

PLIF Measurements of Thermal Stratification in an HCCI Engine under Fired Operation

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ABSTRACT

Tracer-based PLIF temperature diagnostics have been used to study the distribution and evolution of naturally occurring thermal stratification (TS) in an HCCI engine under fired and motored operation. PLIF measurements, performed with two excitation wavelengths (277, 308 nm) and 3-pentanone as a tracer, allowed investigation of TS development under relevant fired conditions. Two-line PLIF measurements of temperature and composition were first performed to track the mixing of the fresh charge and hot residuals during intake and early compression strokes. Results showed that mixing occurs rapidly with no measureable mixture stratification remaining by early compression (220°C at TDC), confirming that the residual mixing is not a leading cause of thermal stratification for low-residual (4-6%) engines with conventional valve timing.

In the second part of the study, single-line PLIF measurements performed later in the compression stroke showed that the distribution of TS and its development are very similar for both motored and fired operation. This finding indicates that the mechanism producing the temperature stratification is the same for both cases, although some differences in magnitude can occur. A subsequent parametric study proved that these differences can be attributed to the impact of both incomplete fuel mixing and cylinder-wall temperature variation, depending on the type of engine operation (DI skipfiring or premixed continuous firing respectively).

In the final part of this study, the simultaneous use of the two lasers allowed correlation of the high temperature zones existing before TDC with the early reaction zones after TDC. These image pairs indicated that the first combustion reactions begin in the highest temperature regions followed by reactions in progressively cooler zones, proving that TS is the root cause of sequential auto-ignition in HCCI-combustion engines. All these measurements demonstrate the feasibility of quantitative tracer-based PLIF diagnostics in harsh engine environments and provide useful information for future HCCI engine development.

INTRODUCTION

The homogeneous charge compression ignition (HCCI) engine strategy provides both high efficiency and low emissions. However, the limited load range is a technical challenge that must be addressed prior to widespread implementation. The high-load limit specifically is constrained by high cylinder pressure rise rates (PRR) during combustion that can lead to engine knock as fueling is increased.

Previous research has shown that naturally occurring thermal stratification (TS) of the in-cylinder charge is central to high-load HCCI operation [1, 2]. The dominant mechanism for TS development is thought to result from wall heat transfer and convection of the near-wall cold gas [1]. However, TS may also result from the retained combustion residual gas, and fuel injection. The resulting localized temperature variations

in the bulk-gas lead to sequential auto-ignition, where the hottest regions ignite first followed by progressively cooler regions [1, 3]. This effectively slows the combustion heat release rate (HRR) and could potentially be exploited to expand the high-load limit.

While recent studies have begun to investigate the impact of thermal stratification, additional characterization is still needed. Chemiluminescence was previously employed to indirectly study its effects on HCCI combustion [1]. It showed the auto-ignition occurring in localized zones that were randomly dispersed within the bulk-gas despite operation with a fully premixed fuel/air charge. High speed chemiluminescence image sequences further showed that reactions occurred sequentially throughout the charge. Although this has been attributed to TS [1, 3], this has not been directly verified. It was also found that TS in the boundary layer has only a secondary effect on the reduction in PRR as the timing of reactions in these regions is well after the maximum PRR [1].

Additionally, multi-zone Chemkin engine simulations demonstrated the necessity of including thermal stratification in HCCI simulations to better match experimental cylinder pressure measurements and apparent heat release (AHR) profiles [2]. In addition, the benefit of a given amount of TS was found to be amplified by retarding the combustion phasing [2]. While these studies do provide evidence of TS, they do not specifically address the distribution, spatial-scale, and evolution of TS during HCCI operation. This fact has motivated the development of several fluorescence-based diagnostics to directly investigate TS.

In an initial work, Dec et al. [4] have developed a single-line, planar laser-induced fluorescence (PLIF) temperature diagnostic using toluene as the fluorescence tracer with 266 nm excitation. Subsequently, the current authors have developed similar single-line [5] and two-line [5, 6, 7] techniques using either 3-pentanone or acetone (both ketones) with excitation at 277 nm and 308 nm. All single-line techniques provided sufficient temperature precision to resolve small temperature fluctuations, and were independently used to study TS development in the same motored HCCI engine. Results from both studies [4, 5] showed similar trends, with TS progressively increasing during the later part of the compression stroke. These results provide useful quantitative TS data for motored experiments with fully premixed fueling. However, it is somewhat unclear exactly how the TS behavior will change when transitioning to fired conditions, as this will introduce other potential mechanisms of TS development such as hot residual gas mixing, direct fuel injection, and changes in wall temperature.

The current work extends the application of the ketone based diagnostics to fired HCCI operation and investigates the

differences and similarities between motored and fired conditions. First, a two-line diagnostic for temperature and composition is applied to study the residual mixing process and to determine the potential impact of residuals on TS for low-residual HCCI operation. Low-residual conditions are achieved with conventional valve timing, resulting in a small quantity of hot combustion residuals. Strategies such as negative valve overlap (NVO) [7] that increase residual gas retention are not considered in this study. The impact of combustion residuals is further studied by comparing single-line temperature results acquired for skipfired cycles with and without hot residuals.

Next, a single-line temperature measurement during the compression stroke is used to characterize the TS development for motored and fired operation. The influence of early direct fuel injection is considered by comparing motored measurement results with fully premixed fuel or early direct injection. In addition, the impact of boundary wall temperature is investigated through comparison of premixed fired results with varying coolant temperature. Finally, spatial correlation between the temperature distribution and subsequent reaction zones are used to study the progression of reaction within the cylinder core, and to demonstrate the importance of TS in the sequential auto-ignition of HCCI combustion.

EXPERIMENTAL METHODS

OPTICAL ENGINE FACILITY

PLIF measurements were performed in the HCCI engine facility shown in Fig. 1a. The optically accessible engine is derived from a Cummins B-series, medium-duty diesel engine that was converted for single-cylinder operation. Detailed descriptions of the engine and facility are available in [1, 8], and will only be summarized here. The engine has a displacement of 0.98 liters and a geometric compression ratio of 14:1 with a pancake-style combustion chamber (flat head, flat piston-crown) depicted in Fig. 1b. Relevant engine specifications are presented in Table 1. Optical laser-sheet access is provided by three fused silica windows integrated into a spacer ring that forms the top portion of the cylinder wall, as shown in Fig. 2. A Bowditch piston assembly outfitted with a large piston-crown window (70 mm diameter) and right-angle mirror permits imaging access from below. A drop-down cylinder liner with hydraulic-piston activation allows rapid cleaning of internal window surfaces between experiments. The engine is coupled to a 125 hp dynamometer to either motor the engine, or absorb load to maintain constant speed for fired experiments.

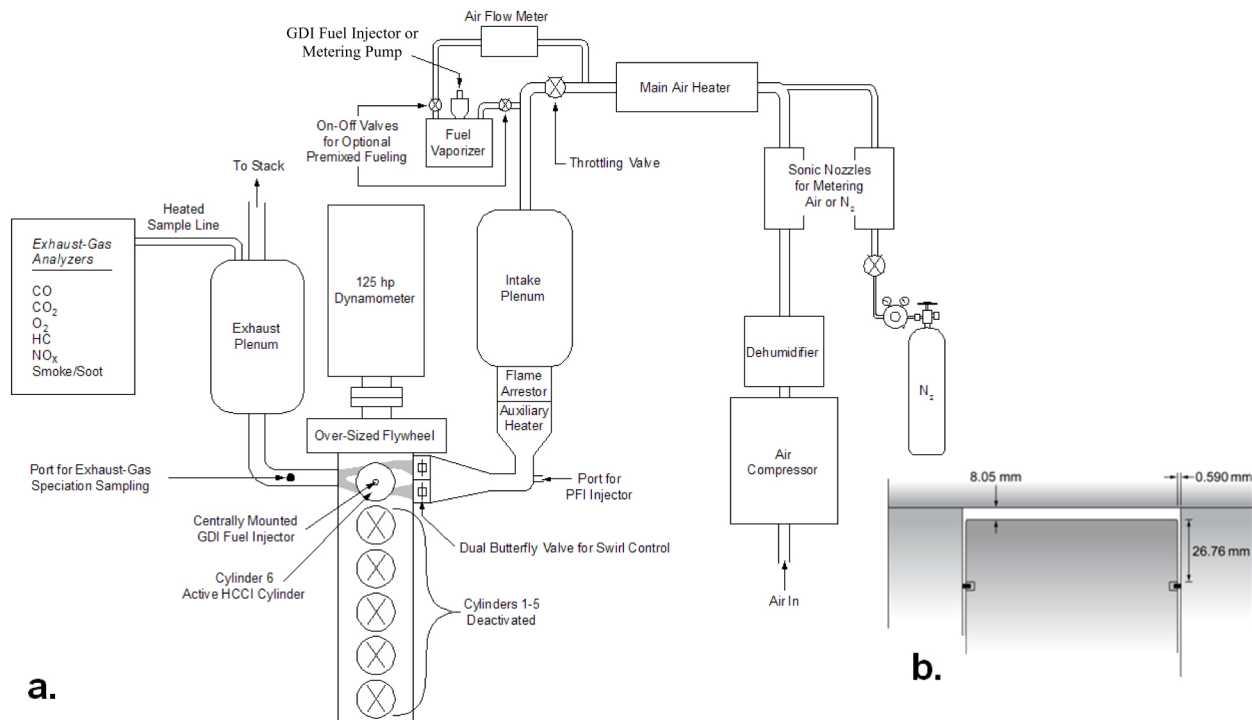


Figure 1. (a) Schematic of the optical HCCI engine facility, (b) Schematic of the optical engine piston at TDC - CR=14.

Table 1. Optical HCCI engine specifications.

Displacement	0.981 liters
Bore	102 mm
Stroke	120 mm
Connecting Rod Length	192 mm
Geometric Compression Ratio	14:1
Clearance Volume Height	8.05 mm
Number of Valves	4
Intake Valve Open (IVO)	0° CA*
Intake Valve Close (IVC)	202° CA*
Exhaust Valve Open (EVO)	482° CA*
Exhaust Valve Close (EVC)	8° CA*
Swirl Ratio	1.3

*360°CA is TDC of combustion

*Valve opening /closing timings refer to 0.1 mm of lift

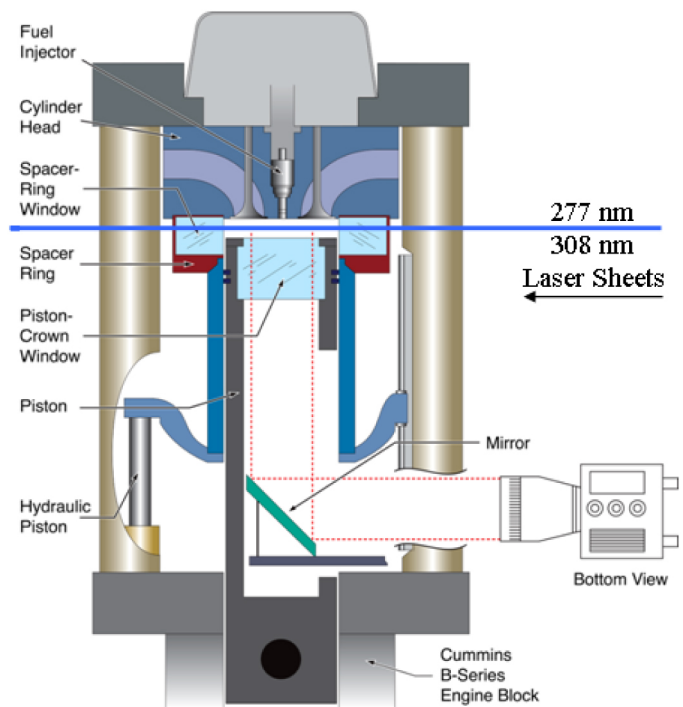


Figure 2. Schematic of optically accessible HCCI engine showing orientation of laser sheets and imaging camera

Intake flow of either air or nitrogen was metered with a sonic-nozzle orifice and was continuously adjusted to maintain a constant intake pressure of 100 kPa for all experiments. The intake streams were electrically heated by a

main and an auxiliary heater to the desired intake temperature. The auxiliary heater, located near the engine intake manifold, provided precise temperature control, and was used for fired experiments to adjust the combustion phasing in real-time. Intake temperatures ranging from 190-198°C were used for the fired experiments depending on the equivalence ratio and mode of operation (skipfired or continuous). For fired experiments, the intake temperature was adjusted to maintain the calculated 50% burn point (CA50) at a crank angle (CA) of 367°. A summary of the engine operating conditions is provided in [Table 2](#).

Iso-octane was selected as the gasoline reference fuel, as it has similar ignition characteristics to gasoline, but does not fluoresce with excitation in the ultraviolet. The fluorescence tracer, 3-pentanone, was seeded in either the fuel or the intake air to provide an average tracer mole fraction of 0.0015 in-cylinder. For most experiments, 3-pentanone was seeded into the intake air and pure iso-octane was directly injected (DI skipfired, DI motored). However, for the premixed fired and premixed motored experiments tracer was blended with the base fuel at 14% by liquid volume to provide the same 0.0015 tracer mole fraction in-cylinder. Addition of this quantity of tracer does impact the combustion, causing advanced combustion phasing due to the lower ignition delay time of 3-pentanone compared to iso-octane [9]. To account for this, the intake temperature has been adjusted to maintain combustion phasing at 367°CA (based on CA50) which gives robust HCCI combustion without knocking. The presence of 3-pentanone is not expected to influence the current study as no comparison with pure iso-octane results is made, and no emissions measurements are considered.

Both premixed and direction injection (DI) fuel delivery methods were used depending on the mode of operation (skipfired or continuous fired). The premixed fueling system consisted of a positive-displacement pump that delivered the fuel/tracer mixture to an electrically heated vaporizer shown in [Fig. 1a](#). The vaporizing chamber was located upstream of the intake plenum to ensure a truly homogeneous fuel/air mixture in-cylinder. The premixed fuel delivery rate was determined by monitoring the mass of fuel delivered (with a lab scale) over 60-second intervals. Direct fuel injection was supplied by a gasoline-type direct injector (GDI 8-hole, 70° included angle) mounted in the center of the cylinder head. The injector was operated at a pressure of 120 bar, and a positive displacement fuel-flow meter was used to monitor the amount of DI fuel supplied.

Table 2. Engine operating conditions.

Intake Temperature	190-198 °C
Intake Pressure	100 kPa
Coolant Temperature	60°C, 100°C
Equivalence Ratio (F/A)	0.32, 0.4
Base Fuel	Iso-Octane
Fuel Delivery	Fully Premixed Direct Injection
Tracer	3-Pentanone
Tracer Seeding [mole fraction]	0.0015*

**Corresponds to 14% of fuel (by liquid volume) for an equivalence ratio of 0.4*

The cooling water and lubricating oil were preheated to 100°C by electrical heaters in the circulation systems for all motored and fired experiments unless otherwise noted. Prior to data acquisition, the engine was motored until the measured cylinder wall temperature reached steady-state, typically 3-5 minutes. During this time the intake mass flow and temperature were adjusted to provide the desired intake conditions. For motored experiments, the fluorescence data were then taken at the desired image timings. Subsequently, the engine was stopped and cleaned before repeating the process for additional tests. For fired experiments, the engine was fired until near-steady combustion phasing was achieved, and the fluorescence image data were acquired. Eventually, the combustion became unstable as the phasing progressively advanced due to increasing surface temperatures, thus limiting the time-window for data acquisition. The duration of fired experiments depended on the mode of operation (skipfired or continuous). Window surfaces generally remained fairly clean throughout testing and were not typically a limiting factor.

A majority of fired experiments in the current study utilize a 17-3 skipfired sequence (17 motored followed by 3 fired cycles) with direct fuel injection to minimize thermal loading on the optical engine. However, a subset of fully premixed and continuously fired experiments was performed to eliminate the need for direct injection. The specifics of each firing mode are described in further detail in each corresponding results section. Complementary premixed motored experiments were also performed to compare the development of TS development between motored and fired operation. These tests were performed with identical intake temperatures and pressures to those used for fired experiments, except that the intake stream was inert to suppress combustion. Individual motored experiments were performed for both skipfired and premixed fired conditions due to small variations in intake temperature. All motored comparison tests were performed on the same day as fired experiments to eliminate any possible variation in diagnostic performance or engine operation.

CONVENTIONAL DATA ACQUISITION AND PROCESSING

Several conventional (non-optical) diagnostics were used to monitor and characterized engine performance. In-cylinder pressure measurements were performed with a transducer (AVL QC33C) mounted in the cylinder head. The pressure transducer output was recorded for 50 consecutive cycles at 1/4°CA resolution and was adjusted (pegged) to match the intake pressure near BDC when the cylinder pressure is effectively constant. A camera reference pulse was also recorded with the pressure record to provide a cycle-specific indication of PLIF image acquisition. This was important when correlating engine performance and PLIF measurements on a cycle-to-cycle basis. For fired experiments, the pressure measurements were used to calculate the apparent heat-release rate (AHRR), and the 10% and 50% burn points (CA10 and CA50) of the cumulative AHRR. Calculations were performed for each cycle assuming constant specific heats and negligible heat transfer [10], and then averaged for the 50 cycles. As previously mentioned, real-time calculations of AHRR and CA50 were used to adjust intake temperature to maintain the desired combustion phasing.

Intake temperature was measured using thermocouples mounted in the two intake runners near the cylinder head. Exhaust gas temperature was also monitored with a similar thermocouple in the exhaust port. Based on these measurements, in-cylinder BDC temperature was estimated following the procedure provided in [11]. Also, upper cylinder-wall temperatures were inferred from a thermocouple embedded in the spacer ring approximately 2 mm beneath the surface and 5 mm below the firedeck. The crank angle convention for all data presented is $0^\circ < \text{CA} < 720^\circ$, with 360°CA corresponding to top dead center (TDC) of combustion.

PLIF SYSTEM

A schematic of the PLIF diagnostic setup is shown in Fig. 3. Laser excitation at 308 nm was provided by a XeCl excimer laser (Lambda Physik ComPexPro 102) providing 200 mJ of max energy output. Excitation at 277 nm was generated by Raman shifting the 248 nm output of a KrF excimer laser (Lambda Physik ComPexPro 102, stable resonator) to the 1st Stokes wavelength in H₂. The Raman cell (custom fabrication) was 112 cm in length with a 37 mm clear aperture, and was operated at a total pressure of 57 bar. A 600 mm focal length spherical lens focused the 248 nm beam through the Raman cell, while an appropriately positioned 500 mm lens collimated the output. This configuration resulted in approximately 15% energy conversion efficiency to the 1st Stoke. The resulting 277 nm beam was spatially separated from the residual 248 nm beam through an equilateral dispersing prism. A long propagation distance for

each wavelength was used to form the sheet width dimension based on the inherent divergence of the laser outputs. After propagating to the optical engine area, each wavelength was passed through separate 1 m focal length cylindrical lenses to form the beam waist, before being spatially overlapped with a dichroic mirror coated to reflect 277 nm and transmit 308 nm. An additional 1 m negative focal length cylindrical lens (orthogonal to waist forming lens) was used to increase the 277 nm sheet width at the engine input window. Finally, the beams were sent through the “vertical elevator” assembly that rotates the beam 90° and elevated the laser sheet to the desired vertical location within the engine.

As indicated in [4], the current engine windows were designed such that the inner and outer radius of curvature are equal. Because of the window thickness, the window acts as a positive cylindrical lens. To counteract the induced beam convergence, a 200 mm cylindrical lens was added to the optical path 650 mm upstream of the engine input window, forming a Keplerian telescope. The resulting laser sheet diverged slightly across the field of view, increasing in width by approximately 4-5 mm. The resulting laser sheets were approximately 43 mm wide and 0.5 mm thick. Typical laser energies per pulse during experiments were 42-48 mJ for 277 nm and 45-50 mJ for 308 nm. These laser energies were measured several optical components upstream of the engine window, so actual laser energies inside the cylinder are 8-10% lower due to surface reflection losses. These laser energies were confirmed to provide linear excitation through in-situ measurements of fluorescence signal as a function of energy performed during motored operation.

The overlapped sheets were aligned nearly parallel to the firedeck, with a small upward angle to avoid co-linear back reflections. As shown in the inset in Fig. 3, the last turning mirror in the vertical setup before the engine was affixed to a vertical translation stage that allowed adjustment of the laser sheet to any desired position below the firedeck. Whenever possible, the laser sheet was positioned at the mid-plane of the combustion chamber volume for each image acquisition crank angle. Typical elevations ranged from 4 to 16 mm below the firedeck. However, for early crank angles the cylinder window dimensions prevented measurement at the mid-plane and the laser elevation was fixed at 16 mm below the firedeck.

The resulting fluorescence was transmitted through the 70 mm diameter piston crown window and imaged onto the camera using a 85 mm f/1.4 Nikon lens. The intensified CCD camera (Princeton Instruments, PIMAX2:1003) is equipped with an interline transfer CCD array, allowing the collection of images from both wavelengths with an interframe timing of 5 μs (2 μs minimum). The 1024×1024 pixel array was binned 8×8 on chip to increase signal levels with a corresponding sacrifice of spatial resolution. The resulting image spatial resolution was approximately 0.56 mm per

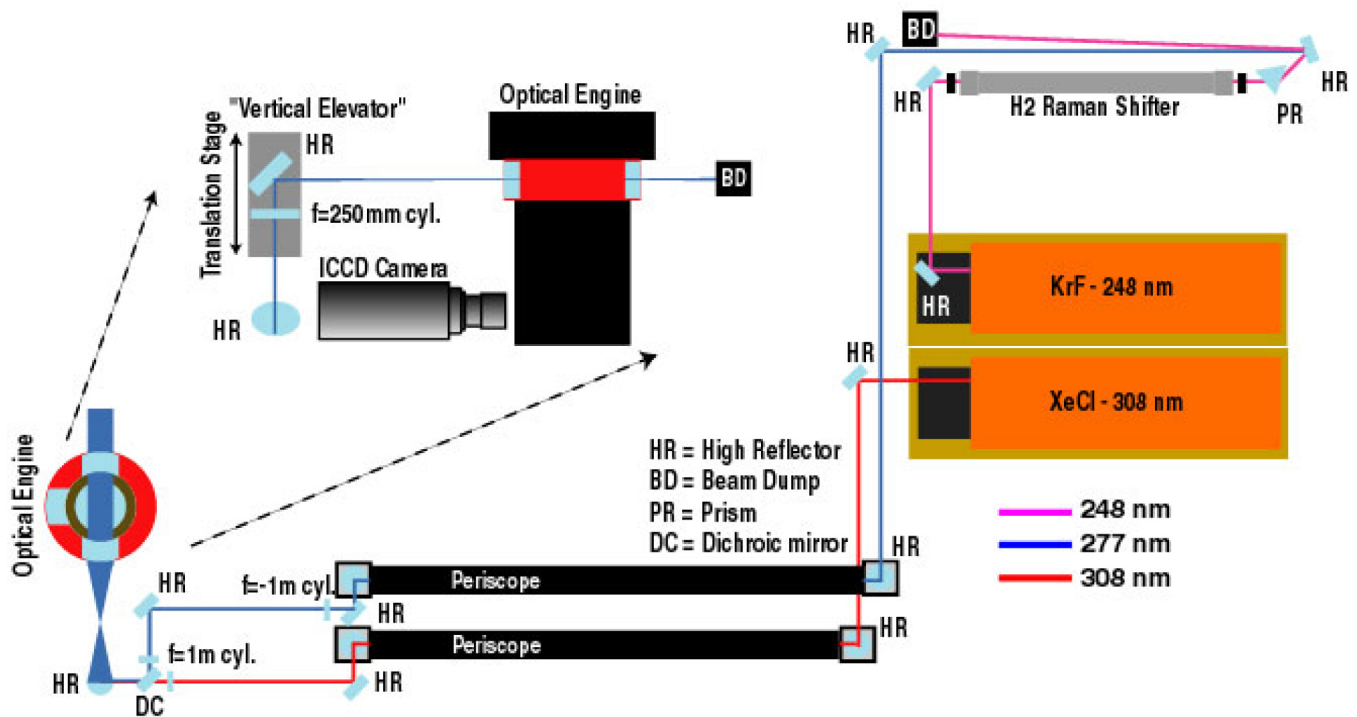


Figure 3. Schematic of experimental PLIF setup for HCCI engine experiments.

pixel, roughly matching the out-of-plane resolution provided by the laser sheet thickness. A sample PLIF image with the valves, injector, and piston window superimposed in the field of view is shown in Fig. 4. The camera exposure and laser output were synchronized with a pulse delay generator (SRS DG535) that was itself triggered by the engine controller. The camera and laser system were operated at 10 Hz for all experiments, allowing one image acquisition per cycle at the fixed 1200 RPM engine speed.

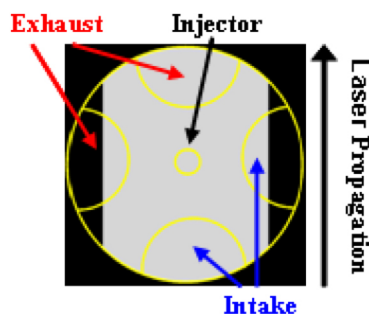


Figure 4. PLIF image field of view with valves, injector, and piston window positions superimposed.

PLIF IMAGING DIAGNOSTICS

BACKGROUND THEORY

The general theory and development of the PLIF techniques were previously presented in detail [5, 12] and are outlined

here for clarity. The fluorescence signal in the linear regime is given by Eqn. 1:

$$S_f = \frac{E}{hc\nu} dV_c \left[\frac{Px_{tr}}{kT} \right] \sigma(\lambda, T) \phi(\lambda, T, P, x_i) \frac{\Omega}{4\pi} \eta_{coll} \quad (1)$$

Where S_f is the number of photons incident [photons/pixel], E is the local laser fluence [J/cm^2], h is Planck's constant [J s], c is the speed of light in a vacuum [cm/s], ν is the excitation laser frequency [cm^{-1}], dV_c is the probed volume [cm^3], x_{tr} is the tracer mole fraction, P is the total pressure [MPa], k is the Boltzmann constant [J/K], T is the local temperature [K], σ is the absorption cross-section [cm^2], Φ is the fluorescence quantum yield (FQY), λ is the wavelength [nm], x_i is the mole fraction of the mixture species, Ω is the solid angle of collection, and η_{coll} is the collection efficiency of the imaging system. This fundamental relationship is the starting point for all diagnostic strategies discussed here.

Single-Line Technique

The single-line technique derives temperature from the fluorescence signal of a single excitation wavelength, as shown in Eqn. 2. Here the measured signal is normalized with a calibration (flat-field) signal acquired under homogeneous conditions of known temperature, pressure and tracer mole fraction. This eliminates the need to directly measure the collection terms (dV_c , $\Omega/4\pi$, η_{coll}). Additionally, the