

Influence of Diesel Injection Parameters on End-of-Injection Liquid Length Recession

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ABSTRACT

Diesel injection parameters effect on liquid-phase diesel spray penetration after the end-of-injection (EOI) is investigated in a constant-volume chamber over a range of ambient and injector conditions typical of a diesel engine. Our past work showed that the maximum liquid penetration length of a diesel spray may recede towards the injector after EOI at some conditions. Analysis employing a transient jet entrainment model showed that increased fuel-ambient mixing occurs during the fuel-injection-rate ramp-down as increased ambient-entrainment rates progress downstream (*i.e.* the entrainment wave), permitting complete fuel vaporization at distances closer to the injector than the quasi-steady liquid length.

To clarify the liquid-length recession process, in this study we report Mie-scatter imaging results near EOI over a range of injection pressure, nozzle size, fuel type, and rate-of-injection shape. We then use a transient jet entrainment model for detailed analysis. Results show that an increased injection pressure correlates well with increasing liquid length recession due to an increased entrainment wave speed. Likewise, an increased nozzle size, with higher jet momentum and faster entrainment wave, enhances the liquid length recession. A low-density, high-volatility fuel does not decrease the strength of the entrainment wave; however, it decreases the steady liquid length causing the entrainment wave to reach the liquid spray tip earlier, which ultimately results in faster liquid length recession. A slow ramp down in

injection rate causes a weaker entrainment wave so that the liquid length recession occurs even prior to injector close.

INTRODUCTION

Due to the challenge of addressing environmental concerns, combustion strategies that produce much lower engine-out emissions than conventional diesel combustion are currently being investigated. Low temperature combustion (LTC) is one of the in-cylinder approaches adopted in modern diesel engines to further decrease engine-out particulate (PM) and nitrogen oxide (NO_x) emissions. In the LTC regime, injection timing is either advanced [1-2] or retarded [3] to increase the ignition delay time so that a well-mixed fuel-ambient mixture is formed before the start of combustion. Another characteristic is a high level of exhaust-gas recirculation (EGR) to decrease the flame temperature and lower NO formation limits [4-5]. Through years of research, the LTC regime is beginning to be adopted in many modern diesel engines particularly at low to medium load conditions [6-7].

This in-cylinder approach provides new ambient conditions that are quite different from those of the conventional regime and thus alter the liquid-phase diesel spray penetration, evaporation, and mixing processes. First, in-cylinder densities and temperatures during the fuel injection are lower, resulting in increased liquid-phase diesel spray penetration rates (lower evaporation rates). When the liquid length is long, it can

impinge on piston surfaces or the cylinder liner [8], increasing unburned hydrocarbon (UHC) emissions [9] and deteriorating the combustion efficiency.

Another change associated with LTC is that the increased ignition delay is often longer than the fuel injection duration, which causes "ignition dwell" (*i.e.* a time from end-of-injection to start-of-combustion). With positive ignition dwell, mixing processes occurring *after* the end of injection (EOI) dominate the following combustion and emissions formation. Overly lean mixtures are formed near the injector nozzle after EOI, which can become a significant source of UHC emissions because of incomplete combustion [10]. The causes of the fuel-lean mixture near the injector must be understood in order to mitigate problematic UHC emissions in LTC regimes. A detailed understanding of liquid-phase spray penetration and mixing processes after EOI would be helpful in this respect.

In a previous work [11], we have begun to clarify the EOI transient liquid-length and mixing processes, including the finding of a "receding" liquid penetration distance after EOI. A summary of the essential findings pre-requisite to discussions of the present study is given in the following section.

BACKGROUND

Liquid Length Recession

Liquid-phase fuel injected into a high-pressure, high-temperature environment reaches a maximum penetration length soon after the start of fuel injection as the fuel spray entrains hot ambient gas that evaporates the liquid-phase fuel [12]. Provided ambient conditions are steady and injection duration is long, this liquid length reaches a maximum that is nearly steady during injection. This maximum is called the "quasi-steady" liquid length [12].

Shortly before EOI, the mass flow rate declines while the injector needle valve closes. We previously examined how this injection ramp-down affects fuel-ambient mixing and the liquid length during this transient [11]. Experiments showed that the liquid length typically decreases from the quasi-steady value during the injection-rate ramp-down and after EOI. The observed "recession" of the liquid length is summarized schematically in Fig. 1, where the decrease in the maximum liquid length from the quasi-steady length is defined as the "liquid length recession". The liquid spray also detaches from the injector after EOI resulting in an increase of the "minimum liquid distance" (see Fig. 1).

From a strict Lagrangian perspective, this result is counterintuitive if one expects that all liquid fuel leaving the nozzle experiences the same mixing with the ambient as it moves downstream. As happens with injection pressure variation in quasi-steady sprays [12], a slower injection velocity could be matched to a slower rate of ambient entrainment during the injection-rate

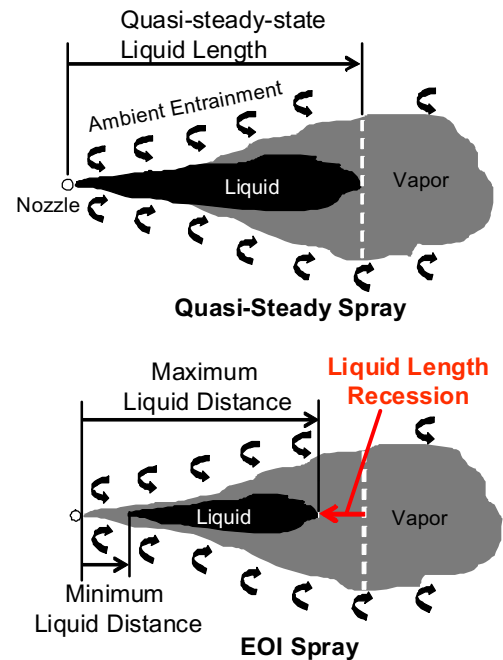


Figure 1 Schematic showing the quasi-steady state liquid length and the recession of the EOI liquid spray [11].

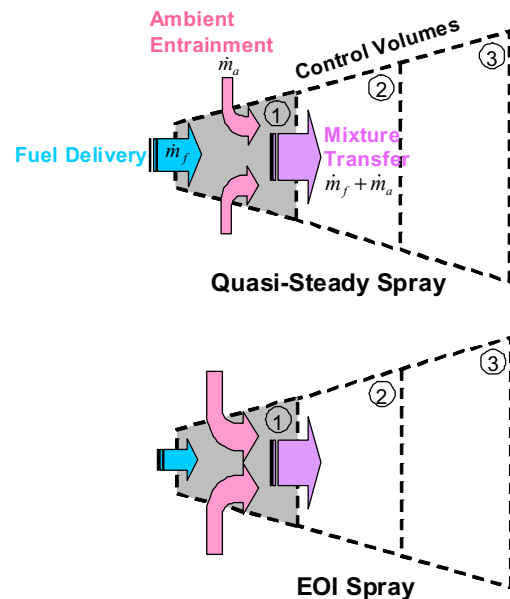


Figure 2 Schematic showing a relative difference in fuel-ambient mixing between the quasi-steady spray and EOI spray.

ramp-down, causing the same liquid length. Instead, the liquid spray recedes back towards the nozzle, opposite to the flow direction.

Initial Increase of Ambient Entrainment

Figure 2 summarizes the potential cause of the observed liquid length recession with simple sketches. For the control volume no. 1, two inputs are (i) a fuel delivery

from the nozzle $\dot{m}_f$ and (ii) an ambient entrainment $\dot{m}_a$ induced by the jet flow. The output is the transfer of fuel-ambient mixture ($\dot{m}_f + \dot{m}_a$) to the next, downstream control volume no. 2. It was experimentally measured [11] and also supported by other studies [10, 13] that the jet spreading angle does not decrease during the EOI transient, although one input ($\dot{m}_f$) does decrease. This means that the downstream flow of the spray is relatively constant as the momentum of earlier-injected fuel continues to carry the flow downstream.

Under these boundary conditions, continuity demands that $\dot{m}_a$ must increase to compensate for the decreasing $\dot{m}_f$. Furthermore, with a decreasing $\dot{m}_f$, the entrainment rate relative to the fueling rate ($\dot{m}_a / \dot{m}_f$) increases even more dramatically. This enhanced mixing permits complete vaporization of the liquid fuel at distances closer to the injector than the quasi-steady liquid length. Accordingly, the liquid length recession is caused by a slower fuel delivery interacting with an increased rate of ambient entrainment during the injection-rate ramp-down.

Entrainment Wave

In Fig. 2, the output (mixture transfer) of control volume no. 1 eventually decreases as the axial component of momentum decreases because of slower fuel momentum and significant ambient entrainment. The decreased axial momentum transfer, in turn, propagates to affect downstream control volumes. The decreased mixture transfer initiates an entrainment increase in subsequent control volumes, just as it did when fuel delivery was reduced to control volume no. 1. To clarify the details of this progress of the increased mixing and its influence on liquid vaporization, we have used a one-dimensional transient jet mixing model that numerically solves the mass and momentum transport between discrete control volumes ([11] and, in more detail, [14]).

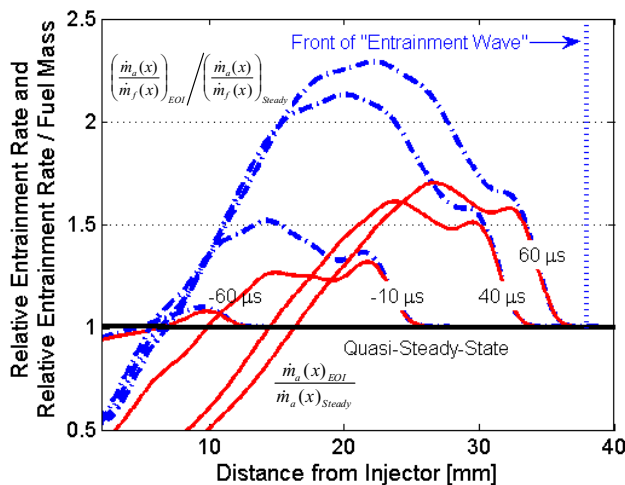


Figure 3 Relative entrainment rate and relative entrainment rate per fuel mass versus axial distance from injector for various times after end of injection. Modified from [11].

Modeling results for multiple control volumes are given in Fig. 3. The figure shows the time history of the ambient mass flux entrainment for the EOI spray relative to the ambient mass flux entrainment for the steady spray (solid lines), which is expressed as:

$$\text{Relative Entrainment Rate} = \frac{\dot{m}_a(x)_{EOI}}{\dot{m}_a(x)_{Steady}} \quad (1)$$

Also shown (dash-dot lines) is the time history of the ratio of ambient mass flux entrainment per fuel mass flux for the EOI spray compared to the ambient mass flux entrainment per fuel mass flux for the steady spray:

Relative Entrainment Rate per Fuel Mass =

$$\left(\frac{\dot{m}_a(x)}{\dot{m}_f(x)} \right)_{EOI} / \left(\frac{\dot{m}_a(x)}{\dot{m}_f(x)} \right)_{Steady} \quad (2)$$

For our condition, the injection-rate ramp-down starts at about -100 μ s after the end of injection (AEI). The downstream portion of the relative entrainment rate becomes higher than the quasi-steady value starting from -60 μ s AEI. This increased entrainment then travels downstream and grows as an “entrainment wave”. As described in [14], the shape of the entrainment wave depends, in part, on the rate at which the fuel injection ramps down. A sharp end of injection produces a single sharp sawtooth entrainment wave, while a slower ramp-down produces a flatter wave. Here, the entrainment wave in Fig. 3 shows two bumps starting from -10 μ s AEI. These bumps correspond to the profile of the measured fueling rate ramp-down, which is used for the calculation as an input. That is, the first small bump is

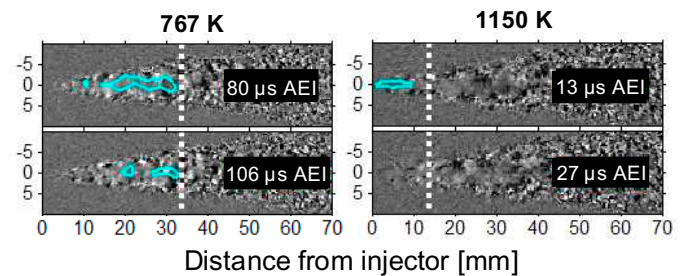


Figure 4 Liquid-phase spray boundaries overlaid on shadowgraph images for two different ambient temperatures [11]. Dashed lines shown are quasi-steady liquid lengths.

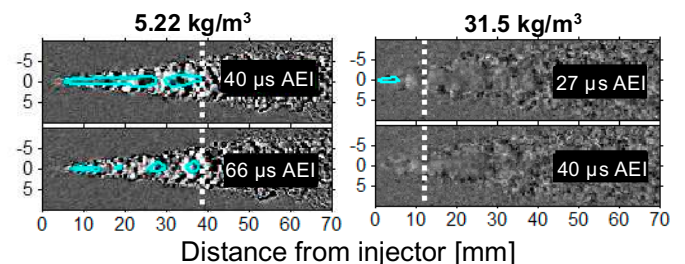


Figure 5 Liquid-phase spray boundaries overlaid on shadowgraph images for two different ambient densities [11].

the result of slow, initial ramp-down of the fueling rate while the following big bump is the result of the more rapid decrease (will be shown later in Fig. 12). Note that, at fixed time AEI, the entrainment rate relative to the fuel mass is much higher as the fueling rate keeps declining. Subsequently, downstream liquid-phase fuel vaporization is accelerated at distances closer to the injector because of this enhanced mixing region.

Ambient Condition Effects

The tendency of liquid recession increased with increasing ambient temperature and density within the range that we tested. Examples are given in Figs. 4 and 5 for different ambient temperatures and densities while all other operating conditions were held constant.

The liquid boundaries (solid lines) in Fig. 4 show an ambient temperature (767 K) that is so low that no liquid recession occurs. On the other hand, at high ambient temperature, the liquid length rapidly recedes all the way back to the injector nozzle. Similar results were acquired for a variation in ambient density as shown in Fig. 5. At low ambient density, the liquid does not recede but instead divides into several regions. The largest region vaporizes completely near the steady liquid length. By contrast, a high density ambient results in fast evaporation and significant recession of the liquid spray.

The transient jet mixing model results from [11] show that this trend is caused by the position of the entrainment wave relative to the quasi-steady liquid length. For high temperature or high density conditions, the steady liquid length is originally short so that the entrainment wave reaches, and quickly affects the quasi-steady liquid length region. By contrast, the entrainment wave does not reach the quasi-steady liquid length region for low ambient temperature or density conditions until the vaporization is complete, leaving liquid and fuel-rich mixtures downstream near the steady liquid length.

CURRENT WORK

The objective of this study is to provide extended information about the liquid-phase spray penetration and evaporation after EOI. Similar to previous work [11], we performed simultaneous high-speed imaging of liquid-phase spray (Mie-Scatter) and vapor-phase spray (Shadowgraph).

As discussed above, the ambient gas entrainment governs the liquid length during the EOI transient. Therefore, many parameters affecting ambient entrainment were examined. From gas jet theory, the mass of ambient gas entrained into a spray up to any axial distance from the nozzle will be linearly proportional to the nozzle diameter (d), the axial distance from the nozzle (x), the fuel injection velocity (U_f), and the tangent of the spray spreading half angle ($\theta/2$) [15]:

$$\dot{m}_a(x) \propto \sqrt{\rho_a \cdot \rho_f} \cdot d \cdot x \cdot U_f \cdot \tan(\theta/2) \quad (3)$$

where ρ_a and ρ_f are the ambient gas and injected fuel densities. Note that this correlation is developed for a steady jet and thereby used only to select the test parameters. Among the parameters, ρ_a has been discussed in [11]. For this study we focus on the effect of the other parameters in Eq. 3. We varied U_f (related to injection pressure) and d to determine how injection parameters affect liquid-phase penetration after EOI. The experiments also include fuels with different ρ_f while using the same common-rail injector. We also examined additional issues affecting liquid length recession such as the effect of heat release, injection duration, and ramp-down shape. For interpretation of the experimental results, we again use the one-dimensional jet entrainment model based on a discrete control-volume analysis [14].

EXPERIMENTS

EXPERIMENTAL APPARATUS

Measurements were obtained in an optically accessible, constant-volume combustion vessel that can tailor ambient temperature and density conditions typical of a diesel engine. The vessel has been used for diesel combustion studies for over a decade. Details about the vessel geometry and operations can be found in [16].

A schematic of the vessel and optical measurement setups are shown in Fig. 6. The vessel has a cubic combustion chamber of 108 mm on each side. Sapphire windows are located in three side ports of the chamber

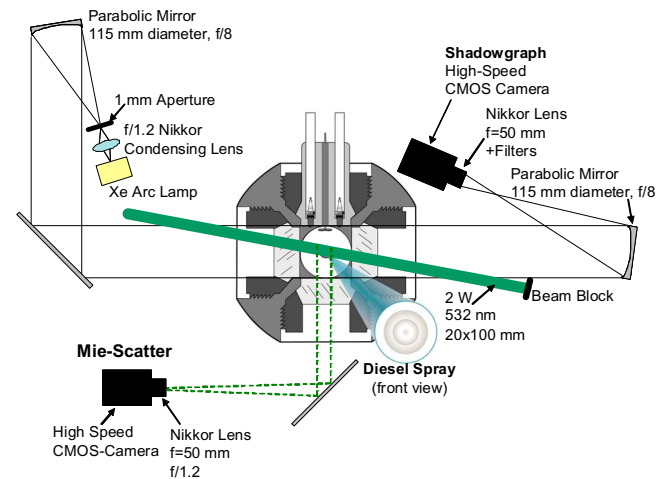


Figure 6 Constant-volume vessel and shadowgraph and Mie-scatter optical setup.

Table 1 Injector conditions

Injector conditions	
Type	Bosch common-rail
Nozzle	Single-hole, KS1.5/0.86
Nozzle diameter	94, 108, 181 μm
Injection pressure	70, 110, 160 MPa

to allow line-of-sight and orthogonal imaging of the injected fuel spray. The ambient conditions are simulated in the chamber by spark-igniting a combustible gas mixture. Once the products of this combustion event cool to a pre-selected pressure and temperature state, the fuel is injected. As listed in Table 1, fuel injection parameters – including injection duration and injection pressure were controlled with a common-rail fuel system (2nd generation Bosch). The injector with a mini-sac-type, axially-drilled, single-hole nozzle is installed on a side-port of the vessel; therefore, a single fuel spray is directed into the center of the chamber. Nozzles from 94- to 181- μm hole-diameter were tested and the injection pressure was varied from 70 to 150 MPa.

For various injection parameters, the fueling rate was calculated using momentum measurement and total injected mass measurement [17] at the same fuel temperature, injection duration, and injection pressure as in the imaging experiment.

High-speed Mie-scatter imaging was performed to image the liquid-phase fuel spray as shown in Fig. 6. The light source was a continuous-wave Nd:YAG laser (532 nm) operating with 2-W power. A 100-mm wide and 20-mm thick laser sheet was formed to volumetrically illuminate the spray. A high-speed CMOS camera (IDT X-Vision) with a 532-nm band-pass filter (10 nm FWHM) and a 50-mm focal length, f/1.2 lens collected Mie-scattered light from the fuel droplets at approximately 50,000 frames per second.

At the same time, high-speed shadowgraph imaging was performed to image the vapor-phase fuel spray. A 150-W (electrical) mercury-xenon arc lamp was used for the light source. The emitted beam passed through a 50-mm focal length f/1.2 Nikkor lens and 1-mm aperture. The beam was collimated by f/8 mirror (115 mm), passed through the chamber windows and then refocused to the high-speed CMOS camera (Phantom v7.1). A zero-incidence 532-nm mirror was used to block laser scatter from the liquid droplets.

The measured vapor-phase spray was mainly used to support the assumption that the spreading angle of the fuel jet does not decrease immediately after EOI. We repeated the same measurement for all the experimental runs and found the results were consistent; therefore, for the sake of brevity, few examples of shadowgraph imaging are presented (see Figs. 4, 5, and 7). Images show that, indeed, the fuel vapor boundary does not change substantially throughout the EOI transient and liquid-phase vaporization (stressed as dash-dot lines in Fig. 7).

EXPERIMENTAL CONDITIONS

The experiments were performed at the specified ambient oxygen concentrations, temperatures, and densities as shown in Table 2. The main fuel used was No. 2 diesel; however, a kerosene fuel was also used as

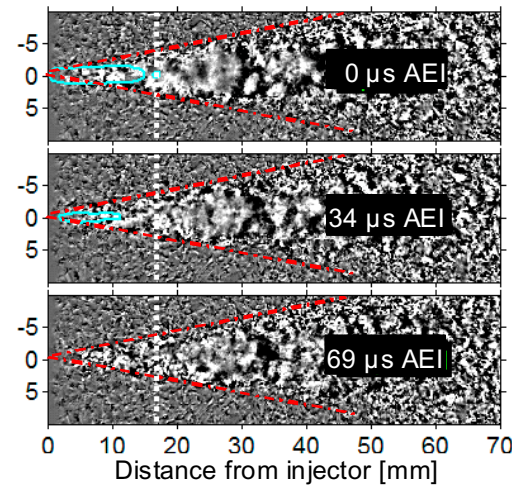


Figure 7 Shadowgraph (vapor-phase spray) imaging time sequence after end of injection (AEI). Liquid boundaries determined from simultaneous Mie-scatter imaging are overlaid on Shadowgraph images. Ambient Conditions: 0% O₂, 900 K, 22.8 kg/m³. Injection Parameters: 94- μm nozzle, 150 -MPa injection pressure.

Table 2 Experimental conditions

Ambient conditions			
O ₂	21%	15%	0%
N ₂	69.33%	75.15%	89.71%
CO ₂	6.11%	6.23%	6.52%
H ₂ O	3.56%	3.62%	3.77%
Molecular Weight	29.47	29.24	28.68
Temperature	600 ~ 900 K		
Density	5.22 ~ 22.8 kg/m ³		
Fuel conditions			
Type	No. 2 Diesel		Kerosene
Density at 288 K	843 kg/m ³		812 kg/m ³
T at 90% Distillation	588 K		539 K
Nozzle Tip Temperature	373 K		

another sample, demonstrating a low-density fuel with low boiling point temperature.

Reacting and Non-Reacting Conditions

While selecting the ambient conditions, it was in question if heat from the downstream reaction region affects liquid vaporization and liquid length recession. We examined this by imaging the reacting (15 and 21% O₂) and non-reacting sprays (0% O₂).

Figure 8 shows the Mie-scatter liquid-phase imaging for the temporal development of the spray shortly after the end of injection (top). Only the ambient oxygen concentration was adjusted to allow reaction as all other injector and ambient conditions were held constant. The Mie-scattered image shows a bright saturated region in the dense part of the spray and decreasing intensity at

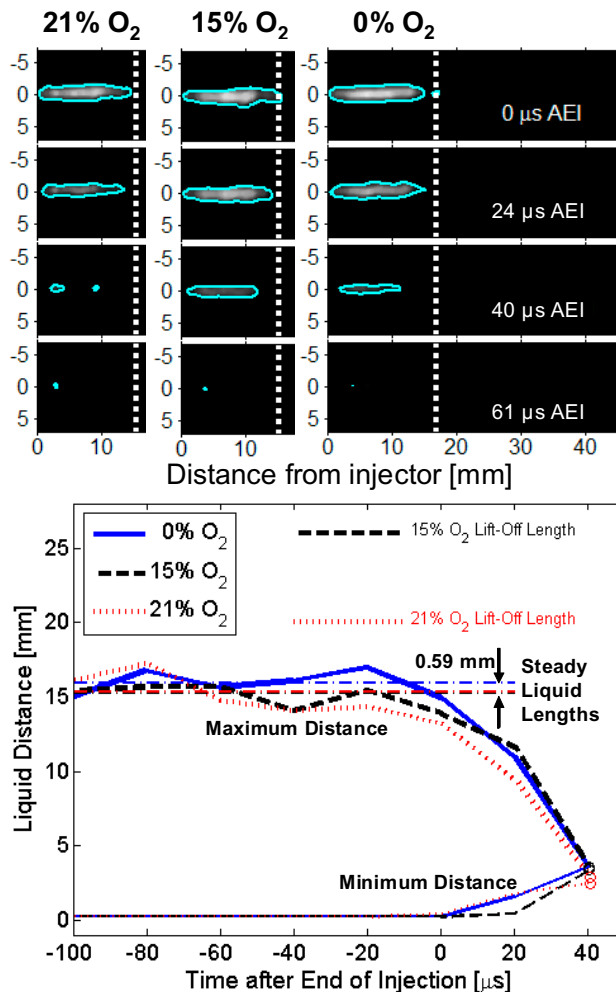


Figure 8 Mie-scatter liquid imaging time sequence AEI (top). The mean quasi-steady liquid length is overlaid as a vertical dashed line. Also shown is the maximum and minimum liquid penetration distances determined from the liquid images (bottom). Ambient Conditions: 900 K, 22.8 kg/m³. Injection Parameters: 94-μm nozzle, 150 - MPa injection pressure.

the tip of the spray. The liquid-phase boundary overlaid on the image (solid lines) is 12/256 intensity counts. The time-averaged “quasi-steady” liquid lengths are shown as a vertical dashed line. As mentioned in the Introduction section, this steady liquid length of typical diesel sprays depends upon the ambient and injection conditions.

A liquid length recession is clearly seen for all oxygen concentrations. This is also evident in a graph of maximum and minimum liquid distances (bottom) which correspond to the liquid boundaries on the upper images. The graph shows that the minimum liquid distance increases after EOI, while the maximum liquid distance decreases. The measured liquid length recession was about 8 mm which was over 50% of the original steady length. As discussed in the Background section, enhanced fuel-ambient mixing after EOI has indeed made the vaporization process complete in a shorter distance from the injector.

The liquid length recessions, however, do not show a difference according to ambient O₂ concentrations at this

particular condition. This was also true for steady liquid lengths shown in the figure. It was likely that the distance from the liquid to the flame lift-off (combustion location) was large enough to isolate the vaporization process from the complex effects of combustion. The locations of combustion (lift-off length)—observed in the shadowgraph images as a strong radial dilation of the jet [18]—were 20 mm for 21% O₂ and 26 mm for 15% O₂. Note that this result may be different for other conditions where there is a shorter distance between the lift-off length and the non-reacting liquid length. However, those conditions are for the conventional regime where the ignition dwell is “negative” and EOI mixing is not as important as in LTC regime. Within the LTC ambient conditions that we varied in this study, the lift-off length was downstream of the liquid length.

Based upon the results in this section, we fixed the ambient O₂ concentration at 0% for later experiments.

Injection Duration

In the previous section, we discussed the liquid length recession only for a long injection duration for which the liquid penetration has a “quasi-steady” length. Short injection durations that may not have steady liquid lengths are also of obvious interest, and it is important to understand the liquid penetration after EOI for this type of injection. Modern diesel engines adopt multiple injections to improve power-output, noise and emissions performance, which tends to shorten the injection duration [19]. In some cases, splits of main injection are utilized at early injection timings to create a well-premixed charge as a method for minimizing liquid spray wall-impingement [20]. Moreover, the LTC regime, which is our primary focus in the present study, is mostly applicable to the low to mid-load conditions with short injections due to its limited power density. The liquid vaporization after EOI for short injection duration, therefore, is important.

To assess this issue, the injection duration was varied at low ambient temperature and density conditions of 600 K and 5.22 kg/m³ as shown in Fig. 9. This low ambient temperature and density condition with long quasi-steady liquid length (83 mm) was selected to create conditions where EOI occurred before the liquid reached the quasi-steady length (“Short Injection”) [21]. Figure 9 shows liquid image time sequences after the start of injection (ASI) for an injection duration of 360 μs (EOI is at 360 μs ASI). The quasi-steady liquid length at the same ambient condition was measured separately and is shown as a vertical dashed line. A graph at the bottom also shows the maximum and minimum liquid distances for three short-injection cases.

For short-injection cases, the maximum liquid distance increases even after EOI, thereby showing no liquid length recession. The increased liquid penetration distance is mainly related to the transient jet penetration, which has yet to reach the steady liquid length. Meanwhile, the minimum liquid distance starts to