

Evaluation of Liquid and Vapor Penetration of Sprays from a Multi-Hole Gasoline Fuel Injector Operating Under Engine-Like Conditions

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ABSTRACT

Liquid and vapor penetration of sprays from a multi-hole gasoline fuel injector operating under engine-like conditions were systematically investigated utilizing a high-speed imaging system capable of acquiring schlieren and Mie scattering images in a near-simultaneous fashion. The influences of ambient conditions and fuel properties on the formation of liquid and vapor envelopes were evaluated. In addition to the compilation of an extensive data set, results of the investigation indicate that mixing-limited vaporization modeling can be utilized to predict the maximum liquid penetration of *short-duration, multi-plume* sprays.

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INTRODUCTION

It is well known that the fuel economy and emissions of direct-injection gasoline engines are significantly influenced by the fuel injection process and in particular the characteristics of the fuel spray [1, 2]. As a result an extensive amount of work has been performed in the area of fuel injector spray characterization. While extensive, the large majority of the work has been confined to characterization of the liquid phase under non-vaporizing conditions [3, 4]. Far less has been reported regarding gasoline spray characterization at engine like conditions [5, 6, 7, 8].

The primary objective of the work reported here was to evaluate liquid and vapor envelopes of sprays from a multi-hole gasoline fuel injector operating under engine-like conditions. The influences of ambient conditions and fuel properties were of particular interest. Generating a systematic data set at relevant ambient conditions with different fuels provides fundamental physical insight regarding fuel penetration and vaporization. Additionally, the data set will enable the evaluation of advanced spray models used in CFD.

While similar work has been reported for diesel sprays [9, 10, 11, 12], the gasoline direct-injection application is considerably different. The overall spray angles for gasoline applications are generally much narrower (~60°-90°) compared to those associated with diesel applications (~140° - 160°). These relatively narrow spray angles result in close proximity of adjacent spray plumes, often leading to significant plume-to-plume interactions. Close proximity of adjacent plumes is a necessity in the gasoline application to promote flame propagation from a fixed ignition location. These plume-to-

plume interactions significantly influence air entrainment and preclude, or significantly limit the use of simplified single-hole injectors for fundamental study often used by the diesel community [9, 10, 11, 12].

Additionally, much of the diesel spray characterization work reported in the literature is associated with large injected quantities that promote quasi-steady conditions. In contrast, a relatively small injected quantity, 10 mg, representative of a low load cruise condition, was of interest in the work reported here. This injected quantity is insufficient to promote quasi-steady conditions and instead results in highly transient conditions. It is also worth mentioning that in the case of direct-injection gasoline engines, full load conditions that do promote quasi-steady conditions are typically associated with early injection timings where in-cylinder gas temperatures are low and not of interest here.

An ultimate goal of the work would be to provide a means of predicting penetration without the need of experimental measurements. To that end, the applicability of applying the mixing-limited vaporization model of Siebers [11] to *multi-plume* gasoline sprays in their *entirety* was evaluated.

Operating Conditions

Conditions relevant to late fuel injection timings were of particular interest. Fuel spray images were acquired with ambient temperatures ranging from 400 to 900 K. At each temperature three ambient pressures, corresponding to densities of 3, 6, and 9 kg/m³, were investigated. Table 1 and Figure 1 summarize the ambient conditions evaluated.

Experiments were performed utilizing three fuels. Iso-octane and ethanol were of interest not only because of their simple single component composition but also because of the differences in their enthalpies of vaporization. Indolene was of interest due to its realistic multi-component composition.

In all cases the fuel pressure and injected mass were fixed at 20 MPa and 10 mg, respectively. Prior to conducting spray measurements, flow measurements were performed to determine the required injection durations to inject the desired fuel mass.

Table 1. Investigated ambient temperatures and pressures.

Temperature (K)	Pressure (bar)		
	(3 kg/m ³)	(6 kg/m ³)	(9 kg/m ³)
400	3.56	7.12	10.68
500	4.45	8.90	13.36
600	5.34	10.68	16.03
700	6.23	12.47	18.70
800	7.12	14.25	21.37
900	8.01	16.03	24.04

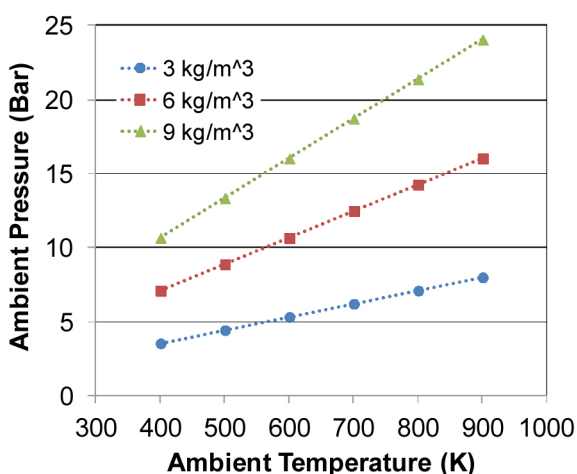


Figure 1. Investigated ambient pressures and temperatures.

Imaging System Background

Schlieren imaging has been used for decades to image a myriad of fluid flow phenomena. Its sensitivity and relative simplicity have made it a popular optical diagnostic. Although rather straightforward in many ways, schlieren imaging is not without difficulties. The technique is sensitive to gradients of index of refraction, and therefore in the case of a multiphase flow, such as a fuel spray, both the liquid and vapor phases contribute to the schlieren signature. This makes it impossible to definitively distinguish one phase from another without an accompanying measurement.

The work presented here describes the use of a high-speed imaging system capable of acquiring schlieren and Mie scattering images in a near-simultaneous fashion along the same line-of-sight. Acquiring the images along the same line-of-sight allows the Mie scattering images, which are

sensitive only to the liquid phase, to be overlaid onto the schlieren images enabling the line-of-sight phase boundary to be determined.

The ability to acquire images at high-speed is advantageous for a couple of reasons. First, it allows the temporal evolution of an injection event to be investigated. Previous investigations have indicated that vapor phase envelopes can vary considerably from injection-to-injection [13]. This makes it difficult to discern temporal evolution from a collection of single shot measurements at discrete points in time. To improve our understanding beyond what occurs on average, the ability to capture continuous temporal evolutions becomes a necessity.

Secondly, and perhaps unique to the schlieren imaging technique, high-speed imaging alleviates problems associated with the identification and removal of artifacts in the background of images. Often schlieren systems are setup to be extremely sensitive to capture minute gradients of index of refraction related to the physics of interest. In this work identification of boundaries of lean fuel vapor mixtures was of interest. Unfortunately this often leads to background schlieren due to minute gradients in density and temperature within the test section. When acquiring images on a single-shot basis, background schlieren are different from shot-to-shot and elaborate image processing must be employed to extract them. In contrast, with high-speed imaging the background schlieren does not change significantly between successive frames. This greatly simplifies the process of eliminating the background schlieren.

High-speed Mie scattering imaging was utilized to visualize the liquid phase while high-speed schlieren imaging was utilized to visualize vapor phase. Accordingly, liquid penetration lengths were determined with the use of the Mie scattering images while vapor penetration lengths were determined utilizing the schlieren images.

EXPERIMENTAL SETUP

The injector used in this investigation was a solenoid actuated, 8-hole, SVCO (stepped-hole valve covered orifice) style injector with a nominal included spray angle of 60 degrees. The diameter and length of each hole was nominally 165 μm and 300 μm , respectively. A coolant jacket surrounding the injector mount was used to control the injector temperature. The fuel temperature was assumed to be equal to the coolant temperature and was set to 90° C to mimic fully warmed up conditions. Injection pressure was maintained at 20 MPa using a PID controlled hydraulic accumulator charged with nitrogen.

Experiments were conducted in a vessel that allowed measurements to be performed at elevated pressures and temperatures. A continuous flow of nitrogen passed through the vessel to provide evacuation of the injected mass and prevent the accumulation of residual droplets.

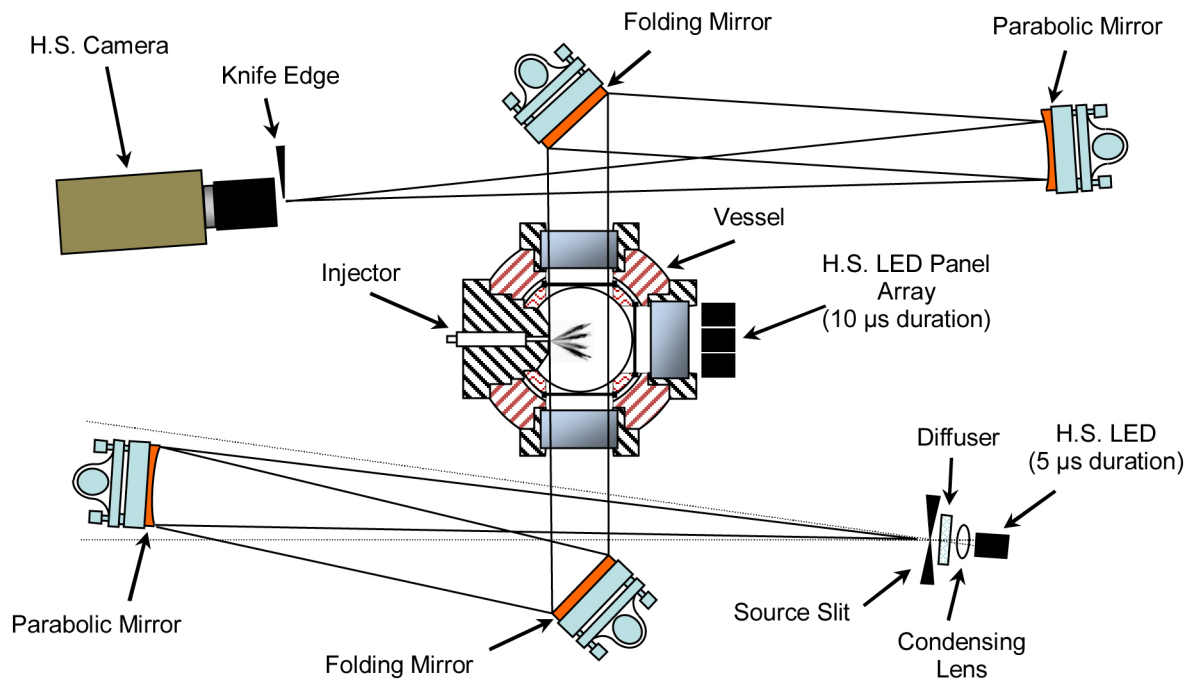


Figure 2. Folded z-type schlieren imaging system.

High-Speed Imaging System

Figure 2 shows the imaging system that was used to acquire schlieren and Mie scattering images. A single high-speed LED was used as a schlieren light source. Output from the LED was focused onto a diffuser utilizing a five power microscope objective as a condensing lens. The use of a diffuser was necessary to produce a uniform light intensity free of any LED structure. A 500 μm slit was placed next to the diffuser to provide geometric definition to the light source. Light emitting from the slit was collimated by a parabolic mirror of 1.2 m focal length to produce a beam approximately 150 mm in diameter. Once collimated a flat mirror was used to turn the beam and direct it through the vessel test section.

The mirrors on the receiving side of the imaging system were identical to those used on the transmitting side. The receiving parabolic mirror focused the beam and produced a well defined image of the slit in its focal plane. A knife edge, mounted parallel to the long side of the slit, was used as a cut-off and was placed at the focus of the beam.

The use of a slit and knife edge results in a schlieren system that is sensitive only to gradients of index of refraction that have components perpendicular to the slit and knife edge orientation. This does not present a problem, necessarily, because index of refraction gradients are produced at all angles. The orientation of the slit and knife edge with respect to the spray does, however, affect the appearance of the resulting schlieren images. Typically an intensity gradient exists in the direction perpendicular to the slit and knife edge arrangement.

Therefore, to make the image intensity appear symmetric about the spray axis, the slit and knife edge were oriented perpendicular to the spray axis. This resulted in an intensity gradient from the leading edge to the trailing edge of the spray. Other than appearance to the eye, this intensity gradient had no discernible impact.

Illumination for Mie scattering was provided by a panel array of high-speed LEDs placed directly opposite of the injector. The resulting Mie scattering images were collected along the same optical path utilized for the schlieren imaging. This resulted in the acceptance of only small angle scattering yielding a large depth of field. Although undesired, the knife edge effectively reduced the Mie scattering intensity by one half.

Images were captured with a high-speed digital camera equipped with a 105 mm lens. Mie scattering and schlieren images were captured in a nearly simultaneous fashion utilizing frame straddling. Frame straddling, most commonly used in high-speed PIV, results in image pairs that are slightly temporally separated.

The primary advantage of utilizing a common camera along with frame straddling, compared to utilizing two cameras [14], is that it eliminates the need to spatially register independent images. One apparent disadvantage is that the images cannot be acquired simultaneously. The degree to which this becomes an issue depends on the speed of the event being captured in comparison to the overall time required to perform the measurements.

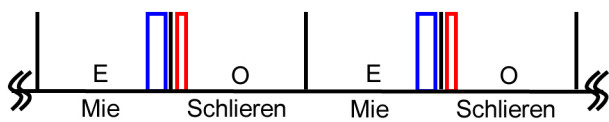


Figure 3. Frame straddling timing diagram. 20 kHz camera framing rate translates to image pairs at 10 kHz. Mie scattering exposures occurred at the end of the even numbered frames while schlieren exposures occurred at the beginning of the odd numbered frames.

Figure 3 illustrates a timing diagram depicting the image acquisition process. To acquire image pairs at a rate of 10 kHz, a 20 kHz camera framing rate was required. The camera exposure time was set to be nearly equal to the frame interval. The Mie exposure occurred at the end of the even numbered frames while the schlieren exposure occurred at the beginning of the odd numbered frames. Image exposures were governed by the LED strobe durations and were set to 10 μ s and 5 μ s for the Mie and schlieren imaging, respectively. These durations were chosen because they produced adequate signal strength; although ideally shorter durations would have been utilized. The total amount of time from the beginning of the Mie exposure to the end of the schlieren exposure was approximately 17 μ s. This translates to 1.7 mm of displacement for objects traveling at 100 m/s. This magnitude of velocity is not uncommon for direct-injection gasoline engine fuel sprays but it is usually associated with the early stages of injection and dissipates quickly. Therefore for most conditions of interest the image exposures were adequately small. Further details of the imaging system, including image processing and a sensitivity analysis can be found elsewhere [15].

RESULTS AND DISCUSSION

In presenting the results of the investigation, first some raw images are presented as example results and details regarding the extraction of the data of interest are discussed. Liquid and vapor penetration data are then presented in the form of both penetration curves and the maximum liquid penetration achieved for each condition. Next, approximations of liquid residence times, representative of the length of time that liquid fuel exists, are presented. Fluid properties of each fuel are then discussed as a means of providing explanation of some of the trends observed. Finally, the applicability of applying mixing-limited vaporization modeling to *multi-plume* gasoline sprays in their *entirety* is presented.

Example Results

Example raw images along with the resulting envelope identifications are shown in Figure 4. Each row corresponds to a different point in time referenced from the start of injection. Although image pairs were acquired at a rate of 10 kHz, only four image pairs are shown at a 0.5 ms interval. While it appears that only four spray plumes are visible, each plume is actually a pair of plumes, one behind the other. Early in time (0.5 ms) the Mie scattering and schlieren images appear similar because insufficient time has passed to produce much vapor. Although the spray is not perfectly symmetric about its

axis, the Mie scattering and schlieren images correlate to one another because both images were acquired nearly simultaneously along the same line-of-sight. As time proceeds, the intensity exhibited in the Mie scattering images diminishes while the schlieren images exhibit continual expansion of the individual spray plumes. Later in time (1.5 ms), individual plumes are no longer discernable in the schlieren images and no Mie scattering is detectable due to complete vaporization of the injected mass.

By comparing each of the schlieren images it can be seen that the background schliere does not change significantly between successive frames. This simplifies the process of eliminating the background schliere by allowing the previous frame to be used for background subtraction. The results of the background subtraction and envelope identification are shown in the third column of Figure 4. The inner contours were derived from the Mie scattering images and therefore represent only the liquid phase. The outer contours were derived from the schlieren images and therefore represent liquid and vapor while they coexist and only vapor upon complete evaporation. Overlaying the liquid phase contour onto the schlieren image allows for the determination of the line-of-sight phase boundary.

Obtaining multiple image sequences at each condition enabled liquid and vapor probability envelopes to be computed, as shown in the far right column of Figure 4. This was accomplished by identifying the liquid and vapor envelopes from 25 independent image sequences. The inner (red) contour was derived from the Mie scattering images and therefore represents the region in space where the perimeter of the liquid phase occurred with 95% probability. The outer (green) contour was derived from the schlieren images and therefore represents the region in space where the perimeter of the vapor phase occurred with 95% probability. The thickness of each contour gives an indication of the variability of the corresponding envelope.

Liquid and Vapor Penetration

Figure 5 shows the liquid and vapor penetration curves for all cases of interest. Each row corresponds to a different fuel and each column corresponds to a different ambient density. Each curve represents a different ambient temperature and is the average of 25 duplicate experiments. The solid lines were derived from the Mie scattering images and therefore represent liquid penetration. The dashed lines were derived from the schlieren images and therefore represent liquid and vapor while they coexist and only vapor upon complete vaporization. Indication of deviation from the average was intentionally omitted for clarity purposes. For reference, Figures A1, A2, A3 (Appendix A) show the liquid and vapor probability envelopes for all cases. The thickness of each contour provides an indication of the injection-to-injection variability.

Not surprisingly, trends are similar for each fluid. With the exception of the majority of the 400K ambient density cases, liquid penetration is shown to increase to a maximum

value and then go to zero due to complete vaporization. High ambient temperatures promote reduced liquid penetration and shorter residence time. High ambient densities promote reduced liquid penetration but do not significantly alter residence time for ambient temperatures of 600K and higher.

Early in time the schlieren penetration curves match those generated from the Mie scattering images indicating that no vapor exists ahead of the liquid. Later in time, but prior to the peak in liquid penetration, the penetration curves begin to deviate from each other. This deviation indicates the existence of vapor phase in addition to liquid phase. It is important to realize that without the complimentary Mie scattering images this could not be concluded from the schlieren images alone due to the technique being sensitive to both liquid and vapor. Later in time as the liquid penetration goes to zero due to vaporization, the vapor penetration continues. While high

ambient temperatures do lead to reduced vapor penetration, the influence of ambient temperature on vapor penetration is not as dramatic as that observed for the liquid phase. In similar fashion to the liquid penetration trends, high ambient densities promote reduced vapor penetration.

Maximum liquid penetration lengths for each case are shown in [Figures 6 and 7](#). [Figure 6](#) shows maximum liquid penetration as a function of ambient temperature whereas [Figure 7](#) shows the same data but as a function of ambient density. The reductions in liquid penetration with increasing ambient temperature and density are expected and are due to enhanced vaporization and the spray having to penetrate through a denser environment.

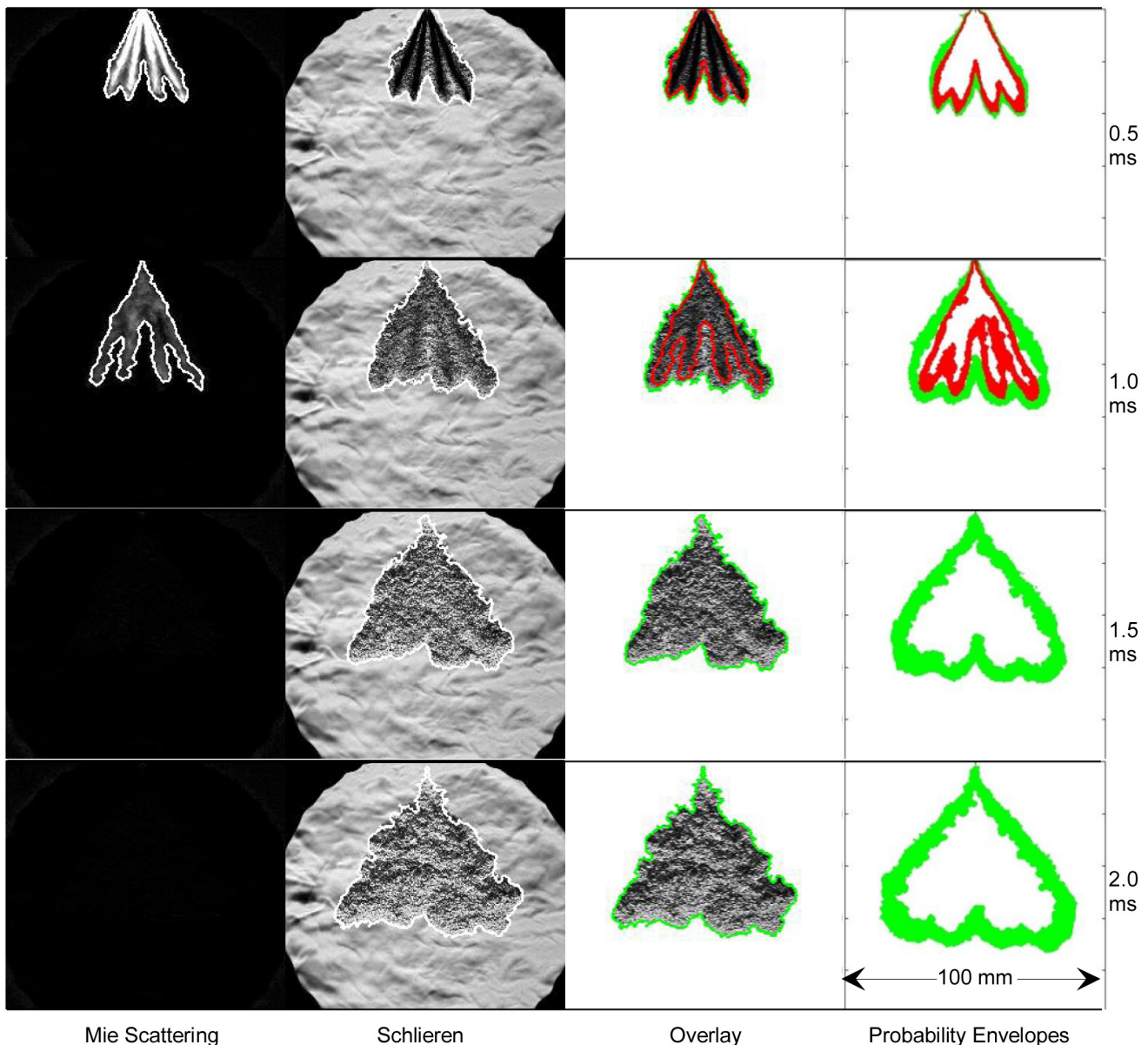


Figure 4. Raw Mie scattering and schlieren images and the corresponding liquid and vapor envelopes. Indolene $M_{\text{injected}} = 10 \text{ mg}$, $P_{\text{injection}} = 20 \text{ MPa}$, $T_{\text{amb}} = 600 \text{ K}$, $P_{\text{amb}} = 5.34 \text{ Bar}$, $\rho_{\text{amb}} = 3 \text{ kg/m}^3$

In general, irrespective of fuel type or ambient density, the maximum liquid penetration of the 400 K ambient temperature cases was greater than that of the 900 K ambient temperature cases by a factor of greater than 2. Likewise, irrespective of fuel type, the maximum liquid penetration of the 3 kg/m³ ambient density cases was greater than that of the 9 kg/m³ ambient density cases by a factor of 1.4 to 1.8. The effects of ambient density were more pronounced at higher ambient temperatures.

By comparing the maximum liquid penetration curves for each of the fuels at corresponding conditions, it can be seen that iso-octane was the least penetrating and ethanol was the most penetrating. In fact, as shown in Figure 8, by normalizing with

respect to iso-octane the penetration of ethanol exceeded iso-octane by about 15% for the 400 K ambient temperature and more than 50% for the 900 K ambient temperature. Only one curve is shown for each fuel because on a normalized basis the effects of ambient density were modest (~ 5%). The curves shown in Figure 8 represent the average increase over the density range.

The increase in liquid penetration for Indolene with respect to iso-octane was more modest ranging from about 15% for the 400 K ambient temperature to about 25% for the 900 K ambient temperature.

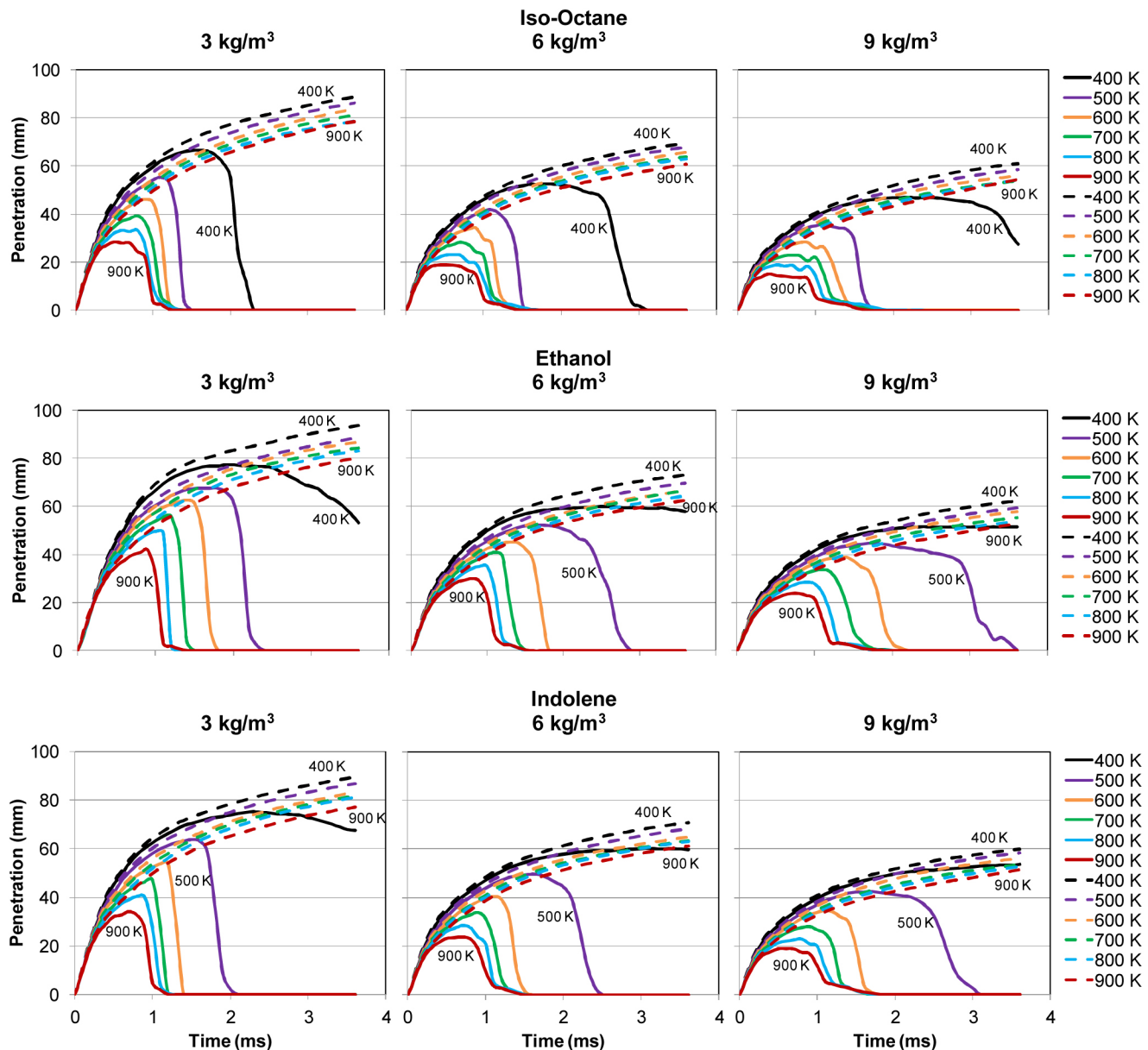


Figure 5. Liquid and vapor penetration curves. The solid lines were derived from the Mie scattering images and therefore represent liquid penetration. The dashed lines were derived from the Schlieren images and therefore represent liquid and vapor while they coexist and only vapor upon complete evaporation. $M_{\text{injected}} = 10 \text{ mg}$, $P_{\text{injection}} = 20 \text{ MPa}$