

Low Temperature Heat Release of Palm and Soy Biodiesel in Late Injection Low Temperature Combustion

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ABSTRACT

The first stage of ignition in saturated hydrocarbon fuels is characterized as low temperature heat release (LTHR) or cool flame combustion. LTHR takes place as a series of isomerization reactions at temperatures from 600K to 900K, and is often detectable in HCCI, rapid compression machines, and early injection low temperature combustion (LTC). The experimental investigation presented attempts to determine the behavior of LTHR in late injection low temperature combustion in a medium duty diesel as fuel varies and the influence of such behavior on LTC torque and emissions. Two experiments were performed: the first studies two operating modes (conventional combustion with -8° after top dead center injection timing and 0% EGR and low temperature combustion with 0° after top dead center injection timing and nominally 42% EGR level) with standard petroleum diesel, palm biodiesel, and soy biodiesel; the second studies a sweep of EGR level from 0% to nominally 45% with petroleum diesel and palm biodiesel with a constant injection timing of 0° after top dead center. LTHR is apparent in all fuels' rates of heat release profiles at the LTC operating condition. Diesel fuel displayed a longer and more intense LTHR phase. Lower amounts of LTHR in the palm biodiesel causes less sensitivity to EGR, less instability, and produces better torque and emission characteristics.

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INTRODUCTION

LTC is an advanced mode of combustion that simultaneously reduces NO_x and soot emissions from the cylinder of an engine [1, 2, 3, 4]. This simultaneous reduction in NO_x and soot emissions results from a combination of low equivalence ratios and combustion events occurring below the soot and NO_x formation temperatures; this is often manifested with high amounts of EGR (e.g., 30-60%) [2, 5, 6, 7, 8, 9]. Low temperature heat release, or LTHR, is the first stage of ignition of highly saturated hydrocarbon fuels and can often be observed in typical rates of heat release of certain LTC operating modes. By itself, LTHR takes place as a series of isomerization reactions at temperatures from 600K to 900K [10, 11, 12]; its role in LTC and the corresponding effect on efficiency and emissions are the interests of this study. Specifically, the objectives of this study are to identify the behavior of LTHR and influence on LTC torque and emissions among different fuels, namely petroleum diesel, soy biodiesel, and palm biodiesel.

Biodiesel-fueled LTC experiments show promise for LTC viability, with most experiments exhibiting the same, if not better, combustion and emission characteristics as petroleum diesel LTC [2, 13]. The oxygen content in biodiesel has been shown to produce lower soot luminosity (which is related to soot concentration) than diesel, for late injection timings [14].

For same energy delivery rates, power output improves with an increase in fuel oxygen content due to improvements in combustion efficiency and faster burn rates. [15]. The large CO and HC emissions that plague diesel LTC show improvements when biodiesel is used [2, 16], reduces cylinder to cylinder variations, and improved combustion phasing [17]. The better combustion phasing caused by the fuel properties of biodiesel may be related to the observed lower level of low temperature heat release (LTHR) occurring during combustion.

LTHR is observed to increase with cetane number of paraffinic fuels [18] [19]. It is often masked in conventional rates of heat release by fuel evaporation, heat transfer, and the rapid transition to high temperature heat release; it is minimal in some biodiesel fuels due to the unsaturated fatty acid content that hinder internal isomerizations typical of causing LTHR [10, 20]. There are eight stages to the reaction that cause two-stage ignition: first hydrogen is abstracted from parent paraffin. Then alkyperoxy radical is formed by the addition of an oxygen atom. Next the alkyperoxy radical undergoes an internal isomerization to form an alkylhydroperoxy radical. The alkylhydroperoxy radical decomposes into a carbonyl, an olefin, and a hydroxyl radical, or cyclic ether species and a hydroxyl radical. The radicals formed from the internal isomerization are attacked by oxygen atoms, followed by another internal isomerization which abstracts a hydrogen

atom. The final step produces a keytonhydroperoxide, and hydroxyl radicals [20]. These reactions continue until the energy no longer favors the isomerizations, and a negative temperature coefficient (NTC) is noticed (in some cases where the overall reaction decreases or stops due to the increase in temperature. LTHR generally increases with cetane number and fuel saturation [21]. It can also occur without the presence of NTC regions [22], as presence of NTC indicates the end of LTHR, and not LTHR presence [23].

The study follows an experimental approach, which is described next. Results and discussion center on two experimental sets of data that evaluate three fuels of various oxygen content and cetane number. A brief discussion is provided that focuses on the role of cetane number and other property differences among the three fuels. A summary and conclusions are provided at the end.

EXPERIMENTAL METHODOLOGY

The experiments in this study were performed on a medium-duty four cylinder diesel engine. The engine utilizes electronically controlled solenoid fuel injectors that are supplied by a common rail fuel system, and a charge air system that houses a variable geometry turbo charger, and cooled EGR that is controlled by an electronically controlled valve. [Table 1](#) displays the engine specifications. A General Electric DC dynamometer is used to control speed of the engine as the load is changed. Engine load is first set with petroleum diesel fuel at a conventional combustion condition of 1400 rpm and 68Nm; after this point energy delivery rate (among different combustion modes and fuels) is held constant. It is noted that different results may be observed if torque were held constant among different combustion modes and fuels. The dynamometer controller maintains the speed by adjusting the electric field current utilizing a feedback loop. To adjust engine parameters, a custom engine controller (National Instruments - Drivven, Austin, Texas) was utilized. LTC is obtained by adjusting EGR level (via valve position), and injection timing. In order to focus on the LTHR and LTC only two conditions are reported from the injection sweep and three conditions from the EGR sweep. Operating conditions for the experiments are given in [Table 2](#) and [Table 3](#). An injection timing of -8° after top dead center (ATDC) with 0% EGR is used for the conventional operating mode with fuel rail pressure, boost pressure, and exhaust back pressure the same as the production system calibration. LTC is manifested with a "late" timing of 0° ATDC and an average EGR level of 42% for all three fuels in the mode comparison. An injection timing of 0° ATDC is used during the EGR level sweep between palm biodiesel and petroleum diesel fuels ([Table 3](#)).

Table 1. Engine Specifications

Bore	106 mm
Stroke	127 mm
Cylinders	4
Piston	Bowl in Top
Compression Ratio	16.57:1(measured) ¹ 17:1 (nominal)
Combustion Chamber	Flat head
Injector Type and Number of Holes	Solenoid, 6 holes (0.18 mm dia)
Rated Power	115 kW at 2400 rpm
Rated Torque	430 Nm at 1500 rpm
Ignition	Compression
Induction	Variable geometry turbocharger with EGR
Fuel System	Electronic common rail, direct injection

¹Measured by oil displacement

Three fuels are used in this study to analyze LTHR during LTC.

1. Petroleum diesel (diesel #2) (reference fuel), 2. palm-olein biodiesel, and 3. soy biodeisel. The biodiesel fuels (GreenEarth Fuels LLC, Houston, Texas) are studied in their neat form (no mixing or blending with diesel #2). Fatty acid profiles for the biodiesel fuels are provided in [Table 4](#). Properties of relevance for all the fuels in this study are shown in [Table 5](#).

Table 2. Combustion mode comparison control parameters for all three fuels.

Injection Timing ($^{\circ}$ ATDC)	EGR Level (%)	Fuel Rail Pressure (Bar)	Energy Input (kJ)	Intake Manifold Pressure (Bar)	Exhaust Manifold Pressure (Bar)
-8	0	816	46.80 $\pm$ 0.49	1.205 $\pm$ 0.005	1.644 $\pm$ 0.011
0	42			1.07 $\pm$ 0.004	1.25 $\pm$ 0.02

Table 3. EGR level sweep control conditions for palm biodiesel and petroleum diesel.

Injection Timing ($^{\circ}$ ATDC)	EGR Level (%)	Fuel Rail Pressure (Bar)	Energy Input (kJ)
0	0	816	47.34 $\pm$ 0.32
	35% (palm biodiesel)		
	37% (petroleum diesel)		
	44% (palm biodiesel) 46% (petroleum diesel)		

Table 4. Biodiesel Fatty Acid Content

Fatty Acids	Soy	Palm
C14:0	0	1.18
C16:0	11.4	41.6
C18:0	4.57	4.47
C18:1	21.4	42.9
C18:2	53.8	9.87
C18:3	7.49	0

¹Fatty acid content determined by United States Department of Agriculture Eastern Regional Research.

Various measurements were taken to provide data to meet the objectives of the study. In-cylinder pressure is measured on a 0.2° crank-angle resolution in all four cylinders using standard non-cooled piezo-electric pressure transducers from Kistler, Inc. (Model #6052C32), and the ordinary calibration and fidelity checks were done for this measurement [24]. In-cylinder pressure is used to calculate rates of heat release and heat transfer, bulk gas temperature, and thermodynamic properties using the methods implemented by the single zone model described in Depcik, et al. [25], and the heat transfer coefficient described by Hohenberg [25, 26].

Additionally, injector needle motion from cylinder #3 and fuel injector current for all cylinders are measured on a 0.2° crank angle basis; these data are used to determine start and end of injections. In-cylinder pressure and injector data are collected for 300 consecutive cycles; averaged data of the 300 cycles are reported in this study.

Table 5. Properties of relevance for the three studied fuels.

Property	Diesel #2 (D2) ¹	B100S (Soy) ²	B100P (Palm) ¹
Carbon mass (%) [SAE J1819]	86.09	76.95	76.18
Hydrogen mass (%) [SAE J1819]	13.53	11.76	12.37
Oxygen mass (%) [SAE J1819]	0.78	11.29	11.45
Density (kg/m ³) [ASTM D4052s]	825.5	885	875
Net Heating Value (MJ/kg) [ASTM D240N]	43.01	37.3	37.19
Cetane Number [ASTM D613]	51.3	49.6	64
Viscosity (cSt) [ASTM D445 40C]	2.247	4.066	4.741

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²Bio-Energy Testing and Analysis Laboratory

Gaseous emissions measurements include carbon monoxide (CO) and carbon dioxide (CO₂), both using non-dispersive infrared detection, total hydrocarbons (HC) using flame ionization technique (on a C3 basis), oxygen (O₂) using magneto pneumatic detection, and nitric oxide (NO) using chemiluminescence technique. Corrections for potential changes to species sensitivities through the flame ionization detector were not made as fuels changed. Exhaust sample is filtered and maintained at 190°C to prevent the NO_x and HC from condensing with H₂O in the exhaust; sample to the CO, CO₂, and O₂ analyzers is chilled and dehumidified. The filter smoke number (FSN) is measured with an AVL415s smoke meter. The smoke meter utilizes a reflectance technique to relate the exhaust to a 0 to 10 number called the FSN. A measurement of 0 suggests no smoke while a number of 10 suggests very high smoke (which is not quantifiably defined). The FSN detection limit is 0.002 and the meter's FSN resolution is 0.001. Five samples are taken each measurement; the average is calculated and reported.

Each experiment was repeated over two days and the collected data were averaged; uncertainty bars on data reflect the range of repeatability for the data in addition to the data uncertainty (accuracy and precision) using methods prescribed by Figliola et al. [27].

RESULTS

The results section proceeds in the following manner: first, an argument is made that the existence of LTHR, and its timing during heat release, are independent of the fuels being studied. Second, the role of LTHR in conventional and LTC heat release is discussed in the context of engine torque and emissions. Third and finally, comparisons are made between petroleum diesel and palm biodiesel as LTC is obtained with increasing EGR to provide explanation to the performance and emission behaviors that are observed.

Figure 1, Figure 2, and Figure 3 show the average mixture temperature (i.e., in-cylinder bulk gas temperature as calculated using ideal gas equation) and rate of heat release for LTC of petroleum diesel, palm biodiesel, and soy biodiesel, respectively. It is first noted, before describing LTHR behavior of the fuels, that all three fuels exhibit mostly premixed burning in spite of their relative cetane numbers; this results from the high level of EGR and late injection timing that causes in-cylinder conditions to be such that ignition delay is prolonged, thus rendering mostly premixed burning. All three figures have three zones identified within them. Zone 1 is crankangle duration that corresponds to the ignition delay as defined as the crankangle location of start of injection to the crankangle location of inflection in the heat release curve when the energy released from combustion overcomes the energy needed to vaporize the fuel (i.e., minimum in rate of heat release). Zone 2 is the crankangle duration believed to capture the first stage of ignition (LTHR); this occurs between the end of the ignition delay period and start of high temperature heat release (or hot ignition). Zone 3 is the crankangle duration believed to capture