

Fundamental Spray and Combustion Measurements of JP-8 at Diesel Conditions

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ABSTRACT

For logistical reasons, the military requires that jet fuel (JP-8, F-34) be used in both jet engines and diesel engines. While JP-8-fueled diesel engines appear to operate successfully in many cases, negative impacts, including engine failures, are occasionally reported. As diesel combustion with JP-8 has not been explored in great detail, fundamental information about JP-8 fuel spray combustion is needed. In this study, we report measurements of liquid-phase penetration length, vapor penetration, and ignition delay made in an optically-accessible combustion vessel over a range of high-temperature, high-pressure operating conditions applicable to a diesel engine. Results show that the liquid-phase penetration of JP-8 is less than that of diesel, owing to the lower boiling point temperatures of JP-8. Despite the more rapid vaporization, the vapor penetration rate of JP-8 matches that of diesel and ignition does not advance. In fact, with no required cetane number specification for JP-8, ignition delay times are 25-50% longer for this 38-cetane-number JP-8 fuel sample compared to a 46-cetane-number #2 diesel sample. High-speed shadowgraph imaging shows that a cool flame precedes ignition for both diesel and JP-8 but the time of the cool flame heat release is delayed for JP-8, consistent with the overall ignition delay trend.

INTRODUCTION

According to the Single-Fuel Concept (SFC), all land-based military aircraft, vehicles, and equipment should be capable of using a single fuel [1]. JP-8 (NATO F-34) is the *de facto* choice for this single fuel because it was chosen as the common fuel for NATO military aircraft [1]. As such, the SFC requires that diesel engines, as well as turbine combustors, operate with JP-8 fuel.

Although widespread field trials showed successful use of JP-8 by military diesel-engine vehicles [2]-[3], failures of critical engine components and fuel handling systems attributed to JP-8 use are reported (e.g. [4],[5]). Even when there are no major engine malfunctions, JP-8 fuel causes engine performance changes such as lower

power output, advanced or retarded combustion phasing, emissions changes, and so forth [4]-[8]. Evaluation of the cause of these differences is hindered by the complexity of the entire engine system. For example, differences in fuel density can affect the fuel delivery rate [6] and injector opening time [8], which directly affects combustion and overall engine performance. Unfortunately, engine-out measurements often reveal little about the in-cylinder combustion process.

Further insight about the effects of JP-8 on diesel spray combustion is needed to better understand and optimize engine design for use with JP-8 fuel. The objective of the current study is to provide fundamental spray and combustion parameter measurements of JP-8 in an optically-accessible combustion vessel over a range of high-temperature, high-pressure operating conditions applicable to a diesel engine. The measurements focus on parameters potentially influenced by differences between JP-8 and #2 diesel, including: (1) spray liquid-phase penetration, (2) jet penetration rate and spreading angle, and (3) ignition delay. This dataset can be used to evaluate detailed or empirical spray and combustion models for JP-8 (e.g. [5]).

COMPARISON OF JP-8 TO #2 DIESEL

JP-8 and #2 diesel are manufactured to given specifications for their fuel class, but there are significant variations even within a certain fuel specification. The fuels used in this investigation will therefore not cover the entire possible range for other #2 diesel and JP-8 fuel samples. However, many of the specifications or measured properties for the JP-8 fuel sample of this study are out-of-specification for #2 diesel or vice versa. To illustrate the differences in fuel properties, as well as specifications, these data are given in Table 1. Note that the specifications shown are for standard automotive fuel, rather than certification diesel fuel or referee-grade JP-8 (MIL-DTL-46162E), which has more defined specifications. This is done intentionally to present the range of fuel types that vehicles may use under the SFC.

Table 1. JP-8 and Diesel fuel specifications and measured properties (gray).

	JP-8 Specification ¹	JP-8 Sample	US Highway #2 Diesel Specification ²	#2 Diesel Sample A	#2 Diesel Sample B	US Highway #1 Diesel Specification ²	European Diesel Specification ³
T ₁₀ [°C]	< 205	170	-	226	211	-	
T ₉₀ [°C]	-	240	282-338	303	315	< 288	< 355 (est.)
T ₁₀₀ [°C]	< 300	266	-	326	350	-	
Cetane Index	Report	39	> 40	47	47	> 40	> 51
Cetane Number	-	38	> 40	46	46	> 40	> 51
Low. Heat. Value [MJ/kg]	> 42.8	43.228	-	42.796	42.975	-	-
Density at 15°C [kg/m ³]	775-840	812	-	847	843	-	820-845
Aromatics Vol. %	< 25	11.0	< 35	33.8	27.0	< 35	-
H ₂ mass %	> 13.4	13.9	-	12.99	13.28	-	-
Sulfur [ppm]	3000	1	15	2272	9		10
Kin. Visc. (-20°C) [mm ² /s]	< 8.0	4.465	-	-	-	-	-
Kin. Visc. (40°C) [mm ² /s]	-	~ 1.4 (est.)	1.9 - 4.1	2.86	2.35	1.3 – 2.4	2.0 – 4.5
Freeze Point [°C]	-47	-57	-	-	-	-	-
Flash Point [°C]	> 38	47	> 52	78	73	> 38	> 55

1- MIL-DTL-83133E

2- ASTM D975-94, 2006 specification.

3- EN590:1999 and 2004

A JP-8 fuel sample and two different #2 diesel samples are shown, along with the fuel specifications based on US and European standards. Diesel Sample A is the fuel used to generate a substantial database on liquid and vapor-phase penetration [9-11], ignition delay [12], lift-off length [13], and soot formation [12] over a very wide range of operating conditions. These data may be downloaded at [12]. One goal of the project was to compare the performance of JP-8 to this existing #2 diesel database when using the same facility, operating conditions, and injector hardware. For further experimentation with diesel fuel, a new diesel fuel sample was required as some of the original dataset were taken more than 10 years ago and diesel Sample A

was not available. As a result, diesel fuel Sample B was used for further comparison between JP-8 for experiments conducted with more modern injector hardware. However, Table 1 indicates that diesel Sample A and Sample B have similar properties, aside from the sulfur and aromatics content.

A comparison of JP-8 and #2 diesel shows the expected difference of a lower distillation temperature range, lower density, and lower kinematic viscosity for JP-8. Further comparison of the distillation curves is provided in Fig. 1, indicating approximately 60°C lower recovery temperatures for JP-8 compared to diesel. The expectation is that these differences will significantly affect evaporation and penetration of liquid droplets, which in turn may affect combustion.

The JP-8 fuel sample has a cetane number of 38, compared to 46 for #2 diesel. This cetane number is out-of-specification for diesel standards, especially the European standard, but there is no required cetane specification for JP-8. Without a specification, other JP-8 samples may or may not have cetane numbers that fall into the same range as diesel. For this set of experiments, we were satisfied with the cetane number of our JP-8 fuel sample because it allows assessment of whether the faster evaporation of JP-8 will lead to a greater percentage of combustible mixtures within the spray, as theorized in [5]. In other words, if the faster rate of evaporation for JP-8 results in a shorter ignition delay, *despite* the lower cetane number, then one would conclude that distillation properties affect combustion in addition to fuel chemistry effects.

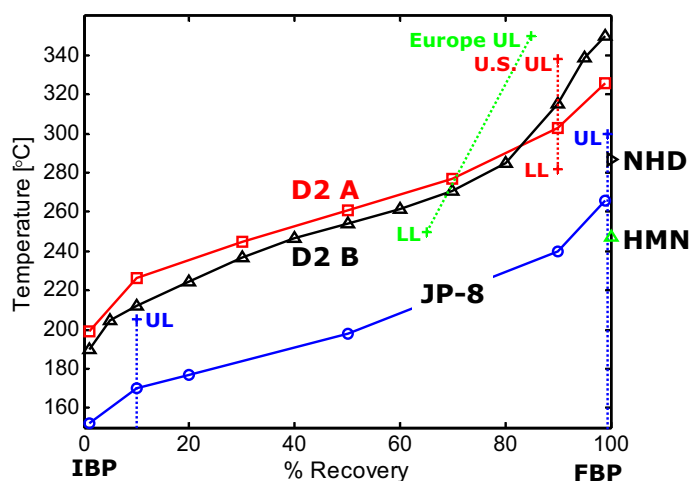


Figure 1. Distillation curve for JP-8 and diesel samples (D2) A and B at atmospheric pressure. Required distillation limits are also shown as dotted lines. The boiling point temperatures of the diesel single-component reference fuels n-hexadecane NHD and heptamethylnonane HMN are also given.

Other differences between the JP-8 fuel sample and #2 diesel samples that may or may not be important include: lower aromatics, higher hydrogen mass percent, and a higher heating value for JP-8. Generally, many of the diesel fuel measured properties fall outside of the accepted range for JP-8, or vice-versa, indicating that consistent physical and chemical property differences will exist between JP-8 and diesel.

EXPERIMENTAL APPARATUS

COMBUSTION VESSEL- Experiments were conducted in an optically accessible, constant-volume combustion vessel under simulated, quiescent diesel engine conditions. A schematic of the combustion vessel is shown in Fig. 2. The vessel has a cubical combustion chamber, 108 mm on a side. The fuel injector is mounted at the center of a metal side-port such that the diesel spray is directed into the center of the chamber. Sapphire windows located in four other ports of the combustion vessel permit line-of-sight and orthogonal optical access to the injected fuel jet. Further details about the combustion chamber geometry and operation may be found in [12].

The vessel was fitted with high-speed pressure transducers and photodiodes to measure the timing of heat release. These data were correlated with imaging measurements described below to provide further details about the spray combustion process.

INJECTORS- As mentioned above, two different common-rail fuel injection systems with single-hole, mini-sac nozzles were utilized to study JP-8 combustion. Each fuel injector was operated at the same injection pressure when compared diesel and JP-8. A description of the injectors and nozzles is listed in Table 2. The first is the DTC injector that was used to generate the database for #2 diesel, Sample A [9, 12]. For the current study, the DTC injector was operated with a sharp-edged 0.180 mm nozzle. Sample injection rate shapes are available to download for this nozzle with an injection pressure difference (fuel minus ambient) of 138 MPa [12], which is the operating pressure used for this injector in the current study. The second injector is a Bosch second-generation injector equipped with a convergent ($K = (d_i - d_o)/10 = 1.5$), hydroground nozzle with a much higher discharge coefficient, C_d , (measured at the fuel injection pressure and temperature) [14]. JP-8 was compared to diesel fuel, Sample B when using this injector.

Table 2. Common rail fuel injectors and nozzles for this study.

Common-rail Injector	Nom. dia. [mm]	K factor	C_d	C_a	Hydro-ground	DP _{inj} [MPa]
DTC	0.180	0.0	0.77	0.82	N	138
Bosch CRI2.2	0.180	1.5	0.93	1.0	Y	110

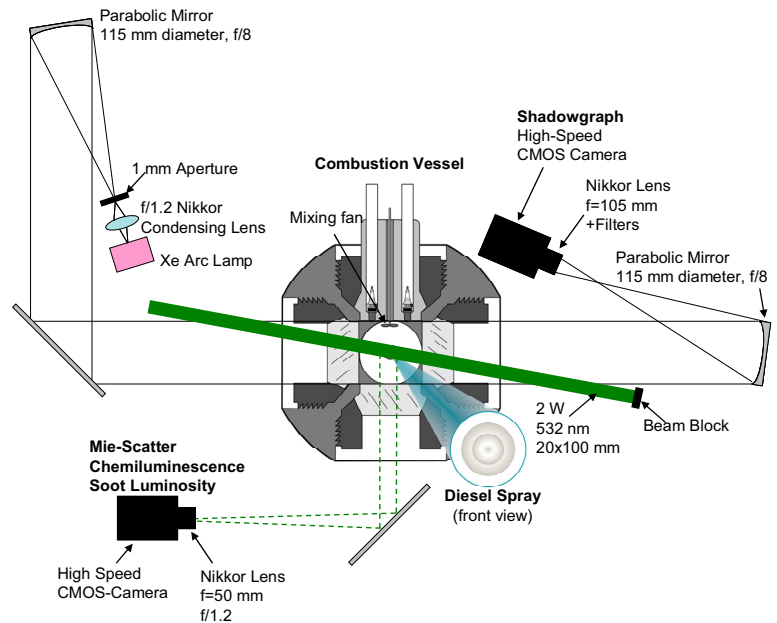


Figure 2. Combustion vessel and high-speed imaging setup. Mirror spacing not to scale.

OPTICAL DIAGNOSTICS

Shadowgraph imaging and Mie-scatter imaging were performed simultaneously using high-speed imaging systems to track both the liquid-phase and vapor phases of the spray simultaneously. Under reacting conditions, the shadowgraph imaging also provided an optical measurement of the ignition timing.

SHADOWGRAPH IMAGING- Shadowgraph and Schlieren imaging have been used for many years to identify refractive index gradients in various experiments [15] (also see high-speed movies under “Diesel Tutorial” at [12]). For vaporizing diesel sprays, these techniques show the boundary between vaporized fuel and background ambient gases because (1) refractive index differences exist between the fuel and ambient gases and (2) density gradients are created in the ambient gases as the vaporized fuel spray cools the ambient. Of course, strong density (and refractive index) gradients are also created at combustion interfaces where the high-temperature combustion creates low-density regions. Shadowgraph/Schlieren techniques therefore provide important information about the temperature and composition of the system.

Figure 2 shows the lighting and imaging arrangement utilized to perform shadowgraph and Schlieren imaging. The setup is similar to that described in [16]. A 150 W (electrical power) mercury-xenon arc lamp with a small (1.7 mm) arc distance system was used as a white light source. Light from the arc was collected with an 50-mm focal length f/1.2 Nikkor camera lens, offering superior broad wavelength performance compared to a simple achromatic condensing lens. The light was passed through a 1-mm aperture to form a high-quality point source that was collimated by an 115-mm diameter f/8

mirror. After passing through the combustion vessel, the collimated beam was re-focused using a second f/8 mirror (positioned 760 mm from the combustion vessel center) and a series of flat folding mirrors (not shown in Fig. 1). The converging light reached a focal point 100 mm before entering a high-speed CMOS camera (Phantom v7.1) equipped with an 105-mm focal length Nikkor lens and various filters. As detailed in [15], the distance from the test section to the image plane affects the system sensitivity to refractive index gradients.

During setup, a knife edge was placed at the focal point to form a Schlieren system (sensitive to the first-derivative of refractive-index gradients). However, as will be shown, the sensitivity to detect the edge of the vaporized diesel spray was sufficient without the knife edge in place. Indeed, the refractive-index gradients created by only the ambient gases are quite significant for this high-pressure system, and more difficult to analyze and interpret when using the knife edge. Therefore, the knife edge was removed to form a less-sensitive shadowgraph system (proportional to the second-derivative of refractive-index gradients).

Several different camera filters, image exposure times, and framing rates were used, depending upon the particular experimental conditions. These parameters are listed in Table 3. A 450-nm short-wave-pass filter was used to block intense soot luminosity if it existed in some experimental conditions. As much of the shadowgraph light is also rejected, this setup required a longer exposure duration and slower framing rate. In other experiments, a zero-incidence 532-nm mirror was used to block laser scatter from spray droplets. This filter transmits a greater percentage of the white light source, since it effectively acts as notch filter near 532-nm, and a shorter exposure duration and faster framing rate were therefore possible.

Table 3. Shadowgraph system filters and camera settings.

Filter	Framing period [μ s]	Exposure duration [μ s]	Pixel resolution
450-nm SPF (1)	66.5	58.0	256x512
450-nm SPF (2)	50.0	42.0	128x512
532-nm 0° mirror	34.25	5.0	128x512

MIE-SCATTER IMAGING- Scattered light from diesel spray droplets were imaged simultaneously with the shadowgraph system using a second high-speed CMOS

camera and continuous-wave laser as shown in Fig. 2. The time-resolved pair of shadowgraph and Mie-scatter images identifies the instantaneous position of both the vapor and liquid phases of the fuel spray. This information is critical to understanding the diesel spray evolution.

The continuous-wave laser source was a frequency-doubled solid-state Nd:YAG laser (532 nm) operating with 2 W power. The laser was formed into a 100-mm by 20-mm volume to illuminate only the liquid-phase region of the spray and also to avoid interference with the shadowgraph setup (Fig. 2). The volume illumination method was utilized to ensure that all droplets spreading from the nozzle were illuminated to identify the maximum axial and radial distances of any liquid-phase fuel [9]. A volume illumination method is also expected to be the most useful for comparison with the shadowgraph technique, as shadowgraphy is also a volume detection technique along a line-of-sight.

A high-speed CMOS camera fitted with a 532-nm bandpass filter (10 nm FWHM) and a 50-mm focal length f/1.2 lens was used to image Mie-scattered light at a near-right angle to the laser source. The bandpass filter was used to reject background soot and thermal radiation from heated vessel walls. The camera was operated at reduced resolution 48 x 512 to allow fast framing periods (20 μ s) needed to capture dynamics of very fast diesel sprays. The lens was set to the maximum aperture (f/1.2) and the camera at maximum exposure duration (17 μ s) to intentionally saturate the camera in the dense region of the spray while leaving sufficient dynamic range to identify regions of the spray where liquid completely evaporates. However, changes in laser power, exposure duration, or image threshold level (8/256 counts) did not significantly affect the measurable liquid penetration, similar to [9].

A demonstration of simultaneous shadowgraph and Mie-scatter high-speed imaging for JP-8 fuel is shown in Fig. 3. For this particular experimental condition, the ambient temperature and pressure are quite low as may be expected for an early-injection timing well before TDC in an engine. The injection duration is also quite short (0.3 ms). Mie-scatter images at the top show an intense liquid core region that saturates the camera during the time of injection as intended. The time after the start of injection (ASI) is given at the image top-left. After the end of injection, the spray detaches from the nozzle and continues to penetrate across the chamber. Liquid at the center of the spray is eventually evaporated by 0.5 ms ASI, as indicated by the blue liquid boundary lines.