

# Measurement of Equivalence Ratio in a Light-Duty Low Temperature Combustion Diesel Engine by Planar Laser Induced Fluorescence of a Fuel Tracer

2011-24-0064

Published  
09/11/2011Dipankar Sahoo, Benjamin Petersen and Paul Miles  
Sandia National Laboratories

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doi:10.4271/2011-24-0064

## ABSTRACT

The spatial distribution of the mixture equivalence ratio within the squish volume is quantified under non-combusting conditions by planar laser induced fluorescence (PLIF) of a fuel tracer (toluene). The measurements were made in a single-cylinder, direct-injection, light-duty diesel engine at conditions matched to an early-injection low temperature combustion mode. A fuel amount corresponding to a low load (3.0 bar indicated mean effective pressure) operating condition was introduced with a single injection. Data were acquired during the mixture preparation period from near the start of injection ( $-22.5^\circ$  aTDC) until the crank angle where the start of high-temperature heat release normally occurs ( $-5^\circ$  aTDC). Despite the opposing squish flow, the fuel jets penetrate through the squish region to the cylinder bore. Although rapid mixing is observed in the head of each jet, rich regions remain at the head at the start of high-temperature heat release. In contrast, the fuel mixture is generally lean in the clearance volume above the bowl, though near-stoichiometric pockets are observed near the bowl rim. Significant pockets of mixture in the central clearance volume, and between the jets in the squish volume, are sufficiently lean that complete oxidation is unlikely.

## INTRODUCTION

Due to their high compression ratio and overall lean operation, compression ignition (diesel) engines are a proven short-to medium-term solution to the problem of reducing fossil-fuel consumption and minimizing green house gas emissions. However, conventional diesel combustion results in high oxides of nitrogen ( $\text{NO}_x$ ) and particulate matter (PM) emissions. Stringent regulations for  $\text{NO}_x$  and PM emissions

require exhaust after-treatment which adversely affects fuel economy and increases overall cost - thereby impeding market penetration and the subsequent impact of this technology. To reduce the cost, complexity, and fuel economy penalty of after-treatment systems, low-temperature combustion (LTC) strategies are being pursued. These strategies strive to control  $\text{NO}_x$  and PM in-cylinder by reducing compression ratio, employing high levels of dilution, and using early or late injection timing to keep peak combustion temperatures low and to increase the amount of pre-mixing. As a consequence of the low temperatures and dilute mixtures, increased emissions of unburned hydrocarbons (UHC) and CO are often observed, with a concomitant loss in efficiency.

Studies of the kinetics of fuel oxidation [1, 2] have shown that to complete the oxidation of UHC and CO under low temperature conditions, the fuel-air equivalence ratio ( $\phi$ ) must be maintained within strict limits. Overly rich mixtures ( $\phi > 1$ ) cannot complete oxidation due to a deficiency in  $\text{O}_2$ , while overly lean mixtures do not achieve the temperatures needed to complete oxidation before cylinder volume expansion quenches the reactions [3]. At low load conditions, UHC and CO emissions stemming from overly lean mixtures are particularly problematic. Moreover, in-cylinder PLIF measurements [1-2, 4, 5, 6] have shown that the squish volume is a major source of these emissions. The focus of this work is thus on the quantitative determination of the equivalence ratio distribution formed within the clearance volume. Mixture in this region is either already within the squish volume, or poised to enter it as combustion and cylinder volume expansion occurs. Our principal objectives are to gain a better fundamental understanding of the mixing processes leading to the formation of overly lean regions, and

to provide quantitative data to validate and improve CFD simulations.

There are several optical diagnostic techniques that have been used to measure the local equivalence ratio in the cylinder of an operating engine, including Raman scattering, Rayleigh scattering, and laser-induced fluorescence (LIF). Of these techniques, laser-induced fluorescence is generally preferred due to its high signal level and the ability to discriminate the signal from elastically scattered and reflected laser light. Hence, laser-induced fluorescence techniques have often been used to qualitatively visualize the fuel distribution in the cylinder [5], both in vapor [9] and the liquid phase [10, 11]. A majority of the engine LIF studies have been focused on spark ignition engine technologies [8,9,10,11] and only a few have investigated the fuel/air ratio in diesel engine configurations [12,13,14,15]. Furthermore, many of the diesel studies were either performed in constant volume combustion vessels [14-15] or were qualitative in nature [13]. Musculus et al. [12] acquired quantitative equivalence ratio measurements under non-reacting conditions in a large-bore (139.7 mm), heavy-duty diesel engine using toluene as a PLIF tracer. However, no quantitative measurements of fuel/air ratio have been previously acquired in a light-duty diesel engine, in which fuel jet interactions with the piston surfaces and swirling in-cylinder flows are much more significant.

## EXPERIMENTAL FACILITY AND TECHNIQUE

### OPTICAL ENGINE AND FUEL INJECTION EQUIPMENT

The single-cylinder research engine used in the current study was developed from a General Motors 4-cylinder 1.9 L light-duty diesel engine with a Bosch CRIP2.2 injector vertically mounted on the cylinder centerline. The engine geometry is summarized in [Table 1](#) and a schematic of the engine is shown in [Fig. 1](#). The cylinder pressure was measured using a Kistler 6125B quartz pressure transducer mounted in the glow plug position. The piston top is constructed from fused silica, but retains the geometric characteristics of a production-like piston geometry featuring a reentrant bowl design and piston crown valve cutouts. The top ring-land crevice width (~0.28 mm) is larger than in the serial production engine (~0.18 mm), and the lower position of the compression rings needed to allow unimpeded optical access into the bowl result in a near 4-fold increase in crevice height. Two gapless compression rings ensure that blow-by is minimal.

**Table 1. Engine and injector specifications for the current experiments. Crank angles listed in this paper are with respect to TDC compression.**

| Engine Characteristics:                             |                                    |
|-----------------------------------------------------|------------------------------------|
| Bore / Stroke                                       | 82.0 / 90.4 [mm]                   |
| Displacement                                        | 477 [cm <sup>3</sup> ]             |
| CR                                                  | 16.7                               |
| Squish Height                                       | 0.88 [mm]                          |
| Swirl Ratio                                         | 2.2                                |
| Injector Characteristics: Bosch Common Rail CRIP2.2 |                                    |
| Type / Sac Volume                                   | Mini Sac / 0.23 [mm <sup>3</sup> ] |
| Number of Nozzles                                   | 7                                  |
| Nozzle Diameter                                     | 0.14 [mm]                          |
| Included Angle                                      | 149°                               |
| Fuel Mixture:                                       |                                    |
| Base Fuel (by volume)                               | 75% n-heptane                      |
|                                                     | 25% iso-octane                     |
| Fuel Tracer (by weight)                             | 0.5% Toluene                       |
| Expected Cetane Number                              | 47                                 |

Standard grade fused silica windows are installed in the upper cylinder-liner for admitting laser light into the cylinder and viewing the resulting fluorescence. The lower thermal conductivity of the fused silica windows and piston-top can affect surface temperatures and hence fuel-film vaporization and bulk-gas oxidation processes near the fused silica surfaces - potentially impacting UHC and CO emissions. However, these effects are apparently minor because the CO and UHC emissions trends from a similar single-cylinder all-metal engine are well captured by the optical engine used in the current experiments [16].

The Bosch CRIP2.2 injector is a production, high pressure, electronically-controlled, common-rail fuel injector. Specifications for the fuel injector nozzle are also included in [Table 1](#). For the experiments presented here, a 7-hole, mini-sac injector cup (tip) was employed, having an included angle of 149° (15.5° down-angle from the firedeck; i.e., the bottom surface of the head). The 7 fuel orifices are equally spaced and have a nominal diameter of 0.14 mm. The nozzle is specified to have 10% hydro-grinding.

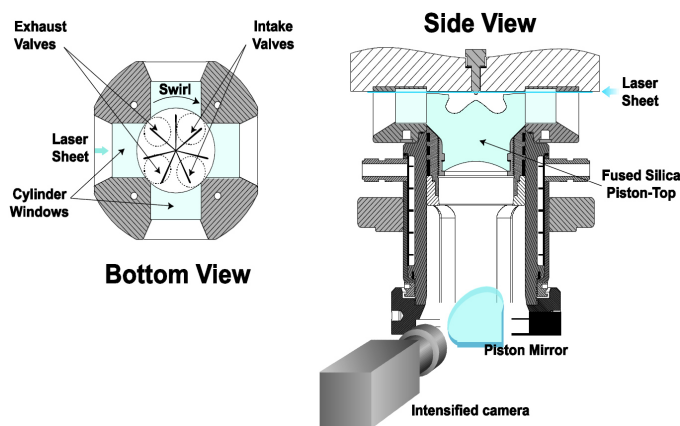


**Figure 1. Schematic of the optical engine depicting the location of the laser sheet and the camera viewing direction. The left-hand side of the figure shows a view of the cylinder head from below and corresponds to the orientation of the images presented below.**

## OPERATING CONDITIONS AND EXPERIMENTAL PROCEDURE

To avoid oxygen quenching of the toluene fluorescence, the engine was operated with a pure nitrogen intake stream and thus under non-combusting conditions. Nevertheless, the measured equivalence ratio distributions are representative of fired (combusting) engine operation until the onset of significant heat release - approximately  $-5^\circ$  aTDC. The near-TDC temperature and density of a baseline combusting operating condition (10%  $[O_2]$ , 3.0 bar IMEP,  $99^\circ\text{C}$  intake temperature, and 1.5 bar intake pressure) that has been studied previously [1, 2, 4, 5, 6, 7] were closely matched by maintaining the same intake charge mass flow rate and lowering the intake temperature to account for the lower molecular weight of the pure  $N_2$  charge.

An engine model was developed using GT Power software to estimate the intake conditions required to match the baseline operating condition. The model included the heat transferred to the intake charge within the cylinder and intake system and accounted for the gas dynamics in the intake and exhaust manifolds. As shown in Table 2, the estimated motored TDC temperature and density of the baseline condition were 909 K and  $20.9 \text{ kg/m}^3$ , respectively. To match these conditions with a pure nitrogen intake flow, the model indicated that an intake temperature of  $27^\circ\text{C}$  was required. With this temperature, the peak pressure achieved near TDC closely matched the baseline peak pressure scaled by the ratio of the molecular weights of the baseline-charge and  $N_2$ . This agreement validates the in-cylinder temperature predictions of the model, which are used in the data reduction process described below.

A consistent thermal state between experimental runs was maintained by following a strict eight-minute measurement schedule. At the beginning of the schedule, the engine was motored for 90 seconds to stabilize the intake plenum pressure. Fuel was then injected once every fifth cycle for an additional 90 seconds. Although no combustion occurred due to the absence of  $O_2$  in the intake charge, this injection strategy was necessary to accommodate the limited speed of the laser and camera systems and to ensure that unburned fuel was thoroughly purged between successive data images. The image acquisition began 30 seconds after the start of the injection sequence. After the images were collected, the engine was stopped and allowed to cool for the rest of the duration of the eight-minute 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 run.

**Table 2. Engine operating conditions.**

|                                                      | Baseline Condition                            | Current Condition |
|------------------------------------------------------|-----------------------------------------------|-------------------|
| Engine Speed [RPM]                                   | 1500                                          | 1500              |
| Intake Charge [mole fractions]                       | $O_2$ : 0.10<br>$N_2$ : 0.71<br>$CO_2$ : 0.09 | $N_2$ : 1.0       |
| Intake Temperature [K]                               | 372                                           | 300               |
| Intake Pressure [bar]                                | 1.5                                           | 1.5               |
| Load (IMEP) [bar]                                    | 3.0                                           | N.A.              |
| Injected Fuel* [mg]                                  | 8.8                                           | 8.8               |
| Rail Pressure [bar]                                  | 860                                           | 860               |
| Global Equivalence Ratio                             | 0.3                                           | N.A.              |
| $SOI_{\text{command}}$ [ $^\circ\text{CA}$ ]         | -26.6                                         | -26.6             |
| $SOI_{\text{actual}}$ [ $^\circ\text{CA}$ ]          | -23.1                                         | -23.1             |
| Injection Duration [CA]                              | 6.4                                           | 6.4               |
| Swirl Ratio                                          | 2.2                                           | 2.2               |
| Motored TDC Density [ $\text{kg/m}^3$ ] <sup>†</sup> | 20.9                                          | 21.1              |
| Motored TDC Temperature [K] <sup>†</sup>             | 909                                           | 908               |

<sup>†</sup>Predicted values based on measured intake pressures and temperatures

We have selected a mixture of 75% (by volume) HPLC-grade n-heptane ( $C_7H_{16}$ ) and 25% (by volume) HPLC-grade iso-octane ( $C_8H_{18}$ ) as our non-fluorescing base fuel components. At the baseline combusting operating condition, this fuel mixture (hereafter referred to as PRF25) matches the heat release characteristics of a conventional US diesel fuel with a cetane number of 47 - as shown in Fig. 2. Previous studies [7] have also shown that the engine-out emissions of UHC and CO at this condition are well matched between the PRF and diesel fuels and follow the same trends with respect to injection timing. This gives us confidence that, although the fuel properties of the n-heptane/iso-octane mixture are different than typical diesel fuel, the PRF25 fuel blend

provides the same general combustion and emissions formation processes that would be observed with diesel fuel.

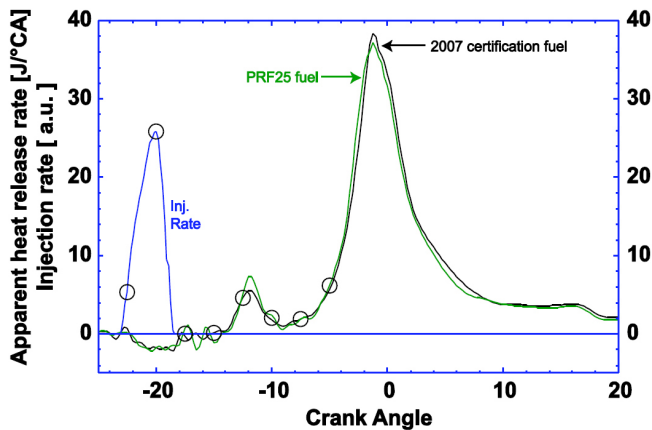


**Figure 2.** Comparison of the apparent heat release rate (AHRR) for a US 2007 certification diesel fuel and the PRF25 fuel mixture employed in the present study. The fuel injection rate was measured with diesel fuel. Open circles represent the crank angles at which equivalence ratio measurements were made.

## LIF-TRACER (TOLUENE) DIAGNOSTIC TECHNIQUE

Commercial fuels contain numerous compounds that strongly fluoresce upon excitation with ultra-violet (UV) light. However, the fluorescence signal level depends not only on the concentration of each fluorescing component in the fuel, but also on temperature, pressure, and local mixture composition. Therefore, a quantitative interpretation of the signal as a fuel/air equivalence ratio is difficult with commercial fuels. To address this problem, a single fluorescing component (tracer) is mixed with a non-fluorescing fuel. A review by Shultz and Sick [17] provides an overview of the state-of-the-art of tracer-based LIF diagnostics.

A variety of tracers which are also natural components of commercial fuel, have been proposed. Aromatic hydrocarbons that are present in commercial fuels are responsible for strong UV absorption and subsequent fluorescent emissions. So, aromatics (benzene like) are natural choices for tracers. To match the boiling range of our PRF25 base fuel components, only the lighter aromatic compounds can be considered. Due to its closely matched boiling point, low toxicity/carcinogenicity, high-temperature stability, and well characterized photo-physics, we have selected toluene as the tracer for this study. Toluene ( $C_7H_8$ ) is added at a rate of 0.5% (by weight) to the PRF25 base fuel. Further details supporting the choice of toluene as a fuel tracer are outlined in [8].

Toluene fluorescence was excited by the 266-nm (UV) output of a 10-Hz pulsed Nd:YAG laser, with a pulse energy of 40 mJ. The laser beam was focused in the cylinder using a cylindrical lens, resulting in a laser sheet of thickness of approximately 500  $\mu m$  across the cylinder bore. The laser sheet was positioned at the mid-plane of the squish volume for each crank angle. The vertical locations of the laser sheet are listed in Table 3 for all the crank angles investigated in this study. The shot-to-shot relative laser energy was also measured by directing a portion of the beam to a Coherent model J-25MB-LE energy sensor.

**Table 3.** Measurements Locations.

| Crank Angle<br>(° aTDC) | Laser Sheet Position<br>(mm below firedeck) |
|-------------------------|---------------------------------------------|
| -22.5                   | 2.5                                         |
| -20.0                   | 2.1                                         |
| -17.5                   | 1.7                                         |
| -15.0                   | 1.4                                         |
| -12.5                   | 1.1                                         |
| -10.0                   | 0.8                                         |
| -7.5                    | 0.6                                         |
| -5.0                    | 0.5                                         |

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 toluene fluorescence, which is emitted in the wavelength range 260-400 nm [19]. The intensifier gate width was set to 250 ns. A WG295 long-wave-pass filter rejected elastically scattered 266-nm laser light, so that its contribution to the background is minimal. At each crankshaft position, a set of 100 images, comprised of images from 100 separate cycles, is acquired. All images were collected with the camera looking through the piston toward the bottom surface of the cylinder head, as shown in Figure 1. Hence, the acquired images were distorted due to the curved surfaces of the piston, particularly within the region above the piston bowl. Fig. 3 identifies the valve cutout and bowl regions.

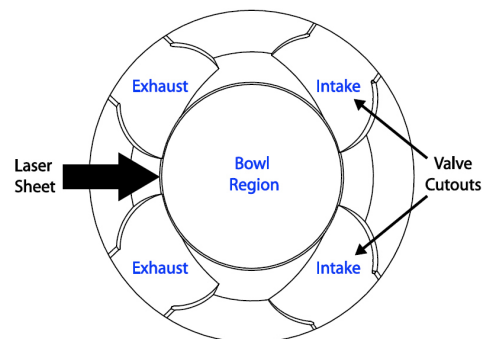


**Figure 3.** Piston geometry with valve cutouts. The UV laser sheet entered the engine from the exhaust side.

## DATA REDUCTION

Quantitative fuel-vapor concentration measurements using fuel-tracer (toluene) fluorescence requires image processing to correct for distortion and background interference, and a careful calibration and accounting for the temperature sensitivity of the fluorescence field [8, 12] to derive equivalence ratio distributions from the corrected images. This section provides examples of the raw data images and an overview of the data reduction procedure employed to deduce the fuel-vapor concentration.

## IMAGE PROCESSING

The field of view encompassed in the images is nominally  $\sim 76 \text{ mm} \times 76 \text{ mm}$ . However because of refraction through the piston window, it changes slightly as the piston moves. The CCD array dimension is  $512 \times 512$ . Hence, the nominal resolution is  $\sim 0.15 \text{ mm/pixel}$ . Different regions of interest are shown in Fig. 4, and will be explained below.

Various image processing steps were performed on the acquired images in order to correct for the optical distortion produced by the piston and to minimize background signal interference:

1. Due to the bowl geometry it was not possible to obtain any meaningful data in the outer, reentrant region of the bowl or in the squish volume above this region. Hence, this portion was eliminated in the data reduction process as shown by the darkened ring in Fig. 4. Likewise, the laser sheet was partially blocked by the injector tip, creating a shadow of the tip. The shadow portion of the image was also eliminated from the analysis.

2. Optical image distortion in the clearance and bowl volumes resulting from the curved piston bottom surface and piston bowl was corrected using locally weighted, piecewise linear transformations derived from images of illuminated calibration grids. Unique transformations were necessary at each crank-angle, and the distortion correction was performed separately for the squish and the bowl regions. Distortion-corrected squish and bowl region images were then recombined to form an image of the entire combustion chamber cross-section.

3. For each crank angle, spurious background signal from the windows and injector tip was eliminated by subtracting an averaged background image, obtained by averaging 100 instantaneous background images (no fuel injection). These background images were acquired approximately 60 s into the motored portion of the operating schedule (i.e. approximately 75 s before the data acquisition), at the same crank angle as the subsequent images with fuel injection.

A sequence of typical, single-cycle data images of the fuel injection event, after distortion correction and background subtraction, are shown in Fig. 5.

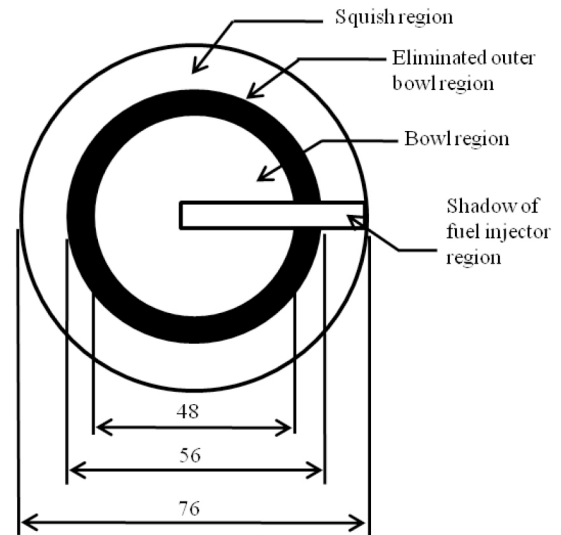


**Figure 4. A schematic of various regions of interest with approximate diameters. All dimensions are in mm. Figure not to scale.**

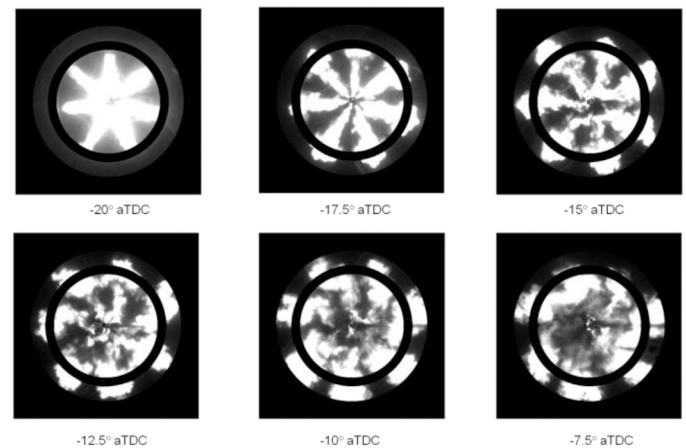


**Figure 5. Sequence of diesel injection images (16-bit) at different CADs in the compression stroke. These are single-cycle images shown after distortion correction and background subtraction. The images were obtained with a swirl ratio of 2.2, in the clockwise direction. Typical images acquired at  $-22.5^\circ$  and  $-5^\circ$  are not shown. Note that the intensity scale is chosen purely for presentation purpose and not to be confused with saturation level**

## EQUIVALENCE RATIO DETERMINATION

To convert the raw ensemble averaged data images into quantitative fuel/air equivalence ratios, the signal dependence of the PLIF signal on the thermodynamic conditions in the cylinder and the photophysical properties of toluene must be evaluated. The signal dependence of toluene is given in Eq. (1), which follows the conventions used in [19].