

Spray Characterization and Ignition Delay Measurements of JP-8 and IPK in a Constant-Pressure Flow Chamber

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ABSTRACT

This research compares the spray development and combustion characteristics of jet propellant 8 (JP-8) and iso-paraffinic kerosene (IPK) through a range of diesel engine in-cylinder operating conditions. Non-reacting spray experiments were performed in a constant-pressure flow chamber with 99% nitrogen gas composition at constant temperature (900 K) and densities ranging from 11–56 kg/m³. Near-simultaneous, high-speed Mie and schlieren images of the spray were acquired to measure the liquid and vapor penetration lengths of the non-reacting jet. Reacting experiments, consisting of photodiode measurements and intensified high-speed movies of OH* chemiluminescence, were performed at the same thermodynamic conditions as the non-reacting experiments, except with a 21%/79% oxygen/nitrogen ambient gas composition. Measurements of the rate of injection, issued from a single-hole axial common-rail fuel injector, showed negligible differences between the fuels. The non-reacting liquid length of IPK was approximately 20% shorter than JP-8 for the range of tested conditions, which was consistent with the average difference in volatility between the fuels. The ignition delay, determined from the photodiode record, was up to 80% longer for IPK fuel at low density conditions. Additionally, the lift-off length of IPK was measured to be approximately 50% more sensitive to ambient pressure than JP-8. These results provide fundamental information for the calibration and optimization of military diesel engines operating on conventional and alternatively sourced jet fuels.

CITATION: Tess, M., Kurman, M., and Kweon, C., "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.

INTRODUCTION

Military-specification jet fuels derived from renewable and alternative sources have begun to supplement petroleum-derived fuel stocks, and in the near future this strategy may be pursued with increased priority [1]. Several research efforts have focused primarily on investigating the combustion characteristics of these alternative fuels primarily for their suitability in turbine engines [2, 3, 4, 5], with comparatively less attention given to operation at the high-temperature and pressure conditions of a reciprocating piston internal combustion (IC) engine [9,31]. There is strong interest within the IC engine combustion community to understand the chemical kinetic behavior of alternative fuels in terms of the underlying physics at the individual component level, especially as new combustion regimes are developed to meet future emissions and efficiency mandates.

Historically, fuels have been broadly characterized by their autoignition properties: the ability to resist ignition (octane number, ON) for gasoline fuels, and the propensity to ignite (cetane number, CN) for diesel fuels [6]. Future IC engines may operate in multimode combustion regimes that span the spectrum between traditional non-premixed conventional diesel and fully-premixed spark-ignition combustion [7], such as homogeneous charge compression ignition (HCCI) or premixed charge compression ignition (PCCI), for which the mode selection will depend in part on the ignition characteristics of available fuels. Recent trends in the petroleum market have made

the production of alternative fuels, such as fuels derived from coal, natural gas, and bio-materials, supportable. The chemical constituents of alternative fuels differ from petroleum-derived fuels, however, and the combustion behavior must be sufficiently understood before certifying their use in legacy IC engines, or tailoring a combustion strategy to the properties of any particular fuel.

Therefore, this paper presents fundamental spray and combustion measurements comparing an average-specification JP-8 fuel and a low-cetane Fischer-Tropsch jet fuel at ambient conditions analogous to a low- to mid-load operating point of a diesel engine. The results indicate significant differences in the fuel ignitability at lower pressures and densities, which could be advantageous for low-temperature combustion strategies. Although the experiments were limited to a single ambient temperature and gas composition, the results help identify specific areas of interest within the broad pressure-temperature operating space of an IC engine to pursue for further research.

EXPERIMENTAL METHODS

Test Fuels

Experiments were performed with two jet fuels in their neat forms that varied significantly in their ignition and volatility characteristics. Table 1 reports the results of fuel property testing by an independent laboratory using ASTM analytical methods.

weights listed in Table 1 are from Hon et al. [8]. Petroleum-derived JP-8 specification fuel (POSF 6169) was selected as the baseline fuel because its properties are representative of currently available jet fuels used in the U.S. military's ground vehicles and aircraft. Isoparaffinic kerosene (POSF 7629) is a coal-to-liquid fuel produced by Sasol in a Fischer-Tropsch process. The cetane number for IPK was undetermined in ASTM D613 testing since it was below the cetane limit of the CFR engine (minimum ≥ 30), while it was reported in [9] to equal 25.2. Alternatively, the derived cetane number (DCN) from ASTM D6890 tests of the same POSF fuel has been measured as 31.3 [8], which must be further qualified as lying outside the validated DCN range of 33-64 [37], and thus subject to unknown uncertainties. These autoignition quality metrics place IPK at the low-ignitability end of the diesel fuel range. The ignitability is low enough that it may be characterized as a gasoline-like fuel according to Kalghatgi's CN-ON correlation [10]. The distillation curves, plotted in Figure 1, show that the end point (EP) of JP-8 and IPK are 262.4°C and 224.5°C, respectively, which places the IPK sample within $\sim 20^\circ\text{C}$ of the final boiling point of a typical gasoline.

Table 1. Fuel properties

	JP-8	IPK
POSF	6169	7629
Cetane number [ASTM D613]	46.9	< 30
MW ^a [8] (g/mol)	153.6	148.5
H/C [ASTM D5291]	1.95	2.19
Density @ 15.6°C (kg/m ³) [ASTM D4052]	796.7	759.4
Viscosity @ 40°C (mm ² /s) [ASTM D445]	1.284	1.120
Heat of combustion [ASTM D240]		
Gross (MJ/kg)	46.4	47.3
Net (MJ/kg)	43.4	44.0
Hydrocarbon types (% vol) [ASTM D1319]		
Alkanes	83.9	95.3
Alkenes	0.9	3.6
Aromatics	15.3	1.1
Sulfur [ASTM 5453] (ppm)	487.2	15.3

^aUncertainty ± 6 g/mol [8]

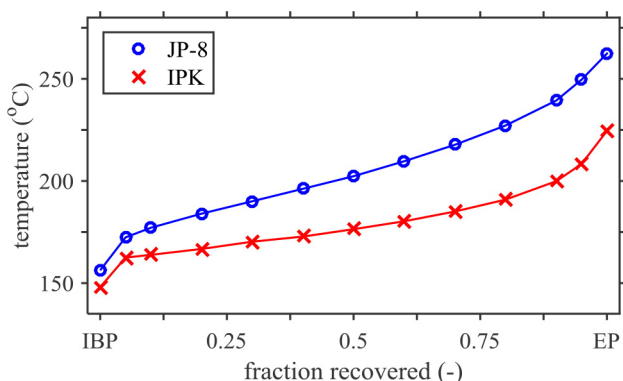


Figure 1. Measured distillation curves using ASTM D86 analytical technique

Injection System

The fuel system was comprised of a Bosch multi-cylinder engine common rail, and a CRIN3-18 fuel injector with a sharp-edged, 90 μm (nominal) diameter single-hole axial nozzle. The fuel rail was pressurized with a Parker Autoclave air-driven pump system. The flow rate for each fuel was measured with a Bosch-type rate instrument [11], and the conditioned signal from the pressure sensor was sampled at 100 kHz. Sound speed data for JP-8 were generated by ARL based on data from NIST [12], whereas the IPK sound speed was calculated from a four-component surrogate mixture [13]. Rates of injection (ROIs) were averaged for 100 injection events, and shot-to-shot variation of the total mass was less than 1% for all conditions. Figure 2 shows an example of the mean ROI profiles for both fuels at 100 MPa fuel pressure (measured in the fuel line between the pump and the rail) and 2.0 ms duration injector solenoid current ($I_{inj\ sol}$) energizing time (ET). The ROIs exhibited a square rate shape that is characteristic of single-hole nozzles. The measured flow rate fluctuations during the quasi-steady period of the injection event, the magnitude of which were as large as $\pm 37\%$ of the mean, were most likely an artifact of several features relating to the sub-components of the fuel injector and the measurement technique itself, including: onand off-axis oscillatory injector needle motion [14] that became amplified for the small orifice diameter, single-axial hole nozzle; the acoustic response of the rate instrument to fluid hammer effects and injector vibrations [15]; and cavitation bubbles near the rate instrument's pressure sensor [16].

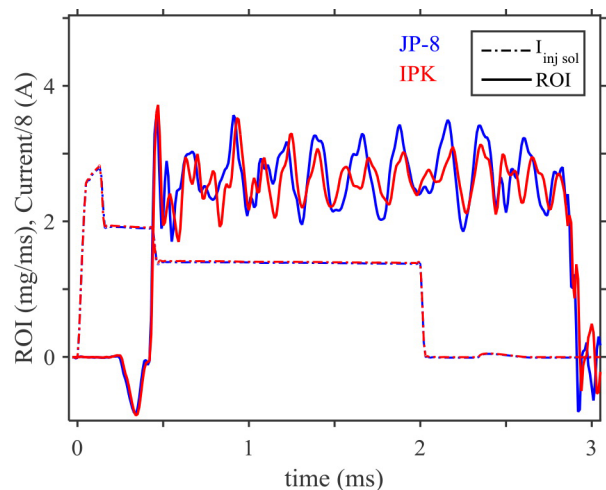


Figure 2. Average rate of injection (ROI) and injector solenoid current ($I_{inj\ sol}$) versus time after start of injection command for both fuels at 100 MPa rail pressure and a solenoid energizing time (ET) equal to 2 ms

All of the chamber experiments were performed with a solenoid command duration of 2.5 ms and 100 MPa fuel pressure, which was selected to allow time for the liquid length and lift-off lengths to reach their quasi-steady equilibrium values. The injection duration (t_{inj}) is not expected to affect the ignition delay time in a non-premixed diffusion combustion regime such as the present experiments, except under two scenarios: when injecting very small quantities of fuel, for which the dwell time, defined as the

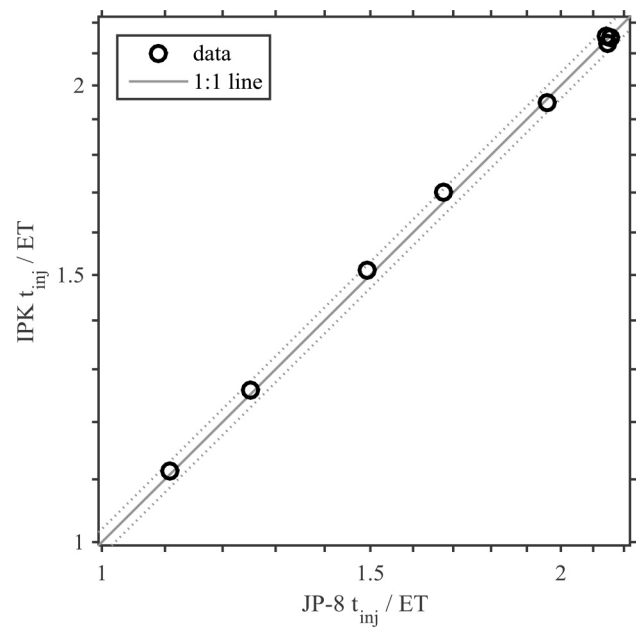
time between the end of injection (EOI) and start of combustion (SOC), could be positive; or when injecting very large quantities of fuel, for which evaporative cooling reduces the local temperature in the jet. The injected mass, injection duration, and start of injection (SOI) were calculated based on a comprehensive analysis of the fuel rate data, as discussed next.

ROI Analysis

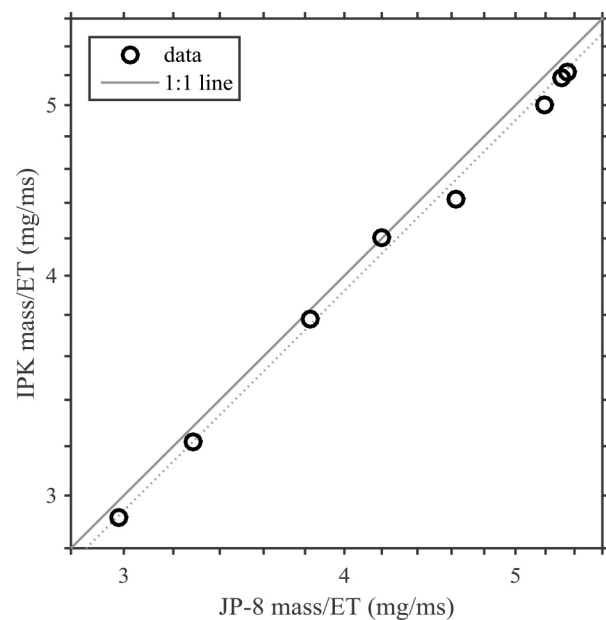
Characterization of the average fuel injection event included fuel rate indicator measurements at eight discrete ETs varying from 0.30 to 5.0 ms with fuel pressure held constant at 100 MPa. Figure 3 (a) shows that the data for t_{inj} , defined as (EOI-SOI), for IPK and JP-8 were within 2% of each other at all test points, although the data were consistently skewed towards slightly longer IPK injection durations at ETs longer than 0.70 ms (or equivalently, t_{inj}/ET less than 1.7). Figure 3 (b) shows that at the same command duration, the injected mass of IPK was less than JP-8 for all points except 0.70 ms ET (corresponds to mass/ET ≈ 4.2), where the injected quantities were approximately equal. For command durations between 0.45 ms and 5 ms, the injected fuel mass and injection duration were observed to be linear functions of ET, suggesting that the needle did not fully lift off of the seat for the two shortest command durations tested (0.30 and 0.35 ms ET).

Considering the nonlinear trends for the shortest ETs, for which the injection event was dominated by the needle dynamics at SOI and EOI, those data were omitted from the following assessments of the fuel effects. Given that the same fuel system components were used for both sets of experiments, and the operating conditions (ET and rail pressure) were constant, the mass differences may be explained by comparing the physical properties of the fuels. Assuming that the internal nozzle flow dynamics were similar for both fuels at equivalent ETs, resulting in similar flow coefficients and volume flow rates, then the injected mass of IPK is expected to be 2.2% less than JP-8 because the mass density for IPK was less than JP-8, and mass flow varies with the square root of density. This agrees very well with the mass results from Figure 3 (b), despite the slight differences in injection duration in Figure 3 (a), which trend to longer durations for the IPK data set. Additionally, the mean fuel mass flow rates, calculated from the quasi-steady period of the injection event (*i.e.*, neglecting the transient portions of the ROI at the start and end of injection), indicate that the mass flow rate of IPK was approximately 2.4% less than JP-8 fuel.

Subsequently, the total mass per injection and injection duration for the 2.5 ms ET and 100 MPa fuel pressure case were calculated from linear fits of the relevant parameter versus ET. Table 2 summarizes the results with their 95% confidence interval as determined from the regression uncertainties; the current data show that the differences in mass and injection duration were statistically insignificant. Finally, the hydraulic delay time between the start of injection command (SOIC) and start of injection averaged 0.29 ms for all command durations and both fuels.



a.



b.

Figure 3. (a) Injection duration (t_{inj} = EOI-SOI) normalized by ET for IPK vs. JP-8 (logarithmic scale). Dotted lines: $\pm 2\%$. (b) Injected mass per stroke scaled by ET for IPK versus JP-8 (logarithmic scale). Dotted line: injected mass of JP-8 2% greater than IPK.

Table 2. Calculated fuel injection parameters for 90 μm (nominal) orifice diameter injector with 2.50 ms ET at 100 MPa, reported with the $\pm 95\%$ confidence interval

	JP-8	IPK
Injected mass (mg/inj)	7.96 ± 0.19	7.81 ± 0.08
Injection duration (ms)	3.01 ± 0.06	3.03 ± 0.05

Combustion Chamber

Non-reacting and reacting spray experiments were performed in a dual-walled, constant-pressure flow (CPF) chamber depicted in [Figure 4](#). The ambient oxygen concentration was 0% for the non-reacting experiments, and 21% for the reacting experiments. The temperature was held constant at 900 K (measured by a sheathed K-type thermocouple mounted near the top of the center section), while parametrically varying the pressure to explore a range of ambient densities (ρ_a) between 11–56 kg/m³. The gas temperature distribution was measured along the spray axis to be within 2% of the nominal 900 K target temperature at all density conditions. The fuel injector was mounted in a water-cooled fixture to offset the effects of wall heat transfer, although the fuel temperature at the tip has not yet been directly measured in ARL's rig. Measurements conducted in a similar CPF rig operating at the same ambient temperature resulted in a fuel temperature estimate of 358 ± 15 K [36]. Orthogonal and axial optical access to the fuel spray was provided by three 147 mm diameter, 85 mm thick UV-grade fused silica (UVFS) windows. Descriptions of the optical diagnostics, which included Miescattering, schlieren, and OH* chemiluminescence, are described in the following sections.

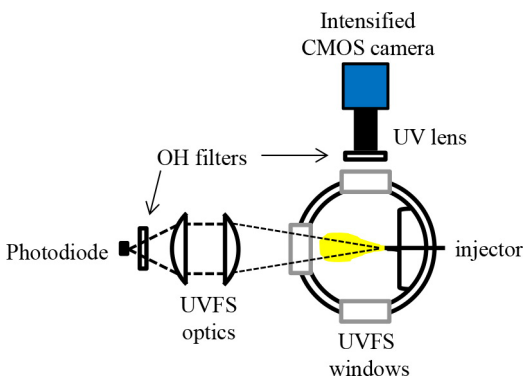


Figure 4. Schematic of the constant-pressure flow chamber and the optical setup for OH* chemiluminescence diagnostics

Optical Diagnostics

Non-Reacting Spray

Near-simultaneous, high-speed Mie-scatter and schlieren images were acquired to measure spray angle and liquid and vapor penetration. For the schlieren system, light from a 638 nm wavelength light-emitting diode (LED) was collimated by a 1220 mm focal length parabolic mirror and directed through the chamber test section in a folded Z-type arrangement [17]. The collimated light was focused to a point by another 1220 mm focal length parabolic mirror, where the refracted rays were blocked from the camera with a horizontally staged knife edge. The Mie-scatter system consisted of a 638 nm wavelength, 24-LED array light source directed opposite to the penetrating jet in a head-on configuration. A digital delay generator synchronized the light sources in an alternating sequence for high-speed recording. A Photron SA5 camera and Nikkor 80-200 mm f/2.8 lens recorded the Mie and schlieren images with a frame-straddling technique described in [18]. The recording rate and frame size were 60 kHz and 512×224 pixels, respectively, with a scale factor of 177 $\mu\text{m}/\text{pixel}$, resulting in a 0.11 magnification ratio.

The image data were acquired and processed with LaVision DaVis 8 software. The image processing routine for the schlieren image set included subtraction of the previous frame, to reduce schlieren effects from the continuous flow of ambient gases, followed by a Gaussian smoothing filter, and finally, a thresholding step to identify the vapor boundary. [Figure 5](#) shows sample images of the previous-framesubtracted schlieren data; the residual schlieren artifacts in the background were due to transient refractive index gradients in the bulk flow and in the boundary layers at the chamber windows. The liquid length was determined from the Mie images by a similar processing routine, with the exception of the previous frame subtraction step. The threshold intensity varied based on the background noise, but did not exceed 20% of the maximum intensity per frame.

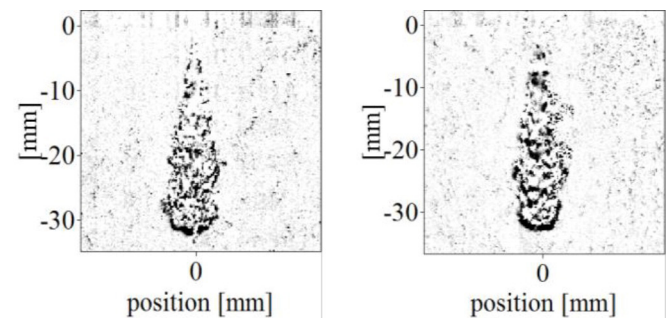


Figure 5. Sample images from the processed schlieren data showing the vapor penetration at 1.29 ms after the start of injection command for JP-8 (left) and IPK (right) at 56 kg/m³ and 900 K ambient conditions

Reacting Spray

Two diagnostic techniques were performed to characterize the ignition delay and lift-off length of the reacting jet: photodetection and high-speed imaging of excited-state OH* radical chemiluminescence. The ignition delay measurements presented in this work result from the time-resolved photodetector signal, as opposed to most pressure vessel and engine studies, which are derived from pressure-based methods.

As shown in [Figure 4](#), OH* chemiluminescence was measured with a fast-response photodiode aligned on the axis of the penetrating jet. Broadband chemiluminescence from the jet was collected by a 300 mm focal length UVFS plano-convex (PCX) spherical lens and focused on the 0.7 mm² active area of a Thorlabs DET10A photodiode with a 100 mm focal length UVFS PCX spherical lens. A 307 nm bandpass filter (10 nm FWHM) was placed between the photodiode and 100 mm PCX lens to selectively transmit OH* chemiluminescence. High-speed imaging was performed by attaching a LaVision UV-enhanced P46 intensifier to a Photron SA5 camera. The camera lens was a Cerco 98 mm f/2.8 UV lens with a 307 nm bandpass filter. The same recording rate and frame size were used, although with a slightly higher 0.19 magnification ratio. After the OH* lift-off location had stabilized, the lift-off length was determined for each frame by identifying the transition point of the line intensity profile in a method similar to that developed by Higgins and Siebers [19]. The algorithm for determining the ignition delay is described in detail in the next section.