure 26 shows clearly that this correlation provides a better agreement than Eqs. (1) and (2) for D_o < 0.8 mm. The graph also includes those results not considered in the development of Eq. (3) (represented by triangles). The location of those data points evidences that the predictions using Eq. (3) for the largest orifices would systematically cause an underestimation of drop sizes.

It is interesting to note the significant difference in the exponent for D_o between Eqs. (2) and (3). When the results are averaged over the whole range of atomizers tested, the

![Fig. 25 Scatter of measurement data points of SMD with respect to Eq. (2).](image-url)
SMD appears to be nearly independent of the orifice diameter. On the contrary, it displays a strong dependence ($D_o^{-0.39}$) for the smallest nozzles.

Jones [6] conducted a systematic study of the influence of $D_o$ on mean drop size for large atomizers ($D_o = 2$–9 mm). The proposed correlations indicate that the median diameter $D_{50}$ is proportional to $D_o^{-0.38}$. Most of the studies do not isolate the influence of $D_o$, but it can be indirectly estimated from other parameters. Mean drop size is usually expressed as a function of liquid flow rate (or, equivalently, flow number) as $SMD \propto Q^a$, the power $a$ ranging from 0.2 to 0.25 [14, 34–37]. Since $Q \propto C_o D_o^{3}$ and $C_o$ is approximately proportional to $D_o^{0.75}$ [6, 33], it can be estimated that $SMD \propto D_o^b$, with $b$ in the range 0.25–0.31. In all the cases, the estimates for the power affecting $D_o$ display a large variation with respect to Eq. (3). Reference [39] is the only one that has found a decrease in SMD, as $D_o$ increases, for orifice diameters in the range 0.356–0.559 mm, smaller than those used in the other studies.

Although a small number of measurements where obtained for plates P-80 and P-110, they allowed us to establish the approximate relationship $SMD \propto D_o^{0.23}$ for orifice diameters between 0.8 and 1.1 mm. This power is not very different from those indicated in the previous paragraph, and it confirms that for $D_o$ around 1 mm, the SMD increases with the orifice diameter. On the other hand, smaller diameters imply a strongly inverse function ($D_o^{-0.59}$). This large variation is attributed to the different flow behavior for small nozzles that has been postulated.

The SMD of the drops formed in the disintegration of a liquid sheet is usually considered a function of the sheet thickness, $e$, in the form $SMD \propto e^c$; the proposed values for $c$ are 0.375 [38], 0.39 [40], and 0.5 [10]. If the flow pattern maintains some similarity when the scale of the atomizer changes, $e$ does increase with the atomizer size and a positive exponent for $D_o$ seems to be logical.

**Fig. 26** Scatter of measurement data points of SMD with respect to Eq. (3).
A strong influence of viscous effects on the flow at the exit orifice has been observed for small nozzles. As a result, a boundary layer is created that can span over a significant fraction of the sheet thickness, and the flow pattern is expected to change with the dimensions of the orifice. This can have several consequences. Viscous effects become smaller for large atomizers and, hence, the increase in film thickness should be smaller than expected from theoretical scaling laws. Also, for a given ΔP, the exit velocity increases with D0. Both effects can result in an increase of SMD with D0 smaller than that predicted for larger nozzles; or even the opposite trend can be observed, as demonstrated in the present work.

Jones [6] reports a dependence of SMD on the inlet slots area as SMD ∝ A0.03. The slightly positive dependence can be explained by the reduction in tangential velocity of the liquid inside the swirl chamber when A0 increases for a given flow rate. The present results, however, display a marked inverse trend (A0.23). In the case of very small atomizers, the rise in friction losses as the cross section of the passages is reduced can overcome the previously mentioned effect.

**CONCLUSIONS**

Laser diffractionometry has been used to characterize heavy oil sprays from simple pressure-swirl nozzles under different experimental conditions. Measurements are performed only along a spray radius in order to avoid errors due to multiple scattering. The arrangement adopted for the laser-diffraction particle size analyzer has proved to yield a valid method for diagnosis of dense sprays, causing only a slight overestimation of mean drop size (around 4%).

High-speed photographs and drop size measurements at different locations provide a detailed characterization of the spray structure. Spatial variation of drop size distributions is a result of many different phenomena. The induced air flow, the occurrence of secondary atomization, and the coalescence of drops are considered the most plausible causes of the observed variations. Other effects can also play a role, but their influence is not evident from the results.

Extensive series of measurements have been conducted analyzing the influence of injection conditions and nozzle internal dimensions on mean drop size. The atomizers tested include exit orifice sizes down to 0.45 mm, which are smaller than the dimensions usually covered in most of the existing works. The empirical correlations derived in this research have been compared with equivalent expressions from other studies. Significant differences arise, which are attributed to the relevant role of viscous effects on the internal flow in small-size atomizers. As a consequence, the powers affecting oil viscosity and injection pressure are remarkably higher than those commonly encountered in available correlations. Whereas mean drop size has been found to increase with orifice diameter for large nozzles, a marked opposite trend is apparent from the present work. A smaller influence of viscous forces for larger-dimension nozzles might explain the different behavior.

The results on drop size reported here are complementary to those for discharge coefficient and spray angle in a previous article [8]; this is a confirmation of the differences discussed with respect to large atomizers. Therefore, they might constitute a valuable database to check the validity of future comprehensive models on atomization by pressure-swirl nozzles.
REFERENCES


