

Comparison of ULSD, Used Cooking Oil Biodiesel, and JP-8 Performance and Emissions in a Single-Cylinder Compression-Ignition Engine

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ABSTRACT

With the rapid growth of biodiesel production, it is prudent to research ways to improve its operation and performance in an engine, especially concerning fuel economy and exhaust emissions. This requires a thorough understanding of both the biodiesel production and engine operating processes. Completion of a published study of the impact of biodiesel fuel properties on engine operation indicated that it is difficult to draw conclusions about the exact causes of increased NO_x emissions with respect to biodiesel properties without the capability of measuring engine cylinder pressures. As improvements were made to the authors' laboratory, a system to monitor and record pressure inside a diesel engine during operation was constructed to test dissimilar fuels. In the current work, three different fuels were tested in order to investigate combustion phasing, emissions, and fuel consumption as a function of fuel properties such as density, viscosity, Cetane Number, and energy content. The fuels tested were Ultra Low-Sulfur Diesel (ULSD), Used Cooking Oil (UCO) biodiesel produced on campus, and jet propellant number 8 (JP-8). ULSD serves as a control fuel for the test since the engine and injector are designed to utilize this specific fuel. JP-8 was included in order to investigate the feasibility of using this fuel in diesel engines as a part of the United States Military's Single Fuel Forward policy. This policy involves a simplification of battlefield logistics through use of a single fuel across all combustion platforms and will result in the use of JP-8 in older engines that were not intended for this fuel.

The engine used for this study was a single-cylinder direct-injection diesel engine, originally packaged as part of an electric generator. The engine was loaded by applying resistance loads while simultaneously recording in-cylinder pressures, engine speed, torque, and air and fuel flow rates at steady-state conditions. The emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and total hydrocarbons (HC) were also measured. The experimental results indicate that fuel chemistry differences between JP-8, UCO biodiesel, and ULSD result in distinctive combustion characteristics affecting both performance and emissions. Specifically, it was found that UCO biodiesel usage advances injection and combustion timing due to an increased bulk modulus and Cetane Number. This leads to improved combustion efficiency, but also higher NO_x emissions due to higher in-cylinder pressures and temperatures (among other factors). In addition, JP-8 combustion occurs later in the engine cycle than ULSD due in part to a lower bulk modulus and resultant later injection. This results in lower combustion efficiency and NO_x emissions than both UCO biodiesel and ULSD. However, the fuel consumption of ULSD and JP-8 were found to be similar across all loads, indicating a possible reduction in fuel consumption for JP-8 to levels below those of ULSD through optimization of injection timing.

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INTRODUCTION

The demand of liquid fuels, such as diesel and gasoline, for the transportation sector is expected to steadily increase [1]. Some predictions indicate that world liquid fuel consumption will grow from a present value of 86.1 million barrels per day up to 110.6 million barrels per day in 2035.

With respect to this level, transportation is expected to account for roughly 60% [1]. Currently, fuel needs are met using primarily non-renewable fuels derived from petroleum [1]. However, research has shown that compression-ignition engines currently produced can be operated on fuels produced from feedstock oils, known as biodiesel [2,3,4]. Widespread acceptance and usage of biodiesel requires that these fuels



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perform similarly to petroleum-based ULSD with respect to power, fuel economy, and emissions. In addition, other obstacles stand in the way of biodiesel being broadly used in order to offset large quantities of petroleum usage. Biodiesel production must be able to keep up with ever-increasing demand, not displace or compete with food production, and meet the aforementioned economic and environmental requirements. Due to these prerequisites, a significant amount of research is going into the advancement of biodiesel production and operation in engines [2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22]. Specifically, researchers are investigating how the varying properties of the initial feedstock oil changes the way that engines operate and the emissions that they produce [4, 7, 11, 17]. In particular, while biodiesel usage typically results in similar power output, it is understood to result in higher fuel consumption (upwards of 10-15%) due to its lower energy content [4, 10, 22]. This increase in fuel consumption would be even higher if it were not for an improved Cetane Number (CN) leading to earlier combustion than diesel, yielding higher in-cylinder temperatures and combustion efficiency [4, 5, 23, 24]. However, the greater in-cylinder temperatures caused by earlier combustion plays a significant role in engine exhaust emissions. In this regard, biodiesel usage generally results in lower emissions of HC, CO and PM. However, emissions of nitrogen oxides NO_x , composed of NO and NO_2 , are often higher for biodiesel when compared to ULSD [2, 4, 7, 9, 17]. In addition to the influence of temperature on NO_x , research has indicated that specific properties of biodiesel have complex interactions during the combustion process causing significant non-linearity in the NO_x production mechanism [2, 4, 11].

In the work by Cecnle et al. [4], seven biodiesel fuels were produced using vastly different feedstock oils yielding fuels with varying physical and chemical properties. By independently investigating measured properties with fuel consumption and emissions in a Yanmar L100V single-cylinder compression-ignition engine, researchers were able to draw specific correlations between the chemical and physical properties of the fuels with emissions and fuel consumption [4]. For instance, it was found that increasing molecular unsaturation promoted higher NO_x emissions and lower fuel consumption through a combination of enhanced energy release during combustion. Moreover, this led to the presence of additional hydrocarbon radicals leading to further prompt NO_x creation [4, 17]. However, in their study, Cecnle et al. were unable to draw definitive conclusions concerning the effects of biodiesel on the start of injection and combustion, as in-cylinder pressure measurement techniques were not available due to the gradual construction of engine laboratories and student knowledge. In regards to combustion phasing, biodiesel is denser and, therefore, has a higher bulk modulus of compressibility. This increased bulk modulus allows pressure waves to travel through fuel lines faster resulting in earlier injection on engines that utilize

mechanical pump-line-nozzle systems (e.g., the authors engine). In fact, injection can be advanced by up to 1-3° [2, 4, 8, 9, 18, 20]. Furthermore, these researchers found direct correlations between fuel CN and NO_x emissions, but without direct measurement of the start of injection and combustion, their findings could not be substantiated with quantitative results [4].

The primary goal of the current work is to obtain a further understanding of the effects of fuel properties on engine operation and the resulting exhaust emissions. In order to accomplish this, the experimental apparatus used by Cecnle et al. is upgraded with an in-cylinder pressure measurement system as a means of determining injection and combustion behavior [4]. The pressure profile data is used to determine the start of injection and start of combustion by calculating the heat release rate [23]. This is accomplished by running the heat release code written by Depcik et al. [25] using the measured pressure data from current tests. By combining the measurements of start of injection and combustion with the measurement of fuel consumption and emissions, the experimental results are directly compared with fuel properties in order to observe the interdependency for this type of engine.

For the current work, a single biodiesel fuel derived from UCO (canola) was selected and produced on campus per ASTM D975-10c standards [26]. Based on the results by Cecnle et al., this biodiesel was understood to be a reasonable representation of the seven biodiesels used in their study [4]. ULSD was the second fuel selected since the Yanmar single-cylinder engine was originally designed to utilize this fuel, with its particular injection timing set to optimize for both fuel economy and emissions. The final fuel chosen for this study is JP-8. This fuel is chosen in order to investigate the feasibility of operating a diesel engine on JP-8, as proposed by the United States Military as part of the Single Fuel Forward (SFF) policy. This policy aims at simplifying battlefield logistics by requiring a single fuel to operate both ground-based vehicles and aircraft [27,28,29,30]. JP-8 is composed of 60% by volume of iso- and n-paraffins, approximately 20% mono-, di-, and tri-cycloparaffins with the remainder as aromatic hydrocarbons [31]. With respect to combustion performance and emissions, JP-8 has a significantly lower distillation curve profile [31] leading to a higher volatility. This leads to an increased level of vaporization, better atomization, and improved spray formation [13, 27]. As a result, using JP-8 may result in greater fuel economy over ULSD, as found in [31]; moreover, it has a higher Lower Heating Value (LHV) on a mass basis. Its chemical make-up is significantly different than biodiesel and it may have a better CN than ULSD and slightly less than biodiesel [31] (Fernandes et al. did find a lower CN than diesel fuel tested [27], this relates to the variability of JP-8 by location and manufacturer [32]). Due to the lower density, viscosity, and bulk modulus of JP-8, research has shown that injection should occur later than

Table 1. Engine and Generator Specifications

Engine	Value
Manufacturer/Model	Yanmar L100V
Type	Vertical Direct-Injection Compression Ignition
Engine Intake	Naturally Aspirated
Cooling	Air-Cooled
Cycle	4-Stroke
Displacement	435 cc
Number of Cylinders	1
Number of Valves	1 Intake, 1 Exhaust
Bore	86 mm
Stroke	75 mm
Compression Ratio	21.2
Injection Timing	15.5 (+/- 0.5) degrees BTDC
Continuous Rated Output	8.3 hp SAE (6.2 kW)
Rated Speed	3600 RPM
Injector Pressure	19.6 MPa
Aftertreatment	None
Engine Oil Used	Shell 15W-40
External EGR	None
Generator	
Manufacturer/Model	NorthStar 5500BDG
Maximum Output	5500 W
Continuous Output	5000 W
Voltage	120/240 V
Phase	Single-phase (4-wire)
Frequency	59.0-62.0 Hz
Power Factor	100%
Allowable Current (120V/240V)	2@20 Amp / 1@20 Amp

ULSD in a compression-ignition engine with a mechanical fuel pump-line-nozzle system [27, 29]. This relationship presents a specific problem for older engines that utilize these fuel systems since they are subject to a shift in injection timing that adversely influences combustion. This may lead to diminished power, fuel economy, and worse partial combustion emissions [23]. Hence, because of its physical properties and military application, JP-8 serves as a unique fuel to compare with ULSD and UCO biodiesel. From a SFF standpoint, the logistical and economic benefits of operating diesel engines on JP-8 must be compared to the anticipated performance degradation.

TEST METHODOLOGY

The engine used for this study is the Yanmar L100V single-cylinder compression-ignition engine as used by Cecrle et al. [4]. It employs a mechanical fuel pump-line-nozzle system in order to control injection and speed. Furthermore, its compact size and low fuel consumption makes testing of small fuel batches possible. To simulate loading on the engine, a NorthStar alternating-current (AC) electric generator is coupled to the engine and resistance loads were plugged into the AC generator to draw electrical power. The specifications of the engine and generator are indicated in Table 1. Located in-line between the engine and

generator, a Futek torque transducer (model #TRS-705) measures the torque supplied by the engine. The fuel consumption rate and fuel density are measured using a Micro-Motion Coriolis mass flow meter (model #CMF010M). In addition to these measurements, the ambient air temperature, pressure and relative humidity, engine intake air temperature and pressure, exhaust port temperature, and downstream exhaust temperature and pressure are measured using appropriate Omega thermocouples and transducers. Measurement of the engine intake air mass flow is accomplished using a Merriam laminar flow element (model #50MW20-2) attached to an Omega differential pressure transducer (model #PX277-30D5V). Engine speed is determined by measuring the generator electrical frequency using a Woodward genset controller (model #GCP-20). To measure the CO, CO₂, NO, NO₂, and HC emissions, a Sensors, Incorporated Semtech-DS Mobile Emissions Analyzer was connected to the exhaust via a flow straightener and a heated sample line (192°C) with a sample flow rate of 8 mL/min.

Measurement of engine cylinder pressure is accomplished by using a Kistler pressure transducer (model #6052C) located in the cylinder head of the Yanmar engine. The signal from the pressure transducer is amplified using a Kistler charge amplifier (model #5011B) which then outputs an

Table 2. Measured and Literature* Fuel Physical Properties [4, 29, 33]

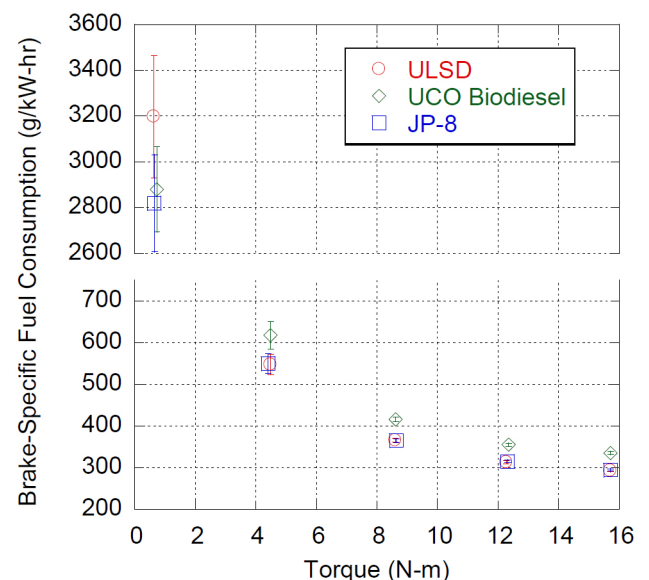
	ULSD	UCO Biodiesel	JP-8
Density (298.15K) (kg/m ³)	831	878	801
Kinematic Viscosity (cSt)	2.268	4.845	1.288
Dynamic Viscosity (cP)	1.885	4.251	1.031
Cetane Number	42.3	52.8	44.5*
Energy Content (kJ/kg)	41530	36210	42700*
Chemical Formula	C ₁₂ H ₂₆	C ₂₀ H ₃₇ O ₂	C ₁₁ H ₂₁ *

analog signal to a National Instruments data acquisition card (model #PCIe-7841R) running LabVIEW 2010. Similarly, the engine crank angle and piston Top Dead Center (TDC) location is determined using a Kistler incremental encoder (model #2614B) connected to a Kistler pulse multiplier (model #2614B4) that passes digital signals to the same National Instruments data acquisition card. During installation of the cylinder pressure transducer, the internal Exhaust Gas Recirculation (EGR) passage in the cylinder head was plugged between the exhaust and intake runners in order to facilitate eventual independent cooled EGR studies while removing the variability of differing levels of EGR. Note that the EGR passage works through an orifice effect that adjusts EGR flow based on a differential between intake and exhaust pressure. Different combustion characteristics that would affect exhaust temperatures would also influence the flow of exhaust gas through the EGR passage and back into the engine. As a result of this orifice being plugged, the results presented do not include the impact of EGR and represent a true measurement of fuel properties on combustion and emissions.

Testing of each fuel occurs at five different loadings of the engine. These are at approximately 0%, 20%, 40%, 60%, and 80% of rated engine torque (engine rated power exceeds generator rated power). Between fuel tests, the fuel tank and line are flushed with the new fuel to be tested. Additionally, sufficient run-time at startup ensures that the previous fuel is no longer present in the testing apparatus. All data is taken at steady-state conditions determined by observing that the exhaust downstream temperature was changing by no more than 1% in one minute. Emissions data is recorded for ten minutes at a sample rate of 1 Hz. During the recording of the emissions data, engine performance data (fuel consumption, torque, air flow, exhaust temperature, etc...) are taken at a sample rate of 10 Hz for two minutes. Concurrently, engine cylinder pressure data is also recorded at a resolution of 0.5° for 20 thermodynamic cycles (40 engine revolutions) to create an average pressure versus crank angle profile from 180° before TDC to 180° after TDC in order to capture both the compression and expansion strokes. Engine motoring pressure data was obtained by recording a pressure profile immediately after disengaging the mechanical fuel pump, thus relying on the engine inertia to provide motion with the air in the cylinder still encountering the hot walls that resulted from combustion.

RESULTS

Following the completion of the testing of ULSD, UCO biodiesel, and JP-8, the steady-state results are analyzed to provide average values to use in comparison between the properties of the fuels as shown in Table 2, with asterisks denoting properties found in the literature. The brake specific fuel consumption (BSFC) of the three fuels at each load is shown in Figure 1. The results indicate an increase of BSFC of about 14% for UCO biodiesel compared to ULSD for loads other than 0%. This increase in BSFC is in agreement with findings in literature and the authors' previous study [4, 10, 22]. Furthermore, the results for JP-8 indicate similar BSFC results to that of ULSD across all loads above 0%, comparable to findings in literature [27, 29]. It is important to mention that because the engine is a single cylinder, there are no other cylinders to smooth out the forces on the crankshaft. As a result, there are increased torque spikes that enlarge the standard deviation of the torque measurements at 0% loading, resulting in higher uncertainty in the BSFC results at this load for all fuels tested.

**Figure 1. Brake-Specific Fuel Consumption vs. Torque for ULSD, UCO Biodiesel, and JP-8**

The brake-specific CO₂, CO, NO_x, and HC emissions results for the three fuels versus engine torque are shown in