

Ethanol/N-Heptane Dual-Fuel Partially Premixed Combustion Analysis through Formaldehyde PLIF

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ABSTRACT

As a result of recent focus on the control of Low Temperature Combustion (LTC) modes, dual-fuel combustion strategies such as Reactivity Controlled Compression Ignition (RCCI) have been developed. Reactivity stratification of the auto-igniting mixture is thought to be responsible for the increase in allowable engine load compared to other LTC combustion modes such as Homogenous Charge Compression Ignition (HCCI). The current study investigates the effect of ethanol intake fuel injection on in-cylinder formaldehyde formation and stratification within an optically accessible engine operated with n-heptane direct injection using optical measurements and zero-dimensional chemical kinetic models. Images obtained by Planar Laser Induced Fluorescence (PLIF) of formaldehyde using the third harmonic of a pulsed Nd:YAG laser indicate an increase in formaldehyde heterogeneity as measured by the fluorescence signal standard deviation. The experimental observations are complemented by a discussion regarding definitions of “reactivity”.

CITATION: Florea, R., Zha, K., Yu, X., Jansons, M. et al., "Ethanol/N-Heptane Dual-Fuel Partially Premixed Combustion Analysis through Formaldehyde PLIF," *SAE Int. J. Engines* 5(2):2012, doi:10.4271/2012-01-0685.

INTRODUCTION

In response to continued demand for improved internal combustion engine efficiency and emissions reduction, previously reported research has focused on Low Temperature Combustion (LTC) modes, such as Homogenous Charge Compression Ignition (HCCI) [1,2,3,4], as potential candidates for future internal combustion engines technologies. While these combustion modes have been shown to yield high indicated efficiency as well as near-zero engine-out emissions, the lack of a combustion “trigger” results in difficult and often impractical control strategies which limit both the engine load range, engine transient behavior as well as the cold-startability of the engine.

Recently proposed dual-fuel combustion modes, such as Reactivity Controlled Compression Ignition (RCCI) [5,6,7,8], seek to maintain the advantages associated with Low Temperature Combustion while addressing the issues related to combustion phasing control and rate of pressure rise limited engine load.

Furthermore, homogenous mixture combustion modes such as HCCI are characterized by volumetric energy release. While the reduced combustion duration improves the thermodynamic efficiency, it also results in high rates of pressure rise and subsequent engine ringing [9] previously associated with knock in spark-ignition engines. This has an undesirable impact on engine integrity and perceived

combustion noise. In order to address these issues along with the need for a method for reliable control of combustion phasing, the internal combustion research community has shown increased interest in kinetically controlled combustion and dual fuel operation. One such combustion mode, the RCCI, is characterized by partially premixed combustion where fuels of different reactivities are used in different ratios in order to obtain a “reactivity” stratification of the combustible mixture. This in turn results in a phase-shift in the ignition delay time experienced by different zones of the combustion chamber and a longer duration of the premixed phase of combustion. Due to the ample time available between fuel injection and high-temperature heat release, the fuel is highly premixed but not fully homogenous. Thus, the amount of diffusion controlled combustion is minimized, reducing the probability of soot formation.

Work reported by Splitter et.al. [5] investigated the dual-fuel operation of a single-cylinder diesel engine operated with different fuel combinations. The results reported indicate that ethanol, a biofuel and thus renewable energy source, has the most significant impact on the partially premixed combustion mode studied. The authors point towards the inhibiting effect of ethanol, previously reported by Hashimoto [10, 11] which is caused by the scavenging of the hydroxyl radical by the ethanol molecules. Thus, one could hypothesize that ethanol and other chemical species which have a significant impact

on the chemical kinetic pathways for fuel decomposition are more suitable for use in reactivity stratification applications compared to other types of fuels. In this work the dual-fuel autoignition process is investigated in an optically accessible diesel engine operated with n-heptane direct injection and anhydrous ethanol (200 proof) intake port injection.

The goal of this research is to investigate the effect of ethanol on formaldehyde formation and formaldehyde heterogeneity. As it has been shown by previous authors [12], formaldehyde plays a significant role throughout the low temperature conditions considered in this work. For this purpose Planar Laser Induced Fluorescence (PLIF) measurements of in-cylinder formaldehyde are reported and analyzed. Further, the experimental observations are supported by chemical kinetic calculations intended to provide additional insight into the impact of ethanol mole fraction, temperature and equivalence ratio on formaldehyde formation and energy release. Finally, a discussion regarding the experimental observation of reactivity stratification is provided as well.

EXPERIMENTAL SETUP

The experimental setup used in this investigation has been reported in previous publications [13,14,15,16,17,18]. The engine specifications are included in Table 1 below while Table 2 presents the experimental conditions. The ethanol intake mole fraction was measured using an FTIR spectrometer (Thermo Nicolet Nexus 670).

During the testing reported, the engine was operated in skip-fire operation in order to improve the thermal stability of the optical engine. Under this engine fueling strategy, fuel was injected for 3 consecutive cycles followed by typically 9 motoring cycles.

Table 1. Experimental engine specifications

Optically accessible engine	AVL SCRE5402
Intake system	naturally aspirated
Exhaust gas recirculation	no
Bore x Stroke	85 x 90 mm
Swept Volume	510 cm ³
Compression Ratio	15:1
Engine Speed	1200 rpm
Injection System	Common Rail CP1
Injection Pressure	800 bar
Injector Number of Holes, Type	5 holes, VCO
Hole Diameter	180 μ m
Hole Included Angle	142°
Fuel	n-Heptane

Table 2. Operating points

Ethanol intake mole fraction	0 ppm	4200 ppm	6600 ppm
N-heptane injection timing demand [°bTDC]	7.5	10.5	12.5
Common-Rail Injector Solenoid activation time [μ s]	450	415	404
N-heptane injection pressure [bar]	800		
Location Peak Premixed Combustion [°aTDC]	7		
Corrected Net IMEP [bar]	2.5		
Intake Temperature [K]	306		
Swirl number	2.0		
Engine speed [rpm]	1200		
Optical diagnostics [y/n]	y	n	y

The single cylinder research engine is provided with full optical access through a 40 mm diameter sapphire window mounted in an elongated piston in order to provide an unobstructed bottom view of the combustion process throughout the entire engine cycle. A cross-section though the engine is shown in Figure 1a) while b) shows the spray orientation and laser sheet positioning. The spray pattern was directed such as to avoid fuel impingement on the laser sheet entrance window. The experimental setup considered in this work is shown in Figure 1c).

The PLIF experiment is carried out using the third harmonic (355 nm) of a Nd:YAG pulsed laser (SpectraPhysics QuantaRay Pro 270), similar to work previously reported in the literature [12, 19, 20]. The engine operating speed was chosen in order to match the nominal frequency of the pulsed laser, i.e. 10 Hz. The laser beam, characterized by a Gaussian profile, has been formed into a laser sheet using a 100 mm focal length cylindrical lens along with a 500 mm focal length plano-concave spherical lens. The laser-sheet is delivered through the combustion chamber of the optically accessible engine via a series of flat fused silica windows mounted in both the adapter plate connecting the cylinder head to the crank-case, and the piston crown respectively. The optical access supplied by these lateral windows is designed to provide laser sheet access for piston positions around the firing TDC of the engine. The laser sheet is aligned parallel to and approximately 4 mm below the fire deck.

In order to account for shot-to-shot laser energy variability, a gated integrator (Stanford Research SR250) is used, resulting in cycle- resolved laser energy measurements. This information is further supplied to the data acquisition system and is used for data processing purposes. The average laser energy is measured using a power meter (Newport 842-PE) connected to the detector head (818P-030-18HP). The experiments reported in this paper used average laser energies of approximately 43 mJ/pulse.

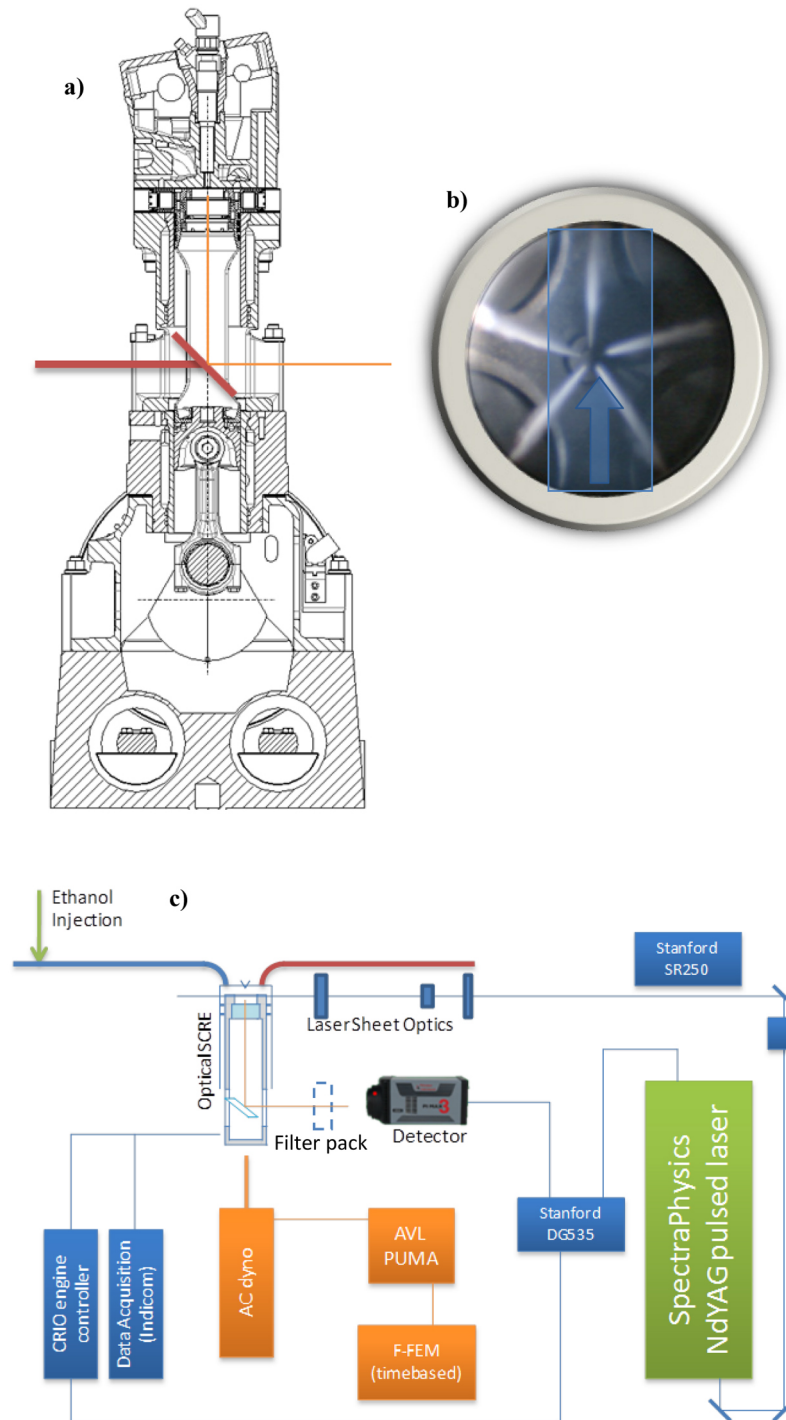


Figure 1. a) cross section through the single cylinder optically accessible engine b) spray pattern orientation and laser sheet configuration c) Experimental setup diagram

The images were acquired by a PIMAX2 ICCD camera (Princeton Instruments) equipped with a 78 mm UV objective (Electrophysics) with a maximum aperture opening $f/3.8$. Each frame is synchronized with the engine operation by an FPGA based engine controller (National Instruments cRIO/Drivven Inc.) which in turn triggers a delay generator (Stanford Research DG535). The delay generator is

responsible for providing triggers for the laser lamp, Q-switch and ICCD gate with minimum jitter.

Engine data regarding in-cylinder pressure, common-rail pressure and injector needle lift has been acquired by a high-speed data acquisition system (AVL Indimeter 621). The engine crankshaft position signal required by the data acquisition system as well as the FPGA-based real-time