

Quantitative Fuel-Air-Mixing Measurements in Diesel-Like Sprays Emanating from Convergent and Divergent Multi-Layer Nozzles

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ABSTRACT

It is the objective of this work to characterize mixture formation in the sprays emanating from Multi-Layer (ML) nozzles under approximately engine-like conditions by quantitative, spatially, and temporally resolved fuel-air ratio and temperature measurements. ML nozzles are cluster nozzles which have more than one circle of orifices. They were introduced previously, in order to overcome the limitations of conventional nozzles. In particular, the ML design yields the potential of variable spray interaction, so that mixture formation could be controlled according to the operating condition. In general, it was also a primary aim of the cluster-nozzle concepts to combine the enhanced atomization and pre-mixing of small nozzle holes with the longer spray penetration lengths of large holes.

The applied diagnostic, which is based on 1d spontaneous Raman scattering, yields the quantitative stoichiometric ratio and the temperature in the vapor phase. The measurements are conducted in non-reacting sprays slightly downstream of the liquid-phase-penetration length, because flame-lift-off stabilization generally occurs in the vicinity of the liquid tip in comparable combusting sprays under quasi-steady, engine-like conditions. It is well established that the stoichiometric ratio in the region of flame lift-off significantly affects the soot formation in Diesel sprays.

The measurements are conducted in a high-temperature, high-pressure vessel. N-decane is used as the fuel, because it is a commonly applied model fuel for standard Diesel. The investigated Diesel-like sprays emanate from a state-of-the-art piezo injector.

In the present work, the results of two ML nozzles with two circles of orifices are compared. The plane of the two holes in each cluster is parallel to the injector axis. The clustered nozzle holes are convergent (-4°) for one of the ML nozzles, whereas they are divergent ($+4^\circ$) for the other one. Two conventional nozzles with one circle of orifices are also investigated, one with the same flow number as the ML nozzles and the other one with halved flow number, corresponding to a single hole of the ML nozzles. The temporal and spatial evolution of the quantitative stoichiometric ratio and temperature is determined and discussed. Furthermore, the shot-to-shot variability in these quantities is analyzed. These measurements essentially show that the ensemble-averaged fuel-air-ratio distributions are very similar for both ML nozzles and the reference nozzle with large orifices, but they are significantly different for the reference nozzle with small orifices. The shot-to-shot variability in the fuel-air ratio is generally very similar for the ML nozzles as compared to a previously investigated cluster nozzle with only one orifice circle, indicating that the particularly complex in-nozzle flow does not lead to enhanced fluctuations of the outcome of the mixture formation process. The results also lead to conclusions on soot formation in comparable combusting sprays emanating from ML nozzles. Apparently, the soot-reduction potential cannot be improved by enhancing evaporation and penetration of the free spray simultaneously using an ML nozzle. Thus, previously observed reduced engine-out soot emissions for ML nozzles could be explained by wall impingement or differences in flame lift-off.

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INTRODUCTION

Mixture formation plays an important role for combustion and pollutant formation in Diesel sprays. Generally, mixture formation depends on the nozzle design. Several different cluster-nozzle concepts were proposed and investigated, in order to overcome the limitations of conventional nozzles [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18].

Matsumoto et al. [1] investigated the effects of reduced nozzle hole diameters for Group-Hole 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. According to [2], the effect of smaller droplets and enhanced evaporation, observed using nozzles with equally spaced micro-orifices, can be realized using clustered nozzle holes. In [3], 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. [4] compared Group-Hole nozzles with standard nozzles using measurements in an optical Diesel engine. For their application a divergent Group-Hole nozzle with a 10° angle was found to be best. It was also noted that larger divergent angles enhance the evaporation, but the penetration of the liquid and vapor phases 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 showed 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. The sprays emanating from Group-Hole nozzles were further characterized with and without wall impingement by using experimental and numerical methods by Moon et al. [5], and Gao et al. [6, 7].

Pawlowski et al. [9] presented an investigation on CC (Cluster Configuration) nozzles in a combustion vessel using visualization techniques and phase doppler anemometry (PDA). There, it was shown that there is a strong interaction between the two clustered sprays, but this effect diminished for larger cluster angles. The combustion and soot formation for the same CC nozzles were investigated in [10] under comparable conditions. There, it was demonstrated that the CC nozzles generated 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 CC nozzles is the higher difference between the penetration length of the liquid phase and the lift-off length. In [19,20,21,22,23,24] the importance of the stoichiometric ratio at the lift-off location is discussed by Idicheria et al., Hottenbach et al., Siebers et al., and Pickett et al.

Both prior studies using this type of CC nozzles [9, 10] also show that a nozzle with a cluster angle of 20° produces two separated sprays and flames with only weak interaction. Thus, smaller cluster angles were chosen for the following

work. A second set of CC nozzles was investigated in [11,12,13,14,15]. Spray formation and combustion were analyzed by Mie, Schlieren, and OH* chemiluminescence imaging in Ref. [13], and by PDA in Ref. [12], respectively by Cardenas et al. Comparable nozzles were also investigated by Won and Peters with regard to engine performance and emissions [14, 15]. The results of a number of different CC nozzles, each with an opening angle of 10° , and a conventional, reference nozzle with slightly larger orifice diameter were compared in both publications. The engine-out soot emissions of the cluster nozzles turned out to be higher than for the reference nozzle under low-load conditions (for conventional injection timing). However, the investigated CC nozzles with one orifice circle showed lower soot formation than the reference nozzle under high-load conditions, using elevated fuel-rail pressures [15]. Thus, comparable CC nozzles with one orifice circle and the fuel-rail pressure dependence were also analyzed in [11]. In Ref. [14], Won and Peters demonstrated that the soot emissions of such CC nozzles can also be reduced by using a modified piston-bowl geometry, which likely promotes air utilization. Lower soot emissions were achieved in this way for one of the CC nozzles as compared to the reference nozzle for all investigated operating conditions.

Comparable CC nozzles were investigated by spontaneous Raman scattering (SRS) in a vessel, in order to clarify the mechanism of soot reduction [11]. The SRS technique yields the quantitative fuel-air ratio and the temperature in the gas phase [25]. It was demonstrated that fuel-air mixing and air utilization can hardly be improved simultaneously by using CC nozzles instead of conventional nozzles (without wall impingement). Thus, the reduced engine-out soot emission, which were found for CC nozzles [13, 15], were likely determined by wall impingement.

The diagnostic approach presented in Ref. [11] is also applied in the present work. However, Multi-Layer (ML) nozzles are investigated in this work, which were previously proposed by Adomeit et al. [8] and Menne et al. [16]. The design of the CC nozzles investigated in Ref. [11] and the one of the ML nozzles is significantly different, so that mixture formation is also expected to be different. In particular, the CC nozzles used in Ref. [11] had one circle of nozzle holes, whereas the current ML nozzles have two orifice circles. Note that different engine-out soot emissions were previously found for CC nozzles with one or two, respectively, orifice circles [15, 14]. There are other experimental and numerical findings, which show that the in-nozzle flow and mixture formation of ML nozzles are indeed significantly different as compared to cluster nozzles with one orifice circle. They are described below.

The ML-nozzle design appears to be particularly interesting, because the fluid flow could be controlled by limiting the needle lift [8, 16]. Thus, nozzle-exit flow and spray-spray interaction (within each cluster) could be controlled according to the operating condition of the engine.

The plane of the two jets in each cluster is parallel to the injector axis for all of the ML nozzles investigated in Refs. [8, 16, 17], and in the current work. The ML nozzles used in an engine experiment reported in Ref. [8] are comparable to the ones of the present work, but the number of clusters, i.e. nozzle holes, is halved in the latter, in order to reduce fuel throughput and improve optical access in the high-pressure vessel.

The performance of two ML nozzles with convergent and divergent jets (in each cluster), respectively, was compared to two conventional reference nozzles in a HSDI Diesel engine in Ref. [8]. A significant reduction of soot emissions by the ML nozzles was reported. The convergent configuration showed advantages in PM-emissions over the divergent one, especially at higher part load. The authors of Ref. [8] concluded that the well known trade-off between emissions and power could be overcome by the ML nozzles. However, the concerning mechanism is not yet fully understood. Thus, comparable nozzles are investigated in more detail in the present work.

The ML design leads to particularly complex in-nozzle flow fields. Thus, the in-nozzle flow was studied by 3d-CFD calculations and injection-rate measurements [16]. These investigations demonstrated that the flow through the two holes of a cluster is different due to a throttling effect of the needle, in particular for limited needle lift. Accordingly, a shadowgraphy image of a convergent (-4°) ML nozzle (CML), which is shown in Fig. 1, illustrates that the penetration lengths of the two jets in a cluster are different in the transient phase, i.e. shortly after the start of injection (this CML nozzle is also investigated in the present work by using the same optically-accessible vessel at the same ambient-air density, but higher temperature).

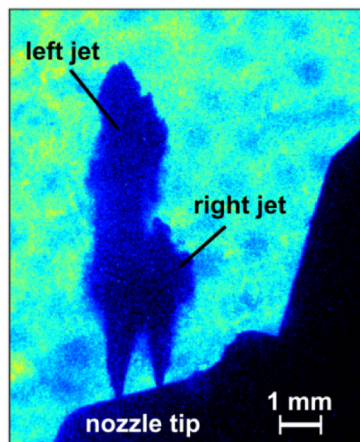


Figure 1. Typical, quasi-instantaneous shadowgraphy image acquired shortly after start of injection for one of the clusters of the CML nozzle ($t_{aei} = 275 \mu s$, $p_{rail} = 1200$ bar, $p_a = 18.6$ bar, $T_a = 300$ K).

The near-nozzle jet velocity field was also probed by laser-flow tagging (LFT) for two ML nozzles and a reference

nozzle with larger hole diameter [17]. For instance, Fig. 2 shows the ensemble-averaged jet velocities and their shot-to-shot variability (error bars) under approximately quasi-steady injection conditions. These measurements confirm that the velocities of the two jets are different (the jets are named “left” and “right” jet, respectively, according to Fig. 1, i.e. the “left” jet is located closer to the nozzle tip than the “right” one). In fact, the nozzle-exit velocity, v_0 , was found to be significantly lower than the result of a Bernoulli estimation, v_B , for both jets (v_0 can be estimated based on these LFT measurements, because the droplet deceleration is relatively weak very close to the nozzle as shown in Fig. 2). In contrast, v_0 measured by LFT was found to be approximately equal to v_B for a conventional nozzle under quasi-steady conditions [26]. Furthermore, the shot-to-shot variability in the velocity turned out to be significantly higher than for a conventional nozzle investigated in [26] (although the shot-to-shot variability shown in Fig. 2 partly arises from measurement errors, in particular for increasing nozzle distance), indicating enhanced hydrodynamic turbulence for the ML nozzles. Accordingly, 3d-CFD calculations showed that the transient in-nozzle flow fields were highly sensitive to the geometric boundary conditions, i.e. needle position, needle movement, and geometric rounding at the hole inlet [16]. Note that the relatively strong fluctuations of the jet velocities may lead to enhanced shot-to-shot variability in the mixture formation process. Thus, the fuel-vapor distribution further downstream is probed by 1d-spatially resolved, single-shot SRS measurements in the present work.

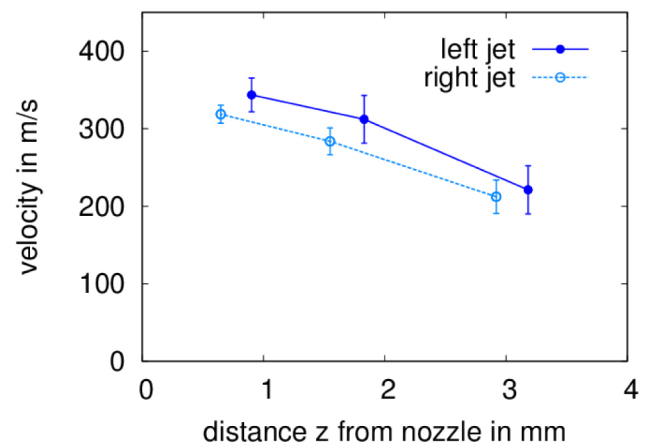


Figure 2. Mean velocities and cyclic variability (error bars) for the two jets in a cluster of the CML nozzle ($t_{aei} = 600 \mu s$, $p_a = 18.6$ bar, $T_a = 300$ K); the data are adopted from [17].

Quantitative stoichiometric ratio measurements in Diesel-like sprays were previously conducted by SRS [25, 27, 28, 29, 30], Rayleigh scattering [19, 31, 32], and PLIF (planar laser-induced fluorescence) [33]. The capabilities of these diagnostic techniques in this application were compared in [25]. The main drawback of SRS is the inherent weakness

of the signal intensities, so that they may be affected by photon-statistical noise (shot noise). However, this problem is greatly reduced in the present application due to the relatively high particle densities in the Diesel environment. The resulting measurement uncertainties are discussed below. The evaporation of sprays emanating from Group-Hole nozzles was previously characterized by line-of-sight laser absorption and scattering (LAS) measurements [5, 6] and references therein. In contrast to LAS, SRS yields quantitative stoichiometric ratios (without assuming adiabatic mixing) with relatively high spatial resolution, which is discussed below. Thus, the mixture composition close to the spray axis, where most of the soot is generally formed, can be studied in detail by SRS.

EXPERIMENTAL

The investigated nozzles are summarized in Tab. 1. Both ML nozzles have identical flow numbers of $185 \text{ cm}^3 / 30 \text{ s}$. Two standard nozzles (R1 and R2) with flow rates of $93 \text{ cm}^3 / 30 \text{ s}$ (R1) and $185 \text{ cm}^3 / 30 \text{ s}$ (R2) are used as reference nozzles. The cluster nozzle configuration consists of 6 orifices distributed in 3 groups. The included angle between the sprays of the ML nozzles is positive for the nozzle with divergent jets (DML), and negative for the nozzle with convergent jets (CML), as shown in Fig. 3. All nozzles are processed in an identical manner with same k-factor and hydroerosion. The left holes of the CML and DML nozzles are placed in the micro-sac zone of the nozzle, while the right holes (CML, DML, R1, R2) are placed in the seat zone. The internal geometry of ML nozzles is depicted in [16].

Table 2. Nozzle specification.

designation	CML	DML	R1	R2
cluster opening angle	-4°	+4°	-	-
spacing between hole layers in mm	0.98	0.98	-	-
theoretical distance of axes intersection from nozzle in mm	43.8	-	-	-
hole diameter in μm	99	99	99	145
number of orifices	6	6	3	3
flow rate in $\text{cm}^3 / 30 \text{ s}$ at $\Delta p = 100 \text{ bar}$	185	185	93	185
k-factor	1.5	1.5	1.5	1.5
hydroerosion in %	10.5	10.5	10.5	10.5

N-decane is used as the fuel in the present work, because it is a widely used model fuel for Diesel combustion [25]. The temperature of the fuel in the nozzle is estimated to be

approximately equal to the one measured previously by a thermocouple in the nozzle tip, i.e. 358 K, due to the similarity of the experimental set-up and operating conditions [27]. However, that measurement was conducted with closed nozzles holes, i.e. stagnant fuel flow. Thus, the real fuel temperature is expected to be slightly lower, due to purging of fuel in the nozzle, although the injection frequency is relatively low (about 0.2 Hz).

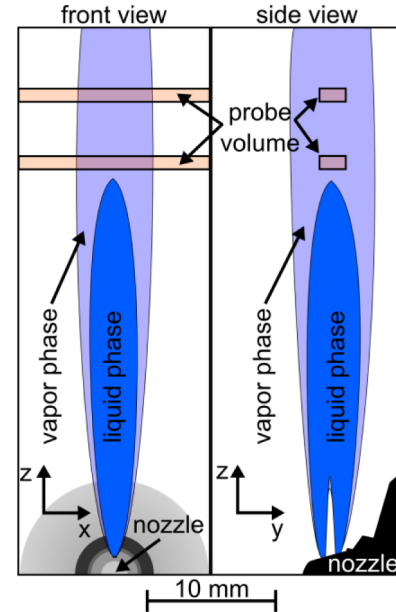


Figure 3. Locations of the probe volumes of the 1d-SRS measurements.

Non-reacting sprays are investigated under ambient-air conditions of 700 K and 43.8 bar in a vessel. The temperature inside the chamber is measured using two thermocouples. The temperature variability without injection within the measurement volume is about $\pm 5 \text{ K}$, due to variations of the temperature control loop. Furthermore, the temperature difference between the area of interest and the area close to the nozzle is about 15K, i.e., there is a certain vertical temperature gradient. The horizontal gradient is much weaker. The common rail sprays emanate from a state-of-the-art piezo injector (Bosch, third generation). The fuel-rail pressure is set to 1200 bar, and the energizing time of the injector is 450 μs . The optically-accessible vessel is described in detail elsewhere [34]. Note that the same experimental set-up was recently used for the investigation of cluster nozzles with only one circle of orifices [11]. The measurement system is also very similar to the one used for SRS measurements in conventional common-rail, n-decane sprays [25], and it is illustrated in Fig. 4. The rectangular laser beam of a KrF excimer laser is focused by a spherical lens ($f = 2 \text{ m}$) and a cylindrical lens ($f = 1 \text{ m}$). The laser-beam axis is directed perpendicularly through the spray axis. The focus is located several centimeters behind the vessel to avoid ignition and gas breakdown in the probe area as well as damage of the

windows. Since the vessel is mounted on a movable table, every spatial position of the spray can be investigated without realigning optics. A 33 mm long section of the focused laser beam is imaged onto the entrance slit of an imaging spectrograph (aperture $f/4$, resolution 0.1 nm) by two spherical lenses ($f = 300$ mm and $f = 150$ mm) with a demagnification of about 2:1. The scattered light passes a liquid, long-pass butyl-acetate filter in front of the spectrometer with a thickness of 10 mm to reduce the Rayleigh signal. An image-intensified CCD camera (LaVision, 1280×1024 pixels without hardware binning) is mounted in the exit plane of the spectrograph. One dimension of the CCD-chip (1024 rows) corresponds to the spectral axis while the other one (1280 columns) yields spatial resolution along the imaged section. For the stoichiometric ratio calibration the relative SRS cross-section of n-decane in relation to the SRS cross-section of N_2 is measured by recording SRS-spectra of saturated nitrogen / hydrocarbon mixtures in a stabilized calibration cell, which can be mounted inside the vessel. Thus, the calibration data are acquired without any changes of the measurement system. The calibration procedure and the heatable cell are described in [11].

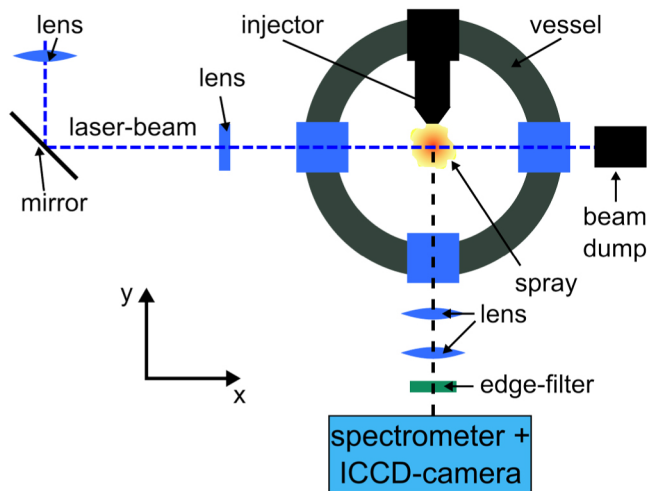


Figure 4. Optical set-up for acquisition of the 1-d SRS spectra. The axis of the investigated spray, z , is perpendicular to the paper.

The spatial resolution in the direction of observation is limited by the 2 mm depth, y , of the laser beam. The spatial resolution along the laser beam axis is determined empirically to be at least about 0.5 mm by analyzing the intensity change along this direction associated with an illuminated very small object in the focal plane. The height of the probe volume (1 mm) is determined by the demagnification and the entrance slit of the spectrometer (500 μm). A typical ICCD image of the CML nozzle, that is averaged over 25 injections ($p_{\text{rail}} = 1200$ bar at $t_{\text{aei}} = 1300$ μs), is shown in Fig. 5. It is measured at a nozzle distance, z , of 30 mm. The measurement is conducted in the droplet-free region, as illustrated in Fig. 3.

The horizontal axis of the image corresponds to a section of the horizontal extension, x , of the probe volume. Its vertical axis corresponds to the emission wavelength. The region of the spray is characterized basically by increased Rayleigh scattering and the CH-stretching SRS line (at about 268 nm). The measurements are conducted perpendicularly to the plane of the orifices of one of the clusters, as shown in Fig. 3.

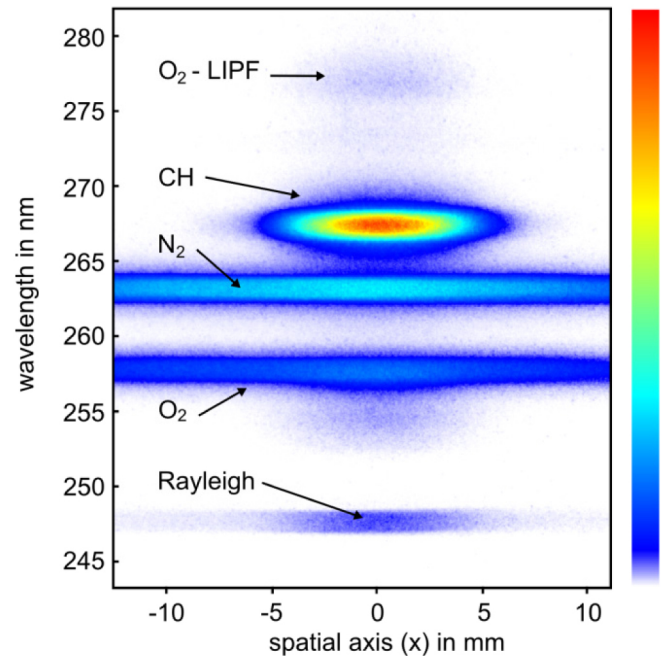


Figure 5. Typical raw ICCD image of the CML nozzle, averaged over 25 injections ($p_{\text{rail}} = 800$ bar, $t_{\text{aei}} = 1300$ μs , $z = 30$ mm, $ET = 450$ μs).

Fig. 5 shows that some of the ambient air is probed on both sides of the spray. It is used for calibration of the temperature measurements. A vertical profile of the image in Fig. 5 averaged over 1.0 mm around the spray centerline yields an emission spectrum, which shows the SRS lines in more detail. It is depicted in Fig. 6. The spectrum indicates that the ensemble-averaged measurements are essentially shot-noise free [25]. (Recall that the relative error induced by shot noise is $1/\sqrt{N}$, where N is the number of photoelectrons generated in the image intensifier. Thus, it is negligible for very strong signals. However, the uncertainty in the ensemble-averaged measurements also depends on the shot noise in the single-shot measurements, which is discussed in detail in the Results section.) Furthermore, it also shows that there is some cross-talk of the N_2 - and CH-stretching lines, which is taken into account in the data reduction procedure.