

Laser-Induced Incandescence Measurements of Tailor-Made Fuels in an Optical Single-Cylinder Diesel Engine

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ABSTRACT

The influence of two oxygenated tailor-made fuels on soot formation and oxidation in an optical single cylinder research diesel engine has been studied. For the investigation a planar laser-induced incandescence (PLII) measurement technique was applied to the engine in order to detect and evaluate the planar soot distribution for the two bio fuels within a laser light sheet. Furthermore the OH* chemiluminescence and broad band soot luminosity was visualized by high speed imaging to compare the ignition and combustion behavior of tested fuels: Two C8 oxygenates, di-n-butylether (DNBE) and 1-octanol. Both fuels have the same molecular formula but differ in their molecular structure. DNBE ignites fast and burns mostly diffusive while 1-octanol has a low cetane number and therefore it has a longer ignition delay but a more homogeneous mixture at time of ignition. The two bio fuels were finally compared to conventional diesel fuel.

The heat release reactions after ignition by means of the OH* chemiluminescence showed the fast igniting behavior of DNBE, with soot formation being delayed. The soot formation for DNBE was very similar to that of conventional diesel fuel. However, the amount of soot formed is lower and starts oxidizing earlier in the cycle according to the PLII signal. The OH* chemiluminescence signal of 1-octanol on the other hand shows a rapid burn out in the combustion chamber. Due to the homogenous mixture, hardly any soot formation takes place.

CITATION: Klein, D. and Pischinger, S., "Laser-Induced Incandescence Measurements of Tailor-Made Fuels in an Optical Single-Cylinder Diesel Engine," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-0711.

INTRODUCTION

Alternative fuels have become a major topic in current research. At the RWTH Aachen University a so called Cluster of Excellence on "Tailor-Made Fuels from Biomass" was established in 2007. The aim is to develop a highly efficient process to produce a fuel from biomass which helps to significantly reduce engine out emission. In the recent years a variety of fuel candidates have been developed. [1]

This study focused on two C8 oxygenates: di-n-butylether (DNBE) and its isomer 1-octanol. Both fuels feature the same amount of C, H and O molecules, however in a different structure, resulting in different properties, see Figure 1. Both fuels differ in their viscosity, with 1-octanol having a more appropriate viscosity for diesel engine operation. The derived cetane number (DCN) is the other major difference. DNBE has a high DCN of about 115, while 1-octanol has rather low DCN of 34. As reference conventional EN590 diesel fuel was measured. In Table 1 the main properties of the fuels are listed.

Both fuels can be produced from lignocellulosic biomass. Therefore their feedstock does not stand in direct competition with the need to grow food and feed plants. DNBE can be synthesized via etherification of n-butanol [2]. 1-octanol can be produced from furfural and acetone [3].

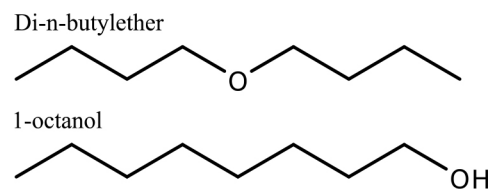


Figure 1. Molecular structure of DNBE and 1-octanol.

The fuels were previously investigated on a thermodynamic single cylinder diesel engine by Heuser et al. [2,4]. The study analyzed the fuels at multiple operation points. For 1500 min⁻¹ and 6.8 bar IMEP at EU6 NO_x emission level of 0.2 g/kWh, it was shown that with both fuels, DNBE and 1-octanol, the soot emissions were significantly reduced compared to diesel fuel. Furthermore, 1-octanol led to an increase in HC emissions, while DNBE helped reducing CO emissions compared to diesel fuel. The analysis of the pressure trace showed the low reactivity of 1-octanol, causing a higher share of premixed combustion due to the long time for mixture formation, resulting in a higher combustion noise level. For DNBE, the pressure trace showed the very high reactivity, resulting in an earlier start of combustion and a very mixing-controlled combustion. The parameters of this operation point were used in the present study and are described in detail in the section "Engine Setup".

Table 1. Properties of investigated fuels 20 °C (s. [2] and references therein)

	Unit	Diesel	di-n-butylether (DNBE)	1-octanol
Molecular formula	-	-	C ₈ H ₁₀ O	C ₈ H ₁₀ O
Boiling temperature	°C	180-350	141	195
Heating value	MJ/kg	42.9	38.2	38.2
Density	kg/m ³	833	770	830
Cetane number	-	53	115*	34*
Oxygen content	m-%	0.14	10.3	10.3
Vapor pressure	Pa	< 100	640	12.5
Surface tension	mN/m	20.5	22.2	27.5
Dynamic viscosity	MPa s	3	0.64	5.8
Enthalpy of vaporization	kJ/kg	358	341	562

* Derived cetane number

Measurements in a high pressure spray vessel by Jakob et al. [5] investigated the mixture formation, ignition and combustion behavior of DNBE and 1-octanol among other fuels. The study was conducted under quiescent conditions closely related to the conditions found in the aforementioned study on the thermodynamic single cylinder engine [2] around top dead center (TDC), albeit in air. It showed that DNBE has a lower liquid penetration length and ignites with a lower lift-off length compared to 1-octanol, diesel and other fuels. The ignition stability is furthermore a lot higher compared to 1-octanol which did not ignite in all of the investigated injection cycles.

Recently the mixture formations of 1-octanol and DNBE were investigated by Hülser et al. [6] using tracer LIF in the same optical single cylinder diesel engine used for the present study. They focused on a low part load operation point with 1200 min⁻¹ and 2.6 bar IMEP investigating the source of higher HC and CO emissions for 1-octanol found in [2]. They found that after injection of 1-octanol, the spray impinged heavily on the piston bowl wall. From there on, the spray was redirected back inwards before it eventually vaporized and formed a ring with a near stoichiometric, homogeneous mixture. The first cold flame reactions took place in this zone.

In the present study, an optical single cylinder diesel test bench was employed. The fuels were investigated by means of OH* chemiluminescence, soot luminosity and planar laser-induced incandescence (PLII) to visualize the ignition, combustion and soot formation behavior of 1-octanol, DNBE and conventional diesel.

EXPERIMENTAL SETUP

Engine Setup

The optical engine was based on an all metal thermodynamic single cylinder test bench, using an identical injection system and being approximately equal with regard to the combustion chamber geometry. In Table 2 the specifications of the engine are shown. Further information can be obtained from [7, 8, 9].

A sketch of the general imaging setup for the optical engine and the shape of the optical piston bowl is provided in Figure 2. The resulting field of view is shown in Figure 3. The optical engine was equipped with an elongated piston and an ω-shaped silica glass piston bowl. The curvature of the central bowl surface of the optical engine was reduced compared to typical ω-shaped piston bowls, in order to avoid strong optical distortion of the images. However, the piston crown still caused spherical image distortion. Therefore, additional image post processing steps were required. The in-cylinder phenomena were visualized via a fixed mirror in the clearance of the elongated piston.

Table 2. Optical Single Cylinder Engine Specifications

	Unit	
Displacement	cm ³	390
Stroke	mm	88.3
Bore	mm	75
Compression ratio	-	13.5
Max. injection pressure	bar	2000
Nozzle	-	8 x 153°
Hydraulic flow rate	cm ³ / 30 s	310
Max. peak pressure	bar	100
Max. engine speed	min ⁻¹	1500

In order to avoid contact between the piston rings and the inner surface of the window cassettes, the fireland height was increased. Therefore, the compression ratio was about 13.5, while the compression ratio of the thermodynamic engine was about 15. The resulting effect on combustion and in particular unburnt hydrocarbon (HC) emissions is weak for high-speed direct injection engines with combustion in the piston bowl and the injection close to top dead center (TDC) of combustion according to Aronsson et al. [10]. Due to the lowered compression ratio, the intake temperature and pressure was adjusted. Accordingly, the intake pressure on the optical engine was about 0.7 bar higher, while the intake temperature was about 25 K higher, so that the in-cylinder pressure rise in the range from 0 °CA to 5 °CA was approximately equal for both engines. This method was used in previous publications [8,9], and is as well discussed in detail in [10, 11, 12].

The optical diesel engine was fired for a limited number of cycles, before soot deposits impaired the quality of the optical diagnostics substantially. Due to this limitation, all operating conditions like engine lubricant temperatures, engine speed, intake temperature, and pressure had to be adjusted prior to the first fired cycle. Cooling water and oil temperature were conditioned to 90 °C. Unlike previous publications [8,9], both not skipped fired and skipped fired operation were used in this study (see the subsections on the optical setup for more information).

Since the limited number of fired cycles of the optical diesel engine was insufficient to enable a controlled exhaust gas recirculation (EGR), a second engine operating on burning diesel fuel was used to provide external EGR. The exhaust gas of this engine was mixed with the intake air of the optical engine before entering the supercharger. The concentration of CO₂ in the intake was used as a measure of the inert gas concentration.

The close comparability of the optical and thermodynamic engine allowed the usage of optimized operating parameters from the thermodynamic to the optical engine. These enabled the operation of the optical engine with realistic boundary conditions at EU6 NO_x level. The operation point investigated was at 1500 min⁻¹ and 6.8 bar IMEP. In order to reach the aforementioned emission level, the CO₂ concentration was set to about 4.5 %, resulting in an O₂ concentration of about 15 % and equaling an EGR rate of about 50 %. The resulting NO_x emissions were 0.2 g/kWh or 40 ppm respectively. The injection timing was adjusted such that all fuels had the same constant center of combustion of 5.8 °CA aTDC, i.e. the °CA where 50 % of the injected fuel mass had been converted was identical. Note that the EGR rate was higher compared to previous publications [8,9], where an EGR rate of approximately 38 % was used resulting in a NO_x emission level of 0.5 g/kWh. Operating conditions and parameters used for engine operation can be found in Table 3.

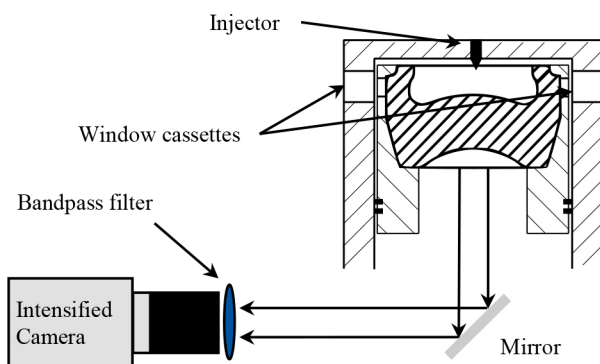


Figure 2. General imaging setup.

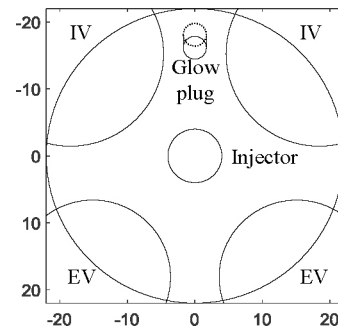


Figure 3. Field of view and description of parts seen within. Dimensions in mm.

Table 3. Operating conditions and parameters per fuel for engine operation

	Unit	Fuel		
		Diesel	DNBE	1-octanol
Speed	min ⁻¹	1500		
Load	bar	6.8		
Rail pressure	bar	910		
Start of Energizing	°CA aTDC	-8.1	-7.0	-9.5
Duration of Energizing	μs	406	447	409
EGR rate	%	48.7	46.6	47.8
CO ₂ Int. Manifold	%	4.78	4.43	4.42
NO _x Emissions	g/kWh	~0.2		

In the soot luminosity and OH* chemiluminescence investigations, a glow plug was installed but not operated. Its position is displayed in Figure 3. The glow plug was removed for the PLII investigations as it would have interfered with laser light sheet.

Optical Setup

Soot Luminosity

Soot luminosity is the broadband thermal radiation from hot soot particles [13]. It is dependent on the local soot volume fraction and the temperature of the soot [13]. Notably, soot luminosity is the dominant source of radiation during conventional diesel fuel combustion [14]. As it is a line-of-sight measurement, it helps identifying if hot soot is formed during combustion and if where.

An intensified high-speed camera (LaVision HS-IRO and Photron SA1) was employed to visualize soot luminosity. The incoming combustion light was filtered using an RG570 filter, which blocks the transmission of wavelengths below 570 nm. The camera was operated with a framerate of 18 kHz, corresponding to a temporal resolution of 0.5 °CA. Furthermore, the engine was operated in a non-skip fire mode. An overview of the setup and used settings can be found in Table 4.

Table 4. Optical measurement setup

	Soot luminosity	OH* chemi-luminescence	Laser-induced incandescence
Camera	Photron SA1		pco. 1600
Recording rate	18 kHz	18 kHz	1.56 Hz
Resolution	512x512	512x512	1600x1200
Recorded cycles	100	100	50
Image intensifier	LaVision HS-IRO		LaVision IRO
Gate	40 μ s	40 μ s	70 ns
Gain	23 %	68 %	75%
Lens	Nikon UV (f = 105 mm)		Nikon (f = 105 mm)
Filter	RG570	DUG11X + BP313	BP450
Laser	-		Litron Lasers Nano L 120-10 PIV
Wavelength	-		1064 nm
Pulse energy	-		100 mJ
Pulse duration	-		10 ns

OH* Chemiluminescence

Chemiluminescence is the emission of a photon from combustion radicals as they relax from excited electronic states after being raised from chemical reactions [13,15]. The chemiluminescence signal is typically 4 to 5 orders smaller in magnitude than soot luminosity in conventional diesel fuel combustion as shown by previous work from Dec and Espey [14]. In this work, the chemiluminescence of the OH* radical was used. Its signal is not associated with the first cold flame reactions [14] but with the second stage of ignition, when H₂O₂ is rapidly decomposed to OH at temperatures about 1000 K, which consequently is being consumed with fuel [16]. Therefore the visualization of OH* chemiluminescence reveals the areas where the second stage ignition occurred and combustion of fuel takes place.

The OH* chemiluminescence was being visualized using the same intensified high-speed camera as in the soot luminosity visualization. The light was filtered using a combination of DUG11X and BP313, as described by Pauls et al. [17]. The filter combination has its maximum transmission at 313 nm with a bandwidth of about 20 nm. The maximum transmission is about 65 %, whereas it is lower than 10⁻⁵ in the wavelength range of 400-1000 nm. Similar to the soot luminosity imaging, the camera was operated with a framerate of 18 kHz and the engine was operated in a non-skip fire mode. An overview of the setup and used settings can be found in Table 4.

The influence of soot luminosity on the OH* chemiluminescence visualization was weak in the present study. Donkerbroek et al. [18] estimated the soot temperatures to be below 2000 K for similar O₂ intake concentrations as in the present study. As the soot luminosity signal is highly dependent on flame temperature as shown by Mueller and Martin [19] and proportional to black body radiation, the signal within the bandpass of the used filter combination was expected to be very low. Furthermore, the study investigated the reaction zones, wherein no cross-talk was expected. As shown in the results section, the soot signal here trailed the OH* signal.

Planar Laser-Induced Incandescence

With laser-induced incandescence (LII) a pulsed laser heats up the soot particles to a common temperature and the subsequently emitted photons are being captured. This signal, unlike soot luminosity, is independent of soot temperature, allowing the direct comparison regarding soot volume fraction. The soot volume fraction has been shown to be directly correlated with the LII signal by the work of Melton [20]. However, in order to quantify the soot volume fraction, a reference is needed from another measurement technique. A review of LII models and experiments can be found in [21,22]. As shown by [21,23, 24, 25, 26, 27], it is important to avoid an excitation wavelength in UV and visible range of light to avoid fluorescence and/or absorption of laser light by other species than soot.

For the PLII measurements, an Nd:YAG laser (Litron Lasers Nano L 120-10 PIV) at 1064 nm was used. The laser beam was formed to a sheet with a width of about 8 mm and a thickness of about 0.7 mm by a cylindrical lens and a spherical lens. As the window acted as a concave lens, a further lens was used close to the window to counter the diverging effect. The laser pulse energy was about 100 mJ, resulting in about 1.8 J/cm². The energy was therefore sufficient to reach the plateau regime, i.e. variation of the laser fluence had hardly any influence on the PLII signal. Thus the soot particles should reach a common temperature, which allowed a direct qualitative comparison of the PLII signals for the different fuels. The complete PLII setup is depicted in Figure 4, the position of the laser light sheet in the piston bowl and the field of view are illustrated in Figure 5. The laser light sheet was 8 mm below the combustion chamber roof. The LII signal was captured using an intensified CCD camera (LaVision IRO and pco. 1600) and filtered with a 450 nm filter with a bandpass of 10 nm and a transmission of about 85 %. Furthermore, the image intensifier was operated with a gate of 70 ns, helping to significantly reduce background signal from natural combustion luminosity.

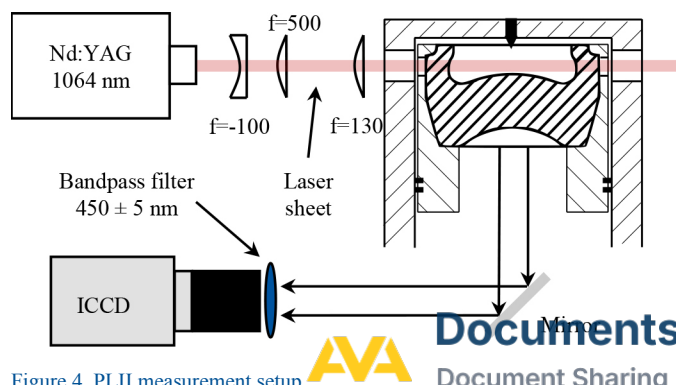


Figure 4. PLII measurement setup.