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An experimental study of the effects of fuel properties on reactive spray evolution using Primary Reference Fuels

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HIGHLIGHTS

- Six different binary blends of PRFuels were tested under different conditions.
- Spray penetration, lift-off length, ignition delay and soot radiation were measured.
- Ignition time and lift-off length were increased with increasing iso-octane.
- A momentum-controlled scaling law for stabilized flame length was validated.

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ABSTRACT

An experimental study on the ignition and combustion of diesel-type sprays using *n*-heptane, *iso*-octane and four intermediate blends is presented. The choice of components was done in order to represent the transition from conventional diesel fuel (*n*-heptane) to a gasoline-like one (*iso*-octane) in terms of ignition behavior. The experiments have been carried out in a high pressure high temperature vessel using specifications from the Engine Combustion Network (ECN). Parametric variations of oxygen concentration and air temperature have been performed for each fuel. In order to investigate the spray development, schlieren imaging for the quantification of spray penetration and ignition delay, OH^* chemiluminescence imaging for the lift-off length, and broadband radiation imaging for the soot intensity and flame length have been applied. The results show the large effect of mixture reactivity on the ignition times and lift-off length values. Regarding the effect of the octane number of the blends on the ignition delay times, a linear effect has been found in the lower half of the blend range, while an exponential trend is evident in the top one. On the other hand, a scaling law for the stabilized flame length based upon momentum-controlled assumptions has shown that results are comparable to those obtained in the literature. Finally, the applicability of the results obtained on the performance and efficiency in real engines is discussed.

1. Introduction

The role of fuel properties on diesel engine performance and emission has been an active field of research for a long time. In recent years, more detailed studies in combustion vessels have helped understanding the fundamental processes dealing with fuel effects on spray development and combustion. Different fuel types are within research focus, such as bio-diesel, synthetic Fischer–Tropsch fuels, oxygenated fuels, diesel–gasoline blends and surrogate fuels, to mention a few. The end goal has been the matching of different combustion strategies and fuel types to improve the engine efficiency and reduce the emission of pollutants. For example, a study with direct diesel injection and port gasoline injection showed that the higher amount of gasoline retarded the combustion phasing. This in turn lowered the heat transferred and allowed for the lowest fuel consumption, which also resulted in low NO_X and *PM* emissions [1]. Another study replaced entirely the diesel fuel with gasoline and also obtained less specific fuel consumption together with lower smoke levels [2]. Blends of gasoline and ethanol have also been used in diesel engines in order to study the effects on combustion and reduce the amount of diesel injected [3]. Results have shown reduction of soot levels, but at the cost of higher NO_X and compromised combustion stability under some conditions. Furthermore, a similar study with blends and changes in the contour conditions also presented improvements in the combustion efficiency [4].

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Among the most used fuels used for the evaluation of diesel-gasoline blends are those known as Primary Reference Fuels (PRFs), which represent both ends of the octane rating scale, namely *n*-heptane ($ON = 0$) and *iso*-octane ($ON = 100$). Such a difference in octane (and thus cetane) numbers makes them good representatives of diesel and gasoline, respectively, in terms of ignition and combustion. A very recent study [5] presents the ignition mechanism of *n*-heptane and *iso*-octane under various conditions, showing the expected increase of autoignition delay times when moving from *n*-heptane to *iso*-octane. Such results are also verified by experimental investigations [6], as the ignition delay of four different PRF blends was shown to increase as the composition of *iso*-octane augmented in the blends. Furthermore, engine tests also report an increase in the ignition delay times as the octane number of the fuel is larger [7–9]. Another work done with PRFs, diesel and gasoline, investigated the combustion recession after the end of injection [10]. The results showed that the fuels with highest cetane numbers presented the least lifted flames and the shortest combustion recession times. Analogously, the lift-off length and ignition delay time relationship was also studied under a wider range of conditions using conventional diesel and a PRF blend of similar properties [11]. Although the trend was not very clear, there was a interaction implying that the condition with longest lift-off length also presented the longest ignition delay times.

The present work reports a fundamental investigation on the ignition and combustion behavior of fuel sprays under Spray A conditions [12], with a detailed focus on fuel properties. For that purpose, binary blends of *n*-heptane and *iso*-octane, which are Primary Reference Fuels (PRFs), have been tested. In terms of ignition behavior, such blends should be representative of a detailed transition from a conventional diesel fuel (*n*-heptane) to a gasoline-like one (*iso*-octane). The main objective of this work is the experimental characterization of spray mixing, ignition and sooting processes. For each fuel blend, the test plan includes parametric variations of ambient temperature and oxygen concentration, which have the largest effect on spray ignition behavior. Experiments have been conducted in a constant pressure vessel, where high ambient pressure and temperature conditions typical of diesel engines can be reproduced. For each condition, high speed schlieren and broadband luminosity imaging have been used to compare ignition, combustion and sooting behavior of all fuel blends; OH^* radical imaging has also been performed to measure lift-off length. The present contribution is structured as follows. After this introduction, both the experimental setup and the optical techniques employed will be presented. Test conditions will be summarized, and results of fuel effects will be analyzed. Finally, the main conclusions from this study are drawn.

2. Experimental setup

2.1. High temperature and high pressure vessel

Tests have been performed in a high temperature and high pressure test chamber where the thermodynamic conditions obtained in a diesel engine at the time of injection can be obtained with a maximum ambient temperature of 1000 K and a maximum pressure of 15 MPa. Compared to similar facilities [13], it is possible to obtain nearly quiescent and steady thermodynamic conditions in the test chamber. More details can be found in [14].

2.2. Optical setup

Different optical techniques have been employed in these experiments. Schlieren imaging has been used to measure spray penetration and autoignition delay, broadband luminosity imaging has been used to assess sooting intensity, and OH^* chemiluminescence imaging has been used to measure flame lift-off length.

2.2.1. Schlieren imaging

The spray evolution inside the combustion chamber has been recorded by schlieren imaging [15]. This technique is sensitive to the first spatial derivative of density within the combustion chamber, which makes it useful to detect spray boundaries and thus evaluate macroscopic spray scales, whether vaporizing or non-vaporizing, inert or reactive. This technique shows the boundary between vaporized liquid and background gas because of the refractive index differences that exist between them, additionally, density gradients are also created in the chamber as the vaporized liquid cools the ambient gas [16,17]; such refractive index gradients are also present during combustion, as the high temperate creates low density regions. Therefore, this method is valid for inert and reactive conditions. For this technique, the spray has to be illuminated from one side by a collimated beam. The shadow produced by the spray is then gathered with a lens and at its focal length a diaphragm is positioned to produce the schlieren effect by eliminating the diverted light beams. The recorded image is then captured by a high speed camera in order to obtain a time resolved evolution of the spray.

An example of an schlieren image can be seen in Fig. 2. The routine used for the processing was developed by Sandia National Laboratories as part of the ECN group and is available on-line [18]. The code is based on the successive calculation of two standard deviation images to remove the schlieren effect of the hot ambient gases and to detect the spray boundary. For every instant (I_t), the processing routine subtracts the two preceding images (I_{t-1} and I_{t-2}), then a two-step derivative process highlights the zones where the pixels have changed due to either spray or background gas movement, then the image is segmented [19–21]. Once the boundaries have been defined, the spray penetration is calculated by the procedure shown in [17]. Additionally, the ignition delay based upon schlieren images has also been calculated using the method described in [12,16,22], which relies on the change in refractive index of the mixture and the shortening of the penetration.

A schematic of the optical arrangement is shown in Fig. 1. The spray has been illuminated from the left window and the light has been captured by a CMOS camera from the opposite side. The light from a Xenon lamp passed through a 1 mm diameter pinhole that simulates a single-point light source. The light was reflected on a 150 mm parabolic mirror to obtain collimated light. After passing through the spray, the light has been collected by a biconvex lens and at its focal point a 4 mm diaphragm has been positioned to produce the schlieren effect. A BG39 bandpass filter (360–580 nm) was used to minimize soot radiation effects. A 10-bit Photron SA-5 CMOS high-speed camera equipped with a Nikon 50 mm $f = 1{:}8$ lens were used, image acquisition frequency was 42,000 fps with exposure time of 4.18 μs and a pixel/mm ratio of 5.26 leading to a field of view of 97 mm.

2.2.2. Broadband radiation imaging

The soot distribution and intensity inside the combustion chamber have been recorded by direct imaging. This technique records the flame broadband radiation, which corresponds to the soot thermal radiation during the diffusion combustion phase.

Fig. 3 shows a sample image of broadband radiation. An average background image is calculated for each repetition and based on that image and a two constant thresholds, a mask is generated to define the region of interest. It is important to clarify that given the strong difference between the intensity levels in the soot onset area (in the vicinity of the lift-off) and further downstream, two threshold values (a lower one for the onset and a higher one for the tip) were selected in order to accurately detect the contour.