

Effects of Injection Pressure, Injection-Rate Shape, and Heat Release on Liquid Length

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ABSTRACT

The in-cylinder extent of liquid-phase fuel penetration (*i.e.*, the liquid length) is an important parameter in combustion-chamber design because liquid lengths that are too long can lead to wall impingement and corresponding degradation of engine efficiency, emissions, and durability. Previous liquid-length measurements in constant-volume combustion chambers have shown that the liquid length is nominally independent of injection pressure, but these measurements have employed common-rail fuel systems where injection rate is approximately constant during the entire injection event, and they have been conducted under quasi-steady ambient thermodynamic conditions. The objective of the current work is to better understand the effects of injection-rate shape and injection pressure on the liquid length, including possible effects of unsteady ambient conditions in an engine. Liquid-length measurements under unsteady, non-reacting in-cylinder conditions have been reported recently, with fuel injected using a hydraulically actuated, electronically controlled unit injector (HEUI) with an unsteady injection rate. In the current work, liquid lengths using the HEUI are compared to those obtained using a common-rail injector, with the same optical setup and engine conditions, at two injection pressures. To ensure that the effects of injection rate and injection pressure are not unique to a specific fuel, measurements were made using both 2,2,4,4,6,8,8-heptamethylnonane and an ultra-low-sulfur #2 diesel fuel. To ensure minimal effects of chemical heat release, all data were acquired under essentially non-reacting conditions. Injection pressure and injection-rate shape were found to have essentially no effect on liquid length for both fuels, suggesting that results can be compared between experiments with different injection systems. In addition, the effect of heat release was evaluated using the common-rail injector by comparing liquid-length measurements obtained under non-reacting conditions to those obtained under partially reacting conditions. Results showed that combustion heat release shortens liquid length, and that the magnitude of the effect is consistent with entrainment of higher-temperature and higher-density gases due to global compressive heating.

CITATION: Fisher, B. and Mueller, C., "Effects of Injection Pressure, Injection-Rate Shape, and Heat Release on Liquid Length," *SAE Int. J. Engines* 5(2):2012, doi:10.4271/2012-01-0463.

INTRODUCTION

Liquid-phase fuel penetration during injection in an engine is important, as wall-wetting from liquid-fuel impingement can lead to reduced combustion efficiency, higher emissions of unburned hydrocarbons and carbon monoxide, and lube-oil dilution [1,2,3,4,5,6,7,8,9,10,11,12]. Fuel films resulting from liquid-fuel impingement can also ignite to form pool fires, which previous work has shown can contribute to higher levels of soot and nitrogen-oxide emissions [4,13]. These issues are of particular concern with the advent of low-temperature combustion (LTC) strategies aimed at higher efficiencies and lower emissions of nitrogen oxides and particulate matter, many of which involve injection of fuel early in the compression stroke when in-cylinder temperatures and densities are low [1,2,3,4,13,14,15,16,17,18,19,20,21,22].

The bulk of previous work characterizing liquid-phase fuel penetration has been done under steady ambient conditions in constant-volume chambers [23,24,25,26,27,28,29,30,31,32] and in engines for near-TDC injection timings, for which in-cylinder temperatures and densities are high and relatively steady [33,34,35,36,37,38,39,40,41]. Most of this previous work was done using common-rail (CR) injectors with relatively steady delivery of fuel, as indicated by "top hat" injection-rate profiles. In a landmark paper, Siebers described the development of a non-dimensional scaling law, based on the assumption of one-dimensional mixing-limited vaporization, that related liquid-phase penetration to injector parameters (*e.g.*, orifice size), fuel properties (*e.g.*, density, volatility), and ambient thermodynamic properties (*e.g.*, temperature, density) [42]. The Siebers scaling relation predicts steady

liquid penetration lengths for a variety of fuels under a wide range of conditions, though it notably displays lower accuracy at lower ambient temperatures and densities [42].

Recent work has been devoted to the measurement of liquid-phase fuel penetration (*i.e.*, liquid length) under unsteady in-cylinder conditions in an optical diesel engine [43,44]. These studies complemented the earlier work and took the measurements a step further by studying injection timings ranging from well before to well after TDC (top dead center) of the compression stroke. Interestingly, these studies concluded that liquid lengths under unsteady in-cylinder conditions were reasonably predicted by applying Siebers' scaling relation [42] (developed for steady liquid lengths) using instantaneous estimates of temperature and density at each crank angle [43,44]. One of the issues with these studies, however, was that the measurements were done using a hydraulically actuated, electronically controlled unit injector (HEUI). The injection-rate profile and delivery of fuel were much less steady with the HEUI than for typical CR injectors. It is not known how large a role the injection-rate shape plays in the determination of liquid length, as it has not been studied explicitly. In addition, the effect of combustion-related heat release on liquid length has also not been characterized. Typically, measurements of liquid length in constant-volume chambers are done under non-reacting conditions. Many of the engine-based studies of liquid length have involved reacting conditions, but few if any have addressed explicitly the effect of heat release on the liquid length.

In the current study, measurements of liquid length were made under unsteady in-cylinder conditions in an optical diesel engine using a common-rail injector. Measurements were made under non-reacting conditions for two fuels at two different injection pressures. The purpose of this was to compare with measurements made using a HEUI [43,44], to determine the effects of injection pressure and injection-rate shape on liquid length. Measurements were also made under partially reacting conditions, to compare with those made under non-reacting conditions and thus to determine the effect of heat release on liquid length. These results have implications regarding the comparability of liquid-length measurements in different facilities with different injection systems and regarding the applicability of non-reacting liquid-length measurements to conditions that include combustion and heat release.

EXPERIMENTAL SETUP

ENGINE

The engine used in this study is referred to as the Sandia compression-ignition optical research engine (SCORE). The primary engine specifications are listed in Table 1 and a schematic of the engine and the imaging setup are shown in Fig. 1. The SCORE is a single-cylinder version of a Caterpillar heavy-duty engine that has been modified to provide extensive optical access to the combustion chamber.

The piston bowl of the SCORE has a flat bottom and vertical side walls (*i.e.*, right-cylinder shape), rather than the contoured shape commonly found in production engines. In addition, the piston rings are positioned lower on the SCORE piston for optical access and to prevent the rings from riding over the optical cylinder-wall windows. In this configuration, the SCORE has a geometric compression ratio of 12.3:1, which is lower than for a typical production engine because the modifications necessary for optical access result in a larger clearance volume. By heating and boosting the intake-charge gas, however, in-cylinder conditions can be closely matched to those in a higher-compression-ratio production engine over a wide crank-angle range of interest (see Appendix A of [43]).

Table 1. Sandia compression-ignition optical research engine (SCORE) specifications.

Engine type	Single cylinder
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore × Stroke	125 mm × 140 mm
Intake valve open ^a	32° BTDC exhaust
Intake valve close ^a	153° BTDC comp
Exhaust valve open ^a	116° ATDC comp
Exhaust valve close ^a	11° ATDC exhaust
Connecting-rod length	225 mm
Connecting-rod offset	None
Piston-bowl diameter	90 mm
Piston-bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Displacement	1.72 liters
Geometric comp ratio	12.3:1

^aAll valve timings are for lift $\cong 0.03$ mm.

Although the engine configuration was basically the same in this work as in the authors' previous studies of liquid length, the specific engine build was slightly different. A different cylinder head was used to accommodate the new common-rail injector and associated high-pressure fuel system. This resulted in a slightly larger apparent clearance volume, as evidenced by slightly lower peak cylinder pressures for identical intake conditions, and therefore a slightly lower geometric compression ratio in this study (12.26:1 rather than 12.34:1). The consequences of this, in terms of estimated in-cylinder conditions and expected liquid lengths, are addressed in the Results section.

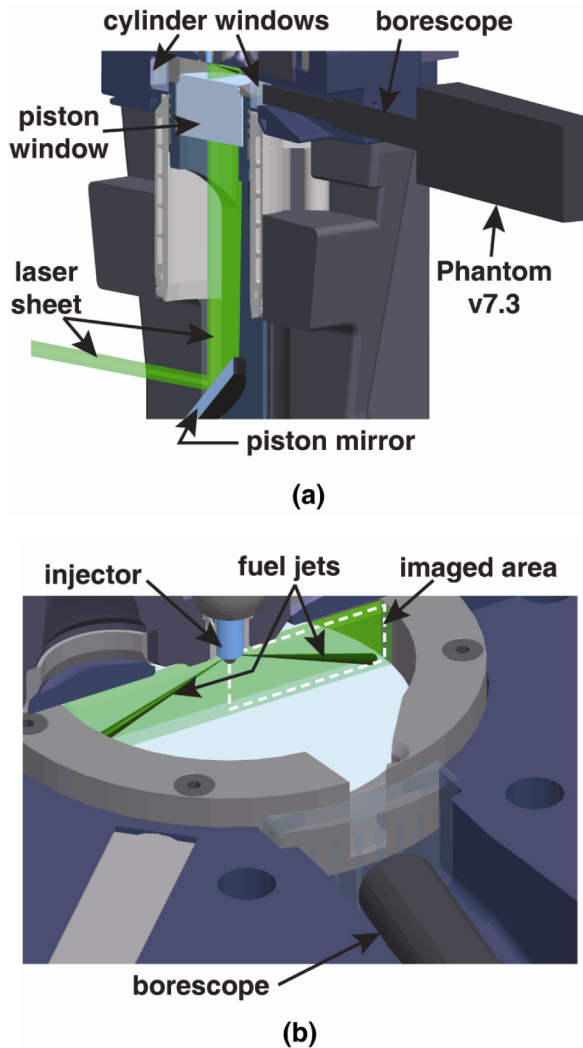


Figure 1. Schematics of the Sandia compression-ignition optical research engine (SCORE) and imaging setup as configured for measuring liquid length. The cutaway overview (a) shows how a laser sheet is directed via the piston mirror through the piston window into the combustion chamber and is aligned in the plane of the fuel jets. The close-up view (b) shows how a notch in the piston bowl-rim enables optical access to the piston bowl when the piston is near TDC.

INJECTOR AND FUEL SYSTEM

The high-pressure fuel-injection system used in the current study consists of a diaphragm pump (Model 46-16060, Newport Scientific Inc., Jessup, MD) and an electronically actuated solenoid-operated common-rail (CR) fuel injector. The pump is capable of producing fuel pressures of ~ 300 MPa, though liquid lengths were measured in the current study for fuel pressures considerably lower than this level. As mentioned above, one of the primary purposes of this study was to compare liquid lengths measured using the current common-rail fuel-injection system to those measured

using a HEUI. A summary of the main parameters of interest for both fuel-injection systems is included in Table 2. As shown, the same injector-tip type and geometry, and similar orifice size, were used in both fuel-injection systems. Fuel pressure in the rail of the CR system was measured using a piezoresistive pressure transducer (Model 4067A5000, Kistler Instrument Corp., Winterthur, Switzerland). Fuel pressure in the HEUI was set by the intensification ratio of the intensifier piston in the injector and the PID-controlled pressure of the oil supplied to the large-diameter side of the intensifier piston. For the purposes of this paper, the generic term “injection pressure” is used to represent the fuel pressure in the *rail* of the CR system and the fuel pressure in the *injector* of the HEUI system.

Table 2. Fuel-injection system specifications.

	<i>HEUI</i>	<i>CR injector</i>
Injector model	CAT HIA-450	CAT CR-350
Orifice type	Minisac	Minisac
# of orifices	2	2
Orifice size	108 μm	105 μm
Included angle	140°	140°
Inj. press (low)	71 MPa (max)	75 MPa (steady)
Inj. press (high)	142 MPa (max)	142 MPa (steady)

Liquid lengths were measured for two fuels. One was 2,2,4,4,6,8,8-heptamethylnonane (HMN; Item #128511, Sigma-Aldrich, St. Louis, MO), a highly branched diesel primary reference fuel with volatility similar to diesel fuel but with low reactivity. The other was a 2007 ultra-low-sulfur #2 diesel (ULSD) certification fuel (from Chevron-Phillips Chemical Company, The Woodlands, TX, USA).

The primary difference between the CR and HEUI fuel systems is the temporal profile of the injection rate. Average injection-rate traces (per orifice) for HMN and ULSD using both fuel-injection systems are shown in Fig. 2. Data for both of the studied fuel pressures (~ 75 MPa and ~ 142 MPa) are included. Injection rate was measured and quantified using a method described in detail in [45]. In addition to the overall unsteadiness of the HEUI injection-rate profiles, there is a peculiarity for ULSD at the lower injection-pressure level (71-MPa max) as shown in Fig. 2b. The reason for the double-peak shape is not known, though it was shown previously to have minimal if any effect on liquid length for ULSD and two biodiesel fuels [44]. The stark difference between the “top-hat” profile of the common-rail system and the highly time-varying profile of the HEUI system was a driving force for this study. In particular, the authors were interested in comparing liquid lengths near the end of injection (EOI), where instantaneous injection rates tend to be considerably higher for the CR injector than for the HEUI. For reference, injected-quantity values for all conditions are shown in Table 3. Since these experiments did not focus on engine performance or emissions, it was not necessary to keep fueling constant for any reason. The objectives of this

work were better achieved by matching injection pressure and injection duration as closely as possible.

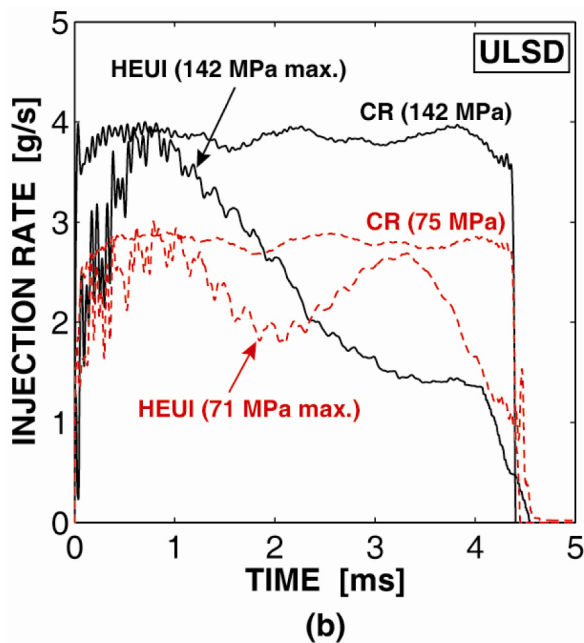
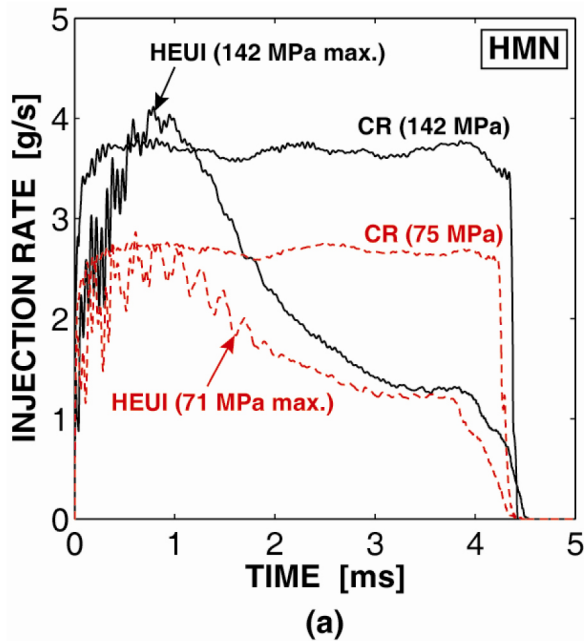


Figure 2. Comparison of injection-rate profiles (per orifice) for the HEUI and the common-rail injector for (a) HMN and (b) ULSD.

Table 3. Injected quantity.

		(mg/injection)	
		HMN	ULSD
Low inj. press	HEUI	14.31	19.77
	Common rail	22.78	24.47
High inj. press	HEUI	19.52	20.32
	Common rail	31.93	33.61

OPERATING CONDITIONS

Operating conditions for the liquid-length experiments are listed in Table 4. The optical engine was operated at a constant speed of 1500 rpm with fuel injected on every 15th cycle, with a maximum of 50 fired cycles per engine run. In the context of this work, the term “fired” describes cycles during which fuel was injected, regardless of whether or not combustion took place. To simulate a higher compression ratio more typical of heavy-duty production engines, the intake-gas mixture supplied to the optical engine was heated and boosted. As shown in Table 4, the coolant and intake-manifold temperatures were both controlled to 80°C and the intake manifold absolute pressure (IMAP) was 1.65 bar.

The SCORE intake pressure and temperature are identical to those used for previous measurements of liquid length for HMN and ULSD, which were shown to produce temperature and density histories that match those that would result from realistic intake and speed conditions in a typical heavy-duty production engine [43]. HMN, with a cetane number of 15 [46], has such low reactivity that there was no discernible chemical heat release (*i.e.*, combustion) even in normal air (21 mol% O₂). ULSD, with a cetane number of ~45 [47], is much more reactive and required intake-mixture dilution to avoid combustion. As shown in Table 4, an intake-O₂ mole fraction of 4 mol% was achieved by mixing, on a molar basis, 19% dry house air, 79.5% nitrogen (N₂), and 1.5% carbon dioxide (CO₂). In addition to suppressing combustion, the diluted intake mixture was also designed to match closely the specific heat of air during the cycle. As shown in previous experiments with ULSD and biodiesel fuels, this goal was achieved [44].

Table 4. Operating conditions for non-reacting liquid-length measurements.

Speed	1500 rpm
Intake mixture –	
HMN	21 mol% O ₂
ULSD	4 mol% O ₂
Intake manifold pressure	1.65 bar
Intake manifold temperature	80°C
Coolant temperature	80°C
Start of injection –	
HMN	–60 to +20° ATDC
ULSD	–50 to +10° ATDC
Duration of injection	~4.5 ms (~41 CAD)

Start-of-injection (SOI) timings ranged from -60 CAD to $+20$ CAD (crank-angle degrees), in equal increments of 20 CAD, for HMN. The lower volatility of ULSD, however, made it impossible to avoid wall impingement at the earliest and latest SOI timings. Therefore, SOI timings for ULSD were -50 , -40 , -20 , 0 , and $+10$ CAD. In the context of this work, TDC of the compression stroke is represented as 0 CAD (e.g., -20 CAD = 20 CAD before TDC). Listed SOI timings, which are nominal values that may vary up to ± 0.2 CAD for different cases, refer to the actual start of injection (i.e., the point at which fuel actually begins to enter the combustion chamber). Duration of injection (DOI) was approximately $4500 \mu\text{s}$ (~ 41 CAD) for all SOI timings, which meant that there was overlap between successive injection-timing windows.

In addition to the non-reacting experiments, liquid lengths were also measured for partially reacting conditions to assess the effect of heat release on liquid length. For these experiments, the oxygen concentration of the intake mixture was raised to levels high enough to produce clear heat-release signatures in the cylinder-pressure data, but low enough to allow a useful measurement of liquid length. If oxygen concentration was raised too high and significant combustion occurred, natural luminosity (presumably from soot incandescence [48]) and liquid-fuel scattering became indistinguishable because a spectral filter was not in place to separate these two different sources of signal. The optimal intake dilution was dependent on SOI timing, and results were only considered in cases for which heat release actually occurred during fuel injection.

All liquid-length measurements presented in this paper are averages of several replicates (typically ≥ 10). As in the authors' previous work, the standard deviation of the liquid-length measurements was no more than $\pm 10\%$ for each case [43,44].

DIAGNOSTICS

Pressure Measurements

Cylinder-pressure data were acquired at 0.5 -CAD resolution using a flush-mounted, water-cooled quartz piezoelectric transducer (Model QC32C, AVL, Plymouth, MI). For each skip-fired sequence, pressure data were acquired during one of the motored cycles in addition to during the fired cycle. Pressure data provide information about heat release and temperature that can be very important in interpreting liquid-length measurements. Further details of the cylinder-pressure data acquisition system and its utilization in the SCORE are available in [1,48,49].

Optical Measurements

The high-speed spray-visualization system and its layout with respect to the engine are depicted in Fig. 1. As in previous studies by the authors, liquid-phase fuel penetration (i.e., liquid length) was determined via elastic scattering of laser light by liquid fuel droplets. Illumination of the spray

was provided by a 532 -nm, 50 -kHz pulsed Nd:YAG laser (Model LDP-100MQG, Lee Laser Inc., Orlando, FL) with a pulse width of $\sim 0.5 \mu\text{s}$. The collection system consisted of a Phantom v7.3 high-speed CMOS camera (Vision Research Inc., Wayne, NJ) equipped with a 20 -mm-diameter variable-focal-length borescope (Abakus Ltd., UK) with a nominal 115° field of view. Spray-visualization images were acquired at 50 kHz, equivalent to ~ 0.2 -CAD resolution at 1500 rpm. During fuel injection, the cylinder-pressure data-acquisition system was used to sample a linear voltage ramp (0 - 10 V, 12 -ms duration) from a function generator at 0.5 -CAD intervals. This enabled conversion from time to crank angle for the time-based spray-visualization images.

The 532 -nm laser beam was formed into a sheet and directed into the combustion chamber from below through a window in the base of the piston bowl, aligned in the same plane as the two diametrically opposed fuel jets. Light scattered from liquid fuel droplets in one of the jets was collected through a window in the cylinder wall, with the notch in the bowl rim allowing unobstructed access to the bowl. The laser sheet was relatively thick (~ 5 mm) and spanned the entire width of the piston bowl, providing confidence that the maximum liquid penetration distance was measured. The camera was positioned such that the field of view stretched from slightly left of the injector tip to the right vertical wall of the piston bowl. Acquired images were distorted due to the curved cylinder-wall window and the wide-angle borescope lens, and required geometric correction. The spatial resolution of the corrected images was approximately 0.37 mm/pixel. In addition to geometric distortion, acquired images were also corrected for non-uniformities in the laser sheet intensity profile and in the collection efficiency of the imaging system. This correction dictated a maximum measurable liquid length of ~ 45 mm in these experiments. Details of the correction procedures are included in a previous study [43].

The scattering signal was strong, such that it was possible to keep the attenuating aperture of the borescope lens in the most closed position to provide the best depth-of-field. In previous work, the authors have shown that the measured liquid length is relatively insensitive to signal level, provided that the maximum measured signal in the raw images is ~ 50 - 75% of full scale and an appropriate black reference is used [43]. After application of the corrections described above, liquid length was determined along the spray axis using a fixed threshold intensity. The authors' previous work has shown that under these experimental conditions, liquid length becomes nearly independent of threshold intensity when the threshold is $\leq 2\%$ of full scale [43].