

Transition from HCCI to PPC: Investigation of Fuel Distribution by Planar Laser Induced Fluorescence (PLIF)

Zhenkan Wang, Sara Lonn, Alexios Matamis, Oivind Andersson,
Martin Tuner, Marcus Alden, and Mattias Richter
Lund University

ABSTRACT

In a previous study, in order to investigate the effect of charge stratification on combustion behavior such as combustion efficiency and combustion phasing which also largely affects the emissions, an experiment was conducted in a heavy-duty compression ignition (CI) metal engine. The engine behavior and emission characteristics were studied in the transition from HCCI mode to PPC mode by varying the start of injection (SOI) timing. To gain more detailed information of the mixing process, in-cylinder laser diagnostic measurements, namely fuel-tracer planar laser induced fluorescence (PLIF) imaging, were conducted in an optical version of the heavy-duty CI engine mentioned above. To the authors' best knowledge, this is the first time to perform fuel-tracer PLIF measurements in an optical engine with a close to production bowl in piston combustion chamber, under transition conditions from HCCI to PPC mode. Results show that four mixing schemes can be distinguished as the SOI timings are varied during the transition. They are linked to the results presented in the reference paper, where emissions were varied in different zones. For SOI at -100 crank angle degree (CAD), fuel distribution is homogeneous as expected. With other SOI timings, a significant part of the fuel mixture was trapped in the squish region and crevice area before start of combustion (SOC) as shown by PLIF results. The observations in the reference metal engine paper were confirmed by this measurement. Results are also in good agreement with computational fluid dynamics (CFD) simulations performed for this engine.

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INTRODUCTION

Homogeneous charge compression ignition (HCCI) and partially premixed combustion (PPC) have attracted interest as both of them share the capability of producing low NO_x and soot emissions without adverse effects on engine efficiency. In PPC mode the combustion phasing can be controlled by the injection timing, that in turn affects the ignition delay (ID) which is defined as the time between start of fuel injection and start of combustion (SOC) [1]. This is not possible to replicate in HCCI conditions as they, per definition require early fuel injection and feature a combustion process that is mainly controlled by chemical kinetics.

For PPC, there is a measurable time interval between end of injection and start of combustion leading to the gas mixture being partially premixed before the combustion process. In PPC mode, the stratification feature brings out different combustion behavior. In order to understand the change in engine behavior and emission characteristics, there is a need for further understanding of the mixture preparation in the transition from HCCI mode to PPC mode.

The start of combustion process during the transition was studied in terms of finding the relation between start of injection (SOI) and SOC and the location of initial ignition sites [2]. Moreover, the variation of combustion and emissions were investigated in this transition by

Shen et al. [3]. In their work, the influence of SOI on the combustion efficiency and emissions was studied. As expected, in pure HCCI mode, small changes in SOI timing will not affect the engine combustion and emission behavior. But as the level of fuel stratification increases, it can affect combustion behavior significantly. It has the potential to achieve better combustion efficiency along with lower emissions, or they can both deteriorate, depending on the degree of mixing in different zones. Therefore, the transition from HCCI to PPC mode needs further investigation.

Recently, this transition behavior was investigated by varying the SOI timing in a single cylinder heavy duty diesel engine by Li et al. [4]. In order to keep CA 50 (the crank angle at which 50% of the fuel energy has been released) constant during the sweep in SOI timing, different intake temperatures were required. Plausible explanations based on the change in mixture formation for different SOI timings were presented. On basis of the required intake temperatures and the resulting emissions the swept SOI range was divided into five zones where the mixing process and stratification were expected to be significantly different. Furthermore, it was claimed that due to fuel trapping in the squish volume and crevices, emissions such as CO and total hydrocarbon (THC) increase tremendously in a segment of the transition in those studies. Nonetheless, the experiments were done in a full metal heavy-duty compression ignition (CI) engine. To

gain more detailed information of the mixing process, in-cylinder laser diagnostic measurement is essential. Therefore, to bring this investigation a step further, fuel-tracer planar laser induced fluorescence (PLIF) imaging was conducted in an optical version of the heavy-duty CI engine mentioned above.

Fuel-tracer laser induced fluorescence is commonly used to measure the fuel distribution in the combustion chamber in order to study the in-cylinder fuel injection process and mixture formation [5, 6, 7, 8, 9, 10]. Some PLIF experiments have been performed in HCCI/PPC engines. For example, Seyfried et al. [11] investigated the effect of turbulence on mixing process by using different geometry of the combustion chamber in an HCCI engine by high speed fuel-tracer PLIF. Results showed that the mixing process influences the heat release rate.

Hence, a homogeneity index was calculated and evaluated for different mixture formations. Later, Persson et al. [12] used a similar system and method to study the homogeneity level of fuel distribution under different amount of fuel in a direct injected, spark assisted compression ignition (SACI) engine. Tang et al. [13] performed a quantitative fuel-tracer PLIF measurement in a PPC engine to get the overall fuel stratification under different double injection strategies.

To the authors' best knowledge, this is the first time to perform fuel-tracer PLIF measurements in an optical engine with a close to production bowl in piston combustion chamber, under transition conditions from HCCI to PPC combustion. The measurements covered PLIF imaging at different crank angle degrees (CADs) to understand how the in-cylinder mixture formation is affected by SOI timing.

EXPERIMENTAL SETUP

The fuel tracer-PLIF experiments were conducted in a Scania D13 heavy duty optical engine. The optical engine was modified from a conventional 6-cylinder diesel engine into a single-cylinder one. The cylinder liner and the piston were extended according to the Bowditch design as shown in figure 1 and 2. The quartz piston geometry was similar to the metal piston used in the reference engine [4]. There are three quartz windows (25×55 mm) placed at right angles between them on a spacer mounted between the cylinder head and the engine block, providing large optical access into the combustion chamber for a wide range of CADs around top dead center (TDC).

The fuel used in this set of experiments was PRF 81, which contains 81% of isooctane and 19% of n-heptane per volume, together with 10% (volume) of acetone as a PLIF fuel tracer. More information about acetone used as a fuel-tracer for PLIF measurements in optical engines can be found in reference. [10, 11, 12, 14, 15, 16, 17, 18, 19, 20]. During the measurement campaign, fresh fuel and acetone blends were used every day.

Limited pressure dependence of acetone PLIF signal at pressures relevant for the compression stroke in internal combustion engines (ICE) has been reported [19]. But the temperature dependence will generate some uncertainties to the performed measurements.

A Nd:YAG (Continuum Powerlite DLS 9010) laser was used combined with a second harmonic generator and a fourth harmonic generator, in order to excite acetone at a wavelength of 266 nm. A Pellin Broca prism was placed at the exit of the laser system to separate the 532 nm and 266 nm wavelength laser beams that were overlapped. The laser energy at 266 nm was measured and set to 60 ± 1 mJ. It was tested that with higher laser fluence, damage to the quartz piston is highly possible.

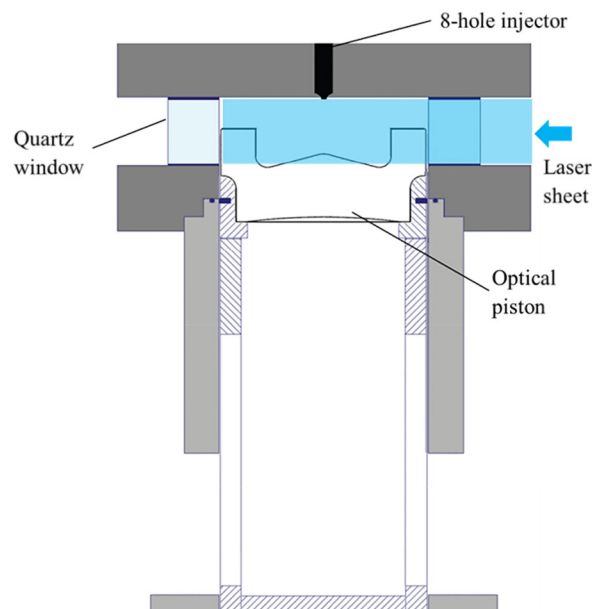


Figure 1. Experimental setup from side view

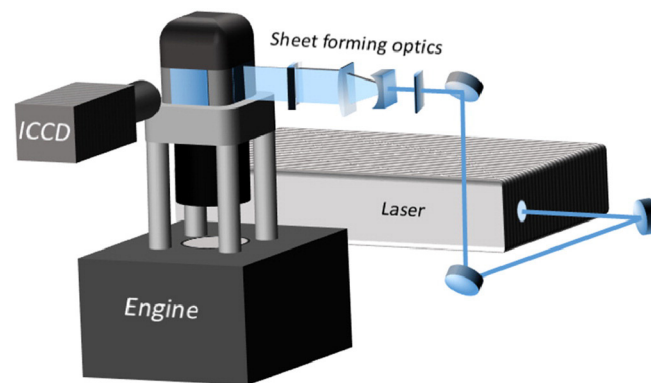


Figure 2. Isometric view of the experimental setup

In the experiment, four cylindrical lenses formed a 28 mm wide and less than 1 mm thick laser sheet to create a 2D fluorescence field. The focal lengths of the four cylindrical lenses were, -40 mm, -75 mm, +310 mm and +500 mm. The Gaussian wings of the laser sheet were then trimmed down resulting in a final height of 25 mm. The laser sheet entered through one of the quartz window and it was placed at the center of the piston bowl, passing through two opposing spray plumes as shown in figure 3.

An ICCD camera (PI-MAX II) was positioned perpendicular to the laser sheet to detect the PLIF signal through the quartz window and an achromatic Bernard-Halle quartz lens ($f = 100$ mm, $f/\# = 2$).

mounted in front of the camera. Two long pass filters were used in front of the camera lens. Each of them was a 20 mm optical path length quartz cuvette, containing the liquid N,N-dimethyl-formamide, that will prevent almost all undesired scattered laser light from entering the ICCD camera. A transmission curve for this filter can be found in reference [21].

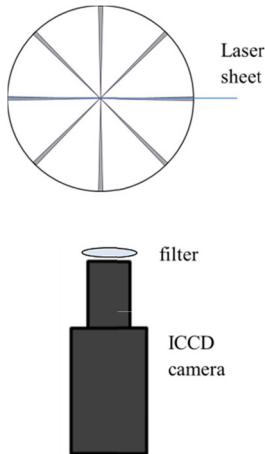


Figure 3. Experimental setup from top view (piston bowl area with 8 spray plumes)

Table 1. Engine specifications.

Engine type	Heavy-duty diesel engine
Number of valves	4
Bore	130 mm
Stroke	160 mm
Connecting rod	255 mm
Displacement	2124 cm ³
Engine speed	1200 rpm
Fuel type	PRF 81
PLIF fuel tracer	Acetone
Common rail pressure	800 bar
Injector type	8-hole Solenoid, 120°
Injection duration	900 μs
Intake temperature, T _{in}	75-150 °C
Intake pressure, P _{in}	1.5 bar
Intake O ₂	21 vol. %

The exposure time of the camera was set to 100 ns. Since little soot was produced in PPC mode and with such a short exposure time, the chemiluminescence signal from the combustion was very low and contributed to the background noise. The original resolution of the camera is 1024×1024. However, due to the limitation of the quartz window size, the resolution was clipped down to 1024×680, which is corresponding to 97×64 mm field of view.

Due to the bowl-in-piston design, some undesired reflections and dark patches are formed in the PLIF images, especially on the exit side. Therefore, only the entrance side of the images was processed and analyzed.

OPERATING CONDITIONS

The engine speed and combustion phasing were kept constant at 1200 rpm and CA50 was achieved at +3 CAD after top dead center (ATDC) for all the conditions. In the below text, the position of the piston which is before TDC of the combustion stroke will be indicated with a ‘-’ sign in front of CAD and after TDC will be a ‘+’ sign. A skip-fire strategy was employed, where one out of ten cycles was fired and the other nine were motored, in order to maintain realistic surface temperatures. This approach reduces the possibility of window failures due to thermal load and resulting mechanical stresses. The laser was triggered by the combustion TDC signal, providing a repetition rate of 10 Hz. The trigger signal of the engine was sent out at different CADs in order to facilitate the following of the evolution of the mixing process for different SOI timings. Table 2 summarizes the operating conditions including different SOI and trigger timings. 50 images were recorded for each CAD of each SOI for statistical data analysis.

Table 2. operating conditions.

Single injection								
SOI	-100	-70	-54	-46	-35	-30	-20	-15
Case name	case100	case70	case54	case46	case35	case30	case20	case15
PLIF imaging CAD	-95							
	-90							
	-85							
	-80							
	-75							
	-70							
	-65	-65						
	-60	-60						
	-55	-55						
	-50	-50	-50					
	-45	-45	-45					
	-40	-40	-40	-40				
	-35	-35	-35	-35				
	-30	-30	-30	-30	-30			
	-25	-25	-25	-25	-25	-25		
	-20	-20	-20	-20	-20	-20		
	-15	-15	-15	-15	-15	-15	-15	
	-10	-10	-10	-10	-10	-10	-10	-10
	-5	-5	-5	-5	-5	-5	-5	-5
	0	0	0	0	0	0	0	0
	3	3	3	3	3	3	3	

IMAGE POST-PROCESSING

Background images recorded during motored cycles were subtracted from the raw PLIF images. Due to the dome-shaped piston bowl the images acquired were optically distorted. MATLAB (The Mathworks, Massachusetts, USA) was used for correction of distorted images. An example of a recorded image before and after distortion correction can be seen in the appendix, figure 16. Detailed information on image correction for a similar piston bowl shape can be found in reference [22, 23, 24, 25].

The distortion corrected PLIF images were compensated for vertical variations in the energy distribution of the laser sheet. The PLIF intensity variations due to time averaged variations in the energy distribution of the laser sheet can be obtained by using pure acetone in the combustion chamber and record the corresponding PLIF image.

Figure 4 represents an example after image post-processing at -5 CAD for case46. The yellow box in the upper image of the figure indicates the area above the piston and the squish volume; the blue box shows half of the piston bowl; in the red box is the area where the mixture preparation has been studied because reliable illumination can be maintained for the investigated CAD range. The region between the blue box and the red one is masked because of insufficient illumination and severe image distortion due to the curvature of the piston bowl.

It should be mentioned that laser attenuation was not accounted for, since with high laser energy and low acetone concentration, the attenuation by acetone can be considered negligible [5]. However, due to the laser absorption by intermediates of the combustion process and soot particles, it is still possible to have a degree of extinction in the measurements.

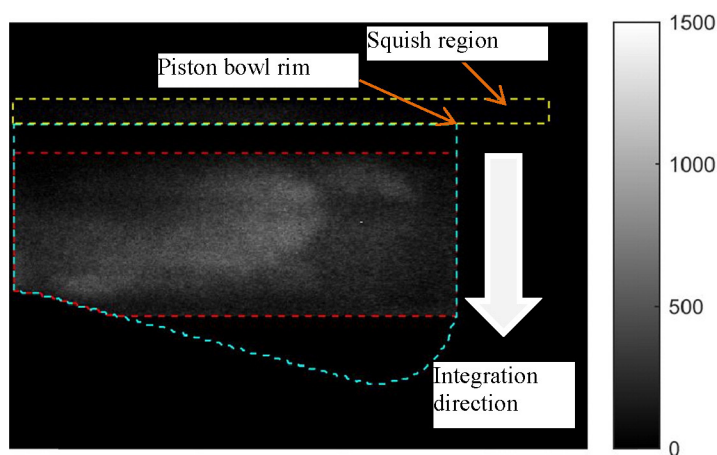


Figure 4. Instantaneous PLIF image after post-processing for case46 at -5 CAD

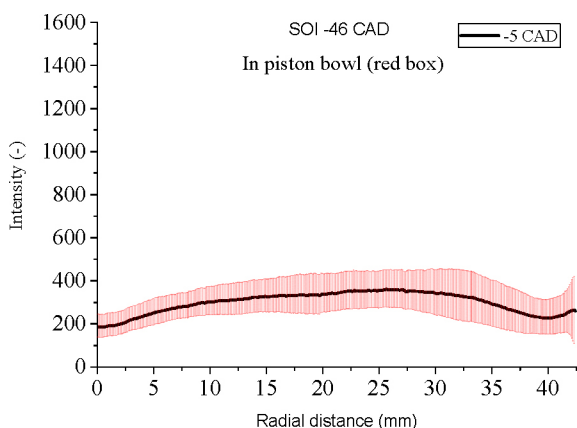


Figure 5. Averaged intensity (black line) and the standard deviation (red envelope) in vertical direction at different radial position inside the piston bowl calculated by PLIF images of 50 cycles for case46 at -5 CAD

Case46 at -5 CAD is taken as an example. First, the mean intensity at a specific radial position in the piston bowl is calculated along the vertical direction (sum of the intensity along the vertical direction and then it is normalized by the pixel numbers). Therefore, the mean intensity is independent on the pixel numbers.

The averaged tracer PLIF intensity profile along the radial direction can be hence calculated together with its standard deviation for 50 cycles. In figure 5, the black line is the averaged intensity over 50 cycles along the radial direction of the piston bowl. The red envelope filling around the averaged intensity is the standard deviation of 50 cycles.

The calculation and data analysis for the region above piston is the same as those for the region inside the piston bowl as described above.

RESULTS AND DISCUSSION

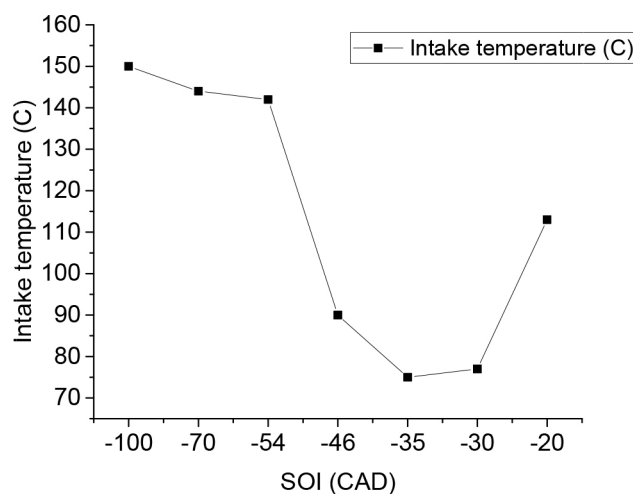


Figure 6. Intake temperatures versus SOI timings.

Figure 6 presents the required intake temperature to keep constant CA50 for the various SOI timings investigated. The profile of the intake temperatures has a similar shape as for the reference engine [4]. This indicates that the in-cylinder conditions from the previous metal engine studies could be approximately replicated in the optical engine. The peak pressure and CA50 were tuned to be the same as those in the metal engine to keep the in-cylinder conditions as close as possible.

1. Instantaneous PLIF Image

The instantaneous PLIF images for all the cases at different CADs from -95 CAD to +3 CAD can be found in the [appendix](#). The images were post-processed as described in the previous section. 5 grayscale ranges (from 8000 to 800) were used in order to present better contrast. The indicators, G1 to G5, at the bottom right corner of each image, show the grayscale bin applied.

After evaluating the images, it becomes apparent that for SOI timings of -15 and up to -35 CAD, all of the fuel is injected inside the piston bowl and most of the mixture formation takes place in that volume. The case of SOI at -35 CAD is the first case where some of the gas mixture appears in the top-land volume of the piston, noticeable at -20 CAD. In case46, the fuel plume interacts with the piston bowl rim at position -35 CAD and some fuel is delivered in the piston top-land and the squish region. As the piston moves towards TDC though, the signal drops in the squish region, indicating that the gas either moves to the piston bowl or dissipates below the noise level. For SOI of -54

CAD a significant part of the fuel mixture is distributed in the squish region as shown in [appendix figure 17](#), from position -45 CAD to -35 CAD. This leads to fuel being deposited in the crevice region and greater heat losses from the surface to volume ratio, contributing to high CO and THC emissions, as demonstrated in the reference engine [4]. For even earlier SOI, as in case70 and case100, the outcome is very similar, requiring high inlet temperatures in order to achieve combustion as the mixture inside the piston bowl is relatively lean. The majority of the mixing takes place above the piston and gradually enters the bowl when the piston ascends towards TDC.

These results are also in good agreement with the computational fluid dynamics (CFD) results shown in reference [4]. According to the modelling results, fuel was trapped on the piston top-land and in the squish volume for SOI from -80 CAD to -50 CAD.

From the PLIF imaging (see [figure 7](#)), four mixing schemes can be identified as the SOI timings are varied during this HCCI to PPC transition.

Scheme 1: When SOI is retarded beyond -35 CAD, most of the fuel is injected inside the piston bowl and that is where all the mixing process takes place. The earlier the injection, the more homogeneous it can become before the onset of combustion.

Scheme 2: When SOI is at -46 CAD or -54 CAD, the injection hits on the rim of the piston bowl. It splits the mixture moving into two directions: inside the piston bowl and towards the squish region as arrows show in [figure 7](#). The mixing processes at these two places interact with each other and finally combine together inside the piston bowl due to piston motion and squish flow. During the mixing process, part of the fuel mixture also dissipates into the crevice areas above the ring pack. This leads to poor combustion efficiency and high emissions [26].

Scheme 3: When SOI is at -70 CAD, no fuel is injected directly into the piston bowl. Therefore, the majority of the mixing takes place above the piston. Due to limited mixing time, the still stratified gas mixture then enters the piston bowl for further mixing before ignition.

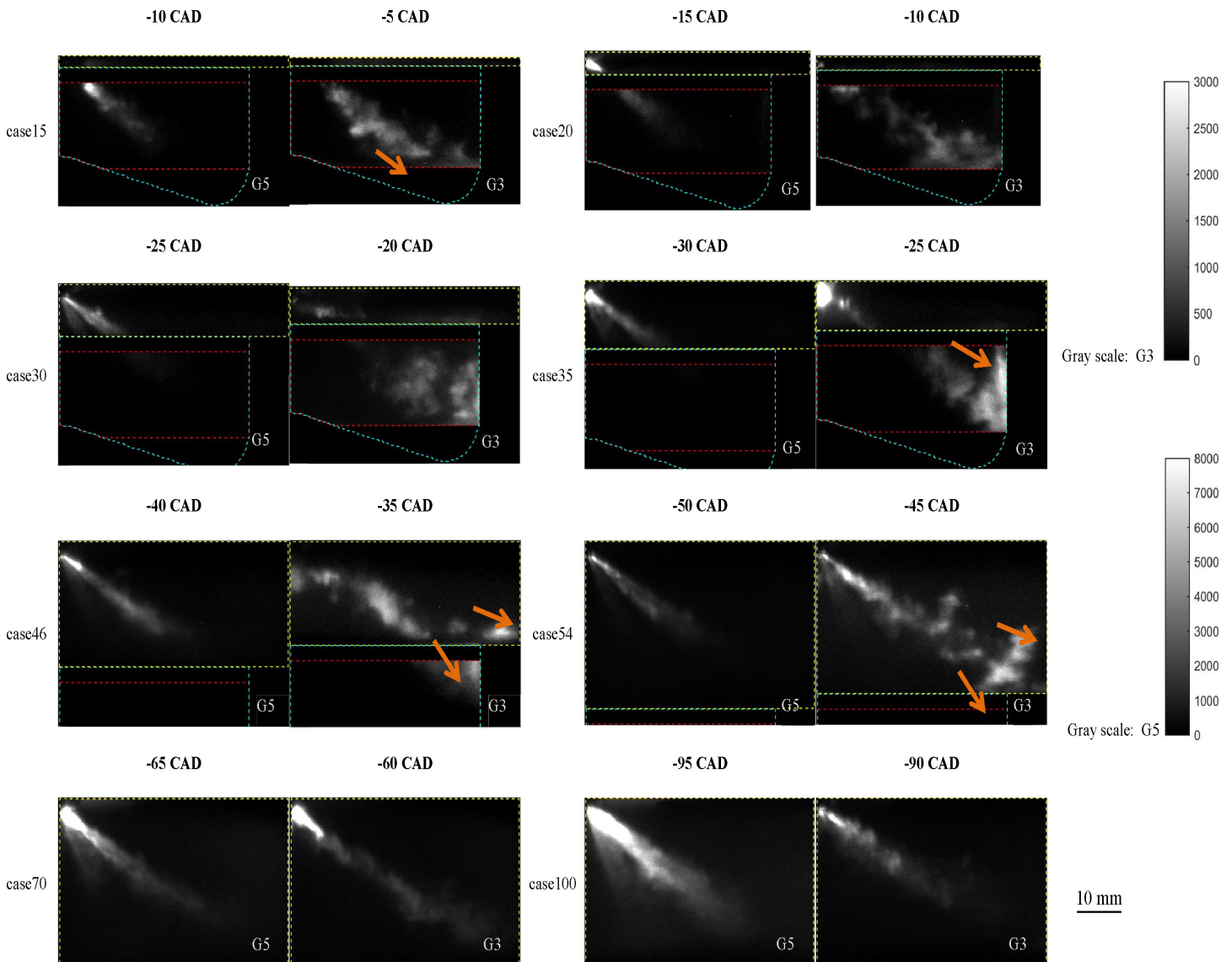


Figure 7. Instantaneous PLIF images at 5 CADs and 10 CADs after SOI for all cases

Scheme 4: When SOI is more advanced than -100 CADs, plenty of time is available for mixing before the mixture enters the piston bowl. A more uniform gas mixture will form and lead to HCCI combustion.

During +3 CAD, 0 CAD (TDC) and -5 CAD, some 'holes' were observed in PLIF images such as in case20 and case30. This is not only because of non-uniform fuel distribution in the piston bowl, but also due to the combustion process which consumes fuel in the combustion chamber. For case100, the PLIF image faded homogeneously while the piston was ascending which means combustion close to HCCI.

The discussion above is based on instantaneous PLIF images. Due to cycle-to-cycle variation of the engine, more analysis with statistical data will be presented.

2. Two Different Fuel Distributions in Scheme-1

Figure 8 shows the PLIF images and the averaged intensity at different radial positions inside the piston bowl for two cases. Due to different injection timings, the fuel impinges at different locations of the piston bowl. This could lead to a clockwise vortex (case35), when the injection hits the vertical wall of the piston bowl, or a counterclockwise vortex (case20), when that hits the bottom of the piston bowl. Therefore, an assumption could be made, that two kinds of fuel distribution exist for scheme-1 mixing process. For case20, with the piston ascending, the gas mixture diffuses towards the periphery of the piston bowl by the momentum of the injection and a vortex is created. Thus, the intensity near the piston bowl wall increases dramatically as the arrows indicate in figure 8(a).

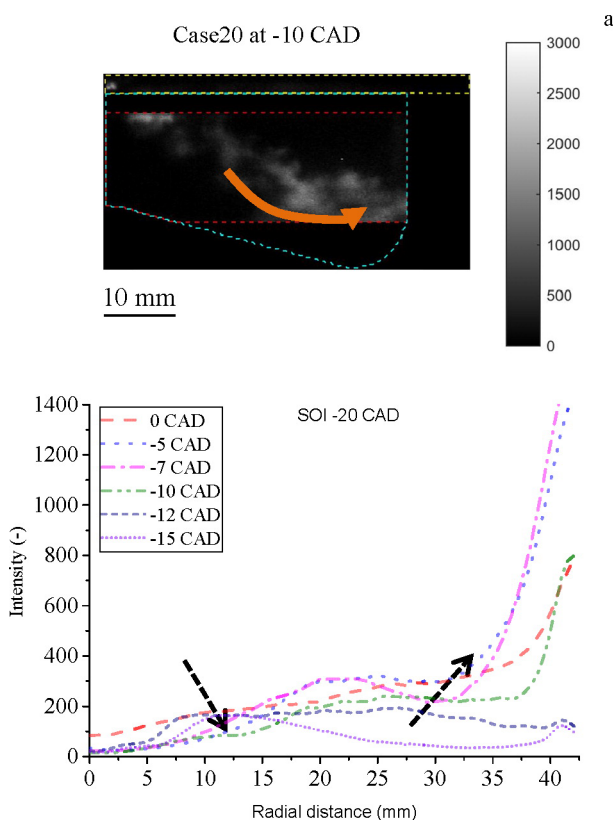


Figure 8(a). Averaged intensity at different radial positions inside piston bowl for case20 at different CADs

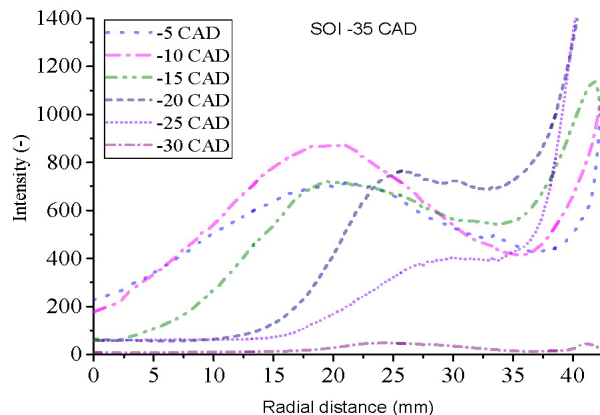
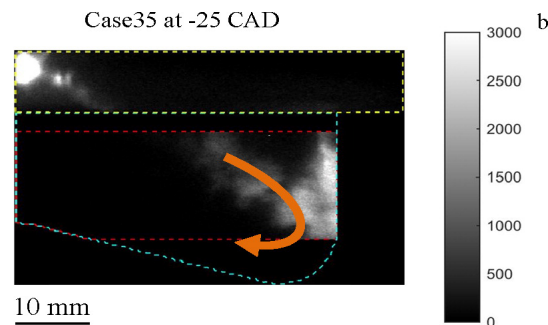


Figure 8(b). Averaged intensity at different radial positions inside piston bowl for case35 at different CADs

On the contrary, for case35, the intensity near the center of the piston increases over time, as shown in figure 8(b) due to the clockwise vortex generated by the injection event and the piston bowl geometry. In order to confirm this assumption, a study on in cylinder flows, such as PIV measurements is needed.

3. Fuel Distributions for Mixing Schemes Inside Piston Bowl

Figure 9 summarizes the intensity profile at different radial positions inside the piston bowl for all cases at different CADs. The arrows in the figure depict the trend of the fuel distribution from SOI at -100 CAD to SOI at -15 CAD.

For case15, due to limited mixing time, the fuel distribution is highly stratified spatially. Thus in figure 9(a) the intensity curve is relatively flat as it is a 2D PLIF measurement. The fuel was aggregated together instead of distributing in space.

For case35, intensity maxima are found both at 20 mm (which is the middle point between the center and the periphery of the piston bowl) and at the periphery of the piston bowl at -10 CAD and -5 CAD as shown in the figure 9(d).

In case30 and case20, the intensity near the center is lower than that of case46 and case54 and more fuel is close to the wall of the piston bowl, as pointed out in figure 9(b) and (c). The fuel distribution is more stratified for case30 than case35. Thus, when SOI is before -35 CAD, the later the injection, the more stratified it can be for the onset of combustion.