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Application of optical diagnostics to the quantification of soot in *n*-alkane flames under diesel conditions

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ABSTRACT

In the present paper, three different soot-measuring techniques, namely laser extinction method (LEM), 2-color pyrometry (2C) and laser-induced incandescence (LII) have been simultaneously employed to characterize soot distribution inside a diesel flame. Two single-component fuels (*n*-Decane and *n*-Hexadecane) and two derived blends (50%Dec/50%Hex and 30%Dec/70%Hex) have been used. Tests have been performed at an optical diesel engine, under different in-cylinder conditions. The study has been complemented with the measurement of ignition delay and Lift-off length.

The present work pursues a twofold objective. On the one hand, the effect of fuel properties on soot formation has been analysed, under different engine operating conditions. On the other hand, sensitivity and performance of the three optical techniques has been evaluated, identifying their main advantages and drawbacks in the framework of the current study. LEM has been considered as the reference technique, as the measurement principle can be implemented without important limitations associated to the other two. Results highlight that larger molecules produce more soot than the smaller ones, with both reactivity and soot formation changing with the proportion of the heavier fraction. Despite describing similar trends, LEM and 2C do not provide the same KL values, with the pyrometry reaching some sort of saturation when increasing flame soot. A detailed analysis confirms that 2-Color measurements are strongly biased by soot and temperature distribution inside the flame. Nevertheless, it could still be a good option for low sooting conditions. On the other hand, an attempt to calibrate LII signal by means of LEM measurements has been reported. This approach should make it possible to obtain additional information on the soot spatial distribution. However, inconsistencies have been identified which stem from the inherent limitations of LII technique in highly sooting conditions.

1. Introduction

Optical diagnostic techniques have been traditionally used to improve the insight on the basic phenomena that dominate combustion within internal combustion engines. In particular, the characterization of the soot formation during combustion is a challenging topic, as it involves complex physical and chemical processes that dominate both formation and later oxidation [1,2]. Three main optical techniques can be found in the literature for the study of this topic: Laser-induced incandescence (LII), 2-Colour Pyrometry (2C) and laser extinction method (LEM). They have been applied traditionally to diesel flames, but they present certain advantages and drawbacks that must be considered before choosing the most suitable tool for each specific study.

LII is based on recording the high intensity radiation emitted by soot particles that are previously heated by a laser pulse. The magnitude of the signal can be correlated with the volume fraction of particles in the detection region. This technique has been used extensively for qualitative [3–6] and even quantitative measurements [7–9]. However, quantitative measurements require a firm understanding of the factors that influence the LII signal, which are detailed in [10]. As an intermediate step, calibration of LII signal with LEM measurements is quite often employed [11–16], in theory should make it possible to derive 2D soot volume fraction distributions. This approach, however, does not solve the inherent limitations of LII related to radiation attenuation processes within the flame.

2-Colour Pyrometry is based on the detection of the spontaneous thermal radiation emitted by incandescent soot particles at two different wavelengths. The technique makes it possible to obtain not only the soot distribution but also the corresponding temperature. Moreover, modern high-speed cameras offer a high time resolution. This technique has been widely used by the diesel engine research

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community [17–27]. However, the analysis of results does not always consider the intrinsic limitations of the technique [22,23].

While 2C and LII could be strongly affected by the interaction of emitted radiation with other soot particles within the flame, the third technique, LEM, is just based on this property. The attenuation can be related to the optical thickness of the soot cloud and, eventually, to the soot volume fraction. This technique has been widely used in single diffusion flames [[28]–[31]] and, with the proper considerations [30], reliable results can be obtained. LEM applications are based on point measurements along the flame, using a small laser beam. It allows high time resolution but it is spatially limited by the beam size. However, nowadays applications start to appear where a larger light source is combined with high-speed cameras, offering both good spatial and time resolution [32].

In the present work, the three techniques (LII, 2C and LEM) have been proposed to characterize soot formation under diesel engine conditions. They have been applied simultaneously, to evaluate the effect of physical and chemical properties of two single-component surrogates (*n*-Decane and *n*-Hexadecane) and two derived blends. The analysis of experimental results will make it possible to fulfil a twofold objective: firstly, describe the effect of fuel properties over soot formation; secondly, identify the strengths and limitations of each methodology. The first part of the paper presents a detailed description of the experimental apparatus and procedure. Then, a comparison among results obtained by each technique is presented. Trends and numerical results are analysed and discussed, trying to clarify the main differences observed. Finally, the main conclusions regarding the influence of fuel properties and the optical techniques, together with recommendations for the proper use of these experimental tools, will be summarized.

2. Experimental methodology

2.1. Experimental test bench

All the tests have been performed at an optically accessible single cylinder engine, which is described in detail in [33]. The facility is based on a 2-stroke single cylinder direct injection diesel engine (Jenbach JW 50), with 3 L displacement and 15.7 effective compression ratio. It is motored at low engine speed (500 rpm). Intake and exhaust processes are handled by transfers on the liner and the cylinder head is specially designed to provide optical access to the combustion chamber. A cylindrical combustion chamber was designed in a way that spray wall impingement is avoided. The chamber has an upper port where the injector can be mounted and four lateral accesses. A pressure transducer is installed in one of the accesses, whereas the other three are equipped with oval-shaped quartz windows, 88 mm long, 37 mm large and 28 mm thick. A cutaway view of the cylinder head is depicted in Fig. 1. The cylinder head and the engine temperature are controlled by means of coolant recirculation. Their temperature was set to 353 K, to guarantee a good performance of the lubricant oil.

In-cylinder thermodynamic conditions during the cycle are controlled by the intake air temperature and pressure. The first one is regulated by two sets of electrical resistors, while the desired intake pressure is achieved thanks to a compressor that is fed with ambient air. The engine is operated under skip-fired mode, so that in-cylinder conditions are not influenced by the remaining residual gases from previous combustion cycles. An injection takes place each 30 cycles, which guarantees that ambient conditions are kept constant between consecutive repetitions and temperature transients are avoided.

A common-rail injection system is used, together with a single-hole piezoelectric injector with a 140 μm outlet diameter nozzle. The injector hole is 1 mm long with conical shape (Ks factor of 1.5). The injected mass is so low that thermodynamic conditions inside the combustion chamber are barely affected by the fuel evaporation [24]. Due to the low injection frequency used during tests, the injected fuel initial temperature can be considered the same.

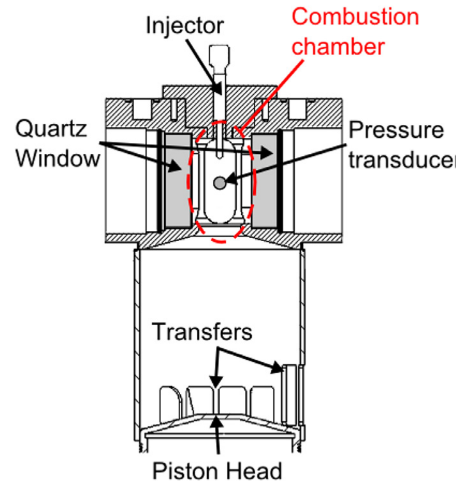

Fig. 1. Cutaway view of the cylinder head layout.

Table 1
Fuel properties.

Fuel	Density at 373 K [Kg/m^3]	Formula	Derived Cetane number	C–C bonds	H/C
n-Decane	669.2	$C_{10}H_{22}$	65.9	9	2.198
50Dec/50Hex	693.9	–	82.2	11.37	2.160
30Dec/70Hex	703.7	–	85.4	12.56	2.146
n-Hexadecane	718.5	$C_{16}H_{34}$	92.9	15	2.123

2.2. Experimental procedure

Two single-component fuels have been used, namely *n*-Decane and *n*-Hexadecane, together with two derived binary blends: 50%Decane/50%Hexadecane and 30%Decane/70%Hexadecane (percentages in mass). The main advantage of using such simple fuels is that it is expected that they will form less soot than other fuels like commercial diesel, thanks to the absence of ring or branched structures as well as sulphur [2]. The most relevant properties of the fuels for the purposes of this work are given in Table 1.

The full test matrix comprises a combination of two in-cylinder top dead centre (TDC) temperature values (800/900 K) with three different TDC pressure values (4.3, 5.3 and 7.3 MPa) and three injection pressures (50/100/150 MPa). In-cylinder thermodynamic conditions (Fig. 2, right) have been calculated from measured in-cylinder pressure, using a first-law thermodynamic analysis as it can be found in [[31], [33]]. The model takes into account blow-by, heat losses and mechanical deformations. The trapped mass is estimated using the intake temperature and volume at the exhaust vent close. Then, temperature along the engine cycle can be calculated using the equation of state and correcting the trapped mass with blow-by estimations.

As previously mentioned, three different optical techniques have been applied simultaneously to measure soot formation inside the flame. The injector energizing time was set to 3 ms (9 CAD) for all conditions, which results in an approximate 6 ms (18 CAD) real injection duration, considering electrical and hydraulic delays. The injector was triggered at 6 CAD before TDC (SoE), while the injection started at approximately 5 CAD before TDC (SoI), so that the variations of the in-cylinder thermodynamic conditions during the injection event were minimized. The 2-color pyrometry and laser extinction method are able to measure the soot formation during the whole combustion event, thanks to the high sampling rate of the