

Analysis of EGR Effects on the Soot Distribution in a Heavy Duty Diesel Engine using Time-Resolved Laser Induced Incandescence

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ABSTRACT

The soot distribution as function of ambient O_2 mole fraction in a heavy-duty diesel engine was investigated at low load (6 bar IMEP) with laser induced incandescence (LII) and natural luminosity. A Multi-YAG laser system was utilized to create time-resolved LII using 8 laser pulses with a spacing of one CAD with detection on an 8-chip framing camera. It is well known that the engine-out smoke level increases with decreasing oxygen fraction up to a certain level where it starts to decrease again. For the studied case the peak occurred at an O_2 fraction of 11.4%. When the oxygen fraction was decreased successively from 21% to 9%, the initial soot formation moved downstream in the jet. At the lower oxygen fractions, below 12%, no soot was formed until after the wall interaction. At oxygen fractions below 11 % the first evidence of soot is in the recirculation zone between two adjacent jets. The initial growth rate of the soot area, in the plane of the laser sheet, increases when the O_2 fraction decreases from 21% to 13%. Also the residence time in the soot area near CA50 increases during this part of the EGR-sweep. In combination, these trends are consistent with greater net soot production with decreasing O_2 . It is reasonable to assume that the increased net soot production is partially associated with reduced soot oxidation at low O_2 fractions, although this cannot be quantified from the present data. Below 12% O_2 , past the peak in smoke emissions, both the area growth rate and the residence time decrease. This should decrease the total net soot formation.

INTRODUCTION

Global warming debate, increasing oil prices, and stringent emission legislation stresses the importance of clean diesel combustion with high efficiency. A deeper understanding of the combustion process may make it easier to reach emission targets with maintained efficiency. During a sweep in Exhaust Gas Recirculation (EGR), the engine out smoke level is typically characterized by an initial increase with decreasing O_2 mole fraction, followed by a drastic decrease below a certain O_2 level [1]. This investigation presents a time-resolved analysis of the in-cylinder soot distribution in a reacting jet during such a sweep in EGR. The purpose is to link trends in soot distribution to the trends in engine out smoke.

Diesel combustion can be divided into different phases based on the heat release characteristics. When ignition occurs, the available combustible fuel and air mixture burns rapidly in the premixed combustion phase. After that, the mixing-controlled period follows, where the fuel burns as a diffusion flame. This phase can be further divided into two parts. During the first, spray driven part, the fuel burns in a jet structure while it is injected, evaporated, mixed with air and ignited. After the End Of Injection (EOI) the late combustion phase takes place [2]. The phases can be identified from heat release analysis, see Fig. 1. In this investigation the soot distribution in the jet is analyzed during the premixed combustion and the major part of the spray driven combustion.

The course of events inside a reacting diesel jet is described in [3]. In summary, the liquid fuel liquid fuel mixes with air, evaporates, and forms a combustible fuel-air mixture. Inside the jet, the fuel goes through a fuel-rich premixed combustion stage. This zone tends to form soot if the local Φ is higher than 2 [1]. The fuel goes through partial combustion and forms soot precursors such as Polyaromatic Hydrocarbons (PAH). Small nuclei are then formed which grow into primary soot particles. These stick together and form agglomerates as they move downstream in the jet. The amount of fuel that goes through the steps of soot formation and oxidation depends strongly on the operating condition but it is normally only a

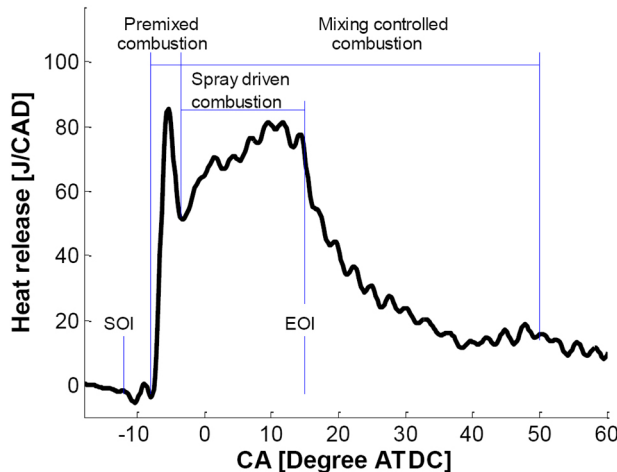


Figure 1. Phases of diesel combustion. Heat release calculated for 14% O₂ mole fraction in the charge gases at 6 bar IMEP with CA 50 at 9 CAD ATDC.

small fraction [4,5]. Near the leading part of the jet the soot concentration reaches a maximum. The jet is surrounded by a high-temperature diffusion flame burning at near stoichiometric conditions. This zone forms Nitrogen Oxides (NO_x) and Hydroxyl (OH) radicals. Most of the soot oxidation takes place here [5].

When high levels of cooled EGR are introduced the structure of the flame is changed. The soot production moves downstream to the head of the jet. The OH and NO production zone is moved inside the jet and occurs over the whole jet cross section [6].

The most upstream part of the burning diesel flame is called the lift-off position and is commonly determined from OH-chemiluminescence. Downstream from this position the oxygen entrainment into the center of the jet is impeded since the oxygen is consumed by the reactions on the surface of the flame. The soot forming process is thought to be strongly affected by the air entrainment upstream the lift-off position [7,8]. Although the usage of EGR changes the jet structure to a great extent, it does not necessarily have a net effect on the equivalence ratio in the lift-off zone [7, 8, 9]. This is due to

two counteracting trends. The lower ambient O₂ fraction gives less O₂ entrainment over a given distance but, at the same time, the lift-off position is moved downstream, which potentially gives the same O₂ entrainment up to the lift-off position.

High levels of cooled EGR can reduce smoke and NO_x emissions significantly. The simultaneous reduction in soot and NO_x formation is due to a decreased combustion temperature rather than a change in equivalence ratio. When the combustion temperature is suppressed the reactions that form soot from PAH cannot take place. The drawback with such combustion concepts is high levels of CO and Unburned Hydrocarbons (UHC) [1].

LII THEORY

Laser Induced Incandescence (LII) is today a fairly mature technique, commonly used in the combustion diagnostics community for soot measurements [10, 11, 12]. In diesel engines, LII is mainly used to acquire soot volume fractions but also the particle size can be obtained [13, 14, 15].

In this investigation a Multi-YAG laser cluster and a SIM 8 high speed framing camera were used to create time-resolved, 2D LII measurements of soot distribution. The LII signal's dependence on laser fluence, laser beam profile, and reduced time separation between laser pulses has been investigated and the output of the Multi-YAG laser cluster has been optimized accordingly.

Measurements of soot in piston engines using LII are extensive [13, 16, 17, 18]. However, the concept will briefly be recapitulated here. LII is created by a laser pulse heating particles to a temperature significantly higher than the surrounding medium. The upper limit of the soot particle temperature is ~4000 K. Above this temperature sublimation of small molecules (e.g. C₂ and C₃) from the soot particles prohibits further temperature increase. Since the laser heated soot particles are much hotter than the surrounding gas their emitted light spectra are blue shifted compared to the surrounding cooler particles. The blue shifted light is collected as the LII signal, usually at short wavelengths where the flame background luminosity is insignificant.

The intensity and origin of the light that is emitted as the particles cool down contain information about the soot particles. There are two major ways to detect this signal. One is time-resolved measurement of the LII signal's decay as the particles cool down. This, together with modeling of the signal, provides information on particle size etc. [19, 20]. Time-resolved measurements are usually limited to point measurements but may be extended to 2D with a high speed framing camera [21]. Secondly, it has been shown that the soot volume fraction is approximately proportional to both the integrated signal and the peak signal level [22, 23]. This

can be used in order to make 2D measurements of the soot volume fraction. To suppress background contribution from the chemiluminescence and Planck radiation from the combustion, spectral filters and a gated intensified charge coupled device (ICCD) camera are used to filter the signal both in the spectral and temporal domain [11]. In this paper the integrated LII signal is measured in 2D. As the elevated pressure in the engine makes the LII signal very short (on the order of 10 ns at 60 bar). A camera gate width of 50 ns is used which covers the entire period with LII signal.

Two major problems with LII measurements in highly sooting combustion environments are the extinction of the laser sheet by the soot particles and the attenuation, or trapping, of the signal while propagating from the measurement plane to the detector. Both of these effects are spatially inhomogeneous and, therefore, time-consuming three dimensional measurements are needed to compensate for them [24, 25].

The effect of laser extinction can be mitigated by carefully selecting an appropriate spatial laser profile and laser fluence. If so, a plateau region can be achieved where the LII signal level is limited by sublimation processes and not by the laser fluence. Hence, the signal will, to a certain degree, be unaffected by laser intensity fluctuation and laser extinction through the sample [26].

At elevated pressures the heat conduction to the ambient medium is more pronounced. Hence, the lifetime and strength of the signal is reduced which in turn reduces the strength of the integrated signal. For pressures typical for combustion engines the lifetime will be on the order of 10-100 ns compared to 1-3 μ s at room pressure [27, 28].

LII has mainly been developed in flames at atmospheric pressures with low repetition rate lasers. When implemented at high repetition rates additional aspects have to be taken into consideration. High-fluence LII is intrinsically a destructive technique. The particles are heated to temperatures where sublimation becomes significant. Therefore, the particles generally have less mass after than before the laser pulse [29]. Consecutive measurements within a time-period shorter than the timescale of the flow might thus show a decline in soot volume fraction caused by the preceding measurements. However, the effect of sublimation from previous laser pulses is expected to be diminished in an engine. The higher pressure (60-70 bars) will result in greatly increased heat conduction to the surrounding medium from the laser-heated particles. This will make the sublimation a less important energy loss mechanism and thus the effect of sublimation from previous pulses is expected to be less significant. Any transportation of new soot particles into the laser sheet between laser pulses also makes the effect of previous sublimation less apparent.

EXPERIMENTS

ENGINE SETUP

A Scania D12 heavy-duty diesel engine, converted into an optically accessible single cylinder engine of Bowditch design, was used in this investigation. Details of the engine setup can be found in Table 1 and the piston bowl shape is shown in Fig. 2.

Table 1. Engine properties.

Compression ratio, r_c [-]	15.6
Displacement volume [l/cylinder]	2.0
Bore [mm]	127
Stroke [mm]	154
IVC [CAD BTDC]	151
EVO [CAD ATDC]	146
Engine speed [rpm]	1200
Swirl number [-]	2.2
Fuel	n-heptane
Included angle [degrees]	146

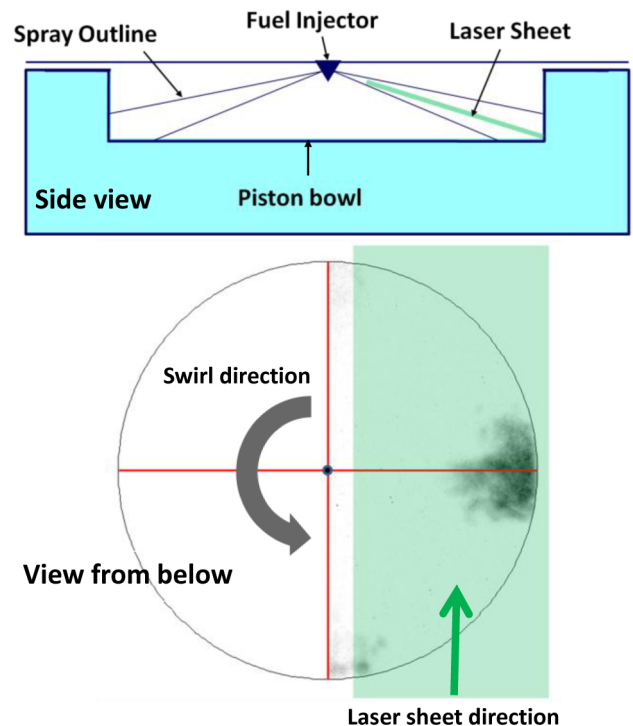


Figure 2. Piston bowl geometry and laser sheet positioning. The upper image shows the side view at TDC and the lower image shows a view from below with the laser sheet and swirl directions indicated.

A Cummins common-rail fuel injection system was used along with a four-hole, solenoid-driven injector with an orifice diameter of 100 μm . Exhaust gas to simulate EGR was taken from an external diesel furnace for domestic heating. It was cooled, mixed with the inlet air, and conditioned using a mechanical compressor and electric heater. This allowed independent control of inlet oxygen fraction, boost pressure, and temperature.

The engine was operated on 99% n-heptane, and 1% of a transparent lubricant, Chevron Synfluid. The lubricant was used in order to ensure the function and lifetime of the fuel pump and the injector. This fuel mixture was chosen since it, as opposed to commercial diesel fuels, has a well known composition and thus minimizes the risk of LIF interference from unknown species.

OPTICAL SETUP

Cycle-resolved 2D LII measurements require several high energy laser pulses to be fired within one engine cycle. This is achieved using a Multi-YAG laser cluster as shown in Fig. 3.

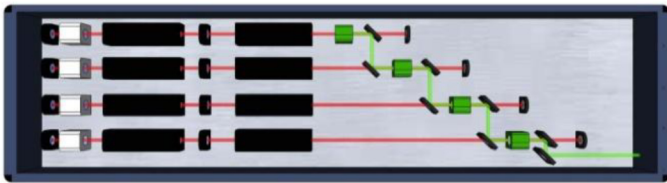


Figure 3. Sketch of the Multi-YAG laser cluster in 532 configuration.

The Multi-YAG laser cluster consists of four Nd:YAG lasers producing 1064 nm radiation with a repetition rate of 10 Hz. The beams are combined using a specially designed doubling and recombination scheme as shown in Fig. 3. The beam from the first laser is frequency doubled to 532 nm using a second harmonic generating crystal. It is then separated from the original fundamental 1064 nm beam and overlapped with the next 1064 nm beam from the second laser using two dielectric mirrors. This combined beam is then sent through a second frequency doubling crystal where the fundamental from the second laser is frequency doubled to 532 nm but leaving the first beam unchanged as the phase matching condition is not met for both 1064 and 532 nm at the same time. This procedure is repeated for all four lasers so that a single output beam with a wavelength of 532 nm is achieved. Since all four lasers can be double pulsed, this setup can produce a train of eight laser pulses with time separations between 5 and 440 μs (for equidistant spacing) and pulse energies up to 1.4 J/pulse. A more detailed description of a Multi-YAG laser system can be found in [30].

During the experiments the pulse separation was set to 139 μs . This gave one crank angle degree (CAD) between the images as the engine was operated at 1200 rpm. A sketch of the pulse train can be seen in Fig. 4. A pulse separation of 139 μs further allows the Multi-YAG laser to operate at the necessary high laser power needed to produce the required fluence for the 2D LII measurements.

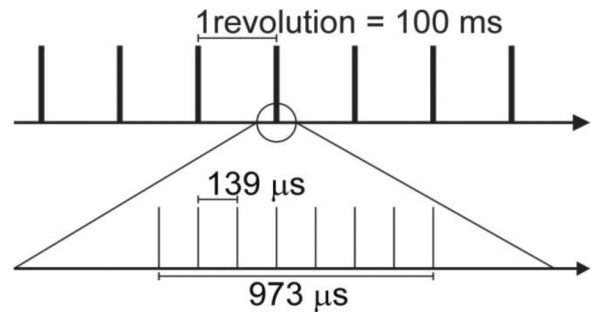


Figure 4. Laser pulse train timing. 139 μs corresponds to 1 CAD at 1200 rpm.

In order to detect the LII signal generated by each of the laser pulses in the burst from the Multi-YAG system, a high-speed framing camera, SIM 8, from Specialized Imaging is used. A Bernard-Halle quartz lens ($f = +100\text{ mm}$, $f/2$) is mounted in front of the single optical input of the framing camera. A fast image intensifier (300 ns decay time) is positioned directly after the optical entrance of the camera in order to enhance the sensitivity and to enable UV detection. The intensified signal is then split up using seven 50-50 beam splitters onto the eight individual ICCD modules. This ensures minimal optical aberration in each image and very small differences between the images. Each module consists of a micro channel plate intensifier and a CCD image sensor with 1280×960 active pixels. The micro channel plate functions as an electronic shutter and further intensifies the signal. The shutter function ensures that each CCD only detects signal from one laser pulse and they are subsequently synchronized with the laser pulse train.

The camera is equipped with two optical filters. A band pass filter with a transmittance of $\sim 50\%$ between 372 and 427 nm, which is the full width at half maximum (FWHM), allows the LII signal to be detected and blocks both the laser light at 532 nm and most of the light from the combustion process. In order to ensure that infrared radiation from the combustion process is not detected a heat-absorbing KG 3 filter is also used. For the Mie scattering images, the filters were exchanged to a 532 nm band pass filter instead.

2D LII is usually conducted with a laser profile that generates a plateau region i.e. where the signal increase from increased laser fluence is balanced by the signal decrease due to increased soot sublimation. To find this region, preliminary test of high speed LII were conducted with the Multi-YAG

laser in an atmospheric, sooting ethylene/air flame with $\Phi = 2.1$ on a McKenna burner [20].

Several different laser sheet profiles were initially tested. A simple sheet formed by a spherical $f = 1000$ mm and a cylindrical $f = -200$ mm lens was found to give a constantly increasing LII signal as a function of fluence for this laser system. No plateau region was observed due to large wing effects in the focal plane from this laser profile [26]. Thus, a top-hat laser sheet profile was selected for the experiments and Fig. 5 shows the optical components as they were positioned for the engine measurements. For the flame measurements the optical components were rotated 90 degrees around the laser beam to get a vertical laser sheet.

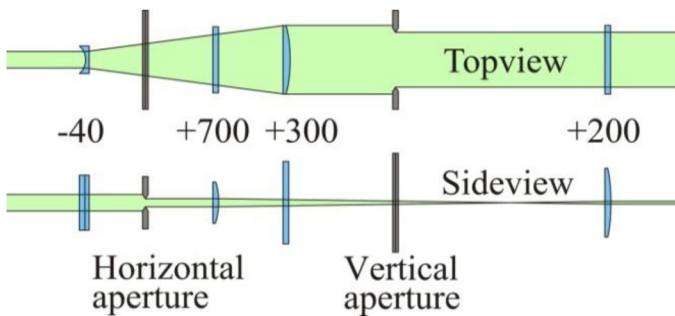


Figure 5. Sketch of the laser sheet forming optics as seen from above and from the side. Optical components from the left to right: cylindrical lens $f = -40$ mm, horizontally aligned aperture 3.5 mm wide, cylindrical lens $f = 700$ mm, cylindrical lens $f = 300$ mm, vertically aligned aperture 40 mm wide and cylindrical lens $f = 200$ mm. The relative distance to the last lens is shortened for clarity.

The sheet forming optics consist of two parts. The first part is a telescope expanding the laser beam in the horizontal plane and two vertically oriented edges forming a 40 mm aperture, thus determining the width of the laser sheet. The second part consists of a telescope with a magnification of 2/7 in the vertical direction. Together with two horizontally aligned edges 3.5 mm apart this gives a laser sheet that is 1 mm thick in the measurement region. There, an image of the vertical cutting edges is created by the last two lenses and the laser sheet has a well-defined top hat profile.

The LII signal's dependence on laser fluence with this optical setup is seen in Fig. 6. The measurements are made in the McKenna burner. The curve shows an initial increase up to 0.15 J/cm^2 . It is here that sublimation balances increased laser fluence. However, after this region the LII signal rapidly decreases due to excessive sublimation. For fluence levels above 0.3 J/cm^2 the LII signal stabilizes again. However, the signal in this region is clearly dominated by sublimation. High-speed LII measurements with several laser pulses

would thus have a greater tendency to be affected by previous pulses if this high fluence were used. Further, photochemical interference is expected to be more severe in this region [31]. The shape of this curve is expected to be preserved for the high pressure measurements in the engine [28]. During the engine measurements a laser pulse energy of 60 mJ/pulse corresponding to a fluence of $\sim 0.2 \text{ J/cm}^2$ was used for each of the pulses to minimize the effect of laser extinction and give a high signal level.

The optical setup in the engine rig is seen in Fig. 7. The laser is sent via two dielectric mirrors to the sheet forming optics shown in Fig. 5. The lenses and the top dielectric mirror are mounted on a single steel beam facilitating adjustments of the laser sheet position in the combustion chamber. The laser sheet is tilted at an angle matching the downward angle of one of the fuel jets, so as to contain the fuel jet axis by intersecting it perpendicularly (as seen in Fig. 2 and in the inset in Fig. 7). Thus, it is possible to study the soot along most of the fuel jet, except for the first three millimeters closest to the injector, where no soot is expected to be present during the injection event. The two recirculation zones formed on either side of the fuel jet are also intersected by the laser sheet allowing the soot in these regions to be studied. The LII signal is detected from below, through the quartz piston top, via a 45 degree mirror positioned in the Bowditch piston extension [32]. The camera is positioned so that almost the entire piston bowl is visible in the images.

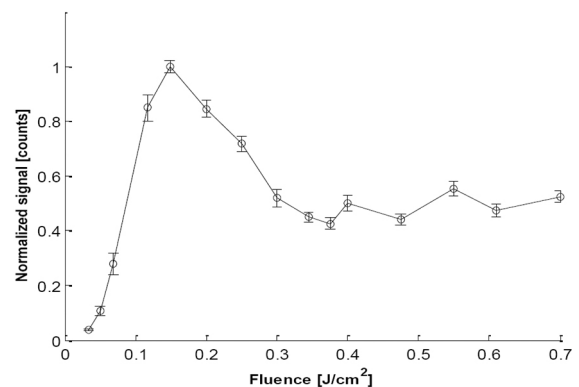


Figure 6. LII signal versus laser fluence with a top hat laser sheet profile. The measurements are conducted in a laminar McKenna burner at atmospheric pressure.

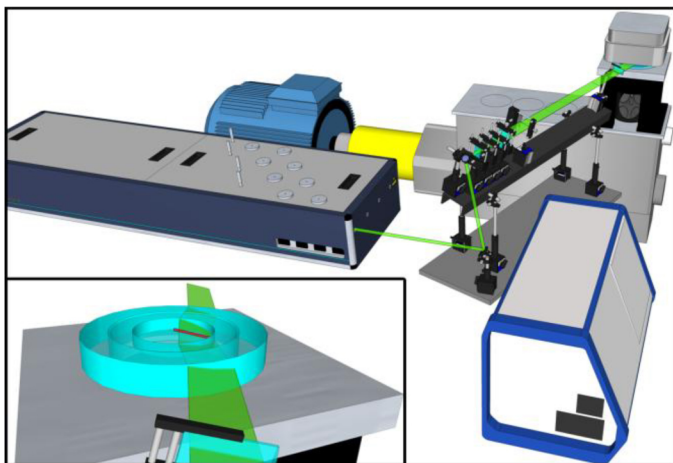


Figure 7. A sketch of the optical setup for the measurements in the diesel engine. To the left is the Multi-YAG laser, behind it are the electric motor and the optical engine, and to the lower right is the SIM 8 camera. The green line indicates the laser beam. The inset in the lower left corner shows how the laser sheet (green) propagates through the combustion chamber and intersects one of the fuel jets (red).

The results presented in this paper are qualitative. The data that will be presented are LII signal levels and additional understanding derived from them. No values of soot volume fraction will be presented. There are several reasons for this but the main reasons are laser extinction and signal trapping. It has previously been shown that these effects can be very severe under diesel-engine like conditions [33]. For this study, with spatially and temporally inhomogeneous soot distributions due to varying oxygen fraction and high turbulence, the evaluation of soot volume fraction from LII signal would give excessively high levels of uncertainty. There are also further considerations that have to be taken into account, like window fouling, beam steering, combustion luminosity, etc. [34] Further, the LII community today does not completely agree on how to model the LII signal [11]. These considerations add up to the conclusion that quantitative in-cylinder soot-volume fraction measurements with 2D LII are not possible in this study.

IMAGE EVALUATION

The location of the piston bowl center in the LII images is identified by fitting a circle to the piston bowl to one of the images in each image series. A threshold value is subtracted from the LII signal corresponding to the mean signal from one of the jets outside the laser sheet. This reduces interference from potential soot luminosity passing through the filter.

OPERATING CONDITION

The test matrix consisted of a sweep in ambient O_2 mole fraction. All presented values of O_2 fraction or % O_2 refers to mole fraction O_2 throughout the manuscript. Measurements were performed at 21% and between 17 and 9% with a spacing of 1%. The test matrix was run twice with an essentially randomized order. The engine was operated at 6 bar indicated mean effective pressure (IMEP). The crank angle of 50% completion of the heat release (CA50) was kept constant at 9 CAD After Top Dead Center (ATDC) over the whole test matrix. The fuel injection pressure was 2000 bar.

The engine was operated continuously during the emission measurements while it was skip-fired during the optical measurements due to the slow acquisition cycle of the framing camera. A routine was developed where the engine was motored before skip-firing, until the temperature of the metal plate under the quartz cylinder liner (see inset in Fig. 7) exceeded 90 °C. Then the engine was skip fired every 60th cycle for 4 fired cycles where one image series of 8 images was acquired during each fired cycle. After the 4th image series the engine was stopped to cool down until the metal plate temperature went down to 80 °C. Two subsequent image sets of 4×8 images were acquired at each operating condition after which the engine was cleaned. This routine of 8 combustion cycles between cleaning minimized signal trapping due to dirty windows.

Despite this sparse firing, the load and combustion phasing was not significantly different from the continuously fired cases. Figure 8 shows that the heat release traces acquired from continuously and skip fired cases at 14% inlet O_2 fraction are similar. Likewise, when comparing LII images between continuously and skip-fired cases there were no obvious differences in the timing or locations of soot formation. The measured soot distributions should thus be representative of the conditions under which the trends in engine out emissions were acquired. Heat release analysis is performed according to the theory in [2], heat losses and errors in the in cylinder volume calculation are partly compensated for by subtracting the heat release trace from a motored cycle.