

The Impact of Fuel Mass, Injection Pressure, Ambient Temperature, and Swirl Ratio on the Mixture Preparation of a Pilot Injection

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ABSTRACT

Fuel tracer-based planar laser-induced fluorescence is used to investigate the vaporization and mixing behavior of pilot injections for variations in pilot mass of 1-4 mg, and for two injection pressures, two near-TDC ambient temperatures, and two swirl ratios. The fluorescent tracer employed, 1-methylnaphthalene, permits a mixture of the diesel primary reference fuels, *n*-hexadecane and heptamethylnonane, to be used as the base fuel.

With a near-TDC injection timing of -15°CA , pilot injection fuel is found to penetrate to the bowl rim wall for even the smallest injection quantity, where it rapidly forms fuel-lean mixture. With increased pilot mass, there is greater penetration and fuel-rich mixtures persist well beyond the expected pilot ignition delay period. Significant jet-to-jet variations in fuel distribution due to differences in the individual jet trajectories (included angle) are also observed. Increased injection pressure significantly increased the mixing rate, leading to leaner mixture distributions, and with lower ambient temperature modestly richer mixtures are found near the heads of the jets. Discrete droplets near the injector were unexpectedly found to be more common at the higher ambient temperature. Lastly, increased swirl displaces the fuel to locations lower in the bowl, while generating a greater amount of over-lean mixture in the upper-central region of the combustion chamber.

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INTRODUCTION

Pilot injection strategies are widely employed in automotive diesel engines to reduce the ignition delay of the main combustion, and hence to reduce the pressure rise rate [1, 2, 3, 4] and part-load HC and CO emissions (e.g. [1, 4]). Moreover, a well-optimized pilot injection strategy can significantly improve low-load fuel economy [2, 5]. On the other hand, pilot injections are usually associated with increased soot emissions [1, 2, 3, 4, 6, 7], and tend to increase NO_x emissions unless the pilot injection is quite advanced [1, 4].

However, with the advent of low temperature combustion (LTC) strategies employing lower compression ratios, nonconventional injection timings, and higher rates of

recirculated exhaust gases (EGR), traditional pilot injection strategies become difficult to apply. With small pilot quantities, low-temperatures, or high-dilution, the pilot injection can fail to ignite [8, 9, 10, 11, 12, 13]. To overcome this difficulty, the pilot injection quantity may need to be significantly increased [9, 14, 15, 16]. Moreover, a careful matching of pilot-main delay times to swirl level has been found beneficial to obtain the lowest possible pressure rise rate [17].

Despite the problems encountered applying pilot injections to LTC strategies, there are compelling reasons to adopt them. The primary advantages of LTC are very low soot and NO_x emissions, whilst the main disadvantages are increased combustion noise and light-load HC and CO emissions. Accordingly, the advantages of pilot injections

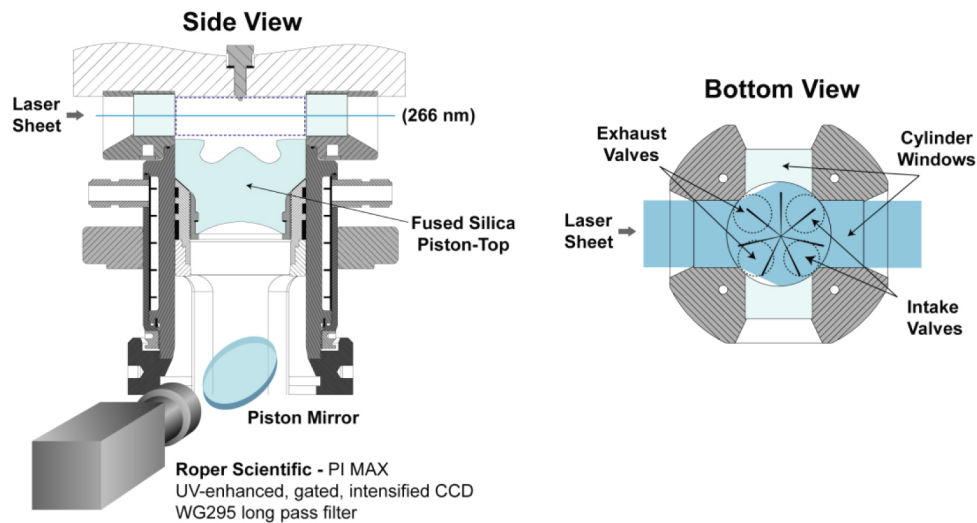


Figure 1. Schematic of the optically accessible diesel engine depicting the location of the laser sheet and camera viewing orientation

compensate for the disadvantages of LTC strategies, and an appropriate adaptation and application of pilot injection strategies to LTC may yield significant benefits.

In this work we seek to clarify the mixture formation process of pilot injections, as a first step toward developing a better understanding of how to best adapt pilot injection techniques to LTC strategies. Because several studies cited above indicate a need for larger pilot injection quantities in order to obtain pilot ignition or stable engine operation, we first examine the impact of pilot injection quantity on the mixture preparation process. Secondly, due to the well-documented advantages of increased injection pressure in mitigating the increases in soot observed when pilot injections are employed (e.g. [2, 18]), and the authors' experience that increased injection pressure exacerbates difficulties with pilot ignition, we examine the mixture preparation process for two different injection pressures typical of light load operating conditions where pilot injection are commonly used: 500 and 860 bar. Thirdly, because we anticipate that the thermal energy content of the ambient charge will impact the rate of liquid vaporization and hence the mechanisms of momentum transfer between the fuel and the ambient charge, we examine the impact of ambient temperature on the mixture preparation process at constant ambient density and injection pressure. Finally, to examine the impact of swirl on both the turbulent mixing and the bulk transport of the pilot fuel, we compare the mixture preparation process at the base engine swirl ratio of 2.2 and at a higher swirl ratio of 4.5.

An additional distinct feature of this study is the use of a new fuel tracer based planar laser-induced fluorescence (PLIF) technique. This technique, which employs 1-methylnaphthalene as a tracer in a mixture of the diesel primary reference fuels, $n\text{-C}_{16}\text{H}_{34}$ and 2,2,4,4,6,8,8-heptamethylnonane (also known as *iso*-cetane), allows the

physical properties of a standard diesel fuel to be more closely matched by the surrogate fuel mixture. In particular, the fuel volatility and density, properties which affect the fuel jet vaporization and entrainment, are much more closely matched than when a PLIF measurement of a toluene/ $n\text{-H}_7\text{C}_{16}/\text{iso-C}_8\text{H}_{18}$ fuel blend is used (e.g. [19]). This technique is a clear step forward in our ability to quantitatively measure in-cylinder fuel-air ratio distributions in diesel engines, particularly under LTC conditions where we anticipate that fuel vaporization processes can be greatly slowed.

Table 1. Engine and injection system specifications and operating conditions employed for the imaging studies

Engine Geometry

Bore [mm]	82.0
Stroke [mm]	90.4
Displacement Vol. [L]	0.477
Geometric CR	16.7
Squish Height [mm]	0.88

Injection Parameters

Injector	Bosch CRI2.2
Sac Type	Mini Sac
Sac Volume	0.23 mm ³
Holes	7
Nozzle Diameter	0.14 mm
Hole Geometry	KS1.5/86
Included Angle	149°
Rail Pressure [bar]	500 & 860
Start-of-Injection [°CA aTDC]	-15
Injected Mass [mg]	1, 2, 3, 4

EXPERIMENT

Engine

The engine used in this study was modified from a 1.9 L GM light-duty diesel engine to provide extensive optical access to the combustion chamber. The main geometric specifications are provided in [Table 1](#) and a schematic of the engine is shown in [Fig. 1](#). The engine features a Bowditch-style piston that has a fused silica piston-top featuring a re-entrant bowl and valve cutouts in the piston top typical of production pistons. Optical access through the sides of the combustion chamber is achieved through fused silica windows (50 mm wide by 25 mm tall) located at the top of the cylinder liner. These windows are positioned to allow unobstructed optical access up to the clearance volume, even when the piston is located at top dead center (TDC).

The swirl ratio of the in-cylinder flow can be adjusted via throttle plates located in each of the two intake ports. With both throttle plates in the fully open position, the swirl ratio is 2.2. Throttling the low-swirl, helical port allows the swirl ratio to be increased to approximately 5.5. The engine is also equipped with a Kistler 6125b pressure transducer mounted in the location of the production engine glow plug, and the in-cylinder pressure is acquired every 0.25° crank angle (CA).

The main geometric modification made to the optical design was an increase in the height of the top ring-land to allow imaging within the bowl portion of the piston. Accounting for a small increase in the crevice width, the resulting ring-land crevice volume is roughly 3-4 times larger than a production diesel engine. Two gapless compression rings were used to minimize blowby. Despite the larger crevice volume and potentially increased wall temperatures of the fused silica surfaces, the optical engine, running in a skip-fired mode, has been shown to reproduce the emissions and combustion behavior of a similar all-metal engine very well [20].

The fuel injector used in this study was a Bosch CRI2.2 high pressure, electronically controlled, common-rail injector. The injector was equipped with a 7-hole, mini-sac nozzle with an included angle of 149°. The 7 fuel orifices are equally spaced and have a nominal diameter of 0.14 mm. Additional specifications for the fuel injector are also included in [Table 1](#).

Operating Conditions and Procedure

For all measurements presented in this study, the engine was operated at 1500 RPM with a fixed “pilot” start-of-injection (SOI) of -15°CA aTDC; there was no subsequent main injection. As a first-step, to determine the crank angles appropriate for imaging of the pilot injection mixture preparation process, pressure measurements characterizing the combustion of a pilot injection were performed at a variety of charge O₂ concentrations, obtained by diluting the intake charge with N₂ and CO₂. These measurements were performed at the same conditions in terms of charge density

([Table 2](#)). In-cylinder temperatures were estimated from 1-D transient simulations of the induction and compression stroke using a commercial code (GT-Power). The near-TDC temperature, averaged between -15° and TDC, varied due to changes in the intake temperature and in the specific heat ratio of the charge. The average temperatures are also shown in [Table 2](#). The pilot combustion experiments were conducted with a swirl ratio of 2.2, using a cetane number 47, US #2 diesel fuel.

Table 2. Operating Conditions

General Operating Conditions

Engine Speed [RPM]	1500
Avg Temp. (SOI – TDC) [K]	850, 930
Peak near-TDC Density [kg/m ³]	21.1
Avg Density (SOI – TDC) [kg/m ³]	19.6
Swirl ratios (Ricardo)	2.2, 4.5

Avg. Temperature with Pilot Combustion

Intake Temp	10% O ₂	12% O ₂	14% O ₂	16% O ₂	18% O ₂
30°C	813 K	820 K	828 K	833 K	841 K
50°C	838 K	845 K	851 K	858 K	866 K
90°C	883 K	890 K	899 K	906 K	915 K
130°C	928 K	936 K	944 K	952 K	961 K

Fuel for Combustion Experiments

US #2 Diesel – CN 47

Avg. Temperature for Imaging Experiments

Intake Temp	0% O ₂ (100% N ₂)
27°C	850 K
108°C	930 K

Fuel for imaging experiments

42 % <i>n</i> -C ₁₆ H ₃₄ ; 58 % heptamethylnonane
0.5 vol% 1-methylnaphthalene tracer

Because the tracer fluorescence is strongly quenched by O₂, for the imaging studies the engine was operated with a pure nitrogen intake stream and combustion did not occur. Two different intake temperatures were employed, 27° C and 108°C (300 and 381 K), which resulted in average temperatures between SOI and TDC of 850 and 930 K. These temperatures are typical of low-compression ratio, low-temperature combustion systems and conventional diesel combustion systems, respectively, and are representative of the lower and higher range of average near-TDC temperatures tested with combustion.

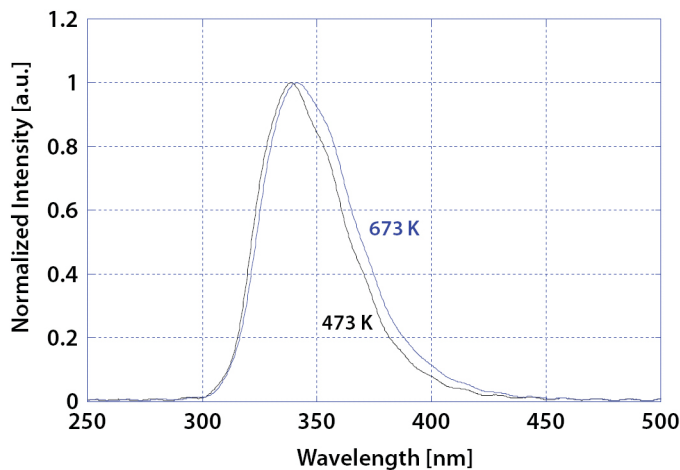


Figure 2. Spectra of fluorescent emissions of 1-methylnaphthalene measured at 10 bar and two temperatures

For the imaging studies, the base fuel used was a blend of 42% $n\text{-C}_{16}\text{H}_{34}$ and 58% heptamethylnonane by volume. To this blend, an additional 0.5 volume percent of the tracer molecule, 1-methylnaphthalene, was added. The two diesel primary reference fuels were used to ensure that the fuel fluorescence from the tracer molecule was the dominant source of fluorescent emissions, as discussed in the next section. With this fuel, the ignition and combustion behavior of a typical cetane number $CN\ 47$ US diesel fuel was matched closely, though the nominal CN for this blend, calculated from the relationship provided by Heywood [21], is 50.7.

To maintain a consistent state of the engine for all measurements, a strict eight and one half minute measurement schedule was followed. Measurements at each crank angle were obtained using the following procedure:

- The engine was initially motored for 75 seconds to stabilize the intake plenum pressure.
- To enable synchronization with the 10 Hz laser, fuel was injected at a rate of 2.5 Hz, corresponding to one out of every five cycles. Fuel was first injected in 9 small injections during the intake stroke to create a homogeneous mixture. 50 flat-field calibration images were then obtained, one from each of 50 fueled cycles.
- The fueling was disabled, and two minutes into the schedule 50 background images were obtained with the laser firing.
- Fuel for the pilot injection to be studied was enabled 2:40 minutes into the schedule, and 50 data images were acquired along with the cylinder pressure trace between 3:00 and 3:20.
- The engine was stopped and allowed to cool for the remainder of the schedule. During this period, any accumulation of fuel films or other deposits were cleaned from the optical and cylinder head surfaces before beginning the next image acquisition cycle.

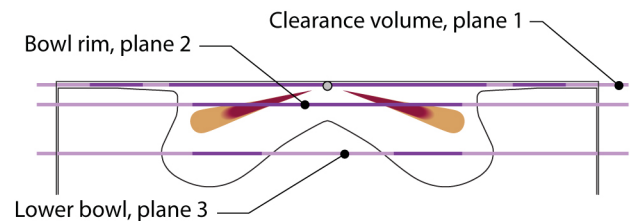


Figure 3. Location of the PLIF measurement planes. Darkened portions of the laser sheets correspond to visualized regions

Diagnostic and Data Analysis

Experimental details

PLIF images of fluorescent emissions from the tracer molecules are acquired in the plane of a horizontal laser sheet entering the engine from the exhaust side, as shown in Fig. 1. The fluorescence was excited by the 266 nm (UV) output of a 10-Hz pulsed Nd:YAG laser, with a pulse energy of 30 mJ. The laser sheet thickness was approximately 0.5 mm across the cylinder bore. A UV-enhanced, gated, intensified charge-coupled device (ICCD) camera (Roper Scientific PI-Max), equipped with a 105-mm focal length $f/4.5$ UV Nikkor lens, captured the tracer fluorescence, which occurs in the wavelength range of 300–450 nm (Figure 2). Similar spectra are reported at atmospheric pressure in [22]. The intensifier gate width was set to 250 ns and a fixed intensifier gain was used for all crank angles. A WG295 long-wave-pass filter was placed in front of the camera to reject elastically scattered 266-nm laser light. Following the procedure described above, a set of 50 images, acquired in 50 separate cycles, was collected for each plane at each measurement location and crank angle. The laser energy was monitored and recorded for each image with a Coherent model J-25MB-LE energy sensor to permit quantitative data reduction.

Measurement locations and crank angles

At each operating condition and for each pilot injection quantity, measurements were made every 2.0°CA , in the range from -12°CA to TDC. With $\text{SOI} = -15^\circ\text{CA}$, this corresponds to a pilot ignition delay period of 15°CA .

The measurements were made in three different planes, which are shown in Figure 3. The upper plane was selected to bisect the clearance volume, and the locations of the two lower planes were fixed with respect to the piston bowl. The vertical position of these planes thus varied with crank angle. However, in the crank angle range considered, the piston moves only 1.8 mm, and for practical purposes the planes can be regarded as fixed in space at the approximate locations shown in Figure 3. Note that in the lower bowl plane (plane 3), the bowl wall acts as a negative lens and increases the thickness of the laser sheet. Portions of the laser sheet entering the bowl along the cylinder diameter increase in

thickness by approximately 1.25 mm by the time they strike the bowl pip.

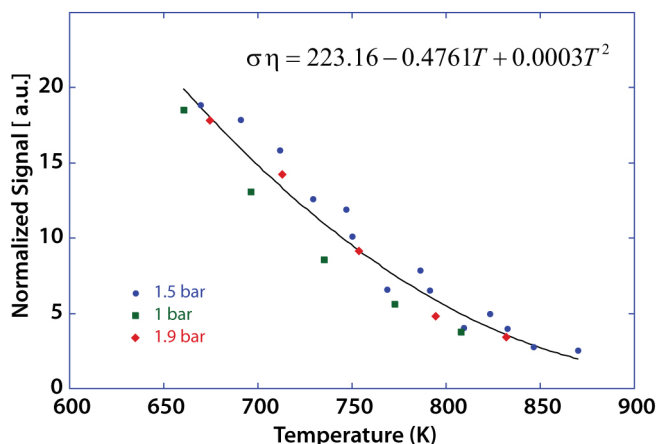


Figure 4. Normalized fluorescence signal per molecule per unit laser energy measured for various ambient temperatures and intake pressures

In the upper measurement plane (plane 1), fluorescent emissions could not be collected from all spatial locations due to reflection and extreme refraction of light from piston surfaces near the re-entrant portion of the bowl. Likewise, the radial extent of the images in plane 1 extends to only 5 mm from the cylinder wall. Regions of the laser sheet where fluorescence emissions were visible and interference was minimal are denoted by the darker portions of the laser sheets shown in Figure 3. In the uppermost plane the laser sheet is also blocked by the injector tip and measurements could not be made in the shadow of the injector tip. In plane 2, measurements are available for $r < 20.2$ mm (2.4 mm from the piston bowl rim) and in plane 3 measurements were obtained for $10 < r < 20.2$ mm, or within approximately 4.9 mm of the bowl periphery and 1.9 mm of the inner bowl pip. Like plane 1, measurements could not be made in portions of plane 3 because the laser sheet was blocked by the bowl pip.

Data analysis

The fluorescence data were converted to quantitative equivalence ratio values using the method described in [23]. The raw fluorescence images were first corrected by normalizing by laser power and then subtracting the average, normalized background image acquired just prior to the data images - resulting in a data image intensity S_d at each pixel. The resulting image is then referenced against the average, background-corrected, normalized flat-field calibration image intensity S_{cal} acquired with a homogeneous in-cylinder mixture just prior to the background images. Additional details and example images are presented in the Appendix.

The known fuel mole fraction $\chi_{fuel, cal}$ in the calibration image is then used to determine the fuel mole fraction $\chi_{fuel, d}$ associated with each pixel in the data image:

$$\chi_{fuel, d} = \chi_{fuel, cal} \frac{S_d}{S_{cal}} \frac{E_{cal}}{E_d} \frac{T_d}{T_{cal}} \frac{P_{cal}}{P_d} \frac{\sigma(T_{cal})}{\sigma(T_d)} \frac{\eta(T_{cal})}{\eta(T_d)} \quad (1)$$

Eq.(1) uses the measured pressure, a calculated temperature, and laser energy corrections (E) to account for the differences in thermodynamic conditions and laser energy between the raw data and the calibration images. Variability in the product of the tracer molecule absorption cross section σ and the quantum yield η is also considered. The temperature and pressure dependency of $\sigma\eta$ was examined using an *in situ* calibration procedure, wherein measurements are obtained in a homogeneous mixture of known χ_{fuel} at various temperatures and pressures. The homogeneous mixture is generated using the same 9 injection sequence during the intake stroke described previously. For the calibration data obtained, no systematic pressure dependency of the signal is observed, and the results are reduced to provide a relation for $\sigma\eta$ as a function of temperature alone (Figure 4).

Because the local temperature T_d is required in Eq.(1), and the local temperature is a function of the local equivalence ratio, Eq.(1) must be solved iteratively for $\chi_{fuel, d}$. Accordingly, we start with T_d assumed equal to the ambient charge temperature to obtain an initial estimate for $\chi_{fuel, d}$. This estimate is then used to calculate an adiabatic mixture temperature achieved when liquid fuel at 90°C is vaporized and mixed with the ambient charge, providing a new estimate for T_d . The process is repeated until convergence is achieved.

Finally, the fuel mole fraction can be related to the fuel/air equivalence ratio. Stoichiometric combustion of 1 mole of $C_{16}H_{34}$ requires 24.5 moles of O_2 . Consequently, dilute mixtures require $24.5/\chi_{O_2}$ moles of charge, and the equivalence ratio ϕ of a dilute charge can be related to the mole fraction of fuel through:

$$\phi = \frac{\chi_{fuel, d}}{(1 - \chi_{fuel, d})} \cdot \frac{24.5}{\chi_{O_2}} \quad (2)$$

In what follows, we report the measured fuel mole fraction for a mixture with 14% O_2 , typical of a high-EGR, light-load operating condition. The results can readily be scaled to any other χ_{O_2} using Eq.(2).

The images were also corrected for the optical distortion generated by the highly-curved surfaces of the optical piston. The correction was based on a mapping created from a distorted image of a calibration grid. Regions of the images where no correction could be made due to extreme optical distortion (above the re-entrant portion of the bowl), near-wall interferences, or lack of illumination (in the “shadow” of the injector tip) were masked.

Errors and interferences

There are three principal sources of systematic interference in the measurements that cannot be removed by