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COMBUSTION STRATEGIES FOR LOW-CETANE FUELS

Michael Tess, Ph.D., Eric Gingrich, Steve Stoll

U.S. Army Combat Capabilities Development Command
Ground Vehicle Systems Center
Warren, MI

ABSTRACT

The effects of advanced fuel injection strategies on the combustion behavior of an unblended low-cetane synthetic jet fuel (Sasol isoparaffinic kerosene, POSF 7629, derived cetane number 31) were investigated in a single-cylinder research engine (SCRE) at several speeds and loads. The most significant finding of the current work is that the introduction of a small pulse of fuel prior to the main fuel injection event, termed a close-coupled pilot (CCP) injection, effectively mitigates the relatively longer ignition delay time of the DCN 31 fuel. Therefore, a potential technical solution exists that would permit the use of low-cetane jet fuels in military ground vehicles if the operational scenario required it.

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1. INTRODUCTION

Synthetic jet fuels are qualified for operational use in U.S. Department of Defense (DoD) ground vehicles on a limited basis [1]. One of the primary challenges restricting broader DoD usage of synthetic fuels is that their combustion behavior in compression-ignition engines differs from that of conventional jet fuels (i.e., fuels derived from petroleum, shale oil, and oil sand feedstocks) [2-3]. Synthetic fuel properties can differ widely from fossil-derived fuels depending on the feedstock and conversion process used to synthesize the fuel. Whereas a conventional fuel is a mixture of hundreds of different hydrocarbon compounds, the variety of individual components in a synthesized fuel is much smaller. Synthetic fuels may therefore resemble a single-component fuel. This type of composition can result in higher volatility and lower ignition quality, which strongly influences the spray combustion event in compression-ignition engines.

In the MIL-DTL-83133 fuel specification for JP-8 (NATO code F-34), the DoD therefore places the additional combustion property specification that finished fuels consisting of blends of conventional and synthetic jet fuels have a minimum derived cetane number (DCN) of 40 [1]. The cetane number measures the ignition quality of a fuel, where a higher cetane number indicates a higher propensity to autoignite [4]. MIL-DTL-83133 further limits the synthetic fuel volume fraction of blended fuels to no greater than 50%. The intent of these additional requirements is to ensure that fuels containing synthetic blending components are a drop-in replacement for conventional jet fuel with no significant degradation in vehicle performance.

In 2015, U.S. Army policy mandated the use of NATO code F-24 fuel for all continental U.S. (CONUS) military training, operations, and testing, and F-34 fuel for outside the continental U.S. (OCONUS) activities [5]. The F-24 fuel formulation is composed of the commercial aviation turbine fuel Jet A with military additive package (static dissipater additive (SDA), fuel system icing inhibitor (FSII), and corrosion inhibitor/lubricity improver (CI/LI) additives). The commercial standards ASTM D1655 [6] and ASTM D7566 [7] govern the specifications for Jet A fuel, where D7566 applies specifically to synthetic jet fuel blends. It is important to note, however, that although D7566 limits the synthetic fuel volume fraction to 10-50% depending on the blending component, it does not require any additional combustion property specifications, leading to the possibility that a low-cetane fuel (DCN less than 40) could be procured by a DoD agency in CONUS and consumed by its customers.

Previous research on the combustion behavior of a low-cetane synthetic jet fuel indicated a region of low reactivity at certain thermodynamic conditions that could result in a misfire condition in an engine [2,3,8,9]. An optical engine study further suggested that the autoignition chemistry of hydrocarbon fuels may be significantly influenced by the transient fluid-mixing processes at the end of injection [10]. These results lead to the hypothesis that a multi-pulse fuel injection strategy could be developed to regain control over the combustion rate and phasing of low-reactivity jet fuels, such as Sasol iso-paraffinic kerosene (IPK) or Gevo alcohol-to-jet (ATJ) fuel, at low ignition temperatures (750 K to 900 K).

There are several calibration parameters that can be adjusted to maintain engine performance when operating with a low-cetane fuel. These include fuel injection parameters, such as injection timing, rail pressure, and injection strategy (single or multiple pulses per engine cycle), and inlet air flow parameters, such as intake manifold temperature and pressure. Currently, the engine control unit (ECU) of a military diesel engine may control one or more these parameters based on the sensor inputs of inlet manifold conditions, engine speed, and the torque required (i.e., accelerator pedal position) to achieve the optimal combustion phasing at a given condition. Combustion phasing is an important engine performance parameter because it affects engine efficiency, fuel consumption, and emissions.

In current production engines, the state of ECU technology varies widely. For instance, the General Engine Products (GEP) 6.5L V-8 diesel engine used in the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) has a mechanical fuel injection system with fixed injection timing and injection pressure based on engine speed. On the other hand, Caterpillar’s Advanced Combustion Emissions Reduction Technology (ACERT) engines, including the C7 engine used in the Family of Medium Tactical Vehicles (FMTV), have an open-loop controller that adjusts certain calibration parameters to minimize U.S. Environmental Protection Agency (EPA) regulated emissions. This ECU has the capability to adjust injection timing and strategy based on fuel properties [11].

Thus, recent research efforts have been aimed at developing an engine controller that adjusts to fuel-related combustion phasing shifts in real time [12-15]. These projects combined the computing power of state-of-the-art ECUs with real-time, in-cylinder sensing of the combustion event to demonstrate a closed-loop, next-cycle feedback control mechanism that compensates for fuel reactivity by adjusting a combination of calibration parameters to maintain engine performance. There is still a fundamental gap, however, in how to design a combustion strategy that takes advantage of the additional capabilities of these advanced engine controller systems.

The purpose of this paper, therefore, is to experimentally examine the sensitivity of a low-cetane fuel's combustion properties to three calibration parameters: injection timing, injection pressure, and pilot injections.

2. EXPERIMENTAL SETUP

2.1. Single-Cylinder Research Engine

Experiments were performed on an AVL 530 four-stroke single-cylinder research engine that has a custom head designed for high-output diesel-engine operation. The cylinder head features a centrally mounted common-rail injector with four valves actuated by a mechanical camshaft. The engine is rated for 107 kW at 2750 RPM; full engine specifications are given in Table 1.

Table 1. Engine specifications.

Displacement [L]	1.49
Bore [mm]	122
Stroke [mm]	128
Number of valves [-]	4
Compression Ratio [-]	14.0
Swirl Ratio [-]	1.3
Injector orifice number [-]	8
Orifice diameter [mm]	0.167
Flow number [cm^3/30 s] at 0.35 mm needle lift	720
Included angle [°]	147

A diagram of the experimental setup is seen in Figure 1. Air was provided by an external compressed air system that dried the air to a dew point less than -40 °C. The intake manifold was temperature- and pressure-controlled to simulate a turbocharger for steady-state measurement points. Exhaust back pressure was controlled via a butterfly valve in the exhaust system. Air was delivered using a control valve with feedback control from a Coriolis flow meter plumbed in series. There are two swirl-control vanes in the intake manifold that provide an adjustable swirl ratio between 0 and 3.5; for these experiments both vanes were fully opened for a swirl ratio of 1.3. The intake temperature and pressure were measured at the intake manifold that leads into the swirl control vanes on the engine. The exhaust gases were sampled and analyzed using a Horiba MEXA-7100 emissions bench. Particulate measurements (FSN) were made using an AVL 415S smoke meter. An AVL 576 oil and coolant cart was used to control oil and coolant temperature. The oil and coolant flow paths were instrumented with Coriolis flow meters to measure mass flow rate.

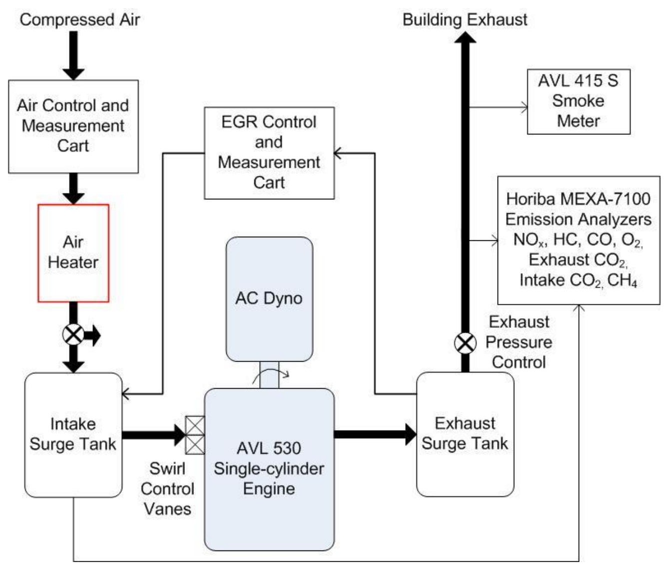

Figure 1: Laboratory setup.

The engine has a high-pressure common-rail fuel system with an open controller able to command multiple injections in an engine cycle at fuel pressures up to 2000 bar. The engine fuel system was supplied by an AVL P404 fuel cart that includes a Coriolis flow meter for fuel mass flow rate measurement.

The combustion behavior of the fuels was explored at the three engine operating conditions listed in Table 2. The types of fuel and their properties are discussed in Section 2.2. Unless otherwise noted in the text (e.g., Section 3.3 Pilot Injection), the injection strategy was a single injection. When changing injection pressure or strategy, the total fuel mass flow rate to the engine was held constant by adjusting the main injection duration.

Table 2: Engine operating conditions.

	Idle	Medium Load	High Speed
Speed [rpm]	750	1700	2750
$IMEP_g$ [MPa]	0.1	1.2	1.2
Intake Pressure [kPa absolute]	102	167	184
Intake temperature [°C]	35	50	50
Air flow [g/cycle]	1.5	2.6	2.6
Rail pressure [bar]	250	1200	1200
Fuel flow [mg/cycle]	10	90	90

2.2. Fuel Properties

A total of two jet fuels were used in this research. The baseline fuel was a locally procured F-24 fuel, and the low-cetane fuel was Sasol IPK (POSF 7629), provided by the Air Force Research Laboratory. The low-cetane fuel was run in the engine in its neat form, that is, unblended with a specification fuel. The fuel properties for the F-24 and IPK fuels are listed in Table 3, along with the applicable specification value according to MIL-DTL-83133 and/or ASTM D1655. The derived cetane number (DCN) reported for each fuel was measured in accordance with ASTM D6890 [16]. Note that the neat IPK fuel does not meet the fuel density and DCN specifications for JP-8. The impact of low fuel density is that engine output and vehicle may range be reduced. Henceforth in this paper, each fuel will be referred to by its DCN value.

Table 3. Fuel properties.

	F-24	IPK	Specification
DCN [-]	42	31	≥ 40 (JP-8 only)
LHV [MJ/kg]	43.0	43.7	≥ 42.8
Density [kg/m^3]	816	761	775–840
Viscosity @ 40 °C [mm^2/s]	1.475	1.129	
Wear scar [mm]	0.54	0.59	
Distillation, 10% [°C]	189	165	≤ 205
Distillation, final [°C]	264	228	≤ 300

2.3. Pressure and Heat-Release Analysis

High-speed engine data, including in-cylinder pressure, were acquired using an AVL Indiset 642 system in conjunction with IndiCom 2.3 software. In-cylinder pressure data were acquired at 0.1° crankshaft rotational angle resolution using an AVL GU22C sensor. An AVL 365C angle encoder measured crank position at 360 pulse/rev, which was subsequently up-sampled to 3600 pulse/rev by an AVL 365Z04M pulse amplifier. Three hundred cycles of engine data were acquired for each operating point then ensemble averaged and filtered using a bandpass type filter with transmission frequencies between 500 Hz and 3500 Hz.

The apparent net heat-release rate (AHRR) was calculated with a single-zone analysis according to Equation 1 [4], where p is cylinder pressure and V is cylinder volume. The ratio of specific heats (γ) was allowed to vary as a function of crank angle (θ), and was based on the instantaneous bulk thermodynamic state. Specific heats were calculated for the varying mole fractions and bulk temperature using NASA ideal gas properties [17]. Mole fractions were modeled assuming an instantaneous and ideal conversion of reactants to products, and a constant fuel mass addition rate was assumed between the start of injection and end of injection. The calculated AHRR is therefore a representation of chemical energy (Q_{ch}) added to the system minus losses, which are primarily dominated by wall heat transfer (Q_w).

$$AHRR = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} = \frac{dQ_{ch}}{d\theta} - \frac{dQ_w}{d\theta} \quad (1)$$

2.4. Determination of Ignition Delay

There are numerous methods in the literature for calculating ignition delay (τ_{ign}) from measurements of a signal acquired in an experimental apparatus such as a shock tube, constant volume combustion chamber, or an engine. This becomes important when comparing τ_{ign} results from various sources. In this paper, the ignition delay was calculated using the pressure recovery method proposed by Groendyk and Rothamer [18]. The pressure recovery method identifies the start of combustion as the crank-angle time at which the cylinder pressure has recovered from the pressure loss due to evaporative cooling effects of the fuel as compared to a reference motored pressure. This method was selected because it was determined to be the most robust and consistent in terms of mitigating the effects of in-cylinder pressure oscillations and the cool flame chemistry more prevalent with low-cetane fuels.

3. RESULTS AND DISCUSSION

3.1. Injection Timing

Advancing or retarding the start of injection (SOI) timing is the most direct strategy to shift the phasing of the combustion event relative to crank position in a diffusion-controlled combustion regime, such as in a conventional diesel engine. For example, Figure 2 shows the cylinder pressure (P_{CYL}) and apparent net heat-release rate (AHRR) versus crank angle (CA) for the 1700 rpm, medium-load operating condition at SOI command (SOIC) timings equal to -22 and -5 crank degrees after top dead center (°aTDC). The cylinder pressure and heat-release rate data clearly indicate a difference in the start of combustion at each injection timing. The longer ignition delay time for the DCN 31 fuel results in more time for fuel-air mixing prior to ignition, which changes the shape of the heat-release rate profile. As a result, the premixed-burn peaks of the DCN 31 fuel are approximately double the magnitude of those of the DCN 42 fuel. Large premixed-burn spikes are undesirable due to their contributions to engine noise, vibration, and harshness, and in extreme cases may exceed the pressure rise rate limit of an engine. In contrast, the diffusion burn portions of the heat-release rate profiles are similar in magnitude and decay to zero at the approximately the same time. The small phasing difference in the end of combustion is explained by the slightly longer injection duration for the DCN 31 fuel case, which was necessary to achieve the same engine load despite the lower density of the fuel.

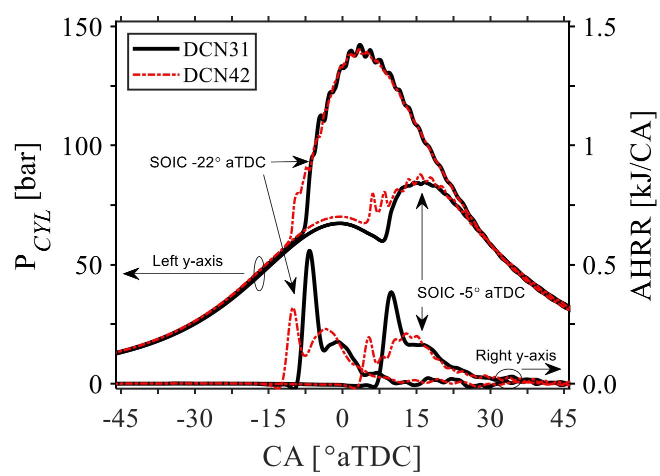

Figure 2: Cylinder pressure (P_{CYL}) and apparent net heat-release rate (AHRR) versus crank angle (CA) degrees after top dead center (°aTDC) for both fuels at 1700 rpm and two injection timings (SOIC -22° and -5° aTDC).

Despite the significant difference in ignition delay between the fuels, the combustion phasing is the same for a fixed SOIC provided the injection duration is long enough to establish a diffusion burn, as in the medium-load and high-speed operating conditions. This is demonstrated in

Figure 3, which plots the ignition delay (τ_{ign}) and crank-angle position where 50% of the net heat release occurs (CA50) for the idle, medium-load, and high-speed operating conditions from Table 2.

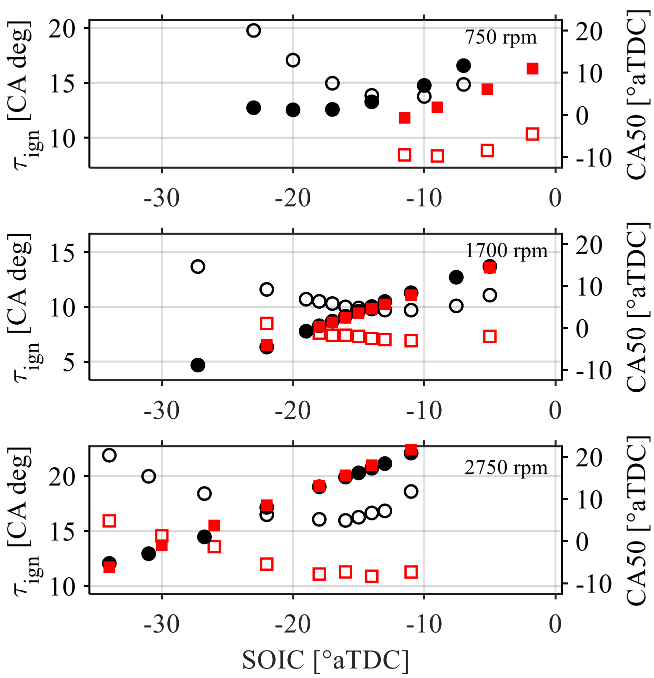

Figure 3: Ignition delay (τ_{ign}, open symbols) and crank angle position where 50% of the net heat release occurs (CA50, filled symbols) versus SOIC at 750 rpm (top), 1700 rpm (middle), and 2750 rpm (bottom). DCN 31 fuel: circles; DCN 42 fuel: squares.

Even though τ_{ign} for the low-cetane fuel averages three degrees longer and five degrees longer across a wide range of injection timings at 1700 rpm and 2750 rpm, respectively, the CA50 timings at each SOIC are remarkably well matched. This finding is significant because it suggests that operating a conventional diesel engine with low-cetane fuel at medium loads and higher does not change combustion phasing, nor require closed-loop feedback control or other tuning of the engine calibration to compensate for the longer τ_{ign}. These results are consistent with the findings of Hansen et al. [11], which evaluated the viable cetane window for two military diesel engines (General Engine Products 6.5T and Caterpillar C7).

Most notably, the top plot in Figure 3 shows that the 750 rpm, idle operating condition follows a different trend with significant implications on engine operability. Ignition delay is a minimum of five degrees longer for a range of injection timings for the DCN 31 fuel, which results in a similar delay in the combustion phasing. These data indicate that engine idle quality may be degraded for low-cetane fuels if the ECU cannot compensate for τ_{ign}. Whereas the rate of combustion is dominated by the fuel-air mixing rate within the fuel spray at medium and higher loads in a diesel engine, the chemical kinetic rates due to fuel composition dominate the combustion rate at low loads. For the short injection durations characteristic of low-load operating conditions, the combustion event is entirely premixed – that is, a standing diffusion flame is not established – so fuel chemistry effects on the ignition delay can impact combustion phasing. This will be explored further in Section 3.2.

3.2. Injection Pressure

Injection pressure has a minor effect on ignition delay through its effect on the physical processes of spray break up and fuel-air mixing. An increase in the injection pressure accelerates spray mixing, but can result in an overmixed condition that negatively impacts combustion efficiency at low loads. This is seen in Figure 4, which shows τ_{ign} and CA50 versus common rail pressure for the idle, medium-load, and high-speed operating conditions from Table 2. Injection timing and total fueling per cycle were held constant to isolate the effect of injection pressure; hence, injection duration necessarily decreased as injection velocity increased.

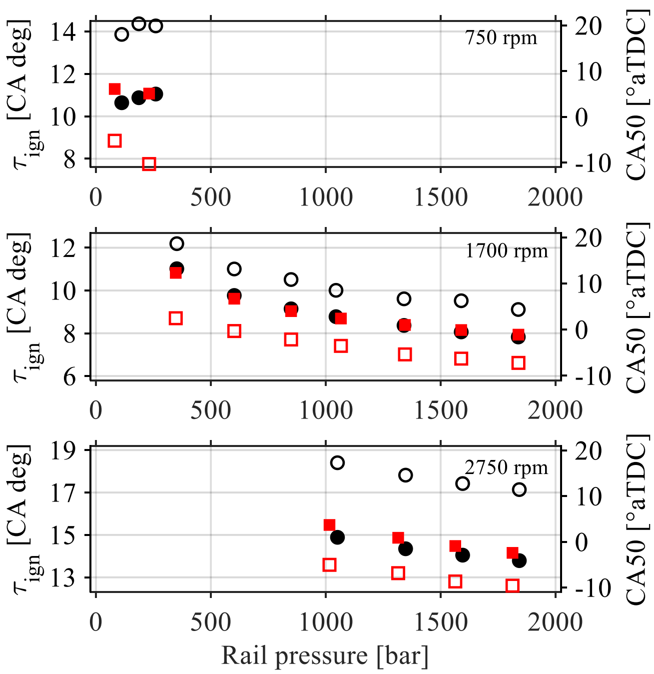

Figure 4: Ignition delay (τ_{ign}, open symbols) and crank angle position where 50% of the net heat release occurs (CA50, filled symbols) versus rail pressure at 750 rpm (top), 1700 rpm (middle), and 2750 rpm (bottom). DCN 31 fuel: circles; DCN 42 fuel: squares.

Two trends again emerge from the data, this time depending on the fuel cetane number. At operating conditions characterized by a pronounced diffusion burn, including the medium load and high speed operating conditions of this work, τ_{ign} and CA50 vary inversely to injection pressure for both fuels. Ignition delay is consistently longer for the DCN 31 fuel regardless of operating condition, and once again CA50 timings show good agreement at 1700 rpm and 2750 rpm. A somewhat different trend is observed for the idle case, where it is noted that injection pressure could only be varied from approximately 100–250 bar to avoid combustion instabilities given the single-injection strategy. Here, the DCN 31 fuel behaved opposite to itself and the DCN 42 fuel at the other conditions: τ_{ign} tended to stay constant or slightly increase with injection pressure, and CA50 actually increased with pressure. Hydrocarbon (HC) and carbon monoxide (CO) emissions were observed to drastically increase with injection pressure for the DCN 31 fuel. These data strongly suggest that the low-cetane fuel became overmixed at higher rail pressures.

This unusual behavior of the DCN 31 fuel at idle is explained by Figure 5, which plots AHRR and injector needle lift (NLFT) for the three injection pressures of Figure 4 (100 bar, 187 bar, and 260 bar). Note that only the lowest injection pressure for the DCN 42 fuel is shown in Figure 5, and the injection timings for each fuel are different to maintain similar CA50 phasing of approximately 3°aTDC.

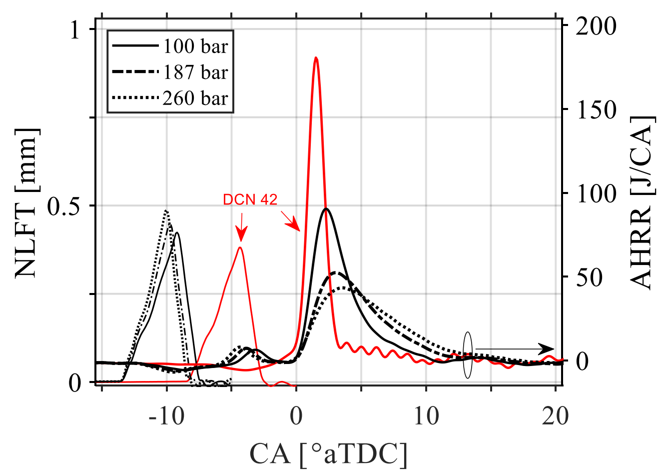

Figure 5: AHRR (right axis) and injector needle lift (NLFT, left axis) versus CA at 750 rpm for three rail pressures. DCN 31 fuel: black traces; DCN 42 fuel: red traces.

Figure 5 shows that the ignition delay for both fuels was sufficiently long at this operating condition that the start of combustion occurred a few crank degrees after the end of injection; this phenomenon is called positive ignition dwell. Interestingly, only the DCN 31 fuel exhibited two-stage combustion behavior, with a low-temperature heat release (LTHR) preceding the main high-temperature heat release (HTHR). As injection pressure increased, the timing of the LTHR advanced slightly while the HTHR remained fixed at TDC with decreasing peak magnitude and a longer late combustion phase. In contrast, the DCN 42 fuel burned to completion in a single-stage HTHR combustion event with a peak magnitude of approximately 180 J/CA; at higher injection pressure (not shown) the peak heat-release rate was also higher. This highlights a disadvantage of high injection pressures: a larger fraction of the total injected fuel burns in the premixed phase, which increases the cylinder pressure rise rates and combustion noise.

From these findings it is hypothesized that combustion of the low-cetane fuel degraded as injection pressure increased because of excessive dwell time between the fuel injection event and the LTHR-HTHR events, during which time the local air-fuel ratios at the periphery of the jet would be too lean to burn and the bulk gas temperature would be decreasing from the expansion process, further slowing the chemical kinetic rates. In short, the increased injection pressures resulted in an overmixed condition for the low-cetane fuel, impeding complete combustion

3.3. Pilot Injection

Multiple injection events per combustion cycle is an increasingly common fueling strategy adopted over the past 20 years to meet diesel emissions regulations, primarily by reducing oxides of nitrogen (NO_x). This advanced injection strategy modulates the heat-release rate of the main combustion event by distributing the total fuel mass per cycle over two or more injection pulses, thereby limiting the high-temperature NO_x formation mechanism. In this section, a pilot-main injection sequence is explored as an approach to compensate for the longer ignition delay of a low-cetane fuel.

The two pilot injection parameters of interest in this work were the pilot dwell, defined as the time period between the end of the pilot injection and the start of the main injection, and the amount of fuel injected in the pilot event. The medium-load operating condition with a fixed main injection timing (SOIC -16° aTDC) was selected as the baseline for comparison purposes because it offered good stability with the DCN 31 fuel. Figure 6 shows the influence of pilot dwell (at fixed pilot quantity) and Figure 7 shows the influence of fuel quantity (at fixed pilot dwell) on two combustion parameters: maximum AHRR (left axis, open symbols) and CA50 (right axis, filled symbols). Data were also acquired with 2000 bar injection pressure for further insights and analysis. The single-injection, baseline conditions for each parameter sweep are represented by the like-colored, styled lines: dashed black lines for maximum AHRR of 1200 bar case; dash-dot blue lines for maximum AHRR of 2000 bar case; thin, solid black lines for CA50 of 1200 bar case; and thick, solid blue lines for CA50 of 2000 bar case. In Figure 7, the pilot quantity parameter was determined from the duration (in milliseconds) the injector needle was open, but because fuel flow scales with injection pressure and the rate of injection data are not available, it is reported herein as an arbitrary unit (a.u.).

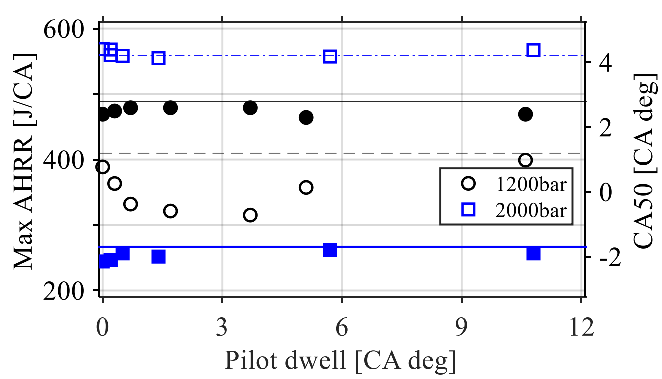

Figure 6: Maximum AHRR (open symbols) and CA50 (closed symbols) versus pilot dwell at two injection pressures with the DCN 31 fuel at 1700 rpm engine speed. Lines: baseline (single injection) cases.

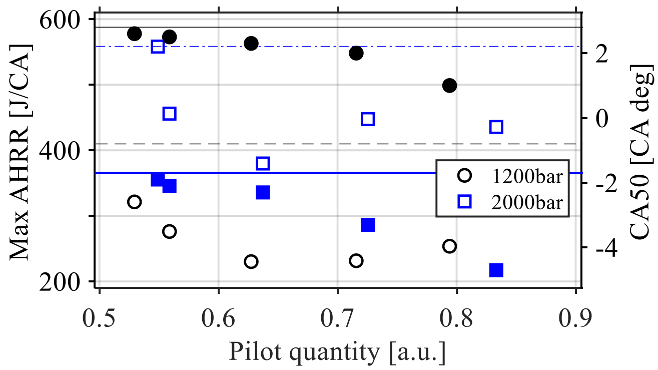

Figure 7: Maximum AHRR (open symbols) and CA50 (closed symbols) versus pilot dwell (top plot) and pilot fuel quantity (bottom plot) at two injection pressures with the DCN 31 fuel at 1700 rpm engine speed. Lines: baseline (single injection) cases.

As previously discussed, the longer ignition delay of the low-cetane fuel can result in very high rates of premixed heat release. The sensitivity of the combustion event to a pilot injection at 1200 bar pressure will be discussed first. Figure 6 illustrates that a small pilot injection (fixed quantity, 0.53 a.u.) with a dwell time of approximately two to four degrees before the main injection event reduced the maximum AHRR to approximately 320 J/CA. In comparison, the maximum AHRR for the single-injection DCN 31 fuel baseline case was 410 J/CA (dashed black line). Figure 7 shows that increasing the quantity of fuel in the pilot injection event (fixed dwell, 1.7 CA degrees) was an even more effective method of tempering the premixed heat-release spike, achieving a minimum of 230 J/CA, or a 44% reduction, at a pilot fuel quantity of 0.63 a.u. Combustion phasing (CA50) was relatively constant with pilot dwell, but advanced about one degree with increasing pilot quantity. At 2000 bar injection pressure, the trends were somewhat mixed. Figure 6 shows that the maximum AHRR and CA50 were insensitive to pilot dwell time at the small pilot quantity (0.53 a.u.) used in this case. Figure 7 confirms the strong dependence of AHRR and CA50 on fuel quantity as was also observed with the 1200 bar fuel pressure cases. The results of Figures 6 and 7 thus suggest that a close-coupled pilot (CCP) injection is an effective technique to compensate for the adverse combustion characteristics of a low-cetane fuel, although the injection timing should be adjusted to locate CA50 at the optimum point for efficiency.

3.4. Close-Coupled Pilot Optimization

Last, this section demonstrates that the combustion characteristics of a low-cetane fuel may be modified using a combination of the previously discussed fuel injection parameters. An optimization of the injection timing, pressure, and CCP will effectively reshape the heat-release rate profile of the low-cetane fuel to mimic that of the high-cetane fuel, thus offering the engine calibrator a robust strategy on how to control an engine operating on a low-cetane fuel.

Figure 8 compares the cylinder pressure and heat-release rate profiles for single injections of DCN 31 and DCN 42 fuels for a fixed injection timing (SOIC -16° aTDC) and injection pressure (1200 bar), and a CCP injection strategy of the DCN 31 fuel. The increased autoignition delay time for the DCN 31 fuel is clearly demonstrated by comparing the cylinder pressure and apparent heat release rate data for the single-injection of the DCN 31 fuel (black traces) to those of the DCN 42 fuel (red traces). The difference in ignition delay for these cases equaled approximately 3.1 CA degrees. Consistent with the results discussed in Section 3.1, the premixed portion of the heat release rate for the DCN 31 fuel was a factor of two larger than the DCN 42 fuel. Switching to an optimized CCP injection strategy with the DCN 31 fuel, plotted in Figure 8 as the blue traces, induced a small LTHR peak while simultaneously aligning the start of combustion and modulating the premixed peak of the HTHR event to closely match those of the DCN 42 fuel. The main injection timing for the CCP case was delayed several degrees to match the CA50 timing of the single injection DCN 42 case (approximately 2° aTDC). For completeness, the optimized injection parameters for the CCP case shown in Figure 8 include 2000 bar injection pressure; SOIC of the main injection event at -10° aTDC; and pilot injection quantity and dwell equal to 0.8 a.u. and zero CA degrees, respectively.

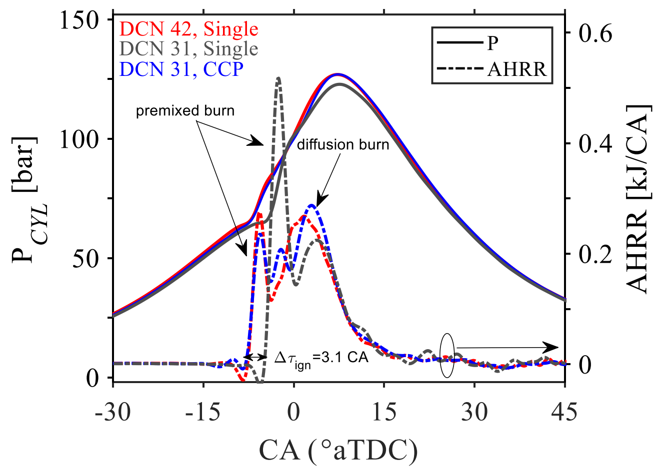

Figure 8: P_{CYL} and AHRR versus CA comparing a single injection strategy with both fuels and a close-coupled pilot (CCP) injection strategy with the DCN 31 fuel.

4. CONCLUSIONS

The most significant finding of this research is that the introduction of a small pulse of fuel immediately prior to the main fuel injection event, termed a close-coupled pilot (CCP) injection, effectively mitigates the tendency of the DCN 31 fuel to delay the onset of combustion. The excessive premixed heat release rates characteristic of a single-injection strategy were also mitigated with the CCP. Also noteworthy is that very low fuel injection pressure (less than 400 bar) with a single-injection strategy was found to avoid combustion misfires at low-load engine operating conditions, such as idle and tactical idle. Therefore, a potential technical solution exists that would permit the use of low-cetane jet fuels in military vehicles if the operational scenario required it.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] MIL-DTL-83133K, Detail Specification: Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37), 2018.

[2] P. Schihl, L. Hoogterp-Decker, and E. Gingrich, "The Ignition Behavior of a Coal to Liquid Fischer-Tropsch Jet Fuel in a Military Relevant Single Cylinder Diesel Engine," SAE Int. J. Fuels Lubr. 5(2):2012, doi:10.4271/2012-01-1197.

[3] P. Schihl, E. Gingrich, and L. Decker, "The Combustion and Ignition Characteristics of Varying Blend Ratios of JP-8 and a Coal to Liquid Fischer-Tropsch Jet Fuel in a Military Relevant Single Cylinder Diesel Engine," SAE Int. J. Fuels Lubr. 8(2):2015, doi:10.4271/2015-01-9073.

[4] J. Heywood, "Internal Combustion Engine Fundamentals, Second Edition", McGraw-Hill Education, New York, 2018.

[5] Army Regulation 70-12, Fuels and Lubricants Standardization Policy for Equipment Design, Operation, and Logistics Support, Headquarters, Department of the Army, Washington, DC, 2015.

[6] ASTM D1655-19, Standard Specification for Aviation Turbine Fuels, ASTM International, West Conshohocken, PA, 2019.

[7] ASTM D7566-19, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, ASTM International, West Conshohocken, PA, 2019.

[8] D. Rothamer and L. Murphy, "Systematic Study of Ignition Delay for Jet Fuels and Diesel Fuel in a Heavy-Duty Diesel Engine," Proc. Combust. Inst. 34(2): 3021-3029, 2013, doi:10.1016/j.proci.2012.06.085.

[9] M. Tess, M. Kurman, and C. Kweon, "Spray Characterization and Ignition Delay Measurements of JP-8 and IPK in a Constant-Pressure Flow Chamber," SAE Int. J. Engines 9(2), 2016, doi:10.4271/2016-01-0736.

[10] M. Musculus, W. Eagle, and L.-M. Malbec, "Ignition Behavior Report for TARDEC Fuel #1 Between 750 and 1000K in the Sandia 2.34L Single-Cylinder Optical Engine", Sandia National Laboratories Report SAND2015-4227, 2015.

[11] G. Hansen, D. Yost, and E. Frame, "Tactical/Combat Engines Cetane Window Evaluation," U.S. Army TARDEC Fuels and Lubricants Research Facility Southwest Research Institute, Interim Report TFLRF No. 436, 2013.

[12] G. Jeal and G. Hunter, "How to Deal with Fuel Found in Theater: CYPRESS-Cylinder Pressure Based Combustion Control for Consistent Performance with Varying Fuel Properties and Types", Proceedings of the 2010 NDIA Ground Vehicle Systems Engineering and Technology Symposium, Dearborn, MI, 2010.

[13] N. Henein, W. Bryzik, C. Jayakumar, et al., "Autoignition Characteristics of Low Cetane Number JP-8 and Approaches for Improved Operation in Military Diesel Engines," Proceedings of the 2011 NDIA Ground Vehicle Systems Engineering and Technology Symposium, Dearborn, MI, 2011.

[14] G. Johnson and G. Hunter, "How to Deal with Fuel Found in Theater: AVL CYPRESS-Cylinder Pressure Based Combustion Control for Consistent Performance with Varying Fuel Properties", Proceedings of the 2012 NDIA Ground Vehicle Systems Engineering and Technology Symposium, Troy, MI, 2012.

[15] N. Henein, W. Bryzik, T. Badawy, et al., "A New Technique to Enable Diesel Engines to Autonomously Operate on Different Military Fuels", Proceedings of the 2013 NDIA Ground Vehicle Systems Engineering and Technology Symposium, Troy, MI, 2013.

[16] ASTM D6890-18, Standard Test Method for Determination of Ignition Delay and Derived Cetane Number (DCN) of Diesel Fuel Oils by Combustion in a Constant Volume Chamber, ASTM International, West Conshohocken, PA, 2018.

[17] B. McBride, M. Zehe, and S. Gordon, "NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species", NASA/TP-2002-211556, 2002.

[18] M. Groendyk, D. Rothamer, "Effects of Fuel Physical Properties on Auto-Ignition Characteristics in a Heavy Duty Compression Ignition Engine," SAE Int. J. Fuels Lubr. 8(1):2015, doi:10.4271/2015-01-0952.