

Investigations of Clustred Diesel Jets under Quiescent High-Pressure and High-Temperature Conditions using Mie, Schlieren and Chemiluminescence Imaging

**Maria Cárdenas, Peter Hottenbach,
Reinhold Kneer and Gerd Grünefeld**

Istituto Motori, National Research Council of Italy

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ABSTRACT

One of the fundamental topics in the design of new injection systems for DI Diesel engines is to decrease the soot emissions. A promising approach to minimize soot production are injection nozzles having clustered holes. The basic idea of Cluster Configuration (CC) nozzles is to prevent a fuel rich area in the center of the flame where most of the soot is produced. For this purpose each hole of a conventional nozzle is replaced by two smaller holes, which are sized to yield the same flow rate. The basic strategy of the cluster nozzles is to provide a better primary break up, and therefore a better mixture formation, caused by the smaller nozzle holes, but a comparable penetration length of the vapor phase due to merging of the spray plumes.

Within this study, six cluster nozzles with cluster angles from 0° up to 15° are investigated and compared to two nozzles of a conventional design, one with the same flow number as the cluster nozzles and the other one with 50% of this value, according to a single hole of the cluster nozzles. The common rail diesel injector is installed in a combustion vessel, in order to provide nearly quiescent high-pressure and high-temperature conditions. Each injection is investigated using three different measurement techniques quasi-simultaneously. The liquid and the vapor phase are visualized using the scattered light of a Nd:YAG laser and back-lit schlieren imaging, respectively. Furthermore, the hot reaction zone is visualized using OH^* chemiluminescence imaging. OH^* occurs during the

second stage of the ignition process. The penetration lengths of the liquid and the vapor phase, as well as the lift-off length and the ignition delay, are determined. The influence of the cluster configuration and the cluster angle on the penetration and the subsequent combustion are analyzed and discussed.

INTRODUCTION

Pickett and Siebers [1, 2] investigated the influence of the orifice diameter on the lift-off length (LOL) and the soot formation of conventional Diesel jet flames and showed that the amount of soot decreases with decreasing orifice diameter because of higher air entrainment in the spray. In engines, the further reduction of the orifice diameter leads to an increased number of nozzle holes for maintaining the same flow rate. But it is shown [3, 4] that the number of nozzle holes, and accordingly the orifice diameter, with the lowest pollutant formation is limited depending on different geometric and aerodynamic parameters, e.g. swirl.

Matsumoto et al. [5] investigated the effects of reduced nozzle hole diameters for multihole nozzles. Smaller nozzle hole diameters were found to cause a slightly shorter spray tip penetration, however, yielding a leaner and more homogeneous fuel-air mixture. The effect of smaller droplets and enhanced evaporation, observed using nozzles with equally spaced micro-orifices, can be realized using clustered nozzle holes [6]. Adomeit et al. [7] investigated several divergent and one convergent Group Hole

nozzle configuration compared to a baseline nozzle in a Diesel engine. A significant reduction of soot emissions by the Group Hole nozzles was reported. The convergent configuration showed advantages in PM-emissions over the divergent ones, especially at higher part load. On the other hand, in [8] it is shown that convergent nozzle holes can produce larger drop size distributions also featuring higher liquid phase fractions in the region of the spray tip. Gao et al. [9] compared Group Hole nozzles with standard nozzles using measurements in an optical Diesel engine without EGR. For their application a divergent Group Hole nozzle with a 10° angle was found to be best for the application in their optical engine. It was also noted that larger divergent angles enhance the evaporation, but the penetration of the liquid and vapor phase is significantly reduced, and therefore less air is entrained, because the two nearly separated sprays are still located very close to each other. It was also a major aim in the design of the cluster nozzles to maintain the penetration of a conventional single spray. The Group Hole nozzle shows much lower soot luminosity compared to the standard nozzle in the optical engine, but also lower heat release rates and a lower IMEP for the same injected fuel mass. Different configurations of cluster nozzles were investigated by Dohle et al. [10]. In this application the convergent configuration also shows slight advantages compared to a divergent one. Nevertheless, no improvements for the cluster nozzles were recognized.

Pawlowski et al. [11] presented a detailed investigation in a combustion vessel using visualization techniques and PDA. There it was shown that the liquid phase from cluster nozzles penetrates significantly slower than a spray from a conventional nozzle. Also a strong interaction between the two clustered sprays was found. This effect diminished for larger cluster angles. The combustion and soot formation of the same cluster nozzles are investigated in [12] under comparable conditions. There it was demonstrated that the cluster nozzles generate less total soot mass compared to a conventional nozzle, at least in the early combustion phase. A possible reason for the benefit in soot formation of the cluster nozzles is the higher difference between the penetration length of the liquid phase and the lift-off length. Both quantities were measured quasi-simultaneously in this study. In [13] the importance of the air-fuel ratio at the lift-off location is discussed, and it is pointed out that a lean spray generated by a nozzle with a $50\text{ }\mu\text{m}$ orifice produces no measurable soot. Both prior studies using the present type of cluster nozzles [11, 12] also show that a nozzle with a cluster angle of 20° produces two separated sprays and flames with only a weak interaction. Hence, smaller cluster angles are chosen for the present work and additionally the steps between the different angles are smaller. Furthermore, the nozzles of the present work are combined with a state-of-the-art Bosch piezo injector, which allows the investigation of fuel rail pressures up to 1600 bar.

Essentially, it is the objective of the present work to support the fundamental understanding of spray formation

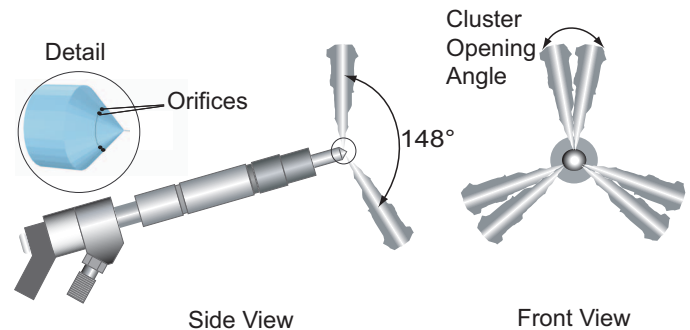


Figure 1: Sketch of orifice orientation for cluster nozzles.

and combustion of a new set of clustered diesel jets by a new experimental approach, which includes the quasi-simultaneous measurement of several quantities. For this,

three different measurement techniques are used. To determine the penetration lengths, the liquid and the gaseous phase are visualized using a Mie scattering and a Schlieren technique, respectively. The OH^* chemiluminescence is measured as a qualitative marker of the second stage ignition (see [14, 15] and references therein). The outcome of this is the time-resolved lift-off length and ignition delay. Also the fluctuations in the lift-off length are discussed.

EXPERIMENTAL SETUP

PRESSURIZED CHAMBER The ambient conditions in the pressurized vessel that is utilized for the investigation are set to 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. The temperature inside the pressurized vessel is measured at the center of the chamber approximately 10 centimeters above the injector nozzle without combustion. As the fluid in the chamber is air, combustion takes place after injection. A test section with four window openings at a 90° spacing was combined with an additional chamber head as heater, which also had a window to allow the optical access necessary for the specific measurement task, as illustrated in Fig. 2.

INVESTIGATED NOZZLES Table 1 summarizes the investigated nozzles in detail. For comparability all cluster nozzles have identical flow numbers of $210\text{ cm}^3/30\text{s}$. Two standard nozzles having flow rates of 210 and $105\text{ cm}^3/30\text{s}$ were used as reference nozzles. The cluster nozzle configuration consists of 6 orifices distributed in 3 groups. The included angle between the sprays is positive, the sprays are diverging, as is shown Fig. 1. The nozzles have been investigated using an energizing time of $850\text{ }\mu\text{s}$ for rail pressures of 600 bar, 1100 bar and 1600 bar and are installed on a state-of-the-art Bosch piezo injector. This corresponds to an end of the injection at 2.6 ms, 3.1 ms and 3.4 ms, respectively. The fuel used for this experimental study was diesel according to the European Standard EN 590.

Number of Orifices	Cluster Opening Angle	Designation	Flow Rate*
3	-	reference 1	105
3	-	reference 2	210
6	0°	0.0°	210
6	2.5°	2.5°	210
6	5.0°	5.0°	210
6	7.5°	7.5°	210
6	10°	10.0°	210
6	15°	15.0°	210

Table 1: Nozzle Specifications. * Flow rate in $\text{cm}^3/30\text{s}$ at a pressure difference of 100 bar.

VISUALIZATION The test section used is shown in Fig. 2. Mie Scattering, using light from a defocused laser light sheet, has been employed to detect the envelope of the liquid phase. A window in the chamber head is used for illumination. Quasi-simultaneously, a modified schlieren technique has been used to detect the envelope of both the liquid and vapor phase, as utilized by Pawlowski et al. [11]. For both Mie Scattering and schlieren visualization the injector was mounted opposite to the camera with the spray propagation oriented upwards. For schlieren visualization, the illumination was provided through a window above the injector holder, see Fig. 2. A CCD camera from LaVision GmbH with 1280 x 1024 pixels (Flowmaster 3) is used in double-frame mode as the detector. The laser pulse for the scattering light images is synchronized with the first frame, whereas the schlieren image is captured by the second frame of the camera, about $10\ \mu\text{s}$ later. Typically, 20 images per time step are recorded and only one double-frame image per injection is acquired. 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 from images. The penetration length corresponds to the distance from the orifice, which injects the fuel upwards, to the leading edge of the vapor phase and the liquid phase, respectively. With the diverging angle between the two sprays originating from one group hole set, this method leads to a small error, which amounts to less than 1% for the 15° cluster nozzle.

CONFIGURATION FOR THE OH^* MEASUREMENTS For the measurement of the OH^* chemiluminescence a double-frame ICCD camera is positioned in front of the chamber, next to the CCD camera for the Mie/Schlieren images (see Fig. 3). The light passing through the quartz window is divided into a visible (VIS) and a UV part. The VIS part is transmitted through the dichroic beam splitter and is collected by the lens of the CCD camera for the Mie/Schlieren images. The UV part is reflected and imaged by an UV-lens (B. Halle, $f = 100\ \text{mm}$, $f_\# = 2$).

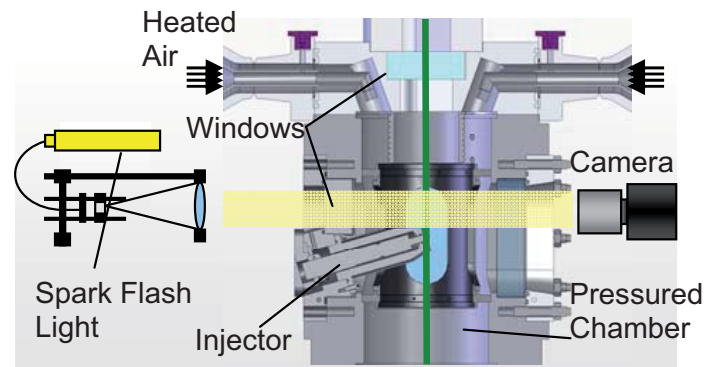


Figure 2: Sketch of the visualization setup in the chamber with four windows openings-side view.

Additionally, a filter combination (BP313, MSO Jena and DUG11X, Schott) with a maximum transmission around 313 nm is used to isolate the OH^* chemiluminescence in the range of 290 nm – 325 nm from the emissions of the soot and other species [15, 16]. The exposure time of the camera is set to $100\ \mu\text{s}$, and the delay of the two frames is $50\ \mu\text{s}$.

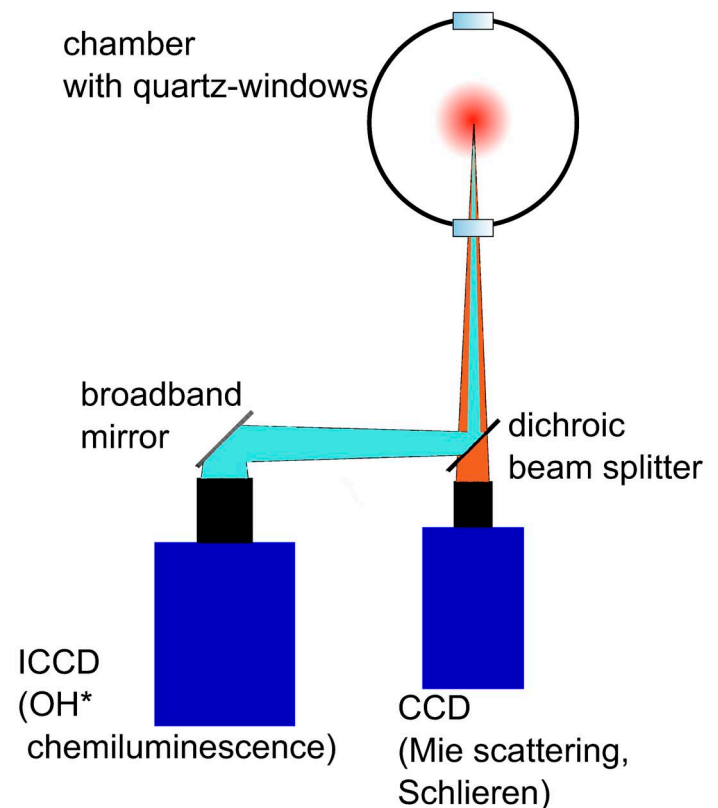


Figure 3: Optical set-up for simultaneous acquisition of Mie scattering, Schlieren and OH^* chemiluminescence images

For example, Fig. 4 shows two images of one typical injection of reference nozzle 2 for $t_{aei} = 2700 \mu s$ and $2850 \mu s$ measured using the double-frame ICCD. Several separated ignition spots can be seen in the first image (Fig. 4 (a)), which will be discussed in more detail below. The weak OH^* chemiluminescence signal on the lower right corner of the images is generated by the flame of another nozzle hole of the three-hole nozzle employed. The image in Fig. 4 (b) shows an established flame starting at about 13 mm downstream of the nozzle hole and reaching the upper edge of the chamber window at a height of about 55 mm.

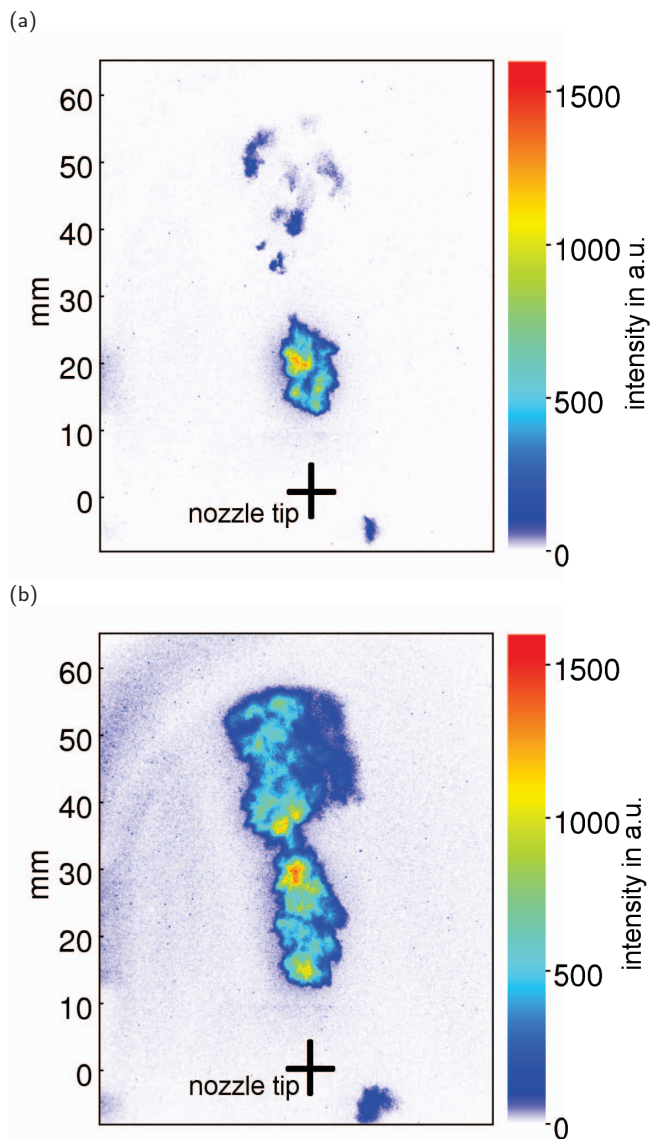


Figure 4: OH^* chemiluminescence images of the reference nozzle 2, typical single injection imaged two times using the double-frame ICCD, $p_{rail} = 600$ bar, $T = 800$ K, $p = 50$ bar, $ET = 850 \mu s$, $t_{aei} = 2700 \mu s$ (a) and $2850 \mu s$ (b)

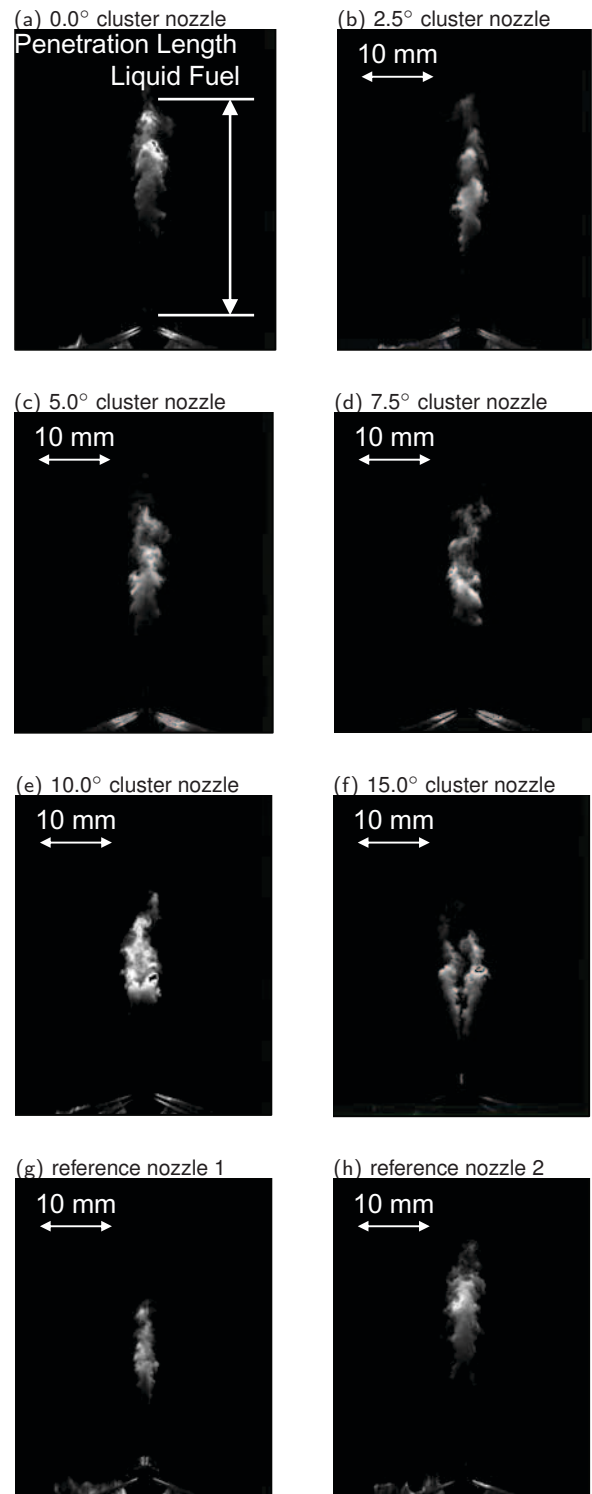


Figure 5: Scattering light images of the sprays from investigated nozzles, 1 ms after energizing the injector, rail pressure 1100 bar.

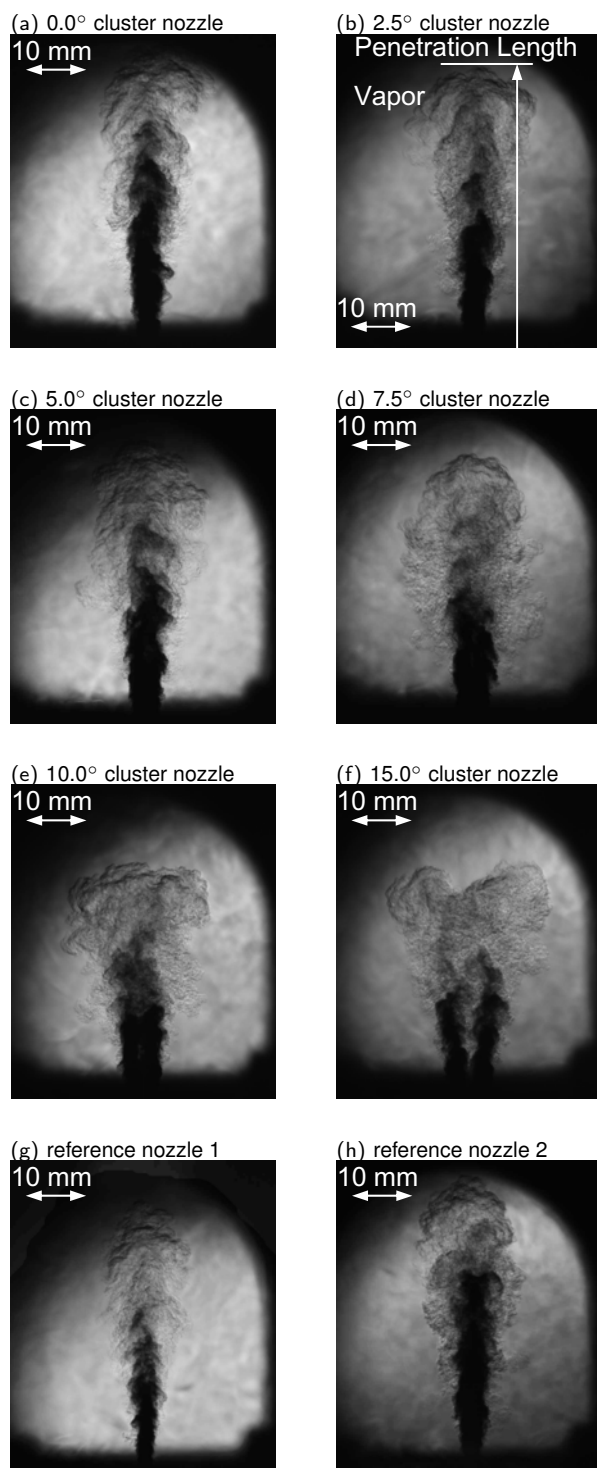


Figure 6: Schlieren images of the sprays from investigated nozzles, 1 ms after energizing the injector, rail pressure 1100 bar.

Lift-off length and ignition delay were not determined in the case of the 7.5° CC nozzle, because the measurements were strongly affected by unwanted temperature variations in the vessel.

RESULTS

VISUALIZATION RESULTS Single Images - First, single images from Mie scattering of the sprays will be discussed.

Images in Fig. 5 show the light scattered by the fuel jet from the nozzles at 1 ms after energizing the injector at a rail pressure of 1100 bar and a total energizing time of 850 μ s. In these images only the liquid phase is detectable due to almost no light scattering from the vapor phase. The sprays are illuminated top down with a defocused laser light sheet with approx. a thickness of 3 mm and a width of 10 mm. When applied to the sprays under investigation this produces strong light scattering in the upper spray regions. A noticeable loss of insity occurs, however, as the laser beam propagates through the entire spray. The Nd:YAG laser has an output energy of up to 200 mJ and a pulse duration of 5 ns. The bottom image in Fig. 5 (h) shows the light scattered fuel jet from the conventional three-hole nozzle, which has a flow rate equivalent to the one of the cluster nozzles at 1 ms after the energizing time. Fig. 5 (a) shows the liquid phase of the 0.0° cluster nozzle with opening angle, i.e. clustered orifices are located parallel to each other. The sprays from this nozzle and the 2.5° cluster nozzle presented the shape and similar results of penetration length related to reference nozzle 2. At the early stages of injection it is possible to distinguish the spacing between clustered sprays from the 5.0° and 7.5° cluster nozzles. However from the first measurable position of penetration length these sprays are already merging, showing one spray wider compared to the sprays from the cluster nozzles with smaller opening angles. For the 7.5° cluster nozzle there is a slight measurable separation between both jets along the spray propagation, but at the tip of the spray both spray plumes are complete merged. Although the jets of the 10.0° cluster nozzle show a strong interaction and propagate closely, they remain separated. In cases of larger opening angles between sprays (in the range of 20° diverging angle), a qualitative (Cárdenas et al. [17]) and quantitative separation between sprays has been observed by Pawlowski et al. [11] through visualizations and PDA measurements. In this investigation a clear separation of sprays in the liquid phase was detected for the 15.0° cluster nozzle.

Fig. 6 shows single images recorded with a modified schlieren method according to Pawlowski et al. [11]. These pictures have been illuminated by a spark flash light with a pulse duration of about 10 ns from behind the injector. Liquid and vapor phases are visible in the images. The injector holder has been mounted in a chamber opening in front of the camera axis. With this viewing direction, the injector is in front of the metal holder, which prevents the detection of the spray closer than 9 mm to