

# Liquid Penetration of Diesel and Biodiesel Sprays at Late-Cycle Post-Injection Conditions

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## ABSTRACT

The liquid and vapor-phase spray penetrations of #2 diesel and neat (100%) soybean-derived biodiesel have been studied at late expansion-cycle conditions in a constant-volume optical chamber. In modern diesel engines, late-cycle staged injections may be used to assist in the operation of exhaust stream aftertreatment devices. These late-cycle injections occur well after top-dead-center (TDC), when post-combustion temperatures are relatively high and densities are low. The behavior of diesel sprays under these conditions has not been well-established in the literature. In the current work, high-speed Mie-scatter and schlieren imaging are employed in an optically accessible chamber to characterize the transient and quasi-steady liquid penetration behavior of diesel sprays under conditions relevant for late-cycle post injections, with very low densities ( $1.2 - 3 \text{ kg/m}^3$ ) and moderately high temperatures (800 - 1400 K). Using #2 diesel fuel and a nozzle orifice size of 0.108 mm, our results show that the quasi-steady liquid penetration ranges from 40 mm ( $3 \text{ kg/m}^3$ , 1400 K) to over 100 mm ( $1.2 \text{ kg/m}^3$ , 800 K), conditions that can cause wall wetting and oil dilution problems in most engines. Wall wetting would increase when using biodiesel fuels, as the liquid penetration length of biodiesel is about 20% higher than that of #2 diesel. These measured liquid penetration lengths can be reasonably estimated using a simple mixing-limited vaporization model, but there is evidence that atomization effects may become important as densities approach these near-atmospheric levels. The maximum liquid penetration can be limited by implementing short injections that end prior to the steady-state jet development period. However, this transient penetration period is short under these very low density conditions, limiting the maximum injection duration to short

injections with small injected quantities, which may not deliver enough fuel for practical application. Multiple short injections can deliver larger quantities of fuel without reaching the steady-state liquid length.

## INTRODUCTION

In today's diesel vehicles, advanced aftertreatment systems are a near requirement to meet recently implemented emissions regulations that call for an unprecedented level of control over oxides of nitrogen (NO<sub>x</sub>) and particulate matter (PM). These aftertreatment systems introduce a new level of complexity in engine operations because they require specific exhaust stream conditions to manage the loading or catalytic oxidation of controlled exhaust species from system devices. For example, lean NO<sub>x</sub> traps (LNTs) require lean-rich modulation of the exhaust stream to activate the catalysis of stored NO<sub>x</sub>, and may also require boosted exhaust temperatures at low load conditions to improve catalytic efficiency (near 400 °C) or for desulfurization (600-700 °C), while diesel particulate filters (DPFs) require regeneration with occasional periods of high temperature (near 600 °C) to burn off the accumulated soot layer [1]. Since the temperature and stoichiometry of the exhaust stream will depend on the speed and load of the engine, there is no assurance that these aftertreatment devices will receive the required conditions on a timely basis. Accordingly, today's diesel vehicles require some method for actively controlling the state of the exhaust stream.

One approach to achieve this type of active exhaust stream management is to employ late-cycle in-cylinder post-injections of fuel [2,3,4]. This strategy is of particular interest because it leverages hardware and control systems already on-board most new diesel vehicles. Furthermore, by

controlling the timing of a post-injection to occur during different periods of the expansion stroke, different exhaust-stream management objectives can be met. For example, systems can employ injections somewhat earlier in the expansion stroke to generate partial oxidation of the fuel, supplying both exhaust stream enrichment and increased engine-out exhaust temperatures for catalyst warm-up procedures during low-load operation[4,5]. For aftertreatment operations that require higher exhaust stream temperatures, such as DPF regeneration or LNT desulfurization, injections can be employed much later in the expansion stroke, when in-cylinder temperatures are lower, introducing raw fuel into the exhaust stream for energy conversion at a diesel oxidation catalyst (DOC) placed upstream [6]. Indeed, most aftertreatment systems using post-injection exhaust stream management employ a range of post-injection timings throughout different stages of the aftertreatment management cycle [2,3,6].

Although post-injection strategies may offer some simplification for aftertreatment management systems, over-penetration of fuel sprays and cylinder wall-wetting can be a concern at low-density conditions [7]. In fact, oil dilution has been documented to increase for engines running late-cycle post-injection strategies [1,5,8]. Not only does fuel fail to reach the exhaust stream, as intended, but oil dilution is a serious concern for engine reliability because oil lubricity will decrease as dilution levels increase, increasing engine friction [8] and putting components at risk for premature wear and damage [9]. Because of these concerns, increased oil dilution levels can demand a reduction in manufacturer-recommended oil drain intervals.

Oil dilution from over-penetration of post-injected fuel sprays is an even bigger concern for engines running biodiesel or biodiesel-blend fuels, because oil dilution levels have been shown to increase with the use of these fuels [10,11]. Furthermore, because of their low volatility, they are more resistant to evaporation from the oil and have a greater tendency to remain in the oil than with neat diesel fuel [10,12,13]. Biodiesel has also been shown to interact with antiwear additives [12], which affects the performance of engine oil beyond just the dilution level. As biodiesel or biodiesel-blend fuels begin to penetrate the market, it is important to consider the compatibility of these fuels with aftertreatment systems.

To properly address the potential for oil dilution with these post-injection strategies, there must be an understanding of fuel spray behavior at these post-injection conditions. Much of the available literature characterizing spray penetration under diesel engine conditions has focused on ambient conditions that occur near top-dead-center (TDC), at high density and temperature [e.g., 14,15]. Recently, sprays have been characterized at early-injection conditions, where densities and temperatures are both low [7]. However, post-

injections for aftertreatment management typically occur quite late in the expansion stroke, under conditions where densities are low, but temperatures are high. Thus, there remains a need to characterize and understand the behavior of sprays in this new regime.

As an assessment of the density and temperature conditions likely to be present at late-cycle post-injection times, [Figure 1](#) illustrates a simulated engine expansion stroke for a typical diesel engine operating at a near-idle condition. It is under this type of operating condition that in-cylinder density and temperature should be lowest, thus providing a “worst-case-scenario” condition where over-penetration of sprays and oil dilution are likely to be worst. The simulated expansion stroke is calculated from a simple polytropic compression and expansion process with a constant specific heat of 1.35 and complete combustion to equilibrium at top-dead-center (TDC) at a global air-fuel (A/F) ratio of 30:1. As seen in [Figure 1](#), densities can be very low at these late-cycle timings. Post-injection strategies in the literature report timings as late as 130° after top-dead-center (ATDC) [6], or even past exhaust-valve-opening (EVO) [8]. At these times, densities are likely to be at near-atmospheric levels, with moderately high temperatures near 900-1000 K. For an earlier timing around 70° ATDC, the density can rise to near 3.0 kg/m<sup>3</sup>, but this density is still very low compared to typical TDC conditions (~20.0 kg/m<sup>3</sup>). Furthermore, the temperature at this post-injection timing is high, near 1300 K, and well above typical TDC temperatures (~900 K). As mentioned, these conditions represent a new regime for diesel spray research, with densities well below and temperatures well above the TDC types of conditions widely characterized in the literature [e.g., 14,15].

This work provides a quantitative characterization of the extent of liquid penetration under these late-cycle post-injection conditions and also evaluates the potential impacts of using biodiesel fuels with these strategies.

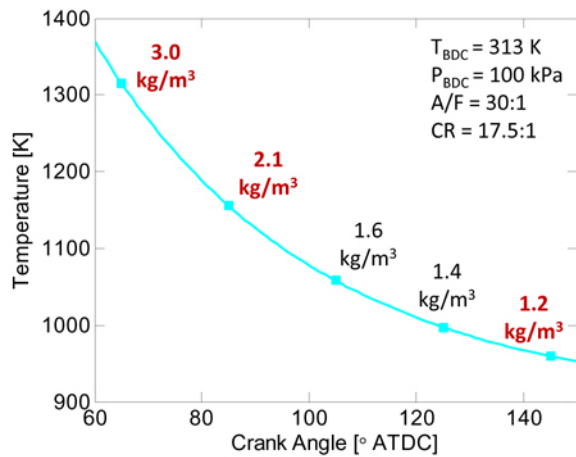


**Figure 1. Computed in-cylinder charge densities and temperatures for a light-duty diesel engine during late-cycle expansion. Intake conditions are representative of an idle or low load condition.**

## EXPERIMENTAL APPARATUS

### COMBUSTION VESSEL

Experiments were performed in a constant-volume combustion vessel under simulated, quiescent diesel engine conditions. The combustion chamber is cubical, measuring 108 mm on each side. The fuel injector is mounted at the center of a metal side-port such that the diesel spray is directed into the center of the chamber. Sapphire windows located in three other ports of the combustion vessel permit line-of-sight and orthogonal optical access to the injected fuel jet. Further details about the combustion chamber geometry and operation may be found in [16].

The thermodynamic state of the ambient gases within the core of the vessel was varied to simulate different late-cycle post-injection conditions like those shown in Figure 1. The ambient pressure, temperature and species are varied in the vessel by igniting a combustible-gas mixture that burns to completion, producing a high-temperature, high-pressure environment with the desired ambient product mixture. A mixing fan is used to maintain the uniformity of the ambient gases within the vessel, but the velocities of the gases ( $<0.5$  m/s) are three orders of magnitude lower than a typical fuel injection velocity and do not noticeably affect the penetrating spray-the vessel is essentially quiescent. Throughout the current study, the ambient gas within the vessel was prepared so that the products of the pre-combustion event were inert, containing 0%  $O_2$ , 89.7%  $N_2$ , 6.5%  $CO_2$  and 3.8%  $H_2O$  [16]. This inert environment eliminates uncertainty associated with heat-release effects on liquid penetration, and enables direct comparison with past steady liquid length research under this environment [15]. Following the premixed combustion, the combustion products cool over a relatively long time ( $\sim 1-2$  s)

due to heat transfer to the vessel walls and the vessel pressure slowly decreases. When the desired pressure is reached, the diesel fuel injector is triggered and fuel injection occurs.

Due to thermal boundary layers that form at the relatively cold vessel walls during the cool down process, temperatures at the core of the vessel are hotter than the bulk-average temperature. To account for this in previous work, core temperatures in the vessel were directly measured to develop a relationship between the core and bulk-averaged temperature in the vessel [15]. However, this previous characterization was conducted at significantly higher density conditions than those in the current study. At low density conditions, the boundary layer thickness at the vessel walls should increase, changing the relationship between the core and bulk-averaged temperature. To account for this, we conducted fine-wire (50  $\mu m$ ) thermocouple measurements of the core temperature during the cool-down process for ambient densities of 1.2, 2.0 and 3.0  $kg/m^3$ . An ensemble-average of 20 of these cool-down measurements at each density provided a modified core to bulk-average temperature relationship for each of the ambient density conditions examined in the current study.

### INJECTION EQUIPMENT

A Bosch second-generation common-rail injector (CRIP 2.2) equipped with a single-spray, axially-drilled, 0.108 mm nozzle was used for this study. The nozzle has a convergent ( $K = (d_i - d_o)/10$ , units in  $\mu m$ ), hydro-ground orifice (KS1.5/86 specification by Bosch) and is a mini-sac type with a sac volume of 0.12  $mm^3$ . The discharge ( $C_d$ ) and area contraction ( $C_a$ ) coefficients for this orifice were measured using a force sensor similar to that described in [17] and are shown in Table 1. The orifice coefficients were determined from long-injection events, where the flow is relatively steady. As seen in Table 1, measurements of the nozzle coefficients were performed with the #2 diesel fuel and soy-based biodiesel used in this study and are statistically equivalent within the measurement uncertainty. Rate-of-injection measurements were also performed using the force sensor and cumulative mass measurements, as shown in the following section.

<table 1 here>

### FUELS

Physical properties for the #2 diesel and biodiesel fuels used in this study are given in Table 2, with the distillation behavior of the two fuels shown in Figure 2. Note that the fuel properties are given at room temperature, which is lower than the 100  $^{\circ}C$  fuel temperature used in the experiments. The biodiesel fuel is a neat (100%) soy-derived biodiesel composed of five methyl esters, outlined in Table 3.

**Table 1. Injector nozzle geometry and measured flow coefficients with fuels used in this study.**

| Fuel          | Nozzle diameter [mm] | K factor | $C_d$             | $C_a$             | $P_{inj}$ [MPa] | Fuel temperature [K] |
|---------------|----------------------|----------|-------------------|-------------------|-----------------|----------------------|
| #2 Diesel     | 0.108                | 1.5      | $0.92 \pm 0.01$ § | $0.99 \pm 0.03$ § | 150 *           | 373 ¢                |
| Soy Biodiesel | 0.108                | 1.5      | $0.93 \pm 0.01$ § | $1.0 \pm 0.02$ §  | 150 *           | 373 ¢                |

§Estimates of uncertainty in the nozzle coefficients include measurement error and uncertainty in the actual fuel temperature at the nozzle exit.

\*The supplied injection pressure is controlled within 5 MPa.

¢Reported fuel temperature is measured at the nozzle tip prior to injection.

**Table 2. Diesel and biodiesel fuel properties.**

|                                            | #2 Diesel   | Biodiesel   |
|--------------------------------------------|-------------|-------------|
| $T_{90}$ [°C]                              | 315         | 351         |
| Density [kg/m <sup>3</sup> ]               | 843 (15 °C) | 860 (25 °C) |
| §Density at 100 °C [kg/m <sup>3</sup> ]    | 767         | 793         |
| Kin. Viscosity, 40 °C [mm <sup>2</sup> /s] | 2.35        | 4.0         |
| Flash Point [°C]                           | 73          | 160         |
| Cetane Number                              | 46          | 51          |
| LHV [MJ/kg]                                | 42.98       | 37.4        |

§Estimated using density dependency on temperature from [15].

**Table 3. Soy-derived biodiesel composition.**

| Constituent name  | Constituent abbreviation | Chemical formula  | %   |
|-------------------|--------------------------|-------------------|-----|
| Methyl palmitate  | C16:0                    | $C_{17}H_{34}O_2$ | 11  |
| Methyl stearate   | C18:0                    | $C_{19}H_{38}O_2$ | 4.0 |
| Methyl oleate     | C18:1                    | $C_{19}H_{36}O_2$ | 25  |
| Methyl linoleate  | C18:2                    | $C_{19}H_{34}O_2$ | 53  |
| Methyl linolenate | C18:3                    | $C_{19}H_{32}O_2$ | 7.0 |

The  $T_{90}$  point reported in Table 2 was derived from an ASTM D1160 test by the manufacturer (Peter Cremer), while the distillation curve presented in Figure 2 was obtained from independent lab testing of the biodiesel, using the ASTM D2887 method.

The reported distillation behavior of the biodiesel appears markedly different from that of the #2 diesel. Not only are distillation temperatures higher, but the curve appears relatively flat and the majority of the fuel evaporation occurs within a range of about 30 °C. This type of flat distillation curve has also been reported for distillation tests of biodiesel fuels using ASTM D1160, as well as ASTM D86, the test method for petroleum diesel fuels [13,18]. However, Andrae et al. [10] present distillation characteristics of a biodiesel fuel that are quite similar to the wide distillation range seen in #2 diesel fuels, but do not report their test method. Thus, the reported distillation behavior of biodiesel fuels may depend heavily on the test method used. Without a standardized test method available for methyl ester-based fuels, the true distillation behavior of biodiesel fuels remains an open research question. The upper distillation fractions of biodiesel fuels (e.g.,  $T_{90}$ ), however, are consistently reported at higher temperatures than those of petroleum diesel fuels [e.g., 10,13,18].

Because biodiesel fuels have a tendency to decompose or oxidize when heated, the standard testing method used to measure the distillation characteristics of diesel fuels (ASTM D86) is not reliable for the testing of biodiesel fuels. Two alternative distillation tests have been suggested for biodiesel, ASTM D1160 and ASTM D2887, though neither method is designed specifically for use with methyl ester-based fuels. Accordingly, a direct comparison of the distillation characteristics of biodiesel and #2 diesel requires some caution and future research will be required to make precise conclusions regarding the distillation behavior of these fuels. Without a widely accepted distillation standard, we have reported distillation characteristics from both ASTM D1160 and ASTM D2887 for biodiesel, and ASTM D86 for diesel.

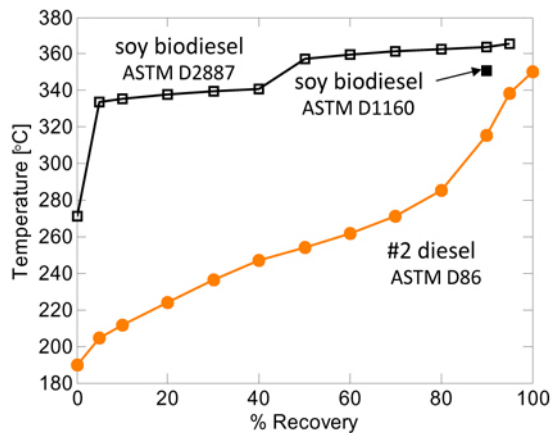


**Figure 2. Distillation curves for #2 diesel and soy-based biodiesel fuels used in this study. Note that the distillation curves are produced using different ASTM distillation methods, as shown. The 90% boiling point for the biodiesel fuel, measured by the ASTM D1160 distillation method, is also given.**

As shown in Table 2, biodiesel has several physical properties that differentiate it from #2 diesel fuel. First, consistent with reports of the distillation characteristics of other biodiesel fuels [10,13,18] and as shown in Figure 2, biodiesel fuels vaporize at higher temperatures than #2 diesel. Biodiesel also has a higher density and a kinematic viscosity that is almost twice that of #2 diesel. As will be shown in the results, these properties contribute to longer liquid penetration distances for biodiesel and may also contribute to differences in spray development processes.

Finally, Figure 3 presents rate-of-injection measurements for the #2 diesel and biodiesel fuels used in the study. Measured mass rate-of-injection profiles for long (3 ms) and short (0.2 ms) duration injections are shown together with the measured momentum flux for the long duration injections. Each rate-of-injection profile is an ensemble-average of 10 injections performed at a 150 MPa rail pressure into an ambient pressure environment, with the injector heated to 100 °C. For both long and short injection durations, the injection profiles have a very rapid start and end of injection, with no significant difference in these rates between the two fuels. Thus, the higher viscosity and density of biodiesel does not appear to influence the needle opening and closing operations of the injector. The initial peak in mass rate-of-injection seen in both long and short injections is the result of a large noise spike in the momentum measurement that occurs when the fuel spray initially impacts the transducer. During long injections, there is a nearly constant mass and momentum flow rate throughout the duration of the injection (i.e., a “top hat” profile). The higher density of biodiesel compared to #2 diesel causes an increase in the mass rate-of-injection, but the measured momentum flux is found to be the same for the two fuels (within the measurement error of  $\pm 0.1$  N). Desantes et

al. [19] have also reported a conservation of momentum flux using biodiesel blends, with densities spanning a similar range as the fuels used in the current study ( $831 \text{ kg/m}^3$  to  $879 \text{ kg/m}^3$ ).

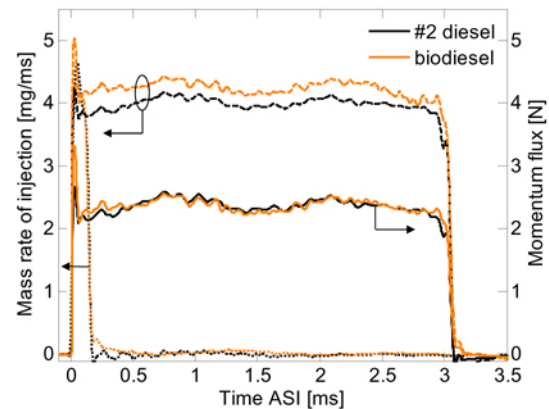


**Figure 3. Measured rate of injection for long, quasi-steady injections (3 ms) and short, transient injections (0.2 ms) with #2 diesel and biodiesel fuels. Fuel was supplied at 100° C, through a nozzle orifice diameter of 0.108 mm, fuel rail pressure of 150 MPa, into an atmospheric ambient pressure environment.**

## OPTICAL DIAGNOSTICS

Mie-scatter and schlieren imaging were performed simultaneously using high-speed imaging systems to track both the liquid and vapor phases of the spray, similar to Ref. [7]. This high-speed imaging allowed for the resolution of spray transients, such as the spray development period and short injections which do not attain a steady behavior. Also, the extent of fluctuation in liquid penetration, even at steady injection conditions, is important to understand the probability of liquid impingement upon in-cylinder surfaces. The average steady liquid length does not fully convey this information. Thus, this imaging system allowed examination of both transient and average spray development processes, offering additional insight into the spray behavior at these conditions.

## MIE-SCATTER IMAGING

Scattered light from fuel-spray liquid droplets was imaged using a high-speed CMOS camera and a continuous-wave laser. As shown in Figure 4, a schlieren system was operated simultaneously using a second high-speed CMOS camera. The time-resolved pair of schlieren and Mie-scatter images identifies the instantaneous position of both the vapor and liquid phases of the fuel spray, respectively.

<figure 4 here>

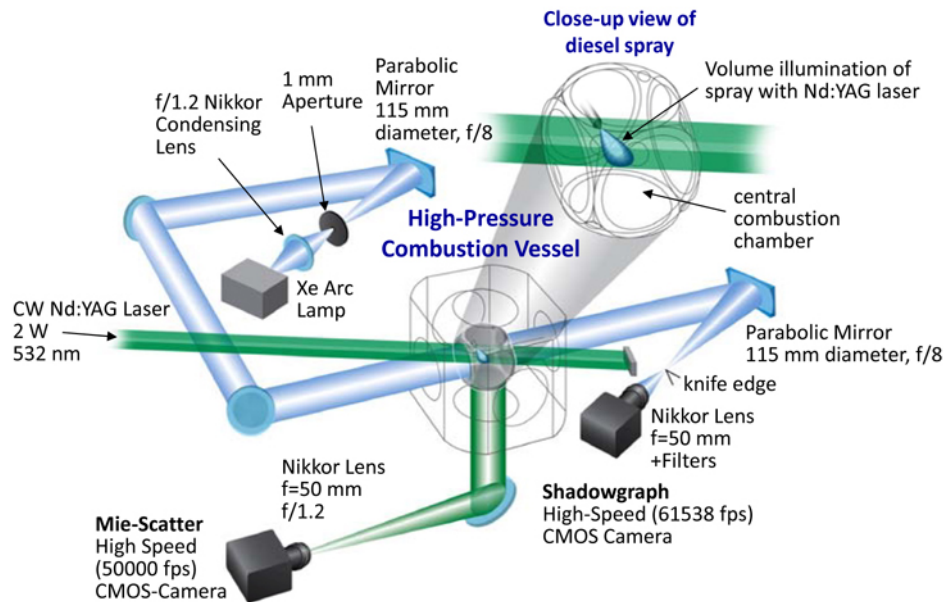


**Figure 4. Combustion vessel and high-speed imaging setup (not to scale).**

The continuous-wave laser source was a frequency-doubled Nd:YAG laser (532 nm) operating with 2 W power. The laser was formed into a volume to illuminate only the liquid-phase region of the spray and also to avoid interference with the schlieren setup (Figure 4). A volume-illumination method, rather than a laser sheet, was utilized to ensure that all droplets spreading from the nozzle were illuminated to identify the maximum axial and radial distances of any liquid-phase fuel [15].

A high-speed CMOS camera, fitted with a 532-nm bandpass filter (10-nm FWHM) and a 50-mm focal length  $f/1.2$  lens, was used to image Mie-scattered light at a near-right angle to the laser source. The bandpass filter was used to reject background thermal radiation from heated vessel walls, or luminosity from combustion in other reacting experiments. The camera was operated at reduced resolution ( $64 \times 512$  pixels) to allow fast framing periods ( $\sim 20 \mu\text{s}$ ) needed to capture dynamics of very fast fuel sprays. The lens was set to the maximum aperture ( $f/1.2$ ) and the camera at an exposure duration ( $9 \mu\text{s}$ ) to intentionally saturate the camera in the dense region of the spray while leaving sufficient dynamic range to identify regions of the spray where liquid completely evaporates. At the maximum spray penetration velocities observed in these experiments, the spray tip can travel up to about 2.5 mm within the  $9 \mu\text{s}$  exposure duration.

## SCHLIEREN IMAGING

Shadowgraph and schlieren imaging have been used for many years to identify refractive index gradients in various experiments [20]. For vaporizing fuel sprays, these techniques can differentiate the boundary between vaporized fuel and background ambient gases.

Figure 4 shows the lighting and imaging arrangement utilized to perform schlieren imaging. The setup and application is described in more detail in Ref. [21]. A 150-W (electrical power) mercury-xenon arc lamp with a small (1.7-mm) arc distance was used as a white light source. Light from the arc was spatially-filtered through a 1-mm aperture and collimated to pass through the combustion vessel. The collimated beam was then re-focused into a high-speed CMOS camera equipped with a Nikkor lens and a 532-nm  $0^\circ$ -incidence laser mirror, which acted to block Mie-scattered light from spray droplets. The camera was operated at a resolution of  $88 \times 256$  pixels, allowing for framing periods of approximately  $16 \mu\text{s}$  with an exposure duration of  $2 \mu\text{s}$ . At the maximum spray penetration velocities observed in these experiments, the spray tip can travel up to about 0.5 mm within the  $2 \mu\text{s}$  exposure duration.

## RESULTS AND DISCUSSION

The Results and Discussion is presented in two sections of analysis. The first section presents measurements of the maximum axial liquid penetration, or liquid length [15], of #2 diesel and biodiesel sprays over a range of simulated late-cycle ambient conditions. In addition, liquid length predictions from a mixing-limited jet vaporization model by Siebers [17] are compared to the measurements. This comparison is significant because the ambient densities explored in this study lie outside of those used for development of the model. Accordingly, we offer an assessment on the extrapolation of the model to these conditions. In the second section, we discuss transient penetration behavior. These transients are of importance in situations where the injected mass is small and where the injection duration may not be long enough for the spray to