

SPRAY & LIQUID LENGTH CHARACTERISTICS OF TETRADECANE AS A SURROGATE IN COMPARISON TO JP-8

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ABSTRACT

Extensive studies have been completed for diesel engine high pressure injection on spray and combustion characteristics with diesel fuel. However the US military's objective is to use JP-8 as a replacement to diesel fuel, which has limited spray and combustion information available. The differences between JP-8 and diesel in terms of fuel properties translate to differing spray and combustion characteristics. To fulfill the Single-Fuel Concept of the military and incorporate JP-8 fuels, knowledge of the fuels spray, vaporization, and combustion behavior is imperative for determining fuel impact on performance. This work quantifies vaporizing spray characteristics of vapor penetration and vaporizing liquid length using high speed imaging methods of combined Mie-scatter and Schlieren in a constant volume combustion vessel. Studies are undertaken at a constant injection pressure of 700 bar, at temperatures of 800, 946, and 1150 K at a density of 24.1 kg/m³. Tetradecane is used as a vaporizing single component surrogate for JP-8, with results compared to spray characteristics of JP-8 and diesel available in the literature. Tetradecane is chosen as a surrogate since prior experimental work using heptamethylonone (HMN) as a surrogate showed HMN does not match JP-8 liquid length trends, especially at low density conditions. Although the boiling point of HMN (240°C) matches the 90% distillation point of JP-8, a higher boiling point fuel (tetradecane at 252°C) may provide a better match to vaporization characteristics of JP-8. Results from this study provide an understanding of spray and vaporization characteristics of tetradecane as a surrogate for JP-8.

INTRODUCTION

The objective of the US military is to use JP-8 as a replacement to diesel fuel, to fulfill the single fuel concept [1]. Spray and combustion characteristics of standard diesel fuel are well established, however, those for JP-8 are not as readily available. To facilitate the ease of study and modeling, the use of surrogate fuels is common. These surrogate fuels will typically match different targets, including property (fuel characteristics and composition), developmental (kinetic and fluid dynamic processes) and application targets (engine) [2]. For this current work, where only vaporizing spray characteristics are of interest, focus is on matching property targets relevant to vaporization. Furthermore, surrogates can be single-component or multi-component. Increasing the number of components typically

results in improved accuracy to match actual fuel characteristics, however, comes at the expense of increased complexity in modeling and simulations.

Research has been undertaken investigating various surrogate fuels for JP-8. One work in particular looks at the evaporation rate of JP-8 matched to a multi-component surrogate. Three fuel components are considered for this surrogate: dodecane, tetradecane and cetane, with the final choice being 18% tetradecane and 82% dodecane [3]. The larger dodecane component is chosen as its boiling point matches the 90% distillation point of the JP-8 sample [3]. The variability in the 90% distillation point of JP-8 merits considerations of other surrogates based on their boiling point.

For the current work, the objective is to match vaporizing spray characteristics, and therefore, a single component

surrogate that matches vaporization characteristics of JP-8 is desired. A single-component surrogate is chosen in that it will have well-known thermodynamic properties for application of a 1-D analytic liquid length model and CFD studies. Typically for a vaporizing surrogate, the surrogate fuel is chosen such that its boiling point closely matches the 90% distillation point of the fuel and density [4]. The distillation curve for ultra-low sulfur diesel (ULSD) (experimentally tested) and JP-8 (data from Pickett and Hoogterp 2008) are compared with boiling points of various single-component hydrocarbons commonly used as surrogates in Figure 1, to examine surrogate selection. Clearly JP-8 has a lower distillation curve than ULSD meaning that typical ULSD surrogates will not be a good match for JP-8 surrogates as distillation differences will have a large impact on vaporization processes.

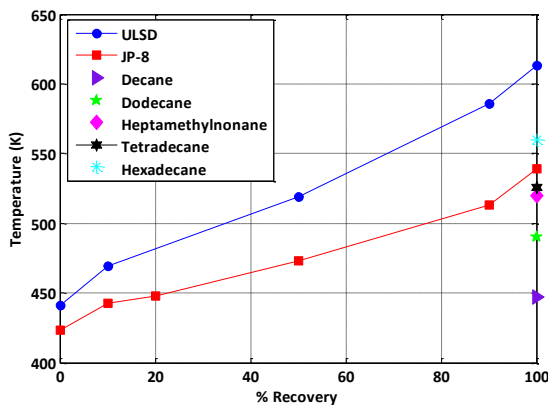


Figure 1: ULSD and JP-8 distillation curves compared to boiling points for single-component hydrocarbons.

Based on property matching for vaporizing surrogates, this would signify heptamethylnonane (HMN) as an appropriate choice for a JP-8 surrogate, as its boiling point (520 K) is 1.4% or 7 K higher than the 90% distillation point of JP-8 (513 K); and similarly HMN density (793 kg/m^3) is only 2.4% lower than that of JP-8 (812 kg/m^3). Prior work [5] has used HMN as a surrogate, comparing results to diesel and JP-8 fuel results. Their work shows that the liquid length of HMN does not match the JP-8 trends, yielding a lower liquid length, especially at low density conditions. This has led to the consideration of other higher boiling point fuels, whose boiling point falls between the 90 and 100% distillation point of JP-8, yielding the choice of Tetradecane in the current work, whose boiling point is 2.5% (13 K) higher (526 K) than JP-8's 90% distillation point and whose density is just under 7% lower. Dodecane was not chosen even though this is a large component of a proposed multi-component surrogate [3] as it has a lower boiling point than HMN, and therefore is expected to fall below the JP-8 liquid length.

Additional fuel properties for JP-8, ULSD and Tetradecane are compared in Table 1. These properties define the fuel properties of ULSD and Tetradecane used in the current test.

Table 1: Fuel properties. [^] - tested fuel properties; ⁻ calculated from chemical formula $\text{C}_{14}\text{H}_{30}$; ⁺ from [10]; [!] from MSDS; * from [5]

Property (unit)	ULSD Diesel [^]	JP-8*	Tetra-decane
Carbon (wt %)	86.94	86.1	84.84 ⁻
Hydrogen (wt %)	13.06	13.9	15.16 ⁻
Sulfur (ppm)	7	1	0
Water (ppm)	92		0
Specific Gravity at 289 K	0.847	0.812	0.762
L. Heating Value (MJ/kg)	42.81	43.23	44.09 ⁺
Cetane Index	40	39	
Viscosity @ 313K (mm^2/s)	2.3	1.4	
Distillation			
Initial Boiling Point (K)	441	423	
10% (K)	468	443	
50% (K)	518	473	
90% (K)	576	513	
Final Boiling Point (K)	613	539	526 [!]

EXPERIMENTAL SETUP

Experimental tests were conducted in the constant volume combustion vessel (CV) at Michigan Tech University [6-8], as shown in Figure 2. The vessel, which is approximately one liter in internal volume, is optically accessible via three sapphire windows to enable visualization of spray processes as they occur. A preburn procedure is used to create conditions (temperature, pressure, and composition) for the spray study. In this work, vaporizing spray tests were completed, which involve fuel injection into an elevated temperature environment, without oxygen, to enable fuel vaporization with the absence of combustion. This environment is created through a preburn procedure. A gaseous mixture of acetylene, hydrogen, oxygen, and nitrogen is created and stored in a 10 L mixing vessel. This gaseous mixture is then filled into the electrically heated combustion vessel (453K) to the desired pressure (defining the test density). The gaseous mixture is spark ignited resulting in an initial combustion event with a pressure and temperature rise. The temperature (and pressure) in the vessel decrease due to heat transfer to the cooler vessel walls. The pressure during this cool-down is monitored, and at the desired pressure (defining temperature at injection),

the injection event and image acquisition are subsequently triggered. The mixing fan at the top center of the CV (see Figure 2) is used during all tests, rotating at approximately 2000 rpm. This helps provide a well-mixed environment to provide improved mixture homogeneity in the CV.

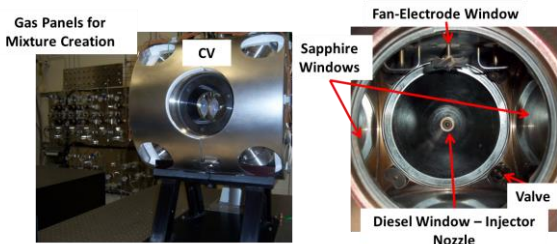


Figure 2: Optically accessible constant volume combustion vessel.

Conditions in the central region of the combustion vessel where injection occurs are core conditions [9]. The CV is characterized by both core and bulk gas conditions. The core gas conditions are those at the center portion of the combustion vessel, and represents condition that the fuel is injected into. The bulk gas conditions are the average conditions throughout the entire combustion vessel, which include the boundary layers that exist near the vessel wall and the crevice regions in the vessel. The bulk temperature and density are lower than the core gas conditions. The bulk and core gas conditions are defined based on experimentally determined coefficients to relate core and bulk temperatures, for a given vessel wall temperature [9]. The coefficient in this relationship is a function of the chamber density.

The injector used in this study is an on-axis, single-hole solenoid fuel injector with a k -factor of 0 (cylindrical hole). The injector has a 100 μm hole diameter and a length to diameter or L/d ratio of 10. A set-point constant injection duration of 1 ms was used, resulting in an actual injection of approximately 2 ms. The tests were conducted with Tetradecane as the main fuel, with one test conducted using ULSD fuel as well, whose spray characteristics are well known and published in the literature. Results are compared to those available in the literature for JP-8 fuels. The test conditions for the current study are defined in Table 2. All tests were conducted at a fixed injection pressure of 700 bar. Tests 1 through 3 are conducted with tetradecane as the fuel, with Test 2 also being conducted using ULSD fuel.

Table 2: Experimental test conditions

Test Condition	Core Density (kg/m^3)	Core Temp. (K)	Bulk Density (kg/m^3)	Bulk Temp. (K)
1	24.1	800	25.1	770
2*	24.1	946	25.4	900
3	24.1	1150	25.7	1080

OPTICAL DIAGNOSTIC AND IMAGE PROCESSING

The imaging diagnostic used was near-simultaneous Mie Scatter and shadowgraph imaging, as shown in Figure 3. Two pulsed LED’s are used with one high speed camera (Photron SA1.1) for imaging. The LED’s are pulsed such that the first image is shadowgraph, second is Mie Scattering, continuing on in this pattern. Images were acquired at 40,000 fps (25 μs interframe time) with an exposure duration of 14.5 μs .

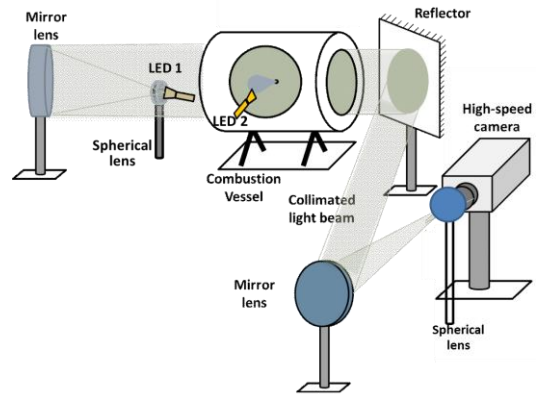


Figure 3: Imaging setup – near-simultaneous Mie Scatter and Shadowgraph Imaging.

Images are post-processed using in-house developed software, with Matlab Mathworks® image processing toolbox. Frames are extracted for independent processing of the shadowgraph images for vapor penetration and the Mie scattering images for liquid length.

Mie scatter images are processed by reading the images into Matlab, applying a background subtraction and subsequently applying a mask to remove the injector tip location. Images are thresholded to black and white and a blob analysis is applied, to define the spray region. The leading edge of the spray boundary is used to define the liquid length, with a scaling of 0.163 mm/pixel.

Shadowgraph images are processed by subtracting the prior frame spray image, and then applying a median filter to minimize noise. Images are converted to black and white by thresholding, and applying some other image enhancement methods to fill and close holes in the images. The spray portion of the image is then defined based on blob analysis. The leading edge of the spray boundary is used to define the penetration, again with a scaling of 0.163 mm/pixel.

RESULTS AND DISCUSSION

Results and discussion include temperature dependent tetradecane spray results, followed by a comparison of tetradecane and ULSD results at one condition. Finally, comparison is made to JP-8 based on available literature to understand the viability of tetradecane as a surrogate for JP-8 in spray and vaporization studies.

Experimental Results - Tetradecane

Results are presented first for tetradecane, showing temporal vapor penetration (Figure 4) and liquid length (Figure 5) as a function of core charge gas temperature.

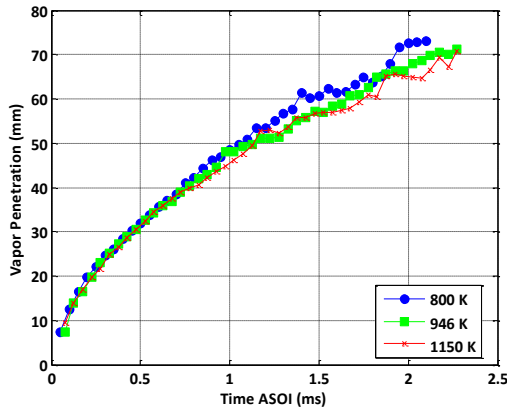


Figure 4: Vapor penetration for tetradecane versus time after start of injection (ASOI) for tetradecane fuel, 700 bar injection pressure, 24.1 kg/m³ core charge gas density.

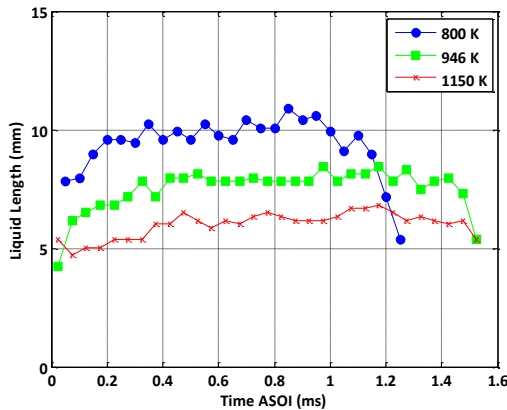


Figure 5: Liquid length for tetradecane versus time after start of injection (ASOI) for tetradecane fuel, 700 bar injection pressure, 24.1 kg/m³ core charge gas density.

As shown in Figure 4, as charge gas temperature increases, there is little change in the vapor phase spray behavior, until the end of injection. Injection ceases at 1.3 ms for the 800 K case and at 1.5 ms for the higher temperature cases. This trend is expected as the vapor penetration is momentum driven, including the entrainment of the charge gas and with the charge gas density constant, the penetration should be constant. After injection has ceased, no additional fuel is being added, but the vapor phase of the spray continues to penetrate. There is increased variability in the penetration data, along with a slight temperature dependence after this

time, as the injected fuel and momentum is no longer controlling the spray behavior. This potential small influence of vapor penetration on temperature is expected, as literature shows that vapor penetration can decrease slightly with temperature, but not conclusively [11-12].

Shown in Figure 5 is the liquid length penetration as a function of time after start of injection with the data for the three core gas temperatures. The liquid length reaches a quasi-steady state value within 0.2 ms after the start of injection and remains nearly constant until the end of injection. Also as expected, liquid length decreases nonlinearly with charge gas temperature [9].

Experimental Results – Comparison to Diesel

Of interest is a comparison of the tetradecane results to diesel fuel. This comparison is conducted at the baseline condition of 946 K core temperature, 700 bar injection pressure and 24.1 kg/m³ core charge-gas density. Images are compared from shadowgraph imaging (Figure 6) and Mie scattering (Figure 7) for both tetradecane and ULSD.

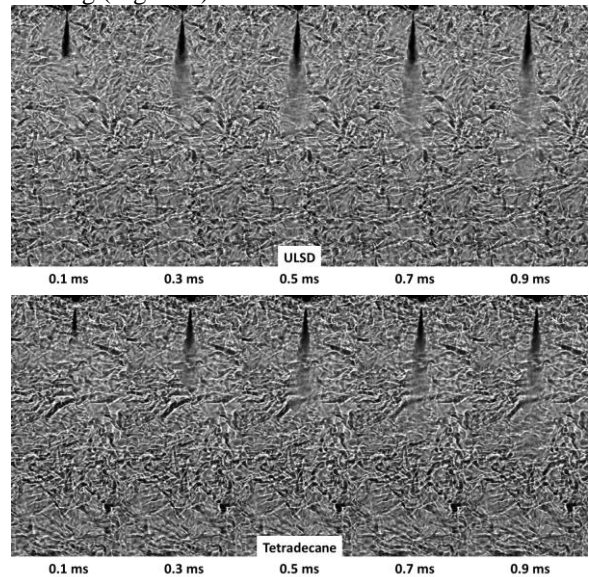


Figure 6: Shadowgraph images for varying times after start of injection for ULSD (top) and Tetradecane (bottom) vaporizing spray characteristics at 946 K core temperature, 24.1 kg/m³ core density, and 700 bar injection pressure.

Several observations can be made from the images. The ULSD and tetradecane fuels exhibit similar vapor penetrations as observed from the shadowgraph images. Also from the shadowgraph images, the temporal change in liquid length can be seen, along with the longer liquid length for ULSD. This is also confirmed in the Mie scatter images (Figure 7), where scaling is preserved. These images will be quantified to characterize the differences in spray behavior.

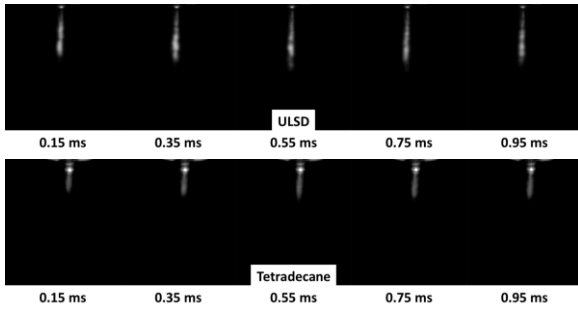


Figure 7: Raw Mie scattering images as a function of time after start of injection for ULSD (top) and Tetradecane (bottom) vaporizing spray characteristics at 946 K core temperature, 24.1 kg/m³ core density, and 700 bar injection pressure.

Image processing results for vapor penetration for both fuels are shown in Figure 8 and for liquid length in Figure 9. Tetradecane has a slightly reduced vapor penetration relative to ULSD; however, the difference is small and within the normal variability in spray penetration. This similarity in vapor penetration signifies comparable spray momentum and air entrainment for both fuels.

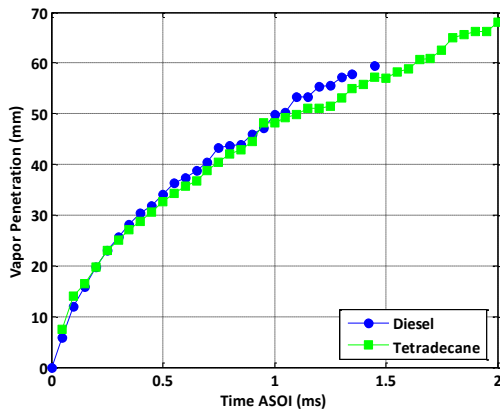


Figure 8: Vapor penetration versus time after start of injection (ASOI) for tetradecane and diesel fuel, 700 bar injection pressure, 24.1 kg/m³ core charge gas density, 946 K core temperature.

The liquid length of ULSD as shown in Figure 9 is significantly higher than that of tetradecane, by almost 72%. This difference is partially attributed to the approximately 9% lower boiling point of tetradecane, relative to the 90% distillation point of ULSD. The significant decrease in liquid length with tetradecane cannot be fully explained by the boiling point distillation difference alone, other fuel properties including vapor pressure, fuel enthalpies at injection and at the liquid length being saturation conditions, molecular weight of the fuel, fuel density, and fuel vapor

compressibility are factors that need additional study and consideration [4].

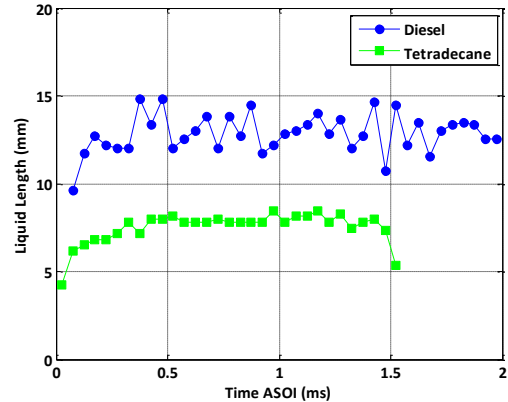


Figure 9: Liquid penetration versus time after start of injection (ASOI) for tetradecane and diesel fuel, 700 bar injection pressure, 24.1 kg/m³ core charge gas density, 946 K core temperature.

Comparison of ULSD, JP-8 and Tetradecane Results

Although JP-8 was not experimentally tested in this work, the results of ULSD and tetradecane can be compared to prior results testing JP-8 and ULSD, to predict JP-8 vapor and liquid penetration for understanding the suitability of tetradecane as a single component surrogate fuel for spray and vaporization. Results from Pickett and Hoogterp [5] are used for this comparison.

First, a comparison of vapor phase spray characteristics is considered. Based on Figure 8, it is observed that tetradecane and ULSD exhibit similar vapor phase penetrations. It is observed that ULSD and JP-8 also exhibit similar vapor phase penetration [5]. This suggests that tetradecane would also provide a good match to the vapor phase penetration of JP-8; however, direct testing should be done to confirm this.

Second, the liquid phase spray characteristics are considered. Observed in Figure 9 are the large liquid length differences between ULSD and Tetradecane. It is also known that there are significant differences in the liquid penetration of ULSD and JP-8, on average JP-8 liquid lengths are 26% lower, when considering densities of 14.8 to 30 kg/m³ at charge gas temperatures of 850 and 1000 K [5]. These conditions encompass those in the current work, where tetradecane exhibits a 72% lower liquid length, compared to ULSD fuel. Therefore, based upon scaling, it is expected that tetradecane liquid length will be shorter than that of JP-8 by 34%. These results are summarized in Table 3 comparing fuel properties of boiling point (BP) or 90% distillation point (T90), along with the liquid length values at

24.1 kg/m³ core charge gas density, 946 K core charge gas temperature, and 700 bar injection pressure. Values for ULSD (MTU) and tetradecane are from the experimental work given here. Those for JP-8, ULSD [5] and HMN are interpolated from available data of Pickett and Hoogterp [2008]. The liquid length values are normalized by nozzle hole diameter to provide a direct value comparison, since liquid length scales linearly with nozzle diameter [4]. Furthermore, although literature tests are at elevated injection pressures (1100 bar), this difference is insignificant as liquid length does not vary with injection pressure [4].

Table 3: BP or T90 and liquid length normalized by Hole Diameter (Experimental or Interpolated [5]) comparison for different fuels considered.

Fuel	BP or T90 (K)	Liquid Length normalized by nozzle diameter LL/D (-)
JP-8	513	95
HMN	520	92
Tetradecane	526	75
ULSD (MTU)	586	129
ULSD [5]	588	121

Values for both the MTU and published reference [5] diesel fuel are similar (121 and 129 respectively), validating the use of this published data to provide reference data for JP-8. As shown in the table, liquid length does not scale with boiling point or the 90% distillation point of the fuel. This signifies that the choice of tetradecane as a JP-8 surrogate for spray and vaporization studies is not an appropriate choice even though its boiling point falls along the distillation curve of JP-8. Other potential single component fuels should be investigated along with the various two or three component surrogates (tetradecane, hexadecane, HMN). There are clearly other important parameters including fuel density and molecular weight, coupled with enthalpies and vapor pressure, that must be investigate for either single or multi-component surrogate for real fuels whether they be diesel or JP-8.

CONCLUSIONS

The current work investigated spray characteristics of tetradecane as a potential single component JP-8 surrogate for spray and vaporization over a set of experimental conditions. Tests were conducted in an optically accessible constant volume combustion vessel using optical diagnostics

of near-simultaneous shadowgraph and Mie scatter imaging for quantifying vapor and liquid phase penetration. It is observed, as expected, that vapor phase penetration does not change significantly with temperature, but liquid length shows a significant reduction as temperature is increased.

Tetradecane and ULSD results were compared at one test condition, and it was observed that they exhibit similar vapor phase penetration, signifying similar spray momentum and air entrainment for both fuels. The liquid length of tetradecane is however 72% lower than that of ULSD, which is not explained by the boiling point difference alone (being only 9% lower for tetradecane relative to the 90% distillation point of ULSD).

Finally, the tetradecane and ULSD results were compared to prior work in the literature characterizing JP-8 and ULSD spray characteristics. JP-8 and ULSD spray characteristics show similar vapor penetration characteristics, which tetradecane would also match since it does match ULSD. The liquid length of JP-8 is 26% lower than that of ULSD in published literature under similar conditions, with that of tetradecane being 72% lower than ULSD in the current work. This would predict a 34% lower liquid length of tetradecane relative to JP-8, signifying that tetradecane alone is not a good candidate for a surrogate for vaporizing spray characteristics of JP-8. The choice of surrogate must match other properties important for the vaporization process. Further studies however are required over a broader range of conditions to fully confirm.

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