

Direct Sugar to Hydrocarbon (DSH) Fuel Performance Evaluation in Multiple Diesel Engines

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ABSTRACT

A new alternative fuel has been tested in a number of engines and compared to conventional Navy diesel fuel performance using in-cylinder based diagnostics and brake performance comparisons. This new fuel is derived from a Direct Sugar to Hydrocarbon (DSH) process in which sugar and yeast produce a farnesene type hydrocarbon molecule (branched hydrocarbon with multiple double bonds) which is then processed into a moderately branched single alkane molecule (> 98% purity) with a moderately higher cetane number than conventional diesel fuels. This new fuel was extensively characterized and has a lower density, viscosity and bulk modulus as compared to conventional diesel fuel. These physical property differences lead to later Start of Injection times in three diesel engines (AM General GEP, Waukesha CFR and Yanmar). However, due to the increased reactivity of DSH, ignition delay is reduced - faster across most of the speeds and loads tested. While engine operation on the neat form of DSH falls just inside the proposed Navy alternative fuel acceptance criteria at all operating points, it is expected that a 50% DSH and 50% diesel fuel blend will be tested for broader application due to acceptable combustion characteristics in this compression-ignition study.

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INTRODUCTION

The United States Navy has been executing multiple programs to test non-petroleum-sourced fuels so that they may be formally qualified for use in fleet operations. These programs support the Secretary of the Navy's Energy Goals, which outline targets to develop a more energy-secure Navy. These goals include sailing a fully operational "Great Green Fleet" by 2016: a goal now supported by the milestone demonstration of a Carrier Strike Group operating on blends of domestic, renewably-sourced Hydro-processed Renewable Jet (HRJ) and Diesel (HRD) fuel on July 2012. The limiting requirement applied in the qualification program for all candidate non-petroleum fuels is that they must be qualified as "drop-in" replacements. This requirement means that qualified fuels or blends of fuel must be invisible to the user and to the mission, and it ensures that there will be no impacts to materials, engine controls, or engine operation requirements.

As part of the fuel qualification program, a laboratory-scale test of combustion metrics is performed to preliminarily assess a candidate fuel's fitness for use in compression ignition engine applications. The testing provides in-cylinder combustion diagnostics and brake metrics comparisons between an

alternative and baseline fuel. Combustion related diagnostics include start of injection, ignition delay, location of peak pressure, and rate of heat release measurements. A major benefit of comparative fuel assessments is the ability to screen out candidate fuels that exhibit characteristics outside the range of acceptability proposed for each of these diagnostics. These assessments, to be discussed shortly, can be made before large quantities of test fuels are produced and used for the full-scale diesel engine testing phase of the qualification program.

Naval distillate NATO F-76 is used as the primary fuel for propulsion and power generation in a majority of Navy compression ignition engines. A new non-petroleum-sourced liquid fuel derived through a Direct Sugar-to-Hydrocarbon process (DSH) is being tested for qualified use as a blend-stock in F-76. A distinctive chemical characteristic of DSH fuel that differs from any conventional diesel fuel is that it is comprised almost entirely (>98%) of farnesene, a single, C₁₅ branched paraffin. Specification properties of DSH that differ from typical diesel fuels include the absence of aromatics and sulfur, a moderately low density, and a moderately high cetane number. It has been shown that blending a neat DSH component at a composition up to 50% by volume into current

stocks of naval distillate fuel can create a product that meets all physical and chemical requirements in the F-76 procurement specification. In this report, this blend has the designation 50/50 F76/DSH.

Studies have been performed on relative changes in combustion diagnostics with changes in fuel composition (i.e. single molecule, binary mixtures, and synthetic surrogate studies) [1, 2, 3]. Characterization of the thermal behavior of farnesene-based fuel has also been studied [4]. However, there is a limited amount of literature that presents relative combustion metrics measured through diesel engine pressure diagnostics of farnesene-based fuels. The study presented in this report provides a characterization of DSH combustion quality and resulting brake metric effects, and it provides a preliminary assessment on 50/50 F76/DSH76 fitness for use in Navy compression-ignition engines.

FUEL CHARACTERISTICS

DSH production is based on a microbe-catalyzed fermentation process of renewable sugar feedstocks. The hydrocarbon product of fermentation is farnesene, a branched C_{15} olefin. Downstream hydroprocessing and separation of crude farnesene yields an end product that is >98% farnesene, 2,6,10-trimethyldodecane, a saturated C_{15} branched paraffin. Relative to typical bulk diesel fuel chemistry, DSH is unique in that it is essentially a single-molecule fuel.

Table 1 shows the key physical property differences of the DSH, 50/50 F76/DSH, and F-76 samples used for testing. DSH is moderately less dense than baseline F-76, a result attributed to the absence of denser aromatic compounds commonly present in conventional diesel fuels. Thus, the net heating value of DSH when normalized to volume is lower than that of the baseline F-76. DSH has a moderately high Cetane number compared to that of the baseline F-76. The bulk modulus of DSH is lower than that of the baseline F76, indicating that DSH is a more compressible liquid. DSH has a flat boiling point curve as evidenced by the distillation temperatures at 10% and 90% recovery volume points, indicating a change in the fuel volatility profile. The DSH sample exhibits a slightly lower viscosity and surface tension than the F-76.

The moderate deviation of the properties of pure DSH from historical distillate fuel experience is a primary driver for qualifying DSH as a blendstock into conventional F-76 rather than a fully-synthetic alternative. Blending DSH at a ratio up to 50% by volume produces a fuel blend that meets all F-76 specification requirements and is within the range of historical experience of procured naval distillate fuel. Notably, all properties trend with blending as expected.

Table 1. Physical Property Comparisons of Fuel Samples

Fuel Property	DSH	50/50 F76/DSH	F76
Density, 20°C ($\pm 0.2 \text{ kg/m}^3$)	769.4	806.4	841.9
Net Heating Value, 15°C ($\pm 0.8 \text{ MJ/L}$)	34.0	35.3	36.5
Derived Cetane No. (± 1 unitless)	60	56	46
Isentropic Bulk Modulus*, 20°C/0.1MPa ($\pm 2 \text{ MPa}$)	1317	1454	1595
Distillation, 10% vol. recover ($\pm 2^\circ\text{C}$)	244	233	217
Distillation, 90% vol. recover ($\pm 1^\circ\text{C}$)	245	303	316
Kinematic Viscosity, 40°C ($\pm 0.01 \text{ mm}^2/\text{s}$)	2.32	2.61	2.94
Surface Tension, 21°C ($\pm 0.2 \text{ mN/m}^2$)	25.0	26.4	26.9

* Bulk Modulus values calculated from speed of sound measurements

The viscosity of the fuels were measured using an SVM 3000 Stabinger Viscometer (Anton Paar™), while the density and speed of sound were measured using a DS5000 Density and Sound Analyzer (Anton Paar™). The DS5000 analyzer was checked before use with degassed distilled water and recalibrated if it failed the check, as specified by the manufacturer. Duplicate samples of each individual fuel were measured at the specified temperature. The accuracy of the SVM 3000 Stabinger Viscometer was tested with a certified viscosity reference standard (Standard S3, Cannon Instrument Company™) and re-cleaned and retested if the density deviated by more than 0.1% from the reference value and if the viscosity deviated by more than 1% from the reference value. The precision of the instrument was determined from duplicate samples. For each fuel, at least two samples were analyzed at specified temperature.

The isentropic bulk modulus, E_v , was calculated at each temperature and ambient pressure from the speed of sound, (c) and density (ρ) [5].

$$E_v (\text{Pa}) = c^2 (\text{m/s}) * \rho (\text{kg/m}^3) \quad (1)$$

A Kruss USA™ DS100 drop shape analyzer was used to measure the surface tension of the fuels. In this analyzer, a droplet of the organic phase is formed in the air for surface tension measurements. The system then determines surface tension by magnifying an image of the droplet and analyzing its shape using the Young-Laplace equation with inputs of air and fuel density.

Net Heating values were measured on a per mass basis in accordance with ASTM D4809. These values were normalized to density measurements of the fuel taken at 15°C. Derived Cetane Number values were measured with an Ignition Quality Tester (IQT) in accordance with ASTM D6890. Distillation measurements were taken in accordance with ASTM D86, and precision of data from these methods is represented as the respective ASTM method's repeatability.

EXPERIMENTAL SETUP

The first engine used in this study is an AM General Engine Products™ (GEP) 6.5 L V-8 HMMWV “HMMWV” turbocharged diesel engine, manufactured in 2007. The engine is an indirect injection military diesel with no electronic control in order to maximize reliability and durability in the field. It is equipped with 150-bar single hole injectors. [Table 2](#) lists the basic specifications of this engine and the operating conditions used in this study. This engine has been used in a number of previous studies by the authors [6, 7, 8].

Table 2. Experimental engine parameters.

Type	Indirect-injection diesel
Bore	103 mm
Stroke	97 mm
Maximum Power	142 kW at 3600 RPM
Maximum Torque	522 Nm at 1800 RPM
Compression Ratio	21
Coolant	water cooled
Intake Air	turbocharged, 0 – 0.5 bar boost
Fuels	U.S. Navy conventional diesel fuel (F-76) 50-50 blend of these two fuels Direct Sugar to Hydrocarbon (DSH)

The second engine used in this study was a Waukesha CFR diesel engine. This cetane rating engine has been additionally instrumented, described shortly, for research purposes. This engine has been used in a number of previous studies by the authors [1, 2, 3]. This engine is also a mechanical injection IDI engine.

The third engine used in this study was a Yanmar L48V This smaller single cylinder diesel engine is useful in fuels' studies due its low fuel consumption. This engine has also been used in a number of previous studies by the authors [9, 10]. This engine is a DI mechanically injected engine.

All three engines were equipped with Kistler™ in-cylinder pressure sensors and 5010B charge amplifiers. A Kistler 6056 pressure transducer was mounted in the HMMWV engine head, while a model 6125 was used in the CFR, and a smaller 5 mm diameter model 6052 in the Yanmar. Kistler high pressure fuel line sensors were used on the HMMWV and Yanmar engines to determine start of injection, while the stock

CFR injector position sensor was used to analyze the CFR data. Airflow was measured with a Meriam™ laminar flow element appropriately sized to each engine. ETAS™ lambda meters were used in the exhaust of each engine. Data were collected using National Instruments™ LabView data acquisition system sampling at a rate of 50 kHz.

EXPERIMENTAL METHOD & ANALYTICAL TECHNIQUE

In order to conduct the fuel evaluation, the fuel must be switched after each fuel test was performed. After testing with an initial baseline fuel, the fuel system was drained, refilled with the next test fuel, and operated until fuel was pushed completely through the engine. This “flushing fuel” was discarded and then testing continued by refilling the engine fuel tank with new test fuel. Data were collected once the engine was allowed to warm up. The testing was all performed at steady-state operating conditions. No modification was done to the stock fuel system in conjunction with the fueling change. HMMWV engine load sweeps were performed at the following engine speeds: 1500, 1800, 2500 and 3400 RPM. CFR engine testing was performed at four loads using the standard 900 RPM engine configuration. Yanmar testing was performed at 2000 RPM with six different fixed load settings. A blend of 50% F76 diesel with 50% DSH was also tested, however the results are not presented here as they generally fall in between the testing results with diesel fuel and neat DSH fuel.

A conventional heat release analysis modeled after MIT's Single Zone was used to further analyze the engine cylinder pressure data [11, 12]. This single zone model uses a first-law energy balance with combined unburned and burned single zone average properties to determine the rate of energy release. Time domain sampling was converted to crank angle degrees and engine wall heat transfer was accomplished with the conventional instantaneous spatially averaged Woschni coefficient. This analysis was conducted to determine variations in burn rate among the different fuels.

A set of proposed combustion acceptance criteria were recently developed in order to evaluate new fuels in legacy engines. The use of in-cylinder pressure combustion based metrics has been established for many decades, and has been widely shown to be an excellent diagnostic for the bulk nature of diesel combustion. Combustion characteristics such as Ignition Delay (IGD), 10% cumulative fuel burn location, 10-90% fuel burn duration, peak pressure and angle of peak pressure location as well as 50% cumulative fuel burn location have been commonly used for many decades now.

So which metrics are most appropriate to evaluate a new fuel? The answer is not easy due to the coupled and complex nature of diesel engine combustion. So three metrics were chosen as a starting point, and specific criteria were initially based on CFR engine results [13].

Proposed Acceptance Criteria

1. Relative IGD of the new fuel as compared to the baseline fuel is the first combustion metric. As definitions of IGD can vary slightly depending on the method used, the ratio of new fuel IGD to that of the baseline fuel reduces the effect of method used to determine IGD. It is the author's experience that having an IGD that is not too short or too long is critical for a new fuel to operate well in an engine. IGD is also a key fundamental combustion measurement made in laboratory combustion rigs (e.g. bomb, rapid compression machines, etc). It is also a future hope that new fuels may be evaluated more simply first in these types of rigs before expensive engine based fuel testing is pursued. As seen in [Figure 1](#), the initial 'green' (acceptable range is a +/- 20%) [0.8 to 1.2] relative change window for modest brake metric changes that will be discussed in this paper. When IGD changes by more than +/-40% [0.6 to 1.4], the author's experience has shown that potential engine damage (very early combustion) or non-combustion (very late combustion) may occur. The 'yellow' or caution region is initially defined as the region in-between acceptable and not acceptable combustion.
2. Angle Of Peak (AOP) combustion pressure was also chosen as a simple metric for combustion evaluation. The acceptable window has been seen to be quite large, from 4° ATC to 18° ATC depending on the nature of combustion (short or long IGD) leading to less or more fuel and air pre-mixing. When combustion occurs too early peak cylinder pressures become very high leading to potential engine damage, when AOP is late, the engine may not run.
3. The maximum Rate of Heat Release (ROHR) was chosen as a third metric as this reflects the dynamic loading on the engine hardware during combustion. If maximum ROHR is too high, then structural issues may be of concern. The initial criterion used for this metric are a +/-15% change or [0.85 to 1.15] new fuel relative effect.

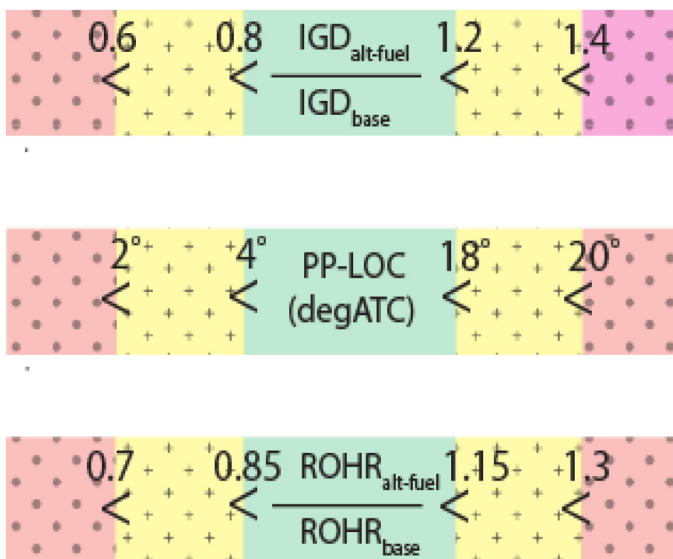


Figure 1. Navy proposed combustion acceptance metrics. Prior work shows the 'green' band (center) differences lead to approximately a ten-percent variation in brake performance metrics. The outside bands are 'red' (with dots). The bands with + signs are the 'yellow' region.

One common combustion metric was not chosen, CA50 or the crank angle where 50% of the fuel is burned. Since CA50 is a strong function of fuel-air premixing (fuel spray effects and fuel kinetic effects), this metric can possess a range of variability making a choice of an acceptable CA50 criterion challenging.

EXPERIMENTAL RESULTS: HMMWV ENGINE

Engine Brake Metrics: BMEP, and BSFC

HMMWV engine data were collected at approximately two dozen speed-load points. Throughout the paper, these data are typically reported as contour lines on a plane of fuel-air equivalence ratio, with ϕ plotted on the horizontal axis with the engine speed on the vertical axis. As shown in [Figure 2](#), the equivalence ratio is proportional to engine brake mean effective pressure (BMEP) for F76 diesel fuel operation. BMEP is engine brake torque normalized by the engine displaced volume, and this metric leads to pressure-based units. As load is increased (increasing Φ) more fuel is injected and thus BMEP increases. At a given level of fueling, brake torque reduces as engine speed increases due to the increased relative importance of engine friction. FMEP (not shown) increases steadily with engine speed and is relatively independent of engine load in this engine. Thus in order to keep brake torque (BMEP) constant at higher engine speeds, more fuel is required.

[Figure 3](#) shows engine torque running DSH normalized to conventional Navy diesel fuel (F76). It can be seen that the torque achieved with DSH fuel is similar to or moderately better (~ 10% better = 1.1 in figure) in the mid-speed & mid-load range. At lower engine speeds the engine brake output is similar with both fuels, while at higher speeds and load the DSH brake output is worse (less than one in the figure). These differences are principally due to changes in combustion phasing as will be discussed shortly.

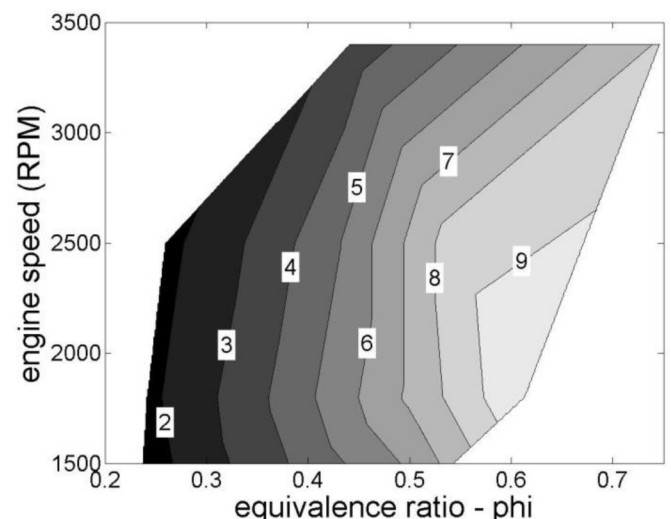


Figure 2. Diesel (F76) BMEP performance.