

Optical Investigation of UHC and CO Sources from Biodiesel Blends in a Light-Duty Diesel Engine Operating in a Partially Premixed Combustion Regime

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ABSTRACT

The influence of soy- and palm-based biofuels on the in-cylinder sources of unburned hydrocarbons (UHC) and carbon monoxide (CO) was investigated in an optically accessible research engine operating in a partially premixed, low-temperature combustion regime. The biofuels were blended with an emissions certification grade diesel fuel and the soy-based biofuel was also tested neat. Cylinder pressure and emissions of UHC, CO, soot, and NO_x were obtained to characterize global fuel effects on combustion and emissions. Planar laser-induced fluorescence was used to capture the spatial distribution of fuel and partial oxidation products within the clearance and bowl volumes of the combustion chamber. In addition, late-cycle (30° and 50° aTDC) semi-quantitative CO distributions were measured above the piston within the clearance volume using a deep-UV LIF technique.

Compared with neat diesel fuel, the palm-based biofuel blends produced the largest decrease in UHC (38-56%) and CO (28-44%), but generated significant increases in both NO_x (17-37%) and soot (41-43%). With soy-based blends, however, UHC decreased by 30-43% and CO by 17-22%, while NO_x (-1-2% increase) and soot (0.8-8.5% increase) emissions varied slightly. The UHC and CO emissions were found to correlate well with the combustion phasing of each fuel at a given injection timing. The UHC PLIF measurements demonstrated several differences in the evolution of the UHC distributions throughout the cylinder volume during the mixture formation, premixed heat-release, and mixing-controlled heat-release portions of the engine cycle. However, the late-cycle UHC PLIF and spectrally resolved CO LIF measurements showed no significant

differences in the main sources of UHC and CO when fueling the engine with either diesel fuel or biofuel blends.

INTRODUCTION

Alternative fuels have been widely studied in recent years to investigate their impact on combustion performance of conventional diesel engines. Biofuels are particularly attractive because they can be domestically produced and have possible CO_2 benefits over the fuel's life cycle [1]. Biofuels have also been found to alter the emissions produced by diesel engines. Reductions in unburned hydrocarbons (UHCs) and carbon monoxide (CO) have been observed using several types of biofuels, while oxides of nitrogen (NO_x) and fuel consumption have generally been observed to increase [2,3,4].

Although UHC and CO are not traditionally a major concern in diesel engines, new low temperature combustion (LTC) operating strategies designed to minimize NO_x and particulate matter can produce high levels of these emissions, especially at low loads. With these strategies, low combustion temperatures and dilute charge mixtures result in both slower chemical reactions and more stringent mixing requirements. Therefore, UHC and CO emissions have been found to increase in engines incorporating LTC operating modes such as partially premixed compression ignition (PPCI) [5]. Alternative fuels, specifically biofuels, provide an opportunity to reduce UHC and CO emissions and enlarge the operating range of LTC in internal combustion engines.

Previous studies have primarily focused on investigating the effects of using biofuels on engine-out emissions and other combustion performance characteristics (fuel consumption,

heat-release, etc.). However, the wide range of operating conditions, engine hardware, fuels, and engine timings used in these studies make it difficult to make clear generalizations about how biofuels affect the formation and consumption of UHC and CO within the combustion chamber. In addition, the vast majority of these studies use a conventional diesel operating mode and their results may not be applicable to LTC strategies. This study takes a more fundamental approach to see how the sources of UHC and CO emissions from a light-duty diesel engine operating in a PPCI mode are affected by the properties of biofuel blends. In-cylinder optical diagnostics in conjunction with cylinder pressure and engine-out emissions measurements are used to investigate the differences that arise between fuel-types. The fuels investigated include: (1) a 2007 certification diesel fuel, (2) 20% and 50% by volume blends of either soy-based methyl ester biofuel (SME) or palm-based methyl ester biofuel (PME), and (3) a neat SME biofuel.

Previous investigations, using the same light-duty, optically accessible diesel engine that was used in the current work, studied a highly dilute (10% O₂), slightly boosted ($P_{intake} = 1.5$ bar), low load (3 bar IMEP) PPCI condition [6,7,8,9]. Multiple optical diagnostic techniques were used to determine the main sources of UHC and CO using a US #2 diesel fuel. Fluorescence from formaldehyde, a species formed in the initial low-temperature stages of combustion, and polycyclic aromatic hydrocarbons (PAH), products of rich combustion, were imaged within the clearance and bowl volumes using a planar laser-induced fluorescence (PLIF) technique based on 355 nm excitation. An additional, spectrally resolved deep-UV (230.1 nm) UHC and CO LIF technique was used to construct distributions of CO and a wider range of PAH compounds. A comprehensive depiction of the distributions of late-cycle (30° and 50° aTDC) UHC and CO within the combustion chamber and a description of the mechanisms by which these products of incomplete combustion were generated was provided. Late-cycle UHC emissions were found to originate from three sources [6,7,8]: (1) liquid fuel dribble from the injector, embedded in a largely lean mixture near the injector tip and cylinder centerline, (2) overly rich and overly lean mixtures within the bowl and central clearance volume, and (3) overly lean mixtures, piston-top films, and ring-land crevice flows within the squish volume. However, the incomplete combustion of overly lean mixtures within the squish volume was determined to be the major contributor to CO emissions, and a significant, if not dominant, source of late-cycle UHC [6].

The current investigation utilized the same UHC PLIF and deep-UV UHC and CO LIF diagnostic techniques and operating condition (10% O₂, $P_{intake} = 1.5$ bar, 3 bar IMEP) as these previous studies [6,7,8,9]. The behavior of the heat-release and engine-out emissions for five different biofuel blends is first compared to the certification diesel fuel by

examining UHC, CO, NO_x, and soot emissions behavior over a wide range of injection timings. Using the engine-out emissions results as a guide, UHC PLIF and CO LIF data are used to investigate the mechanisms through which the sources of UHC and CO emissions were modified by the addition of the SME and PME biofuels. The focus of this paper is on identification of the physical processes responsible for the differences in UHC and CO emissions observed with common biofuels relative to traditional diesel fuel.

EXPERIMENTS

The following sections describe the experimental facility, operating conditions, and diagnostic techniques used in this study. The engine facility has been used in a number of previous investigations and additional details regarding the engine and its performance relative to all-metal test engine performance can be found in [10,11].

ENGINE

The single-cylinder research engine used throughout this work was derived from a General Motors 4-cylinder 1.9 L light-duty diesel engine. A cross-section of the optically accessible engine and a schematic of the UHC PLIF setup are shown in Fig. 1, with the engine and fuel injection system specifications provided in Table 1. Note that the nomenclature used to describe the sub-volumes within the clearance volume is also defined in Fig. 1. Optical access to the combustion chamber was achieved through quartz windows placed within a metal ring that comprises the upper 31 mm of the cylinder liner. The engine also features a fused-silica piston top that includes the detailed reentrant bowl and valve cut-out geometries of a typical production piston. The only significant deviation from a production piston geometry is the elongation of the top ring-land crevice to accommodate imaging within the piston bowl. The lower ring-pack position results in a crevice volume 3-4 times larger than that of a typical engine. However, two gapless compression rings were used to minimize blowby and compensate for the larger crevice volume. The engine has a geometric compression ratio (CR) of 16.7, but an effective CR of 14.0 more closely matches the pressure behavior predicted by a one-dimensional engine model [10]. The discrepancy between the geometric and effective compression ratios is due largely to heat transfer within the increased crevice volume. A previous study conducted on the same engine [11] has shown that the CO and UHC emissions trends from a similar single-cylinder all-metal engine with a more typical ring-land crevice were well captured by the optical engine.

<figure 1 here>

Table 1. Engine, valve timings, and fuel injection specifications.

Engine Geometry	
Bore	82.0 mm
Stroke	90.4 mm
Displacement Volume	0.477 L
Geometric CR	16.7
Effective CR	14
Squish Height	0.78 mm
Valves	
Intake Valves	2
IVO	-359 °CA
IVC	-152 °CA
Exhaust Valves	2
EVO	132 °CA
EVC	360 °CA
Injection Parameters	
Injector	Bosch CRI2.2
Sac Type	Mini Sac
Sac Volume	0.23 mm ³
Holes	7
Nozzle Diameter	0.14 mm
Nozzle Area	0.0154 mm ²
Included Angle	149°
Rail Pressure	860 bar

OPERATING CONDITIONS

A light load (3 bar IMEP), highly dilute (oxygen mole fraction, $x_{O_2} = 10\%$), boosted ($P_{intake} = 1.5$ bar) baseline operating condition was chosen to match the conditions studied extensively in previous investigations on the same engine [6,9]. Soot, UHC, CO, and NO_x emissions measurements acquired over a wide range of O₂ mole fractions, injection timings, and intake pressures showed that the above condition provided an adequate combustion efficiency (~98%), although the UHC and CO emissions were high relative to conditions with higher oxygen concentrations [10]. This condition represents a limit to the amount of charge dilution that can be achieved before the combustion deteriorates to unacceptable efficiency levels. A further understanding of the mechanisms of UHC and CO formation at this condition could lead to improvements in light load PPCI operation-where UHC and CO emissions are most problematic. The conditions used in this study are summarized in Table 2.

Table 2. Baseline PPCI conditions.

Engine Speed	1500 RPM
Intake Pressure	1.5 bar
Intake Temperature	99° C
Oxygen Mole Fraction	10%
Load	3 bar IMEP
Swirl Ratio	2.2
SOI	-23.1° bTDC
EOI	-16.7° bTDC
Air Mass Fraction	0.460
N ₂ Mass Fraction	0.402
CO ₂ Mass Fraction	0.138

To control the combustion chamber surface temperatures and to minimize optical surface fouling, the engine was fired once every 5 engine cycles. The skip-fired operation required simulated EGR consisting of N₂ and CO₂ to be used to obtain the desired O₂ concentration. The N₂ and CO₂ were added to the intake stream in proportions such that the specific heat ratio of the simulated EGR matched the specific heat ratio of complete combustion products at 600 K. The mass fractions of the 8 g/s intake flow are included in Table 2. Note that the intake flow mass fractions correspond to an EGR rate of 73%. A previous study using the same engine [11] investigated the effects of including H₂O, CO and C₃H₈ in the simulated EGR stream. It was determined that the inclusion of these species affected the ignition delay and emissions levels modestly. However, the emissions trends were closely matched to those obtained with the less reactive simulated EGR (N₂ and CO₂).

To avoid excessive wear of the oil-less piston rings and enable regular cleaning of the optical components, the engine run times were limited. Consequently, a steady-state condition was not achieved and a strict 8 minute schedule was followed to ensure that the thermal state of the engine was consistent for each run. The schedule began with 105 seconds of motored operation to stabilize the intake plenum pressures and was followed by 60 seconds of skip-firing to preheat the combustion chamber surfaces. Imaging and emissions data were then collected within the next 30 seconds, and the engine was stopped and allowed to cool for the remainder of the 8 minute cycle while the piston and liner window surfaces were cleaned.

FUEL PROPERTIES

A total of 6 fuel blends were used, consisting of blends of a 2007 certification US #2 diesel fuel and two common biofuels: (1) Soy Methyl Esters (SME) and (2) Palm Methyl Esters (PME). Neat diesel fuel and SME were also tested. The SME and PME biofuels were processed using straight

vegetable oil and were made from 100% soy and palm oil, respectively. The main fuel properties anticipated to impact combustion performance and emissions include: density, cetane number, lower heating value (LHV), distillation behavior, and composition—all of which are provided for each of the constituent fuels in Table 3. The compositional data for the SME and PME fuels were determined by an independent lab and the composition of the diesel fuel was supplied by the manufacturer. The compositions of the SME and PME fuels used in this study (provided in Table 3) are typical of SME and PME biofuel compositions cited in the literature [2,4].

Table 3. Properties of fuel blend constituents.

	Cert. Diesel	SME	PME
Density [kg/m ³]	840	880	870
Cetane Number	47.1 [‡]	47.2 [‡]	63.0 [‡]
Heating Value [MJ/kg]	42.9	36.9	36.2
Composition (Fatty Acid)*			
C12:0 (Lauric)	-	0.06	0.77
C14:0 (Myristic)	-	0.12	1.25
C16:0 (Palmitic)	-	11.51	42.06
C16:1 (Palmitoleic)	-	0.23	0.30
C18:0 (Stearic)	-	4.53	4.70
C18:1 (Oleic)	-	23.49	37.78
C18:2 (Linoleic)	-	51.05	10.29
C18:3 (Linolenic)	-	7.38	0.30
Aromatics	27.5 % vol.	-	-
Olefins	1.7 % vol.	-	-
Saturates	70.8 % vol.	-	-
SFC Aromatics	31.3 % wt.	-	-
Polynuclear Aromatics	9.44 % wt.	-	-
- indicates no data available			
‡ ASTM D-613			
† based on the compositional correlation of ref. [12]			
* AOCS method Ce 1c-89 with correction for FID response factors			

Table 4 provides the properties and nomenclature of the fuel blends used in this study. The distillation curves for each fuel blend are also shown in Fig. 2. These curves were estimated by fitting a curve to the data reported in [2] to generate an interpolated curve for each constituent of the fuel blends. The composite distillation curves were created by weighting the volume % recovered values for each fuel by its volume fraction, as shown in Eq. (1):

$$Vol(T) = \sum_{i=1}^N v_{f,i} \cdot Vol_i(T) \quad (1)$$

where Vol is the estimated volume percent recovered of the fuel blend at a given temperature, T , N is the total number of fuels that comprise the blend, $v_{f,i}$ is the volume fraction of fuel i , and Vol_i is the volume percent recovered of fuel i . The distillation curves indicate that the biofuel blends are less volatile than the diesel fuel at low distillation temperatures, but the distillation behavior of all the fuels becomes similar above the T_{90} point.

Table 4. Fuel Blends and Corresponding Nomenclature.

	Diesel [% vol]	PME [% vol]	SME [% vol]	LHV [MJ/kg]	Cetane
Cert. Diesel	100	0	0	42.9	47.1
PME-20	80	20	0	41.5	50.3
PME-50	50	50	0	39.5	55.1
SME-20	80	0	20	41.6	47.0
SME-50	50	0	50	39.9	46.9
SME-100	0	0	100	36.9	44.5

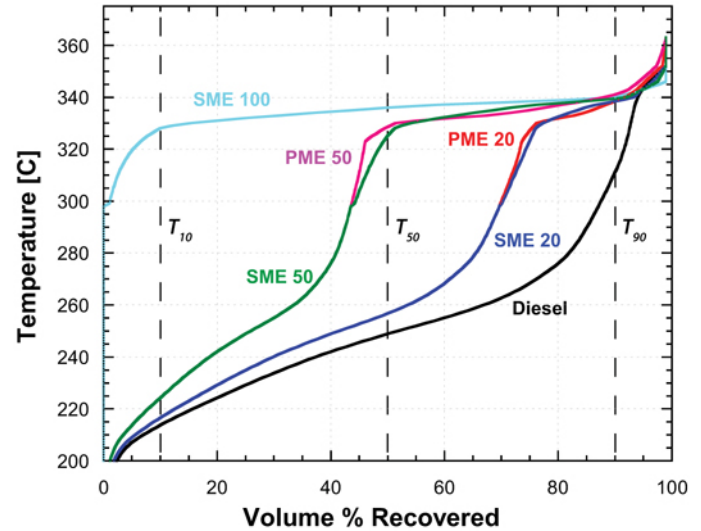


Figure 2. Distillation curves for each of the investigated fuels. The biofuel blends are less volatile than the diesel fuel at low distillation temperatures. Above the T_{90} point, distillation behavior of all the fuels is similar.

Note that the certification diesel used in this study is different than the diesel fuel used in previous studies in the same laboratory [6,7,8]. The certification fuel resulted in a slightly advanced ignition timing ($\sim 0.5^\circ$) and higher UHC ($\sim 11\%$) and CO ($\sim 8\%$) emissions compared to these previous studies.

DATA ACQUISITION

In-cylinder Pressure and Engine-Out Emissions

In-cylinder pressure measurements were acquired with a 0.25° CA resolution by a Kistler 6125 quartz pressure transducer mounted in the glow plug position within the head. The pressure measurements were used to determine the apparent heat-release rate (AHRR) and the indicated mean effective pressure (IMEP) for each experimental run, by averaging over 50 fired cycles. A heated sampling line was used to feed sampled exhaust to a California Analytical Instruments (CAI) flame ionization detector (CAI 600 MHFID) to measure the engine-out UHC emissions. Measurements of CO and NO_x were made after the UHC and water were removed from the exhaust sample by a condenser. The engine-out CO was measured by a CAI Nondispersive

Infrared (NDIR) gas analyzer and NO_x emissions were measured with a CAI Chemiluminescence (HCLD) analyzer.

UHC PLIF

Laser-induced fluorescence from formaldehyde (CH_2O), polycyclic aromatic hydrocarbons (PAH), and parent fuel compounds were excited with an 8 ns, ~ 25 mJ pulse from the third harmonic (355 nm) of a Nd:YAG laser (Spectra-Physics Pro-290). The beam was shaped into a vertical sheet with a combination of spherical and cylindrical lenses. Within the cylinder, the laser sheet was roughly 30 mm high and 500 μm thick, with an approximately ± 25 μm thickness variation throughout the cylinder. The laser sheet entered the cylinder through the fused-silica windows in the upper cylinder liner and was aligned with the axis of one of the 7 fuel jets, as shown in Fig. 1. The right-hand side of the cylinder is referred to hereafter as the “jet-axis plane” and the left-hand side is referred to as the “off-axis plane”.

The PLIF diagnostic can detect UHC originating from overly-rich regions (equivalence ratios, $\phi > 2$) where PAH formation occurs, low-temperature (typically lean, $\phi < 0.3$) regions where CH_2O is present, and regions where fluorescing compounds in the parent fuel have not yet been oxidized [6]. Significant PAH formation is not expected in regions with moderately rich pre-combustion equivalence ratios ($1 < \phi < 2$) [13]. In this range of equivalence ratios, homogeneous reactor simulations indicate that the UHC is principally composed of CH_4 , C_2H_4 , and C_2H_2 . None of these species are excited by 355 nm radiation. Therefore, the UHC PLIF diagnostic may be unable to detect potentially significant sources of UHC [6,7].

The PLIF images were obtained with a Roper Scientific PI-Max intensified camera (512×512 pixels) equipped with a Vivitar 28-135 mm f/2.8-3.8 macro zoom lens. For each test condition, 50 single cycle images were acquired at each crank angle considered, using a 100 ns camera gate. All images were obtained at the same camera gain. An average background image, collected during motored operation prior to firing, was subtracted from the data images to eliminate spurious signal from the windows and injector tip. Variations in laser sheet irradiance caused by refraction and reflection from the piston surfaces were accounted for by normalizing the data with an average flat-field image. The flat-field images were acquired at each crank-angle by seeding the intake charge with ~ 3000 ppm of CH_2O . The CH_2O was introduced well upstream of the intake port to ensure a spatially-uniform intake mixture. The effect of noise on the data was reduced with a 3×3 pixel median filter and the images were lightly smoothed with a 5×5 Gaussian filter ($2\sigma = 1.6$ pixels, corresponding to ~ 0.1 mm). Image distortion caused by the cylinder liner windows and the complex piston geometry was corrected for using images of calibration

targets placed within the bowl and upper clearance volumes [14].

Deep-UV CO LIF

Late-cycle CO distributions were measured using a deep-UV CO LIF technique used in a number of previous engine studies [7,8,9]. Fluorescence from CO and PAH was excited by a 230.1 nm laser beam generated by frequency doubling the 460.2 nm output of an optical parametric oscillator (Spectra-Physics MOPO 730). Swan band C_2 fluorescence is also observed at this excitation wavelength resulting from laser-induced fragmentation fluorescence (LIFF) of acetylene and other combustion intermediates [15,16]. The excitation beam was focused in the center of the cylinder by a cylindrical lens ($f = 1000$ mm), resulting in a laser sheet width of ~ 500 μm . The location of the laser sheet was adjusted daily to ensure the most intense portion of the sheet was imaged. Typical laser pulse energies of 15 mJ were delivered to the engine cylinder. These high laser energies required the laser access windows in the liner (Fig. 1) to be replaced with smaller, ArF grade fused silica windows ($d = 20$ mm). The mounts required for the ArF windows impeded laser access into the clearance volume until $\sim 30^\circ$ aTDC.

Fluorescence was collected by an f/4, 1/4-meter spectrograph (SPEX 270M) equipped with a 384×576 pixel intensified CCD detector (Princeton Instruments ICCD-576E). The spectrograph contained a 400 groove/mm grating providing a spectral range of 394 to 510 nm, and the entrance slit was adjusted to 0.5 mm giving a 5.3 nm spectral resolution. The resulting horizontal “line” images (see Fig. 1) contain spectral information along the cylinder radius traversed by the laser. The spectrally resolved measurements were acquired at 30° aTDC for two separate heights located 2.9 and 6.0 mm below the head and at 50° aTDC for heights 2.9, 10.4, and 17.9 mm below the head. Corrections for background signal, noise, and variations in laser irradiance were performed and the data were further separated into 13 spatial bins, each 3 mm wide, spanning radial locations from the injector tip to within 2 mm of the cylinder wall. A LIF spectrum was generated for each spatial bin by integrating the image intensity at a given wavelength over all the pixels within each bin.

Figure 3 shows a sample measured spectrum highlighting the characteristics of the CO, C_2 , and PAH signals. The individual contributions from the CO and C_2 fluorescence were determined by modeling the measured spectrum as a superposition of a linear PAH background and three Gaussian functions centered on the CO and C_2 transitions. A least-square error minimization procedure was used to determine the best fit coefficients to the linear background and to the amplitude, center wavelength, and full width at half maximum (FWHM) of each Gaussian function. An example of a measured spectrum, and the modeled fit, is shown in Fig.

3. An approximate two-dimensional CO distribution was generated at each crank angle (30° and 50° aTDC) by applying a spline fit to the data obtained in each spatial bin at each height, and extrapolating the results to the walls using a constant slope boundary condition. This technique can also provide an alternative measure of the UHC distribution from the PAH and C₂ components of the modeled fit. Except as noted below, the results obtained are comparable to those seen in the PLIF images and are therefore not presented here. Additional details on the setup and data processing techniques mentioned thus far can be found in [7,8,9].

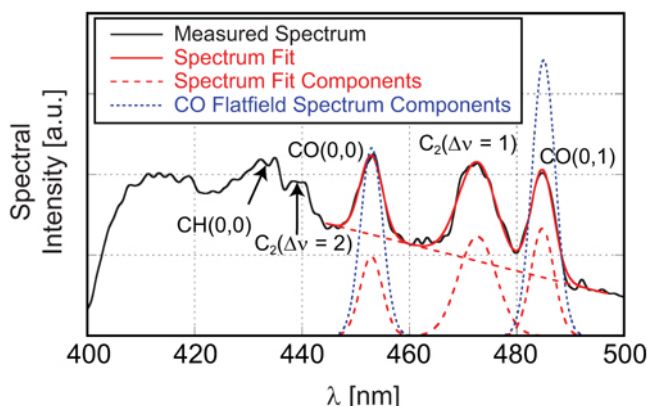


Figure 3. Sample measured spectrum, 6.0 mm below the head at 30° aTDC, showing measured CO, CH and C₂ transitions along with estimated PAH background and Gaussian fits between 445 and 495 nm. CO signals derived from a flatfield image are shown for comparison.

In this study, the qualitative CO distributions were further processed to convert the measured signals to CO mole fraction values. This was done by referencing the signal to the signal obtained in a homogeneous mixture, following Eq. (2):

$$x_{\text{CO}ij,\text{corrected}} = x_{\text{CO}} \frac{S_{ij,\text{data}}}{S_{ij,\text{homogeneous}}} \quad (2)$$

where $x_{\text{CO}ij,\text{corrected}}$ is the corrected CO concentration distribution in units of ppm, x_{CO} is the measured CO mole fraction associated with the homogeneous images in units of ppm, and $S_{ij,\text{data}}$ and $S_{ij,\text{homogeneous}}$ are the data and homogeneous mixture signal levels in units of camera counts. The subscripts i and j refer to the radial location (bin) and height, respectively. The homogeneous field images were acquired during motored operation by introducing CO into the intake plenum far upstream of the intake valve to ensure proper mixing. The engine-out emissions of CO were recorded simultaneously with the homogeneous images to determine x_{CO} in Eq. (2). Additional temperature and pressure corrections were performed to account for the

differences in thermodynamic conditions between the data and homogeneous field images. These corrections incorporated absorption and quenching effects, assuming a quenching-dominated fluorescence regime. Differences in the two-photon absorption rate, which is temperature and pressure dependent, were corrected for using a polynomial fit to the magnitude of the calculated, pressure-broadened absorption spectrum at the excitation wavelength. The effects of absorption of the excitation laser and fluorescence emissions by in-cylinder soot and other molecules were not incorporated into the data correction procedure.

The temperature and compositional dependency of the quenching rate coefficient was evaluated from the composition and temperatures predicted by homogeneous reactor simulations constrained to follow the measured cylinder pressure, which were performed over a broad range of equivalence ratios. Little compositional dependency was observed, and a polynomial fit to the temperature dependency, averaged over the compositions expected for each temperature range, was developed. The absorption and quenching corrections were evaluated at the measured cylinder pressures and estimated temperatures. For the motored, homogeneous field images, the in-cylinder temperatures were estimated as the isentropic compression temperature at the proper crank angle. The temperatures appropriate to fired operation were estimated as the adiabatic temperature predicted by the homogeneous reactor simulations performed at $\phi = 0.3$. Additional details of the temperature and pressure corrections applied to the CO diagnostic are supplied in [Appendix A](#).

RESULTS

The results of this study are presented in two stages: (1) the combustion performance (AHRR) and engine-out emissions measurements, and (2) the results of the UHC PLIF and deep-UV UHC and CO LIF imaging. The emissions and AHRR are used to characterize the effect of fueling the engine with the selected biofuel blends and the optical diagnostics are, then, used to provide insight into the observed differences in combustion performance.

ENGINE-OUT EMISSIONS AND HEAT-RELEASE

Engine-out emissions were initially investigated by performing a start of injection (SOI) sweep for each of the fuel blends. Engine-out emissions of UHC, CO, NO_x, and soot were acquired at actual SOI timings ranging from 30.3° to 5.1° bTDC in 1.8° increments. The injection duration for each condition was modified to maintain a consistent IMEP of 3.0 bar, and was approximately 6.4°. Measured UHC, CO, NO_x, and soot emissions are shown in [Figs. 4,5,6,7](#).

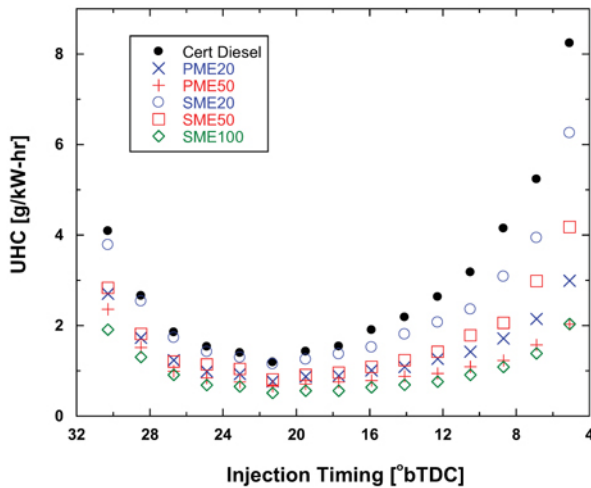


Figure 4. Engine-out UHC emissions results from SOI timing sweep. Operating condition: 1500 RPM, 3.0 bar IMEP, 10% O₂. Behavior of UHC emissions is similar for all fuels with a minimum located near SOI = 21° bTDC.

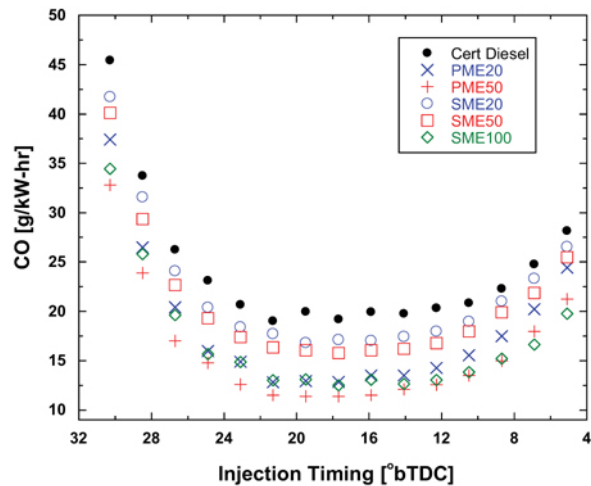


Figure 5. Engine-out CO emissions results from SOI timing sweep. Operating condition: 1500 RPM, 3.0 bar IMEP, 10% O₂. Behavior of CO emissions is similar for all fuels with a minimum located near SOI = 19° bTDC.

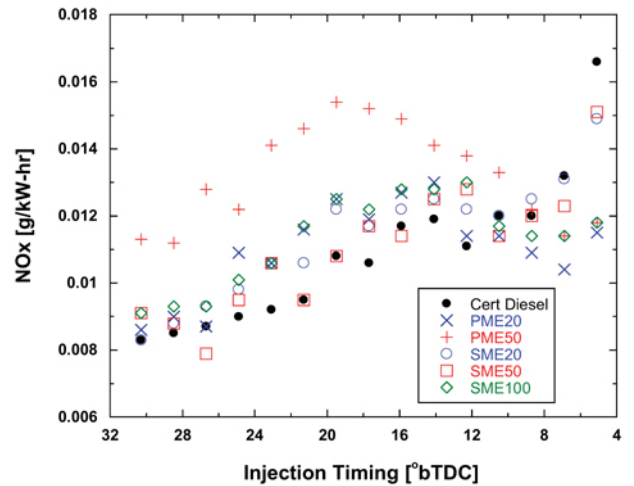


Figure 6. Engine-out NO_x emissions results from SOI timing sweep. Operating condition: 1500 RPM, 3.0 bar IMEP, 10% O₂.

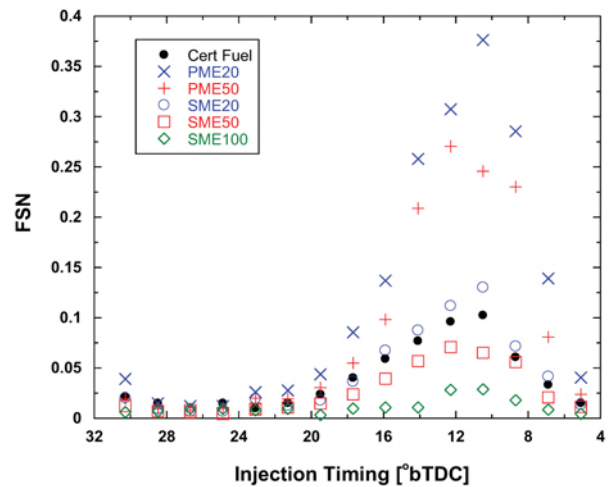


Figure 7. Filter Smoke Number (FSN) results from SOI timing sweep. Operating condition: 1500 RPM, 3.0 bar IMEP, 10% O₂.

The general behavior of the UHC and CO emissions with respect to SOI is independent of the fuels studied. In all cases, a minimum in UHC exists at an SOI of 21° bTDC while the minimum in CO is located closer to 19° bTDC. As the injection is advanced or retarded from these timings, the UHC and CO emissions increase. Previous investigations attributed the increased emissions at advanced injection timings to larger amounts of fuel penetrating into the squish region [5,9,17] and the increase at retarded timings to formation of lean mixtures in the squish region incapable of completing combustion [9]. The fact that the SOI behavior of the UHC and CO emissions is the same for each of the selected fuels suggests that the effects of spray targeting (mainly controlled by the SOI timing) has a larger impact on UHC and CO emissions than the property differences that