

Investigating the Development of Thermal Stratification from the Near-Wall Regions to the Bulk-Gas in an HCCI Engine with Planar Imaging Thermometry

Nicolas Dronniou and John Dec
Sandia National Laboratories

ABSTRACT

A tracer-based single-line PLIF imaging technique using a unique optical configuration that allows simultaneously viewing the bulk-gas and the boundary layer region has been applied to an investigation of the naturally occurring thermal stratification in a HCCI engine. Thermal stratification is critical for HCCI engines, because it determines the maximum pressure rise rate which is a limiting factor for high-load operation. The investigation is based on the analysis of temperature maps that were derived from PLIF images, using the temperature sensitivity of fluorescence from toluene introduced as tracer in the fuel. Measurements were made in a single-cylinder optically accessible HCCI engine operating under motored conditions with a vertical laser-sheet orientation that allows observation of the development of thermal stratification from the cold boundary layers into the central region of the charge. Sequences of temperature maps acquired at various crank angles were used to analyze the temporal evolution of thermal stratification.

The temperature maps showed that the thermal stratification in the bulk-gas was not due to a consistent gas flow coming from the cylinder walls or to the transport of isolated cold gas pockets. Rather it is a consequence of cold turbulent structures extending from the firedeck and the piston-top. Furthermore, the cold structures extending from the firedeck appear to be especially important, since they are bigger and penetrate further toward the central region of the charge than those from the piston top. Comparison with previous measurements made in the horizontal mid-plane with the same optical engine showed a good agreement. However, these side-view measurements extend this previous work by highlighting new patterns which were impossible to identify with a bottom-view setup. Beyond the qualitative analysis of temperature fields, quantitative measurements of the thermal stratification are also provided both in terms of magnitude and characteristic dimensions of cold pockets.

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INTRODUCTION

Homogeneous charge compression ignition (HCCI) has been extensively studied during the past decade as an alternative to conventional spark-ignition and Diesel engines. This combustion strategy has advantages in terms of high thermal efficiency and very low emissions of NO_x and particulates, but its limited load range is still one of the most significant technical barriers to its widespread implementation. This load limitation occurs because the cylinder-pressure rise rate (PRR) increases with increased fuel rate, eventually becoming so rapid that acoustic oscillations are induced (i.e. engine knock), which causes excessive noise and potentially engine damage.

Previous research has shown that naturally occurring thermal stratification of the mixture plays a major role in

determining the maximum PRR in HCCI engines. Even with fully premixed operation, this thermal stratification explains why the experimental PRR is much lower than that predicted by single-zone kinetic modeling [1]. While recent studies have begun to investigate the thermal stratification, additional characterization is still needed to understand the distribution, spatial-scale and evolution of the in-cylinder temperature field prior to ignition, as well as the mechanisms producing them. Because this lack of understanding makes it difficult to directly control the heat release rate (HRR) by "adjusting" the thermal stratification, several studies have tried to control the HCCI combustion by adjusting the mixture stratification instead. Although some of these studies have shown promising results, the need to better understand the development of thermal stratification remains relevant for

three reasons. First, the authors have shown that the benefits of partial fuel stratification strategies depend strongly on the fuel chemistry properties and especially on their autoignition sensitivity relative to equivalence ratio [2]. Depending on the fuel characteristics or operating conditions, mixture stratification strategies may not be effective (e.g. naturally aspirated gasoline fueling), so being able to enhance the temperature stratification is still of great interest. Second, it should be noted that even when advanced injection strategies are used to create mixture stratification, naturally occurring thermal stratification is still present, and it still affects the combustion process. Investigating the development of thermal stratification is an important step toward understanding any combined effect with mixture stratification. Third and certainly most important, enhancing the natural thermal stratification has strong potential to allow HCCI engines running at higher loads (see modeling investigations in [1]). All these reasons together led the authors to investigate the nature and the development of the natural thermal stratification, with the objective of understanding its underlying mechanisms and ultimately to determine the potential for enhancing it.

BACKGROUND

In a previous study, the authors used chemiluminescence imaging to investigate the progress of combustion in an optically accessible engine [3]. They showed that initial hot combustion reactions occurred in localized and randomly dispersed regions despite a well premixed fuel/air charge. High-speed chemiluminescence sequences further showed that combustion reactions occurred sequentially throughout the charge from presumably hotter to progressively cooler zones. Another key finding from this study was that the thermal stratification extends throughout the bulk-gas rather than being confined to the boundary layer. The authors have shown that it is this bulk-gas stratification that is mainly responsible for reducing the maximum PRR at higher loads. The boundary-layer regions are much cooler and they autoignite after the maximum PRR timing, so they have only a secondary effect.

Although these chemiluminescence imaging experiments provide valuable information on the HCCI combustion process, they do not provide any information about the magnitude, spatial distribution or the development of the thermal stratification itself. Planar Laser Induced Fluorescence (PLIF) can provide measurements of the in-cylinder temperature fields, and therefore offers the best means of gaining this desired understanding. A literature review shows several previous in-cylinder temperature-imaging investigations. Initial work by Einecke et al. [4] used a two-line excitation of 3-pentanone to image the end-gas temperature in a two-stroke SI engine. A similar two-line technique with ketone tracers (3-pentanone and acetone) was more recently applied by Rothamer et al. [5, 6], Snyder et al. [7] and Loeffler et al. [8, 9] to simultaneously obtain

quantitative temperature and composition measurements. Earlier, Fujikawa et al. [10] also used multi-shot averaged two-line excitation but with toluene as a tracer to measure thermal distributions resulting both from fuel stratification and dual-temperature intake streams. Kakuho et al. [11] measured temperature fields using a single laser but two different dopants (3-pentanone and triethyl-amine). An alternative single-excitation technique taking advantage of the changes of the toluene emission spectra with increasing temperature was also proposed by Devillers et al. [12] and Luong et al. [13] to compute the in-cylinder temperature fields.

Although these previous studies provide good insight into the latest developments in optical methods to measure in-cylinder temperature fields, none of them were really dedicated to the understanding of the naturally occurring thermal stratification. In order to focus on this specific point, the authors applied a toluene single-line PLIF imaging technique [14] in the same optical engine previously used for the chemiluminescence experiments [3]. Because the findings of this previous work are closely related to the motivation of the current study, some key results are reproduced in [Fig. 1](#) and reviewed here.

[Figure 1a](#) presents the optical setup used for the experiments in Ref. [14], which were performed with a fully premixed charge. A horizontal laser sheet was positioned in the mid-plane of the combustion chamber, and PLIF images were obtained through the piston window (bottom-view setup). Temperature maps (T-maps) in [Fig. 1b](#) show that the bulk-gas temperature distribution is extremely uniform at 305° crank angle (CA), indicating no significant thermal stratification and verifying that the charge is very well mixed. The thermal stratification, however, increases later in the compression stroke, with a rapid increase after 340° CA, reaching a maximum at TDC. [Figure 1b](#) shows that this increase occurs both in the number of hot and cold regions and in the temperature difference between these regions. After TDC for this motored-operation study, the thermal stratification decreases because of the reduction of the temperature difference between cold and hot regions, but the number of cold pockets remains nearly unchanged. Based on the available images, the authors reported a characteristic spatial scale of 5-11 mm which is similar to the TDC clearance of 8 mm. They also indicated that the spatial distribution of thermal non-uniformities showed no consistent pattern from cycle to cycle. Rather, the distributions were random, suggesting a turbulent nature to the flow structures producing them.

Two subsequent studies performed with the same engine, but with a two-line excitation and ketone tracers, extended this work [15, 16]. The two-line excitation capability was used to provide additional information which was impossible to obtain with the previous single-line toluene setup. First, the authors showed by two different methods that the mixing of residual gases has almost no influence on the thermal stratification near TDC for a low residual engine

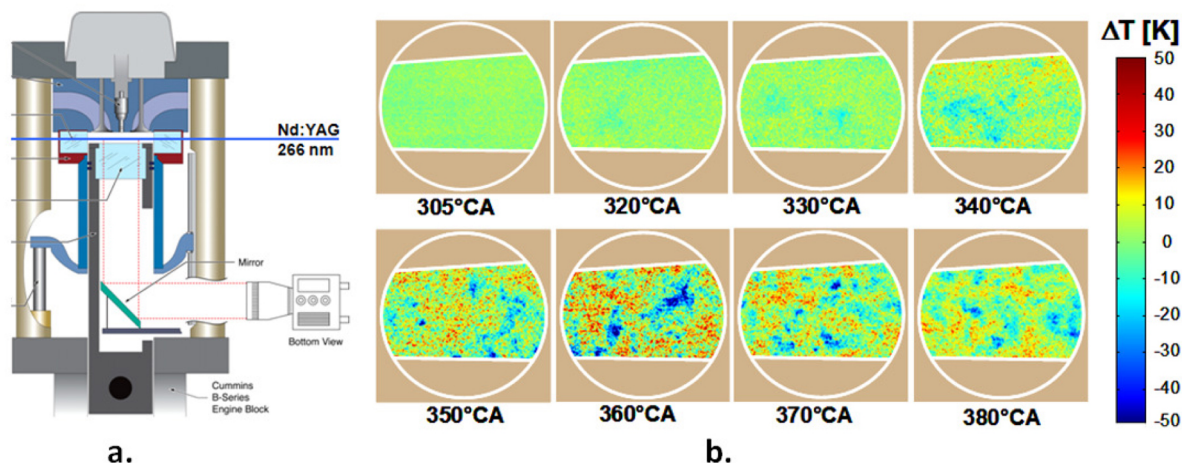


Figure 1. PLIF measurements with the horizontal laser sheet setup. Adapted from [14]. (a) Optical setup with the horizontal laser sheet. (b) Evolution of the thermal stratification in the mid-plane.

(conventional valve timing, residual gas fraction around 4-8%). Second, they showed that the magnitude of thermal stratification for both motored and fired experiments was very similar if the wall temperature was properly matched. This finding is important because it proves that motored conditions are relevant to investigate the thermal stratification in HCCI engine operation. Third, they temporally shifted the two laser pulses to prove there was a correlation between regions of high-temperature and location of early combustion zones.

The combination of these previous studies offers an initial description of how bulk-gas thermal stratification develops in a HCCI engine. Since residual-gas mixing was shown to have virtually no influence when conventional valve timing is used, the transport of cold gases from the walls to the central region of the charge appears to be the primary cause of the naturally occurring thermal stratification. However, the mechanism that is responsible for this transport remains largely unknown. For example, it is not possible to tell whether the cold areas seen in the horizontal mid-plane (see Fig. 1b) are produced by large flows generated by piston motion, by turbulence remaining from the intake stroke or by some other means. Because identifying the transport mechanism is essential to understand and ultimately modify the bulk-gas thermal stratification, a new set of optical experiments is implemented in the current study. For these experiments, the laser sheet is oriented vertically and images are viewed from the side through a window in the upper cylinder wall. This new optical setup has the substantial advantage in that it allows simultaneous viewing of the temperature in the bulk-gas and near the wall. The aim of this study is then to identify the nature, evolution and spatial-scale characteristics of the transport of cold gases from the walls to the bulk-gas. The planar temperature imaging diagnostic chosen for this new study is based on the single-line toluene PLIF technique previously used by the authors [14]. This technique was selected because previous work has shown that

a single-line technique has a better accuracy [16] than a two-line technique as long as the charge is well mixed. The data were acquired in a motored engine, since previous work has shown that motored engine data match well with those from a fired engine up to the onset of combustion [15]. Motored operation has the additional advantages to not overheating the optical engine and preventing tracer breakdown.

ENGINE EXPERIMENTAL SETUP

EXPERIMENTAL FACILITY

The optically accessible HCCI engine used for this study was derived from a Cummins B-series six-cylinder Diesel engine, which is a typical medium-duty Diesel engine with a displacement of 0.98 liters/cylinder. The engine, which has been converted for single-cylinder operation by deactivating cylinders 1-5, has a geometrical compression ratio of 14:1 and a nominal swirl ratio of 1.3. Engine specifications are listed in Table 1 and detailed descriptions of the facility may be found in Refs [3, 17, 18].

Table 1. Engine Specifications

Displacement (single-cylinder).....	0.98 liters
Bore	102 mm
Stroke	120 mm
Connecting Rod Length	192 mm
Geometric Compression Ratio	14:1
No. of Valves	4
IVO.....	0° CA*
IVC.....	202° CA*
EVO	482° CA*
EVC	8° CA*
Swirl Ratio.....	1.3

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

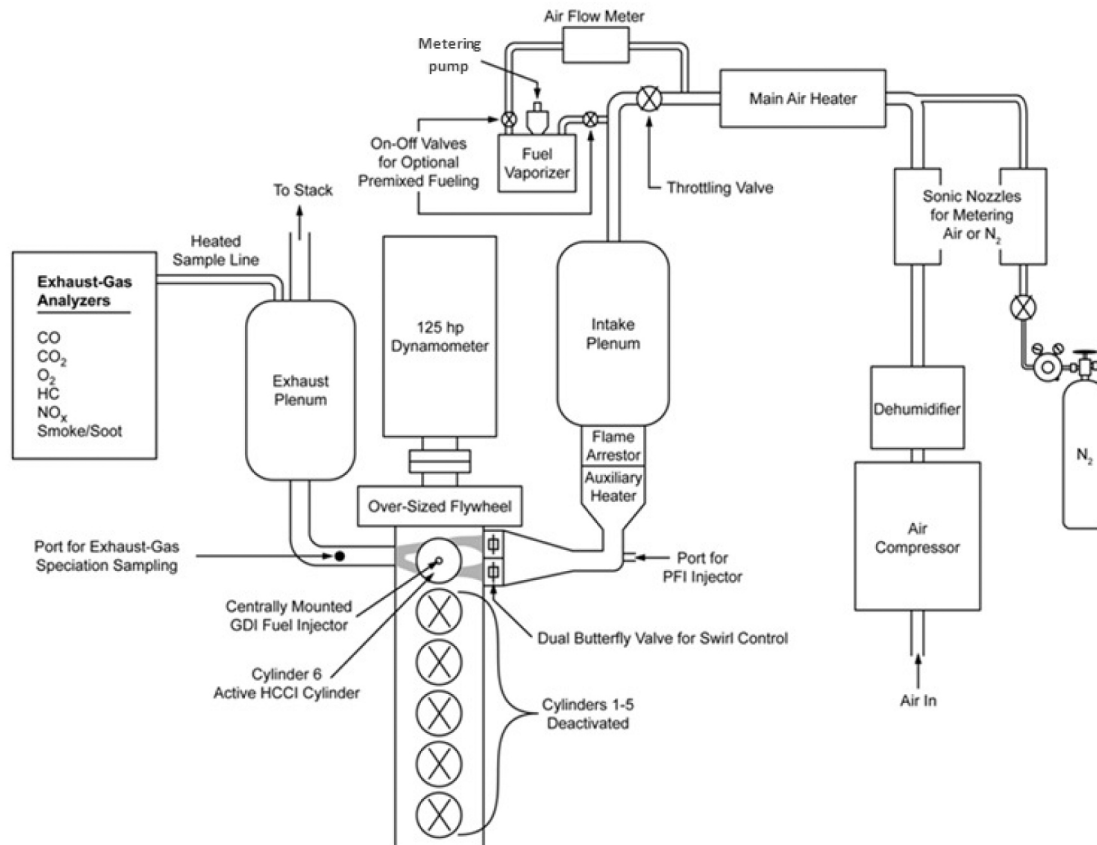


Figure 2. Schematic of the HCCI engine facility.

The intake charge was fully premixed to ensure a homogeneous air-fuel mixture inside the cylinder. The fuel and tracer were introduced into the fuel vaporizer with a metering pump. The fuel vaporizer itself consists of an electrically heated chamber and appropriate plumbing to ensure thorough premixing upstream of the intake plenum. In order to minimize quenching of the toluene PLIF signal and to prevent breakdown of the tracer, the intake charge was made inert by operating with nitrogen instead of air. The use of nitrogen instead of air should not affect the development of the thermal stratification, because both gases have very similar polytropic coefficient and gas composition is likely to have only a very limited influence on the in-cylinder flows. 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 with a main heater located upstream of the fuel vaporizer and an auxiliary heater mounted close to the engine to provide precise control of the intake temperature.

OPTICAL ENGINE

The schematic of the optical engine used for this study is presented in Fig. 3a. The engine utilizes a Bowditch piston arrangement with a large piston-crown window (70 mm diameter). The spacer ring that forms the top part of the

cylinder wall contains three large windows to provide optical access that extends downward 29.5 mm from the firedeck (*i.e.*, the flat cylinder-head surface). As shown in Fig. 3a, the spacer ring and windows are recessed into the cylinder head to allow optical access up to the firedeck surface. The inner surfaces of the spacer-ring windows are curved to match the cylinder bore. Figure 3b shows that the flat piston-crown window and the firedeck create a pancake combustion chamber. For the current study, the piston length was set to give a geometric compression ratio (CR) of 14:1 with a clearance of 8.05 mm at TDC. 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. As illustrated in Fig. 3a, the optical engine has a drop-down cylinder liner with hydraulic-piston actuation to allow rapid cleaning and the optical configuration allows two different laser-sheet and camera orientations. The bottom-view which was used for previous studies [14,15,16] allows imaging a horizontal laser sheet via the 45° mirror and the piston-crown window. For the current study, the laser sheet was oriented vertically and images were acquired through the side-view window using the upper camera position shown in Fig. 3a. Although the piston-crown window is not needed to obtain side-view images, the piston

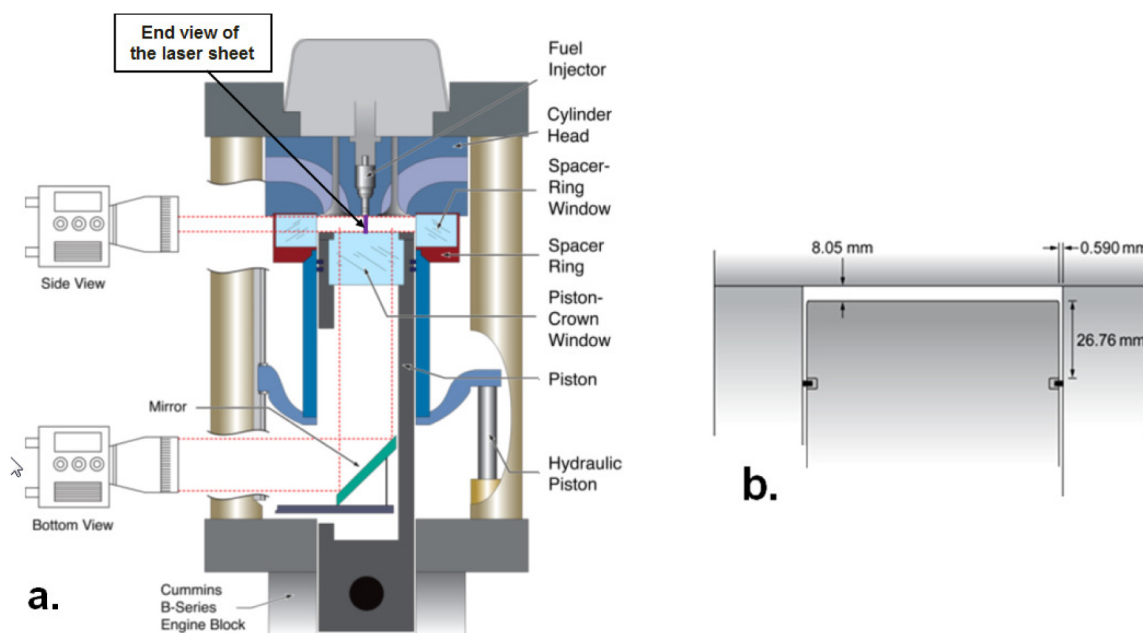


Figure 3. Schematic of the optical accessible HCCI engine. (a) Position of the cameras used for the temperature PLIF imaging (Bottom view: references [14,15,16], side view: current study). (b) Schematic of the CR=14:1 piston at TDC.

assembly was not modified for this set of experiments. Because the engine was motored, the fuel injector shown in Fig. 3a was replaced by an injector blank. As shown in Fig. 3b, there is a significant piston crevice because the first of the three piston rings (not to scale in Fig. 3b) is located almost 27 mm below the piston top.

ENGINE OPERATION

Table 2 reviews the engine operating conditions selected for this work. As for the previous studies [14,15,16], data were taken at an engine speed of 1200 rpm with the intake flow adjusted to provide an intake pressure of 100 kPa, simulating naturally aspirated conditions. All data were acquired in a motored engine with the charge made inert with nitrogen instead of air to prevent toluene tracer breakdown and oxygen quenching of the PLIF. 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. For all the data presented in the results section, the intake temperature was set to 170°C, which is representative of the intake temperature required for iso-octane/air mixtures near the high-load limit with CR=14:1 ($\phi=0.4 - 0.5$). However, images were also acquired for intake temperatures of 65, 100, 135 and 205°C in order to calibrate the temperature dependence of the PLIF signal. As indicated in Table 2, the base-fuel used for the experiments is iso-octane. This reference fuel has similar characteristics to gasoline, but does not fluoresce with the ultraviolet laser light used to excite the toluene PLIF. Iso-octane was mixed with toluene prior to engine operation to obtain a blend of 96% iso-octane and 4% toluene by volume. This blended fuel was then delivered to the fuel vaporizer at a rate corresponding to

an equivalence ratio of 0.4 if the nitrogen were replaced with air. Overall, engine operating conditions summarized in Table 2 are identical, or very similar, to those used in previous studies from this laboratory [14,15,16]. This consistency allows comparison of results with previous thermal stratification measurements made with other optical configurations, for a more comprehensive overall understanding.

Table 2. Engine operating conditions

Engine speed.....	1200 rpm
Intake gas composition (without fuel)	100% nitrogen
Intake pressure.....	100 kPa
Intake temperature.....	65 → 205°C
Base Fuel.....	Iso-octane
Tracer seeding.....	4% toluene by vol.
Charge-mass phi (ϕ_{m1})	0.4

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 $\frac{1}{4}^\circ$ CA increments for 100 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

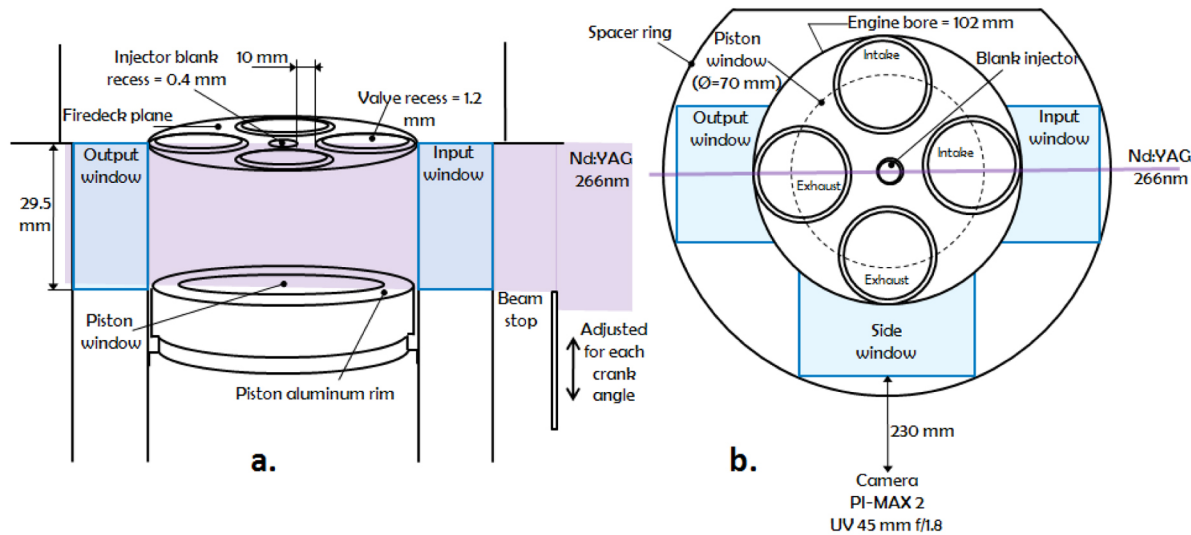


Figure 4. Vertical LIF setup. (a) Exploded side view. (b) Top view.

firedeck, provided an indication of in-cylinder surface temperatures. For all data presented, 0° 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

EXPERIMENTAL PLIF SETUP

The PLIF experimental setup is shown in Fig. 4. Figure 4a presents the vertical laser sheet inside an exploded side view of the cylinder, while Fig. 4b shows the laser sheet position together with the spacer ring and the firedeck as viewed from below. The 4th harmonic of a Nd:YAG laser (266-nm, 6-ns pulse at 10 Hz) was used as the excitation source. A combination of spherical and cylindrical lenses, not shown in this figure, formed a thin vertical laser sheet. A beam-stop located just before the input window blocked the bottom part of this laser sheet to prevent it from hitting the piston. The position of this beam-stop was adjusted for each crank angle of interest using a motorized translation stage. The laser energy was typically around 0.5 mJ/mm in the vertical direction of the laser sheet. Depending on the crank-angle of interest and hence of the beam-stop position, the laser energy entering the engine typically ranged from 4.5 mJ at TDC up to 15 mJ when the beam stop was positioned below the input window. The laser sheet was also angled slightly upward to ensure that its upper edge hits the firedeck surface all across the engine bore. However, the engine valves and injector blank are recessed slightly above the firedeck surface, so the laser sheet reached the cylinder head in only two locations between the valves and the injector blank (Fig. 4b). The drawback of this upward angle is that it prevents the laser sheet from skimming the piston-top all across the engine bore. Nevertheless, because this upward angle was very

small, and the laser sheet was slightly diverging, measurements could be made along the piston top surface except for the last millimeters near the output window for crank angles around TDC.

As can be seen in Fig. 4b, the spacer ring windows have curved inner surfaces and flat outer surfaces, making them diverging lenses in the horizontal direction. The laser-sheet forming optics were selected to work with this window shape to create a nearly constant sheet thickness of about 1 mm across the engine bore. The side window through which the camera views the laser sheet is wider than the input and output windows. The wide divergent lens formed by this window allows imaging the full bore diameter in a single image. Although this lens-effect creates some optical distortion, the images can be corrected by digital post-processing.

For each crank angle of interest, 100 PLIF images were acquired with an intensified CCD camera (PIMAX 2). The camera and laser system were operated at 10 Hz for all experiments, allowing one image acquisition per cycle at the 1200 rpm engine speed. The 512×512 pixel array was binned 3×3 on the chip to increase signal levels with a sacrifice of spatial resolution. Because of the distortion, the resulting image spatial resolution was approximately 0.45 mm per pixel in the horizontal direction and 0.33 mm per pixel in the vertical direction. The camera was equipped with a 45 mm f/1.8 UV lens. A 277-nm long-wave-pass filter blocked elastically scattered laser light, and a UG5 bandpass filter (220-400 nm) was used to substantially reduce undesired interference from visible background light.

Some image vignetting occurred near TDC because the piston clearance was significantly smaller than the lens aperture as evident in the schematic in Fig. 5. For this study, the centerline of the camera was deliberately positioned below the combustion chamber mid-plane in order to avoid significant vignetting near the firedeck. Such a camera

position, however, causes more vignetting near the piston-top surface when the piston is near TDC. Although reference images from static tests performed prior to engine experiments allowed correcting for most of the vignetting (see [Appendix](#) for details), quantitative measurements will be less accurate near the piston-top surface for crank angles near TDC.

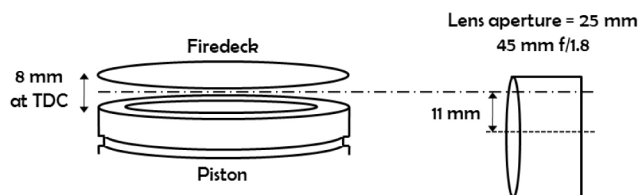


Figure 5. Illustration showing why vignetting occurs near TDC.

PLIF DIAGNOSTIC

The diagnostic selected for the temperature imaging is based on the temperature sensitivity of single-line PLIF signal of toluene with UV excitation at 266-nm. As noted by Koban et al. [19], for homogeneous mixtures at constant pressure, the fluorescence from 266-nm excitation of toluene is a function of temperature only. For the current engine experiments, the engine was supplied with a homogeneous fuel-nitrogen mixture, but pressure varies with crank angle. In order to remove any effect of pressure and number density variation, the piecewise calibration technique applied in [14] was used. With this technique, a separate in-situ calibration for each crank angle of interest is derived from PLIF images acquired at five different intake temperatures, but at a constant intake pressure. Although differences in intake temperature will create differences in heat transfer and hence some pressure differences for a given crank angle, the difference is small (≈ 2 bar at TDC between extreme cases), and previous studies [12, 20] have shown that this limited pressure variation barely affects the fluorescence of toluene in nitrogen.

Previous studies by the authors and co-workers have shown that 3-pentanone can also be a good tracer candidate for single-line thermal imaging techniques using excitation at 277 and 308-nm [15, 16]. Preliminary experiments, not shown here, confirmed that using 3-pentanone could also be relevant with 266-nm excitation. Although this tracer has a major advantage of not being sensitive to oxygen quenching, it was not selected for this study because of noise from background fluorescence. As the laser sheet enters the cylinder, the beam or one of its reflections can create significant background visible-light emission. The location of this undesired background light was critical, because most of it was superimposed with the fluorescence near the cylinder wall which is a major region of interest for this study. The use of toluene as a tracer virtually eliminates this problem because its PLIF signal is in the UV (260-360 nm, [20, 21]),

so the UG5 filter could be used to remove this visible-light background noise. This solution was impossible with 3-pentanone because its fluorescence spectrum (325-525 nm, [21]) occurs mainly in the visible.

IMAGE POST-PROCESSING

Compared to previous works by the authors and co-workers [14,15,16], the image post-processing used in this study is significantly different. In these previous studies (and in other works in the literature), single-shot images are normalized by their set-average to remove laser attenuation and laser-sheet profile uniformities. This normalization technique, often referred to as a “flat-field” correction, could not be applied in the current study, because it would remove any cold boundary layer that is consistent from cycle to cycle. This issue did not exist in the previous studies, because temperature fluctuations in the horizontal mid-plane were so randomly distributed that sufficient averaging produced a near-homogeneous flat-field correction, and boundary layers at the cylinder walls were not visible through the piston-top window. The inability to use a flat-field correction creates major challenges for the image post-processing. All the non-uniformities that could have been with a flat-field correction must now be independently identified and corrected.

The image post-processing used for this study consists of four main steps which are illustrated in [Fig. 6](#). This figure shows an example of conversion from a raw single-cycle PLIF image to its corresponding T-map. The image post-processing is only summarized in this section, but further details with illustrated examples are provided in the [Appendix](#).

Step 1: Set-Averaged images

For each condition, a set of 100 PLIF images was acquired and averaged. The set-averaged raw image was then successively modified with the list of corrections described in [Table 3](#). The analysis of set-averaged images allows determining the attenuation coefficient and the normalized profile needed to correct for the laser sheet profile drift (see [Appendix](#) for details). These two parameters were impossible to determine with single-cycle PLIF images, because the real temperature stratification dominates the light intensity variation within the image. Since instantaneous temperature variations in the central part of images were shown to disappear with sufficient averaging, set-averaged images are well suited to compute parameters and patterns that are consistent from cycle-to-cycle. After these parameters and patterns have been determined, they can be applied back to the single-cycle PLIF images. For instance, [Fig. 6b](#) shows that the left side of the image is brighter after the use of the laser attenuation correction than it was in [Fig. 6a](#). Influence of the vignetting (low intensity regions near the piston-top in the raw image) and distortion corrections are also evident when comparing the [Figs. 6a](#) and [6b](#).

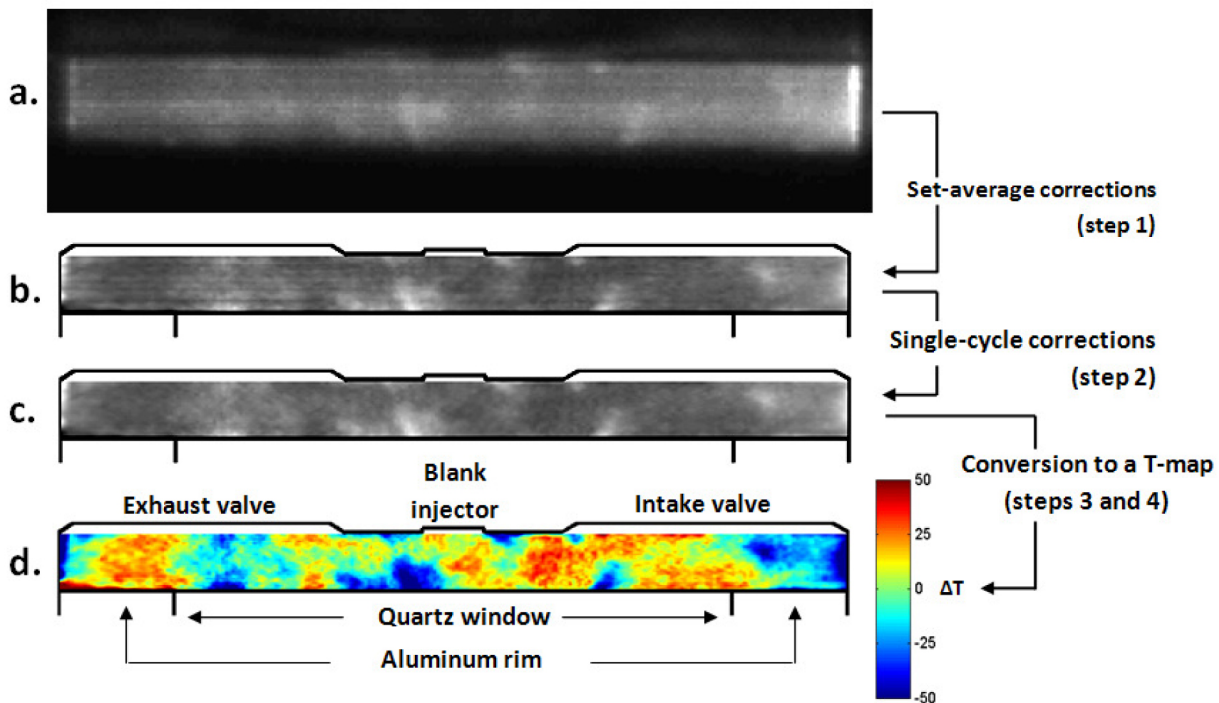


Figure 6. Conversion of a raw PLIF image to a T-map. (a) Single-cycle raw PLIF image at 360 °CA. (b) Single-cycle intensity image after set-averaged corrections. (c) Single-cycle intensity image after single-cycle stripe correction. (d) Corresponding T-map.

Table 3. List of image corrections for set-averaged images

1. Camera gain
2. Normalization by the laser energy
3. Tracer concentration correction
4. Background subtraction
5. Beam profile correction using a normalized average image taken at BDC (no thermal stratification)
6. Distortion correction
7. Attenuation correction
8. Vignetting correction
9. Laser profile drift correction

Step 2: Single-cycle images

Following all the set-averaged corrections listed in [table 3](#), additional corrections still need to be applied to each individual image in order to remove horizontal stripes (see left side of [Fig. 6b](#)) created by the laser shot-to-shot laser profile variation and by the beam steering created by the temperature gradient existing at the inner surface of the input window. Although it is difficult to isolate the exact relative contribution of these two mechanisms, both of them occur simultaneously during engine experiments and affect each individual PLIF image in a different manner. Set-average corrections cannot correct for these shot-to-shot perturbations, so a new set of corrections should be applied to

each individual image. The algorithm used is detailed in the [Appendix](#) and is essentially based on the spatial scale separation existing between thermal stratification patterns and the thin-elongated shape of horizontal stripes. [Fig 6c](#) shows that the use of this algorithm successfully removes the stripes without altering the main features of the image.

Step 3: Calibration curves

Once all the individual images have been corrected, a calibration is needed to convert PLIF intensity into temperature. To calibrate the temperature sensitivity of the toluene-PLIF signal, images were acquired for five intake temperatures: 65, 100, 135, 170 and 205°C. For each condition, the adiabatic core temperature was first computed by assuming adiabatic compression following the ensemble-averaged pressure trace and using real gas properties. In this manner, the computed temperature accounts for the overall effects of heat transfer (through the measured pressure trace), but assumes the existence of an adiabatic core. This approach is similar to that used in our previous studies [[14,15,16](#)]; however, a more advanced method is now used to identify the adiabatic core in PLIF images. Rather than assuming that the central region of the image is representative of the adiabatic core, all individual corrected-PLIF images are scanned to select the intensity corresponding to the hottest zones. Since the toluene fluorescence decreases with increasing temperature, the hottest regions, which are the most representative of an adiabatic core, have the lowest intensity.

Illustrated examples and additional explanation of this method are available in the [Appendix](#). For each intake temperature and crank angle of interest, the temperature of the adiabatic core estimated from the pressure trace is assigned to the corresponding intensity of these dimmest regions of the PLIF images.

Calibration curves are presented in [Fig. 7](#). [Figure 7a](#) shows the calibration curves for various crank angles before TDC. This figure confirms that the toluene fluorescence intensity strongly decreases with increasing temperature. However, the correlation between intensity and temperature varies with crank angle, because corrections for the number density are not included. Therefore and as illustrated in [Fig. 7b](#), a separate calibration curve is created for each crank angle of interest by fitting the five intensity-temperature data points. It may be noted that no calibration curves exist for crank angles after TDC. Since heat transfer increases during the engine cycle, the assumption of an adiabatic core is likely to be less valid for late crank angles. Since the before-TDC crank-angles are less affected by heat transfer and the pressures are similar to those at the same number of CA degrees after TDC, the calibration curves for the corresponding crank angles before TDC were used for analyzing the after-TDC images.

The absolute accuracy of the PLIF measurements depends on the validity of the adiabatic core assumption. While it should be valid at early crank angles, significant heat transfer has already occurred by crank angles near TDC, so the assumption that the hottest regions of the charge are adiabatic could be questioned. The absolute temperature of the calibration points shown in [Fig. 7b](#) could then be a little overestimated, but the shape of the curve is likely to be only modestly affected. It is the shape of the curve that quantifies temperature variations in PLIF images, and thus the temperature stratification. Since the development of the thermal stratification is the only focus of this study, the use of these calibration curves is justified.

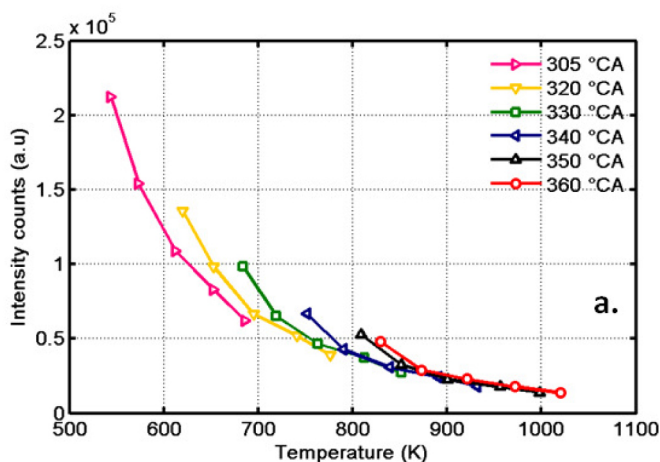


Figure 7.

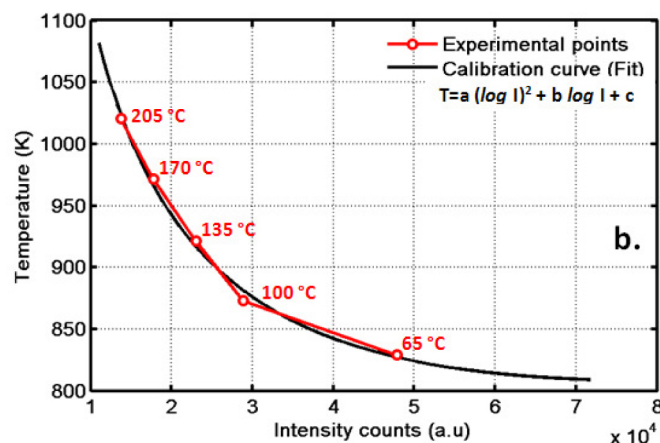


Figure 7 (cont'd). Calibration curves for converting PLIF intensity to temperature. (a) PLIF Intensity against temperature for different crank angles. (b) Temperature against PLIF intensity at 360 °CA showing the curve fit (Each experimental point corresponds to a different intake temperature).

Step 4: Conversion to a T-map

Once the calibration curves have been computed, the intensity of each pixel can be converted to temperature in order to provide the T-map shown in [Fig. 6d](#). T-maps are presented in terms of temperature variation (ΔT) around the averaged temperature of each image, rather than in absolute temperature (see above discussion about the accuracy of the calibration curves). This choice also allows the use of a single temperature scale ($-50 \rightarrow +50$ K) to compare the development of the thermal stratification at different crank angles.

The example presented in [Fig. 6](#) also illustrates some experimental limitations that must be considered when analyzing the T-maps presented in this study.

First, [Fig. 6a](#) shows that the PLIF intensity is lower on the left side of the image because of laser attenuation. Although the attenuation correction allows correcting for this intensity decrease, the measurement accuracy on the left side of the T-map is still less because of a lower signal-to-noise (SNR) ratio. [Figure 6a](#) also illustrates the slight upward angle of the laser sheet (note that the input window is on the right side of the image). As described in the Experimental PLIF Setup section, this angle was chosen to make sure that the laser sheet hits the firedeck surface all across the engine bore. Around TDC, the drawback of this angled sheet is that it does not illuminate the piston-top surface near the output window, resulting in the artificial high-temperature zone in the bottom-left corner of the T-map presented in [Fig. 6d](#). The laser attenuation and this slight upward angle both indicate that the accuracy will be higher on the right-side of the T-maps.

Another major difficulty associated with this experimental setup is the vignetting caused by the small piston clearance at TDC (8.05 mm compared to 25 mm for the lens aperture). To