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A diesel engine study of conventional and alternative diesel and jet fuels: Ignition and emissions characteristics

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HIGHLIGHTS

- In-cylinder ignition delay decreases with increasing DCN, 15% for DCN from 40 to 80.
- BSFC and CO and NO emissions are lower for hydroprocessed and F-T fuels.
- Fuel consumption and CO emission are correlated and decrease with increasing DCN.
- NO emissions are correlated and decrease with increasing H/C.

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ABSTRACT

Measurements of ignition delay, CO and NO emissions, and fuel consumption were carried out in a light-duty single-cylinder direct-injection diesel engine for operation with petroleum and alternative hydroprocessed and Fischer–Tropsch diesel and jet fuels. Ignition measurements carried out for a fixed engine speed and injection timing quantify the decrease in in-cylinder ignition delay with increasing derived cetane number (DCN) over a range of DCN relevant to diesel engine operation (DCN = 40–80) and show no discernible dependence of ignition delay on other fuel properties. Brake specific fuel consumption (BSFC) was found to decrease with increasing DCN with strong correlation due to a reduction in ignition time for fixed-injection-timed operation. Brake specific CO emissions were also found to decrease with increasing DCN due to increased time provided for CO burn out due to earlier ignition. Brake specific NO emissions were found to decrease with increasing hydrogen-to-carbon (H/C) ratio, due to the lower peak combustion temperatures and thermal NOx occurring for fuels with higher H/C.

1. Introduction

Fischer–Tropsch (FT) and hydroprocessed diesel and jet fuels are becoming commercially available in larger quantities and have been a focus of the United States Department of Defense for potential use in military aircraft gas turbine engines and diesel engines for power generation, ground transportation, and ship propulsion as a means to reduce dependence on petroleum-based fuels. FT and hydroprocessed fuels can also provide reductions in engine emissions of particulate matter, CO, and NOx [1–3], and avoid the lower energy density and poor cold flow properties of biodiesel.

FT fuels from gas-to-liquid conversion processes and hydroprocessed fuels are primarily composed of n- and iso-alkane components [4] and therefore have different physical and combustion properties, including lower density and higher cetane ratings than petroleum-based diesel and jet fuels, which contain appreciable quantities of aromatics and cycloalkanes. However, note that FT fuels from coal-to-liquid conversion contain large fractions of cyclo-alkanes in addition to n- and iso-alkanes and therefore may have lower cetane ratings [5]. Fuels with unique compositions and properties are also being developed from engineered microbial processes [6].

With the introduction of FT, hydroprocessed, and other alternative fuels into the marketplace and the potential for further utilization of these fuels in combustion engines of a variety of architectures, researchers are motivated to understand the fundamental combustion characteristics of these fuels as well as their performance in engines. The development of predictive models to describe the influence of fuel variability on combustion phenomena and engines is an ultimate goal that requires experimental data for quantitative model validation and trends in combustion characteristics and performance metrics for variations in fuel properties.

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There have been many diesel engine studies where emissions have been measured for operation with different petroleum, FT, and hydroprocessed fuels; for example, see [1–3,7–12] and references within. There have also been experimental studies of diesel engine in-cylinder ignition variability comparing petroleum and FT or hydroprocessed fuels [12–15], although fewer in number than those focused on emissions. Additionally, there have been recent studies on the ignition of FT and hydroprocessed fuels in shock tubes [16,17] and rapid compression machines [18–21] which show the range of gas-phase reactivity of these fuels in controlled reactor environments.

In the present study we investigate the variability of ignition delay, emissions, and fuel consumption for a light-duty diesel engine fueled with a variety of conventional and alternative hydrocarbon diesel and jet fuels of interest to the United States military, with variation in important physical and combustion properties. The results provide information concerning the correlation of important engine performance parameters with variable fuel properties and targets and trends for future modeling studies focused on predicting the influence of fuel variation on diesel engine operation.

2. Experimental method

Experiments were conducted using a Yanmar L100V four-stroke single-cylinder direct-injection diesel engine with specifications listed in Table 1. The L100V has been used by prior investigators [22–25] and provides an inexpensive test-bed for fuel combustion property studies. The light-duty engine (435 cm^3 displacement and 6.2 kW maximum continuous output) has a compression ratio of 21.2 and a mechanical fuel pump-line-nozzle direct injection system. The start of injection is fixed (15.5 degrees BTDC) and engine output is controlled by variation of injection duration. A fixed exhaust gas recirculation (EGR) port exists to reduce NOx emissions, which causes some differences in EGR fraction as a function of load. The engine was operated at a continuous speed of 3600 RPM, common for generator sets and reasonable for other light-duty diesel application, and coupled to a Northstar electric generator capable of output from 0 to 5.5 kW. Electric resistance heaters (Holmes, 1500 W) were used to load the engine-generator set and the electrical power dissipated was measured, acting as a constant speed dynamometer. The heater resistance could be tuned to dial in the desired load, reported here as brake mean effective pressure (BMEP), for a given fuel-load combination.

The engine was instrumented with an in-cylinder pressure transducer and a crank encoder for recording crank-angle-resolved pressure. In-cylinder pressure was acquired every 0.144 crank-angle degrees and averaged for 40 cycles but not filtered. Exhaust emissions of carbon monoxide (CO; 1 ppm resolution, ±10 ppm accuracy) and nitric oxide (NO; 1 ppm resolution, ±5 ppm accuracy) were measured in a ~5 l surge plenum located after a muffler using an electrochemical cell emissions analyzer with a sensor integration/averaging time of 10 s. NO_2 was also measured but for the fuels studied NO_2 emissions were very low, around 5% of NO emissions, due to the high combustion temperatures and negligible oxygen content of the fuels. Electrochemical cell measurements of NO emissions can be subject to cross-sensitivities, particularly when NH_3 is present; however, in this study, where high combustion temperatures are achieved and purely hydrocarbon fuels are studied, the emissions of other nitrogen containing emissions, other than N_2, NO, and NO_2, are expected to be negligible and NO emissions measurements made via electrochemical cells are reliable. Mass-based fuel consumption was determined by measuring the depletion of fuel mass in an auxiliary fuel tank with a high-precision scale (Mettler PM6100, precision of ±0.1 mg for fuel consumption rates of 15–30 mg/min). A schematic of the engine experimental setup is shown in Fig. 1.

The engine can be switched from the primary fuel tank to the auxiliary fuel tank on the fly, allowing the engine to warm up to a thermal steady state using pump diesel prior to switching to operation with a fuel sample of interest. This permitted the use of smaller fuel samples than otherwise would have been required. In the present study, the engine was run on pump diesel for 30 min at a fixed load to allow for complete engine warm up. Then the fueling source was switched on the fly to the fuel of interest contained in the auxiliary fuel tank. The engine then was run at the same fixed load for 4 min at which point steady-state operation could safely be assumed. Measurements showed that the ignition delay, exhaust gas composition, and exhaust gas temperature reached steady state after less than 2 min of operation following the switching fuel sources. Once the engine reached steady operation, the ignition delay, CO and NO emissions, and fuel consumption were measured. Reported CO and NO emissions were averaged over 1 min of operation (i.e., six sensor measurements with 10 s integration times were averaged). Fuel consumption measurements were also carried out for a period of 1 min of engine operation. Ignition delay was determined using in-cylinder pressure, averaged over 40 cycles.

Crank-angle-resolved pressure was used to determine ignition delay, the time interval between the start of injection (SOI) and the start of combustion (SOC). The Yanmar specifications state SOI for this engine is 15.5 degrees before TDC. Measurements of SOI were carried out for all fuels and loads with a high-frequency piezoelectric pressure transducer integrated into the injector line.

Table 1
Engine specifications.

Engine	Yanmar L100V: four-stroke; single-cylinder; vertical direct-injection; compression ignition; naturally aspirated; air cooled
Displacement	435 cm^3
Bore	86 mm
Stroke	75 mm
Connecting rod length	118 mm
Compression ratio	21.2
Valves	Overhead; one intake and one exhaust
Injection	Mechanical fuel pump-line-nozzle injector; start-of-injection (SOI) at 15.5 degrees BTDC at 19.6 MPa *SOI measured with pressure transducer on injector
Speed	3600 RPM
Max rated cont. output	6.2 kW
Generator	Northstar: loads from 0 to 5.5 kW
Pressure transducer	PCB Piezotronics, Model 112A05 in-cylinder (SOC) and injector (SOI)
Crank encoder	US Digital Encoder, Model HD25
Emissions measurements	E instruments emissions analyzer, Model E4400-C (electrochemical cells for CO and NO)