Fuel Effects on Illumination Ignition Delay and Soot Lift-off Length in Diesel Combustion

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Abstract
Ignition behavior of different fuels is investigated by recording broadband soot luminosity at high speed (60 kHz). The tested fuels are regular low sulphur EN 590:2004 fuel, EN 14214:2003 (FAME), n-heptane and IDEA (2 component surrogate fuel), all with a Cetane Index between 51 and 57. For this an optically accessible, high density, high temperature, constant volume cell is used. It appears that molecular structure of the fuels results in large differences in illumination ignition delay and soot lift-off length between the fuels tested.

Introduction
Meeting increasingly stringent exhaust gas emission regulations while improving or maintaining fuel economy, is the main drive for modern Diesel engine development. The fuel-air mixing process inside the engine has major influence on both the combustion process and emission formation. In order to study Diesel combustion in detail, usually optically accessible engines or dedicated high density, high temperature cells are used. The latter have advantages with respect to optical accessibility, variety and controllability of conditions inside the cell. At Eindhoven University of Technology therefore the Eindhoven High Pressure Cell (EHPC) is constructed and used [1, 2, 3].

Specific Objections
The goal of the work presented here is to obtain more knowledge about the illumination ignition delay and soot lift-off lengths of a combusting spray from different (bio/renewable/surrogate) fuels and compare it to the behaviour of regular EN 590 fuel. To detect both phenomena, broadband soot luminosity recorded with a high speed camera is used. Results for both parameters are shown for the different fuels tested.

Experimental Setup
The EHPC (108 x 108 x 108 mm³) is an optically accessible, cubically shaped, constant volume cell used to validate diesel fuel spray models, mainly for Heavy Duty diesel engines [1, 2, 3]. The walls of the cell are heated up electrically to 403 K to prevent water condensation on the windows. The top surface, in which the diesel fuel injector is mounted, is cooled to 333 K to prevent premature fuel vapourisation. Optical access is obtained via up to three sapphire windows of 50 mm thickness and 100 mm visible diameter. The fuel injector is coupled to an in house developed common rail system, equipped with an air driven Resato high pressure pump to create fuel pressures up to 250 MPa. Currently a 6-hone Heavy Duty diesel engine common rail sac hole nozzle injector is used (Ø 177 ±3 µm, Bosch DLLZ160PV3770683, 447 ccm). For the measurements shown here a common rail pressure of 103 (±2) MPa is used. The injector is equipped with a Micro Epsilon U05 eddy-current needle lift sensor, and a piezo-resistive Kistler 4067 fuel pressure sensor is used to measure the fuel pressure just before the fuel injector.

The 6-hole fuel injector nozzle used is unmodified, but to prevent oxidation of the nozzle it is coated with titanium nitride. In order to study a single fuel spray from this nozzle, a (removable) thimble is constructed, which covers all but one orifice. The fuel delivered by the 5 covered orifices is led to the bottom of the cell by a drainpipe. As the injector is mounted at an angle inside the EHPC, the centerline of the single fuel spray enters the cell at an angle of 37° to the horizontal plane, as can be seen in Figure 1.

Figure 1: Schematic drawing of fuel injection equipment used, the dotted circle indicates the entrance/exit EHPC windows for the collimated light beam, which travels perpendicularly to the figure plane (camera and optics not shown); DA = data acquisition, CR = common rail.

For more details on the fuel injection equipment the reader is encouraged to consult the paper by Klein-Douwel et al. [3].

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Experimental Preparation

To obtain conditions inside the EHPC that are similar to those inside an engine cylinder at the time of the injection of fuel, the so-called pre-combustion technique is used. This proven technique \cite{4, 5} is illustrated in Figure 2, which displays a typical pressure history of an experiment to create the high temperature, high pressure engine conditions.

Figure 2: Pressure history in the EHPC, illustrating how the high temperature and pressure conditions are generated. Ambient gas conditions at the moment of fuel injection: \( \rho \approx 10.0 \text{ kg/m}^3 \), \( T_{\text{GAS}} \approx 1070 \text{ K} \). The fuel injection duration is 5.0 ms.

An experiment is started by filling the EHPC sequentially up to the desired pressure with a lean (\( \phi \approx 0.37 \)) mixture of \( \text{C}_2\text{H}_2, \text{Ar}, \text{N}_2 \) and \( \text{O}_2 \). During the filling procedure of the gas a mixing fan runs continuously up to 5 s, before the gas mixture is ignited. The mixture is ignited with a sparkplug located at a rear upper corner of the cubic cell. The ignition of the combustible mixture creates a first rapid rise of pressure and temperature above engine-like conditions, as can be seen in Figure 2 at 0.045 s. After the combustion, pressure and mass-averaged temperature decrease due to cooling, and once the desired gas temperature is reached the diesel fuel injector is triggered, in this particular case at 0.773 s. This results in a sequence of events: first the fuel injection, followed by, after an ignition delay, auto-ignition and the establishment of a combusting spray. The combusting spray is responsible for the second pressure rise in Figure 2, at 0.774 s.

The ambient gas density up to the time of the fuel injection is constant. Of course, the fuel injection takes place in the residual gas resulting from the pre-combustion used to create the high pressure, high temperature conditions. The ambient gas temperature of this mixture is determined from the measured gas pressure and residual gas mixture composition at the moment of fuel injection. The decrease in ambient gas temperature during the fuel injection itself is very small. The ambient gas temperature spatial distribution at the moment of fuel injection is topic of research at this moment. However it is estimated to be within \( \pm10\% \) of the mean, calculated, temperature as the test rig used is comparable to others \cite{6}.

For the experiments, simulated air environments were produced (i.e., with \( X^{\text{U}}_{\text{O}_2} = 0.21 \)). The mixture burned to generate the simulated air was a lean (\( \phi \approx 0.37 \)) mixture of \( X^{\text{U}}_{\text{C}_2\text{H}_2} = 0.047, X^{\text{U}}_{\text{Ar}} = 0.064, X^{\text{U}}_{\text{N}_2} = 0.567 \) and \( X^{\text{U}}_{\text{O}_2} = 0.322 \). The residual gases, before fuel injection, had a composition of \( X^B_{\text{H}_2O} = 0.048, X^B_{\text{CO}_2} = 0.096, X^B_{\text{Ar}} = 0.066, X^B_{\text{N}_2} = 0.581 \) and \( X^B_{\text{O}_2} = 0.210 \). The mean molecular weight of the residual gas mixture is 30.686. The reason for the addition of argon is to tune the specific heat capacity of the residual gases to those of regular air at high temperature and density. Figure 3 shows that the calculated heat capacity of the residual gases is within 2% to air in a temperature range from 500K up to 1500K, in this case the specific heat of the EHPC residual gas was tuned similar to that of air at 1500 K and 25 kg/m\(^3\). Both pressure and temperature are used to calculate the specific heat.

Optical Diagnostics

In the work presented here the primary diagnostics are pressure measurements and temporal-spatial resolved Schlieren images of the Diesel combustion, using a Phantom v7.1 high speed CMOS camera. Figure 4 shows the Schlieren setup used. An 800 W Xenon arc lamp is used as a light-source, focused through a pinhole, which acts as a point source of light, into a collimated light beam. This beam passes the EHPC and the spray, as is shown in Figure 1. The beam is then focussed again onto a pinhead. This method enables to distinguish the vaporizing Diesel spray, first visible location of auto-ignition (\( > 315 \text{ nm} \)) and soot lift off length. The employed image acquisition rate is 59,000 Hz, which gives a temporal resolution of just below 17 \( \mu \text{s} \). The images have a size of 224 x 104
pixels, 12 bit dynamic range and a spatial resolution of 0.4 mm/pixel. The static pressure of the mixture is measured with a piezoresistive pressure transducer Druck PMP 4070 (0-0.7 MPa). The combustion pressure, up to 20.0 MPa is recorded with a Kistler 7061 piezoelectric pressure transducer. For pressures up to 30.0 MPa a Kistler 6041 AU20 is used. The pressure transducer, located at an upper corner of the cell, is coupled to an AVL 5011B charge amplifier. The high-speed camera and the ignition unit, which is coupled to the spark plug, receive a synchronous start trigger from the TUeDACS data acquisition and control equipment.

The fuels tested are shown in Table 1. EN 590 is low sulphur (< 50 ppm) regular Diesel fuel. FAME (Fatty Acid Methyl Ester) is also known as Biodiesel (regularly available in Germany, EN 14214 fuel). The IDEA (Integrated Diesel European Action) surrogate fuel, known from literature, is a mixture of 30% VOL n-decane and 70% VOL α-methylnaphthalene. This fuel was thoroughly investigated in the Idea-Effect program and the engine heat release behavior of IDEA is almost similar to that of regular diesel fuel, as for example shown by Barths et al. [10]. The last fuel tested is n-heptane, an often used single component reference fuel. The last two fuels were also used in studies comparable to this work, for example by Verhoeven et al. [5].

### Table 1: Specifications of the fuels tested.

<table>
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<tr>
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<th>EN 590</th>
<th>FAME</th>
<th>IDEA</th>
<th>n-heptane</th>
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<tr>
<td>O (‰)</td>
<td>-</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ρ [kg/l @ 298 K]</td>
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<td>0.880</td>
<td>0.817</td>
<td>0.684</td>
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<td>Cetane Index</td>
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<td>&gt; 51</td>
<td>56</td>
<td>55</td>
</tr>
<tr>
<td>T95 [K]</td>
<td>608</td>
<td>&gt; 593</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tb [K]</td>
<td>-</td>
<td>-</td>
<td>447 - 516</td>
<td>371</td>
</tr>
<tr>
<td>Sulphur [mg/kg]</td>
<td>35</td>
<td>&lt; 20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5 displays a collage of a combusting EN 590 fuel spray. The time step between the 6 frames shown is approximately 339 µs. The figure shows the initial vaporizing spray entering the cell (frame 1 up to 3), then a first appearance of a bright flame can be seen as a result of auto-ignition, localised approximately 23 mm downstream of the nozzle, 1.691 ms after triggering of the CR injector. Frame 5, 339 µs later almost the complete fuel spray is burning and in frame 6 the combusting spray is in the quasi-steady phase of the Diesel combustion process. The upstream borderline of the diffusion flame stabilizes at some distance downstream of the nozzle due to a balance between Diesel spray speed and flame front speed. In this case the soot illumination lift off length is determined to be approximately 24 (± 0.4) mm. In this quasi-steady period, the characteristic description of Diesel combustion as described by Dec [8], does not change.

Figure 5: Image sequence of a combusting fuel spray, the displayed elapsed time is 1.675 ms. Ambient gas conditions at the moment of fuel injection: $\rho \approx 16.7$ kg/m$^3$, $T_\text{GAS} \approx 800$ K. The fuel used is EN 590. Ignition delay, based on moment of triggering the CR injector and first illumination, is 1.691 ms. $P_\text{CR} = 103$ (±2) MPa. In the first four images the spray contour is outlined for better recognition. The wrinkles on the background are caused by density gradients resulting from the pre-combustion. Every image is 224 x 104 pixels (89.6 mm x 41.6 mm).

To determine the illumination ignition delay properly from the images, the time difference between the actual start of fuel delivery and the timing of the images has to be determined. Earlier work of Seykens et al. [9] showed that elastic deformation of the CR injector needle is an important effect. There, a linear dependency of fuel pressure on elastic deformation of the fuel injector needle is found for a CR injector similar to the one used here. For fuel injection pressures used in this work, i.e. 103 (± 2) MPa an elastic deformation of 30% is estimated. Start of delivery is corrected for that, as the actual first spray tip cannot be seen because the fuel injector nozzle is covered by the thimble.
The, in this work so-called, soot luminosity lift-off length (SLOL) is determined from the Schlieren images. The SLOL is here defined by the visible luminosity of what is assumed to be originating mainly from soot (i.e. soot incandescence). Of course it is known from literature, e.g. the work of Higgins et al. [11], that soot illumination is not the best indicator of the most upstream location of the combustion zone. In the near future we will apply cut-off filters to detect chemiluminescence. The current results are therefore biased and depending on the sooting tendency of the fuels. The real lift-off location [11] will be further upstream. The fuel spray travels 3.77 mm before it exits the nozzle covering thimble. So the mean lift off length is determined by time averaging the images and localization of the point where the intensity has a steep increase up to overexposure of the camera.

Fuel and temperature impact on illumination ignition delay

Influence of density on temperature on illumination ignition delay (n.b. $\tau$) for FAME is shown in Figure 6, for a density of 16.5 (±0.3) kg/m$^3$. From the results it is clear that a higher gas temperature results in a shorter illumination ignition delay, but the influence of temperature decreases as it increases. Also at higher density a similar behaviour of illumination ignition delay is found. But now the temperature influence is much stronger. In literature, similar behaviour of decreasing illumination ignition delay due to increasing temperature or density was observed by for example Baert [14] and Higgins et al. [7].

Figure 6: Illumination ignition delay $\tau$, as a function of gas temperature, for two different densities (16.5 (±0.3) and 20.7 (±0.2) kg/m$^3$). The fuel used is FAME. $P_{CR} = 103 (±2)$ MPa.

Similar behaviour is obtained for the other fuels, as can be seen in Figure 7, which shows $\tau$ as a function of temperature, for a density of 16.5 (±0.3) kg/m$^3$ and in Figure 8, which shows $\tau$ as a function of temperature, for a density of 20.7 (±0.2) kg/m$^3$ it. All fuels, for both densities, do show a similar trend observed in Figure 6, but for IDEA fuel, although the observed trend is still visible, there is a considerable amount of scatter in the data. Between the fuels measured different results are obtained. Between EN 590 and FAME there is no clear difference in illumination ignition delay based on soot illumination. $n$-heptane has a relative long illumination ignition delay compared to EN 590 and FAME, but this difference decreases at higher temperatures. For IDEA the behaviour is almost similar to $n$-heptane, but the measurements at 1100 K show almost no difference in illumination ignition delay compared to EN 590 and FAME.

Figure 7: Illumination ignition delay $\tau$, as a function of gas temperature, for 4 different fuels (EN 590, FAME, IDEA and $n$-heptane). The density is 16.5 (±0.3) kg/m$^3$. $P_{CR} = 103 (±2)$ MPa.

Figure 8: Illumination ignition delay $\tau$, as a function of gas temperature, for 4 different fuels (EN 590, FAME, IDEA and $n$-heptane). The density is 20.7 (±0.2) kg/m$^3$. $P_{CR} = 103 (±2)$ MPa.
fuels shown become less obvious. The difference between EN 590 and FAME seems slightly bigger for these higher density experiments, resulting in a somewhat shorter illumination ignition delay for FAME compared to EN 590. A similar result was observed by Klein-Douwel et al. [14] in an optically accessible CI engine. So although the Cetane Index of all fuels is quite similar relative large differences in illumination ignition behaviour are obtained. Especially between EN 590 and IDEA there is a large difference, while both fuels should have similar ignition behaviour according literature. Of course the differences observed could be caused by the determination of the illumination ignition delay by observing first broadband light of soot illumination, instead of OH chemiluminescence, but the observed difference at for example 800 K is around 1.5 ms. Unfortunately no rate of heat release analysis could be performed, which could give a possibly better explanation for the observed differences. In the near future this will be added.

**Fuel and temperature impact on lift-off length**

Figure 9 shows the soot luminosity lift-off length (SLOL) as a function of temperature, for the 4 fuels tested. The gas density used in the experiments is 16.5 (±0.3) kg/m³. In general the behaviour of the SLOL is quite similar to that of the illumination ignition delay: decrease of temperature or density result in an increase of the SLOL. The influence of temperature is much more pronounced compared to the density influence, but this weakens at higher temperatures (> 900 K). These results are also similar to others like Higgins et al. [7]. Figure 9 also shows that the difference between EN 590 and FAME decreases as temperature rises. At lower temperatures IDEA shows similar SLOL’s compared to EN 590, but at higher temperatures IDEA has a shorter SLOL than EN 590. At every temperature n-heptane results in a significant longer SLOL compared to the other fuels tested.

At higher densities it seems that the differences between the fuels tested become less pronounced. This is shown in Figure 10 where the SLOL’s for the 4 different fuels are plotted as a function of temperature for a gas density of 20.7 (±0.2) kg/m³. Like in Figure 9 n-heptane has the longest SLOL. There is no clear difference in SLOL between the other fuels tested.

Figure 10: Soot luminosity lift off length, as a function of gas temperature, for 4 different fuels (EN 590, FAME, IDEA and n-heptane). The density is 20.7 (±0.2) kg/m³. $P_{CR} = 103$ (±2) MPa.

If the results for SLOL are combined with the illumination ignition delay results the different fuels tested can be distinguished better.

Figure 11 shows the SLOL as a function of illumination ignition delay $\tau$ for 4 different fuels (EN 590, FAME, IDEA and n-heptane). The density is 16.5 (±0.3) kg/m³. $P_{CR} = 103$ (±2) MPa.

Figure 11 shows the SLOL as a function of illumination ignition delay $\tau$ for 4 different fuels at a gas density of 16.5 (±0.3) kg/m³. In general, no clear difference in SLOL is observed below 0.5 ms illumination ignition delay, but this changes above 0.5 ms. For FAME the
longest SLOL for a given illumination ignition delay above 0.5 ms is measured. For illumination ignition delays shorter than 1 ms, n-heptane and EN 590 show quite similar SLOL. Above 1 ms n-heptane gives a longer SLOL compared to EN 590. IDEA has the shortest SLOL above 0.5 ms, compared to the other fuels tested.

In Figure 12 a similar data comparison as in Figure 11 is shown, but now for a gas density of 20.5 (± 0.2) kg/m³. As already observed for illumination ignition delay and SLOL separately, the differences between the fuels tested become much less pronounced at higher gas density. Only IDEA differs clearly from the other fuels and has clearly the shortest SLOL for a given illumination ignition delay.

Possible cause for the longer SLOL’s for FAME, observed best in Figure 11, is that FAME results in a longer liquid length due to its higher latent heat of vaporization and T₉₅ [15] compared to the other fuels tested. IDEA has the shortest SLOL.

Conclusions

The illumination ignition delay and broadband soot lift-off length (SLOL) were determined for 4 fuels with a Cetane Index between 51 and 57 at engine like temperatures and densities. Both illumination ignition delay and SLOL decrease for increasing temperature or density. The influence of temperature on illumination ignition delay and SLOL is the strongest, but this levels off for temperatures above approximately 900 K, as found by others [7]. Although the Cetane Indexes of the fuels were reasonably comparable, large differences between the fuels in illumination ignition delay were found. Apparently there can be a large difference in illumination ignition delay between fuels which have a comparable start of auto-ignition (e.g. Cetane Index).

The results also suggest a strong dependence on SLOL, at equal illumination ignition delays, by fuel related molecular structure effects, especially at lower densities. For future research on this topic, rate of apparent heat release analysis and the use of OH chemiluminescence are necessary, supported by observations made in the optically accessible Diesel engine of the Radboud University Nijmegen [14].

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References