

Ignition Quality Effects on Lift-Off Stabilization of Synthetic Fuels

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ABSTRACT

The ignition and flame stabilization characteristics of two synthetic fuels, having significantly different cetane numbers, are investigated in a constant volume combustion vessel over a range of ambient conditions representative of a compression ignition engine operating at variable loads. The synthetic fuel with a cetane number of 63 (S-1) is characterized by ignition delays that are only moderately longer than n-dodecane (cetane number of 87) over a range of ambient conditions. By comparison, the synthetic fuel with a cetane number of 17 (S-2) requires temperatures approximately 300 K higher to achieve the same ignition delays. The much different ignition characteristics and operating temperature range present a scenario where the lift-off stabilization may be substantially different. At temperatures below 1000 K, the S-2 fuel undergoes a long transient stabilization phase during which the lift-off location moves as much as 15 mm upstream (i.e., toward the injector orifice) after the ignition of the first flame kernel. This behavior is much different than S-1, n-dodecane, or with conventional diesel, in which past research shows that the lift-off location stabilizes very close to the ignition location shortly after the premixed burn. The longer ignition delays for S-2 frequently result in fuel-lean mixtures at the ignition location where the spray becomes over-mixed (i.e., too fuel-lean) and the high-temperature ignition event is noticeably less robust (i.e., smaller and less intense ignition kernels) as observed by high-speed chemiluminescence imaging. High-speed chemiluminescence imaging and pressure measurements show strong evidence of cool-flame (i.e., first-stage or low-temperature) reactions prior to high-temperature ignition for S-1 while they are less evident for S-2.

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INTRODUCTION

In the early 1990's the United States Army introduced the "one fuel forward" policy as a means to simplify the logistics of fuel supply for its ground and air vehicles around the world [1]. A single common fuel, JP-8 (Jet Propellant 8), is used for both turbojet and diesel engines. JP-8 is derived from the commercial aviation fuel Jet-A. The United States Army is now interested in alternative fuels for aviation and ground applications that can supplement and/or replace traditional JP-8 while meeting the specifications for the "one fuel forward" policy. Alternative fuels are developed that meet the requirements for JP-8, but their properties and performance in compression ignition engines may vary widely depending upon the region of the world and the production method. A better understanding of how synthetic, alternative fuels affect diesel combustion is required to screen particular fuels or to potentially modify fuel standards for "one fuel forward".

The basic characteristics for JP-8/Jet A that affect gas turbine combustion have been revealed through the development of formulated surrogates [2,3,4,5,6,7,8]. A body of research has also been developed for alternative, synthetic fuels applied to compression-ignition engines [9,10,11,12,13]. Gill and coworkers [9] provide an overview of the technologies for Gas-to-Liquid, Biomass-to-Liquid and Coal-to-Liquid fuels issued from Fischer-Tropsch processes [9]. Muzzell *et al.* [10] studied Fischer-Tropsch blends with JP-8 and the US domestic supply potential for synthetic fuels. Experiments were also conducted in light-duty single cylinder engines with a focus on ignition and emission characteristics of alternative hydro-processed, Fischer-Tropsch and jet fuels [11]. Investigations of the ignition characteristics of Fischer-Tropsch and JP-8 have also been conducted in combustion vessels [12]. Practical blends of Coal-to-Liquid and Fischer-Tropsch fuels for military applications were tested in a single cylinder engine [13]. Schihl *et al.* [13] identified the ignition properties of synthetic fuels as problematic

below a certain in-cylinder bulk gas temperature and density; however, it was demonstrated that this drawback can be mitigated by using blends of synthetic fuels with JP-8.

Before alternative fuels can be fully integrated into real-world applications, however, the combustion behavior of these fuels must be sufficiently characterized to ensure that proper equipment performance will be maintained. The selected fuel will be used over a wide range of applications which could be especially problematic for diesel engines. For instance, ignitability at cold start conditions or during idling operation are among the most challenging requirements. In that context, ignition quality and flame stabilization are two critical parameters that must be characterized to assess the suitability of an alternative fuel for military applications.

The present work uses a high-pressure constant volume pre-burn chamber to investigate the ignition and flame stabilization characteristics of two different synthetic fuels with significantly different cetane numbers. For reference, comparisons to n-dodecane data from the Engine Combustion Network (ECN) data archive are performed. The synthetic fuels' physical properties are also discussed alongside those of n-dodecane and diesel #2 (standard diesel fuel in North America). The layout of the manuscript is as follows: A description of the experimental equipment is given first, providing information concerning the constant-volume combustion vessel, the injection system and fuels, and the diagnostics used in the study. The results are presented beginning with the liquid fuel penetration and ignition delay time measurements, which includes an in-depth analysis of some distinctive features observed for the low cetane fuel. Flame stabilization distance (lift-off length) results are presented next, followed by a comparison and analysis of the pressure-traces for a few selected cases. The last section summarizes the findings and concludes this study.

EXPERIMENTAL SETUP

Combustion Chamber and Injection System

Experiments were conducted in an optically accessible, high-pressure, constant-volume combustion vessel. Diesel-like combustion of free-jets occurred under the quiescent ambient conditions described in [Table 1](#). The vessel is nearly cubical with a volume of approximately one liter. Sapphire windows provide optical access to the spray event from four sides. Prior to an injection event, the temperature of the entire vessel is maintained at 461 K by electric heaters. Spark-ignition of a combustible gas mixture rapidly elevates the pressure and temperature within the vessel. The spray event (i.e., fuel injection) takes place when the desired ambient thermodynamic conditions (temperature, density, and oxygen concentration) are achieved after a short cool-down period. A detailed description of the vessel and its operation can be found in Siebers [14]. The vessel is equipped with high-speed pressure transducers permitting the determination of a speed-of-sound corrected, pressure-based ignition delay time. The pressure signal contains a relatively small amount of noise prior to high-temperature ignition and larger noise or "ringing" after ignition as acoustic waves propagate through the vessel. The pressure-based ignition delay time corresponds to the time at which the smoothed vessel pressure exceeds a specified threshold-typically

between 1.0 and 3.0 kPa. The pressure trace prior to ignition is smoothed using a low-order filter, while the signal after ignition is low-pass filtered using a fast Fourier transform with a Gaussian roll-off as described in detail in [15, 16].

Table 1. Experimental conditions

T [K]	750	800	850	900	950	100	110	120
S1 – 21% O₂								
ρ [kg/m ³]	15.2	15.2	15.2	15.2	-	-	-	-
	18.8	18.8	18.8	18.8	-	-	-	-
	22.8	22.8	22.8	22.8	-	22.8	22.8	22.8
S1 – 15% O₂								
ρ [kg/m ³]	22.	22.	22.	22.	-	-	-	-
S2 – 21% O₂								
ρ [kg/m ³]	-	-	-	15.	15.	15.2	15.2	15.2
	-	-	-	2	2	18.8	18.8	18.8
	-	-	-	18.	18.	22.8	22.8	22.8
S2 – 15% O₂								
ρ [kg/m ³]	-	-	-	-	15.	15.2	15.2	15.2
	-	-	-	22.	2	22.8	22.8	22.8

Experiments were performed using a common-rail diesel fuel injector equipped with a single 90- μ m diameter orifice (# 210370) belonging to the family of Spray A injectors from the ECN (Engine Combustion Network) [17]. The injection pressure was kept at 1500 bar and the actual injection duration was approximately 6 ms for the entire dataset. The injector is housed in a water-cooled mount and the fuel temperature at the nozzle is 90°C. The majority of the test matrix (see [Table 1](#)) focused on a 21% by volume oxygen concentration case, where no exhaust gas recirculation (EGR) was applied. Nevertheless, selected points have been repeated at lower oxygen concentration (15% vol.) for comparison with the large body of n-dodecane data available under this condition. Properties for the high-cetane fuel (S-1) and low-cetane fuel (S-2) used in this study (see [Table 2](#)) will be discussed later.

The nominal ambient temperatures are provided in [Table 1](#). Note that the different ignition characteristics of the two fuels required that different temperature ranges be investigated. Specifically, S2 jets did not ignite before the end of injection for ambient temperatures below 900 K. The density (ρ) and the oxygen mole fraction (XO_2) are relevant to moderately boosted modern diesel engines, and they have been kept constant for all experiments.

Optical Diagnostics

Simultaneous optical diagnostics are employed to measure the time evolution of the liquid length as well as the flame stabilization distance and ignition delay of reacting diesel jets. A schematic of the complete optical arrangement used for the experiments is provided in [Figure 1](#).

High-Speed Diffused Back Illumination Imaging

Diffused back-illumination (DBI) has been used to detect and quantify liquid penetration under vaporizing and reacting sprays. This technique is preferred over Mie scatter because DBI permits quantification of optical extinction, which leads to better standardization of liquid length measurements among different researchers [18]. The main components of the high-speed DBI setup

consist of a high-output, ultra-fast, blue (450-nm, 20-nm FWHM) LED, an engineered diffuser, a field lens, and a high-speed CMOS camera equipped with a 50-mm f/1.2 Nikkor lens, a bandpass filter (400 nm, 20-nm FWHM), and a neutral density filter of OD 1.9 to reject broadband flame luminosity (under reacting conditions). The diffuser has a 50° circular pattern and the field lens is a Fresnel type with a 152-mm focal length. The engineered diffuser in conjunction with the Fresnel lens create a large (60-mm diameter) uniformly illuminated background with minimal light intensity losses (more than 90% transmission). This light source setup directs a bundle of diffused rays toward the object plane resulting in minimal light extinction by density gradients (i.e., beam steering, schlieren effects). Images were recorded at 82,000 fps (frames per second) for the S-1 fuel and 100,000 fps for the S-2 fuel.

Each image is processed to provide a quantitative measurement of light extinction by relating the instantaneous intensity I to the reference intensity recorded before injection I_0 . A two-dimensional map of the optical thickness (τ) is obtained by applying the Beer-Lambert law (see Eq. 1).

$$\tau = -\ln\left(\frac{I}{I_0}\right) \quad (1)$$

The liquid boundary is processed in each image at an optical thickness of 0.6, which targets the optical thickness at the traditional Mie-scatter threshold of Siebers (3% of maximum) [14]. To reduce or eliminate extinction caused by density gradients in the surrounding fuel vapor, this threshold also accounts for 0.2-0.3 optical thickness units attributed to vapor-phase beam steering. The maximum axial distance of the liquid boundary at each time step defines the instantaneous liquid length. The time-average over the quasi-steady period of injection then defines the mean liquid length. In addition, the Actual Start of Injection (ASOI) can be detected with these images due to the high temporal resolution of the DBI setup.

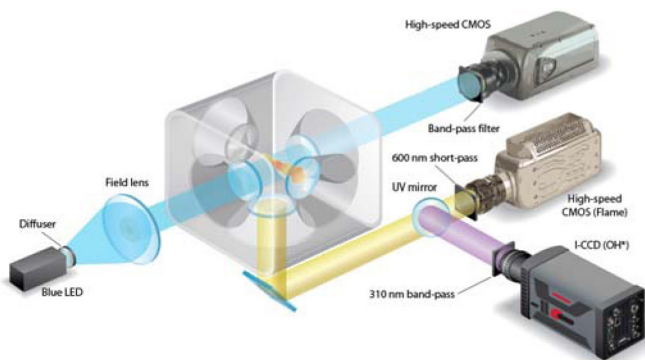


Figure 1. Experimental setup with the high-speed DBI, the high-speed luminosity and the OH chemiluminescence imaging systems.

High-Speed Luminosity Imaging

A high-speed CMOS camera acquired images of broadband flame emission (luminosity) at 20,000 fps with a 50- μ s exposure time for the S-1 fuel. For the S-2 fuel, two combinations of frame-rate/exposure-time settings (52,000 fps/18 μ s and 20,000 fps/49 μ s) were used. The higher-speed setting better resolved ignition delay times

while the slower setting was more sensitive to low levels of flame luminosity. The camera was equipped with a 50-mm f/1.2 lens and a 600-nm short-pass filter to suppress the high intensity soot luminosity and take advantage of the camera's dynamic range. Ignition location, temporal evolution of the lift-off length, and ignition delay time were extracted from these images. The intensity threshold for detecting ignition and the flame boundary were specified according to the ECN standard, i.e., the intensity threshold is specified as 50% of the time-averaged maximum intensity in the lift-off region [17]. Because ignition occurred near the vessel wall for the S-2 fuel under the lowest temperature condition (900 K), a lower threshold was selected. For the relatively long injection duration cases of this study, the quasi-steady lift-off length measured by high-speed imaging was consistent with the single-shot OH chemiluminescence imaging described below.

OH Chemiluminescence Imaging and Lift-Off Length

The quasi-steady lift-off length was measured following the guidelines described by Higgins and Siebers [19]. An intensified CCD camera equipped with a UV lens and a 308 nm (10 nm FWHM) bandpass filter collected excited state OH (OH*) chemiluminescence from the burning fuel jet. The short-lived OH chemiluminescence emission dominates in the lift-off length region as it results from the high-heat-release reactions occurring under near-stoichiometric conditions, which are representative of the lifted diffusion flame. Image acquisition lasted 4 ms, beginning after auto-ignition and ending at the end of injection. This resulted in time-averaged images free from the appearance of turbulent fluctuations.

For conditions where ignition occurs away from the vessel wall, OH chemiluminescence appears at a well-defined distance from the injector orifice. In such cases, the signal is characterized initially by a steep gradient followed by a plateau region as has been observed in previous works [19]. Similar to the ECN standard [17], the lift-off length is defined as the axial distance between the orifice and the location where OH chemiluminescence intensity is 50% of the maximum prior to the plateau region. In cases where ignition occurred at or near the vessel wall, the evaluation of the lift-off length was not feasible.

Fuel Description

As mentioned previously, the higher cetane number fuel is referred to as S-1, while the lower cetane number fuel is referred to as S-2. The physical properties of the two synthetic fuels, n-dodecane, and #2 diesel are shown in Table 2. Given the large Engine Combustion Network (ECN) database compiled for n-dodecane, this fuel will serve as a reference case when possible for comparison with the behavior of the two synthetic fuels. Furthermore n-dodecane is a relevant surrogate for jet fuels and also for diesel fuels. The cetane number of S-1 and S-2 have been measured according to the test protocols ASTM D-613 and ASTM D-6890. S-2 has a low cetane number below 30. For comparison, the Phillips Research diesel #2 has a cetane number of 45.7 (diesel #2 properties are also listed in Table 2). S-1 is more volatile than S-2 as can be seen in the distillation curves presented in Figure 2.

