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LEAN BLOWOUT AND IGNITION PERFORMANCE STUDIES OF F-76 MARINE DIESEL FUELS

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14. ABSTRACT
The cold-start ignition and lean blowout (LBO) performance of F-76 marine diesel fuels, alternative diesel fuel formulations and several blends of F-76 with alternative fuels and a high viscosity diesel calibration fluid, were evaluated in a single-cup swirl-stabilized combustor. The goal was to explore and demonstrate a more cost-effective, flexible and reliable marine diesel fuel qualification protocol for the assessment of F-76 fuel ignition and LBO performance. The study was conducted at the Air Force Research Lab (AFRL) at Wright Patterson Air Force Base. Test results show that the fuel ignition performance is strongly impacted by the physical properties, particularly viscosity. Improved performance are consistently observed for lower viscosity fuels. Ignition is also impacted by fuel distillation temperatures. The results show that the LBO performance was also strongly correlated with the physical properties, particularly viscosity with best performance observed for lower viscosity fuels.

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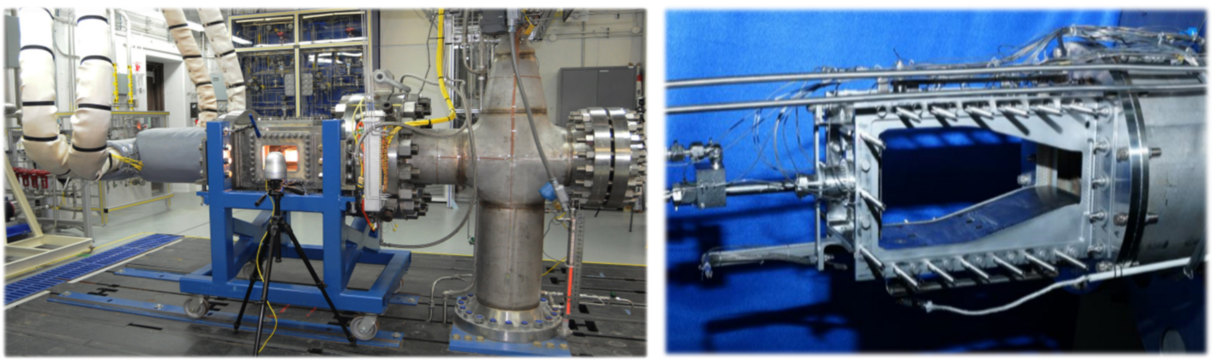
1 SUMMARY

The cold-start ignition and lean blowout (LBO) performance of F-76 marine diesel fuels, alternative diesel fuel formulations and several blends of F-76 with alternative fuels and a high viscosity diesel calibration fluid, were evaluated in a single-cup swirl-stabilized combustor. The goal of the study was to explore and demonstrate a more cost-effective, flexible and reliable marine diesel fuel qualification protocol for the assessment of F-76 fuel ignition and LBO performance. Currently, the F-76 fuel qualifications protocols employed by the Navy use platform-specific tests, which do not provide global fuel performance assessments due to specific hardware performance, and limits testing to a very small number of contracted facilities. The test combustor used in this effort is a single-nozzle swirl-stabilized combustor designed by turbine engine original equipment manufacturers (OEMs) to mimic many of the characteristics found in actual turbine engine combustor. The goal for this combustor is to function as a "referee" device for initial evaluation of the combustion performance of fuels. For these studies, the fuel and air were set at 278K and atmospheric combustor pressures for the cold-start ignition experiments, and for the LBO experiments, air and fuel temperatures were set at 394K and 322K, respectively with combustor pressure to 2 atm. The study was conducted at the fuels and combustion evaluation facility at the Air Force Research Lab (AFRL) at Wright Patterson Air Force Base from August 2018-January 2019. Test results show that the fuel ignition performance is a strong function of the physical properties of the fuel, particularly viscosity. Improved performance, i.e., lower equivalence ratios required for ignition, are consistently observed for lower viscosity fuels. Ignition is also impacted strongly by fuel distillation temperatures, as fuels with lower T_{90} (temperature at which 90% fuel evaporates) in most cases showed better ignition performance. (Note that T_{90} and viscosity have a relatively strong correlation for the fuels tested in this study.) The results show that the LBO performance was also strongly correlated with the physical properties, particularly viscosity with best performance observed for lower viscosity fuels.

2 EXPERIMENTAL

2.1 Test Facility

The ignition and LBO experiments were conducted at the Fuels and Combustion Evaluation Facility at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB), Ohio. A picture of the facility is shown in Fig. 1a. A modular combustor (also referred to as "referee" combustor) (Fig. 1b), developed under the Combustion Rules and Tools Program [1], was used to evaluate the combustion characteristics of the test fuels. The referee combustor, designed in collaboration with turbine engine manufacturers, is a plenum-fed swirl-stabilized single-cup burner, 26.2 cm long and 10.9 cm in height and width at the dome area, installed inside a 30 cm x 30 cm pressure vessel. Several characteristics of the combustor and hybrid fuel nozzle and swirler are similar to those found in commercial turbine engine combustors. The swirler nozzle consists of a single central pilot injector surrounded by five main injection nozzles and three co-annular air swirlers similar to previous designs. For the current study, fuel was injected only through the pilot injector. The combustor liner walls have effusion cooling passages as well as two stages of dilution holes. The flow for effusion cooling was ~60% of the total air flow to help



(a) **(b)**

Figure 1 (a) Fuel and Combustion Evaluation Facility at the AFRL at WPAFB, Ohio and (b) Single-nozzle swirl-stabilized ("referee") combustor

prevent combustor damage and geometry changes during extended combustion tests. Fused silica windows on each side of the combustor allows optical access for high speed imaging and non-intrusive diagnostics.

Ignition for the combustor was provided by an auxiliary power unit (APU) igniter mounted on the top liner wall near the dome. The facility air system currently allows operation up to 0.91 kg/s air flow at pressures from 1-5 atm and air temperatures up 811 K. A low temperature air and fuel capability allows operation of the combustor air and fuel at temperatures as low as 239 K using two recirculating fluid process chillers and five heat exchangers. The air is cooled in two stages via four heat exchangers with heat transfer fluid from two different chillers. With this setup, the fuel and air temperature were typically maintained within ± 1.0 K of the target temperature for the current experiment.

The combustor ignition source is provided by spark igniter plug mounted 7.12 cm downstream of the dome on the top liner wall. The igniter is connected to a custom-built thyratron-based exciter similar in design to turbine engine exciters, except that the spark energies and repetition rates can be varied electronically. The exciter provides an initial high-voltage pulse to break down the anode-cathode gap of an igniter and then provides current to the igniter for a desired pulse duration.

The current and pulse width are determined by multiple factors, including the exciter capacitance and inductance, the charging voltage of the exciter, and the operating impedance of the igniter. The spark frequency used for the experiments was 3.5 Hz, and was controlled by output from a function generator. The voltage and current waveforms for each spark were measured and recorded along with a calculated energy supplied to the plug by measuring the current through and the voltage across the igniter. The voltage was attenuated 1,000x with a Tektronix 6015A high voltage probe before measurement and the electrical current was measured with a Pearson 6600 current monitor. The voltage and current signals were recorded using with a Lecroy HDO 4034A digital storage oscilloscope operating at 125 MHz. To minimize data storage requirements, each spark was captured by triggering the oscilloscope for a period of 50 μs after the start of each spark.

Test facility data were measured continuously at 1Hz using a National Instruments-based data acquisition system. A subset of these measurements were recorded during each ignition attempt at higher frequency (15Hz). A photodiode directed at the primary zone was used to determine the number of sparks as well as the ignition event. For spark counting, the photodiode signal and several acoustic transducers were measured using a separate National Instruments system operating at 100 kHz acquisition frequency. The photodiode signal was measured on both data systems to allow alignment of the time base for the results in subsequent analysis. Visualization of the ignition events was provided by color video camera operating at 1.1 kHz (Edgertronic SC1). The camera was triggered by the photodiode at combustor light-off and was post-triggered to allow the two sparks before ignition to be recorded for each ignition along with an overall video time acquisition time of 2 seconds per ignition.

Further details on the combustor and facility are provided in references [2-3].

2.2 Fuels

Eight test diesel fuels and a previously tested high flash point jet fuel [JP-5, designated as A-3 under the National Jet Fuel Combustion Program (NJFCP)] were evaluated in this study. The test fuels and several of their properties are listed in

Table 1. Gas chromatograms for several of the fuels tested are shown in Figure 1, and show the similarity in component distribution between the fuels up to n-C_{18}. The fuels were selected to determine impacts of chemical and physical properties on ignition and LBO performance. An F-76 marine diesel with average properties was selected as the baseline fuel. The Catalytic Hydrothermolysis Conversion Diesel (CHCD) is an alternative diesel fuel derived from a variety of feedstocks (e.g. oils, fats and greases), and is similar in composition to petroleum-based diesel. The CHCD fuel was tested neat. The Hydrodepolymerized Cellulosic Diesel (HDCD) fuel is derived from cellulose and lignin, and has a higher viscosity and density, and lower flash point than conventional F-76 [4]. It consists mostly of alicyclic, cyclic and aromatic compounds. The HDCD was tested at a blend ratio of 20/80 HDCD/F-76 by volume. Two blends of Synthetic Iso-paraffinic (SIP) fuel (farnesane – 2,6,10 trimethyl-dodecane) and F-76 were tested at blend ratios of 50/50 and 80/20 F-76/SIP. A blend of Hydroprocessed Renewable Diesel (HRD) in F-76 at a 50/50 HRD/F-76 blend ratio was also tested. Two blends of F-76 with Viscor (a high viscosity reference fluid), were tested at 50/50 and 38/62 F-76/Viscor blend ratios to investigate the ignition and LBO performance of fuels with very high viscosities.

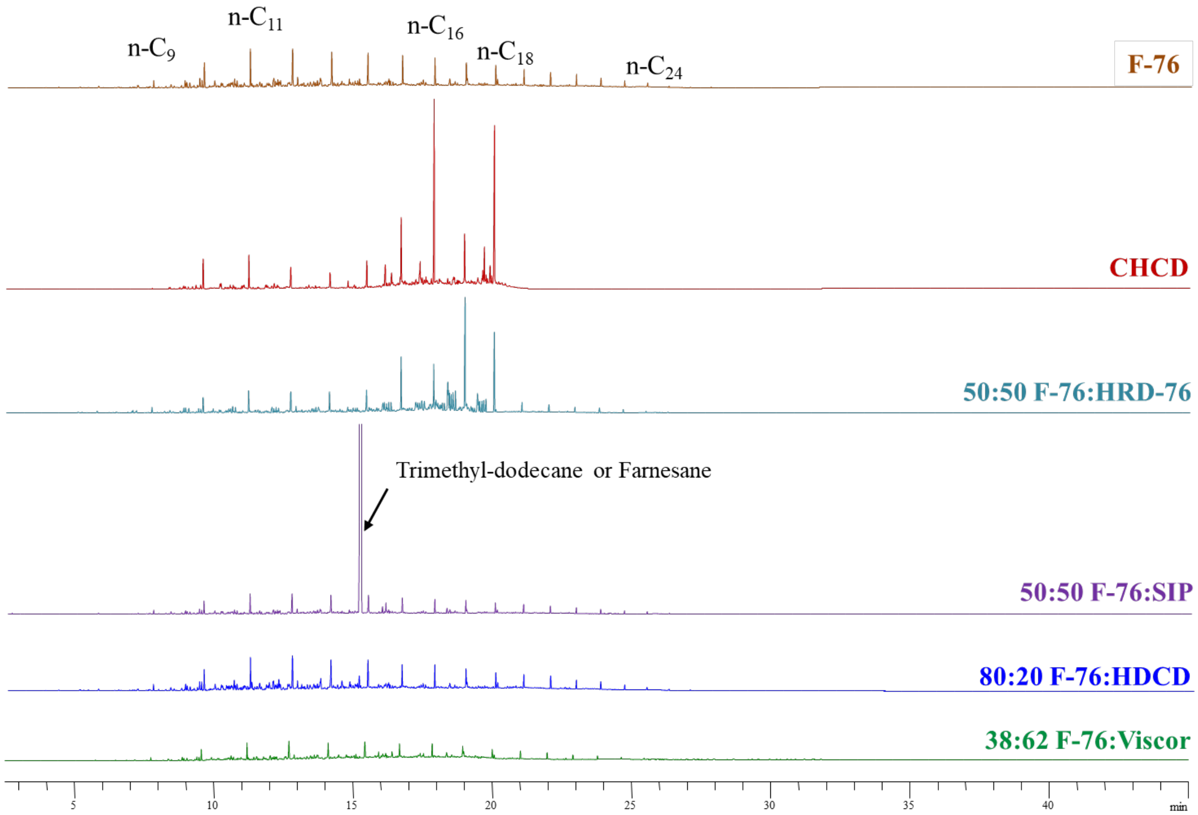


Figure 2 Gas Chromatograms of several of the test fuels

Table 1 Properties of the Test Fuels

Navy ID	POSF ID	Fuel Type	C/H ratio	Viscosity at 233 K (cSt)	Viscosity at 278 K (cSt)	Density at 288 K (g/cm^3)	DCN	Distillation Temp K 10%	Distillation Temp K 90%
15337	13336	F-76 Marine Diesel	14.0/26.5	5.77	2.50	0.833	48.9	477.5	602.2
15338	13337	Catalytic Hydrothermolysis Conversion Diesel (CHCD)	14.8/27.8	6.85	2.86	0.838	54.3	510.42	568.2
15339	13338	50:50 F-76:HRD (Hydroprocessed Renewable Diesel)	14.8/29.7	6.05	2.62	0.806	60.3	495.0	580.2
15340	13339	80:20 F-76:SIP (Synthetic Iso-paraffinic) Farnesane	14.2/27.5	5.66	2.47	0.821	50.3	483.7	595.2
15341	13340	50:50 F-76:SIP (Synthetic Iso-paraffinic) Farnesane	14.5/29.2	5.51	2.41	0.802	53.5	497.7	572.2
15342	13341	80:20 F-76:HDCD (Hydroprocessed depolymerized Cellulosic Diesel)	13.8/25.3	6.03	2.57	0.848	44.3	478.1	600.2
15453	13343	50:50 F-76:Viscor	14.8/27.7	11.86	4.18	0.852	49.4	492.7	657.2
15454	13344	38:62 F-76:Viscor	15.0/28.0	14.11	4.71	0.856	50.1	498.5	656.2
-	10289	JP-5 (A-3)	11.9/22.6	3.12	1.61	0.827	39.2	467.2	519.2

2.3 Experimental Procedure - Ignition Tests

Spark ignition in a gas turbine combustor with liquid spray is a very stochastic process. There are fuel-to-air (f/a) ratios that are too low to ignite, and above this region there are f/a ratios where the combustor may or may not ignite with increasing probabilities as the f/a ratio is increased. Our procedure is to map out the region from low (nearly zero) to high ignition probabilities by counting sparks, and the corresponding ignition successes and failures. Binomial logistic regression is used to convert the failed ignition events (0s) and successful ignition (1s) to a probability curve. A typical curve is composed of more than 50 separate ignition attempts which may consist of up to 40 separate spark events each.

Prior to the ignition experiments, careful flushing of the pumps and the rest of the fuel system (mass flow meter, heat exchanger and tubing) was completed. Residual fuel in the head space of the pumps was addressed by executing a complete flush and fill cycle for each pump four times. The fuel system was flushed by flowing ~1.5 gallons of the new test fuel while the combustor was operating. To verify no fuel contamination with the previous test fuel (<0.1% by mass), a fuel sample was extracted near the fuel nozzle and analyzed via two-dimensional gas chromatography (GCxGC). For each separate ignition test, the test parameters (T_{fuel}, T_{air}, ΔP and P) are preset and held constant. The combustor operating test points for the ignition experiments are summarized in Table 2. The combustor pressure before ignition for the cold experiments was approximately one atmosphere and the fuel and air were controlled to the same temperature ($T_{air} = T_{fuel} = 278K$). On each ignition attempt, the fuel was allowed to flow through an internal bypass loop until the desired fuel temperature was reached before starting the sparks. Fuel control was provided by two sets of high pressure syringe pumps, and the fuel flow rate was measured via a Coriolis meter. For each combination of fuel type and flow conditions, five or six fuel flow rates were selected between high and low ignition probabilities. At each fuel flow rate, there were ten ignition attempts which consisted up to 40 sparks occurring at a frequency of ~3.5 Hz.

Table 2 Target Operating Conditions for Ignition Study

Test Parameter	Value
Air Temperature (K)	278
Air Flow (kg/s)	0.181
Fuel Nozzle	Pilot Only
Fuel Temperature (K)	278
Combustor Pressure (Atm)	1.0
ΔP_{dome} (% of Plenum Pressure)	2

Ignition performance is assessed using the ignition probability (IP), which requires a method to count the spark events before ignition. A photodiode is used to count and locate in time the spark events. Figure 3 shows the photodiode signal, measured at a rate of 100 kHz before and after ignition, during a typical ignition test. Each of the non-ignition sparks are shown as a sharp peak. The ignition event is evidenced by a continuous photodiode signal above the baseline. The same photodiode that was used to detect ignition was also used to detect LBO. During combustion, the photodiode signal showed a continuous signal above a threshold. As the flame is extinguished completely, the photodiode signal drops rapidly to the baseline.

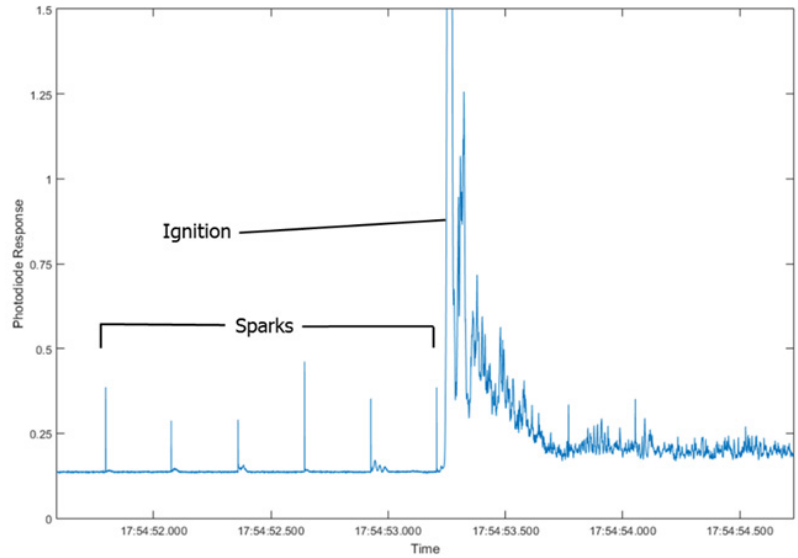


Figure 3 Typical Photodiode Trace from an Ignition Experiment Showing Five Unsuccessful Sparks Before Ignition and the Ignition Event.

After a successful ignition attempt was confirmed by visual examination of a flame in the combustor, the spark sequence was stopped, and then the fuel flow was stopped to end the ignition attempt. For attempts when ignition did not occur within 40 sparks, the ignition attempt was halted to avoid filling the exhaust with unreacted fuel. Approximately 3-5 minutes were required between each ignition attempt to refill the fuel pumps and allow the combustor hardware to cool down from successful ignition.

2.4 Experimental Procedure - LBO Tests

The combustor conditions for the LBO study are summarized in Table 3. Steady operation conditions were obtained by setting the combustor air mass flow, temperature and pressure at a constant level required to achieve the desired combustor ΔP. After setting the air flow rates and pressures, the fuel flow rate and the supply temperature were then adjusted slowly to achieve the desired equivalence ratio (φ). The acoustic response at the combustor wall was measured by a high frequency pressure transducer, with a frequency response of 150 kHz, using a semi-infinite tube technique as a high pass filter to measure only the fluctuating pressure. The transducer was sampled at 20 kHz because the dynamics of interest were all below 2 kHz. The tap for the high frequency transducer was located in the near field of the injector at the same axial location as the tap for the combustor static pressure. Static pressures were also measured at five other locations along combustor wall.

Table 3 Target Operating Conditions for LBO Study

Test Parameter	Value
Air Temperature (K)	394
Air Flow (kg/s)	0.391
Fuel Nozzle	Pilot Only
Fuel Temperature (K)	322
Combustor Pressure (atm)	2.04
ΔP_{dome} (% of Plenum Pressure)	3

During an LBO test, the combustor conditions are carefully controlled while slowly decreasing the fuel flow at a constant rate using syringe pumps. A sufficiently slow fuel ramp rate is important to allow the wall temperatures to respond to reductions the fuel flow rate. Excessively fast reductions in fuel flow rate will tend to bias the LBO event to lower φ values because of higher wall temperatures. The combination of thin combustor walls and high effusion cooling, allowed the wall temperatures to quickly reach a steady state condition. A fixed fuel flow reduction ramp at a rate of 0.25 ml/min every 2 seconds provided a smooth, repeatable ramp of the fuel flow rate vs time. This rate maximized the number of test points acquired while ensuring that the LBO φ was not biased by a high ramp rate for fuel reduction. During each LBO test, while the fuel flow was decreased, the fuel temperature and combustor pressure were maintained at constant levels, and measurements were acquired at a rate of 15 Hz. The LBO point was determined by the rapid drop of the signal from a photodiode directed at the combustor primary zone. The average time required to ramp the fuel down to LBO was typically 200-300 seconds.

Prior to evaluating each fuel, the fuel system is flushed out following the procedure outlined in the ignition tests section. The LBO tests were conducted over twenty five times for each fuel to improve the statistical significance of the results. A JP-5 fuel, designated as A-3, was used as a baseline by testing on multiple days to assess the relative performance of the combustor throughout the test program.

3 TEST RESULTS

3.1 Ignition Results

Careful control of the experimental conditions was maintained throughout the ignition tests. A summary of actual experimental conditions maintained is presented in Table 4. The combustor pressure fluctuated slightly from day to day as a result of barometric pressure variation, but as observed, it was within a very tight 1.44 kPa band. The fuel and air temperatures were controlled within a standard deviation of less than ±0.33K and ±0.17K for the fuel and air, respectively. Note that the minimum and maximum values in Table 4 represents the total range of combustor conditions for all of the 6056 counted sparks in the study.

Table 4 Summary of Facility Experimental Conditions

	P_{cmb} (Atm)	T_{air} (K)	T_{fuel} (K)	Air □ P % of Plenum
Average Value	0.993	277.6	277.7	2.02
Standard Deviation	0.003	.17	.33	0.021
Maximum	1.003	278.2	278.8	2.11
Minimum	0.987	276.5	276.3	1.92

The spark energy delivered to the plug was determined by the integration of voltage and current traces for each spark. The delivered energy depends on the stored energy in the ignition system, the impedance losses in the leads, and the local conditions at the plug, which are affected by the pressure, temperature, and the chemical composition in the vicinity of the discharge. In particular, the presence of fuel droplets increases the delivered voltage and thus increases the delivered energy at the plug. The stored spark energy was set to be the same for all experiments, but temporal variations in the conditions at the plug result in shot-to-shot variations in the delivered energy. Table 5 shows the average energy delivered to the igniter plug along with its standard deviation for each fuel tested. Note that the spread of average spark energy delivered for the fuels in this study was is less than 5%.

Table 5 Average delivered energy to the igniter plug for each fuel tested

Fuel	POSF #	Average Delivered Energy (J)	Standard Deviation For Delivered Energy (J)
A-3	10289	1.39	0.025
F-76	13336	1.47	0.030
CHCD	13337	1.46	0.034
50:50 F-76:SIP	13340	1.48	0.029
80:20 F-76:SIP	13339	1.49	0.035
80:20 F-76:HDCD	13341	1.49	0.033
50:50 F-76:HRD	13338	1.51	0.035
38:62 F-76:Viscor	13344	1.52	0.038
50:50 F-76:Viscor	13343	1.45	0.035

Table 6 average delivered energy to the igniter plug for each fuel tested. For each fuel there were approximately 60 ignition attempts, with each attempt containing 1-40 sparks. Figure 4 gives a summary of the total sparks in the study, along with a breakdown of sparks resulting in ignition success and failure. Note that the raw ignition results are more biased toward ignition failure as there can be only one ignition success for each ignition trial while there can be up to 40 sparks resulting in ignition failure during an ignition attempt. Also note that successful ignition was achieved for all fuels. The ignition probability was found to be a strong function of the fuel type and the φ.

Each individual spark resulted in either a successful ignition, determined by spreading of the visible flame upstream of the spark igniter and across the combustor, or an ignition failure. The successful ignition was determined from the photodiode traces as a continuous elevated signal above the threshold extending in time past the next spark. In cases where there was ambiguity from the photodiode signal, high speed (1100 Hz) video and combustor pressure signals were used to confirm ignition. The results from each spark were used to calculate ignition probabilities, with the sparks counted using the photodiode and characterized as either a 1 for ignition or a 0 for non-ignition. At low φ values the probability of ignition is essentially zero, whereas at higher values the probability approaches one. In between these two extremes there is a region where the successful and non-successful ignition sparks overlap.

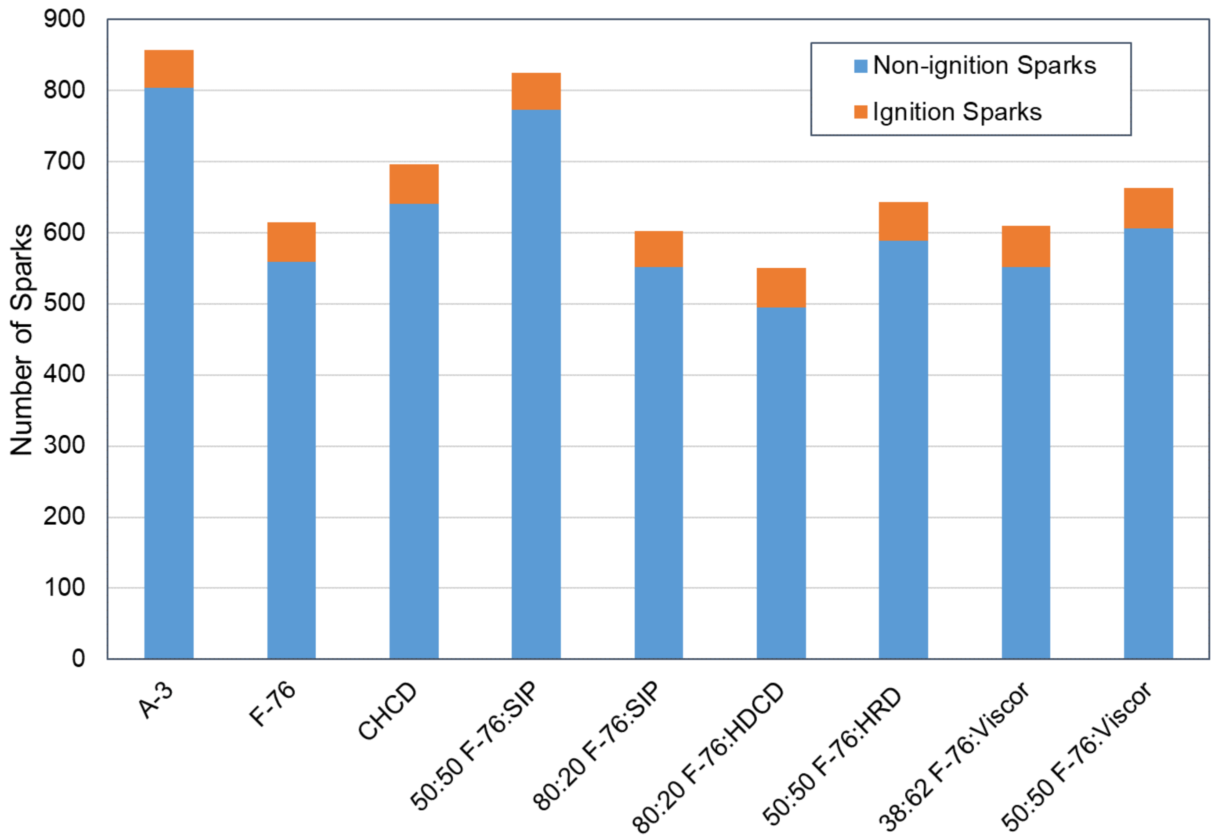


Figure 4 The Summation of Spark Attempts during the Ignition Experiments. Total Sparks =6056, Total Successful Ignitions = 489.

Binomial linear regression was used to reduce the 0s and 1s from the individual sparks into an ignition probability curve vs the φ to produce the following curve fit for ignition probability using the logistic function shown in Equation 1:

$$IP = \frac{1}{1+e^{(-k(\phi-A))}} \qquad (1)$$

where,

- IP is the ignition probability,
- φ is the equivalence ratio,
- A is a constant equal to the φ at 50% ignition probability,
- k is a constant equal to 4 times the slope of the IP curve at the 50% ignition probability point

The logistic function is a monotonic function that approaches probability limits of 0 and 1 and has been used in combination with binomial regression for other ignition studies to produce ignition probability curves vs φ and other variables [5-9]. A typical ignition probability curve plotted vs the φ is shown in Figure 5. The individual sparks are shown as either an ignition spark at 1 or a non-ignition spark at a level of 0. It can be seen that there is an overlap region where both ignition and non-ignition events occurred. The ignition probability increases with increased φ. Below a lean limit for a particular fuel the fuel spray will not ignite. When comparing two or more fuels, the fuel that ignites at the lowest φ at a given ignition probability has the best ignition performance. Also shown are the 95% confidence intervals which were determined using the methods as described by Bane [5]. Note that the confidence intervals at high ignition probabilities are broader near the higher ignition probabilities and decrease in width as the ignition probability decreases.

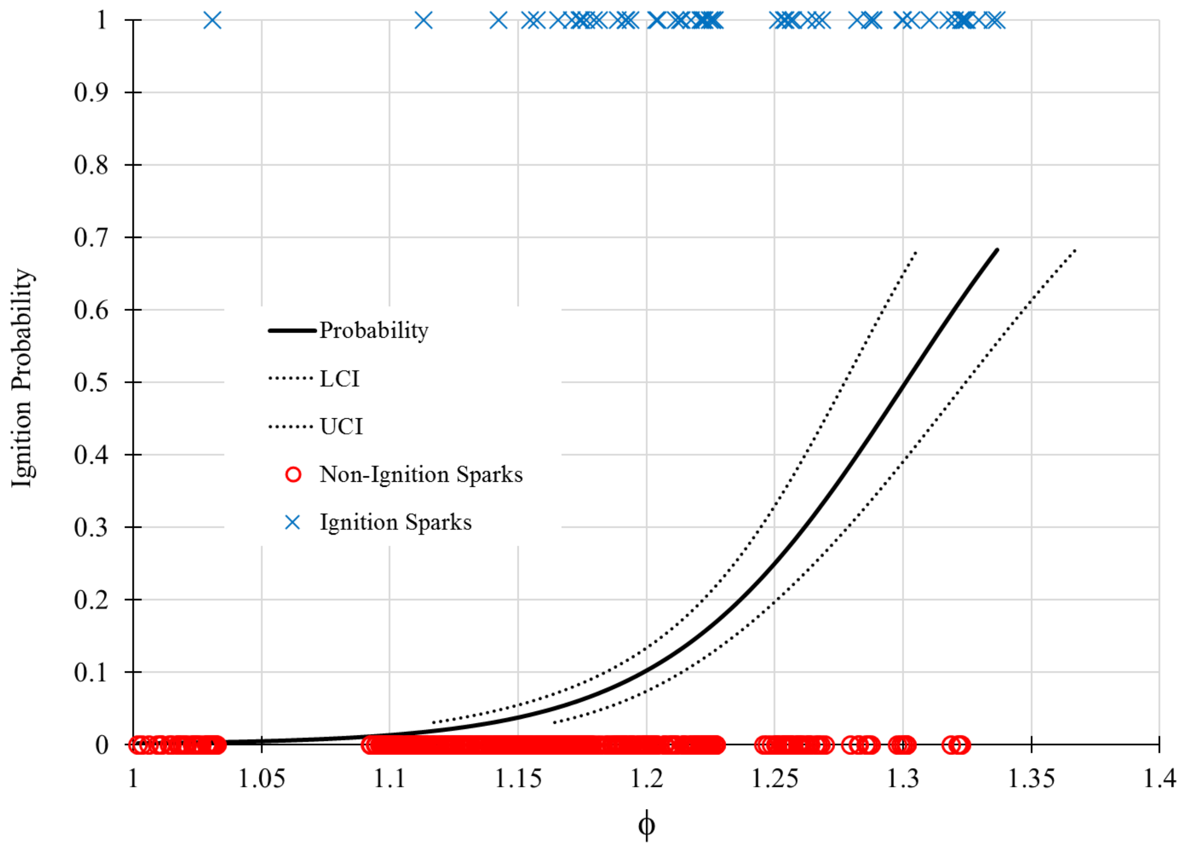


Figure 5 Binomial Regression Results for POSF 13344, Showing Ignition and Non-Ignition Sparks, and 95% Upper and Lower Confidence Intervals (UCI, LCI).

The ignition probability curves for all of the fuels, determined by binomial logistic regression of the experimental results, and plotted against the overall φ, are shown in Figure 6. The solid lines represent the probability curves and the dashed lines represent the 95% confidence intervals. The regression curves are shown only over the range of actual data, i.e., not extrapolated toward 0 or 100 % probability. The confidence interval lines for the F-76 and 50/50 F-76/HRD curves are omitted for clarity, but are included in the close up shown in Figure 7 which shows the results for a subset of fuels that have overlapping confidence intervals.

Six of the fuels have statistically significant different performance from all of the other fuels. The best performing fuel for ignition was A-3 (JP-5), which was tested as a reference fuel. The diesel test fuel with the best ignition performance (ignition at lowest φ) was the 50:50 F-76:SIP fuel. The three fuels with the poorest ignition performance were the highly-viscous Viscor:F-76 blends, followed by the CHCD fuel.

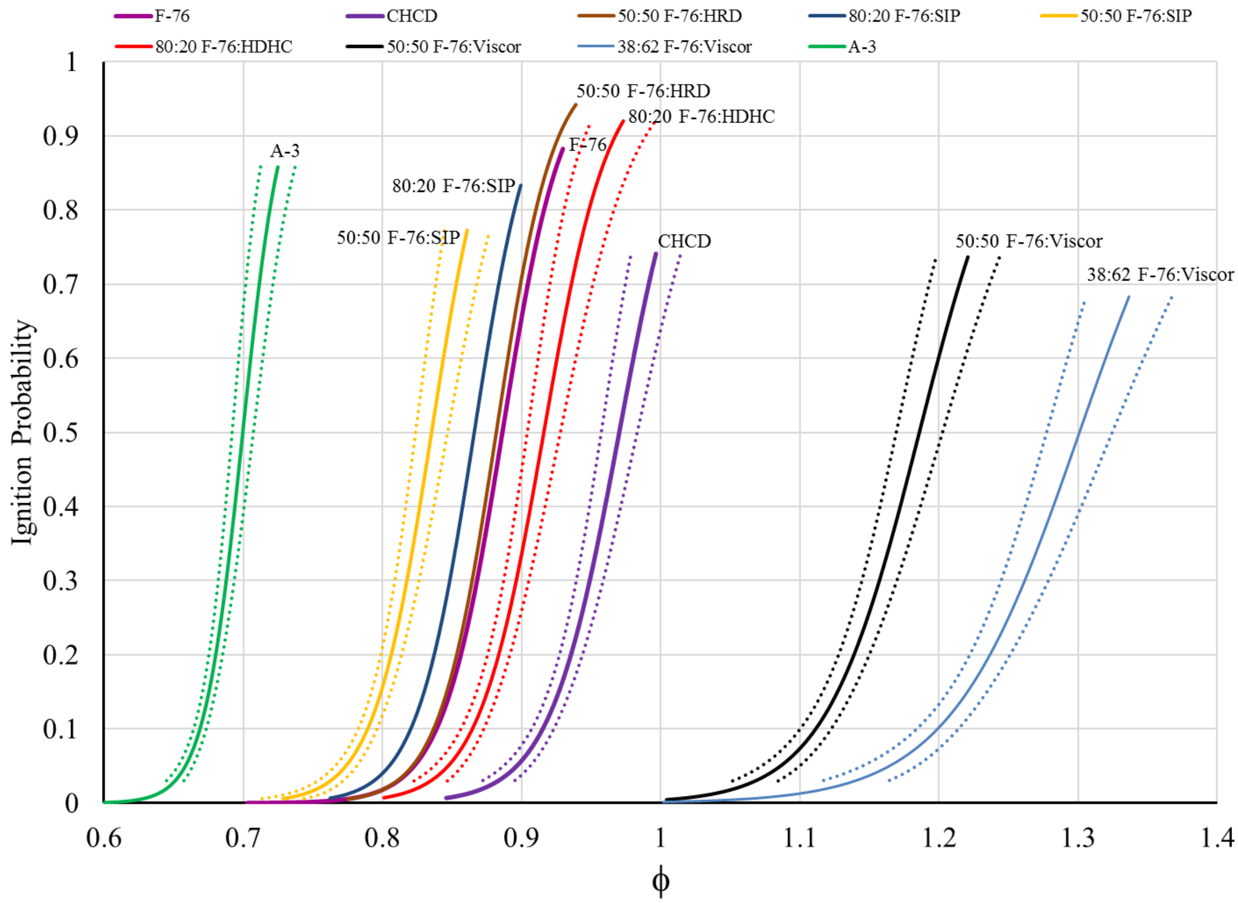


Figure 6 Ignition probability curves for all fuels tested

As shown in Figure 7, three of the fuels, F-76, F-76:HRD, and 80:20 F-76:SIP show an overlap in the confidence intervals over much of the range of φs considered.

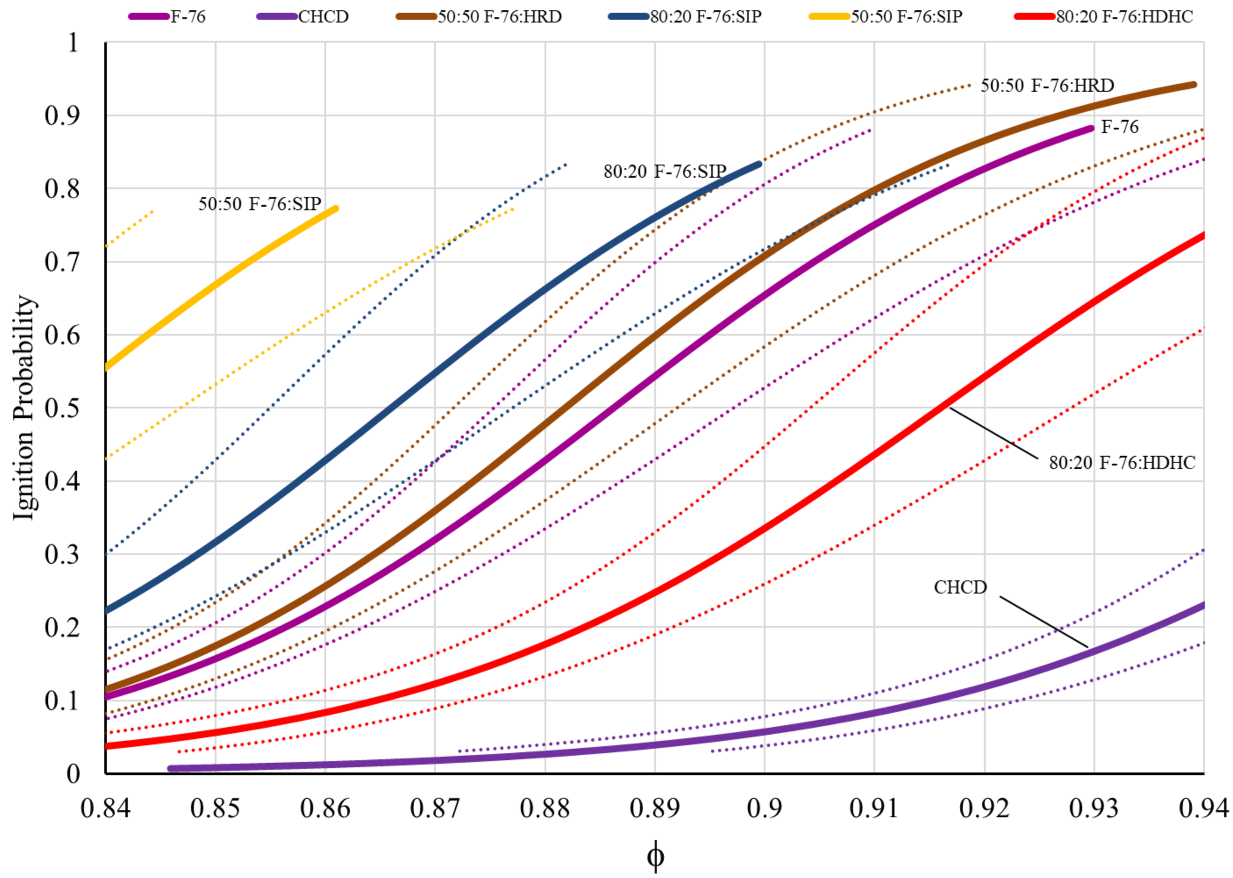


Figure 7 Close-up of the ignition probability curves for fuels with overlapping ignition performance

Table 6 provides the ignition performance for each fuel, expressed as the φ where the regression curve crosses the 50% ignition probability point. The width of the confidence interval for the ignition φ and fuels for which ignition performance overlap are also provided.

Table 6 Performance ranking at 50% ignition probability (IP) listed from best to worst

Navy #	POSF#	Description	ϕ at 50% IP	95% CI for ϕ at 50% IP	% Width of CI	Confidence Interval at 50% IP Overlaps With
n/a	10289	A-3	0.699	0.0076	1.09%	none
15341	13340	50:50 F-76:SIP	0.835	0.0115	1.38%	none
15340	13339	80:20 F-76:SIP	0.866	0.0110	1.27%	POSF 13338 & POSF 13336
15339	13338	50:50 F-76:HRD	0.882	0.0102	1.15%	POSF 13339 &POSF 13336
15337	13336	F-76	0.886	0.0109	1.23%	POSF 13338 & POSF 13339
15342	13341	80:20 F-76:HDHC	0.916	0.0119	1.30%	none
15338	13337	CHCD	0.970	0.0129	1.33%	none
15453	13343	50:50 F-76:Viscor	1.186	0.0166	1.40%	none
15454	13344	38:62 F-76:Viscor	1.301	0.0236	1.82%	none

Data from Table 6 was plotted against several fuel properties to study trends and assess the effects of the physical and chemical properties on the ignition performance. The resulting plots are shown in Figure 8 through Figure 13. As shown in Figures 8 through 10, there is little correlation of ignition performance with the fuel Derived Cetane Number (DCN), carbon-to-hydrogen (C/H) ratio and molecular weight (MW). These properties are associated with the chemistry of the fuels, which indicates that the ignition performance for this set of fuels is not significantly influenced by the fuel chemical properties.

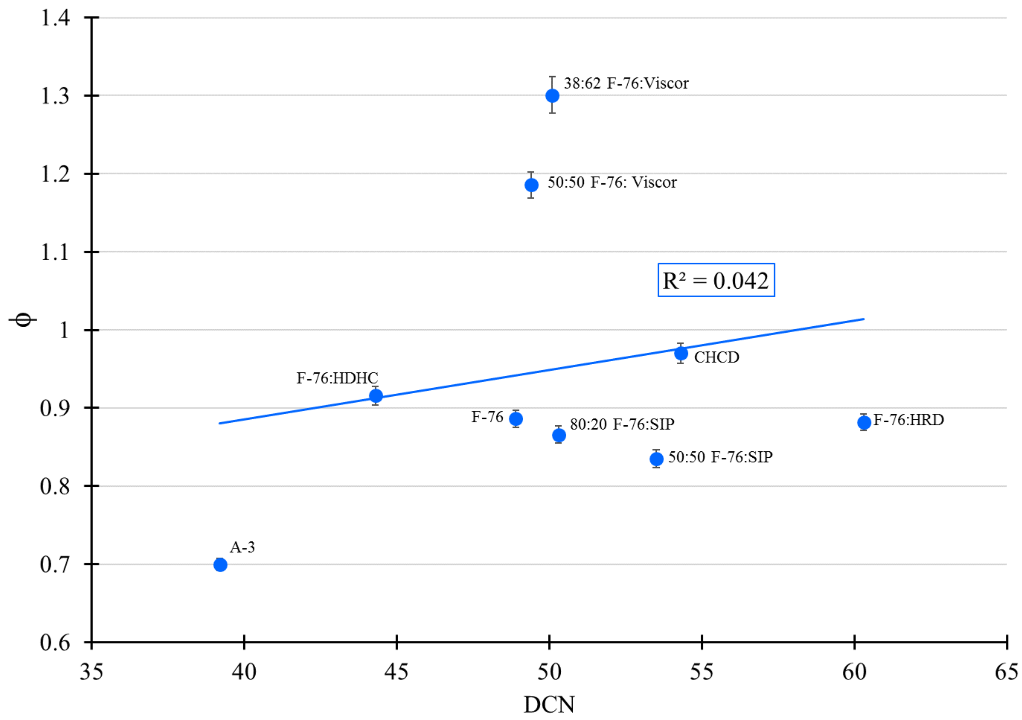


Figure 8 Global φ at 50% Ignition Probability vs DCN

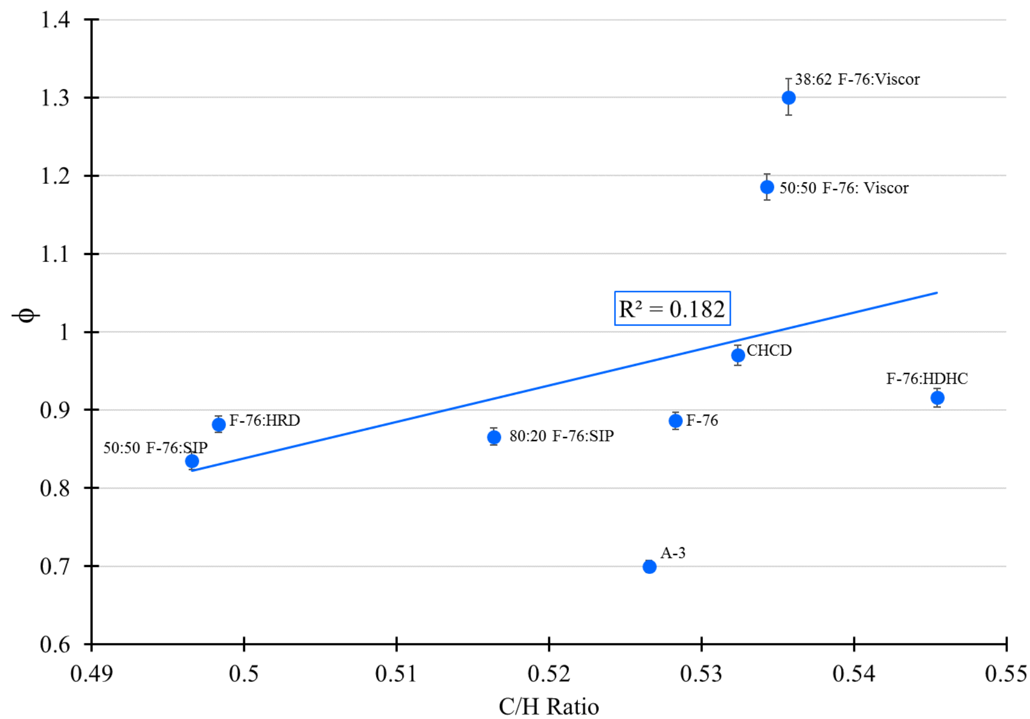


Figure 9 Global φ at 50% Ignition Probability vs C/H Ratio

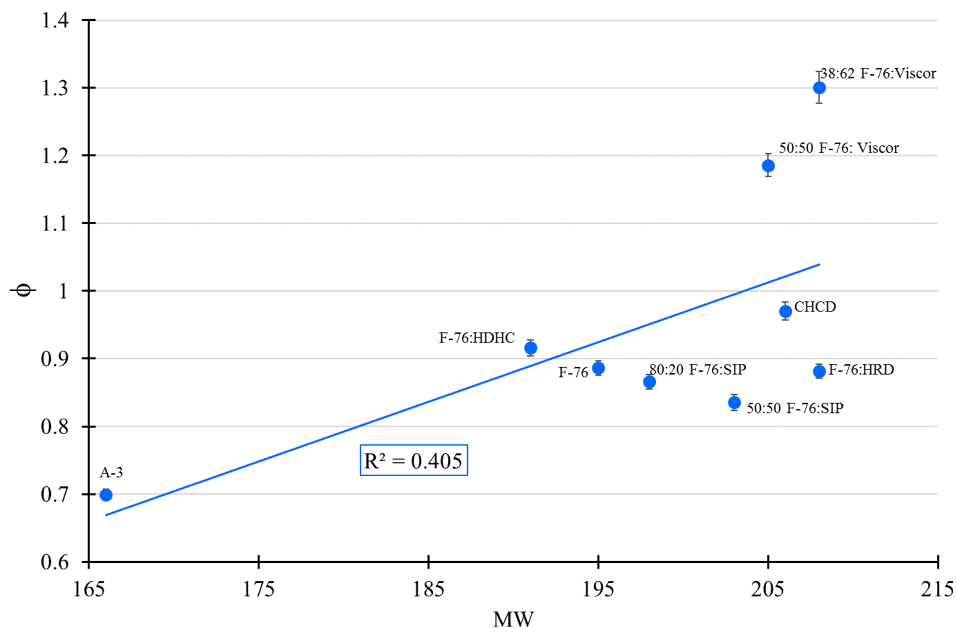


Figure 10 Global φ at 50% Ignition Probability vs MW

Figure 11 compares the ignition performance (φ at 50% IP) to fuel distillation properties. As shown, a poor correlation between the lower distillation temperature (T_{10}) and ignition performance is observed, while the correlation to T_{90} is significantly stronger with a $R^2 = 0.772$. This suggests that for relatively high density fuels, the higher molecular weight components (which have lower vapor pressures) have a higher impact on ignition than the lighter components that vaporize at or below T_{10}.

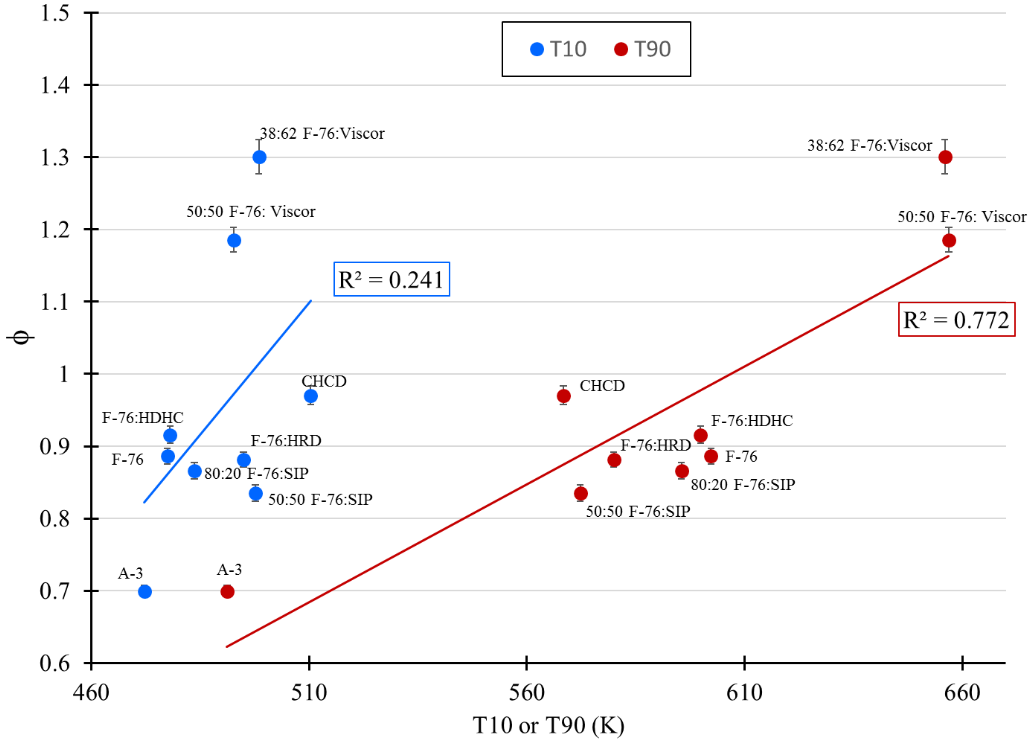


Figure 11 Global φ at 50% Ignition Probability vs T10 and T90

Fuel density and viscosity are both associated with the fuel spray characteristics, which are known to affect fuel ignition. Figures 12 and 13 show the correlations of fuel density and viscosity to ignition performance (φ at 50% IP). A moderately good correlation of fuel density with ignition performance is observed in Figure 12, while the correlation of the viscosity with ignition performance shown in Figure 13 is the strongest for all of the properties examined.

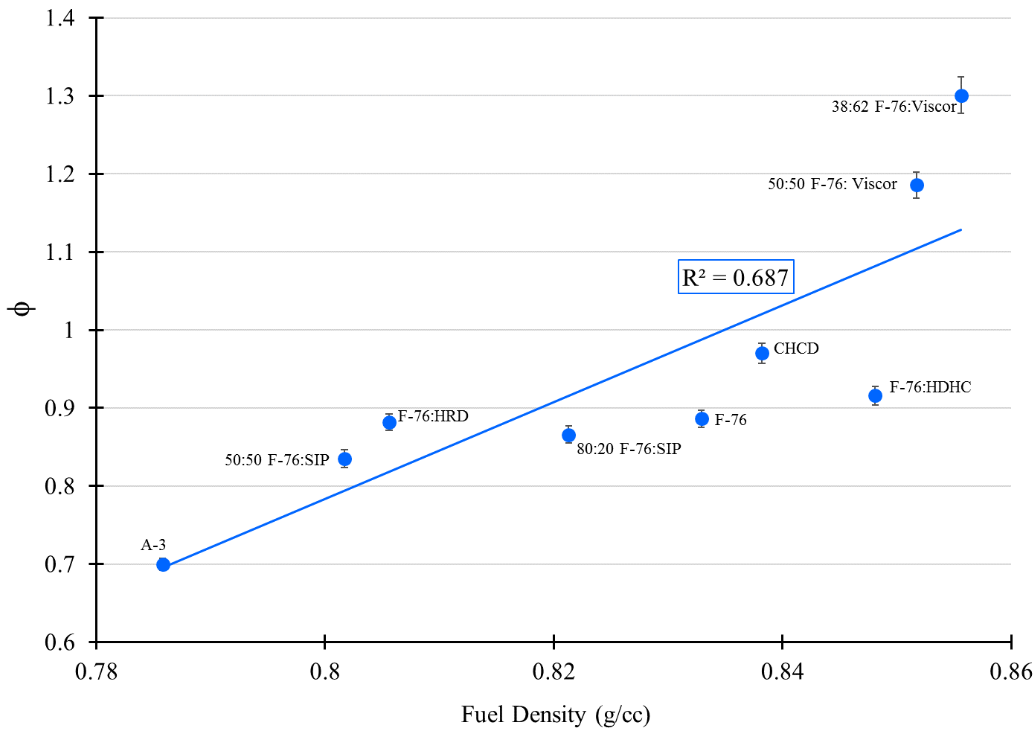


Figure 12 Global φ at 50% Ignition Probability vs Fuel Density at 288K

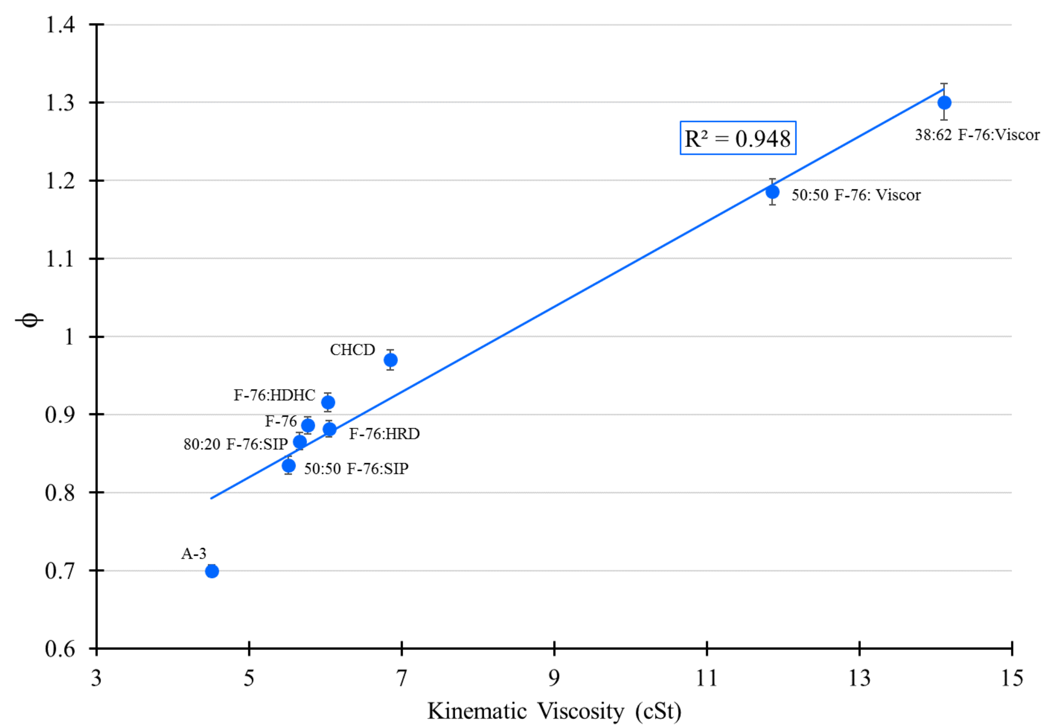


Figure 13 Global φ at 50% Ignition Probability vs Kinematic Viscosity

A multiple variable regression analysis was performed to investigate potential synergistic effects of several fuel properties on ignition performance (φ at 50 % IP). Fuel properties which showed weak correlations with ignition performance were not considered for the multiple regression model. Also, while T_{90} shows good correlation (R^2 = 0.772) for φ at 50 % IP, it also has a strong correlation with viscosity as shown in Figure 14, and was omitted from the multiple regression to eliminate collinearity. A multiple regression model was developed using fuel density and kinematic viscosity, and the results are shown in Figure 15. The figure shows the calculated value of φ at 50 % IP from the regression equation compared the actual values. As observed, the predicted φ using the model yields excellent agreement compared to actual values, and provides a moderate improvement compared to the linear correlation using only the viscosity. The regression equation accounts for 98.0 % of the variance of the 50 % IP, using only two physical properties.

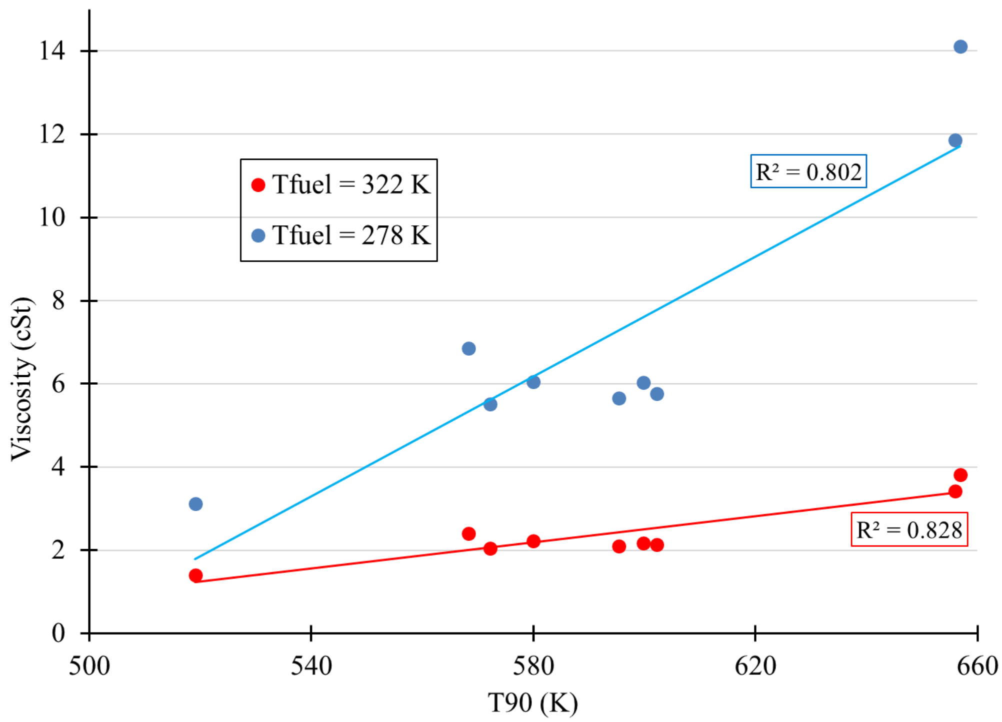


Figure 14 Fuel Viscosity vs T90

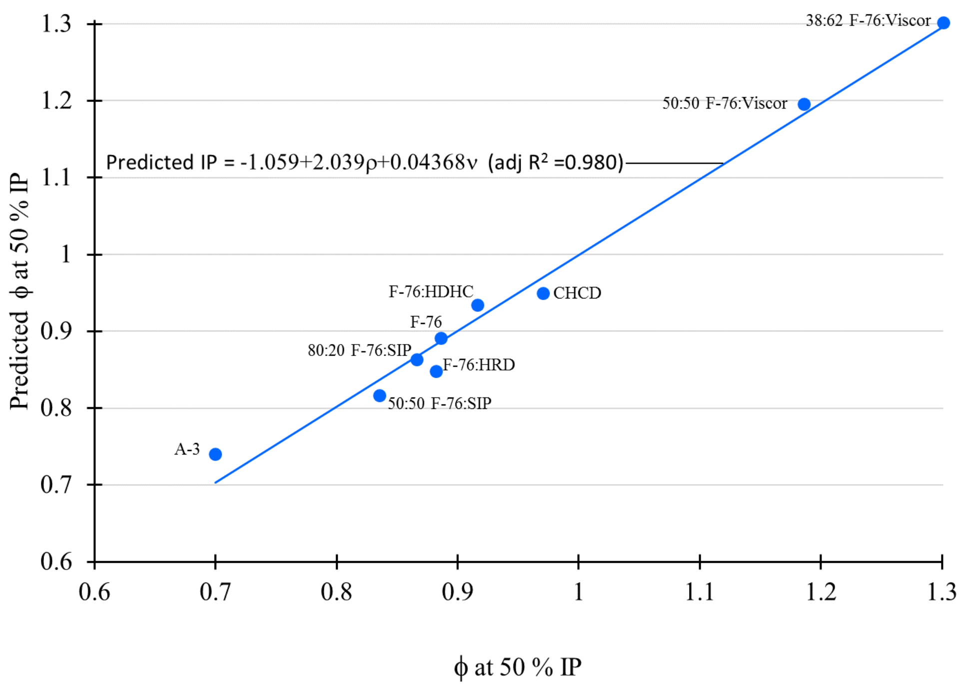


Figure 15 Predicted Values of Ignition φ at 50% IP using Multiple Variable Linear Regression vs Actual φ at 50% IP for All Fuels Tested

A-3 (JP-5) is an aviation gas turbine fuel used in Navy aircraft, and within the NJFCP program represents a "worst case for JP fuel for combustion" due to its higher flash point and viscosity. However, compared to the F-76 fuels and blends in this study, many of the physical characteristics of the A-3 fuel are more favorable for ignition performance in a spray combustor. Because of the significant differences between A-3 and the other fuels in this study, a similar multiple variable regression was developed excluding A-3 data. The results in Figure 16 show an improved prediction of ignition performance, with an adjusted $R^2 = 0.994$. Note that while an excellent LBO correlation with density and viscosity is observed, potential LBO correlation with fuel surface tension (which correlates strongly with fuel density) also merits investigation. Surface tension data for the test fuels were unavailable for this study.

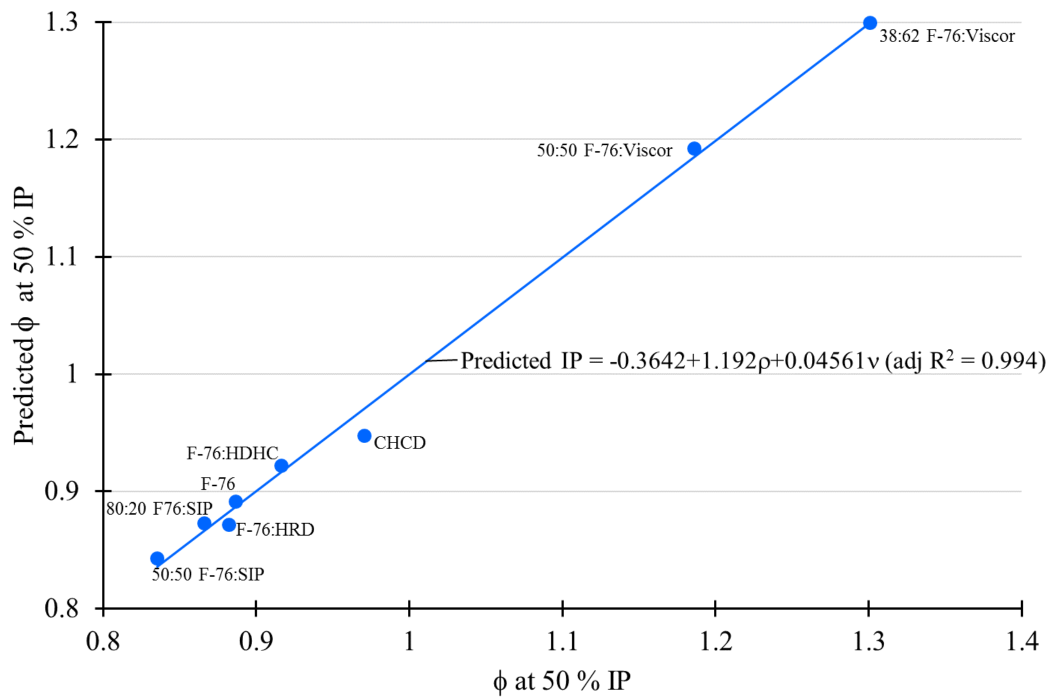


Figure 16 Predicted φ at 50% IP using Multiple Linear Regression vs Actual φ at 50% IP for F-76 Fuels and Blends

3.2 Comparison with Previous Ignition Results

Previous ignition studies using the same combustor system and similar experimental conditions, have been conducted to study aviation gas turbine fuels and research fuels to support the NJFCP [3]. The experiments were conducted on jet fuels and blends with much lower distillation temperatures, MW and viscosity with an emphasis on cold start characteristics. Similar to the present effort, the fuel and air temperatures were matched, but at much lower temperatures (239K and 258K). As in the current study, the ignition performance of jet fuels was found to correlate best with fuel viscosity. Figure 17 displays the ignition performance results from both the previous and current studies plotted against viscosity. Fortuitously, the range of fuel viscosities for the aviation fuels at the lower temperatures overlap those for the current study. The results show that the correlation of fuel ignition performance with viscosity is significantly stronger for F-76 diesels fuels (current study) than for jet fuels (previous studies). In addition, the ignition performance for the F-76 diesel fuels and blends is observed to be worse than that for the aviation jet fuels at similar viscosities, even though the latter were tested at lower air temperatures. The data points for the A-3 fuel for all three data sets are noted in Figure 17. Note that the A-3 data from the current study (278K) falls on or closer to the two regression lines for the jet fuels than it does for the F-76 diesel fuels. This is likely due to the similarities in chemical composition and distillation properties of the A-3 fuel compared to the jet fuels tested previously relative to the fuels evaluated in this effort.

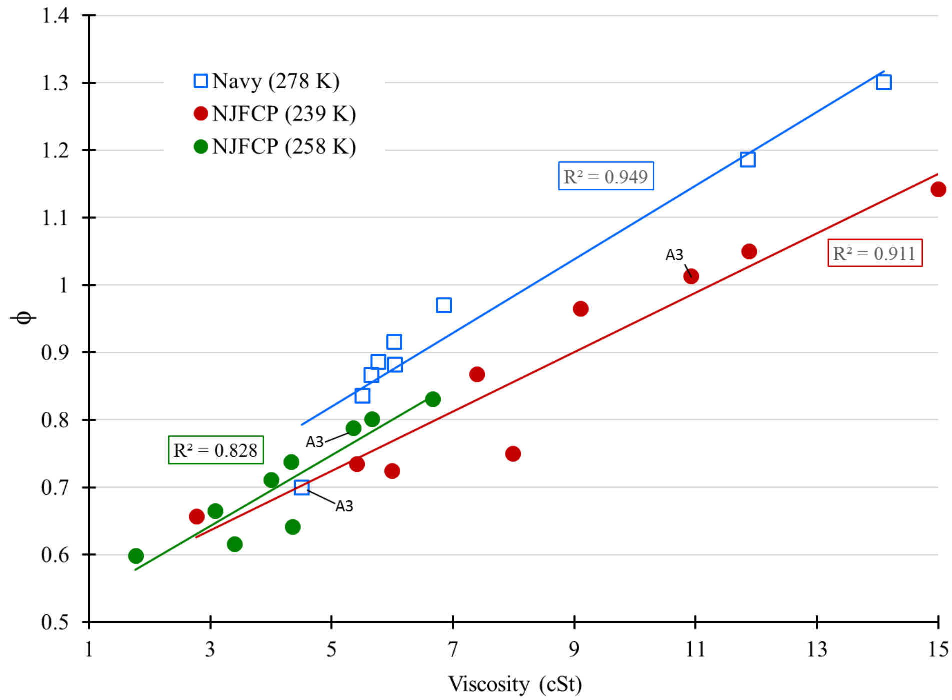


Figure 17 Measured φ at 50% IP vs Kinematic Viscosity for Current Study and Aviation Fuels Study from Reference 2.

3.3 Lean Blowout (LBO) Results

LBO experiments were conducted using the target conditions stated in Table 3. A total of at least 25 separate LBO trials were conducted for each fuel. Table 7 gives a summary of the range of conditions maintained during the LBO experiments. Repeatability of test conditions for an LBO experiment is difficult to achieve on a day to day basis due factors such as: soot deposits on nozzles, swirlers and effusion holes, control hysteresis or minor air fluctuations. For this reason, A-3 was used as a reference and screened throughout the experiments to determine and mitigate the effects of any rig variation. It should be noted that the fuels in this study produced high accumulations of soot on the combustor walls and windows. The overall average LBO φ for all A-3 data (122 individual test points) was φ= 0.0843, which varied between φ = 0.0836 and 0.0853, a range of 2%, through the course of the experiments. Although this is a relatively small variation, the individual LBO data for each fuel were normalized by the average of the LBO φ values of two adjacent A-3 fuel tests to mitigate the effect of rig variation on the results. Table 8 lists the values for the A-3 LBO φ values that were used for the normalization of the data. The range of the average values that were used to normalize the data were less than 1.2%.

Table 7 Boundary Conditions maintained During the LBO study

	P_{cmb} (atm)	T_{air} (K)	T_{fuel} (K)	Air ΔP % of Plenum
Average	2.038	394.5	322.3	3.04
Standard Deviation	0.0041	0.136	0.683	0.031
Maximum	2.051	395.2	324.0	3.13
Minimum	2.028	394.0	320.7	2.92

The results for LBO φ normalized by the A-3 LBO are shown in Figure 18. Note that all the diesel test fuels have worse LBO performance than the A-3 fuel (JP-5), with LBO φ ranging from 4% to 19.5 % higher than the A-3 fuel. A ranking chart is presented in. Table 7. For the Navy fuels the best LBO performance was seen for the 50:50 F-76:SIP fuel. The two F-76:Viscor fuel mixtures showed the worst performance. LBO performance for the remaining fuels showed a large degree of overlap of confidence intervals (CI).

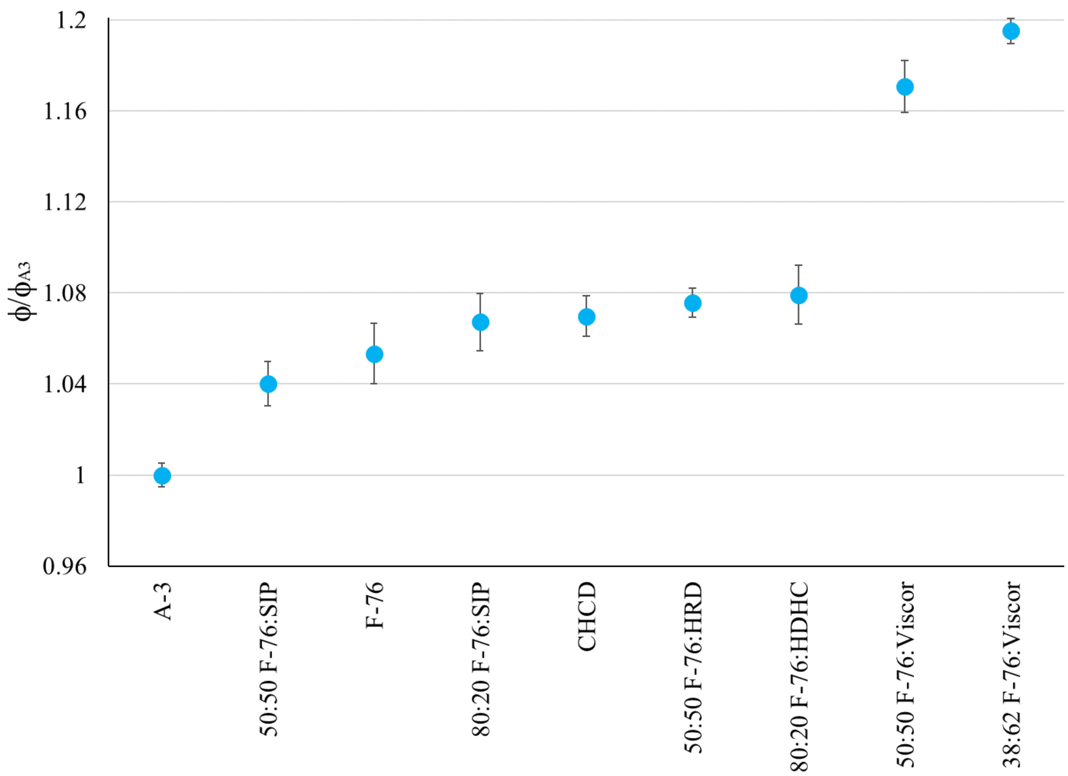


Figure 18 The LBO φ Normalized by the LBO φ for A-3. Error bars are 95% CI of the Mean

Table 8 Ranking of LBO Performance of the Fuels from Best to WorstError! Not a valid link.

Fuel LBO data were plotted against several fuel physical and chemical properties to study trends and assess their effects on the LBO performance. The resulting plots are shown in Figure 19 through Figure 24. As shown in Figure 19-21, very poor correlations of LBO performance with the fuel Derived Cetane number (DCN), carbon-to-hydrogen (C/H) ratio and molecular weight (MW) are observed. These properties are associated with the chemistry of the fuels, indicating that the LBO performance for this set of fuels is not strongly influenced by the fuel chemical properties. The comparison of LBO with the 10% and 90% distillation temperatures is shown in Figure 22. As shown, the correlation of the LBO with the low end of the distillation curve (T_{10}) is poor while the correlation with the upper end of the distillation curve (T_{90}) is significantly better. Note that there is also a strong correlation between T_{90} and viscosity as was shown in Figure 14. The correlation of the two properties which affect the spray characteristics, i.e., density and viscosity, are shown in Figure 23 and 24. Density shows little correlation, while the viscosity shows the strongest linear correlation ($R^2 = 0.973$) with the LBO performance of all properties studied.

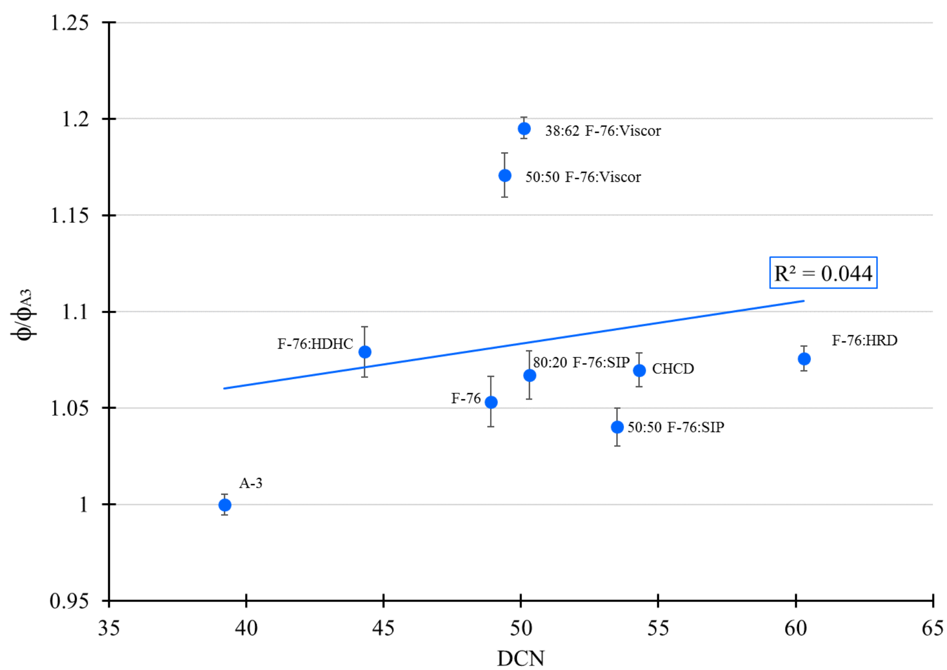


Figure 19 The LBO φ Normalized by the A-3 LBO vs DCN

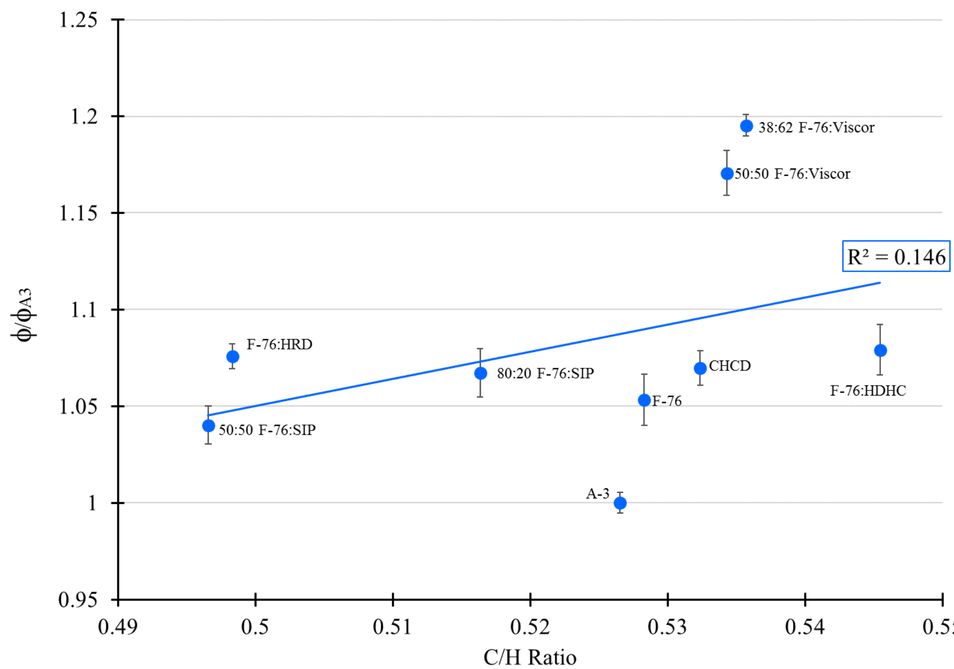


Figure 20 The LBO φ Normalized by the A-3 LBO vs C/H Ratio

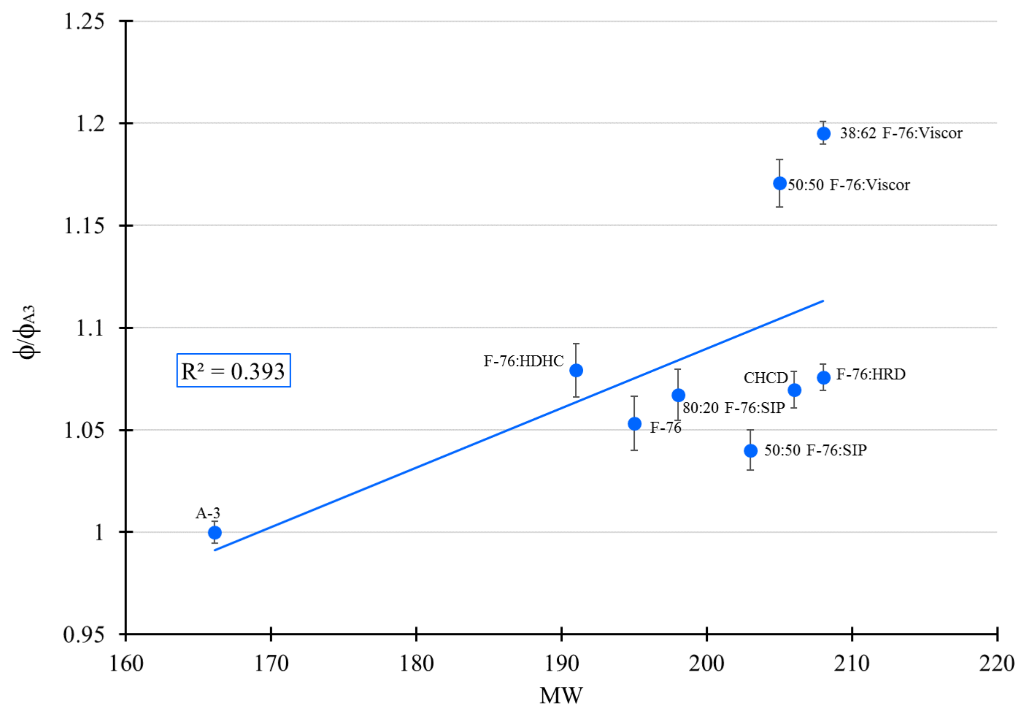


Figure 21 The LBO φ Normalized by the A-3 LBO vs MW

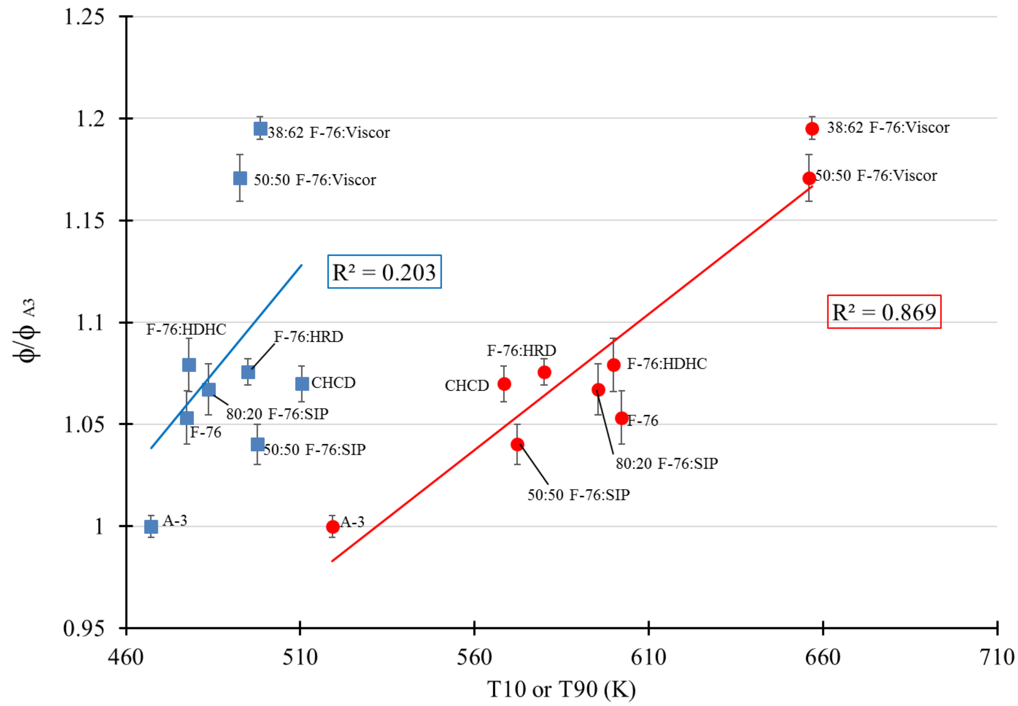


Figure 22 The LBO φ Normalized by the A-3 LBO vs T10 and T90 Distillation Temperatures

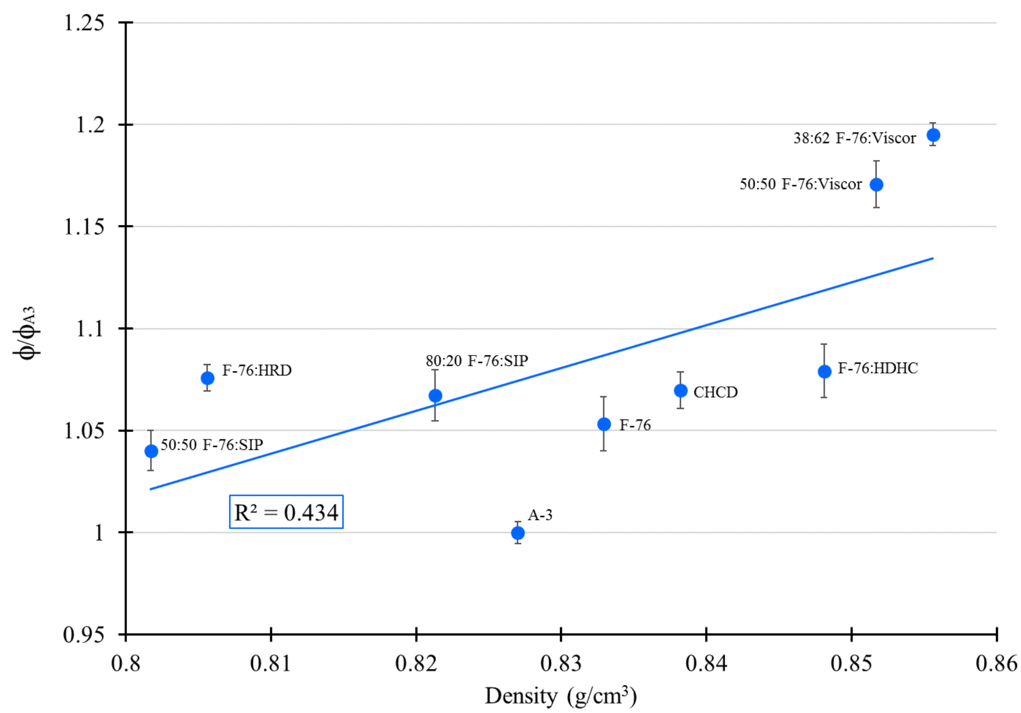


Figure 23 The LBO φ Normalized by the A-3 LBO vs Fuel Density

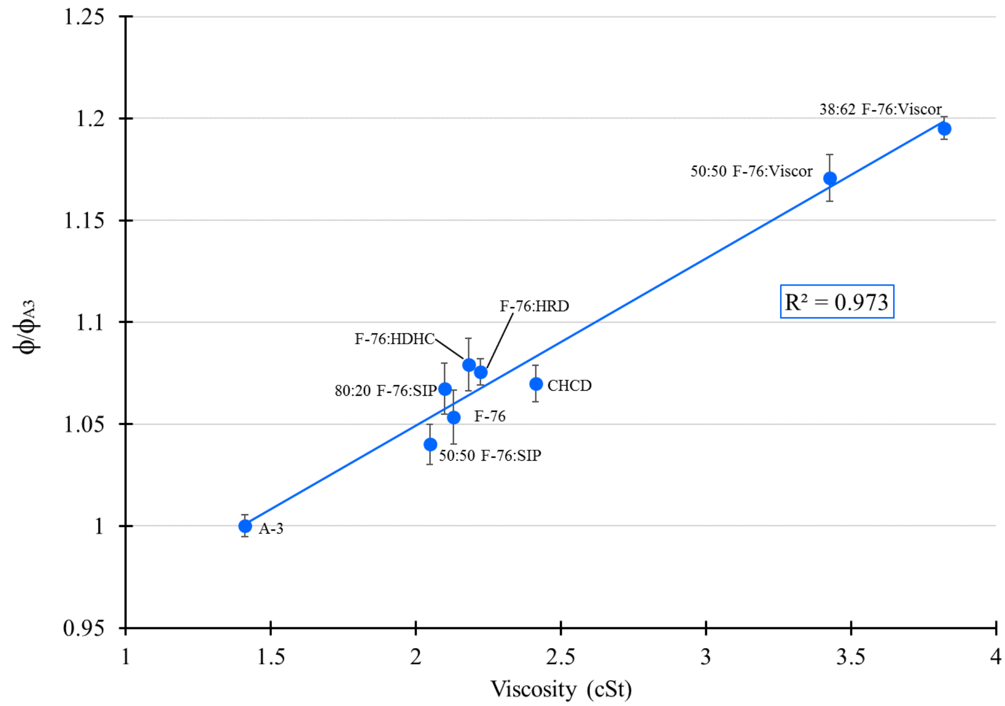


Figure 24 The LBO φ Normalized by the A-3 LBO vs Fuel Viscosity

The possibility of improving the already good correlation of the LBO performance with viscosity by developing multiple variable linear regressions was explored, but it was found that the inclusion of available physical properties did not substantially improve the correlation. This does not conclusively prove that viscosity alone is the controlling factor for LBO performance, but rather it shows the high correlation of LBO performance with the viscosity. Other properties not examined, such as surface tension, and other distillation temperatures (other than T_{10} and T_{90}) may also impact LBO performance.

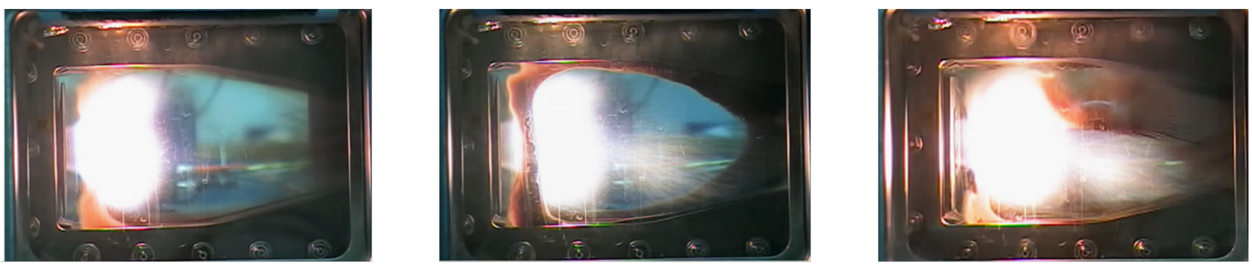
3.4 Comparison with Previous LBO Results

Previous LBO research with the same combustor configuration and boundary conditions using aviation fuels [2] showed two major differences with the present study with the diesel test fuels. First, the LBO φs in the present effort were substantially higher than those observed in the previous study. Secondly, while the present study shows that kinematic viscosity has a major effect on the LBO performance, this trend was not observed in the previous study. Instead, the aviation fuels study showed a large dependence on the fuel DCN, which was not observed in the current study. This trend with DCN indicates that the chemistry characteristics of the fuels in the previous study (for the conditions considered) were much more important than the physical properties that affect the spray quality. This suggests that the atomization quality of the aviation fuels was sufficiently good that it did not play a major role in the LBO performance. For the present diesel test fuels, the viscosities were sufficiently high to affect the spray and the LBO performance.

Examination of the videos from the high-speed and surveillance cameras showed large flaming droplets of fuel exiting the recirculation zone downstream of the dome for the diesel test fuels.

This effect was most pronounced for the most viscous fuels, 50:50 F-76:Viscor, and 38:62 F-76:Viscor. A-350:50 F-76:Viscor, 8:62 F-76:Viscor

Figure 25 shows a two-second average image extracted from the facility camera for the least viscous fuel, A-3, and the two F-76:Viscor blends. For A-3, the luminous flame is confined to the recirculation region immediately downstream of the dome. In contrast, the two high viscosity fuels produced long streaks due to large fuel droplets with enough momentum to escape the recirculation region. The unreacted fuel escaping the recirculation region did not provide significant heat release, and thus led to an increase in the fuel flow required to maintain combustion near LBO. The other diesel test fuels also showed fuel droplets escaping the recirculation region but the effect was not dramatic enough to be seen on the average video images.



A-3 **50:50 F-76:Viscor** **38:62 F-76:Viscor**

Figure 25 Average of Video Image of the Last Two Seconds before LBO for A-3 and F76:Viscor fuel blends. Pictures show unreacted fuel droplets escaping the primary zone for the high viscosity fuels.

4 CONCLUSIONS

The cold-start ignition and LBO performance of F-76 marine diesel fuels, alternative diesel fuel formulations and several blends of F-76 with alternative fuels and a high viscosity fluids, were evaluated in a single-cup swirl-stabilized combustor. The ignition study was conducted at conditions of P_{cmb}=1 atm, T_{fuel} =T_{air} =278 K and $\Delta P/P_{cmb}$ =2%. It was found that:

1. For the conditions considered, successful ignition was achieved with all of the fuels. The ignition probability was found increase with increases in φ, and ignition performance was dependent on the fuel type.
2. The ignition performance, defined as the φ at 50% ignition probability, showed the strongest correlations with fuel viscosity, density and T_{90}. Ignition performance correlations with fuel chemical properties were not apparent.
3. The ignition performance correlated best with viscosity, with improved performance with lower fuel viscosity.
4. A multiple variable regression using fuel density and viscosity produced the best predictions of ignition performance, and was able to account for 99% of the variance in the ignition performance.

The LBO study was conducted at conditions of P_{cmb}=2 atm, T_{fuel} = 322 K, T_{air} =394 K and $\Delta P/P_{cmb}$ =3%. It was found that:

1. The LBO performance, defined as the average φ at which the combustor blows out, varied over a 19.5% range for the fuels considered.
2. The LBO performance was found to correlate best with the fuel viscosity and T_{90}, with little correlation shown with the rest of the fuel properties. Like ignition, the LBO performance improved as the viscosity and T_{90} decreased; note that T_{90} correlated strongly with viscosity for the fuels considered in this study.
3. Multiple variable regressions did not improve the linear regression of the LBO performance with viscosity, which accounted for 97% of the variance of the LBO performance.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A-3	-	A worst case jet fuel (JP-5)
AFRL	-	Air Force Research Laboratory
APU	-	Auxiliary Power Unit
CHCD	-	Catalytic Hydrothermolysis Conversion Diesel
CI	-	Confidence Interval
F-76	-	Marine Diesel Fuel
GC x GC	-	Two-dimensional Gas Chromatography
HDCD	-	Hydrodepolymerized Cellulosic Diesel
HRD	-	Hydroprocessed Renewable Diesel
IP	-	Ignition Probability
LBO	-	Lean Blowout
NJFCP	-	National Jet Fuel Combustion Program
SIP	-	Synthetic Iso-paraffinin
WPAFB	-	Wright-Patterson Air Force Base