

On the Ignition Behavior of JP-8 in Military Relevant Diesel Engines

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US Army TARDEC

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ABSTRACT

U.S. Army ground vehicles predominately use JP-8 as the energy source for ground vehicles based on the 'one fuel forward policy'. Though this policy was enacted almost twenty years ago, there exists little fundamental JP-8 combustion knowledge at diesel engine type boundary conditions. Nevertheless, current U.S. Army ground vehicles predominately use commercial off-the-shelf or modified commercial diesel engines as the prime mover. Unique military engines are typically utilized when commercial products do not meet the mobility and propulsion system packaging requirements of the particular ground vehicle in question. In either case, such engines have been traditionally calibrated using North American diesel fuel (DF-2) and overall engine performance degradation while operating on Jet Propellant 8 (JP-8) wasn't given much consideration since any such associated power loss due to the lower volumetric energy density was not an issue for most applications at then targeted climatic conditions. It is becoming more apparent that current and future commercial diesel engine combustion system strategies will be adversely affected by use of JP-8 in comparison to DF-2 due to combustion affecting chemical and physical property differences of 'out laying' global JP-8 samples that are problematic under largely premixed combustion strategies. One important example is ignition quality where the mean cetane index for JP-8 utilized by the U.S. Army during the last five years has been typically in the 43 to 44 range, but the variance has been relatively large depending on the particular supply source with worst case scenarios exhibiting values near 30. Similar variances have been observed with other key properties such as distillation and viscosity.

To date, there has been little research performed on assessing ignition behavior differences between a mean physical and chemical property JP-8 and DF-2. The objective of this

submission is to study and document JP-8 autoignition characteristics under diesel engine-like thermodynamic conditions in order to provide information that might be useful in generating JP-8 ignition models. This effort includes recent ignition data from a single cylinder diesel engine, a production multi-cylinder diesel engine, a shock tube, and a constant volume bomb.

INTRODUCTION

Only within the last decade has the U.S. military focused on research aimed at better understanding JP-8 evaporation characteristics, ignition chemistry, and overall combustion behavior as related to practical combustion devices such as gas turbine combustors and compression ignition engines. Such studies have targeted aviation applications where (1) combustor pressures are low in comparison to diesel engines, (2) nozzle sizes are much larger than typical heavy-duty diesel engines, and (3) injection pressures are an order of magnitude less than today's light or heavy-duty diesel engines. Such efforts have included assessing surrogate pure hydrocarbons that represent JP-8 low and high temperature ignition behavior, laminar flame speed, and evaporation characteristics under pre-ignition pressures typically less than 25 bar [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Extrapolation of such low pressure studies toward diesel engine type pre-ignition conditions is difficult since ignition chemistry tends to vary non-linearly with pressure. This situation is further exacerbated because JP-8 by ASTM D975 standards (DF-2) is a multi-fuel within a single fuel specification - see [Table 1](#) - and in particular, there currently is lack of an ignition quality threshold and narrow range distillation curve.

For example, JP-8 procurement data collected during the last five years has shown that the mean cetane index has varied between 43 and 44 on an annual basis, but the minimum values vary between 35 and 29 within a given year. The JP-8 cetane index distribution for 2007 is shown in figure 1. This

Table 1. Comparison of JP-8 and DF-2 Property Specifications

Property	MIL-SPEC-83133F (JP-8)	ASTM 975 (DF-2)
Cetane index	None	Min 40
Sulfur content (ppm)	Max 3000	Max 15
Lower heat value (MJ/kg)	Min 42.8	None
10% Distillation Point (C)	Max 205	None
90% Distillation Point (C)	None	282 to 338 C
Viscosity (mm ² /s)	Max 8 (-20 °C)	1.9 to 4.1 (40 °C)
Density at 15 C (kg/m ³)	775 to 840	None
Aromatics	Max 25	Max 35

distribution implies that the ignition quality of JP-8 for North American based diesel engines is acceptable over 98% of the time given that ASTM D975 requires DF-2 to have a minimum cetane number of 40. The same statement cannot be made for European based diesel engines that are calibrated to run on higher cetane number diesel fuel in comparison to North American commercial off-the-shelf (COTS) engines. Likewise, the 90% distillation temperature has a worldwide mean value of 253 °C though 5% of the samples fell in the 200 and 225 °C range. ASTM D975 allows DF-2 to have a 90% distillation temperature range of 282 to 338 °C, and thus JP-8 evaporates considerably faster than DF-2 [11-12]. The impact of this difference has never been quantified to date, but it is anticipated to have a minor impact on the heat release event if the mean cetane number of DF-2 and JP-8 are close to their mean values assuming that the mean density of DF-2 is approximately 5% higher than JP-8.

One recent study conducted by the Hellenic Air Force Academy [13-14] focused on combustion variances between European grade DF-2 and JP-8 in single cylinder small bore open (Lister, 3 × 0.23 mm nozzle, 85.73 mm bore, SOI 26 BTDC) and divided chamber diesel engines (Ricardo E-6, 76.2 mm bore, CR 20:1, SOI 38 BTDC). The cetane index of these fuels were 54.8 and 47.0 respectively which are both higher than representative fuels typically employed at U.S. Army test and evaluation centers. The results of this study did show a noticeable impact of JP-8 on the open chamber engine performance, but did not provide much detail concerning thermodynamic conditions during the ignition event and any subsequent heat release analysis.

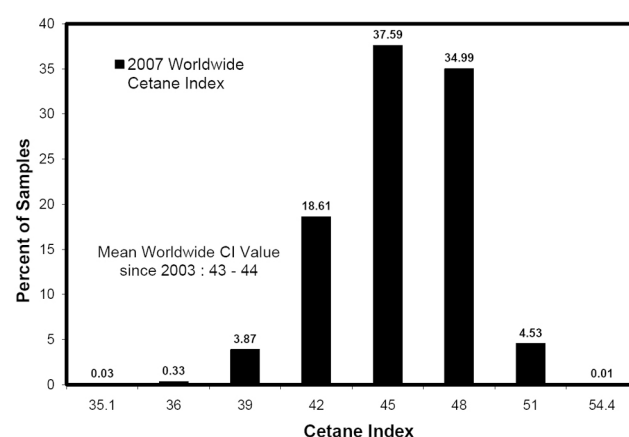


Figure 1. The 2007 Global JP-8 Cetane Index Distribution

Another recent experimental single cylinder engine study by Nargunde et al. [15] showed there was little difference between the ignition behavior of similar ignition quality North American ultra low sulfur DF-2 and JP-8 at a small set of operating conditions. Similarly, single cylinder JP-8 and DF-2 ignition delay data collected by Schihl and Hooterp [16] over a significant bulk temperature and density range using three different nozzle geometries and fuels with similar ignition quality revealed a modest impact of evaporation rate on the ignition delay period. In particular, the smaller geometry nozzle (7 × 0.176 mm) JP-8 ignition delay measurements were 5 to 15 % shorter than DF-2 with the largest variances exhibited at lower cylinder densities. Conversely, there was very little variance in the JP-8 and DF-2 ignition delay measurements for the large nozzle (7 × 0.215 mm). This study was inconclusive because the mean injection velocity did vary between JP-8 and DF-2 because of

injection system dynamics and the lower bulk density of JP-8 in comparison to DF-2 with JP-8 tending to have slightly higher mean injection velocities.

The major objective of this study is to address the impact of differences in evaporation rate and ignition quality between an average JP-8 and representative off-road DF-2 in a single cylinder diesel engine and other relevant combustion devices while documenting any observed variances or similarities between these two fuels in various combustion devices. The focus of this effort is on the ignition characteristics of JP-8.

EXPERIMENTAL SETUP

Four experimental apparatus provided JP-8 evaporation and combustion data for this study. The first device was a shock tube that was employed to generate chemical ignition delays for a JP-8 sample provided by the U.S. Army and a Jet-A sample provided by the U.S. Air Force [1] while the second device was a high pressure, constant volume bomb used to generate liquid length (evaporation) and ignition delay data for a lower than average cetane number JP-8 [12]. The latter two devices were single and multi-cylinder diesel engines that are described in more detail below; for details of the shock tube and constant volume bomb apparatuses, please see Vasu et al. [1] and Pickett and Hoogerp [12]. Additionally, data generated from earlier studies on DF-2 combustion characteristics were also utilized in the ignition delay portion of this study and the description of these three engines is given in table 2; for completeness see [17-18].

SINGLE CYLINDER ENGINE (SCE)

The main engine utilized in this study was a modified AVL 521 single cylinder, high output diesel as shown in table 2. A prototype low-pressure, oil-based common rail injection system was integrated into the base engine design through modification of the injector sleeve and valve cover. The original aluminum piston was machined below the second compression ring and retrofitted with a bolt-on steel crown. As a result of this change in reciprocating mass, the crankshaft and two counter balancing shafts were rebalanced to provide the necessary operating speed range. Both the coolant and lubrication systems were removed and replaced with externally controlled systems that provided engine speed independent desired flow rate and supply temperature through necessary heat exchangers and valves.

A LabVIEW™ (Laboratory Virtual Instrument Engineering Workshop) application was used to collect and process low speed temperature and pressure measurements, and analog output from various flow meters associated with fuel and air consumption, coolant flow rate, and lube oil flow rate. High-speed instrumentation included injector needle lift, oil rail pressure, injection command pulse, driver current, and in-cylinder pressure. Each of these signals was collected using a

sixteen (16) channel HiTechniques™ data acquisition system (DAS) through crankshaft triggering from a BEI 1440 count optical encoder.

The original four-valve head configuration included shrouded intake valves for variable swirl capability and individual rocker arm covers for both intake and exhaust valve systems. These individual covers were replaced with a two-piece cover that would properly accommodate the prototype injector for both installation and removal processes and the intake valves were oriented to provide a swirl ratio of approximately unity.

Fuel Injection System

The original base engine was equipped with a Bosch pump-line-nozzle (PLN) injection system that had a maximum peak injection pressure of 700 Bar and variable start of injection capability. This PLN system was replaced with an Indiana Research Institute (IRI) HEUI-type (hydraulically actuated electronically controlled unit injector) injection system. The injector was designed to allow for peak injection pressures up to 1900 bar and maximum injected quantities up to 240 mm³ per stroke, and a prototype driver was developed to provide multiple injection capability with minimum dwell times near 0.5 milliseconds and minimum quantities of 10 mm³ per stroke. An AEC gap sensor was integrated into the injector needle button in order to provide a direct real-time needle lift measurement. Fuel system control was provided by a custom built Southwest Research Institute RPECS™ (Rapid Prototype Electronic Control System) cart.

A test stand was developed to directly measure injection pressure in a simulated engine environment in order to indirectly determine on-engine injection pressure and rate. The test stand included an injector nozzle adapter that allowed for real-time nozzle pressure measurement by drilling a hole through the nozzle tip along the injector axis and using an adapter designed with a cavity that included necessary sealing, drainage, and a Kistler piezo-resistive transducer. The cavity was always filled with calibration fluid during the experiments that readily allowed for pressure wave measurement in the injector needle-nozzle volume during the injection event. A timing card was employed to properly trigger the injection system at a simulated crankshaft speed of 1300 rpm.

This destructive test method limited the test and evaluation nozzle quantity to just two specimens. One nozzle was a large flow cup (5 × 0.240 mm) and the other was a medium flow cup (7 × 0.215 mm). The performance of the prototype injection system was assessed during a comprehensive study of the impact of oil rail pressure and command pulse to the injector driver on the measured injection pressure. For illustration purposes, an example data set captured for the medium flow cup nozzle at a medium load type of operating condition is shown in figure 2. Similar experiments were

Table 2. Engine Characteristics

Engine Parameter	AVL 521	GEP 6.5L	Detroit Diesel Series 60	Cummins VTA-903	Ford DIATA
Number of Cylinders	I-1	V-8	I-6	V-8	I-1
Injection System	IRI BETA (HEUI)	Stanadyne PLN	EUI	MUI	FEV CORA II (HPCR)
Maximum Injection Pressure (bar)	1600	700	2000	1300	1200
Nozzle geometry (mm)	Variable	Single hole	8 x 0.190	7 x 0.190	6 x 0.124
Bore x Stroke (mm)	120 x 120	103 x 97	130 x 160	140 x 125	70 x 78
Peak Firing Pressure (bar)	200	NA	150	124	150
Compression Ratio (nominal)	13.7	20.2	15.0	12.5	19.5
Swirl Number	1 – 3	Nt Available	Quiescent	Quiescent	2.4
Displacement per Cylinder (cc)	1357	808.5	2116	1850	300
Standard Operating Speeds (rpm)	800 – 3000	900 – 3400	900 – 2100	900 – 2600	1500 – 3000
Operating Range for this Study (rpm)	2500	1500 - 3000	900 – 2100	1600 – 2600	2500
Evaluated IMEP or BMEP* Range (bar)	5 -12	2 – 10*	5 – 18*	5 – 14*	3 and 5
Boost System	Shop air	Turbocharger	Turbocharger	Shop air	Shop air
Evaluated Fuels: type and cetane number or index*	DF-2 : 43 JP-8 : 43	JP- 8 : 44.9	DF-2 : 43	DF-2 : 47*	DF-2 : 53

conducted on the medium flow cup nozzle that covered a wide range of injection duration and oil rail pressure conditions. A synopsis of the peak injection pressure as a function of injector command pulse width is shown in [figure 3](#) and [4](#). Single cylinder engine experiments reported in this submission included command pulse widths of 3 to 4 millisecond and thus had peak injection pressures of 1000 to 1500 bar.

MULTI-CYINDER ENGINE (MCE)

A General Engine Products (GEP) 6.5L, turbo-charged, indirect injection diesel engine was used to supplement JP-8 ignition delay measurements taken from the constant volume bomb and the SCE - its characteristics are given in [table 2](#). This engine was instrumented with Kistler piezo-resistive transducers in the pre- and main chambers that were triggered by an AVL 3600 count optical encoder. All high speed data was collected using a sixteen (16) channel HiTechniques™ DAS and a LabVIEW application low speed DAS was employed to collect a variety engine system temperatures and pressures. Start of injection was determined from a GEP provided crankshaft timing meter.

COMBUSTION ANALYSIS

Heat release analysis was performed using standard first law of thermodynamic analysis. The specific heat ratio was calculated based on an ideal gas mixture of CO₂, H₂O, N₂, O₂ and gaseous diesel fuel when appropriate, i.e. after start of injection, and the bulk cylinder temperature was determined based on corrected real gas behavior[19] and estimated in-cylinder charge mass - the corresponding equation of state is given below:

$$v = \frac{RT}{P} + 1.09059 \times 10^{-3} - \frac{8.50053 \times 10^{-3}}{(T/100)^{1.64}} + \frac{4.34248 \times 10^{-10}}{(T/100)^{2.49}} P - \frac{6.52579 \times 10^{-18}}{(T/100)^{2.92}} P^2 + \frac{2.95689 \times 10^{-26}}{(T/100)^{3.17}} P^3 \quad (1)$$

where P is pressure, T is temperature, R is the gas constant, and v is specific volume. This corrected real gas equation of state was used for the analysis of high speed cylinder pressure for each engine except the Detroit Diesel Series 60 - see [table 2](#). Each specie mole fraction was initialized at a chosen time following intake valve closure and thus, the heat release calculations did account for residual gas effects. Furthermore,