Optical Investigations of Clustered Diesel Jets under Quiescent Conditions

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One of the fundamental topics in the design of new injection systems for DI Diesel engines is to decrease the soot emissions. For this purpose nozzles with clustered holes seem to be a promising approach. In this study, the penetration and combustion behaviour of cluster hole sprays are characterized by three different optical measurement techniques.

Abstract

Pickett and Siebers [1,2] showed that the amount of soot decreases with decreasing orifice diameter because of higher air entrainment. Matsumoto et al. [3] investigated the effects of reduced nozzle hole diameters for multihole nozzles. They reported that smaller nozzle hole diameters cause a slightly shorter spray tip penetration, but produce 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 [4]. A basic idea of the Cluster Configuration (CC) nozzles is to prevent a fuel rich area in the center of the flame where most of the soot is produced, and to minimize the overall soot formation in this way. Adomeit et al. [5] investigated divergent and convergent Group Hole nozzles compared to a baseline nozzle in a Diesel engine. They found out that Group Hole nozzles can significantly reduce the emissions. The convergent nozzle showed advantages over the divergent one, especially at higher part load. On the other hand, in [6] it is shown that convergent nozzle holes can produce larger SMD and higher liquid phase fraction in the region of the spray tip. Gao et al. [7] compared Group Hole nozzles with standard nozzles using measurements in an optical Diesel engine without EGR. For this application a divergent Group Hole nozzle with a 10° angle was found to be best. They pointed out that larger divergent angles enhance the evaporation, but the penetration of the liquid and vapor phase is significantly reduced caused by smaller air entrainment.

Pawlowski et al. [8] presented a detailed investigation of cluster nozzles in a combustion vessel using visualization techniques and PDA. It has been 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 diminishes for larger cluster angles. The combustion and soot formation of the same cluster nozzles is investigated in [9] under comparable conditions. There it is demonstrated that the used 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, so this is a serious motivation to measure both quantities simultaneously in this study.

For the investigated nozzles each hole of a conventional nozzle is replaced with two smaller holes in order to reduce soot formation. The diameter of the smaller holes is chosen so that the flow rate of all nozzles should be equal. The basic strategy of these cluster nozzles is to provide a better primary break up and therefore a better mixture formation caused by the smaller nozzle holes, while keeping the penetration length of the vapor phase comparable to the base line of the conventional nozzle.

Experimental setup

Pressurized Chamber - The ambient conditions in the pressurized vessel for the investigation have been set at a temperature of 800 K and a pressure of 50 bar.

Investigated Nozzles - Table 1 documents the nozzles that have been investigated in detail. For comparability all nozzles have identical flow numbers of 210, additionally a nozzle with half of the flow rate as a second reference was used. The cluster nozzle configuration consists of 6 orifices distributed in 3 groups. The included angle between the sprays is positive causing the sprays to diverge. The nozzles have been investigated using an energizing time of 850 µs for investigated rail pressures of 600 bar, 1100 bar and 1600 bar. The nozzles are installed on a state-of-the-art Bosch piezo injector. All measurements are conducted for a wide range of taei (time after energizing the injector).

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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°	5.0	210
6	7.5°	7.5	210
6	10°	10	210
6	15°	15	210

Table 1: Nozzle Specifications

Visualization - Mie Scattering, using a light from a defocused laser light sheet has been employed to detect the envelope of the liquid phase. Quasi-simultaneously a modified Schlieren technique has been used to detect the envelope of the vapor phase. A CCD camera from LaVision GmbH is used as dectector. Typically, 20 images per time step are recorded and the penetration length is extracted from the images. The spray propagation is oriented upwards.

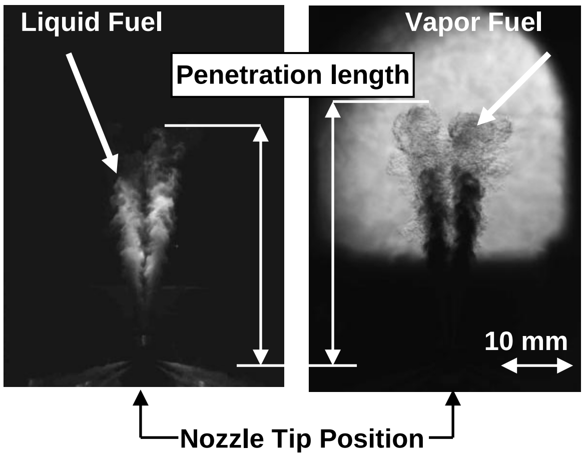

Fig. 1: Sample images of the sprays from a 15° cluster nozzle, p_{rail} = 600 bar, taei = 1000 µs. Determination of penetration length, (Left) Mie-Scattering for liquid phase and (Right) Schlieren for vapor phase.

OH measurements set-up* **-** 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. The light passing through the quartz window is divided into a VIS and a UV part. The VIS part is transmitted through the dichroic beam splitter and 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 mm, f# = 2). 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 [9]. The exposure time of the camera is set to 100 µs and the delay of the two frames is 50 µs.

The penetration lengths of the liquid and the vapor phase (Fig. 1) as well as the lift-off length (Fig. 2) and the ignition delay are determined. The ignition delay Δt is defined as the taei when the ignition probability has reached 50%. Lift-off length and ignition delay are not determined in the case of the 7.5° CC nozzle, because the concerning measurements were strongly affected by unwanted temperature variations in the vessel. The influence of the cluster configuration and the cluster angle on the penetration and the combustion are analyzed and discussed.

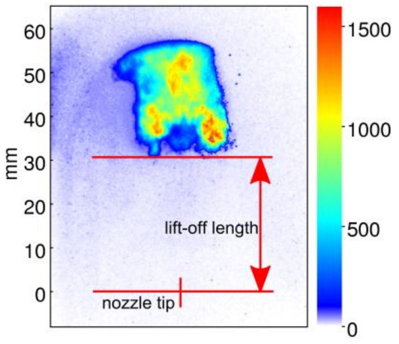

Fig. 2: OH chemiluminescenccence, typical single-shot image of the 15° cluster angle nozzle, p_{rail} = 600 bar, T = 800 K, taei = 2800 µs, ET = 850 µs*

Results

In the case of the cluster nozzles the penetration length depends strongly on the opening angle between two sprays. The influence of this parameter decreases with increasing of the opening angle. However this behaviour does not present a linear function of the opening angle. Therefore, the following classification can be made:

- *Group 1: Conventional nozzle behavior - (reference nozzle 2, cluster nozzles 0° and 2.5°)*

The 0° nozzle and the 2.5° nozzle yield similar results compared to the reference nozzle with identical flow number. Slightly decreasing penetration of the liquid phase for the 2.5° nozzle related to the Reference nozzle 2 was detected, however in the gas phase no major differences were found. These two cluster nozzles represent an interesting option to replace conventional nozzles in terms of penetration length.

- *Group 2: Transition behavior - (cluster nozzles 5° and 7.5°)*

The 5° nozzle and the 7.5° nozzle show different tendencies of penetration between both phases. In the liquid phase these two cluster nozzles presented higher values of penetration length compare to the reference nozzle with half of the flow number. However, in the vapor phase the same range of penetration from both cluster nozzles compared to the reference nozzle with half of the flow number was detected. The reason for this behavior is most likely due to transition between the behavior of one hole from a conventional nozzle and two smaller holes corresponding to a cluster nozzle.

- *Group 3: Low interaction behavior - (reference nozzle 1, cluster nozzles 10° and 15°)*

The 10° cluster nozzle and the 5° cluster nozzle presented similar results compared to the reference nozzle 1. The 10° opening angle corresponds to the largest angle where the merging of the clustered sprays was visually determinated. The liquid phase penetration of the 10° cluster nozzle spray is slightly higher than one of the reference nozzle. However, the vapor phase penetration is clearly inferior. The penetration length from the 15° cluster nozzle is, for both phases, slightly inferior to the reference nozzle behavior. For this group, the results show that after the separation of the clustered spray this design does not present advantages in terms of penetration length.
The lift-off length (lol), its fluctuations (cov) and the time-resolved ignition probability are determined and discussed for all nozzles (except the 7.5° CC nozzle) and three different injection pressures. The following conclusions can be stated:

- As expected, the cluster nozzles produce a broader flame with increasing cluster angle. However, all of the nozzles essentially generate a single ensemble-averaged high-temperature reaction zone.
- The quasi-steady lol (around taei = 3ms) of all nozzles with p_{rail} = 600bar is very similar ($\approx$ 28mm), although the hole diameter of reference nozzle #2 is much bigger compared to the other nozzles. This unexpected behavior can be explained by separated ignition spots which are detected only a few mm downstream of the orifices of the reference nozzle #2. Accordingly, the quasi-steady cov of the lol is about twice as high ($\approx$ 27%) as for the other nozzles ($\approx$ 13%).
- The CC nozzles generate a quasi-steady lol of about 34mm at p_{rail} = 1100bar, and about 39mm at 1600bar, respectively. The lol tends to increase slightly with decreasing cluster angle.
- Both reference nozzles generate larger lols than the CC nozzles with p_{rail} = 1100bar and 1600bar (Ref#1: 38mm and 43mm, respectively; Ref#2 42mm and 48mm, respectively). The behavior of reference nozzle #2 compared to all other nozzles could be expected [1]. The longer lol of reference nozzle #1 compared to the CC nozzles indicates spray-spray interactions.
- The cov of the quasi-steady lol in the case of both reference nozzles with p_{rail} = 1100 and 1600bar is about 7%. It is generally higher for the CC nozzles, i.e., in the range 7-20%. The spatial distributions of the ignition spots with regard to the nozzle axis are generally broader for the CC nozzles in comparison to the reference nozzles (except in the case of reference nozzle #2 with p_{rail} = 600bar, see above).
- The ignition probability increases from 0% to 100% within a transition time of about 0.4 ms for all nozzles and all p_{rail}.
- A correlation of Δt and lol is observed when the ambient temperature is slightly changed as expected. But Δt also changes and it is generally not correlated to the lol when different nozzles and p_{rail} are compared (at 800K). This indicates that Δt also depends on mixture formation. Δt of the reference nozzle #1 strongly depends on p_{rail} (Δt =2.4, 2.2, 2.0 ms for p_{rail} = 600, 1100, 1600 bar respectively), whereas Δt is rather independent of p_{rail} for the other nozzles (ref. nozzle #2: Δt = 2.55, 2.5, 2.55ms for 600, 1100, 1600bar; CC nozzles: Δt is in the range 2.35$\pm$0.15, 2.25$\pm$0.1, 2.25$\pm$0.5 for 600, 1100, 1600bar, respectively). Δt of the CC nozzles increases slightly with increasing cluster angle, in particular for lower p_{rail}.
- There is always a gap Δx between the quasi-steady penetration length of the liquid phase and the lol in the case of the reference nozzles (except for reference nozzle #2 with p_{rail} = 600 bar, due to ignition spots close to the nozzle as mentioned above). Δx increases with increasing p_{rail} as expected [1].
- The gap Δx is always smaller for the CC nozzles than in the case of the reference nozzles with p_{rail} = 1100 and 1600 bar. Δx is even vanishing, i.e., $\Delta x \leq 0$, for the CC nozzles at p_{rail} = 600bar. This may lead to higher soot formation by the CC nozzles in comparison to the reference nozzles.

Acknowledgments

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