

Investigation of the Interaction of Sprays from Clustered Orifices under Ambient Conditions Relevant for Diesel Engines

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ABSTRACT

The objective of this research is to investigate the behavior of interacting sprays, so-called spray clusters, under typical Diesel combustion conditions. Visualizations and Phase-Doppler Anemometry are employed to characterize the macro- and microscopic spray properties. A significant effect of the cluster geometry on spray formation is noticed. Direct spray-spray interaction is found in all cases, with varying intensity depending on the included angle of the orifices within a cluster. The sprays from all investigated cluster nozzles penetrated significantly slower than those of a comparable conventional nozzle. The stability of the sprays is found to be very sensitive to the orientation of the cluster. Depending on this parameter the sprays from one cluster penetrate very similar or exhibit significant instabilities, especially at lower injection pressures.

INTRODUCTION

Nozzles with more and smaller orifices have contributed significantly to the improvement of Diesel engines in the past years. Kobori et al. [1] have investigated the influence of micro-hole nozzles on combustion in a rapid compression machine. As they reduced the orifice diameter and increased the number of orifices, they noted a reduction of ignition delay and soot emissions. Later Pickett and Siebers [2] have investigated the influence of the orifice diameter on soot formation in Diesel combustion for micro orifice nozzles. A reduction in orifice diameter results in a reduced soot formation. Pickett and Siebers claim to use very sensitive instruments but find no soot formation detectable at all for sprays from nozzles with a single 50 μm orifice. Their interpretation of the result is that mixing is increased to a point where the mixture is lean enough to prevent the formation of soot.

In engines, however, a reduction of orifice diameter leads to an increased number of orifices. This is due to

the necessity to deliver a defined fuel quantity at full load in a given time at a given fuel pressure. However, for equispaced orifice configurations no improvement is recorded for hole numbers above a certain threshold. Benajes et al. [3] have tested an engine with an equispaced nozzle design with 6, 12 and 18 orifices with and without swirling in-cylinder flow (for brevity denoted by swirl). They find the lowest emissions in the case with swirl for the nozzle with 6 orifices. Without swirl, the nozzle with 12 orifices leads to the lowest emissions. However, the emission level in this case is significantly higher than for 6 orifices with swirl. Adomeit et al. [4] have performed a study on the number of orifices in nozzles of engines for passenger car applications with 0.4 to 0.55 l displacement per cylinder. They find a constant number of 5 orifices per nozzle from the late 80s to the late 90s. In the last 10 years, there are between 6 and 8 orifices per nozzle. From this, they derive a trend indicating that the number of orifices per nozzle increases by about 1.5 every decade. However, the data shown exhibit a noticeable scatter around the trend line. They also plot a trend line for the orifice diameter, showing a decrease of 40 μm per decade. Fasolo et al. [5] investigate the influence of the number of orifices of the injector on soot emissions with CFD and find for their 2 l displacement, 4 cylinder engine an optimum at 6 holes. Also remarkable is the publication by Schommers et al. [6] where the layout of a 5 year old production engine is redesigned and equipped with an injection system from a different supplier in this process. Nonetheless, the number of orifices in the nozzle remains unchanged.

A lot of possibilities have emerged recently to manufacture nozzles with small orifices. Besides laser-drilling also manufacturing methods for micro-systems have been employed to produce orifices. With such methods, Baik et al. [7,8] have demonstrated "shower-head" nozzles containing up to 169 orifices close to each other, each with 40 μm diameter. However, they noted similar properties to sprays produced by conventional nozzles with one large orifice and concluded that the

quantitative impact of orifice geometry on spray propagation is smaller than they had anticipated.

One possibility to realize the desired decrease in orifice diameter and increase in orifice number is to abandon the equispaced design and to cluster the orifices. Nishida et al. [9] and Gao et al. [10] study group-hole nozzles, as they call them, consisting of two sprays with an included angle of -10 to 10° . They find the included angle between the sprays to be an important parameter influencing spray propagation. For converging sprays, i.e. negative included angle, a similar behavior like for the corresponding conventional nozzle is observed in terms of penetration. For the diverging nozzles with positive included angle between the sprays a reduction in the penetration of the spray tip is found. Zhang et al. [11,12] investigated the spray-wall interaction of sprays from group hole nozzles. They found better atomization characteristics and asymmetries in the impinging spray on the wall when comparing the group hole nozzles to conventional ones.

Adomeit et al. [4] investigated a 4-cylinder engine with a displacement of 1700 cm^3 . In part load conditions they find the usage of cluster nozzles advantageous and note improvements in the soot- NO_x -tradeoff. They observe a slight advantage for convergent configurations compared to divergent clusters. However, in full load operation a conventional nozzle with six orifices shows a better soot- NO_x -tradeoff than the cluster nozzles. Dohle et al. [13] have investigated a number of cluster nozzles in a 400 cm^3 single cylinder engine. Among the investigated cluster configurations they also find the convergent layouts to be the most advantageous. Over the whole engine operation range, the best performance is observed in this study for a conventional 7-hole nozzle. Gao et al. [14] investigate the flame propagation of sprays from a conventional nozzle and a cluster nozzle with two orifice circles and 10° between the divergent sprays in an optical engine. They observe significantly reduced soot luminosity for the sprays in the test runs with the cluster nozzles. They conclude that these nozzles have major advantages compared to conventional nozzles in terms of soot *production* in the engine due to the leaner equivalence ratio. As the results reported in [4] and [13] find no emission advantage for such nozzles in engines, it seems that the sprays from cluster nozzles have deficits in terms of soot *oxidation*. However, none of the studies modified the piston bowl. It is expected that such an approach favors convergent cluster configurations as for them the spray targeting remains the same compared to conventional nozzles.

In this study the sprays from cluster nozzles are investigated in a pressurized vessel under thermodynamic conditions relevant for Diesel engines. The aim of this paper is to answer some fundamental questions about the interaction of clustered sprays and to provide experimental data for the validation of numerical simulations. The included angle of the sprays in the cluster and the orientation of the cluster is varied.

The cluster nozzles are also compared to a conventional nozzle. For the macroscopic behavior of the sprays visualizations are employed. A defocused laser light sheet is used to detect the liquid phase of the spray. The vapor phase is detected with a simple schlieren technique. Additionally the sprays are investigated using Phase-Doppler Anemometry to record droplet velocities and sizes for the first time, as no other Phase-Doppler data from sprays of clustered orifices have been found in the literature.

EXPERIMENTAL SETUP

PRESSURIZED CHAMBER - The ambient conditions in the pressurized vessel for all investigations have been set at a temperature of 800 K and a pressure of 50 bar . A continuous air flow of about 25 kg/h delivered by a compressor is heated electrically to the desired temperature before entering the chamber. As the fluid in the chamber is air, combustion takes place after injection. However, in the scope of this investigation, the resulting combustion processes have not been studied. The chamber can be configured according to the needs of the desired investigation. Several test sections with three and four windows can be combined with a variety of heads and heaters to allow for the optical access necessary for the specific measurement task.

INVESTIGATED NOZZLES - Table 1 documents the four nozzles that have been investigated with visualizations and PDA in detail. For comparability all four nozzles have identical flow numbers of 168. This means that at a pressure difference Δp of 100 bar a fuel volume of 168 cm^3 flows through the nozzles in 30 s . The KS-factor of all nozzles is 1.3. The included angle between the sprays is positive, the sprays are diverging. The spray, respectively the cluster axes are located on a cone with a full opening angle of 148° . The nozzle design is the so-called "Combined Nozzle Layout" (CNL) with a midi-sac hole. The nozzles have been investigated using a "short" energizing time of $630\text{ }\mu\text{s}$ for 600 and 900 bar rail pressure and $835\text{ }\mu\text{s}$ for 1350 bar rail pressure. Also a "long" energizing time has been investigated, using 3.5 ms independent of the rail pressure.

Number of Orifices/ Orifice Circles	Angle between Cluster Sprays	Orifice Diameter
3/1	-	$131\text{ }\mu\text{m}$
6/1	$+10^\circ$	$93\text{ }\mu\text{m}$
6/1	$+20^\circ$	$93\text{ }\mu\text{m}$
6/2	$+20^\circ$	$93\text{ }\mu\text{m}$

Table 1: Nozzle Properties

For optical accessibility nozzle configurations with three clusters have been chosen for this investigation. Each cluster contains two orifices. The distance between the orifices in each cluster is 0.6 mm . Cluster nozzles with one- and two-orifice-circle configurations (see Figure 1) have been employed. Especially in the two-orifice-circle

configuration, the access to the region between the spray will be very difficult in future investigations employing nozzles with five and more clusters.

VISUALIZATION - Visualizations are a comparably simple yet powerful tool to perform phenomenological investigations of spray processes and are therefore in widespread use. The chamber configuration for this investigation employs a test section with four window openings at a 90° spacing, see Figure 2. Light from a defocused laser light sheet has been used to detect the envelope of the liquid phase. A window in the chamber head is used for illumination. This procedure uses the fact that virtually only droplets scatter the light, whereas the light scattering by ambient gas and fuel vapor is negligible. To ensure a uniform illumination of the sprays in the cluster, an additional window in the chamber head has been employed.

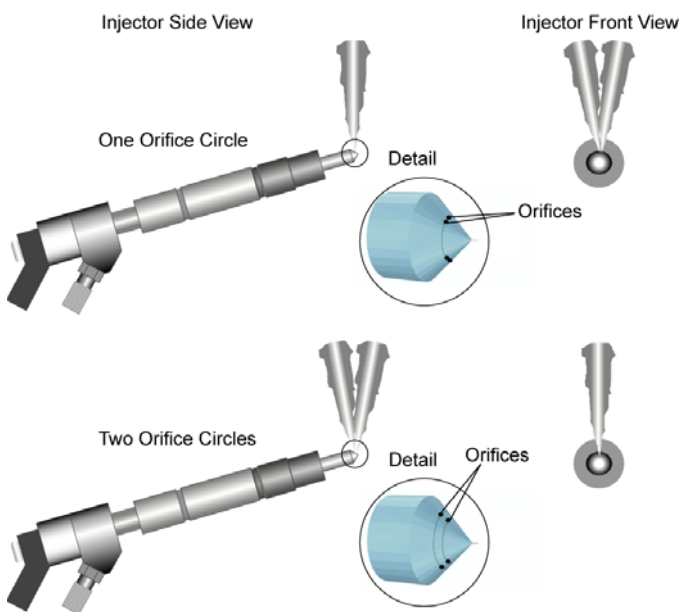


Figure 1: Sketch of orifice orientation for cluster nozzles with one (top) and two (bottom) orifice circles

Quasi-simultaneously a backlight technique has been used to detect the envelope of both the liquid and vapor phase. Settles [15] calls such an approach a “Large Colored Grid Background Distortion” technique and classifies it as a simple schlieren method, with the schlieren cutoff being in the background. This technique detects the refractive index gradients caused by the presence of fuel and it requires the light source, the object and the detector to be aligned on a straight line. Therefore the cluster configuration with one orifice circle had to be mounted opposite to the camera, using a window in the injector holder for illumination. The single orifice nozzle and the nozzle with two orifice circles have been mounted in one of the two window openings perpendicular to the one used for the camera. Typically, 20 images per time step are recorded. The image recording has been completely automatized based on the DaVis software from LaVision GmbH.

An automatic image processing tool based on Matlab has been developed to extract information about the penetration length and cone angle from the images. The liquid phase is extracted from the scattering light images using a threshold value defined for each image by Otsu’s method [17]. The schlieren caused by the fuel in the backlight image exhibit small structures with steep intensity gradients. They are detected from the schlieren images with an edge filter based on Canny’s method [16]. The resulting binary images are closed and filled. From this, selecting the largest region reliably delivers the spray envelope in the images.

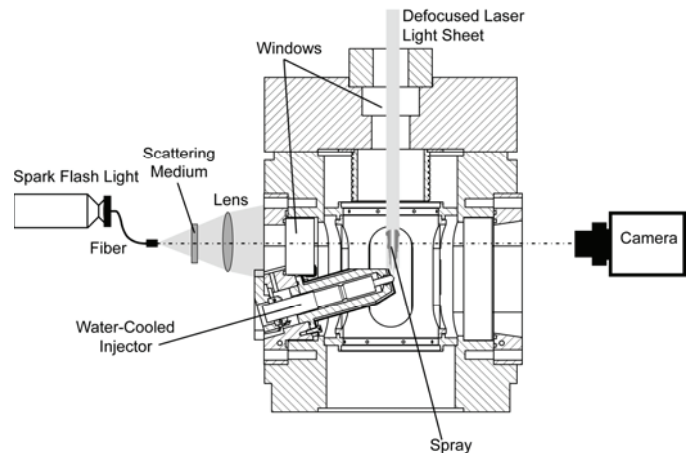


Figure 2: Sketch of the visualization setup in the chamber with four window openings – side view

PHASE DOPPLER ANEMOMETRY - The integral information gained by visualisations is supplemented by Phase-Doppler Anemometry (PDA) measurements. The PDA uses an Ar⁺-laser as light source to create a small measurement volume. The PDA-system can then determine the velocity and the diameter of single particles crossing the measurement volume from the light they scatter. For a detailed description of the technique see [18]. This technique has its difficulties when there is more than one particle in the measurement volume, therefore it cannot be applied to the dense part of a Diesel spray, but is restricted to the area around the stationary penetration length [18, 19]. A typical distance from the orifice to the measurement volume is 35 mm. The setup at the pressurized chamber is shown in Figure 3. The same injector holder, which is used for shadowgraphy, is also used for PDA. In order to minimize the sensitivity to the temperature-depending refractive index of the fuel, the detector probes are positioned 65° off-axis. The size of the measurement volume is about 100 µm in diameter. At each radial position the data of 100000 droplets or 330 injections has been recorded.

VISUALISATION RESULTS

SINGLE IMAGES - First some characteristic single images of the sprays from the investigated nozzles will be discussed. The top image in Figure 4 shows the light scattered by the fuel jet from the conventional three-hole

nozzle 1 ms after energizing the injector. The rail pressure for this injection and all the injections in this section has been 900 bar, the total energizing time 630 μ s. This image has been illuminated by a comparably thick laser light sheet coming from above the injector. Only the liquid phase is visible in the image, as the vapor phase scatters almost no light. The nozzle tip is located in the center bottom part of the image. To the left of the nozzle tip is the injector holder, which has been mounted in a chamber opening perpendicular to the camera axis. Due to the strong light scattering in the upper regions of the spray the intensity of the light sheet reduces as it passes through the spray. Therefore the light from the upper part saturates the camera whereas in the part closer to the nozzle, structures in the spray become visible.

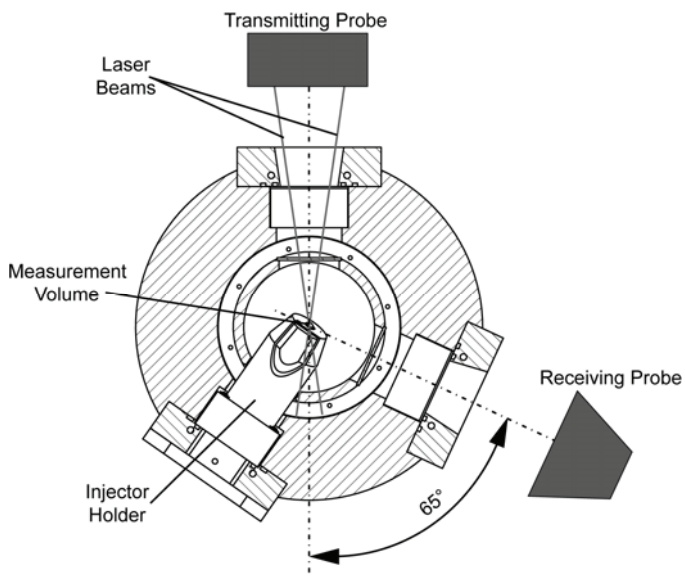


Figure 3: Sketch of the PDA setup in the chamber with three window openings – top view

The bottom image in Figure 4 shows a back-lit schlieren image of the same injection event 15 μ s later, taken by the same camera. As the liquid phase of the spray, which is bright in the top image, is optically very dense, practically no light from the background is transmitted. In fact the connected dark area in the image indicates the presence of liquid fuel. Strong intensity differences to the background as well as to the vapor phase are observed. The vapor phase is indicated by the presence of schlieren downstream of the liquid phase. Randomly there are a few droplets present in this area, but they appear not to be responsible for the schlieren, see Staudt [19]. Close to the nozzle tip, no schlieren surrounding the liquid phase can be observed, which is in accordance with Staudt [19] and Naber and Siebers [20]. Close to the nozzle, the liquid phase therefore determines the cone angle of the fuel jet. Further downstream, the fuel droplets are decelerated and heated by the ambient gas. Close to the liquid penetration length the liquid fuel is surrounded by fuel vapor. In this region the vapor determines the cone

angle. The evaporation process starts at the periphery of the fuel jet and propagates to its center.

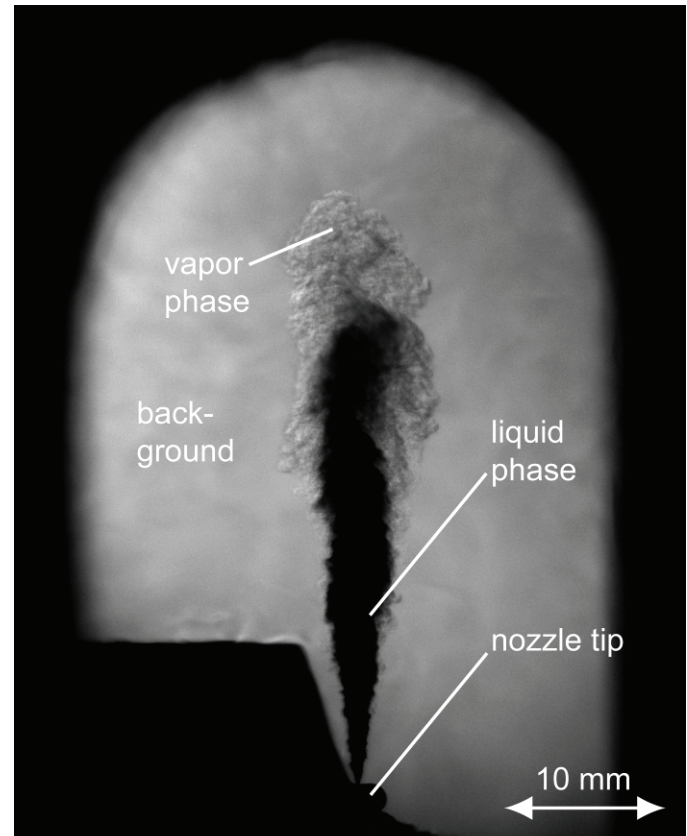
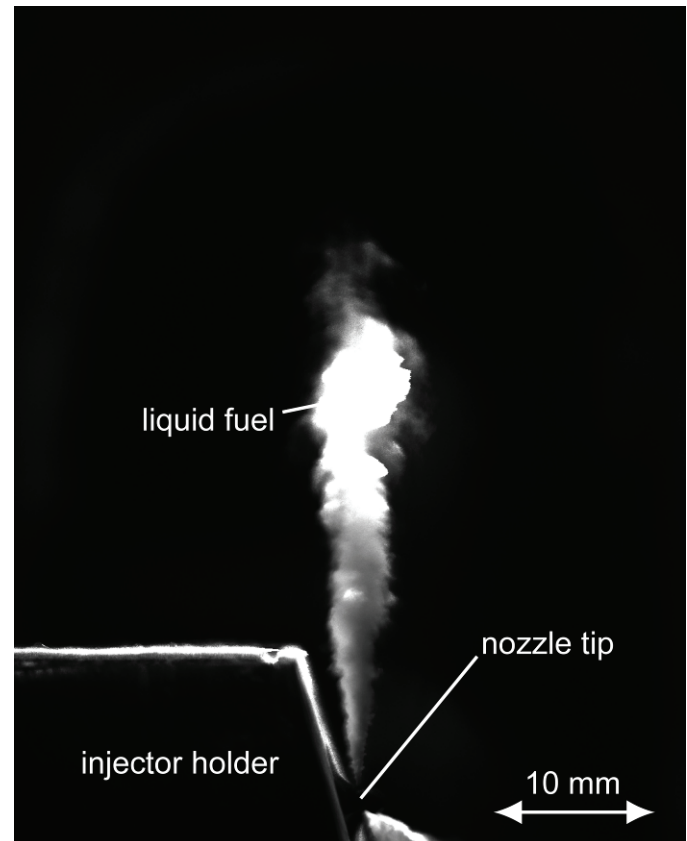


Figure 4: Scattering light (top) and schlieren (bottom, 15 μ s later) image of the spray from the conventional three-hole nozzle, 1 ms after energizing the injector

Figure 5 shows sprays from the cluster-nozzle with one orifice circle and 10° between the sprays. As the orifices of this nozzle are aligned on one circle, the nozzle had to be mounted in a chamber opening opposite to the camera. A window in the upper half of the injector holder has been used to light the background for the schlieren technique. Mounting the injector in a way that the cluster sprays point exactly upwards was not feasible due to interference of the common rail connector and the back light optical setup. Therefore the injector had to be mounted 10° tilted. However, the error in penetration length is only about 1.5 %. This seems tolerable for the purpose of this investigation. As the optical access in the injector holder has not been necessary for the PDA-measurements presented in the next section, these experiments have not been restricted in a similar fashion. As the injector holder is mounted in the chamber opening opposite to the camera, it forms the background for a part of the spray in Figure 5. The position of the light sheet has been carefully adjusted in order to ensure an adapted background, reducing the saturated area in the top image of Figure 5 compared to Figure 4. Sprays from all three clusters can be observed in Figure 5. One spray cluster points upwards, the other two clusters can be seen in the bottom part of this image. Close to the nozzle a distinction between the two sprays in the cluster can be seen, but about 10 mm downstream of the nozzle, the liquid phases of both sprays merge. Despite the fact that there is an included angle of 10° between the orifices in the cluster, the axes of the spray plumes in the cluster seem to be parallel. The explanation for this fact is that the two sprays mutually entrain air from the zone between them, which finally leads to the merging. This may be an effect similar to that in parallel single-phase jets, where Anderson and Spall [21] report a pressure below ambient pressure between the jets. The vacuum between them deflects the jets toward each other and accelerates their merging.

Nishida et al. [9] and Zhang et al. [11,12] have investigated comparable nozzles with only one cluster. They studied converging and diverging cluster configurations with an included angle between the sprays from -10° to $+10^\circ$, at ambient condition of 833 K and 40 bar in a pure nitrogen atmosphere and an injection pressure of 900 bar. They found merging sprays for all configurations investigated. So their findings are consistent with the result shown in Figure 5.

In the schlieren image, bottom in Figure 5, only the portion of the sprays further than 10 mm downstream of the nozzle is visible as the injector holder prevents the lighting of the area close to the nozzle. The liquid phase of the fuel, bright in the top image corresponds to the dark region in the bottom image. Above the actual injector holder, only one connected dark area is visible, indicating like the scattering-light image, that the liquid phases of both sprays have merged. Some schlieren surround the liquid phase showing the presence of vapor around the liquid phase. However, there is no hint that significant evaporation takes place between the sprays.

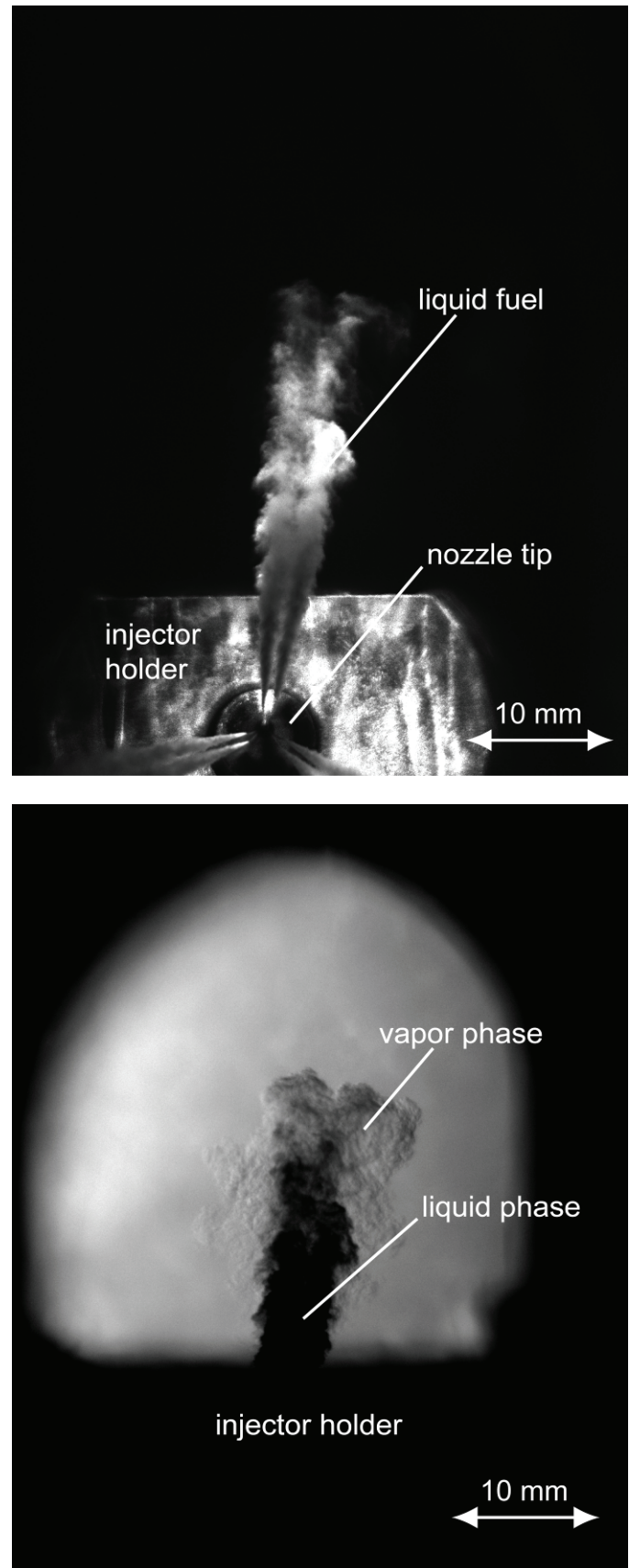


Figure 5: Scattering light (top) and schlieren (bottom, 15 μ s later) image of the sprays from the nozzle with one orifice circle and 10° between the sprays, 1 ms after energizing the injector