

Characterizing the Development of Thermal Stratification in an HCCI Engine Using Planar-Imaging Thermometry

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ABSTRACT

A planar temperature imaging diagnostic has been developed and applied to an investigation of naturally occurring thermal stratification in an HCCI engine. Natural thermal stratification is critical for high-load HCCI operation because it slows the combustion heat release; however, little is known about its development or distribution. A tracer-based single-line PLIF imaging technique was selected for its good precision and simplicity. Temperature-map images were derived from the PLIF images, based on the temperature sensitivity of the fluorescence signal of the toluene tracer added to the fuel. A well premixed intake charge assured that variations in fuel/air mixture did not affect the signal. Measurements were made in a single-cylinder optically accessible HCCI research engine (displacement = 0.98 liters) at a typical 1200 rpm operating condition. Since natural thermal stratification develops prior to autoignition, all measurements were made for motored operation. Calibrations were performed in-situ, by varying the intake temperature and pressure over a wide range. Although the absolute accuracy is limited by the pressure-derived temperatures used for calibration, an uncertainty analysis shows that the precision of the diagnostic for determining temperature variations at a given condition is very good.

Application of the diagnostic provided temperature-map images that showed a progressive development of natural thermal stratification in the bulk gas through the latter compression stroke and early expansion strokes. Applying a PDF analysis with corrections for measurement uncertainties provided additional quantitative results. The data show a clear trend of going from virtually no stratification at 305° CA (55° bTDC), to significant inhomogeneities at TDC. Near TDC, the images show distinct hotter and colder pockets with a turbulent structure. Images were also acquired across the charge from the mid-plane to outer boundary layer at 330° CA and TDC. They show an increase in thermal stratification and a change of its

structure in the outer boundary layer, and they provide a measure of the boundary-layer thickness. Where possible, results were compared with previous fired-engine and modeling data, and good agreement was found.

INTRODUCTION

The limited high-load capability of homogeneous charge compression-ignition (HCCI) engines is one of the most significant technical barriers to the implementation of this promising technology. HCCI has advantages of high thermal efficiency and very low emissions of NO_x and particulate; however, the maximum load is well below that of spark-ignition (SI) and diesel engines. This load limitation occurs because the cylinder-pressure rise rate (PRR) with combustion increases with increased fueling, eventually becoming so rapid that it results in engine knock.

Previous research has shown that naturally occurring thermal stratification of the charge-gas mixture plays a key role in determining the maximum PRR in HCCI engines [1,2]. For a typical low-residual engine, natural thermal stratification results from wall heat transfer and convection by in-cylinder flows [1]. The resulting thermal inhomogeneities cause the charge to autoignite sequentially starting with the hottest region [1,3], which substantially slows the combustion heat release rate (HRR) compared to a fully homogeneous charge [1]. Moreover, the benefit of a given amount of thermal stratification can be amplified by retarding the combustion phasing [2]. With retarded phasing, the increased expansion rate during combustion increases the induction time of sequentially cooler zones, further slowing the HRR and allowing even higher loads without knock. As a result, the high-load limit of an HCCI engine is closely coupled to the amount of thermal stratification [4], and computational results have shown that increasing the thermal stratifica-

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tion has a strong potential for extending the high-load limit [2].

Despite the critical importance of thermal stratification to the high-load limits of HCCI, only a little is known about the in-cylinder distribution of the thermal inhomogeneities and how they develop. Chemiluminescence imaging of HCCI combustion has provided evidence of the thermal stratification by showing that even for a well-premixed fuel/air charge, autoignition begins in localized regions located randomly throughout the combustion chamber. High-speed chemiluminescence image sequences then show the remaining charge autoigniting sequentially as a result of the thermal stratification [1,3]. Another key finding from chemiluminescence imaging is that thermal stratification extends throughout the bulk gas rather than being confined to the boundary layer [1]. Moreover, it is this bulk-gas stratification that is mainly responsible for reducing the maximum PRR to allow higher loads, while boundary-layer stratification has only a secondary effect, as discussed in detail in the next section.

Although these chemiluminescence imaging studies provide valuable information on the effect of thermal stratification on the combustion process, they provide no information about the thermal stratification itself. Specifically, they do not show the magnitude of the thermal stratification, its spatial distribution within the bulk gas and boundary layer, or how this stratification develops through the cycle. Understanding these aspects of the thermal stratification is a key step toward developing methods of enhancing it to extend the high-load limit of HCCI.

Planar temperature-map images offer the best means of gaining this desired understanding of the natural thermal stratification. However, previous investigations involving planar imaging of the in-cylinder temperature distribution have been directed at other concerns. Initial work by Einecke *et al.* [5] involved single-shot planar imaging of the end gas temperature in a two-stroke SI engine using two-line excitation of 3-pentanone as a dopant in the fuel. Later, Fujikawa *et al.* [6] used multi-shot averaged two-line excitation of toluene (dopant) in an SI engine to measure thermal distributions resulting both from fuel stratification and from dual-temperature intake streams. A different approach by Kakuho *et al.* [7] involved using a single laser to excite two different dopants (3-pentanone and triethyl-amine) to obtain temperature distributions in an HCCI engine resulting from dual-temperature intake streams. Finally, Rothamer *et al.* [8] obtained simultaneous single-shot temperature-maps and EGR distributions in an HCCI engine using two-line excitation of 3-pentanone as a fuel dopant.

The objective of the current study is to develop an appropriate planar temperature diagnostic and to apply it to an investigation of the development of natural thermal stratification in an HCCI engine. For these measurements, the main purpose is to determine the magnitude and distribution of the temperature inhomogeneities across the charge. Therefore, in selecting a diagnostic, an emphasis was placed on obtaining high precision in

measuring the relative temperature variation within an image rather than high absolute accuracy. The technique selected is single-line planar laser-induced fluorescence (PLIF) of toluene as a trace dopant in the fuel (iso-octane). This technique provides sufficient signal to minimize shot noise, and the signal is sufficiently sensitive to temperature variations in the range of interest. It is also straightforward and inexpensive compared to two-laser techniques.

The principle of this diagnostic is based on the temperature sensitivity of the toluene-PLIF signal produced by excitation with a frequency-quadrupled Nd:YAG laser at 266 nm [9,10]. Since variations in fuel/air mixture can also affect the toluene-PLIF signal intensity, the charge was fully premixed. In addition, the intake air was replaced with nitrogen to minimize quenching of the toluene-PLIF signal, and to prevent combustion reactions from breaking down the toluene dopant, which would affect the signal. The absence of combustion is considered acceptable since the focus of this work is to investigate the development of the thermal stratification prior to autoignition. A complete discussion of the diagnostic, including the calibration technique and error analysis, is given in the Experimental Setup and Diagnostics section.

This planar temperature diagnostic was then applied to an investigation of the development of thermal stratification at a typical HCCI high-load operating condition. The results are presented in three parts, following the Diagnostics section. First, temperature-map (T-map) images show the evolution of the thermal stratification in the bulk gases through the latter compression and early expansion strokes. Second, the trends in these images are quantified using a PDF (probability density function) analysis. Third, T-map images of the thermal boundary layer at two representative crankangles are presented and discussed. After presentation of the results, the findings are summarized and conclusions are drawn in the final section.

BACKGROUND

As discussed in the introduction, chemiluminescence imaging has provided considerable information on the effects of thermal stratification on HCCI combustion. Because these findings are related to the motivation and approach for the current study, some key results are briefly reviewed in this section.

In a recent work [1], the authors used chemiluminescence imaging from two different views to determine the progress of combustion in an optically accessible HCCI engine, as shown in Fig. 1. Selected images from these two views are presented in Fig. 2, for a well-premixed operating condition. Figure 2a presents three representative images showing the progress through the combustion event from the bottom view. For this operating condition, the peak HRR and 50%-burn point (CA50) occur at 368° crankangle (CA),¹ as shown in Fig. 3. Even though the charge was well premixed, the combustion is

¹ 0° CA is taken to be top dead center (TDC) intake.

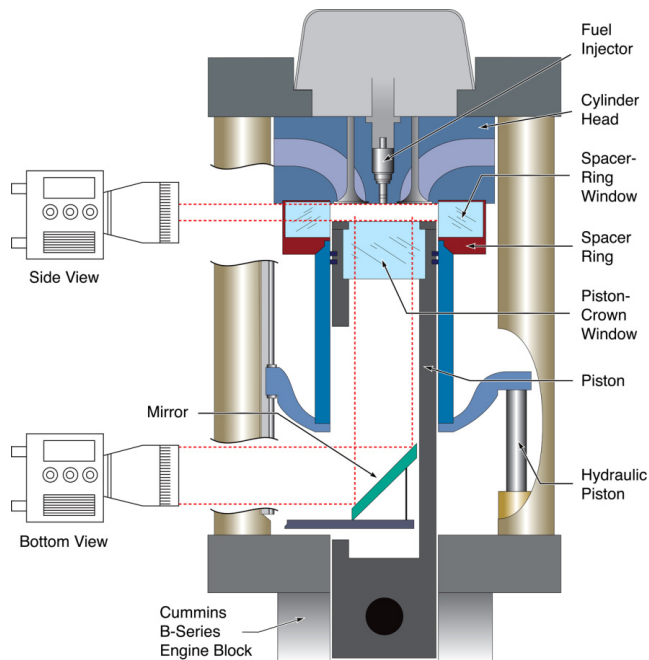


Figure 1. Schematic of optically accessible HCCI engine showing the two different views used for chemiluminescence imaging in Ref. [1].

heterogeneous due to naturally occurring thermal stratification. Early in the combustion event (365° CA), the combustion reactions are underway in localized regions, presumably corresponding to regions of higher temperature. Other regions are still dark indicating that they have not yet autoignited, presumably because they are cooler. These cooler regions sequentially autoignite [1], and by CA50 (368° CA), most regions are reacting intensely. Late in the combustion event (372° CA), the chemiluminescence is weaker (as noted by the higher gain number in white) and spatially more intermittent.

Although the non-uniformities in the bottom-view images in Fig. 2a show the effects of thermal stratification, the role of the thermal boundary layers is not readily apparent. As shown in Ref. [1], for typical engines, thermal stratification results mainly from wall heat transfer. As a result, thermal boundary layers might be considered to play a major role in contributing to the sequential autoignition that controls the maximum PRR. However, the side-view chemiluminescence images in Fig. 2b show that this is not the case. (In the following discussion, it should be noted that the side-view chemiluminescence intensity tracks the HRR well during the main combustion event as shown in Fig. 3.) As evident in the 364° CA image, hot ignition begins in localized regions in the central part (in the vertical direction) of the charge. From $364 - 368^\circ$ CA, the number of regions showing hot ignition increases rapidly, although inhomogeneities remain, as evident in the bottom view (Fig. 2a). Up past the time of the peak HRR (368° CA, see Fig. 3), hot ignition and combustion occur in the central part of the charge, *i.e.* the bulk gases [1]. There is no indication of any preferential boundary-layer combustion until 370° CA. Then, by 372° CA, the boundary layer combustion along the firedeck (*i.e.*, the flat cylinder-head surface) and piston-top surfaces becomes distinct, while the chemilumines-

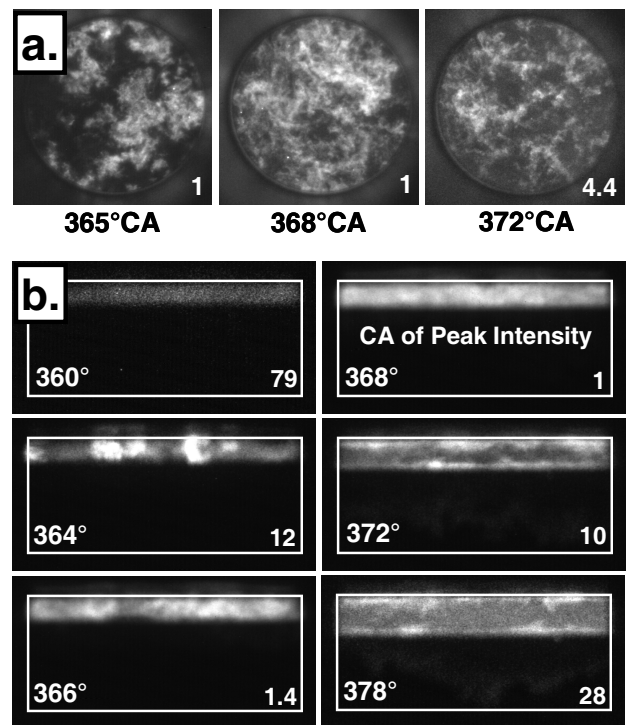


Figure 2. Chemiluminescence image sequences of HCCI combustion obtained through (a) the piston-crown, and (b) spacer-ring windows. Iso-octane, 1200 rpm, $\phi = 0.38$, CA50 = 368° CA. Relative camera intensifier gains are given at the lower right of each image. Adapted from Ref. [1].

cence in the central region dies out. Based on this, the weaker more intermittent chemiluminescence in the bottom-view image at 372° CA is mainly due to boundary-layer combustion. These findings on the timing of the bulk-gas and boundary-layer combustion relative to the PRR are even more evident in plots of the chemiluminescence-intensity profile from the fire-deck to the piston top averaged over many engine cycles, presented in Ref. [1].

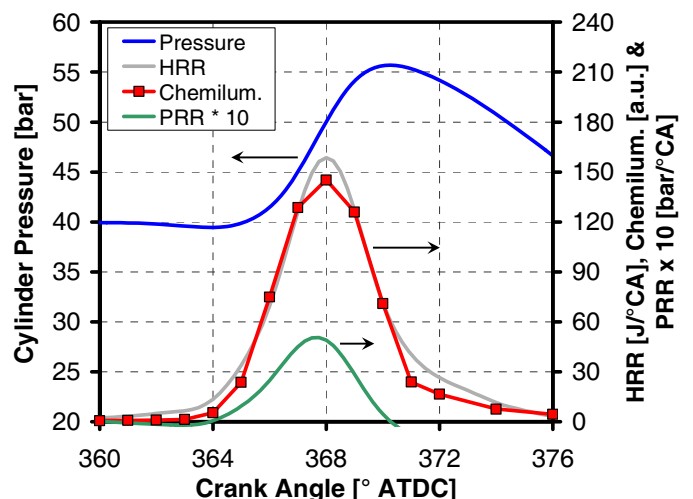


Figure 3. Cylinder pressure, HRR, PRR and average side-view chemiluminescence intensity corresponding to the images in Fig. 2. Adapted from Ref. [1].

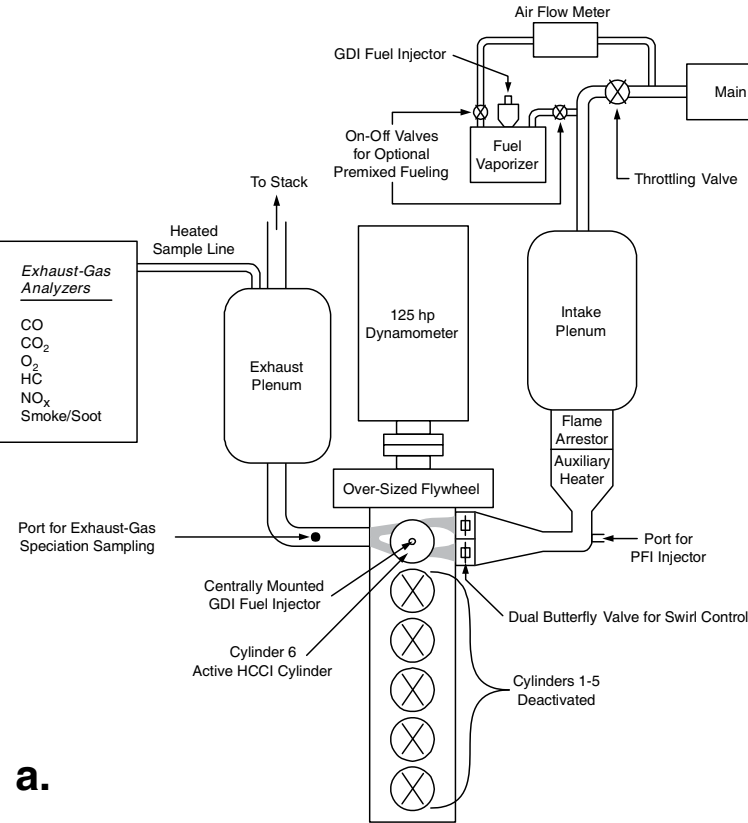
Since the vast majority of combustion occurs in the central part of the charge up past the time of the maximum PRR (367.75° CA), it is mainly thermal stratification within the bulk gases that controls the maximum PRR and engine knock. Distinct boundary layer combustion does not begin until well after the time of maximum PRR. Therefore, thermal stratification between the bulk gas and the boundary layer has only an indirect effect on the knock limit, by reducing the portion of the charge in the bulk-gas.

The highly intermittent nature of the chemiluminescence in the central part of the charge indicates significant thermal stratification throughout this region. These thermal inhomogeneities presumably result from the transport of cooler gases from the near-wall region into the bulk gas by large-scale turbulence, but the mechanism is not well understood. Nevertheless, this bulk-gas stratification is critical to the high-load limit of HCCI, so a major portion of the current investigation focuses on planar temperature-map images and analysis showing the development of this bulk-gas thermal stratification.

EXPERIMENTAL SETUP

ENGINE FACILITY

The optically accessible HCCI engine shown schematically in Fig. 1 was used for the current study, as well as in Ref. [1]. The engine was derived from a Cummins B-series medium-duty diesel engine with a displacement of 0.98 liters/cylinder. As shown in the facility schematic in Fig. 4, the six-cylinder production engine was converted

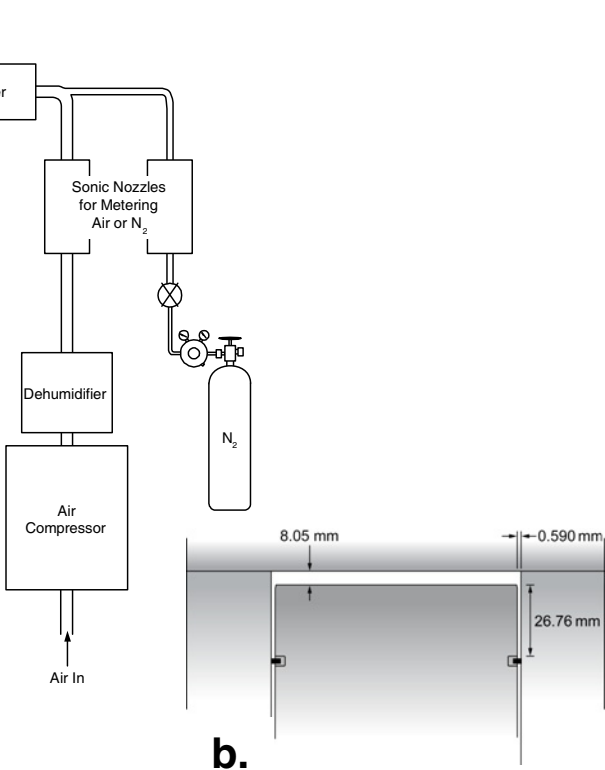


a.

Displacement (single-cylinder)	0.981 liters
Bore	102 mm
Stroke	120 mm
Connecting Rod Length.....	192 mm
Geometric Compression Ratio (current study)	14:1
Geometric CR (chemilum. images, Ref. [1])	18:1
No. of Valves	4
IVO	0° CA*
IVC.....	202° CA*
EVO.....	482° CA*
EVC	8° CA*
Swirl Ratio.....	1.3
Fueling system	Fully Premixed
Engine Speed.....	1200 rpm
Intake Pressure	100 kPa (abs.)
Intake Temperature.....	170°C (443 K)
Coolant Temperature	100°C
Fuel.....	Iso-Octane with 2% Toluene

* 0° CA is taken to be TDC intake. The valve-event timings correspond to 0.1 mm lift.

to single-cylinder operation by deactivating cylinders 1-5. The engine specifications and operating conditions are listed in Table 1. Detailed descriptions of the engine and facility may be found in Refs. [1 & 11], so only a brief description is given here.



b.

Figure 4. (a) Schematic of the HCCI engine facility. (b) Schematic of the CR = 14 optical-engine HCCI piston, at TDC

As shown in Fig. 1, the engine utilizes a classic Bowditch piston arrangement with a large piston-crown window. The spacer ring that forms the top part of the cylinder wall contains three large windows to provide a horizontal view of the combustion chamber. This optical access extends downward 29.5 mm from the firedeck (*i.e.*, the flat cylinder-head surface). To allow horizontal optical access up to the firedeck surface, the spacer-ring and windows are recessed into the firedeck as shown in Fig. 1. The inner surfaces of the spacer-ring windows are curved to match the cylinder bore. As evident in Fig. 1, the flat piston-crown window and firedeck create a pancake combustion chamber. For the current study, the piston length was set to give a geometric compression ratio (CR) of 14; however, for the previous chemiluminescence imaging study presented above, a slightly longer piston was used to give CR = 18. Like most optical engines, the top ring-land crevice is quite tall to prevent the rings from riding over the edge of the spacer-ring windows. The volume of the top ring-land crevice is included in the geometric compression ratio. Figure 4b shows a detailed schematic of the pancake combustion chamber at top dead center (TDC), with dimensions.

The intake charge was fully premixed using the fueling system shown at the top of the schematic in Fig. 4a. This fueling system consists of an electrically heated fuel vaporizer and appropriate plumbing to ensure thorough premixing upstream of the intake plenum. A positive displacement fuel flow meter was used to determine the amount of fuel supplied. As discussed in the introduction, the intake charge was made inert by operating with nitrogen instead of air, to minimize quenching of the PLIF signal and to prevent breakdown of the toluene tracer. The nitrogen was metered and controlled by a sonic orifice with the upstream pressure being continually tuned by an electronically controlled pressure regulator. The nitrogen was electrically heated to the desired temperature. An auxiliary heater mounted close to the engine provided precise control of the intake temperature. For all data presented, the intake temperature was set to 170°C, which is representative of the intake temperatures required for iso-octane/air mixtures near the high-load limit with CR = 14 ($\phi = 0.4 - 0.5$). However, intake temperatures ranging from 100° - 205°C were used to calibrate the temperature dependence of the PLIF signal. This resulted in peak compressed-gas temperatures of about 1000 K and 1080 K for the 170°C and 205°C intake temperatures, respectively. Since these temperatures are well below the 1150 K autoignition temperature of toluene, no thermal decomposition of the toluene tracer is expected.

All data were taken at an engine speed of 1200 rpm with the intake nitrogen flow adjusted to provide an intake pressure of 100 kPa, simulating naturally aspirated conditions. Prior to data acquisition, the engine was fully preheated to 100°C by means of electrical heaters on the “cooling” water and lubricating oil circulation systems. All data were taken under motored operation.

CONVENTIONAL DATA ACQUISITION

Cylinder pressure measurements were made with a transducer (AVL QC33C) mounted in the cylinder head approximately 42 mm off center. The pressure transducer signals were digitized and recorded at 1/4° CA increments for one hundred consecutive cycles. The cylinder-pressure transducer was pegged to the intake pressure near bottom dead center (BDC) where the cylinder pressure reading was virtually constant for several degrees. Intake temperatures were monitored using thermocouples mounted in the two intake runners close to the cylinder head. In addition, a thermocouple mounted in the spacer ring with its junction embedded in the ring approximately 2 mm beneath the surface, 5 mm below the firedeck, provided an indication of in-cylinder surface temperatures by extrapolating its reading to the expected value at the surface. For all data presented, 0° crank angle (CA) is defined as TDC intake (so TDC compression is at 360°). This eliminates the need to use negative crank angles or combined BTDC, ATDC notation.

TEMPERATURE IMAGING DIAGNOSTIC

The diagnostic selected for the T-map imaging was single-line PLIF of toluene with excitation at 266 nm. The principle of this diagnostic is based on the temperature sensitivity of the PLIF signal of toluene in nitrogen. As first noted by Koban *et al.* [9], for homogeneous mixtures at constant pressure, the fluorescence from 266 nm excitation of toluene is a function of temperature only. The engine was supplied with a homogeneous fuel/nitrogen mixture, but pressure varies with crank angle, so it is necessary to account for pressure effects on the signal, as discussed below. Single-line temperature measurements are also possible with PLIF of ketone tracers [10,12] such as acetone or 3-pentanone. However, previous work in our laboratory [13] has shown that toluene provides a substantially better signal/noise (S/N) and requires lower tracer concentrations in the base fuel. In addition, the toluene-PLIF signal is much more sensitive to temperature variations [10]. With its strong signal, this toluene-PLIF diagnostic provides measurements with good precision, as discussed later.

For all measurements, the toluene was mixed to a concentration of 2% (by liquid volume) with the iso-octane fuel. Iso-octane was chosen as the fuel because it is a good surrogate for gasoline [14,15], and it does not fluoresce with UV excitation, unlike gasoline which has multiple fluorescing constituents. For all conditions studied, the same toluene concentration was supplied by fueling the engine at a rate that would correspond to an equivalence ratio (ϕ) of 0.4 if the nitrogen was replaced with air.

DIAGNOSTIC SETUP

The PLIF setup is shown in Fig. 5. The 4th harmonic of an Nd:YAG laser (266 nm) was used as the excitation source. A combination of spherical and cylindrical lenses formed the laser beam into a thin sheet. Since

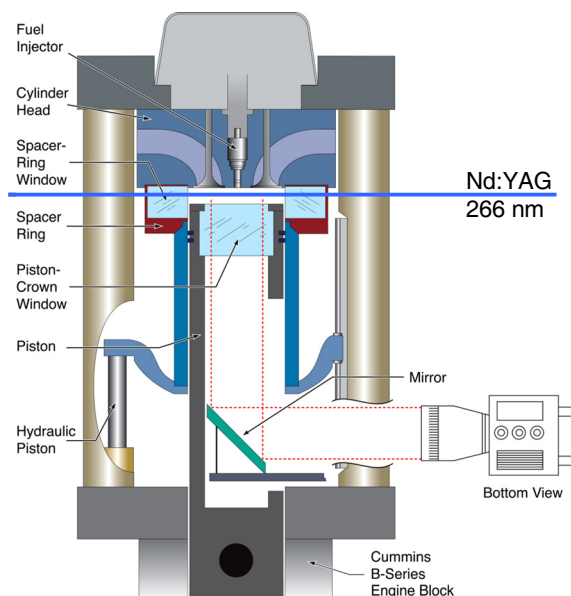


Figure 5. Engine schematic showing the setup for PLIF imaging.

the 4th harmonic laser-beam had a very irregular profile, the laser sheet was overly expanded, so an iris could be used to isolate the most intense and uniform portion of the sheet. In this manner, the laser-sheet intensity in the engine varied less than 20% from the center to the edge. The final sheet width occupied the full width of the spacer-ring window. These windows were designed to have the same inner and outer radii of curvature to prevent the window from acting as a lens. However, the windows were thick, so the focusing effect could not be completely eliminated, and the sheet width slightly converged, from 43 to 39 mm over the field of view in the cylinder. The sheet exited the engine through the spacer-ring window on the opposite side and was captured by a beam dump. Except for the outer boundary-layer measurements, discussed later, the laser sheet was angled slightly downward to prevent damage from back reflections. The laser-sheet energy measured after the iris was 24 mJ/pulse. The final laser-sheet formation optics were mounted on a motorized translating stage that allowed the sheet to be positioned at any desired elevation below the firedeck. For most data, the sheet was positioned in the mid-plane of the pancake combustion chamber (most representative of the bulk gas), which varied from 4 to 16 mm below the firedeck for 360 to 305°CA, respectively.

An intensified CCD camera, sensitive in both the visible and UV ranges, captured the PLIF images through the piston-crown window at a resolution of 640 x 480 pixels. The camera-intensifier gate and laser pulse were synchronized with the engine to obtain images at any desired crank angle. Toluene fluoresces in the UV (265 – 330 nm), and was imaged with a 45 mm f/1.8 fused silica camera lens using a 277 nm long-wave-pass (LWP) and a UG5 UV-bandpass (mainly between 220 and 400 nm) filter. The 277 nm LWP filter blocked elastic scattering from the excitation laser. The UG5 filter substantially reduced undesired interference from visible and near-IR

light emission, thought to be largely due to fluorescence of residual oil in the metal (cylinder head and valves) that was excited by scattered and reflected laser light. The piston-crown window provides a field of view of 70 mm in diameter, which corresponds to approximately half of the area of the 102 mm diameter combustion chamber. For all T-map images presented, a white circle around the imaged area shows the limits of the 70 mm field of view.

Initially, the laser sheet was configured using a 770 mm lens to form a waist near the center of the combustion chamber that was approximately 0.2 mm thick. For images acquired near TDC (pressure ~ 29 bar), this provided images of nearly uniform intensity across the field of view. However, at early crank angles the images had a dark area at the laser-waist location as shown in the left-hand image of Fig. 6. (Note that for all images presented the laser sheet propagates from right to left.) This effect is thought to result from photo-bleaching of the ground state. It is very pronounced at 305°CA because at the lower pressures (~4.5 bar) the collisional rates are not adequate to repopulate the ground state at the rate it is being depleted by laser-pumping to the excited state. Although laser-sheet normalization (discussed below) can largely remove this effect, S/N would be poor in this waist region. Therefore, the optics were reconfigured with a 1550 mm lens forming the waist. Additionally, the waist was positioned beyond the cylinder so the sheet thickness varied from 1.6 to 0.7 mm across the field of view. This increased thickness was more than that required to eliminate photo-bleaching, but the waist could not be moved closer to the cylinder without causing window damage. Fortunately, this thicker sheet still provides sufficient resolution to visualize the thermal stratification. With this long focal-length spherical lens forming the waist, a combination of two diverging lenses (-750 mm and -30 mm) was used to expand the beam into a sheet. This laser-sheet configuration resulted in a uniform image intensity at 305°CA as shown by the right-hand image in Fig. 6.²

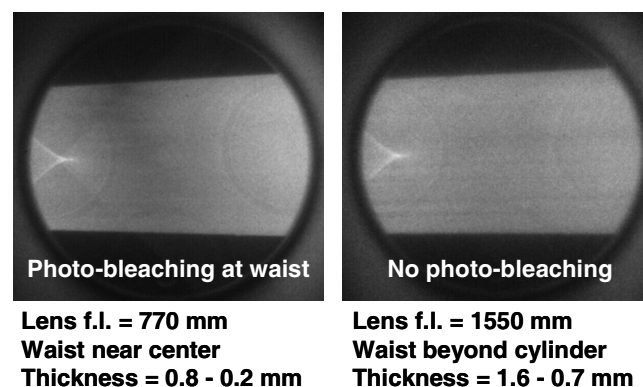


Figure 6. Toluene PLIF images at 305°CA, with different sheet-forming optics.

² The bright triangular-shaped region at the left side of both images in Fig. 6 is a focused back reflection from the exit window. This non-uniformity in laser intensity was removed by the flat-field normalization process discussed in the next subsection.