

Liquid and Vapor Envelopes of Sprays from a Multi-Hole Fuel Injector Operating under Closely-Spaced Double-Injection Conditions

Scott E. Parrish, Gaoming Zhang and Ronald J. Zink
General Motors Company

ABSTRACT

Liquid and vapor envelopes of sprays from a multi-hole fuel injector operating under closely-spaced double-injection conditions were investigated using a combination of high-speed schlieren and Mie scattering imaging. The effects of mass split ratio and dwell time between injections on liquid and vapor penetration have been investigated under engine-like pressures and temperatures. For the conditions evaluated, the results indicate that closely-spaced double-injection generally reduces liquid and vapor penetration.

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INTRODUCTION

There is an abundance of work reported in the literature regarding closely-spaced multiple-injection in diesel engines. Many have shown that in diesel engines, closely-spaced multiple-injection can be utilized to reduce particulates and NO_x emissions [1, 2]. Often, however, the underlying physics responsible for the improvement are alluded to but not completely understood. Some have performed spray characterization studies and have shown that small quantity pilot injections penetrate slowly and are easily overtaken by subsequent larger quantity injections [3]. Others have demonstrated that two equal quantity closely-spaced injections penetrate at different rates depending on the dwell time between injections [4, 5].

The majority of work reported in the literature regarding closely-spaced multiple-injection in gasoline engines is associated with the use of outwardly opening piezoelectric injectors. Piezoelectric injectors are well suited for the application due to the speed at which they can open and close. Luttermann et al. [6] reported the use of multiple injection to reduce smoke emission and oil dilution as a result of reduced wall wetting. To reduce spray penetration, double injection was used for mid load points while triple injection was used at higher engine loads. Additionally, double injection was employed to promote quick catalyst light-off leading to lower hydrocarbon emission while maintaining combustion stability. Schwarz et al. [7] alluded to the use of multiple injection to prevent large injection quantities,

associated with turbocharged engines, from wetting combustion chamber surfaces. These studies did not include detailed spray characterization work. Skogsberg et al. [8] performed spray characterization experiments utilizing a piezoelectric injector and found that spray tip penetration is reduced for double injection compared to single injection.

Far less work has been reported utilizing solenoid injectors operating under closely-spaced multiple-injection conditions. That is the injector type of interest here. Multi-hole injectors are of interest because their sprays tend to maintain their shape when exposed to high ambient pressures and they offer considerable flexibility in fuel placement. Mitroglou et al. [9] performed a double-injection study utilizing 6-hole and 12-hole injectors and reported that spray structure and droplet velocities were similar for each injection if the dwell between injections was greater than 0.5 ms.

The primary objectives of this investigation were to determine the influences of injected mass and dwell time between injections on resulting liquid and vapor envelopes. The data generated should be of interest to combustion system engineers to assist in combustion system development and to computational modelers for model validation.

In the case of solenoid injectors, although closely-spaced multiple-injection is possible, it is not uncommon for subsequent injection events to be influenced by the previous event. Special care is required to ensure that the intended injection quantities are achieved and that the injection events have adequate stability. Prior to conducting spray measurements, detailed injection rate measurements were

performed to determine the required injection durations to inject the intended mass in each injection event. For this purpose a rate tube type meter was utilized. Injection stability was also assessed to ensure injection events were repeatable event-to-event.

In this investigation idle-like conditions were of particular interest. A total injected fuel quantity of 3.6 mg was utilized in all cases. The total injected mass was proportioned between two injections as described in [table 1](#). The dwell time between injections was varied at 5°, 7°, 9°, and 11° from the end-of-injection to end-of-injection. At an idle speed of 800 rpm these dwells translate to 1.042, 1.458, 1.875, and 2.292 ms, respectively. Injection durations varied between 0.195 ms and 0.271 ms. For comparative purposes a 3.6 mg single injection was also evaluated to serve as a baseline.

High-speed planar Mie scattering imaging was utilized to visualize the liquid phase while, in subsequent experiments, high-speed schlieren imaging was utilized to visualize both liquid and vapor phases. Liquid penetration lengths were determined with the use of the Mie scattering images while vapor penetration lengths were determined utilizing the schlieren images.

Table 1. Double injection mass proportions.

Mass Ratio 1 st Injection/ 2 nd Injection	1 st Injected Mass (mg)	2 nd Injected Mass (mg)	Total Injected Mass (mg)
20 / 80	0.72	2.88	3.60
35 / 65	1.26	2.34	3.60
50 / 50	1.80	1.80	3.60
65 / 35	2.34	1.26	3.60
80 / 20	2.88	0.72	3.60

EXPERIMENTAL SETUP

The injector used in this investigation was an 8-hole, VCO (valve covered orifice) style injector with a nominal included spray angle of 60 degrees. 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 25° C to mimic cold conditions. Injection pressure was fixed at 20 MPa and maintained using a PID controlled hydraulic accumulator charged with nitrogen. Indolene was chosen as the test fluid due to its realistic multi-component composition.

Experiments were conducted in a vessel that allowed measurements to be performed at elevated pressures and temperatures. In order to mimic idle conditions, the vessel pressure and temperature was fixed at 11 bar and 700° K,

respectively. A continuous flow of nitrogen passed through the vessel to provide evacuation of the injected mass and prevent the accumulation of residual droplets.

HIGH-SPEED PLANAR MIE SCATTERING

High-speed Mie scattering imaging was utilized to visualize the liquid phase of the spray. As illustrated in [Figure 1](#), a high-speed Nd:YAG laser at a wavelength of 355nm was used to illuminate the spray. The combination of a spherical lens and a cylindrical lens was used to produce a light sheet approximately 60 mm in height and 0.5 mm in thickness. A power meter was used to monitor the laser to ensure that a constant laser power was maintained for each test condition. The Mie scattering images were collected through a window that was 17.5° from the orthogonal direction of the laser sheet by a high-speed camera operating at a rate of 10 kHz. Due to the viewing angle, the Mie images were distorted and therefore required perspective correction. This was accomplished through post processing utilizing image processing algorithms. An example image is shown in [Figure 2](#).

HIGH-SPEED SCHLIEREN IMAGING

To visualize the vapor phase of the spray, high-speed schlieren imaging was employed. The schlieren technique is sensitive to gradients in index of refractive and therefore both the liquid and vapor phases contribute to the image. The vapor phase envelope can be deduced by comparing the Mie scattering images to the schlieren images due to the fact that the Mie scattering images are sensitive only to the liquid phase.

The experimental configuration for the high-speed schlieren system is illustrated in [Figure 3](#). It was a folded Z-type schlieren configuration. A continuous fiber bundle incandescent light source was used for illumination. A condensing lens was used to focus the light source onto a slit to produce a well defined geometric source. The light from the source slit was collimated by a parabolic mirror and directed by a folding mirror through the vessel test section. Upon passing through the vessel, the light was then directed by another folding mirror and focused by a second parabolic mirror onto a knife edge located at the focal point of the parabolic mirror. A high-speed camera, located behind the knife edge was used to capture the spray images. As is the case in all schlieren experiments, the sensitivity of the system was proportional to the amount of cut-off by the knife edge. An example image is shown in [Figure 4](#).

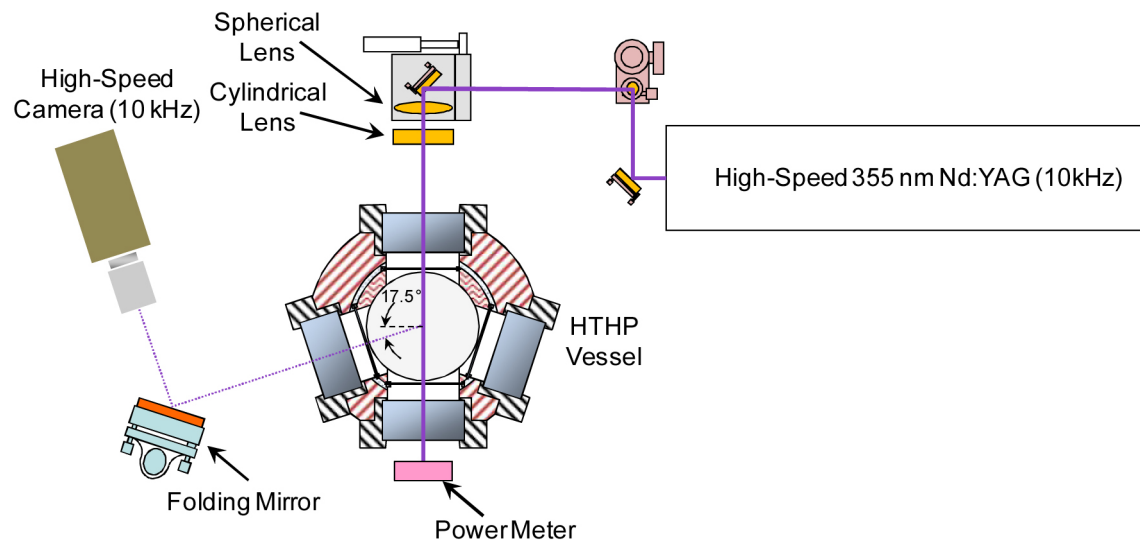


Figure 1. High-speed planar Mie scattering experimental setup.

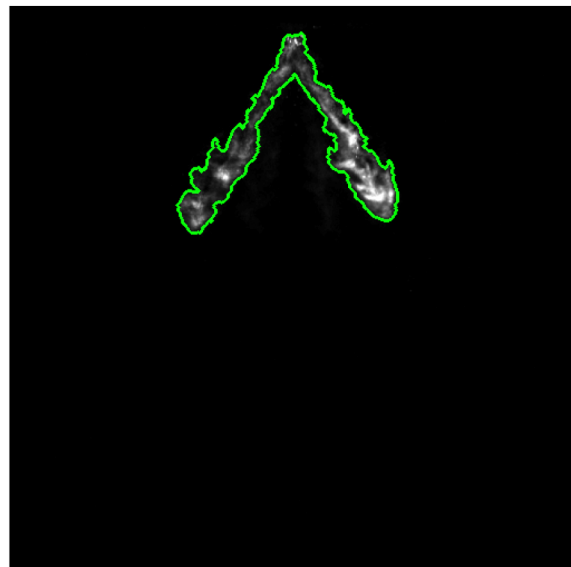


Figure 2. Example planar Mie scattering image. 50/50 mass ratio, 7° dwell, 2.0 ms.

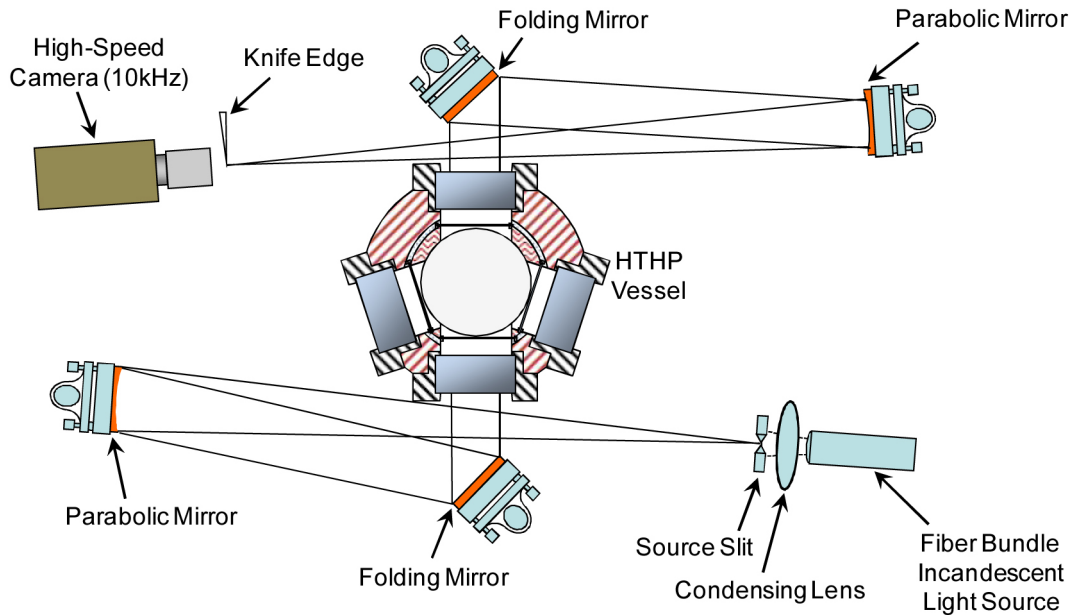


Figure 3. High-speed schlieren experimental setup.

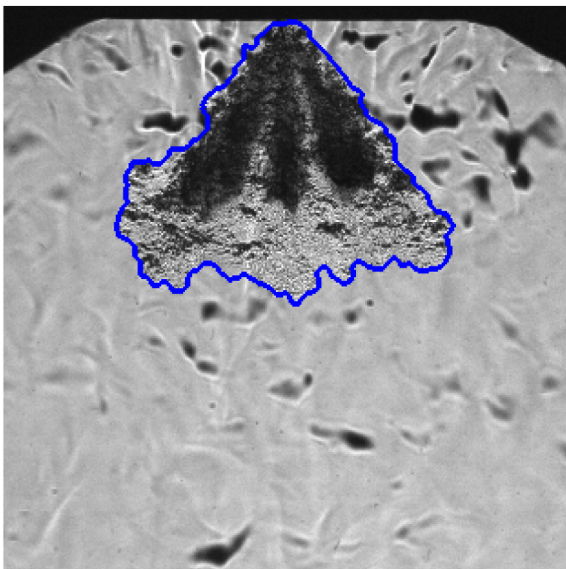


Figure 4. Example schlieren image. 50/50 mass ratio, 7° dwell, 2.0 ms.

RESULTS AND DISCUSSION

20/80 CASE

Figure 5 shows the penetration curves for the 20/80 case. Each curve represents the ensemble average of ten duplicate experiments. Four dwells are shown along with the single injection case for reference. In all cases, liquid penetration is shown to increase to a maximum value and then go to zero due to vaporization. As expected the liquid penetration of the first injection appears similar for each dwell. It is also

apparent that the liquid penetration of the first injection is approximately half that of the single injection case. This is not surprising as penetration increases with injected mass. Although delayed in time, the liquid penetration of the second injection appears similar for each dwell and is slightly less than that of the single injection. This indicates that, for the dwells evaluated, the flow field produced by the first injection was not of sufficient strength to assist the penetration of second event in any meaningful way.

Also shown in the figure are the penetration curves derived from the schlieren images. As previously mentioned the schlieren technique is sensitive to both liquid and vapor phases. Early in time the schlieren penetration curves match those generated from the Mie scattering images. This is an expected result and indicates 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. Not surprisingly the vapor penetration for the first injection event appears similar for each dwell up until the point of the second injection. It is also apparent that the vapor penetration of the first injection is much less than that of the single injection case.

At about the time the liquid phase penetration of the second injection reaches the vapor phase penetration of the first injection an abrupt change occurs in the schlieren derived penetration curves. At this point the liquid

penetration of the second injection is overtaking the vapor penetration from the first injection and both liquid and vapor phases coexist. In a similar fashion to that of the first injection, later in time but prior to the peak in liquid penetration for the second injection, the penetration curves begin to deviate from each other. Once again this deviation indicates the existence of vapor phase in addition to liquid phase. Later in time as the liquid penetration of the second injection goes to zero, the vapor penetration continues. Although shifted in time, this trend is common to all dwells.

To complement the penetration data, cross sectional areas were calculated for each case and are shown in [Figure 6](#). Not surprisingly, the trends in cross sectional area are quite similar to those just described for penetration. It is noteworthy that for each case the first injection event resulted in a peak liquid cross sectional area of only 1 cm^2 . Additional it is apparent that the area of the vapor envelopes far exceed those of the liquid envelopes.

As mentioned previously, for each case ten duplicate image sets were acquired. [Figure A1](#) shows one image set for each dwell and the single injection case for reference. The inner and outer contours were derived from the planar Mie scattering and schlieren images, respectively. These contours were utilized to determine penetration and cross sectional area.

35/65 CASE

[Figures 7](#) and [8](#) show the penetration and cross sectional area curves for the 35/65 case. [Figure A2](#) shows one image set for each dwell and the single injection case for reference. In general, the trends appear similar to those associated with the 20/80 case, however, there are some significant differences. As expected, due to the additional mass in the first injection, the first injection liquid penetration is greater for the 35/65 case compared to the 20/80 case. Of greater significance are the differences in liquid penetration of the second injection. Even though the second injection of the 35/65 case contained less mass than that of the 20/80 case, the maximum liquid penetration of the second injection for the 35/65 case was equal to or greater than those associated with 20/80 case. In fact, the liquid penetration of the second injection for the 5° dwell equals that of the single injection case. It is also apparent that a subtle trend exists between the dwell time between injections and the second injection penetration. The second injection penetration decreases as the dwell time between injections increases. These trends indicate that the first injection produced a flow field with sufficient strength to assist the penetration of second injection. It is reasonable to expect that as the dwell time between injections is increased, the strength of the flow field produced by the first injection will dissipate. At a sufficient dwell time between injections, the flow field produced by the first injection would dissipate to the point where it no longer assists the penetration of the second injection.

In terms of vapor penetration, only the two shortest dwells exhibit an abrupt change in penetration occurring soon after the second injection peak liquid penetration. This indicates that the first injection was of such strength that the resulting vapor envelope was only minimally affected by the second injection. In fact for the two longest dwells, no obvious change in vapor penetration is detectable. This results in equivalent cross sectional areas, governed by the first injection, as shown in [Figure 8](#).

50/50 CASE

[Figures 9](#) and [10](#) show the penetration and cross sectional area curves for the 50/50 case. [Figure A3](#) shows one image set for each dwell and the single injection case for reference. As expected, due to the additional mass in the first injection, the first injection liquid penetration is greater for the 50/50 case compared to the 35/65 case. Liquid penetration of the second injection is greater than the first injection for the two shortest dwells and about equal for the two longest dwells. This dwell dependency occurs for the same reasons mentioned in the previous case. Although the penetration of the second injection was greater than the first injection for the two shortest dwells, it was less than that of the single injection case. This differs from shortest dwell associated with the 35/65 mass split where second injection liquid penetration was shown to be equal to the single injection case. This decrease in second injection liquid penetration is due to the reduction in the second injection mass.

The vapor penetration for the 50/50 case appears similar for each dwell. Unlike the 20/80 and 35/65 mass ratios, no abrupt changes in vapor penetration are detectable. This indicates that the first injection was of such strength that the resulting vapor envelope expanded at a sufficient rate to be unaffected by the second injection. This results in vapor envelopes of equivalent cross sectional areas, as shown in [figure 10](#).

65/35 CASE

[Figures 11](#) and [12](#) show the penetration and cross sectional area curves for the 65/35 case. [Figure A4](#) shows one image set for each dwell and the single injection case for reference. Once again, as expected, due to the additional mass in the first injection, the first injection liquid penetration is greater for the 65/35 case compared to the 50/50 case. Liquid penetration of the second injection is reduced in comparison to the 50/50 case and is about equal for each dwell. It is interesting to compare the 65/35 case to the 35/65 case shown in [Figures 7](#) and [8](#) because equal quantities were injected but in reverse order. By comparing the second injection of the 65/35 case to the first injection of the 35/65 case, it is apparent the liquid penetration is nearly the same. This indicates that for the 65/35 case the flow field produced by the first injection is not assisting the penetration of the second injection in any meaningful way. In contrast, comparing the first injection of the 65/35 case to the second injection of the 35/65 case, it is apparent that for the shortest dwell the liquid