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SPRAY-WALL INTERACTION OF CLUSTERED SPRAYS UNDER CONDITIONS RELEVANT FOR DIESEL ENGINES

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ABSTRACT

The reduction of the orifice diameters in nozzles for Diesel injectors enhances the mixing processes in the spray and leads to a leaner equivalence ratio, which is known to reduce soot formation. Therefore, nozzles with more and smaller orifices have contributed significantly to the improvement of Diesel engines in the past years. However, above a certain number of orifices, no further improvement is recorded for equispaced orifice configurations. The reason for this is probably an increased interaction between the sprays for an increased number of holes per nozzle. There are several possibilities to enhance engine performance by the usage of more sprays per nozzle. One option is to cluster the orifices.

The interaction of the sprays of such clustered orifices with walls is studied using visualizations under ambient conditions of 50 bar and 800 K. The included angle of the orifices in the cluster is varied and a corresponding conventional nozzle and the interaction of the sprays with one flat and two divided walls are investigated.

The results display significant influence of the cluster geometry on spray formation. The impinging sprays exhibit direct spray-spray interaction, with varying intensity depending on the included angle of the orifices within a cluster.

In most cases a cross over point between the sprays exists. The reason for this behaviour is most likely the increased momentum transfer to the gas phase for the sprays from the cluster nozzles, which leads to a faster momentum decay in the sprays. Therefore at late times of the spray propagation there is less momentum left for the formation of wall jets.

Key Words: Diesel Engine, Cluster nozzle, Schlieren Technique

INTRODUCTION

A promising path to lower particulate emissions from Diesel engine combustions seems to be the reduction of the nozzle orifice diameter. The resulting sprays show higher air entrainment and a better evaporation behaviour, which according to Pickett & Siebers [1] leads to a higher equivalence ratio, which in turn results in less soot. However, for keeping the injected fuel mass constant compared to conventional nozzle, the number of orifices has to increase.

Some investigations are reported in which the geometrical distribution in cluster nozzle was varied. Nishida et al. [2] studied nozzles consisting of two small holes with a small spatial interval and small included-angle between -10° to +10°. These angles were divided in diverging (+) and converging (-) group hole, dual hole and a single hole nozzle were used as reference. For the diverging group hole configuration, the sprays tip penetration was smaller than the single hole nozzle, and it decreases as the diverging angle increases. For the converging group hole configuration, they have a similar effect to the group hole nozzle with two parallel holes on the spray and mixture properties. Zhang et al. [3] studied group hole nozzles with each group consisting of two micro-orifices with a small spatial interval and a small angle between the sprays of 0° to 10°. The group-hole nozzle spray has a smaller mean drop size and an equivalent tip penetration compared to a conventional single-hole with the same total section area of injection hole(s). Pawlowski et al. [4] employed visualizations and Phase-Doppler Anemometry to investigate the interaction of sprays from clustered orifices. They studied different distributions of orifices, two cluster nozzles with one orifices circle and different diverging angle, a cluster nozzle with two orifice circles and a nozzle with three single-orifices as reference. The spray from all investigated cluster nozzles penetrated significantly slower and showed smaller axial drop velocities than those of the conventional nozzle.

Since the results from equispaced orifices configurations are not encouraging, the objective of this investigation is to analyse a different distribution of the orifice in a so called cluster nozzle and the interaction between sprays and three types of walls.

EXPERIMENTAL SETUP

PRESSURIZED CHAMBER - The ambient conditions in the pressurized vessel for all investigations have been set to a temperature of 800K and a pressure of 50 bar. A continuous air flow of about 25 kg/h is delivered by a compressor and 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 chamber heads and heaters to allow for the optical access necessary for the specific measurement task. For the reported experiments three different wall inserts have been placed in the chamber, a straight divided wall, a slant divided wall and a flat wall. Divided wall have been chosen, as it is a better representation of the piston geometry than a flat wall.

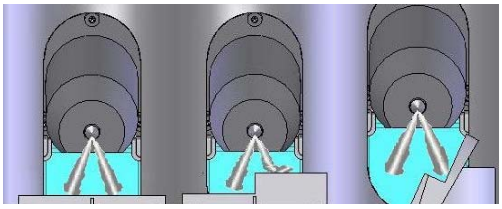

Figure 1: Sketch of the wall setups in the chamber, Front View.

INVESTIGATED NOZZLES - Table 1 documents the three nozzles that have been investigated with visualizations in detail. For comparability all three nozzles have identical flow numbers of 165 $cm^3/30s$ at Δp =100 bar. The included angle between the sprays is positive and the sprays are diverging. The sprays, as well as the cluster axis 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 µs for 600 and 900 bar rail pressure and 835 µs for 1350 bar rail pressure.

Number of Orifices	Angle between Cluster Sprays	Orifice Diameter
3	-	131 µm
3x2	+10°	93 µm
3x2	+20°	93 µm

Table 1: Nozzles Specifications

Each cluster contains two orifices. The distance between the orifices in each cluster is 0.6 mm. Cluster nozzles configuration with one orifice circle (see Figure2) has been employed.

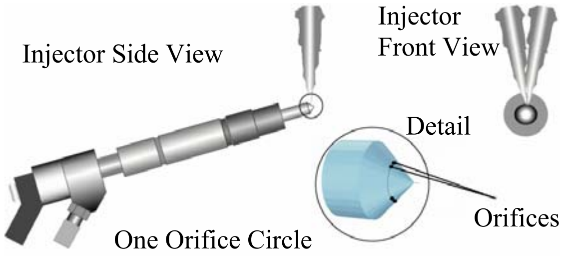

Figure 2: Sketch of orifice orientation for cluster nozzles.

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 3).

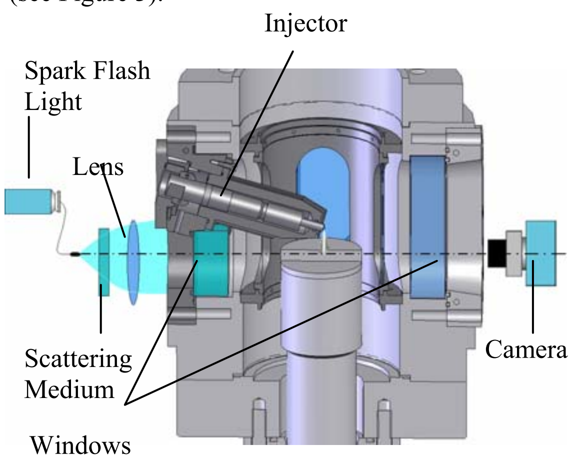

Figure 3: Sketch of the visualization setup in the chamber with four windows openings-side view.

A backlight technique has been used to detect the envelope of both the liquid and vapor phase, also denoted as "Large Colored Grid Background Distortion" by Settles [5]. This is a simple schlieren method with the schlieren cutoff 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. For this reason the injector configuration had to be mounted opposite to the camera, using a window in the injector holder for illumination in the front view (see Figure 4). For the side view the injector has 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 spray width from the images.

VISUALIZATION RESULTS

SINGLE IMAGES – Figure 4 shows a back-lit schlieren image by the fuel jet from the cluster nozzle with 20° between sprays at 1.5 ms after energizing the injector. The rail pressure for this injection and all the injections in this section is 900 bar and the total energizing time is 630 µs. This front view image has been illuminated by a nanolite light source coming from above the injector. The nozzle tip is located in the center top part of the image. Behind the nozzle tip is the injector holder, which has been mounted in a chamber opening parallel to the camera axis.

A window in the bottom half of the injector holder has been used to illuminate the background for the schlieren technique. As the injector holder is mounted in the chamber opening opposite to the camera, it forms the background for a part of the spray. The extent of the vapor phase is indicated by the presence of schlieren in Figure 4 downstream of the liquid phase.

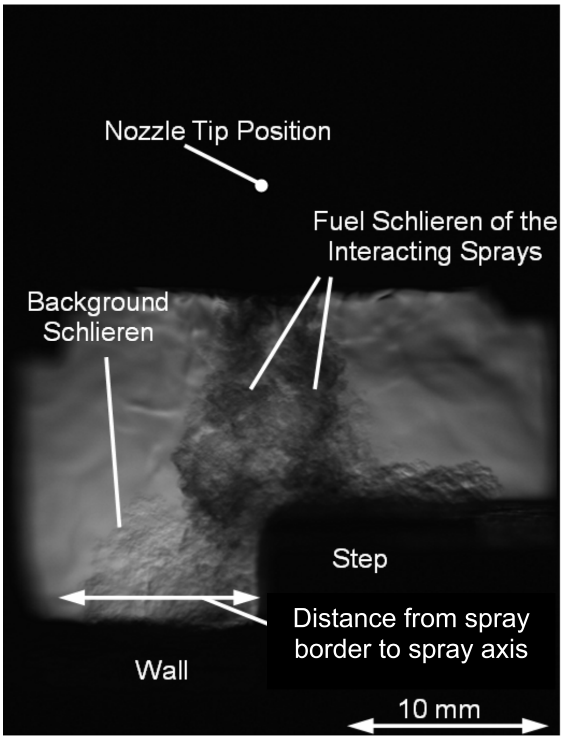

Figure 4: Schlieren image of the sprays from the nozzle 20° between the sprays, 1.5 ms after energizing the injector and 900 bar.

The nozzle shown in figure 4 has three spray clusters, each consisting of two orifices with an included angle of 20°. Only the sprays from one cluster are visible. After impinging on the divided wall, the sprays are separated and propagate along the wall.

Only the portion of the sprays further than 10 mm downstream of the nozzle is visible in all images presented here, as the injector holder prevents the illumination of the area close to the nozzle. This image shows the position where jets hit the wall. For both cluster nozzles the axis of symmetry between the sprays was orientated to coincide with the edge of the divided walls. Figure 5 shows the cluster nozzle with 10° angular spacing between the sprays. The two jets are directly interacting with each other, thus it is not possible to identify the individual sprays in the cluster nozzle. However, after the impingement on the wall, both sprays seem to be separated.

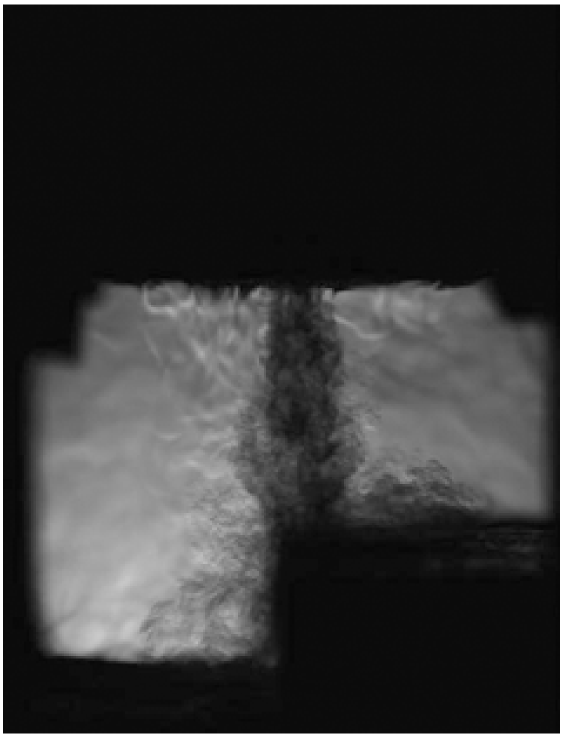

Figure 5: Schlieren image of the sprays from the nozzle with 10° angular spacing between the sprays, 1.5 ms after energizing the injector and 900 bar. Straight divided wall.

Figure 6 shows the spray emerging from one of the three single orifices. The fraction of the spray in the upper portion of the image, which is no impinging on any part of the wall, is quite thinner as the jets in Figures 4-5. In contrast to the other sprays the liquid phase, indicated by the dark regions in the image, is denser.

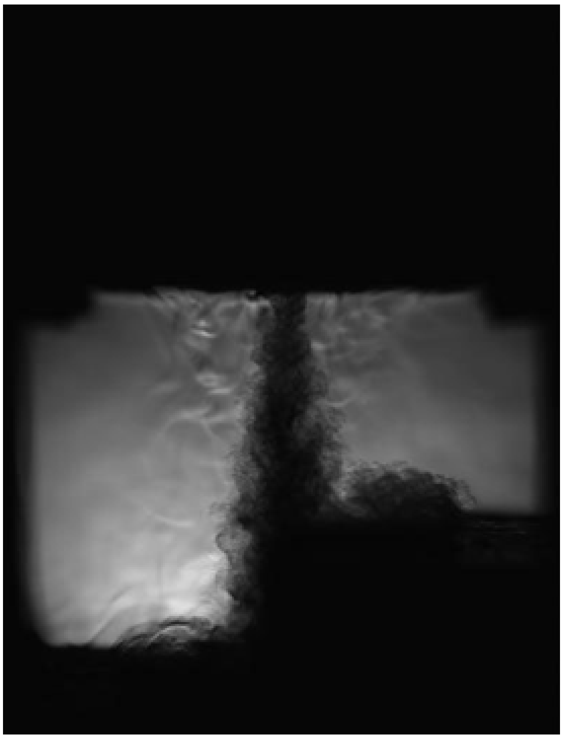

Figure 6: Schlieren image of the spray from the conventional three-hole nozzle, 1.5 ms after energizing the injector and 900 bar. Straight divided wall.

Figure 7: Schlieren image of the sprays from the nozzle with 20° angular spacing between the sprays, 1.5 ms after energizing the injector and 900 bar. Slant divided wall.

Figures 7-9 are images from the divided wall, positioned in a slanted way in the pressurized chamber. The sprays coming out from the cluster nozzle are also orientated like the first example and the jet from the single orifice nozzle directly hits the edge of the wall.

Figure 8: Schlieren image of the sprays from the nozzle with 10° angular spacing between the sprays, 1.5 ms after energizing the injector and 900 bar. Slant divided wall.

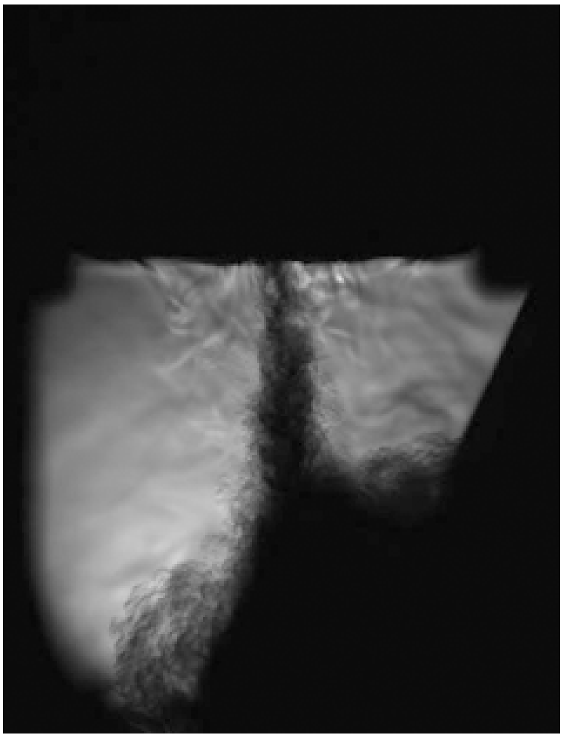

Figure 9: Schlieren image of the spray from the conventional three-hole nozzle, 1.5 ms after energizing the injector and 900 bar. Slant divided wall.

Up to the first spray-wall contact, the wall has no influence on spray propagation (Figures 7-9). After impinging on the edge of the wall the clustered sprays, and the single spray of the conventional three-hole nozzle respectively, are separated. The left part of the spray propagates along the wall outwards. The right part of the spray remains mainly in the spray close to the edge and does not propagate outwards. All the investigated cases show the same behaviour.

Figure 10 shows the interaction of the spray from the nozzle with 20° angular spacing between the sprays with the flat wall.

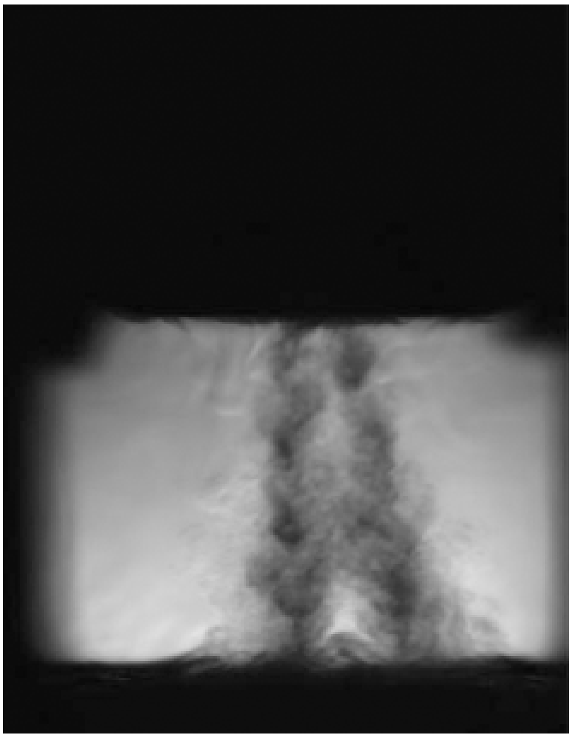

Figure 10: Schlieren image of the sprays from the nozzle with 20° angular spacing between the sprays, 1.5 ms after energizing the injector and 900 bar. Flat wall.

Figure 11 shows the interaction of the spray from nozzle with 10° angular spacing 10° between the sprays. In this case the spray width is smaller than the two other nozzle.

The flat wall, allowed the recording of images from two different views. Figure 12 indicates the side view, where the sprays were illuminated from the perpendicular side.

Figure 11: Front view. Schlieren images of the sprays from the nozzle with 10° angular spacing between the sprays, 1.5 ms after energizing the injector and 900 bar. Flat wall.

Figure 12: Side view. Schlieren images of the spray from the conventional three-hole nozzle, 1.5 ms after energizing the injector and 900 bar. Flat wall.

RESULTS FROM IMAGE PROCESSING - In order to extract the spray geometry from the images for a quantitative comparison an automatized image evaluation like used by Pawlowski et al. [4], has been attempted. However, close to the wall this evaluation proved to be too error prone and therefore here the spray geometry was detected unusually. In the experiments with the divided walls the symmetry axis of the spray respective to the cluster has been aligned with the edge of the wall. This edge has been used as a reference point and therefore in these cases the distance of the spray border to this reference point has been evaluated. In the case of the flat wall the nozzle position has been used as a reference point. However, for the front view images it proved to be easier to evaluate the full spray width instead of the spray border distance to a reference point.

In Figure 13 the spray width is shown for the conventional three-hole nozzle and the cluster nozzles for the straight divided wall for 600 bar. Figure 14-15 presents also the three different nozzles for 900 bar and 1350 bar rail pressure. The curves shown in this image represent the average of 20 images taken at each point in time.

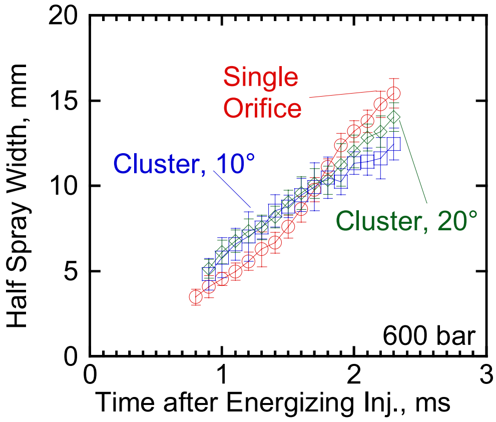

Figure 13: Spray width for the conventional three-hole nozzle and the cluster nozzles, straight divided wall for 600 bar.

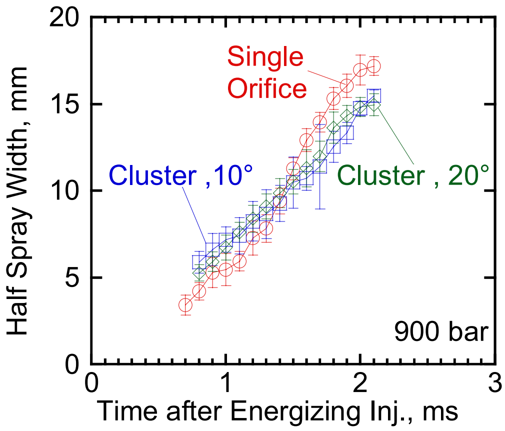

Figure 14: Spray width for the conventional three-hole nozzle and the cluster nozzles, straight divided wall for 900 bar.

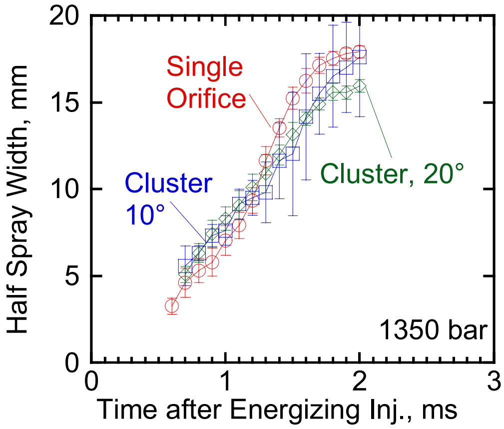

Figure 15: Spray width for the conventional three-hole nozzle and the cluster nozzles, straight divided wall for 1350 bar.

(Figure 13-14-15) In the beginning the sprays from the cluster orifices show a larger distance to the cluster axis, as they exit the nozzle under an angle to this axis. It is expected that this remains also after wall impact, which occurs around 1 ms. However, there is a cross-over in terms of spray width between the conventional nozzle and the cluster nozzles. For a rail pressure of 600 bar, shown in figure 13, this cross-over takes place at around 1.7 ms. The same effect is observed also for other injection pressures. This is in accordance to the findings of Zhang et al. [3], who investigated the spray-wall interaction of sprays from similar nozzles, although with a flat wall. They found similar characteristics and asymmetries in the impinging sprays on the wall when comparing the cluster nozzles to conventional ones.

The curves for the slanted positioned wall show similar behaviour as the curves for the straight divided wall (Figure 16). The cross-over in terms for spray width is observed again. Due to the different configuration between the two divided walls the cross-over takes places at an earlier time in the slat divided wall as the straight divided wall. Depending on the rail pressure the point of intersection occurs about 1.3-1.6ms after start of energizing.

The reason for this behaviour is most likely the increased momentum transfer to the gas phase for the sprays from the cluster nozzles, which leads to a faster momentum decay in the sprays. Therefore at late times of the spray propagation there is less momentum left for the wall jets. This may have implications for the critical soot oxidation processes close to the wall in Diesel engines during the later part of the combustion event.

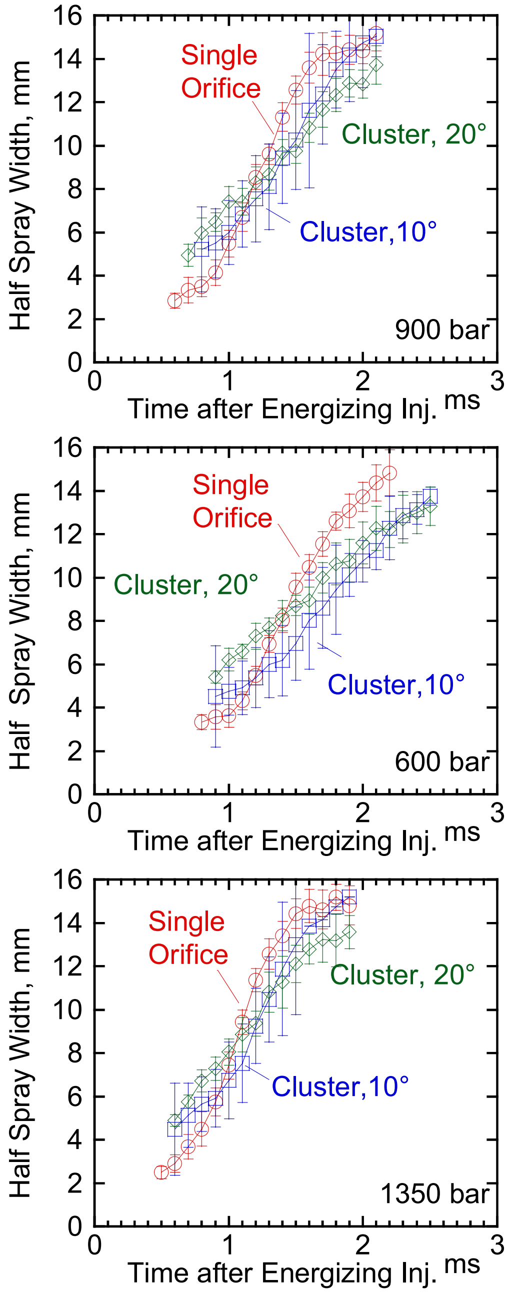

Figure 16: Spray width for the conventional three-hole nozzle and the cluster nozzle, slant divided wall for 600, 900 and 1350 bar.

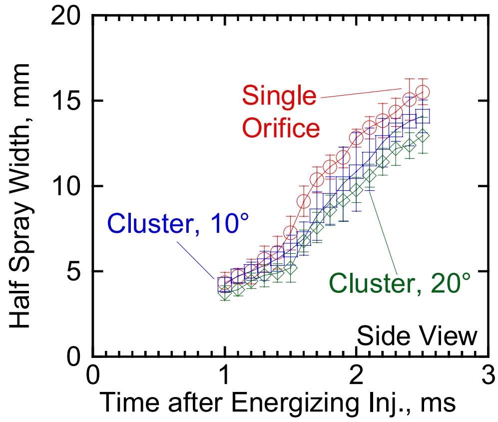

Figure 17: Side view. Spray width is shown for the conventional three-hole nozzle and the cluster nozzle for the flat wall for 600 bar.

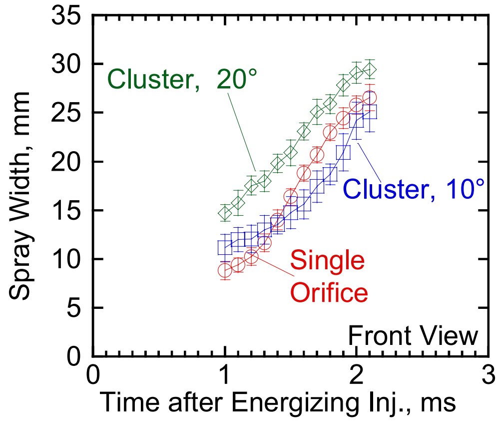

Figure 18: Front view. Spray width is shown for the conventional three-hole nozzle and the cluster nozzle for the flat wall for 600 bar.

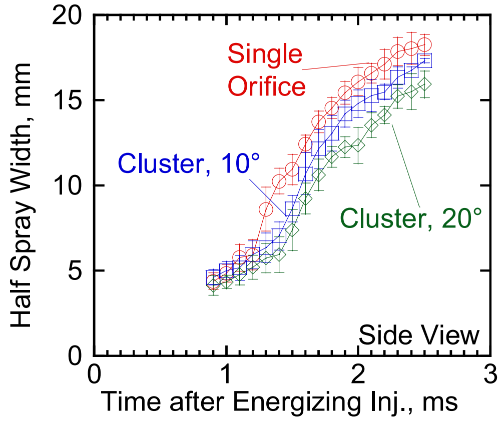

Figure 19: Side view. Spray width is shown for the conventional three-hole nozzle and the cluster nozzle for the flat wall for 900 bar.

In Figure 17, before any spray impinges the wall, the spray width is almost the same for all the investigated nozzles. After impingement the single orifice has the widest spray. The cluster nozzle with 10° separation between sprays has the second-widest spray and the cluster nozzle with 20° separation between sprays produces the thinnest spray. The same trend is observed at the other rail pressures, 900 bar and 1350 bar, figure 19-21. The higher the injection pressure, the wider the spray is.

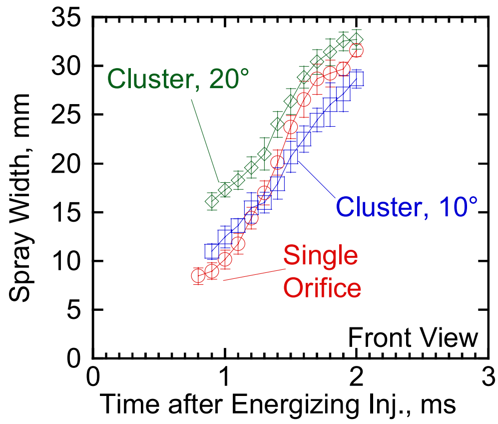

Figure 20: Front view. Spray width is shown for the conventional three-hole nozzle and the cluster nozzle for the flat wall for 900 bar.

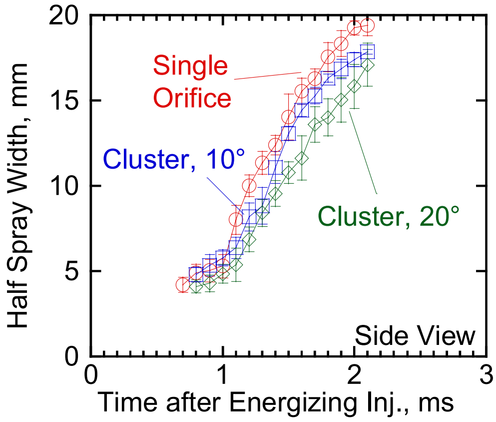

Figure 21: Spray width is shown for the conventional three-hole nozzle and the cluster nozzle for the flat wall for 1350 bar.

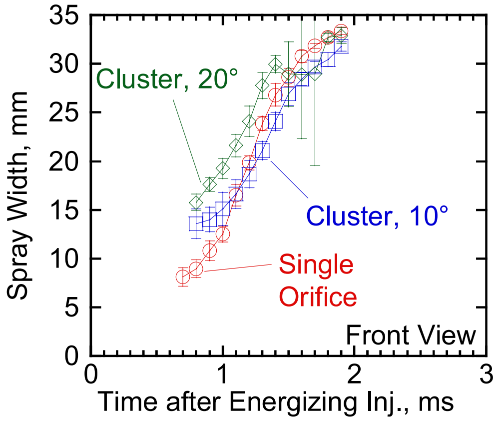

Figure 22: Spray width is shown for the conventional three-hole nozzle and the cluster nozzle for the flat wall for 1350 bar.

(Figures 18-20-22) The cluster nozzle with 20° exhibits the widest characteristics over all nozzles at any time and pressure during the injection. Before the spray impacts the wall, the cluster nozzle with 10° angular spacing between sprays presents an expected greater width than the single orifice. After the impingement a cross over point is found and the same effect is observed for the other injection pressures. This can also be explained by an increased momentum transfers to the gas phase for the sprays from the cluster nozzles. As has been shown by Pawlowski et al. [4], the interaction between sprays is reduced for the cluster nozzle with 10° angular spacing between sprays compared to the 20° cluster nozzle configuration. There, a deflection of the two sprays in the 10° configuration towards each other has been observed. Especially the positions in the sprays, where the highest velocities are measured, differ significantly from what is expected from purely geometric considerations. This may be the explanation for the behavior observed here in Figures 17-22. The spray from the cluster configuration with 20° shows consistently the largest widths in the front view and the smallest in the side view. The sprays behave like two individual sprays as they interact with the flat wall. However, the spray width for the sprays from the 10° configuration is smaller after wall impact than the one of the spray from the conventional nozzle in both, the side and the front view. This is probably due to the increased interaction for the sprays from the 10° configuration shown in Pawlowski [4] and is in accordance with Zhang [3].

CONCLUSIONS

The sprays from a set of nozzles with clustered orifices have been investigated and compared to a spray from a conventional Diesel injector. Visualizations were used to characterize sprays from such nozzles. 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.

In most cases a cross over point between the sprays exists. The reason for this behaviour is most likely the increased momentum transfer to the gas phase for the sprays from the cluster nozzles, which leads to a faster momentum decay in the sprays. Therefore at late times of the spray propagation there is less momentum left for the wall jets.

The momentum available close to the wall in an engine is critical for the soot oxidation process in this region. This may be at least partly the explanation for the poor engine results achieved so far with the cluster nozzles.

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