PERFORMANCE AND EMISSIONS CHARACTERISTICS OF HYDROPROCESSED RENEWABLE JET FUEL BLENDS IN A SINGLE-CYLINDER COMPRESSION IGNITION ENGINE WITH ELECTRONICALLY CONTROLLED FUEL INJECTION

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To offset the usage of petroleum-based jet-propellant, alternative jet fuels made from sustainable sources are being researched. Due to the Single Fuel Forward Policy, these jet propellant fuels are being used in compression ignition (CI) engines designed to burn ultra-low-sulfur-diesel (ULSD). In the current study, a single-cylinder CI engine with electronic injection timing burns ULSD, jet propellant (Jet-A), and blends of Jet-A with hydrotreated renewable aviation fuel (R-8). Results for Jet-A and R-8 indicate that injection modulation provides performance that is similar or improved compared to ULSD, particularly when considering fuel consumption. Nitrogen oxides, carbon monoxide, and hydrocarbon emissions are all lower than ULSD for both aviation fuels while yielding similar particulate matter emissions. Results show that re-calibration of engine injection timing in order to account for differing aviation fuels could prove advantageous for military logistics through improved fuel consumption.

Keywords: Combustion; Diesel; Hydrotreated

INTRODUCTION

In order to improve battlefield logistics and costs, the North Atlantic Treaty Organization and the U.S. Armed Forces have specified that all land-based military vehicles and aircraft should use a single fuel, Jet-Propellant 8 (JP-8), as part of a Single Fuel Forward Policy (SFFP) (Wadumeastyhigre et al., 2010). Implementation of this policy dictates that engines originally designed to utilize other fuels, such as ultra low sulfur diesel (ULSD), must now utilize JP-8 and associated blends with synthetic/alternative aviation fuels (Mangus and Depcik, 2012; Murphy and Rothamer, 2013; Rothamer and Murphy, 2012). However, these aviation fuels differ in their physical and chemical properties, which can result in significant changes to the combustion process.

JP-8 is a liquid fuel designed for military aircraft that utilize turbines for power, including fighter jets, helicopters, and turboprop engines (Corporan et al., 2007, 2011; Topal et al., 2004). This kerosene-based fuel is composed of approximately 60% of iso- and n-paraffins, about 20% mono-, di-, and tri-cycloparaffins, and aromatics (Hileman
et al., 2010; Mangus and Depcik, 2012). Because of a lower distillation curve, JP-8 has higher volatility than other petroleum-based fuels, such as ULSD (Wadumesthrige et al., 2010). Additionally, this fuel has a relatively low viscosity that leads to better atomization, vaporization, and spray formation inside the combustion chamber of the turbine. The result is enhanced combustion and lower emissions than that of a more viscous fuel like ULSD (Fernandes et al., 2007). Finally, the higher energy content of JP-8 as compared to other petroleum fuels means that aircraft, with limited fuel weight and volume capacity, have improved range and payload capability than would be possible with these other fuels (Hileman et al., 2010). Of note, JP-8 is similar in fuel specifications to Jet-A, which is used for commercial aviation. The difference between these fuels is the requirement that JP-8 also has corrosion and icing inhibitors, as well as additives to improve thermal stability and lubricity (ASTM International, 2009; Murphy and Rothamer, 2013; Topal et al., 2004; United States Department of Defense, 2013).

The use of jet propellants in compression ignition (CI) engines as part of the SFFP is of concern since no standard exists for their cetane index, or cetane number (ASTM International, 2013; United States Department of Defense, 2013). This characteristic, which defines a fuel’s ignition delay following injection, means that the timing of combustion in a reciprocating engine will vary based on batch-to-batch cetane index variation (Heywood, 1988). Since turbines utilize a continuous combustion process, cetane index is not an issue. However, this is a critical concern for a CI engine, where combustion timing is a primary factor in engine performance and emissions behavior (Heywood, 1988; Mangus and Depcik, 2012; Murphy and Rothamer, 2013). To compound the potential issues with cetane index variability, jet propellant fuels also have a lower density than ULSD. Lower density is particularly problematic for older CI engines that utilize mechanically actuated fuel systems (Boehman et al., 2004; Cecrle et al., 2012; Mangus et al., 2014; Mueller et al., 2009; Szybist et al., 2005) where the injection process is dependent on engine speed and the rate at which fuel pressure waves travel from the mechanical pump to the injector (Boehman et al., 2004; Mueller et al., 2009). As a result, jet fuel with a lower density (and associated bulk modulus of compressibility) than ULSD acts to delay injection timing and subsequent combustion phasing in the cylinder as a result of slower moving pressure pulses (Cecrle et al., 2012; Szybist et al., 2005). The delay in combustion timing results in an energy release occurring later in the engine cycle than desired, which results in lower combustion efficiency and an increase in fuel consumption and hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM) emissions.

For more modern CI engines that employ a high-pressure rail injection system, density also influences the injection and combustion event. This occurs because these types of fuel systems inject fuel on a volume-metered basis; hence, a less dense fuel will result in less fuel mass being injected into the cylinder. This affects the amount of fuel available for the start of combustion and the premixed burn phase, subsequently altering the combustion behavior (Demirbas, 2008; Heywood, 1988).

In addition to a variable cetane rating and lower density, JP-8’s higher volatility acts to increase evaporation following injection, leading to changes in mixing and combustion behavior. However, Murphy and Rothamer, in separate works using a single-cylinder compression ignition (CI) engine with both ULSD and jet fuel blends, found that the influence of volatility on combustion, particularly during the premixed burn phase, is negligible (Murphy and Rothamer, 2013; Rothamer and Murphy, 2012). Moreover, jet propellant also has lower fuel viscosity, which will improve the effectiveness of the injector through improved atomization and act to advance combustion. Therefore, in comparison to ULSD,
JP-8 (and Jet-A via its similar nature) can have either a shorter ignition delay due to a higher cetane number and lower viscosity (and possibly owing to a higher volatility), or, in the case of mechanically actuated fuel systems, a longer ignition delay because of its lower density and bulk modulus of compressibility.

Since both JP-8 and Jet-A are derived from petroleum crude oil, there has been significant investigation into sustainable jet fuels that can be produced through renewable sources. One option includes hydrotreated fuels that are produced via a multi-step process in order to generate the desired chemical properties for both long-term storage and combustion (Allen et al., 2013; Blakey et al., 2011; Daggett et al., 2007; Edwards et al., 2010; Hileman et al., 2010; Hui et al., 2012; Kallio et al., 2014; Shonnard et al., 2010). First, feedstock oils (e.g., camelina, tallow, jatropha, and other oils and fats) are converted via transesterification (Kallio et al., 2014) leaving fatty acid chains that are then deoxygenated to remove oxygen present in the fatty acid molecule. Removing oxygen facilitates proper thermal stability, characterized by fuel degradation at high temperatures when oxygen is present (Hazlett, 1991). The remaining $n$-paraffin hydrocarbons are hydrocracked to generate alkanes of desired length, resulting in usable aviation fuel that is approximately 10% $n$-alkanes and 90% iso-alkanes (Blakey et al., 2011; Corporan et al., 2011). Limited turbine experimental results using renewable jet fuel produced via this hydroprocessing methodology show a decrease in HC, CO, and PM emissions. This reduction is attributed to a lower aromatic content for this fuel, as compared to petroleum-based fuels (Blakey et al., 2011). Additionally, experimentation has found that nitrogen oxides (NO\textsubscript{x}) emissions vary between renewable and petroleum-based fuels based on engine and operation parameters (Blakey et al., 2011). Finally, carbon dioxide (CO\textsubscript{2}) emissions and fuel consumption are found to improve for the renewable jet fuel because of an enhanced combustion efficiency and higher fuel energy content (Blakey et al., 2011).

As a combined result of the implementation of the SFFP and the gradual increase of renewable fuel blends in military aviation applications (Blakey et al., 2011; Hileman et al., 2010; Kallio et al., 2014; Moran, 2003; Murphy and Rothamer, 2013; Rothamer and Murphy, 2012), it is critical to investigate the behavior of renewable fuels in reciprocating CI engines. Of particular interest is the behavior of modern common-rail fuel injection systems when using both petroleum and renewable aviation fuels. Because of the similar fuel energy content and advantageous fuel viscosity and volatility, it may be possible to use electronically controlled fuel injection systems to reduce aviation fuel consumption to lower than that of the ULSD, which the CI engine was designed to employ (Mangus and Depcik, 2012; Wadumesthrige et al., 2010).

In the current study, the viability of both Jet-A and its blends with renewable jet fuel in a CI engine is tested. The single-cylinder engine utilized is typically packaged with a mechanical pump-line-nozzle fuel system, as demonstrated in a previous study with jet propellant (Mangus and Depcik, 2012). However, it was updated with an electronically controlled common-rail fuel system that uses a higher fuel injection pressure, subsequently improving fuel spray atomization as compared to the stock fuel system. Additionally, electronic control, combined with real-time in-cylinder pressure measurements, allows for dynamic adjustment of injection timing and quantity. This ability allows for any fuel burned in this engine to be normalized based on the timing of peak pressure for ULSD (Mattson, 2013; Mattson and Depcik, 2014; Zhu et al., 2003). In the current study, blends of Jet A and a renewable fuel are tested using two injection timing strategies to determine the effects of these fuels on ignition delay and combustion. In-cylinder pressure data is used to determine heat release rates and cylinder temperatures in the engine in order to further understand the
influence of these fuels on premixed and diffusion burn behavior. Additionally, measurements of fuel flow and exhaust emissions of the jet propellant fuels are compared to those of ULSD. Findings can be used to not only understand the behavior and viability of a CI engine burning blends of various jet fuels, but also how engine operating parameters may be changed as a means of improving engine performance as a function of fuel used.

FUELS TESTED

In total, seven experiments composed of three fuels and various blends were performed using the single-cylinder CI engine. Locally purchased, non-winterized ULSD serves as the baseline fuel. Jet-A is used as a surrogate to JP-8 because it is locally available and it has similar properties. In addition, blends of Jet-A with 5%, 10%, 20%, and 50% (by volume) renewable jet fuel were examined. Currently, 50% represents the high end of alternative jet fuel blends that have been investigated in either military or commercial aviation applications and is the highest blending level at which these fuels are certified for aviation use (Blakey et al., 2011; Rothamer and Murphy, 2012). Finally, a test of neat renewable jet fuel was performed. This synthetic jet fuel, known as R-8, is produced through hydrotreating using animal fats as the feedstock source.

The fuel properties of interest for this study are cetane number, energy content, kinematic viscosity, density, and flash point, as shown in Table 1. Due to laboratory limitations regarding cetane number measurement, the value for ULSD is assumed based on the ASTM minimum specification (Murphy and Rothamer, 2013). In addition, the cetane number for Jet-A is based on an average of the literature; however, a significant variation with this fuel (from 31.8 to 56) has been observed by other authors (Blakey et al., 2011). Finally, the R-8 cetane number was calculated via ASTM D 976 as indicated by the manufacturer. Cetane number values for intermediate blends of Jet-A and R-8 are based on a mass-weighted average.

Energy content is measured via ASTM standard D240 using a 6200 Paar calorimeter and 600 mg samples. Viscosity is determined using a Koehler KV4000 Series Digital Constant Temperature Kinematic Viscosity Bath per ASTM D445 specifications. ASTM standard D4052 is used to measure density with an Anton Paar Density Meter Analyzer (model 5000 M). Finally, flash point is found with a Pensky-Martens closed cup ISL by PAC (model FP93 5G2) as specified by ASTM D93. Significant uncertainty exists in the measurement of energy content and flash point as shown in Table 1. For example, the measured energy content of the 50% R-8 and Jet-A blend is higher than the energy content of

| Table 1 Fuel properties of ULSD, Jet-A, and R-8 |
|-----------------------------------------------|
| Fuel             | Cetane number | Energy content (kJ/kg) | Energy content (MJ/m³) | Viscosity (mm²/sec) | Density @ 20°C (kg/m³) | Flash point (°C) |
| ULSD             | 40.0          | 45,636 ± 47            | 38,224 ± 39             | 2.578 ± 0.008       | 837.58 ± 0.01          | 55.8 ± 8.4       |
| Jet-A            | 43.4          | 45,956 ± 47            | 36,811 ± 38             | 1.431 ± 0.004       | 801.02 ± 0.01          | 49.3 ± 6.4       |
| 5% R-8/95% Jet-A | 44.6          | 46,109 ± 47            | 36,738 ± 38             | 1.473 ± 0.004       | 799.03 ± 0.01          | 43.1 ± 8.4       |
| 10% R-8/90% Jet-A| 45.8          | 46,127 ± 47            | 36,633 ± 38             | 1.441 ± 0.004       | 797.10 ± 0.01          | 45.8 ± 5.8       |
| 20% R-8/80% Jet-A| 48.3          | 46,270 ± 47            | 36,680 ± 38             | 1.445 ± 0.004       | 792.74 ± 0.01          | 46.4 ± 9.3       |
| 50% R-8/50% Jet-A| 55.8          | 46,610 ± 47            | 36,241 ± 37             | 1.475 ± 0.004       | 779.82 ± 0.01          | 44.8 ± 7.2       |
| R-8              | 68.8          | 46,253 ± 47            | 35,084 ± 36             | 1.542 ± 0.005       | 758.54 ± 0.01          | 48.5 ± 4.6       |
either neat fuel. However, the overall results are consistent with existing literature, with ULSD having a lower energy content and volatility than both Jet-A and R-8 (Murphy and Rothamer, 2013; Rothamer and Murphy, 2012). By inspecting the fuel properties in Table 1, it can be observed that viscosity increases with blend percentage. Additionally, an inverse relationship exists between density and viscosity, indicating that as R-8 blend (and mixture viscosity) increases, fuel density decreases. No general trend can be discerned for flash point, whereas energy content does generally increase with blend percentage. This information is utilized alongside the measured combustion results later in this work in order to analyze engine output emissions and fuel consumption as a function of blend percentage.

TEST APPARATUS AND METHODOLOGY

The single-cylinder CI engine used for this study is a 0.435-liter, 6.2 kW Yanmar L100V that is upgraded from the original mechanical fuel system to a common-rail fuel system. This naturally aspirated engine is manufactured with an exhaust gas recirculation (EGR) port between the exhaust and intake runners; however, this port was blocked to remove the influence of EGR. The original mechanical fuel system is replaced with a common-rail fuel system that utilizes a Bosch MS 15.1 engine control unit (ECU) to manage fuel pressure and injection timing and quantity through the Bosch fuel injector (part #0 445 10 183). The Bosch injector has a different spray configuration than the stock Yanmar injector, but is intended to replicate modern fuel injection systems. Injection pressure is set at 42.0 (±0.03) MPa for these experiments as higher pressure could lead to excessive cylinder pressures and the risk of engine damage. Engine loading is facilitated by using a Dyne Systems, Inc. Dymond Series 12-horsepower regenerative alternating-current dynamometer controlled by a Dyne Systems, Inc. Inter-Loc V OCS controller. Engine torque is measured with a Futek in-line torque transducer (model #TRS-605). Engine fuel flow is measured using a Micro-Motion Coriolis flow meter (model #CMF010M).

In-cylinder pressure measurement is achieved using a Kistler piezoelectric transducer (model #6052C) and a Kistler charge amplifier (model #5011B). Corresponding engine crank angle measurement is determined using a Kistler incremental encoder (model #2614B1) and Kistler pulse multiplier (model #2614B4) at a resolution of 0.5° of engine crank angle. Using a custom LabVIEW program, operators can observe in-cylinder pressure measurements in near real-time for use in injection adjustment. The program saves 60 thermodynamic cycles (120 engine revolutions) of in-cylinder pressure data with the result presented as an average of those 60 combustion events. Gaseous engine exhaust emissions are measured using an AVL SESAM emissions bench, which includes a Magnos 106 oxygen sensor and a flame ionization detector to measure total hydrocarbons. PM data is gathered using an AVL 415SE Smoke Meter. The output of the Smoke Meter provides volumetric concentration in mg/m³, which can be converted to brake-specific PM emissions using engine performance data.

Fuel experimentation occurs through a series of load sweeps from 0.5 N-m to rated load (18 N-m) by 25% increments for each fuel/blend. The engine speed is set to 1800 RPM because this speed represents a mid-point in the engine’s speed envelope that provides a mixture of loads that are predominantly premixed (9.0 N-m) and diffusion burn (18.0 N-m) operating regimes. The first test performed is ULSD, chosen to serve as a control for these experiments. Injection timing for ULSD is based on previous calibration efforts used to determine the minimum fuel consumption at each tested load (Mattson, 2013).
trace data recorded at each load for ULSD is used to subsequently normalize Jet-A combustion timing based on the crank angle at which peak cylinder pressure occurs (Mattson and Depcik, 2014; Zhu et al., 2003). Following the completion of the Jet-A load sweep, testing of 5%, 10%, 20%, 50%, and 100% R-8 blends are performed. For each subsequent mixture, data is first recorded at the ‘unadjusted’ injection timings that were used for Jet-A efforts. Then, the injection timing is changed to normalize combustion timing for each blend based on the measured peak pressure crank angle. This removes the bias of combustion phasing from the analysis where ignition occurs sooner with a higher cetane number fuel (Heywood, 1988; Mangus et al., 2014). The resulting timings (in degrees before top-dead center) used for this study are shown in Table 2.

At each load during a sweep, data recording takes place at steady-state conditions as determined when the exhaust temperature changes by less than 1% over a minute following a change in loading. At steady-state, emissions data collection occurs over a 5-min period at a frequency of one sample per second. Concurrently, engine data is recorded for 2 min at a frequency of 20 samples per second (with internal data filtering). During the collection of engine and emissions data, in-cylinder data is also collected.

**RESULTS AND DISCUSSION**

The results from a steady-state data collection are shown in the figures in this section. First, the behavior of combustion of ULSD, Jet-A, and blends with R-8 is discussed using in-cylinder pressure data along with heat release and cylinder temperature results. Then, brake-specific fuel consumption, emissions, and engine efficiencies are discussed. To demonstrate the importance of injection timing, cylinder pressures as a function of blend are indicated with both the unadjusted and adjusted combustion timing cases. In the interest of brevity, results for adjusted injection timing at 9.0 N-m and 18.0 N-m are presented as examples. These conditions are more repeatable than the 0.5 N-m and 4.5 N-m cases where cycle-to-cycle-variability increases uncertainty. All data is available upon request.

**Combustion Behavior**

The unadjusted and adjusted results for ULSD, Jet-A, R-8, and Jet-A/R-8 blends are shown in Figures 1 and 2. As discussed in the introduction, combined factors act to enhance the premixed combustion phase for Jet-A as characterized by the shorter ignition

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**Table 2** Injection timing for various fuel blend tests at all engine loadings (in degrees before top-dead center)

| Fuel                        | 0.5 N-m | 4.5 N-m | 9.0 N-m | 13.5 N-m | 18.0 N-m |
|-----------------------------|---------|---------|---------|----------|----------|
| ULSD                        | 12.5    | 12.5    | 11.0    | 10.0     | 11.0     |
| Jet-A and unadjusted blends | 12.1    | 12.1    | 10.6    | 9.6      | 10.7     |
| 5% R-8—Adjusted             | 12.0    | 11.9    | 10.4    | 9.5      | 10.6     |
| 10% R-8—Adjusted            | 11.8    | 11.8    | 10.4    | 9.4      | 10.6     |
| 20% R-8—Adjusted            | 11.6    | 11.6    | 10.1    | 9.2      | 10.5     |
| 50% R-8—Adjusted            | 11.1    | 11.1    | 9.7     | 8.8      | 10.4     |
| R-8—Adjusted                | 10.5    | 10.5    | 9.4     | 8.6      | 10.1     |

*Note: Unadjusted blends are injected at Jet-A injection timings at respective load (bold).*
delay of Jet-A for each load tested. The lower viscosity of Jet-A provides the opportunity for better mixing with air in the cylinder. The higher cetane number of Jet-A reflects chemical properties, such as molecule size and configuration, which influence the readiness of the fuel to combust. Findings by Murphy and Rothamer concluded that volatility does not act to shorten ignition delay, but that other factors, such as air entrainment and cetane number, are more influential, particularly at high engine load (Murphy and Rothamer, 2013). Due to the similar magnitude of flash point measured, it is difficult to make any additional conclusions regarding volatility. With respect to the lower density of Jet-A compared to ULSD, the influence of the constant-volume injection of the common-rail fuel system acts to lower the rate of energy (e.g., Table 1—MJ/m³) entering the combustion chamber, particularly before combustion begins reducing the premixed burn phase. Finally, since combustion is
happening closer towards top dead center (TDC) at a higher compression pressure, this added effect promotes higher cylinder pressures. Overall, while less neat Jet-A is being combusted, its peak pressure (shown later in far-left point on Figure 3) is higher than that of ULSD because of an enhanced premixed burn (i.e., viscosity and cetane number) and combustion phasing.

Once peak combustion pressure is aligned by delaying the injection timing (of note, only a 0.3 to 0.4 crank angle change is needed for neat Jet-A in Table 2), the peak cylinder pressure of the tested Jet-A was found to be equivalent to the unadjusted case (also shown later in Figure 3). Combustion is now happening slightly later in the engine cycle during the expansion phase when the piston is expanding the working fluid. Hence, lower pressures are seen during fuel injection and mixing, which acts to increase the ignition delay of Jet-A. As a result, more fuel will enter the cylinder prior to the start of the premixed phase. Therefore, while combustion is happening later, more fuel is entering the cylinder and is prepared for combustion prior to ignition, resulting in an equivalent peak pressure. Similar to the unadjusted case, the enhanced properties of Jet-A promotes a more efficient combustion process over ULSD and a higher pressure.

For the other points shown in Figure 3, the unadjusted pressure traces of Figures 1 and 2 indicate that as R-8 blend increases, combustion advances accordingly because of a higher R-8 cetane number. This advance occurs despite the higher viscosity of R-8 causing larger fuel droplets, which leads to reduced mixing though diminished atomization (He et al., 2008). Overall, this observed advance in combustion timing with R-8 blend causes combustion to happen more towards TDC. Initially, this advance causes the peak cylinder pressure to be higher for R-8 blends in comparison to ULSD as indicated in Figure 3 even though less fuel is combusted. However, the decrease in volumetric fuel energy and increase in viscosity with R-8 blend (Table 1) begins to play a more dominant role and starts to reduce the peak pressure below ULSD.

Similar to the prior discussion with Jet-A, when adjusting R-8 blends for ignition timing, lower in-cylinder pressures are encountered since combustion is occurring when the cylinder volume is expanding more rapidly (Figure 3). More fuel will be injected before
combustion begins; however, inspection of the cylinder pressure results show that as R-8 blend increases, the peak cylinder pressure decreases below ULSD. This is caused largely by the lower volumetric energy content and higher viscosity of R-8, which both act to reduce the premixed burn phase. The reason that R-8 blend peak pressure changes more dramatically with adjustment to injection timing than Jet-A is because of its significantly different properties. As shown in Table 1, Jet-A is relatively similar to ULSD with respect to cetane number, density, and energy content when compared to the differences between R-8 and ULSD. Hence, the adjustment of Jet-A injection timing is somewhat minor. However, the assumed large change in cetane number of R-8 promotes a greater combustion phasing effect (indicated via Table 2). Therefore, accounting for this influence demonstrates a much more dramatic change in peak pressure with blend as elucidated in Figure 3. Hence, the connection between peak pressure and blend percentage is stronger when combustion phasing is normalized, as indicated by the linear curve-fits in both Figures 3a and 3b. This demonstrates why removing combustion phasing promotes a better correlation of results with respect to fuel properties.

For the purposes of this work, the heat release results show the changes in injection duration, timing, and magnitude of premixed combustion, and relative reduction/enhancement of diffusion burn phases (Mattson, 2013). The results from the adjusted injection strategy at 9.0 N-m and 18.0 N-m are shown in Figures 4a and 4b, respectively. The heat release results clearly show the injection event, beginning around 10° before piston TDC (depending on load and injection strategy) and extending towards TDC based on necessary fuel input. It is important to note that the rate of heat release during injection is indicated as a positive rate (negative in reality). This is an artifact of the heat release model used, which assumes that fuel is instantaneously vaporized at injection; hence, energy is assumed to be added to the gas via liquid fuel instantly converting to a gas. This is not physically what is taking place, as a loss occurs in bulk gas energy during fuel vaporization, but was assumed in this model to simplify computational burden during development (Mattson, 2013). Nevertheless, this characteristic is useful for analyzing the injection event due to clear indication of the start and end of injection. Notice that the injection event for higher

![Figure 4](image-url)  
**Figure 4** Heat release rate vs. engine crank angle for adjusted fuel blends at 9.0 N-m loading (a) and 18.0 N-m loading (b).
blends of R-8 is longer than those of Jet-A and low-concentration blends. This is best viewed in the 18.0 N-m results in Figure 4b. In this case, injection is still taking place for 50% R-8 and neat R-8 in both injection strategies when combustion begins. These results support the findings of the cylinder pressure analysis by indicating that R-8 injection takes longer as a result of decreased volumetric energy content, which subsequently acts to reduce the premixed burn phase and increase the diffusion burn phase.

The influence of lower density and associated volumetric energy content for R-8 is apparent for all loads, as the premixed burn phase of combustion is proportionally diminished with increasing R-8 fraction, as shown in Figure 4a, and becomes more pronounced as load increases (Figure 4b). As a result, additional diffusion burn is necessary for R-8 (and neat Jet-A) in order to achieve the proper engine load for both injection timing strategies. Of interest, due to the relatively similar energy content of Jet-A and ULSD, the premixed burn heat release rate magnitudes are comparable at both loads indicated.

The average cylinder temperatures calculated using the heat release model for 9.0 N-m and 18.0 N-m are shown in Figures 5a and 5b, respectively. The results for 9.0 N-m follow largely the trend with premixed burn of Figure 4a since combustion at this load is mainly a function of this phase. In particular, ULSD has lower peak cylinder average temperatures than other fuels/blends because it has the greatest amount of premixed burn (i.e., lowest amount of diffusion burn promoting the coolest residual gas). Correspondingly, the average cylinder temperature of Jet-A exhibits a comparable peak temperature to ULSD because of its similar premixed burn magnitude and crank angle alignment. For Jet-A and R-8 blends, the highest temperature occurs for the lower R-8 blends (e.g., 5% in Figure 5b). This is a function of only a slight reduction in the premixed phase and the augmented diffusion burn phase leaving a relatively hotter residual gas (note the cylinder temperatures around TDC) with an energy input relatively similar to Jet-A. As more R-8 is added, the reduced energy content and density of this component plays a significant role in reducing cylinder temperatures. A longer fuel injection process occurs promoting a slower (less constant volume like), and relatively colder burn. Therefore, while combustion is happening slightly closer to the opening of the exhaust valve (which promotes higher residual temperatures), its cycle temperatures are actually reduced as compared to blends, such as 5% R-8.

![Figure 5](image-url) Cylinder temperature vs. engine crank angle for adjusted fuel blends at 9.0 N-m loading (a) and 18.0 N-m loading (b).
As load increases to rated torque (Figure 5b), the influence of diffusion burn on peak temperature becomes more visible. Specifically, the lowest peak temperatures for the adjusted cases occur for ULSD and Jet-A due to their reduced levels of diffusion burn. As R-8 blend increases and more diffusion burn is necessary, the cylinder temperature rises. This causes a much hotter residual gas as indicated by the wider variation of cylinder temperatures around TDC in Figure 5b. Therefore, the significantly longer injection event and combustion process (due to low volumetric energy content) ends up raising the end gas and initial temperatures causing overall higher temperatures for R-8 blends. In order to eliminate combustion duration effects, follow-up work should increase the fuel injection pressure with blend in order to account for the decreased volumetric energy content of R-8.

Emissions

For this section, only the trends of emissions when combustion is normalized will be discussed in order to understand the direct influence of these fuels on emissions. All data is available upon request.

Nitrogen oxides emissions. Emissions of NO\(_x\) (primarily NO with a smaller fraction of NO\(_2\) ), occur due to high combustion temperatures and a relatively long residence time at these conditions. For the sake of brevity and because of the fact that combined NO\(_x\) is the regulated emissions species, only NO\(_x\) results are discussed here. Furthermore, the individual NO and NO\(_2\) results (available upon request) show similar behavior among all fuels discussed.

The brake-specific results as a function of Jet-A/R-8 blend percentage are shown for 9.0 N-m and 18.0 N-m in Figures 6a and 6b, respectively, with ULSD provided for comparison as a horizontal line. In this figure, comparable values for Jet-A and ULSD are presented. This is to be expected based on the cylinder temperature results and the similarity of Jet-A and ULSD heat release profiles. However, as the fraction of R-8 increases, the NO\(_x\) emissions decrease linearly. While adding R-8 mostly causes the temperature to
increase, the reduction in pre-mixed burn phase (i.e., constant volume like combustion) due to a decreasing volumetric energy content (longer injection duration) and greater viscosity (larger droplet size) results in a slower and more gradual energy release rate, influencing thermal NO\textsubscript{x} emissions. Furthermore, the different molecular structure of R-8 (as noted by the significantly dissimilar cetane number) may play a role in decreasing the prompt NO\textsubscript{x} chemistry pathway (Romero et al., 2013). The effects of injection timing show that the relationship between blend and NO\textsubscript{x} is strengthened slightly when combustion timing is adjusted and combustion happens later. This is because the residence time at high temperatures (promoting NO\textsubscript{x}) is reduced. This results in the unadjusted and adjusted NO\textsubscript{x} emissions diverging as blend percentage increases, demonstrating the usefulness of injection timing modulation in order to address NO\textsubscript{x} levels.

**Partial combustion products emissions.** In the interest of brevity, only the results of CO are present here due to the similar behavior of HC (available upon request) with these fuels and blends. In the CO results of Figure 7, ULSD and Jet-A exhibit analogous CO emissions again based on the similarity of temperatures and heat release profiles. In contrast, R-8 combustion finds significantly lower CO emissions. A rise in CO emissions would be expected because the R-8 diffusion burn is more pronounced than ULSD and Jet-A (Figure 4). As discussed previously, the higher viscosity, and associated fuel droplet size, of R-8 would yield more fuel-rich zones in the cylinder where complete combustion may not occur. However, the mass-based energy content of R-8 is higher than both Jet-A and ULSD. Therefore, while fuel injection takes longer because of its volumetric energy content, the actual amount of fuel needed for power is less (verified later in the fuel consumption discussion). Thus, there is less carbon in the cylinder to form CO, which subsequently leaves more oxygen available to complete combustion. Finally, the higher cetane number and larger global cylinder temperature of R-8 are indicative of a fuel that is more ready to combust, promoting greater combustion efficiencies. This is verified via lower CO emissions with R-8 blend.

**Particulate matter emissions.** PM emissions as a function of R-8 blend ratio at 9.0 N-m and 18.0 N-m of torque are shown in Figure 8, with ULSD indicated as a horizontal
Figure 8 Brake-specific PM emissions vs. blend percentage for unadjusted and adjusted blends at 9.0 (a) and 18.0 N-m (b) loading. Tier 4 regulation at 0.4 g/kW-hr (not displayed).

line. With respect to neat fuels, Jet-A exhibits the lowest PM emissions for all loads below 18.0 N-m. This is a result of Jet-A having the lowest viscosity, leading to advantageous atomization promoting greater premixed burn levels, and an accompanying reduction in diffusion burn, where PM is primarily produced (Heywood, 1988). R-8 and its blends have higher PM production than Jet-A (and ULSD at higher blend percentages) at 9.0 N-m as a result of its reduced volumetric energy content which, as discussed previously, leads to more diffusion burn as compared to Jet-A (Figure 4a). Furthermore, R-8 is more viscous than Jet-A, so atomization by the injector is less effective, increasing the possibility of PM production through larger fuel droplets.

At full load, ULSD and Jet-A produce relatively similar amounts of PM based on the comparable amounts of premixed and diffusion burn between these fuels (Figure 8b). The higher viscosity of ULSD is reasoned why PM is slightly higher than Jet-A. The use of R-8 results in lower PM emissions at rated torque because it has the highest mass-based energy content, lower viscosity (than ULSD), and shorter ignition delay suggesting an advantageous molecular structure. As a result of higher energy content, the overall equivalence ratio in the cylinder is lowest for this fuel, reducing the carbon available to form PM. Furthermore, the higher average cylinder temperatures at this load may help the fuel combust more readily than Jet-A and ULSD in the extensive diffusion burn phase.

Fuel Consumption

Due to the economic and logistical benefits of operating CI engines on aviation fuels, it is important to consider the fuel consumption of CI engines when jet fuels are used. It is also important to consider volumetric energy content to minimize transportation costs. In general, ULSD has the highest fuel consumption because it has the lowest mass-based energy content. The higher viscosity of ULSD, which acts to lower the fuel conversion efficiency, compounds this characteristic result. Because Jet-A has higher mass-based energy content than ULSD it uses less fuel to produce power, thus improving fuel conversion efficiency. Finally, R-8 produces the lowest fuel consumption (and highest
efficiency—plots available upon request) at loads above 0.5 N·m due to R-8 having the highest mass-based energy content. In blends with Jet-A, fuel consumption is improved as R-8 percentage increases, as shown in Figure 9. This decrease in fuel consumption occurs despite the reduced premixed burn phase observed and the longer combustion duration. A future study with timing sweeps of Jet-A and R-8 would provide the opportunity to more thoroughly understand the influence of these fuels on fuel consumption optimization and combustion behavior in a CI engine. Furthermore, investigating the behavior of R-8 with variable injection pressure to increase fuel volume injection rate would provide additional opportunity to understand the effects of renewable jet fuel chemistry on the combustion process.

CONCLUSION

The Single Fuel Forward Policy set forth by the United States military and the North Atlantic Treaty Organization dictates that military internal combustion engine vehicles utilize aviation fuel. This policy is intended to simplify battlefield logistics and costs through transport of a single fuel. Even with modern, adaptive fuel systems, the regulation of jet-propellant fuels does not include cetane number specifications, which are critical fuel parameters needed for optimum compression ignition operation. The challenge of using aviation fuel in a compression ignition engine is further compounded by the addition of renewable jet fuels and variable blends, which have properties that vary compared to petrol-based jet propellants.

The current work uses a single-cylinder compression ignition engine, outfitted with a common-rail fuel system, to investigate the feasibility of petroleum-based jet propellant and its blends with renewable aviation fuels in this type of engine. The common-rail fuel system allows for dynamic adjustment of fuel injection timing. Using this system, Jet-A and blends with a renewable aviation fuel produced through hydrop-processing (R-8) were tested to determine the effects of these fuels on combustion behavior and resultant emissions
and fuel consumption when the engine is left unadjusted, and when it is changed through
dynamic fuel injection control. To serve as a benchmark, these fuels and their respective
blends are tested alongside ULSD.

Comparison of Jet-A to ULSD results shows that an improvement in fuel consump-
tion can occur through injection timing calibration of Jet-A. The results also showed NO\textsubscript{x},
CO, HC, and PM levels that were similar to, or lower than, those of ULSD. This is pri-
marily a result of increased energy content and improved fuel mixing via lower viscosity.
As a neat fuel, R-8 consistently showed lower fuel consumption and emissions of NO\textsubscript{x},
CO, and HC than either ULSD or Jet-A, with PM emissions that were relatively similar to
these fuels. This is caused by the unique combination of higher energy content than either
ULSD or Jet-A, as well as a lower density that made the injection event longer. The effects
of blending Jet-A and R-8 produced generally linear progression from the behavior of one
fuel to the other with blend.

To consolidate the previous discussions, Table 3 summarizes the independent effects
of each fuel property on the combustion process and associated fuel consumption and emis-
sions. Specifically, this table shows the influence of an increase in a specific fuel property
as an increase/decrease (up/down arrow) on measurable performance metrics. Of note,
cetane number is a measured index based on other fuel factors, such as fuel chain length
and structure. Therefore, its effects noted here are based on what occurs for the unadjusted
injection strategy only.

While the long-term effects of renewable aviation fuels on a compression ignition
engine and modern fuel system are unknown, initial engine behavior shows promising
fuel performance because of relatively high energy content and advantageous combustion
characteristics, particularly during the diffusion burn phase of combustion. However, these
positive results require either the recalibration of the engine or the ability of the engine
control system to adapt to the fuel being used.

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**SUPPLEMENTAL MATERIAL**

Supplemental figures for this article can be accessed on the publisher’s website.
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