

Comparison of Direct-Injection Spray Development of E10 Gasoline to a Single and Multi-Component E10 Gasoline Surrogate

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ABSTRACT

Optical and laser diagnostics enable in-depth spray characterization in regards to macroscopic spray characteristics and in-situ fuel mixture quality information, which are needed in understanding the spray injection process and for spray model development, validation and calibration. Use of fuel surrogates in spray researches is beneficial in controlling fuel parameters, developing spray and combustion kinetic models, and performing laser diagnostics with known fluorescence characteristics. This study quantifies and evaluates the macroscopic spray characteristics of a single and multi-component surrogate in comparison to a gasoline with 10% ethanol under gasoline direct injection (GDI) engine conditions. In addition, the effect of fuel tracers on spray evolution and vaporization is also investigated. Both diethyl-methyl-amine/fluorobenzene as a laser-induced exciplex (LIEF) fluorescence tracer pair and 3-pentanone as a laser-induced fluorescence (LIF) tracer are examined. The spray is issued from a seven-hole production GDI injector and investigated in an optically-accessible spray and combustion vessel. Optical diagnostics include shadowgraph and Mie scattering, and the images are analyzed to reveal the characteristic spray penetration curves and the vaporization process of different fuels. Results reveal the ability of fuel surrogates in representing the target fuel and the effect of the tracer's addition to the surrogate. While many past spray characterization works using laser diagnostics in which fuel surrogates and tracers were used assumed the spray characteristics of the surrogate/tracer mixture were similar to those of the real fuel, the assumption is fully addressed in this work, which is part of a study in which in-situ characterization of the local equivalence ratio is performed based upon the results from this work.

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INTRODUCTION

Adoption of direct-injection on engines has seen a rapid increase from very limited applications in 2007, to 38% in 2014, and 46% in 2015 [1, 2]. Fuel economy benefits have made GDI a competitive technology to achieve stringent Corporate Average Fuel Economy (CAFE) standards. However, higher particulate matter (PM) emissions from GDI engines needs to be addressed [3]. Both fuel economy benefits and increased PM emissions are closely related to the fuel spray injection and the subsequent processes including fuel vaporization, fuel-air mixing and/or wall impingement. Thus, fuel spray characterization is essential to understanding and improving engine design and operation.

Due to the complex composition of commercial fuels (gasoline, diesel, kerosene, etc.) used in engines, fuel spray investigations have extensively used fuel surrogates to represent the commercial fuels, both for thermophysical and chemical characteristics [4]. For example, in planar laser induced (exciplex) fluorescence (PLIF/PLIEF) techniques, it is often essential to use non-fluorescing fuel

surrogates with 10% or less tracer dopants [5, 6, 7, 8], though qualitative investigations using commercial gasoline are possible [9, 10]. Commercial fuels contain aromatics, which fluoresce upon laser excitation. However, the aromatics have higher boiling points than other components, which may lead to differences in spatial distribution of aromatics and other components, thus making it difficult to represent early vaporization and mixing [11]. The use of fuel surrogates and tracer dopants are the limitations of the PLIF/PLIEF spray diagnostics since the mixture may not be able to fully represent the spray injection of commercial fuels [12]. The limitations are largely pertinent to how well fuel surrogates could represent the commercial fuel and what influence the addition of tracers has on the spray. It has been recognized that multi-component surrogates better represent key fuel properties including the distillation curve and chemical classes than single-component surrogates [13, 14].

Adoption of multi-component fuel surrogates is seen in multiple works. Scholz [15] used a near-standard colorless gasoline with bitumen content removed and without any tracers (fluorescing substances present in the fuel) in a fuel-air-ratio-LIF (FA-LIF) application to measure the

mixture equivalence ratios. Stevens [16] designed a six-component surrogate that ensured co-evaporation with three tracers representing the light, medium and heavy fraction in gasoline. This six-component surrogate was used by Williams [17] to investigate the effect of residual exhaust gas on quantitative PLIF. However, Steven's six-component surrogate did not use the volatility of a specific type of gasoline as the target. Styron [18] designed a four-component surrogate based on matching the distillation curve of the California Phase II gasoline. This surrogate could work with tracer pairs representing light and heavy fractions in gasoline, and were used in a PLIEF investigation of vapor and liquid distribution in a port fuel injection engine. Ma [19] formulated a five-component surrogate that both simulated gasoline's distillation curve and ensured co-evaporation with the same three tracers as in [16, 17]. These studies have generally focused on matching the surrogate's volatility to their targeted commercial fuels and co-evaporation of tracers with the surrogates. Validation studies that compare the spray injections of the fuel surrogate and the commercial fuels using optical diagnostics are seen in [20, 21]. However, the effects of adding tracers to fuel surrogates have not been fully understood from the previously mentioned works. In many works related to using PLIEF and PLIF it is an assumption that the use of fuel surrogate and tracer mixtures could reasonably represent the spray characteristics of the real fuel, without full proof to support the assumptions. Thus it is the objective of this study to understand and evaluate the effect of fuel surrogates and tracers on spray characteristics.

EXPERIMENTAL METHOD

The experiments are carried out in an optically-accessible spray and combustion vessel which is 1 liter in volume and rated at 345 bar maximum pressure. Temperatures due to piston compression in an engine and the gas compositions are created by a lean/dilute preburn process. Temperatures below 473 K are achieved by electric heaters. A combustible mixture consisting of C_2H_2 , H_2 , N_2 and O_2 is ignited by a spark plug, and by adjusting the proportion of the combustible gas and O_2 , different levels of O_2 are achieved to simulate different levels of exhaust gas recirculation (EGR). The injection event is triggered during the cool down after preburn is complete. Readers are referred to [22] for more details on the gas mixtures for preburn and the cool-down process. The vessel is equipped with six windows for optical access and experimental instrumentation, as well as eight corner ports for gas exchange valves and a pressure transducer. The spray is issued by a seven-hole Bosch HDEV-5 injector (S/N 0261500 147) for direct-injection applications, and the injector is mounted on one of the six windows on the side. The distribution of the seven nozzle holes is shown in Figure 1 by a front view image.

Shadowgraph and Mie scattering techniques are employed in the current study to visualize fuel sprays in the vapor phase and the liquid phase, respectively. A Z-type shadowgraph optical setup is used as shown in Figure 2(a), and the Mie scattering setup is shown in Figure 2(b). The Mie scattering setup used the same optical path as shadowgraph technique by replacing the shadowgraph light source with two different light sources while retaining all other optics. This setup ensures the same pixel size between images from two optical setups. A high speed camera FASTCAM SA 1.1 was used with a Nikon 85 mm lens. The frame speed was 20,000 frame per second, shutter duration was 14.3 μs , and aperture size was f/1.4.

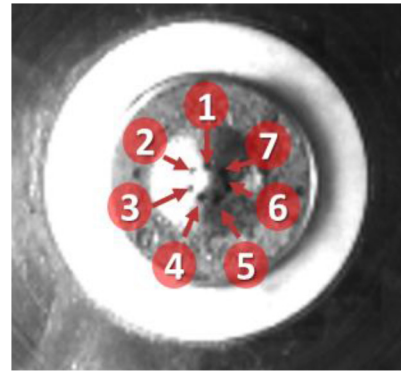


Figure 1. Spatial distribution of the seven nozzle holes of the Bosch HDEV-5 injector.

Table 1. Test conditions.

Condition	Compression	TDC
Injection pressure, bar	100	
Injection duration, ms	1 (trigger signal length)	
Fuel temperature, K	363	
Charge density, $kg \cdot m^{-3}$	3.0	9.9
Charge pressure, bar	4	20
Temperature, K	452	680
Charge gas	N_2	0% O_2 after preburn

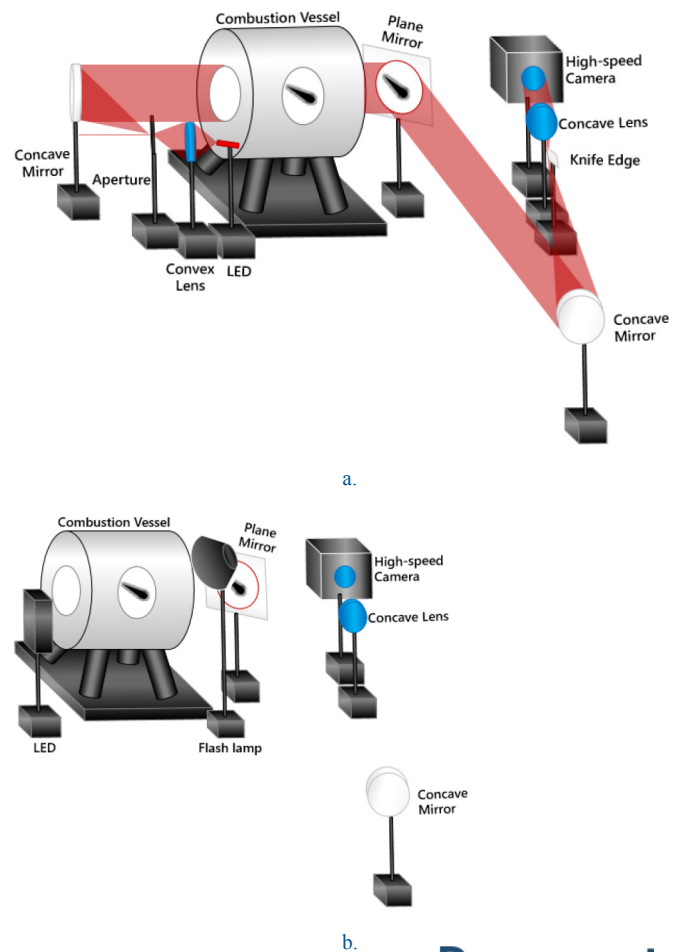


Figure 2. (a) Z-type shadowgraph optical setup (b) Mie scattering optical setup

The experimental conditions used in the current study represent the injection at two timings during the operation of an engine: one condition is during the compression stroke and the other is near the top dead center (TDC). Details are shown in [Table 1](#).

Fuel Mixtures

It is the objective of the current study to understand the effect of fuel and tracers on spray characteristics, thus fuel surrogates are formulated based upon the baseline fuel of CARB LEV III E10 Certification Fuel [23], referred to as “E10 Gasoline” hereafter. A summary of the fuel properties is shown in [Table 2](#). The important properties for spray investigations are fuel density (important for spray penetration), latent heat of vaporization and distillation curve (both affecting vaporization and vapor-liquid equilibrium).

Use of single component fuel surrogates in spray investigations are often favored when used to study certain phenomena (e.g. diesel fuel ignition) and developing spray/chemical kinetic models. Important limitations of single-component surrogates include: inability to model multiple fuel properties and the detailed chemical processes, which could be overcome by using multi-component surrogates [24]. Thus for this study, both single- and multi-component E10 Gasoline surrogates are used based upon the three important properties: fuel density, latent heat of vaporization and volatility.

In the current study, the interest is to understand the spatial distribution of E10 Gasoline’s mid-range distillation in the fuel spray, thus n-heptane is selected based on the match of its boiling point to T50 of E10 Gasoline. As shown in [Table 3](#), n-heptane has 8.3% lower density and 13.7% lower latent heat of vaporization compared to the E10 Gasoline.

Table 2. Fuel properties for E10 Gasoline certification fuel [23].

Carbon, wt%	82.52
Hydrogen, wt%	13.78
Oxygen, wt%	3.7
Ethanol, vol%	10
Sulfur, ppm wt	10
Density, kg/m ³	744
Latent Heat of Vaporization, kJ/kg	417 [25]
Distillation, K	10%: 332
	50%: 371
	90%: 431
Net Heat of Combustion, MJ/kg	41.84

For the multi-component surrogate, a palette of surrogate components is selected as: n-pentane, n-hexane, n-octane, n-decane and ethanol, whose properties spanned around those of E10 Gasoline and whose chemical classes are n-alkanes and alcohols. The reason to limit the chemical classes to be mainly n-alkanes is because the formulated surrogates need to work with PLIEF/PLIF tracers for a quantitative in-situ characterization of the spray mixture (which is the objective of a companion work, not the current one). Alcohols are added to replicate the latent heat of vaporization of the E10 Gasoline.

Table 3. Comparison of E10 Gasoline, multi-component surrogate, n-heptane, and fluorescent tracer properties, DEMA, fluorobenzene and 3-pentanone.

	Density, kg/m ³ [26]	Latent Heat of Vaporization, kJ/kg [27]	Distillation / Boiling Point, K [27]		
			10%	50%	90%
E10 Gasoline	744	417	332	371	431
Multi-comp Surrogate	718	482	329	372	431
n-heptane	682	360	371		
DEMA	702	365	338		
Fluorobenzene	1019	359	358		
3-pentanone	810	450	375		

Reaction Design’s Reaction Workbench code is used to calculate the fuel mixture’s properties based on the target fuel property constraints (fuel density and distillation curve) and the selected surrogate component palette. Latent heat of vaporization is a constraint not implemented in Workbench and is calculated separately by mass-fraction-weighted latent heat of vaporization of single components. The final composition of the multi-component surrogate is given in [Table 4](#) and is composed of: 20% ethanol, 4% n-pentane, 10% n-hexane, 36% n-octane and 30% n-decane by volume. This final composition has 10% more ethanol content compared to E10 Gasoline, and this done as a compromise between the density and the latent heat of vaporization of the multi-component E10 Gasoline surrogate. Among the five components, ethanol has the largest liquid density and the latent heat of vaporization compared to the rest of the compounds. As shown in [Table 3](#), the formulated multi-component surrogate mixture has 3.5% lower liquid density and 15.6% higher latent heat of vaporization compared to the targeted E10 Gasoline. The distillation points at 10%, 50% and 90% volume fractions matches those of the E10 Gasoline within 3 K; however, these values are based on numerical models without experimental validations.

Table 4. Summary of the fuel mixtures used in this work.

Baseline fuel	E10 Gasoline
Multi-component E10 surrogate	20% ethanol, 4% n-pentane, 10% n-hexane, 36% n-octane and 30% n-decane by volume
Single-comp. E10 surrogate	n-heptane
PLIEF mixture	89% n-heptane, 9% DEMA, 2% fluorobenzene by vol.
PLIF mixture 1	90% multi-component surrogate, 10% 3-pentanone by vol.
PLIF mixture 2	90% n-heptane, 10% 3-pentanone by vol.

Also shown in [Table 3](#) are the properties of fuel tracers, in which diethyl-methyl-amine (DEMA) and fluorobenzene are used as a pair of tracers for PLIEF technique, and 3-pentanone is used as a tracer for PLIF technique. Tracers are added to the multi-component surrogate and n-heptane with volume fraction of 9% DEMA, 2% fluorobenzene in the PLIEF mixture, and 10% 3-pentanone in the PLIF mixture. The fuel mixtures used in this work are summarized in [Table 4](#). The

multi-component surrogate is not used with DEMA and fluorobenzene since a companion work found that the liquid phase fluorescence intensity of this mixture is too low to characterize the sprays.

Image Processing Methods

High-speed shadowgraph and Mie scattering images are recorded and processed to obtain temporal development of the macroscopic spray characteristics. Details on the processing method for shadowgraph and Mie scattering images are shown elsewhere [28]; here, only a brief description is provided in terms of the workflow:

1. Background subtraction;
2. Thresholding grayscale images to binary images;
3. In Schlieren/shadowgraph images, pixel dilation and region closing operations are necessary to track the entire spray plume; such operation is not necessary for Mie scattering images;
4. Boundary tracking based on binary images;

A sample shadowgraph image is shown in Figure 3(a), and a sample Mie scattering image is shown in Figure 3(b). Both images are shown with processed boundaries overlaid on the spray and definitions of key parameters. The injector is mounted horizontally pointing leftward, and the injector tip location is indicated by a yellow plus sign. By referencing to the SAE J2715 standard [29], the vapor/liquid penetrations are defined as the distance along the injector axis from the injector tip to the leading edge of the spray. In this study, the vapor and liquid penetrations are the distances along the x direction (indicated by the yellow dashed line) between the leading edges of the vapor and liquid envelopes and the location of the injector tip. Definitions of the spray angles and the spray bend angles are modified based on SAE J2715 standard to adapt to the spray in the current research: two lines are drawn at 2 mm and 7 mm downstream of the injector tip, and the spray boundaries between these two lines are linearly fitted. The spray angle is defined as the angle enclosed by the two linearly fitted lines and the spray bend angle is defined as the half of the absolute difference between the two angles. This definition is similar to SAE J2715 standard but the distances of the two lines are modified from 5 mm and 15 mm to 2 mm and 7 mm, particularly due to the images at high ambient temperature and pressure condition (TDC condition in Table 1) where a transition occurs along the spray edge that affects the linear fit result. The two conditions for calculating spray angles are shown in Figure 3(a) and Figure 3(b). The spray angle in Figure 3(a) is the sum of two angles shown by equation (1), while the spray angle in Figure 3(b) is the difference between two angles shown by equation (2). Under both conditions, the spray bend angles are both calculated as equation (3).

$$\theta_{\text{SprayAngle}} = \theta_1 + \theta_2 \quad (1)$$

$$\theta_{\text{SprayAngle}} = \theta_2 - \theta_1 \quad (2)$$

$$\theta_{\text{SprayBendAngle}} = (\theta_2 - \theta_1)/2 \quad (3)$$

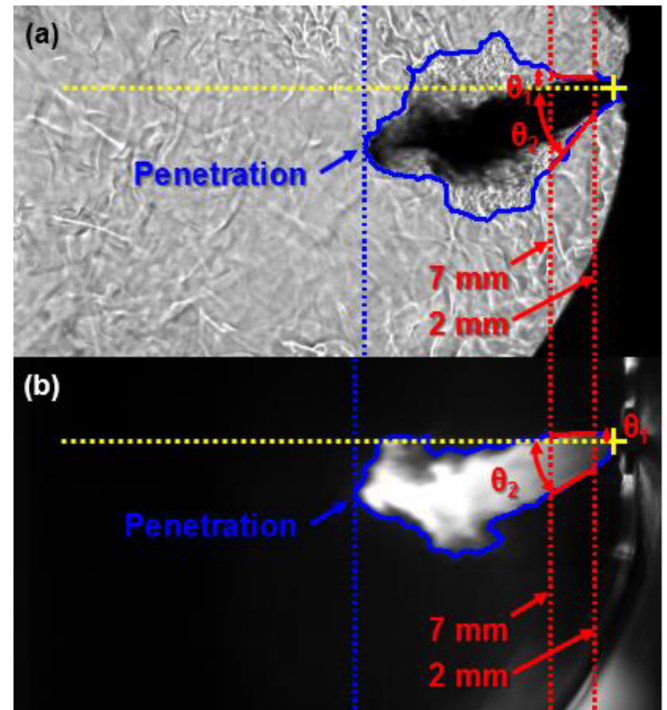


Figure 3. (a) Sample Shadowgraph image; (b) Sample Mie scattering image; Processed boundaries are overlaid on sprays and key parameters illustrated. Refer to text for further details.

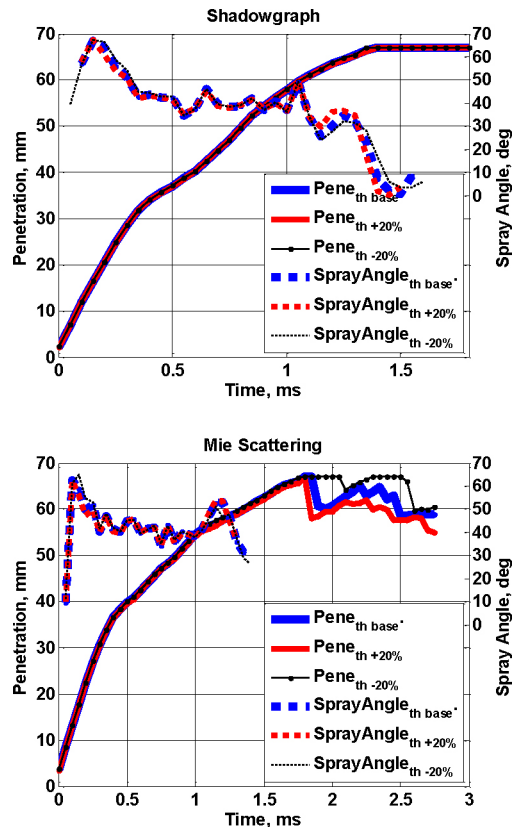


Figure 4. Sensitivities of the results to the thresholds in both shadowgraph and Mie scattering images.

Sensitivities of the results to the thresholds in the image processing operations are shown in Figure 4. Results on the vapor and the liquid penetrations and the spray angles based on both image types are shown to be threshold insensitive to ensure proper interpretation of the results.

RESULTS AND DISCUSSIONS

Fuel Effects - E10 Gasoline & Surrogates

The penetration is an important macroscopic spray characteristic as it quantifies the fuel-air mixing process, which involves momentum exchanges between the fuel and the ambient charge gas.

Comparisons of the vapor and the liquid penetrations of the three fuel mixtures (E10 Gasoline, the multi-component E10 surrogate and n-heptane) are shown in Figure 5 (A), (C) for the 452 K test condition, and in Figure 6 (A), (C) for the 680 K test condition.

The penetration curves are averages of five individual injections. The injection durations are 1 ms in all cases. At the 452 K condition the spray reaches the extent of the field of view at 1.5 ms and the data reaches its maximum value.

To understand the statistical significance of the test repeats, results from the Welch ANOVA (analysis of variance) test [30] on the penetration curves are shown in Figure 5 (B), (D) and Figure 6 (B), (D). The ANOVA method allows evaluating the data to understand if the means of different groups are equal with assumptions of independence, normality and homogeneity of variances of the different groups of data. The null hypothesis states that all group means are equal. Based on the comparison of the calculated probability p with a designated significance level, the null hypothesis that the means from different groups of data are the same is retained or rejected. The Welch ANOVA method allows evaluating data with violations in the homogeneity of variances and is used in this study [31]. From Figure 5 (B) and Figure 6 (B), there are two periods of time that correspond to the early phase of injection and the mid-portion of the spray development (0.05 - 0.30 ms & 0.70 - 1.00 ms for the 452 K condition, 0.05 - 0.10 ms & 0.75 - 1.45 ms for the 680 K condition) in which the p value is lower than the significance level of 0.05, which means the differences in the vapor penetrations shown in Figure 5 (A) and Figure 6 (A) during the two periods are statistically significant. The two periods during the early phase of injection do not occur in the liquid penetration curves as shown by Figure 5 (D) and Figure 6 (D); however, the differences in the liquid penetrations are statistically significant towards the end of injection for the two fuel mixtures under both test conditions.

With the previous statistical analysis, the results show that during the early phase of injection, n-heptane has larger penetration than the other two fuel mixtures. The spray velocity expressed by the Bernoulli's equation is:

$$V_{\text{spray}} = \sqrt{\frac{2 \cdot (P_{\text{inj}} - P_{\text{charge}})}{\rho_{\text{liquid}}}} \quad (4)$$

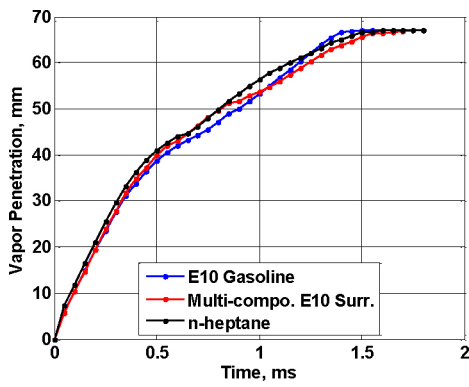
N-heptane has the largest Bernoulli velocity due to its lowest density among the three fuel mixtures, and this suggests that the early phase of the spray is velocity-controlled, and it is important to match the density of the fuel surrogate to the target fuel for this phase. The momentum of the spray can be expressed as:

$$\begin{aligned} p &= \dot{m} \cdot V_{\text{spray}} = \rho_{\text{liquid}} \cdot A_{\text{orifice}} \cdot V_{\text{spray}}^2 \\ &= 2 \cdot A_{\text{orifice}} \cdot (P_{\text{inj}} - P_{\text{charge}}) \end{aligned} \quad (5)$$

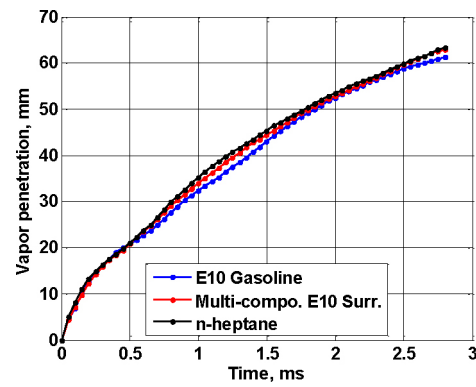
It is observed from equation (5) that the spray momentum remains the same regardless of the liquid mixture density. The fact that n-heptane spray has larger penetrations than the other two fuels suggest that the fuel air mixing among the three fuels are different.

Differences in the vapor penetration curves during the mid-portion of the spray development are statistically significant and occur under both test conditions as shown by Figure 5 (A) and Figure 6 (A), in which both fuels have larger penetrations than E10 Gasoline, with the largest penetrations from n-heptane. The hydraulic injection ends at approximately 1 ms after start of injection (ASOI), and the time durations cover the late half (452 K condition) and extend to after the end of the spray injection (680 K condition). This suggests that multi-plume GDI spray has transitioned away from being velocity-controlled during the early phase of injection. The differences are likely due to vaporization, mixing and plume-to-plume interactions.

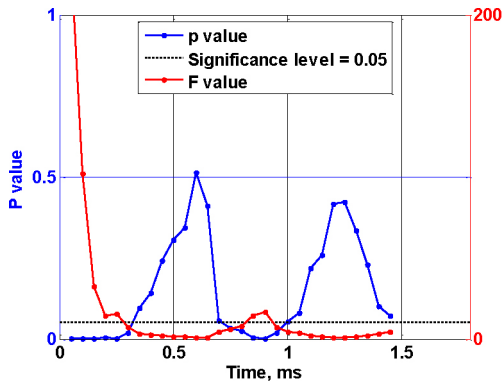
Differences in the liquid penetration curves after 1.8 ms occur under both test conditions. Since the liquid front has recessed relative to its locations during the injection, the liquid penetration would be more properly described as the distance from the liquid front to the injector tip. N-heptane has the largest reduction in the distance from the liquid front to the injector tip and the multi-component E10 surrogate has the least reduction after the end of injection. The liquid front locations of n-heptane after 2.5 ms ASOI are almost zero under 680 K. This suggests liquid droplet vaporization occurs at the spray front. Since this time period is after the end of hydraulic injection, vaporization is believed to be the main reason for the differences. The larger distances from the liquid front to the injector tip of the multi-component E10 surrogate than E10 Gasoline is likely due to its larger latent heat of vaporization since their distillation points matches within 3 K. The smaller distance between the liquid front and the injector tip of n-heptane compared to E10 Gasoline is due to both its lower boiling point compared to the final boiling point of E10 Gasoline, as well as its lower latent heat of vaporization.



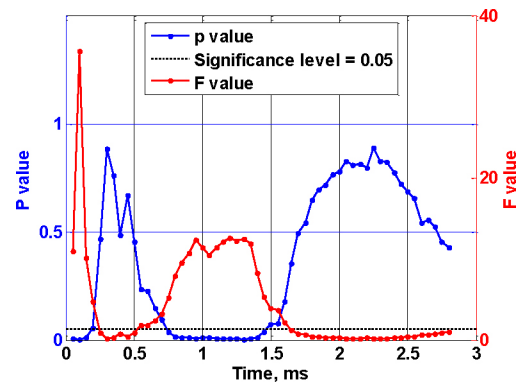
a. Vapor penetrations at 452 K



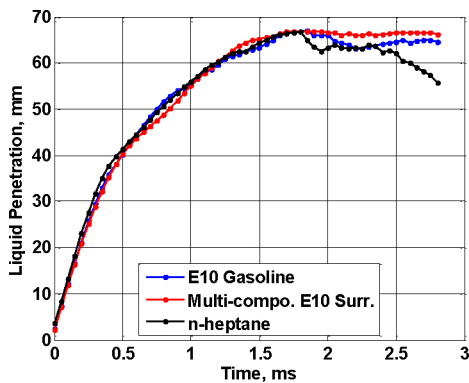
a. Vapor penetrations at 680 K



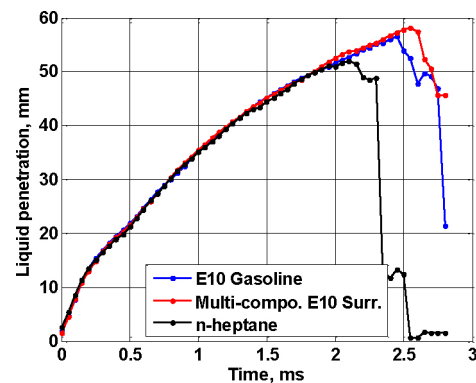
b. Welch ANOVA test on vapor penetrations



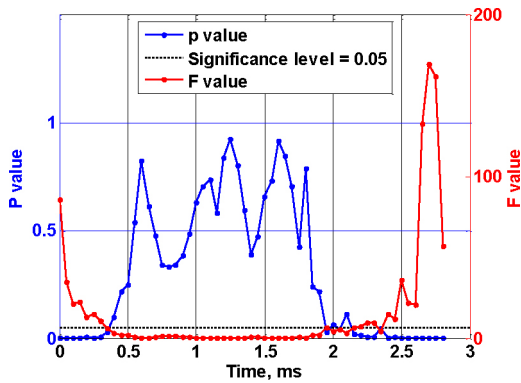
b. Welch ANOVA test on vapor penetrations



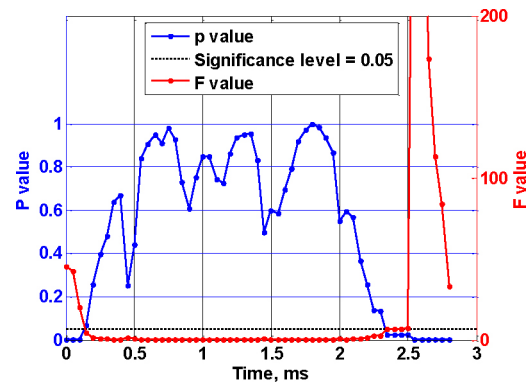
c. Liquid penetrations at 452 K



c. Liquid penetrations at 680 K



d. Welch ANOVA test on liquid penetrations



d. Welch ANOVA test on liquid penetrations

Figure 5. (a) Vapor penetration curves of E10 Gasoline, the multi-component E10 surrogate, and n-heptane. (b) Welch ANOVA test results on vapor penetrations. (c) Liquid penetrations curves of E10 Gasoline, the multi-component E10 surrogate, and n-heptane. (d) Welch ANOVA test results on liquid penetrations. Test condition: 452 K and 4 bar ambient.

Figure 6. (a) Vapor penetration curves of E10 Gasoline, the multi-component E10 surrogate, and n-heptane. (b) Welch ANOVA test results on vapor penetrations. (c) Liquid penetrations curves of E10 Gasoline, the multi-component E10 surrogate, and n-heptane. (d) Welch ANOVA test results on liquid penetrations. Test condition: 680 K and 20 bar ambient.