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Spray Characterization of Gasoline Direct Injection Sprays Under Fuel Injection Pressures up to 150 MPa with Different Nozzle Geometries

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Abstract

Maximum fuel injection pressures for GDI engines is expected to increase due to positive effects on emissions and engine efficiency. Current GDI injectors have maximum operating pressures of 35 MPa, but higher injection pressures have yielded promising reductions in particle number (PN) and improved combustion stability. However, the mechanisms responsible for these effects are poorly understood, and there have been few studies on fuel sprays formed at high injection pressures.

This paper summarizes experimental studies on the properties of sprays formed at high injection pressures. The results of these experiments can be used as inputs for CFD simulations and studies on combustion behavior, emissions formation, and combustion system design. The experiments were conducted using an injection rate meter and optical methods in a constant volume spray chamber. Injection rate measurements were performed to determine the injectors’ flow characteristics. Spray imaging was performed using a high-speed video camera. Several spray properties such as the liquid spray penetration, spray plume angle, and the spray breakup point were determined as functions of the fuel injection pressure and injected fuel mass by image post-processing. The impact of fuel pressure on spray droplet size was also investigated using two-component Phase Doppler Interferometry.

Piezoelectric injectors for diesel engines were used with modified nozzles that produce sprays resembling those generated in gasoline engines. Experiments were performed with fuel injection pressures ranging from 20 to 150 MPa, and chamber pressures of 0.1 and 0.6 MPa. In addition, four different nozzles with three different nozzle configurations and either 6 or 10 holes were used to determine how hole geometry affects spray formation.

The study’s key findings are that increasing the fuel injection pressure advances spray breakup and creates smaller droplets, improving mixture formation and accelerating evaporation. The nozzle type and the ambient pressure both significantly affect aspects of spray behavior such as spray tip development.

Introduction

Emissions regulations have profoundly influenced engine development over the last 50 years, prompting the introduction of cleaner and more efficient engines. Strict regulations governing CO₂ and particle number (PN) emissions from vehicles have been introduced in recent years, and more stringent standards are expected in the near future. To comply with these regulations, vehicle manufacturers are introducing hybrid and electrified automotive powertrain architectures. Hybrid systems combine electric propulsion with an internal combustion engine, whose emissions and fuel consumption must be minimized. One way in which gasoline engines’ efficiency has been increased has been by replacing conventional port fuel injection systems (PFI) with gasoline direct injection (GDI). A negative aspect of GDI engines is their tendency to produce higher particulate emissions [1, 2]. However, emissions of particulates and other pollutants can be reduced by increasing the fuel injection pressure. Injection pressures in production engines have been rising since the introduction of GDI; current GDI engines use a fuel injection pressure of around 35 MPa. It has been demonstrated that particulate emissions decrease with increasing injection pressure up to 40 [3] or 50 MPa [4]. This trend has been attributed to better spray atomization, faster evaporation, and better mixture formation. However, few studies have explored the mechanisms responsible for the beneficial effects...
of high fuel injection pressures, and very few have investigated injection pressures above 100 MPa.

When utilizing fuel sprays with higher fuel injection pressure, the injector nozzle shape should also be considered. Higher injection pressures give higher spray velocities, increasing the risk that the spray will hit the wall of the combustion chamber if not adequately decelerated. Control over spray direction, spray-air interaction, and penetration is therefore essential for reducing emissions and improving fuel consumption. These nozzle effects on the spray were reported in [5, 6], but the investigations did not find any effect of the combination of high injection pressure and nozzle types on gasoline sprays.

Postrioti et al. [7] investigated spray evolution, injection rates and atomization at injection pressures between 5 and 60 MPa using a 5-hole side-mounted prototype GDI injector. Measurements of atomization characteristics by Phase Doppler Anemometry (PDA) revealed that atomization outcomes are very sensitive to the fuel injection pressure. The most significant improvement in atomization was observed when the injection pressure was increased from 5 to 20 MPa; further increases caused additional smaller improvements. Migliaccio et al. [8] analyzed the patterns and spray tip penetration of hollow cone sprays formed using an outwardly opening piezoelectric injector at injection pressures of up to 120 MPa in a constant volume spray chamber. These experimental results were used to validate a CFD spray model, which was then used to compare sprays emitted via hollow-cone and multi-hole nozzles. The investigation concluded that the hollow-cone sprays were more finely atomized and better distributed, with shorter penetration lengths than sprays formed using multi-hole injectors. Moreover, further reductions in emissions and gains in efficiency could be achieved by combining hollow-cone injectors with tailored combustion chamber designs. Medina et al. [9] investigated the effects of fuel injection pressure on transient gasoline fuel spray development over a wide range of injection pressures in a constant volume spray chamber using high-speed imaging. Injection pressures between 30 and 150 MPa were investigated using a diesel injector with a single nozzle having a 110 μm orifice diameter and an orifice length of 900 μm. The investigation concluded that spray tip penetration increased with the fuel injection pressure, and that higher chamber pressures resulted in wider spray cone angles at any given fuel injection pressure. Payri et al. [10] compared diesel and gasoline fuel sprays formed at injection pressures between 60 and 150 MPa with a diesel-type piezoelectric injector at chamber pressures of 2.5 and 5 MPa. Their investigations revealed no significant differences in spray momentum between the two fuels. Wetzel [5] investigated the influence of injector nozzle geometry on mixture formation using GDI injectors with cylindrical, divergent, stepped, and convergent nozzles. These studies revealed that smaller nozzle hole diameters resulted in smaller droplets. However, there was no clear effect of nozzle hole configuration on droplet sizes.

There have been several studies on the effects of high fuel pressures on diesel sprays. However, investigations of gasoline sprays have typically used injection pressures of 20 to 40 MPa. Studies on gasoline sprays formed at injection pressures above 100 MPa commonly use unmodified diesel injectors. However, it is important to understand how nozzle shape affects spray behavior at higher injection pressures because nozzle geometry strongly affects the benefits of high injection pressures.

This work investigates the basic characteristics of sprays formed using different injection pressures and nozzle types. To this end, injection rates, spray penetration lengths, spray cone angles, spray breakup, and droplet size were analyzed using a rate meter and optical measurements.

### Experimental Setups

#### Injectors

Most spray investigations using fuel pressures above 100 MPa have used diesel-type nozzles, which have a relatively large L/D (nozzle thickness to hole diameter) ratio to withstand high pressures. A diesel nozzle typically has L/D of 8-9, whereas that of a GDI injector is usually around 2-3. The nozzle thickness refers to the axial distance between the nozzle’s inlet and outlet, while the hole diameter is the smaller of the inlet and outlet diameters. These quantities are depicted for three different nozzle configurations in Figure 1. A spray from an injector with a large L/D ratio will differ significantly from one emitted via a low L/D nozzle because of differences in the nozzles’ internal flow structures. For instance, an injector with a large L/D nozzle will have a straighter internal nozzle flow, resulting in a lower spray width and plume angle [11]. Four kinds of nozzles with relatively high L/D ratios (at least for GDI engines) were examined in this work. High L/D nozzles were chosen to ensure that all the studied nozzles had sufficient mechanical strength to avoid mechanical failure when used at extremely high fuel injection pressures. The holes’ diameters were chosen to match typical GDI injector static flow rates. The injectors’ specifications are shown in Table 1, and the three nozzle hole configurations (divergent,

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![FIGURE 1](https://via.placeholder.com/150)

Schematic depictions of three nozzle hole configurations.

### Table 1 Specifications of injectors used to study spray properties.

<table>
<thead>
<tr>
<th>Injector</th>
<th>Hole shape</th>
<th>Number of holes</th>
<th>Mass flow rate</th>
<th>L/D</th>
<th>Cone angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Divergent</td>
<td>6</td>
<td>15 mg/ms at 20 MPa</td>
<td>5.45</td>
<td>15°</td>
</tr>
<tr>
<td>#2</td>
<td>Convergent</td>
<td>6</td>
<td></td>
<td>5.56</td>
<td>2°</td>
</tr>
<tr>
<td>#3</td>
<td>Divergent</td>
<td>10</td>
<td></td>
<td>5.34</td>
<td>15°</td>
</tr>
<tr>
<td>#4</td>
<td>Cylindrical</td>
<td>10</td>
<td></td>
<td>5.47</td>
<td>0°</td>
</tr>
</tbody>
</table>
Piezoelectric injectors were used because they enable quick and accurate control of the needle’s movement. These injectors open and close the needle using the pressure difference between the fuel injection and return flow pressures. Therefore, the needle’s opening and closing speeds increase with the fuel injection pressure (as discussed in the section below dealing with injection rates). Conventional GDI injectors, on the other hand, use a solenoid or piezo stack to open and close the needle, and the needle is controlled directly by the actuators. These two injector types thus produce different types of needle motion, which affects spray characteristics, especially when the needle is moving.

Diesel-type injectors with modified nozzles were used in this work because they can tolerate injection pressures above 100 MPa. The nozzles were modified to make the spray as similar to a GDI spray as possible with respect to quantities such as the flow rate, hole diameter and spray angle. In terms of the needle opening and closing characteristics, there is difference of sprays between diesel type and GDI type especially in situations where the rates of needle opening and closing are particularly influential (e.g. when the injection mass is small). However, it was expected that the modified diesel injectors would adequately reproduce key properties of sprays generated by GDI injectors (such as their droplet size and penetration length) operated at high fuel pressures.

The nozzle holes were arranged symmetrically as shown in Figure 2. All four injectors were manufactured to have identical flow rate characteristics. Fuel pressures of up to 150 MPa were established using a custom-made high pressure pump consisting of a piston, cylinder, and hydraulic oil pump. Unlike mass production diesel pumps, this custom-made unit can operate without lubricant improvers.

### Injection Rate Meter

Injection rates were measured with an injection rate meter (Loccioni Mexus 2). The injection rate measurement system consisted of a control chamber, a pressure sensor, a regulation valve, and a Coriolis meter (see Figure 3). The control chamber was pre-pressurized with fuel up to a pre-defined back pressure (2.5 MPa in this study). There was a continuous outflow due to injections, and the needle of the regulation valve was adjusted automatically to maintain the specified backpressure inside the control chamber. When the injector injected fuel into the pressurized control chamber, the pressure sensor detected the resulting pressure wave. The signal of the pressure wave was then filtered and post-processed to derive the injection rate. The Coriolis meter accurately measured the injection mass and the mean mass flow, which were used to calculate the injection rate. The injectors were mounted in a custom-made injector fixture designed to ensure that the mechanical vibrations of the injector’s actuator would have minimal effects on the pressure signal. The system’s backpressure was set to a value significantly higher than that expected in a real engine to suppress internal cavitation in the hydraulic volume. High back pressures generally have only minor effects on the injection rate [12], in the current study it was found to not have a significant impact. The injection frequency, injection duration, chamber pressure and signal analysis were controlled by the Loccioni software. The experimental conditions are listed in Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>n-heptane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel temperature K</td>
<td>293</td>
</tr>
<tr>
<td>Fuel pressure MPa</td>
<td>20, 40, 60, 80, 100, 120, 150</td>
</tr>
<tr>
<td>Control chamber pressure MPa</td>
<td>2.5</td>
</tr>
<tr>
<td>Control chamber temperature K</td>
<td>323</td>
</tr>
<tr>
<td>Injection frequency Hz</td>
<td>20</td>
</tr>
<tr>
<td>Number of shots shot</td>
<td>200</td>
</tr>
<tr>
<td>Measuring range mg/shot</td>
<td>0.4 - 150</td>
</tr>
<tr>
<td>Resolution mg</td>
<td>0.01</td>
</tr>
<tr>
<td>Accuracy mg/shot</td>
<td>± 0.05 (range 0 - 50 mg/shot)</td>
</tr>
<tr>
<td>Accuracy mg/shot</td>
<td>± 0.2 (range 0 - 150 mg/shot)</td>
</tr>
</tbody>
</table>
Spray Imaging

A high-speed video (HSV) camera was used to capture shadowgraph images of the liquid spray’s evolution in a constant volume chamber using a LED light and a diffuser. Figure 4 shows a schematic depiction of the experimental setup. The images were post-processed and analyzed to quantify spray characteristics such as the spray tip penetration and spray plume angles. The experimental conditions (including the HSV settings for the spray imaging experiment) are listed in Table 3.

Back illumination is a robust method for measuring penetration and spray plume angles because it creates a clear boundary between the liquid spray region and the surrounding air, giving a high signal to noise ratio. To evaluate spray penetration, captured spray images were binarized using an adjusted threshold. Because of the high signal to noise ratio (especially at the spray tip), the measured liquid spray penetration was relatively insensitive to the choice of threshold level. A mask was applied to crop the spray plume whose properties were to be determined. After defining the nozzle tip’s location, the spray tip penetration along the injector axis was estimated as the “vertical” distance between the nozzle tip and the spray tip. These estimates were then rescaled based on the camera’s viewing angle to determine the liquid penetration along the spray axis (see Figure 5 (a)). The spray tip penetrations reported in the results section are averages based on 20 images each. A similar post-processing procedure was used to estimate the spray plume angle. After binarizing and masking the captured image, four points (two at the height of the nozzle tip and two 5 mm downstream of the injector tip) on the boundary of the spray were selected and used to define two lines running along the plume’s boundaries (see Figure 5 (b)). The spray plume angle was defined as the angle between these two lines. Because of the image’s high signal to noise ratio, the errors from the algorithms are small. Breakup points were determined using the procedure developed by Hiroyasu and Arai [13].

Phase Doppler Interferometry

An Artium 2D Phase Doppler Interferometer (PDI) was used for droplet size measurement. PDI uses two intersecting laser beams to form a measurement volume. To optimize signal strength and quality, the interferometer was used in refractive mode, and a receiver was positioned with an off-axis angle of 34 degrees. The PDI settings and conditions used in these experiments are listed in Table 4. A programmable three-axis traverse system was used to control the measurement position. The measurement position chosen in this work was 80 mm downstream of the injector tip and 5 mm outside the spray core. This position was chosen because the droplet number density at the center of the spray was too high to permit the gathering of reliable droplet data. The divergent 6-hole injector was used since measuring outside of the center provided a way to achieve acceptable droplet number density for the measurement system to handle in the measurement point. Even so, at the studied high injection pressures, the droplet number density becomes high when the injection rate is high, greatly reducing the number of validated droplets. Additionally, the measurement time window was chosen to investigate the droplet size during the injection event only. A typical time window together with a pulse input and an injection rate are shown in Figure 6. There is a small delay between the needle opening signal and start of size measurement.
Results and Discussion

Injection Rate

Effect of the Common Rail on Injection Pressures To enable reliable system studies, the fuel injection pressure should be kept as constant as possible during the injection event and between different injection events. To ensure the fuel system was capable of maintaining an acceptably steady injection pressure, the pressure drop upstream of the injector was investigated. A large pressure drop during the injection, or pressure pulsations upstream of the injector before the injection, would yield an unstable injection rate that would adversely affect the injection mass accuracy and the spray behavior. The injection rate was therefore measured with and without a common rail system upstream of the injector. The volume of the pressurized fuel in the upstream fuel lines was 15 cc with the common rail and 5 cc without it. The resulting injection rates and upstream pressures are shown in Figures 7 and 8. The differences observed towards the end of the injection are due to differences in the amount of needle lift, which varies with the fuel injection pressure [14]. Therefore, the end of the injection varies even when the energized time is held constant. As expected, without the common rail, the injection pressure before the start of injection is unstable because of residual pressure pulsations from the last injection. Furthermore, the pressure drops during injection and fluctuations after injection are larger, and the maximum difference between the set

<table>
<thead>
<tr>
<th>TABLE 4</th>
<th>PDI test conditions and settings.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
<td>Divergent 6 hole</td>
</tr>
<tr>
<td>Fuel type</td>
<td>n-heptane</td>
</tr>
<tr>
<td>Fuel temperature</td>
<td>K 293</td>
</tr>
<tr>
<td>Fuel pressure</td>
<td>MPa 20, 40, 60, 80, 100, 120, 150</td>
</tr>
<tr>
<td>Chamber gas</td>
<td>air</td>
</tr>
<tr>
<td>Chamber gas temperature</td>
<td>K 293</td>
</tr>
<tr>
<td>Chamber gas pressure</td>
<td>MPa 0.1</td>
</tr>
<tr>
<td>Energizing time</td>
<td>ms 3</td>
</tr>
<tr>
<td>Wavelength</td>
<td>nm 532 / 561</td>
</tr>
<tr>
<td>Focal length of transmitter</td>
<td>mm 350</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>mm 2.33</td>
</tr>
<tr>
<td>Expander factor</td>
<td>1.00</td>
</tr>
<tr>
<td>Frequency shift</td>
<td>MHz 40</td>
</tr>
<tr>
<td>Fringe spacing</td>
<td>μm 3.1 / 3.3</td>
</tr>
<tr>
<td>Collection angle</td>
<td>degree 34</td>
</tr>
<tr>
<td>Static range</td>
<td>μm 0.6 - 93.7</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.45</td>
</tr>
<tr>
<td>Number of droplets</td>
<td>&gt; 10000</td>
</tr>
<tr>
<td>Measurement range</td>
<td>μm 0.6 - 93.7</td>
</tr>
<tr>
<td>Size accuracy</td>
<td>μm ± 0.5 μm</td>
</tr>
<tr>
<td>Size resolution</td>
<td>μm ± 0.5 μm</td>
</tr>
</tbody>
</table>

because of the delayed appearance of the liquid spray. Similarly, at the end of the measurement period, there is a delay between the closing of the needle and the ejection of the final spray. The measurement time window was chosen to end when the droplet velocity fell to two-thirds of its value (see Figure 6).

FIGURE 6 A typical measurement time window.

FIGURE 7 Injection rate and upstream pressure traces without a common rail.

FIGURE 8 Injection rate and upstream pressure traces with a common rail.
injection pressure and the maximum or minimum pressures caused by fluctuations is roughly 20%. This pressure drop changes the shape of the injection rate curve, which is intended to be flat when the needle is fully open. Pressure fluctuations will also influence the pressure levels of each individual injection event during a multi-injection sequence, depending on the injection frequency and pressure. An experimental system set-up without a common rail would thus be inappropriate for spray measurements in which accuracy and repeatability must be maintained. The inclusion of the common rail reduced the pressure drop by up to 10% during a 100 MPa injection while also suppressing pressure fluctuations significantly. All injection rate and spray data presented in the remainder of this paper were acquired using a system with a common rail.

**Effect of Injection Pressures on Injection Rates** Injection rate data for several injection pressures with a constant injection mass (50 mg) are shown together with the corresponding injection pulse signals in Figure 9. The injection duration for the injection pressure of 150 MPa was 60% shorter than that for injection at 20 MPa. Higher fuel pressures also reduced the opening time: it took 1.3 ms to open the needle fully at 20 MPa, but only 0.2 ms at 150 MPa. The delay between the start of signal and start of fueling was more or less the same for all fuel injection pressures, but the delay between the end of signal and end of fueling was much longer due to the previously discussed properties of diesel injectors. A detailed study on the relationship between the needle movement and injection rate was presented by Postrioti et al. [15]. Generally, diesel injectors (including the one used here) exploit the pressure difference between the rail pressure and backflow pressure to open and close the needle at ultra-high injection pressures [16]. When the pressure difference increases, so does the needle’s speed. This reduces the throttling effect inside the nozzle created by the small space between the needle and the seat. This throttling causes a pressure drop that adversely affects atomization, as discussed in the section on droplet sizes.

**Spray imaging**

Figure 10 shows images of sprays formed with identical injection masses of 27 mg at the end of injection (EOI), which was defined as the time at which the fuel injection ended. The energized time and the time ($t_d$; see Figure 6) between the start of injection (SOI) and EOI are given in Figure 10. All sprays shown in Figure 10 contain the same mass of fuel at EOI, so these images can be used to analyze the dependence of spray shape on the fuel injection pressure and ambient pressure. There is little variation in the spray penetration at EOI at injection pressures between 40 and 150 MPa with 0.1 MPa back pressure, but the spray plume becomes wider at higher injection pressures. The same behavior is observed with a back pressure of 0.6 MPa (which was used to simulate injection conditions during the compression stroke). Sprays formed with an injection pressure of 150 MPa were similar in shape to those formed at 40 MPa even though the time between SOI and EOI in the former case was around half that in the latter case.

The results also show that the higher back pressure generally reduced the spray’s penetration, as expected. This effect was significant for all injector types but was more pronounced for sprays emitted from convergent and cylindrical nozzle injectors. The nozzle type also profoundly affected the spray shape: sprays emitted from divergent holes were wider and shorter, while those emitted from convergent and cylindrical nozzles were narrower and longer. For all nozzles to achieve the same flow rate, the 10 hole nozzles must have smaller holes than their 6-hole counterparts, and therefore produce shorter sprays with wider spray distributions. To characterize differences in spray development in detail, time-resolved spray penetration was analyzed.

The penetration length plots presented in Figure 11 show how the spray tip developed after SOI for the four studied nozzles at different injection pressures. The vertical penetration was calculated by image post-processing and then recalculated to account for the different camera view angles. The plotted values thus represent the liquid penetration in the spray direction. Figure 11 shows the spray tip penetrations including error bars and standard deviations measured over 20 shots. The penetration at EOI is also shown for most sprays in Figure 11 but not for those emitted by the convergent and the cylindrical nozzles at atmospheric chamber pressure because in these cases the spray tip passed beyond the camera’s field of view too quickly. As expected, higher injection pressures yielded more faster spray development (based on the penetration after SOI). Interestingly, the penetration at EOI did not vary greatly with the injection pressure. The limited variation of the liquid penetration at EOI was attributed to the fact that higher injection pressures produce higher outlet...
velocities but also reduce the injection durations and strengthen the aerodynamic forces that decelerate the spray.

The injection pressure affected the development of the penetration length most significantly at pressures of up to 60 - 80 MPa. Increases in injection pressure above 80 MPa had diminishing effects on the penetration development. This was also observed in the analysis of the breakup point and droplet size, as discussed below. The nozzle type also strongly influenced spray tip development after the SOI. Under atmospheric ambient pressure conditions, the spray from the divergent 10-hole nozzle had the shortest penetration, and the spray from the divergent 6-hole nozzle had a shorter penetration than those from the convergent and cylindrical nozzles. The spray from the convergent nozzle had the longest penetration. The divergent nozzles were expected to have lower penetration lengths because they inject the fuel at a wider angle, resulting in greater deceleration of the liquid. The convergent and cylindrical nozzles produce narrower plume angles, which have the opposite effect.

Some of the penetration length curves do not follow the general trend. The generally accepted tendency of penetration development is that a high gradient is observed just after SOI because of the high spray tip velocity at this time. This gradient gradually becomes shallower because of drag forces imposed by the surrounding air. This behavior was observed under both atmospheric (0.1 MPa) and pressurized (0.6 MPa) conditions with divergent nozzles. However, the convergent and cylindrical nozzles behaved differently, especially under atmospheric chamber pressure conditions (see for example the plot for the convergent 6-hole nozzle at 0.1 MPa back pressure and 20 MPa injection pressure in Figure 11). In these cases, a penetration gradient developed during injection, indicating that there was no deceleration of the spray tip. Instead, droplet/spray acceleration was observed during injection events with the convergent nozzle at injection pressures of 20 or 40 MPa.

This penetration behavior can be explained by considering the movement of the injector needle. Near-nozzle spray images for the divergent and convergent 6-hole nozzles are shown in Figure 12, illustrating the sprays’ development over time. Plots of the time-resolved spray plume angle under these conditions are shown in Figure 13. To evaluate the development of the spray plume angle during an injection event, an injection mass of 54 mg was used to ensure the needle is fully open during the injection. The spray plume angle from the divergent nozzle was almost constant throughout the injection event. Conversely, the spray plume angle from the convergent
nozzle was larger at the SOI and EOI than during the intermediate period. In other words, the spray had a larger plume angle when the needle was opening and closing than when the needle was fully lifted. This observation is consistent with the results of Blessing et al. [17]. This explains the acceleration in liquid penetration: the spray’s velocity increases when the plume angle decreases. The change in spray plume angle is closely related to the structure of the internal nozzle flow. Three different types of cavitation reportedly occur inside the nozzle: geometry-induced cavitation, hole-to-hole string cavitation and needle-originated string cavitation [18, 19]. These three cavitation models are depicted in Figure 14.
Geometry-induced cavitation is induced around a hole’s inlet and develops along the inside wall of the hole. Hole-to-hole string cavitation is similar to hole-to-hole string cavitation and gradually extends towards the interior of the hole, as in hole-to-hole string cavitation. This cavitation starts around the needle tip area and gradually extends towards the interior of the hole, as in hole-to-hole string cavitation. During needle opening and closing, needle-originated string cavitation is the dominant form of cavitation [18, 19, 20]. This is believed to increase the spray plume angle at the beginning and end of the injection because the cavitation creates turbulence at the nozzle outlet. Geometry-induced cavitation and hole-to-hole string cavitation occur when the needle is fully lifted. However, those kinds of cavitation are suppressed by the contraction flow created by the shape of the convergent hole because they develop less extensively than needle-originated string cavitation [19]. Therefore, the spray plume angle during full lift is smaller than that during needle opening and closing. Consequently, the axial velocity of the spray tip is higher in the middle of the injection than at the SOI, and the spray tip develops without decelerating. This cavitation process is also expected to occur inside divergent nozzles, but the shape of the divergent hole enhances geometry-induced cavitation significantly [21]. Therefore, the spray plume angle does not change significantly over time.

Spray breakup is the atomization process whereby a bulk liquid breaks up into small droplets. The breakup point is a quantity that indicates a spray’s degree of atomization; it is defined as an inflection point in the penetration development curve [13]. However, no clear inflection point was observed in the spray development plots for the convergent and cylindrical nozzles at atmospheric chamber pressure. The penetration development and the spray tip velocity at injection and ambient pressures of 100 MPa and 0.1 MPa, respectively, are shown in Figure 15. Under these conditions, the spray from the divergent nozzles clearly decelerates after reaching its maximum velocity at around 0.1 ms after SOI. However, the sprays from the convergent and cylindrical nozzles do not decelerate enough after the first peak of velocity to create a clear inflection point. Therefore, breakup points were determined for all sprays except for those from the convergent and cylindrical nozzles at 0.1 MPa ambient pressure. The calculated breakup times and lengths for different experimental conditions are plotted in Figures 16-20. Figures 16 and 17 show the effect of different nozzle types at an ambient pressure of 0.6 MPa, while Figures 19 and 20 show the effect of varying the ambient pressure.

The breakup time was reduced for all four nozzles when the injection pressure increases, indicating that atomization
is enhanced by increasing the fuel injection pressure. Spray breakup depends on the balance between disruptive and consolidating forces [22]. The disruptive forces are aerodynamic forces on the liquid surface, while the consolidating forces are the surface tension and the liquid’s viscosity. Both of these quantities depend on the chosen fuel, and only one fuel was tested in this work. Therefore, the observed breakup trends are primarily due to differences in aerodynamic forces. These forces can be modeled as drag forces using Equation (1), where $F_D$ is the drag force, $\rho$ the mass density of air, $U_R$ the relative velocity, $D$ the droplet diameter and $C_D$ the drag coefficient. The drag coefficient depends on the spray’s shape and is therefore a function of the mass density, flow velocity, and reference area.

$$F_D = \frac{1}{2} \rho U_R^2 C_D \pi D^2$$

(1)

The droplet diameter fell (due to better atomization) when the injection pressure was increased. In addition, the spray velocity and number of droplets increased. This suggests that...
sprays formed at higher injection pressures are subject to stronger overall drag forces than those formed at lower injection pressures. Therefore, breakup occurs closer to SOI when using higher injection pressures.

The breakup time for the divergent nozzles was greater than that for the convergent and cylindrical nozzles at injection pressures of 20 and 40 MPa (see Figure 16). This difference became less pronounced at higher injection pressures. Figure 17 shows that the breakup length for the divergent nozzles was almost constant for all injection pressures, but that for convergent and cylindrical nozzles increased with the fuel injection pressure. Figure 18 shows the maximum spray tip velocity for different injection pressures and nozzles. The maximum spray tip velocity increases almost linearly with the injection pressure. Therefore, the breakup length also increases almost linearly even though the breakup time does not change significantly at higher injection pressures. However, the breakup lengths observed for the cylindrical nozzle and the divergent 6-hole nozzle differ, especially at the 150 MPa injection pressure, even though the maximum velocities for these nozzle types are very similar. This can be attributed to the different flow structures inside these nozzles. Zandi [23] showed that the flow inside a convergent nozzle creates almost no cavitation whereas that inside a divergent or cylindrical nozzle often creates considerable cavitation. Moreover, the cavitation intensity in the divergent nozzle is higher than in the cylindrical nozzle. Cavitation enhances turbulence at the nozzle outlet, resulting in a wider spray and faster atomization. It is therefore likely that the spray from the divergent nozzle broke up earlier and closer to the nozzle than the spray from the cylindrical nozzle. This dependence of cavitation on nozzle conicity may also explain why the spray from the divergent nozzle had a much higher maximum tip velocity (see Figure 18).

The breakup length and time also depend on the chamber pressure. The data presented in Figure 19 shows that the measured breakup times for a back pressure of 0.1 MPa clearly differed from those seen at a back pressure of 0.6 MPa for injection pressures of 20, 40 and 60 MPa. However, these differences become smaller at higher injection pressures. This indicates that once the velocity reaches a certain threshold, its impact on breakup is reduced. However, the impact of injection pressure remains higher than it at lower chamber pressures. At higher chamber pressures, the air density is higher, which will change the magnitudes of the drag forces and surface tension. Figure 20 shows that the breakup length increased with injection pressure at a chamber pressure of 0.1 MPa but was more or less constant when the chamber pressure was 0.6 MPa. Figure 21 shows the maximum velocity of the spray tip at different injection pressures and back pressures. The maximum velocity at atmospheric ambient pressure was higher than at 0.6 MPa back pressure, so the breakup length increased with the injection pressure.

One benefit of increasing the injection pressure is that it promotes earlier spray breakup. For example, the breakup time was more than halved when the injection pressure was raised from 20 MPa to 150 MPa. This earlier breakup creates more smaller droplets within a shorter time, improving fuel-air mixture formation even at high engine speeds. The effects of the fuel injection pressure on the droplet size are discussed below.

**Droplet Size**

The experiments discussed above indicated that sprays formed at higher injection pressures break up earlier than those formed at lower injection pressure. Breakup is a part of the atomization process, so the effect of injection pressure on atomization was investigated by performing droplet size measurements.

The mean droplet size ($D_{10}$), Sauter mean diameter (SMD), and $D_{90}$ for different injection pressures are shown in Figure 22. $D_{90}$ is a drop diameter value that serves as a statistical indicator of the size of the largest droplets in the spray. Specifically, 90% of the spray’s liquid volume consists of droplets with a diameter less than or equal to $D_{90}$ [24]. Figure 22 shows that $D_{10}$ decreased slightly with increasing fuel injection pressure, whereas SMD and $D_{90}$ decreased significantly. This indicates that most droplets were small at all injection pressures. However, sprays formed at lower injection pressures have a large number of big droplets (SMD and $D_{90}$ both are greatly influenced by the number of large droplets).

Time-resolved SMD data is shown in Figure 23. The SMD decreased as the fuel injection pressure increased, in accordance with the data presented in Figure 22. For all injection pressures, the SMD at the beginning of the injection was greater than that during the injection because the opening of
the needle leads to a pressure drop inside the nozzle. This reduces the beneficial effect of higher injection pressures on atomization, so the spray at the beginning of the injection contains larger droplets than that formed when the needle is fully open. This effect becomes less pronounced and persists for less time as the fuel pressure increases. Larger droplets predominated for about 1 ms after the SOI at an injection pressure of 20 MPa, but only for 0.3 ms at 150 MPa injection pressure (see Figure 23). The duration of the large droplet period is related to the time required for needle opening. Figure 9 shows that needle opening takes around 1 ms at 20 MPa injection pressure but takes only about 0.2 ms at 150 MPa injection pressure. Higher fuel injection pressures thus increase the speed of needle opening, preventing the formation of larger droplets shortly after the start of injection.

No such effect of needle movement on droplet size was observed at the end of injection (see Figure 23). In principle, because the needle moves both at the beginning and at the end of the injection, the proportion of large droplets should increase on both occasions. However, the number ratio of large droplets to smaller droplets at the end of the injection is different from that at the beginning because the conditions at the beginning differ from those towards the end. For example, at the start of injection, the spray tip contains fewer droplets because it is injected into a quiescent environment with no residual fuel droplets from the previous injection event. However, at the end of the injection, the spray is mixed with droplets from the current injection, which contains several small droplets. Larger droplets are therefore quite abundant in the spray at the beginning of the injection but much rarer at the end of injection.

Figures 24 and 25 show the droplet size distribution in terms of volume fractions at the beginning of the injection and during the injection, respectively. For all injection pressures, the diameters with the largest volume fractions at the beginning of the injection (see Figure 24) were greater than those in the mid-period of the injection (see Figure 25). This also indicates that the relative abundance of larger droplets was higher at the beginning of the injection than during the injection. The impact of fuel pressure on droplet size 80 MPa; no droplets larger than 20 μm were detected above this threshold. This indicates that the fuel injection pressure has a strong effect on atomization up to 80 MPa, but that its impact was muted at injection pressures above this value. These observations are consistent with the previously discussed trends in breakup time.

The change in the relationship between injection pressure and atomization may be linked to an increase in the energy required for atomization. Atomization is based on spray breakup, and the breakup of spray droplets is controlled by aerodynamic forces, surface tension, and viscosity [23]. A spray droplet’s integrity is maintained by its surface tension and the liquid’s viscosity, and disrupted by aerodynamic forces. When the disruptive force exceeds the force consolidating the droplet’s shape, breakup occurs. The case in which these forces are equal is described by Equation (3) using Equation (1), where σ is the surface tension and the subscript crit denotes a critical condition.
Theoretical relationship between droplet size and the critical relative velocity for a single droplet.

\[
\frac{1}{2} \rho U_{\text{crit}}^2 C_D \frac{\pi D^2}{4} = \pi D \sigma
\]  

The critical relative velocity at which the droplet will be disrupted is given by Equation (4).

\[
U_{\text{crit}} = \left( \frac{8 \sigma}{C_D \rho \pi D} \right)^{0.5}
\]  

Equation (3) can be used to derive an expression relating the size \(D\) of a single droplet to its critical relative velocity \(U_{\text{crit}}\); this relationship is plotted in Figure 26. The critical relative velocity is the velocity needed to induce droplet breakup when the droplet size is \(D\). That is, the forces maintaining the droplet’s integrity are outweighed by the disruptive forces if the droplet’s relative velocity exceeds \(U_{\text{crit}}\). Higher injection pressures produce higher relative velocities and thus smaller droplets. While this relationship is true for a single droplet, the case of an entire spray is more complex because the atomization process also depends on the flow structure at the nozzle outlet and the number of droplets. A comprehensive investigation that considers the effects of the internal nozzle flow on spray behavior would therefore be needed to determine why the effects of injection pressure become less pronounced once the injection pressure exceeds 80 MPa.

**Conclusions**

The dependence of spray properties on the fuel injection pressure was investigated experimentally using various nozzle types at injection pressures between 20 and 150 MPa. Based on experimental measurements of variables such as the injection rate, analyses of spray development by imaging, and droplet size measurements by PDI, the following conclusions were drawn:

- The penetration length generally increases with the fuel injection pressure. However, for a given injected fuel mass, the penetration at EOI is almost independent of the injection pressure. The divergent 10-hole nozzle produced the sprays with the shortest penetration, while the convergent 6-hole nozzle produced those with the longest penetration. At atmospheric ambient pressure, the sprays formed by the convergent and cylindrical nozzles exhibited no detectable deceleration. This was due to variation of the spray plume angle over time during the injection event: the spray became narrower during the injection than at the start and end of injection.

- Increasing the fuel injection pressure induced earlier breakup by strengthening aerodynamic forces: the breakup time was reduced by a factor of more than 2 upon raising the injection pressure from 20 to 150 MPa. The breakup length also increases with the injection pressure, but this increase can be minimized by using a divergent nozzle and a higher ambient pressure. The combination of a divergent 10-hole nozzle and a pressurized chamber yielded the shortest and earliest breakup.

- Measurements of D10, SMD and Dv90 revealed that higher fuel injection pressures yielded better atomization and smaller droplets. The effect of injection pressure on droplet size is most pronounced at injection pressures below 80 MPa, and becomes less significant at injection pressures above this threshold. Higher injection pressures also significantly reduced the number of large droplets; no droplets larger than 20 μm were detected when the injection pressure exceeded 80 MPa.

- The droplet size during needle opening was larger than at full lift. This difference in the droplet size between needle opening and full lift was less pronounced at higher fuel injection pressures because high injection pressures result in faster needle opening.

**References**


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