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# Combustion and soot processes of diesel and rapeseed methyl ester in an optical diesel engine

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## HIGHLIGHTS

- The magnitudes of FLoL and SLoL are longer for RME compared to ULSD.
- Longer FLoL, presence of fuel-bound oxygen and zero aromatics in RME reduces soot.
- Formation of vortex structures leads to spay to spray ignition fluctuations.
- Un-oxidised soot left at the end of visible luminous combustion is less for RME.
- The size of RME generated soot is relatively of smaller size compared to ULSD.

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## ABSTRACT

In-cylinder combustion and soot processes for ultra-low sulphur diesel (ULSD) and rapeseed methyl ester (RME) fuels were investigated in an optically accessible high speed direct injection diesel engine (HSDI) using in situ optical and laser measurement techniques. High speed imaging techniques were used to study the spatial distribution of spray flames, soot formation and oxidation through simultaneous measurements of $OH^*$ chemiluminescence and natural soot luminosity, during the luminous combustion process. The amount of un-oxidised soot left in the cylinder after the end of luminous combustion for these fuels were investigated using planar laser induced incandescence (PLII). In addition to PLII, time resolved laser induced incandescence (TR-LII) technique was used simultaneously to explore crank angle resolved variation of primary soot particle size during the expansion stroke. The ignition for RME occurs earlier compared to ULSD, and the early phase of RME combustion proceeds quicker compared to ULSD. The flame lift off length (FLoL) and the length based on the first appearance of soot (SLoL) are longer for RME. The combined effect of relatively longer FLoL and the presence of fuel-bound oxygen reduced the overall soot formation process for RME. PLII data confirmed that the relative amount of soot left in the cylinder after the end of visible luminous combustion is less for RME, and the soot formed are oxidised well within the combustion chamber before it is exhausted out of the engine compared to ULSD. The measured in-cylinder primary soot particles are in the size range between 15 and 35 nm and it decreases with crank angle. The sizes of particles generated from the combustion of RME were slightly smaller compared to ULSD.



## 1. Introduction

Diesel engines account for a major percentage of passenger car market in Europe because of their higher thermal efficiency and lower fuel consumption. However, increasingly stringent exhaust emission regulations, particularly for $NO_x$ and PM require most diesel vehicles to be fitted with more complex and expensive exhaust gas after treatment systems, which also contribute to higher fuel consumption. Various EU incentives and mandates would require up to 45% of bio-components in the fossil fuel by the year 2030 [1]. For automotive applications, it has been shown that bio-fuels in the form of pure plant oils cannot be effectively used in diesel engines because of technical problems arising from their relatively higher viscosity, corrosive nature and increase in exhaust smoke emissions [2–4]. However these oils can be used in diesel engines after removing the glycerol components and this can be achieved by transesterification, in which the plant oil is converted to Fatty Acid Methyl Ester (FAME) (or in some cases a Fatty Acid Ethyl Ester). The most commonly used bio-diesel in Europe is

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Rapeseed Methyl Ester (RME), which contains more oxygen than ultra-low sulphur diesel fuel (ULSD). It has been shown through several investigations that the exhaust soot emissions are lower for biodiesel compared to ULSD [5–7]. The presence of oxygen content in fuel is beneficial for the reduction of exhaust soot emissions. The presence of chemically bonded oxygen in biodiesel causes relatively higher oxygen content in fuel spray, which results in reduced oxygen equivalence ratio in the fuel rich regions of the jet and this alters the rate of formation of soot precursors and the overall soot formation process.

Several investigations have been performed to study combustion and soot processes in a constant volume chamber at high pressure and high temperature ambient conditions [8–10] and also in optical diesel engines [11–13]. In-cylinder investigations have led to the proposal of several conceptual models that helps in the understanding of diesel spray combustion process [14–16]. It has been shown that ignition takes place in the regions where the temperatures of the reactive fuel air mixtures are high with favourable equivalence ratio. The initiated flame consumes the fuel-vapour-air mixture and stabilizes at a distance downstream of the nozzle tip, and the distance from the nozzle tip to the first appearance of flame is defined as lift off length (LoL). The high temperature reaction zones in flame are normally characterised by the presence of OH radicals. The chemiluminescence emitted from OH radicals is detected at their respective emission wavelengths through spectrally resolved measurements [17]. These $OH^*$ radicals are used as markers to determine the location of the flame and the flame lift-off length [18]. These radicals also contribute to the oxidation of soot that is produced during the high temperature combustion process [19,20]. The mixture downstream of LoL is premixed and the heat release in this region is quite rapid. Further downstream the mixtures are rich, which results in soot formation and growth in the central region until the tip of the flame [21,22]. At the periphery of the spray flame the oxygen concentration is high where soot oxidation occurs, fast oxidation at the periphery minimises entrainment downstream of the LoL. Thus LoL is strongly related to the amount of oxygen in the fuel-rich core which controls the soot processes in spray flames, longer flame LoL allows more entrainment of air into the fuel jet, which results in less fuel rich regions and reduced soot generation. Amongst other parameters, the flame lift off length is also dependent upon the nozzle hole diameter, injection pressure, injection velocity, ambient density, ambient temperature and fuel properties [21–24]. Once all the premixed oxygen is consumed in spray flame, fuel undergoes rapid pyrolysis and further oxidation with surrounding air in the mixing-controlled combustion phase. The soot formed during the combustion process in optical engines are investigated by determining natural soot luminosity using high speed imaging techniques [11–13]. Challenges associated with the measurement of natural flame luminosity, signal interpretations and their relation to in-cylinder soot concentration are presented in [13]. Besides high speed imaging, in-cylinder soot processes have also been explored through non-intrusive laser diagnostics. Laser Induced Incandescence (LII) and Time Resolved Laser Induced Incandescence (TR-LII) are generally used for measuring soot volume fraction, and primary soot particle sizes [25,26]. The LII techniques have been successfully applied to study soot processes in flames [27–31] as well as in internal combustion engines [32–36]. Combined PLII and TR-LII techniques were used for characterisation of soot emitted during combustion of laminar diffusion flame at atmospheric pressure and in an optical diesel engine [25]. It has been shown that the soot volume fraction increased after the start of combustion and reached a maximum at about 10° aTDC and decreased thereafter with crank angle during the expansion stroke. The measured soot particle sizes also had a similar trend to that of the soot volume fraction as reported in [32–35]. Attempts were made to quantify the measured soot particle size and number density in an optical diesel engine by using LII and laser induced scattering (LIS) techniques simultaneously [37]. The same measurement technique (LII and LIS) was used to study the spatial distribution of particle size and its number density distribution in spray flames, in a rapid compression machine [38]. High number densities of smaller sized particles were detected in the central part of the spray flame, while a reduced particle number density and increased size of particles were observed in the regions downstream of the jet. It can be seen that more physical parameters can be elucidated through the use of two or three measurement techniques simultaneously.

In order to understand and control the formation of soot, a detailed insight into the spray development, combustion and soot processes are essential. In this investigation, in-cylinder processes for renewable oxygenated fuel and non-oxygenated fossil fuel were explored in an optical engine during and after the high temperature visible luminous combustion. High speed imaging technique was used to explore crank angle resolved $OH^*$ chemiluminescence and natural soot luminosity simultaneously during the stages of high temperature luminous combustion. The un-oxidised soot that was left within the combustion chamber after the end of the high temperature luminous combustion was explored using time resolved laser induced incandescence (TR-LII) and planar laser induced incandescence (PLII) techniques simultaneously to measure soot particle size and the soot volume fraction.

## 2. Experimental set-up

The schematic of the experimental set-up used in this work is shown in Fig. 1 and the engine specifications are detailed in Table 1. The measurements were performed in a single cylinder Ricardo Hydra optical engine. The intake air temperature was raised to approximately 85 °C and it was supercharged to 0.12 MPa to simulate thermodynamic diesel engine conditions.

A Kistler 6125 piezoelectric transducer was used for in-cylinder pressure measurements and the data was recorded at a resolution of 0.2° crank angle. A common rail fuel injection system controlled by an EmTroniX system provided the ability to precisely control the injection timing and the quantity of injected fuel. The combustion chamber was optically accessible through a window mounted at the base of the piston and through three rectangular windows fitted in the upper part of the cylinder block. Before each engine run, the engine was preconditioned and care was taken to maintain the same temperatures during each set of measurements. In-cylinder combustion processes were visualised through a flat piston window, 45° mirror placed below the piston and to the imaging device. The high speed images were recorded using a high speed camera (Memrecam FX 6000 coupled with DRS intensifier ILS-3-11

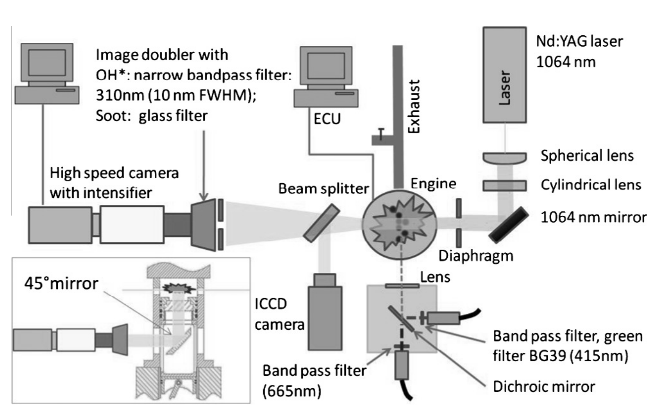


**Fig. 1.** Schematic of experimental test facility, side view is presented in the left bottom corner.