Investigation of Particulate Emissions for Cluster-Nozzle Concepts in DI Diesel Engines

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Abstract

In a conventional Diesel engine, air is gradually drawn into the fuel spray from the surrounding area. The ignition delay period is short, so combustion starts before the fuel has thoroughly mixed with the air. Consequently, the center of the spray is overly rich, resulting in smoke, while stoichiometric mixture is formed in the surrounding area, resulting in a high NOx concentration. Based on the Diesel concept, it is practically impossible to totally avoid fuel-rich and stoichiometric pockets, but the formation of soot and NOx are also time-dependent. If the mixing time is sufficiently small, both pollutants could be reduced simultaneously without getting into the well known soot-NOx tradeoff. In order to develop a low-emission engine, research is necessary to come up with a new combustion strategy for Diesel engines which includes the use of cluster nozzles. Decreasing the hole-size improves mixing in the center of the spray and therefore the soot production is lowered tremendously. Based on this experience, three cluster designs were developed for the present work. The basic strategy of the cluster nozzles is to provide a better primary breakup and therefore a better mixture formation caused by the smaller nozzle holes, while keeping a comparable penetration length of the vapor phase due to merging of the sprays. In this study, two different cluster-nozzle designs were investigated in a combustion vessel and compared to a conventional nozzle with the same flow rate. Two different measurement techniques are employed to investigate the combustion process. The local soot concentration during combustion is measured semi-quantitatively using Laser Induced Incandescence (LII). The natural soot luminosity is recorded simultaneously using a double frame camera. The results indicate that soot formation can be reduced by using cluster nozzles, at least in the early combustion phase under the investigated conditions. Three cluster designs similar to the ones used in the combustion vessel, were investigated through engine measurements. The nozzles used in this study were designed for improved homogenization of in-cylinder charge. They were tested in a single-cylinder engine with CRI 3.3 piezo-injectors under part-load conditions for a partly homogenous mode of Diesel combustion, and also under high load conditions for conventional Diesel combustion. Numerical simulations were also carried out to explain the observations of the engine experiments. Certain test cases were simulated to get some detailed information on performance of cluster nozzles, giving more insight into soot formation. Another nozzle was designed based on the results from the three clusters. Engine experiments with the nozzle show improvements in soot emissions under high-load conditions.

Introduction

Nozzles with more and smaller orifices have contributed significantly to the improvement of Diesel engines in the past years. A reduction in ignition delay and soot emissions has been observed for a higher number of smaller diameter orifices in a rapid compression machine by Kobori et al.[1]. Later, Pickett and Siebers [2] have observed a reduction in soot emissions with a reduction in orifice diameters. They attribute this effect to increased mixing, which eliminates the occurrence of pockets of rich mixture. In engines however, a reduction of orifice diameter means reduced fuel delivery, which then has to be compensated by the use of a higher number of orifices to maintain the same fuel delivery within a definite amount of time at a given rail-pressure. However, for equispaced orifice configurations no improvement is recorded for hole numbers above a certain threshold [3, 4].

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. [5] and Gao et al. [6] study group-hole nozzles, as they call them, consisting of two sprays with an included angle of -10 to 10°. For converging sprays (negative included angle), spray penetration behavior was found to be similar to the corresponding conventional nozzle. For the diverging nozzles (positive included angle), a reduction in the penetration of the spray tip is found. Zhang et al. [7, 8] investigated the spray-wall interaction of sprays from group-hole nozzles. They found better atomization characteris-

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tics and asymmetries in the impinging spray on the wall when comparing the group-hole nozzles to conventional ones. Different studies have suggested advantages of cluster nozzles in engines under part-load conditions with convergent configurations being more advantageous than the divergent ones [9, 10]. Gao et al. [11] have shown advantage of divergent cluster nozzles over conventional ones in terms of soot formation through soot luminosity measurements in an optical engine. As no such advantage in terms of soot emissions in engines has been observed in other studies, it seems that the sprays from cluster nozzles have deficits in terms of soot oxidation.

For the present study 3 Clusters were designed keeping in mind better homogenization of the mixture in cylinder. Two included angles of 10° (Cluster 14x150/130) and 20° (Cluster 14x160/120) were used for clusters with orifices along the injector axis. Additionally a cluster with included angle of 20° with orifices in a plane perpendicular to the injector axis was designed (Cluster 14x140/140). The Clusters were named according to their geometry. The first part denotes total number of orifices (14 for all cases). The two numbers separated by a slash denote the spray cone angle formed by the orifices in different orifice circles (only one orifice circle in case of 14x140/140). All the orifices were of 144µm diameter (Flow Number 490). The two orifices of a cluster were separated by 0.6mm. One more cluster was designed using the results from the three clusters to improve soot emissions under high-load condition. The new cluster (Cluster 14x158/158) with included angle of 10° having orifices in a plane perpendicular to the injector axis was designed with the same spray-cone angle as the reference injector(158°) for better targeting.

Two clusters with included angles of 10° and 20° were tested in high pressure chamber using LII for semi-quantitative soot measurements. Engine measurements were done under part load conditions for PCCI (Premixed Charge Compression Ignition) operation and high load for conventional diesel operation. PCCI operation under high load is limited by intense diesel knock. The results were compared with a conventional 7-hole nozzle for reference. Numerical simulations were carried out to help in explaining the experimental observations.

Experimental Setup/Test points

For the Laser Induced Incandescence (LII) measurements, a double-frame ICCD camera (NanoStar, LaVision) equipped with a fast lens (Nikon, f = 85mm, f# = 1.4) is used. A narrowband band-pass filter (Semrock) with a center wavelength of 395 nm and a FWHM of 11 nm is used to separate the LII signal from the natural soot radiation. A pulsed Nd:YAG laser with a second harmonic generator at 532 nm is used. The laser light is formed to a thin sheet in the probe volume (height 42 mm, thickness 0.3 mm). The laser intensity in this application is approximately 1 J/cm² while the pulse duration is 8 ns. The first image of the double-frame ICCD is taken shortly before the laser pulse with a gate width of 1 µs, thus measuring the soot luminosity alone. After a delay of 2 µs the second image (gate width of 100 ns) is taken simultaneously with the laser pulse containing LII signals, and also some weak signals from the natural radiation of the surrounding soot. The first image is subtracted from the second image (intensity corrected for the different gating times) to get the pure LII signal. The chamber is operated at a temperature of 800K and a pressure of 50 bar. European standard Diesel fuel is used. The measurements are conducted for the reference nozzle as well as for the 10° and 20° cluster-angle nozzles with one circle of holes. It should be noted that the soot luminosity arises from the entire flame, whereas the LII is measured only in the central plane. The soot luminosity images are also affected by chemiluminescence interferences from small molecules formed in the reaction zone. This explains why the extension of the region where the luminosity is detected is slightly wider than the soot distribution measured by LII. In addition, the natural luminosity is highly temperature-dependent, as opposed to the LII signal. However, some features in the line-of-sight luminosity image can also be found in the LII image. This indicates that the luminosity is dominated by soot radiation at least in the region where most of the soot is formed.

The engine experiments are performed on a 0.8 liter single-cylinder engine (16:1 compression ratio) with a swirl ratio of 1.5 based on a V-8 Duramax engine from General Motors. Piezo injectors (CRI 3.3) were used for the experiments. The three clusters from the first set were tested at 1400 rpm, 5.5 bar IMEP (Indicated Mean Effective Pressure) and 800 bar rail-pressure. The clusters 14x160/120, 14x158/158 and the reference nozzle were separately tested under low-load at 1400 rpm, 4.5 bar IMEP, and under high-load condition at 1400 rpm, 10.5 bar IMEP, 1500 bar rail-pressure and a constant NOx Emission Index of 4.8 g/kg of fuel. The injection duration was varied to maintain the IMEP, while NO_x was maintained at constant levels for different sets of experiments by varying EGR (Exhaust Gas Recirculation). Injection rate measurements were carried out for all the nozzles to determine the actual injected mass for the test points.

Numerical Setup

The simulation of the engine was performed by the AC-FluX code solving numerically the Unsteady Reynolds Averaged Navier-Stokes Equations (URANS) on an unstructured mesh by a finite volume approach. Turbulence was modeled by the k-ε model. The calculations were carried out on a sector mesh with a sector angle of 51.4°, using periodic boundary conditions at the side faces of the mesh. The grid consists of 52613 cells and the average cell dimension is 0.5 mm. The liquid phase is simulated using Discrete Droplet Model (DDM). Secondary droplet breakup is taken into account by Kelvin-Helmholtz and Rayleigh-Taylor models. Combustion was simulated by the RIF model, which couples the flow and the unsteady flamelet solvers interactively. The model parameters were calibrated for a reference case (900 bar Rail-Pressure, 10° Cluster nozzle) in order to match the experimental and numerical pressure and heat release curves. The model parameters were kept constant for all simulated cases.

Results and Discussion

Figure 1 shows the soot luminosity measurements, while in Figure 2 the corresponding LII measurements are depicted. The images are taken 2000 µs after energizing the injector using an energizing time of 1200 µs. All images are averaged over 25 injections. The soot luminosity images of the reference nozzle show an established flame with the conventional shape. The LII measurements show that most of the soot is formed in a broad area around the spray axis as expected for conventional nozzles. Both cluster nozzles generate shorter penetration lengths of the flame compared to the reference nozzle. For both cluster nozzles droplets can be observed close to the sooting region (at a height of nearly 20 mm), due to Mie scattering in the images. The LII images for the 10° cluster angle nozzle show a narrower soot distribution compared to the reference nozzle, except for the upper part, i.e., the sooting region is mushroom-shaped. In the LII images of the 20° cluster nozzles two separated soot distributions can be identified which are only slightly connected. Comparing signals of the different nozzles, the shape (and symmetry) of the soot distributions differ. Thus, a different fraction of the total soot mass is probed by the LII technique, since the measurements are only done in the central plane of the flames. Therefore, in comparison to the results for the reference nozzle the total soot mass for the cluster nozzles is relatively lower than that indicated by the LII results. This is particularly true for the 20° cluster nozzle. But it is impossible to compute the total soot precisely from the LII results, because the exact 3-d shape is not known. Using the LII measurements, it can be estimated that at least in the early combustion phase the reference nozzle produces more soot in the central plane than both the cluster-nozzles. Based on the LII data it can not be decided which cluster nozzle generates more soot. The line-of-sight luminosity data essentially corroborates that the reference nozzle generally produces more soot than the cluster nozzles.

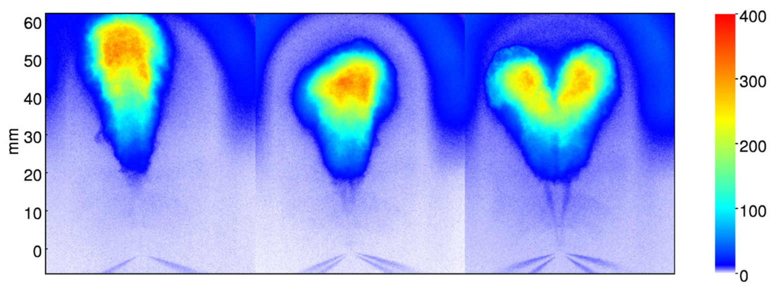

Figure 1. Soot luminosity images of the reference nozzle (left), 10° cluster nozzle (middle), 20° cluster nozzle (right), prail = 900 bar, T = 800 K, p = 50 bar, 2000 µs after energizing the injector

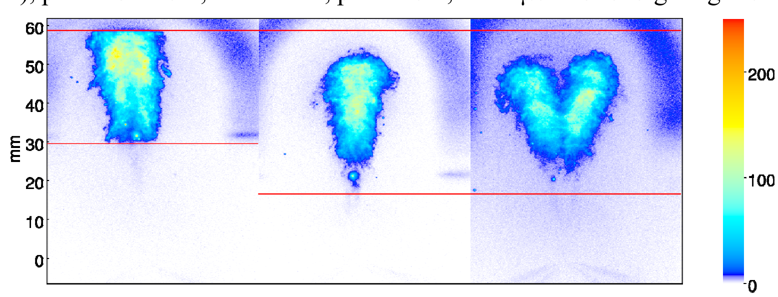

Figure 2. LII images of the reference nozzle (left), 10° cluster nozzle (middle), 20° cluster nozzle (right), same conditions as in Fig. 2, red lines mark the edges of the laser sheet

Figure 3(a) shows the pressure traces and heat release curves for the three cluster-nozzles for part-load operation of the engine for start of pulse (SOP) 12° bTDC. Figure 3(b) compares the pressure curves from experiments and numerical simulations for the three clusters. The cluster 14x160/120 has the highest peak pressure and heat release rate, while the start of combustion was found to be similar for all the nozzles.

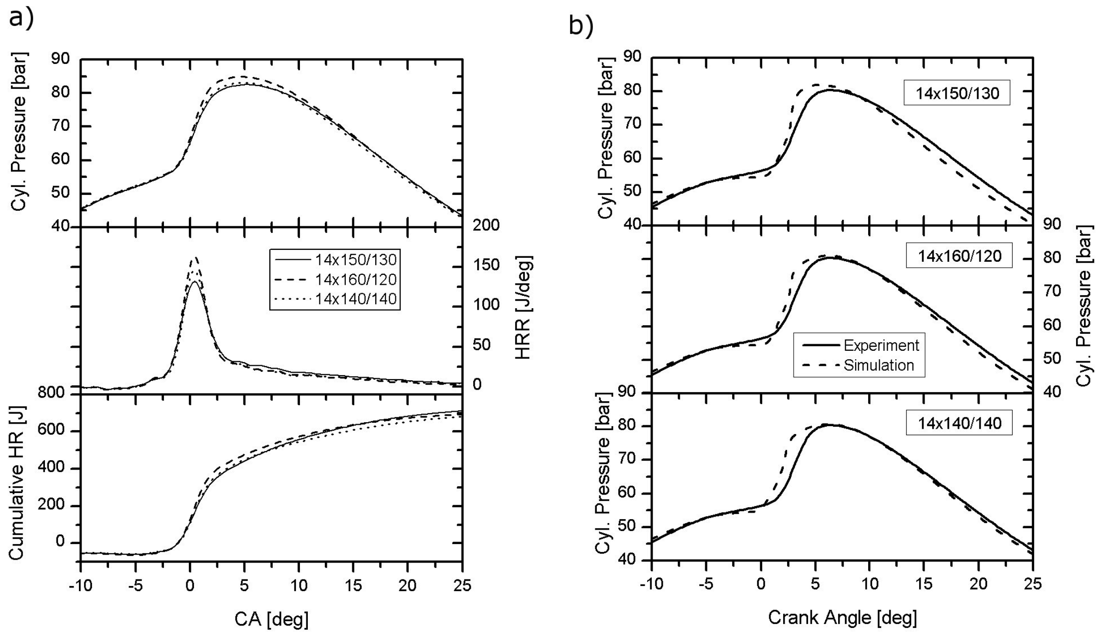

Figure 3. Pressure, Heat Release and Cumulative heat release for the three clusters (a), and comparison with simulation data (b).

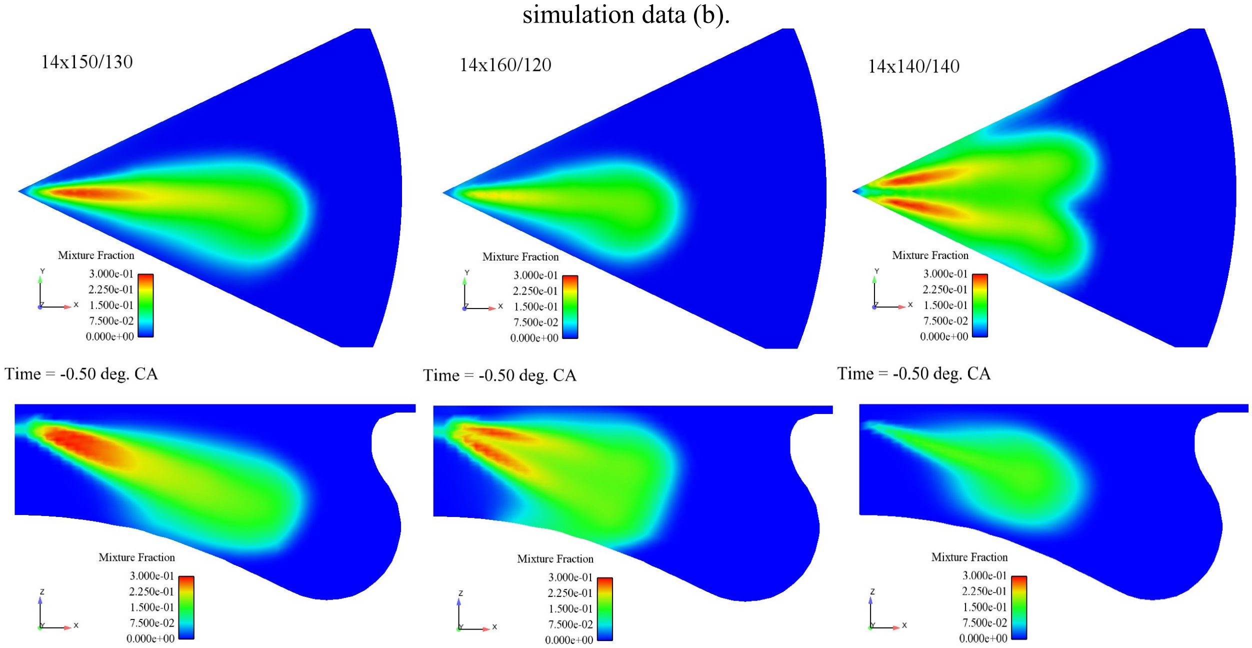

Figure 4. Mixture fraction distribution in cylinder for the three clusters for 6°bTDC SOP, part-load condition

The simulation results match well with the data from the experiments. Figure 4 depicts the mixture fraction distributions in the horizontal and vertical injector cut-planes for the three investigated nozzles from the simulation. For the cluster 14x160/120 the vapor phase originating from the two orifices exhibits a separation. For the cluster 14x150/130 the vapor phase merges and behaves like a single spray. This leads to a higher gaseous penetration compared to 14x160/120. However, when compared to cluster 14x160/120, the cluster 14x150/130 exhibits a richer mixture in the horizontal cut plane. The larger cluster angle for cluster 14x160/120 increases the contact between the vapor phase and the bowl.

Smoke-NO_x and Hydrocarbon-NO_x tradeoffs are shown in Figure 5 for different start of injection (SOI). The cluster 14x160/120 had relatively better results for smoke than the base 7-hole nozzle for early start of injection points. All the clusters show higher smoke than base 7-hole nozzles for conventional injection timings. The lowest smoke number for all the experiments was found around 25° CA bTDC for cluster 14x160/120. Smoke mostly depends on the mixing process and fuel rich regions close to the bowl wall. The sprays from the clusters having a narrower center-line angle lose momentum because of improper targeting under conventional injection timings, which worsens the mixing process and increases soot formation.

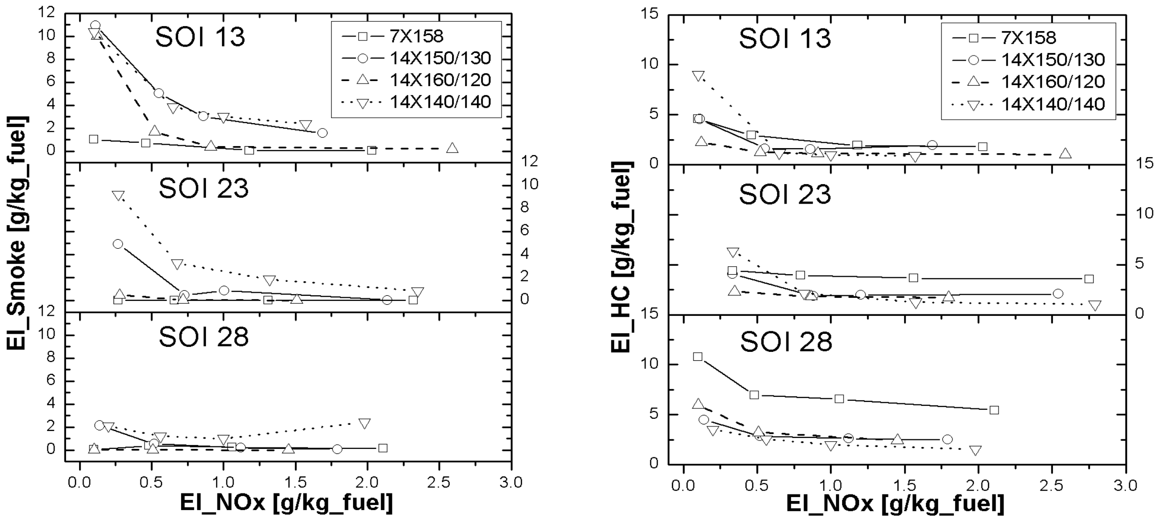

Figure 5. Smoke-NOx and Hydrocarbon-NOx Tradeoff

THC (Total Hydrocarbons) for all the clusters were lower than those for the reference nozzle for early injection timings but were found to be similar to the reference nozzle for conventional injection timings. The clusters had a narrower spray-cone angle compared to the reference nozzle. So, for the clusters at early injection timings, the fuel vapor spreads along the curved interior of the combustion chamber wall, and then turns towards the cylinder center, instead of dispersing to the squish area which happens with the reference nozzle due to the larger spray-cone angle. Fuel-air mixture present in the squish space is the main cause of THC emission. Thus the reduction in fuel-air mixture in squish space reduces THC. The results indicate that by using cluster nozzles with early injection timing and high EGR, low NOx and low soot combustion is possible for lean mixtures, while simultaneously low THC combustion is possible by preventing the dispersion of the fuel-air mixture to the squish area.

The results of the spray measurement in the combustion vessel show a potential for improvement in soot emissions for all the clusters, but the engine experiments for high-load operation show a different trend. Among the three clusters, 14x160/120 showed the lowest soot, but it still was much higher than the conventional nozzle. The anomaly between the relative trends of soot emissions for early injection under part-load operation and conventional timings under high-load operation was found to be caused by improper targeting.

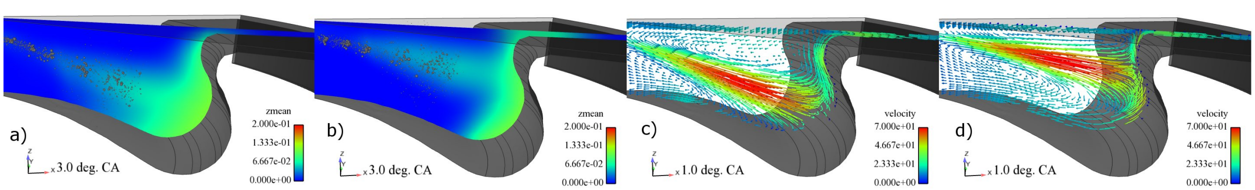

Figure 6. Mixture Fraction field for Spray-cone angle of 140° (a), 158° (b) and Velocity distribution for Spray-cone angle of 140° (c) and 158° (d), SOP 6° bTDC

Figure 6 explains the issue of targeting. Here we see results of simulations for two conventional nozzles with spray-cone angles of 140° (a & c) similar to the clusters of the first set and 158° (b & d) similar to the reference nozzle. The simulation is done for a conventional SOP (6° bTDC). It is evident that the spray from the 140° nozzle loses momentum close to the piston-wall(Fig. 6(c)) and leaves more amount of rich mixture there (Fig. 6(a)), whereas the spray from the 158° nozzle turns towards the center of the bowl (Fig. 6(d)) and doesn't leave much of rich mixture near the wall. For earlier injection timings the spray from the cluster nozzles also turns towards the center of the bowl as described above in discussion of THC results for part-load operation.

Based on the above observations, a new cluster (14x158/158) was designed and tested under part and high-load conditions. The cluster was compared with conventional nozzle 7x158 and 14x160/120 (best among the first set of clusters). Figure 7 shows the tradeoffs for part-load and variation of smoke and hydrocarbons with SOP for high-load operation. As seen from the graphs, the new nozzle maintains the advantage of a cluster nozzle under part-load conditions. It significantly improves the performance over the other clusters, reaching levels comparable to the reference nozzle for conventional injection timings under high-load conditions.

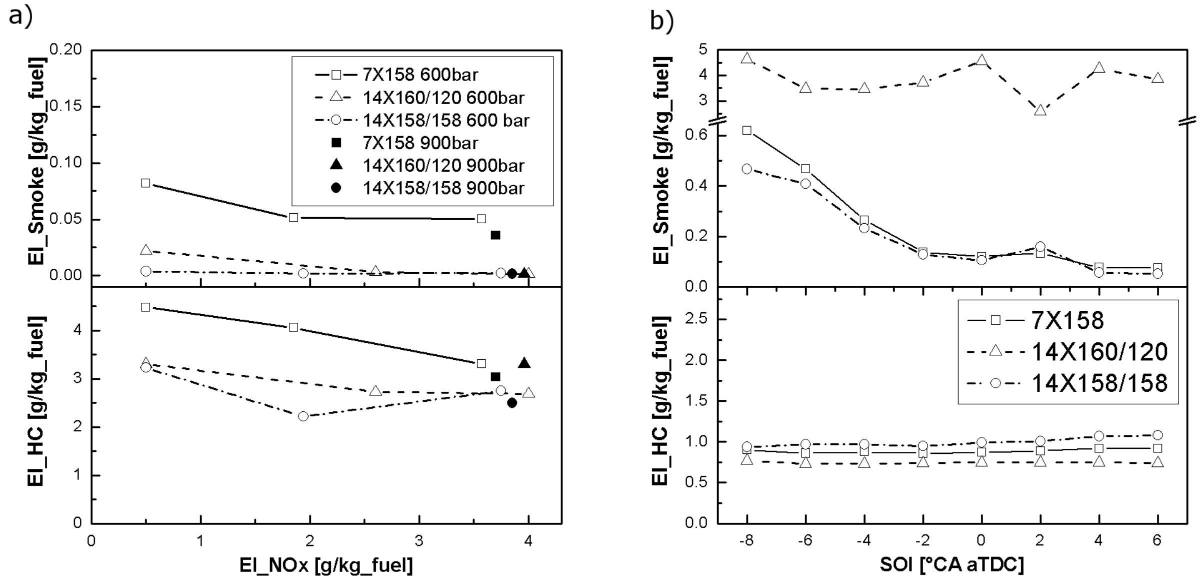

Figure 7. Smoke-NOx & HC-NOx Tradeoffs for SOI 25° bTDC for part-load (a) and Smoke and HC for different injection timings under high-load for the new cluster compared with the reference and one cluster from the first set

Conclusions

The cluster nozzles exhibit a smaller penetration for the flame than the conventional nozzle. The 20° nozzle shows two separated soot "kernels" while the 10° cluster shows only a single one with lower intensity than the conventional nozzle. The LII measurements demonstrate that the total soot mass generated by both the cluster nozzles is smaller than that in the case of the reference nozzle, at least in the early combustion phase. The first set of clusters which were designed with a smaller spray cone angle keeping in mind early injection operations, demonstrate the soot reduction potential of cluster nozzles under early injection conditions. But, the disadvantage due to improper targeting overweighs the advantage of the cluster concept under conventional timings. Simulations confirm the findings of the experiments and hint towards required improvements in targeting. The new cluster with larger spray cone angle demonstrates applicability of cluster concept to high-load operations under conventional injection timings. The cluster also maintains the advantage of the cluster concept under early injection timings.

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