

Application of High-Speed PIV Diagnostics for Simultaneous Investigation of Flow Field and Spark Ignited Flame inside an Optical SI Engine

Minh Khoi Le, Takashi Furui, Atsushi Nishiyama, and Yuji Ikeda
 Imagineering Inc.

ABSTRACT

High speed, time resolved Particle Image Velocimetry (PIV) diagnostics was applied to an optical SI engine to study the interactions between in-cylinder flow field and flame development. Optimisation and certain adaptations have been made to the diagnostic setup to enable time-resolved, simultaneous measurements of both PIV data and flame tomography imaging from the same original captured image set. In this particular study, interactions between flow and flame during lean-burn operating conditions at various tumble strength have been investigated and compared to a standard stoichiometric operation. Diagnostics were performed for both the vertical plane (x-y) and the horizontal plane (r- Θ) of the combustion chamber with a particular focus in the pent-roof area. Some major differences in the tumble flow-field prior to ignition has been observed between the lean and stoichiometric conditions. Moreover, lean flames show a high degree of convolution and distortion during the early growth period but start to round off in later development stages for higher tumble condition. In terms of flow-flame interactions, the strong stoichiometric flame induces a very high turbulence energy for a wide region of unburned charge all around its flame front. While the lean flame also induces high turbulence in the unburned region near its flame front, the size and scale of these regions are very small in comparison, and are limited to only certain sections of its flame front. However, in the horizontal plane, lean flames under higher tumble condition induces relative high turbulence energy for a wider region all around its flame front, similar to the stoichiometric flame case. These could be the explanation for lean-burn at higher tumble condition having improved CA50 timing and lower combustion variations. The captured data is also useful for engine development efforts to utilise the flow-flame interaction for more stable lean combustion.

CITATION: Le, M., Furui, T., Nishiyama, A., and Ikeda, Y., "Application of High-Speed PIV Diagnostics for Simultaneous Investigation of Flow Field and Spark Ignited Flame inside an Optical SI Engine," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-0656.

INTRODUCTION

Lean and ultra-lean burning spark ignited (SI) engine is still the most useful approach in order to satisfy the stringent regulations on harmful engine-out emissions and greenhouse gases while continually improve combustion efficiency. However, engine operation with lean mixtures is difficult because of the instability in lean burn combustion, with issues such as misfiring as well as knocking [1, 2]. Due to its importance, advance gasoline engine in general has enjoyed many great research efforts over the years which has helped tremendously to push its operational capability. For the current downsized lean burning engines, advanced ignition technology such as non-thermal plasma [3] has been shown to successfully increase the lean limit of SI engines. Moreover, in terms of in-cylinder conditions, high tumble has been demonstrated to be very beneficial for fuel stratifications and enhancing flame propagation for lean operations [4, 5, 6]. In particular, some research has reported that the large-scale flows across the spark plug is a major controlling factor for lean flame growth [4]. The lean flames have also been shown to be highly convoluted and distorted, then retain this shape while growing in a random convection [7]. However, the relationship between this type growth and flame shape with the incylinder flow and turbulence has not been well explored.

The valuable results from such studies that helped build the knowledge base for SI engines have been successfully obtained thanks to the advent of optical engines and optical diagnostics techniques. Together, they offered a non-intrusive view into the combustion process inside a realistic engine environment which is crucial not only for understanding but also for future development of engines. In particular, techniques such as chemiluminescence and OH-Planar laser induced fluorescence allows the imaging of premixed flame front while Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) are widely used to study the incylinder flow field. Furthermore, in recent times, the advancement in laser and camera technologies have enabled such diagnostics to be performed with much higher temporal and spatial resolutions. This essentially allows further improvement in combustions research in general and engine research in particular. For instance, complex cyclic variations, of which the understanding is crucial for stable operation of lean burning, can now be studied not only with point based measurements like LDV but also with high spatial-resolved data of high speed PIV diagnostics [8, 9].

To further explore the gaps in knowledge and explore the interactions between flow field and flame growth, attempt to simultaneously observe flow field and flame with high temporal and spatial

resolutions has been made by combining chemiluminescence, flame tomography or OH PLIF with high-speed PIV. However, despite many good studies being carried out [10, 11, 12], there are still certain limitations. In particular, the details near the flame front can be questionable, the PIV data within the burned region are often lost and line-of-sight integration can decrease the accuracy greatly, especially for these highly-convoluted shapes of lean flames. The techniques often involve multiple lasers setup and can be costly and difficult for engine developers to implement. In dealing with these challenges, we have successfully optimized and developed the setup of high-speed PIV to not only provide time-resolved flow field data but also time-resolved flame imaging [13, 14]. Both PIV data and flame characteristics can be derived from the same captured image which essentially means the setup is simplified to one high speed laser and one camera. Furthermore, no flow field data is lost in both the burned and unburned region in the measurement area. Previously, the technique has been applied to study the flame and flow interactions during low load stoichiometric application [14]. In this study, the technique has been greatly improved and will be used to study the interactions between flow field and flame development under difficult homogeneous lean conditions at various tumble strength which is very useful in improving the knowledge base for advance lean burning SI engine development.

Table 1. Engine specifications

Engine type	4 stroke, single cylinder, PFI
Displaced volume	500 cm ³
Stroke	86 mm
Bore	86 mm
Compression ratio	10.4
Wall temperature	353 K
Intake temperature	300 K

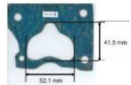
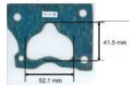
EXPERIMENTAL SETUP AND DIAGNOSTICS

Engine Setup and Operating Conditions

The experiments were carried out in a single-cylinder optical spark ignition engine. Table 1 summarises the specification of this optical engine. Common gasoline fuel is used and delivered into the combustion chamber using a commercial port-fuel injection (PFI) system with an air-assist injector from Honda. The engine has a bore of 86 mm and stroke of 86 mm, with a 500 cm³ displacement and a compression ratio of 10.4. Optical access into the combustion chamber of the engine is provided by a full quartz liner together with quartz windows in the pent-roof and at the top of the piston (54 mm diameter). To allow for optical laser diagnostics within the pent-roof region, the cylinder head (fire-deck) is also coated with a heat-resistant, anti-reflection paint to minimise laser reflection. A 45° mirror placed in the hollow extended-piston provides the viewing path for observations of the bottom-view of the combustion chamber as well as providing an optical-access path for laser. The temperature of the engine head and cylinder block was continuously controlled at 353 K and intake air temperature was maintained at room temperature of 300 K.

Table 2 lists the parameters of different engine operating conditions used in this study. Across all experiments, the engine was operated under naturally aspirated mode and at low load due to safety limit of the optical parts. Fuel was port injected at 300 kPa and fueling quantity is controlled for two different equivalence ratio $\phi = 1$ for stoichiometry mixture and lean mixture at $\phi = 0.72$. Two tumble conditions were also tested with the intake port fully open and 50% blocked. Engine speed is held constant at 1200 rpm and absolute intake pressure is 60 kPa. The spark timing was kept at -19° Crank-Angle after Top Dead Center (CA aTDC) across all conditions. This timing was selected instead of Maximum Brake Torque (MBT) timing to ensure similar ambient conditions for comparison purposes. In-cylinder pressure are monitored and recorded using a Kistler pressure transducer and the engine is fired continuously during the PIV capturing process. The resultant net IMEP are: stoichiometry 100% open intake IMEPnet = 391.2 kPa, A/F 20 100% open intake IMEPnet = 157.4 kPa and A/F 20 50% open intake IMEPnet = 305.5 kPa

Table 2. Engine operating conditions tested

PFI Pressure	300 kPa		
Equivalence ratio	1	0.72	
Intake port opening	100% open 	100% open 	50% open 
Engine speed	1200 rpm		
Intake pressure	60 kPa		
Ignition timing	-19° CA aTDC		

High Speed Particle Image Velocimetry (HS-PIV)

HS-PIV for Flow Field Measurements

Figure 1 illustrates the setup used for HS-PIV diagnostics in the optical engine of this study. A double Nd:YLF laser (Litron, 20 kHz max repetition frequency) was used to generate two beams of 527 nm wavelength for a HS-PIV capturing frequency of 7.2 kHz, which correlates to 1° CA resolution for engine speed of 1200 rpm. The beams were converted to 500-μm thin sheet via a sheet-making optics prior to penetration into the combustion chamber. The time delay between the two laser pulses was set at 40 μs. The result PIV images were captured using a high-speed CMOS camera with a resolution of 800×1280. In order to maintain traceability during combustion, a special in-house mixture of burning-resistant silica-based tracer particles was selected and added into the intake manifold. Moreover, a bandpass filter at 527 nm (10 nm FWHM) was applied and placed in front of the camera lens to eliminate most of the interferences from the premixed flame luminosity and chemiluminescence. These selections also allow for distinguishing between burned and unburned regions, which improves flame tomography imaging capability as to be discussed in the following section.



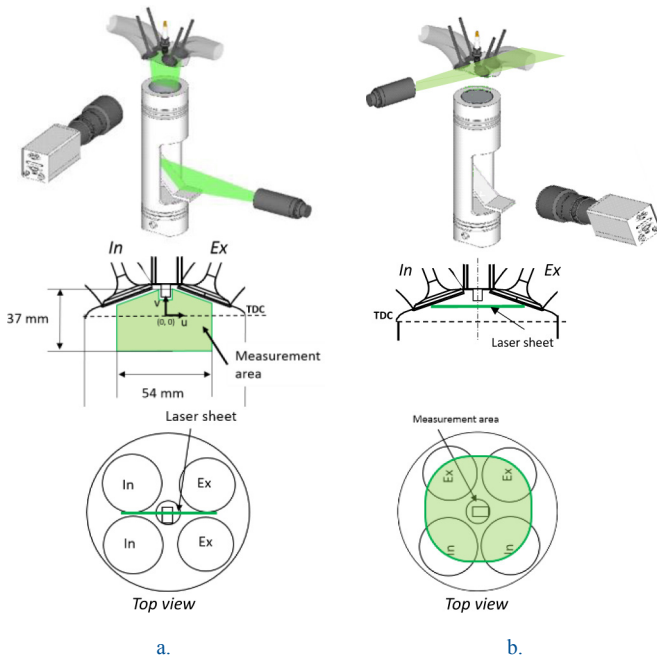


Figure 1. Illustrations for the setup of HS-PIV for a) vertical plane measurement and b) horizontal plane measurements. Also shown are front view (middle) and top view (bottom) of the measurement area applied for each configurations

Two different laser-position setups were applied to provide measurements for two different viewing-planes of the combustion chamber, with a particular focus in the pent-roof region where early flame development and most of the flow and flame variations are expected. Fig. 1a shows the HS-PIV setup for measurements in the xy plane of the pent-roof region. The output laser sheet was introduced into the engine combustion chamber by reflecting off the 45° mirror that was placed inside the hollow piston and through the piston-top quartz window. It was positioned such that the sheet is in the centre of the piston bore, in-line with the spark plug. The camera was placed perpendicular to the sheet and focused onto the pent-roof area. Fig. 1b displays the setup for the other orientation of the laser sheet in the horizontal plane (or r-θ). The laser sheet was introduced via the pent-roof windows and was positioned to be in the middle of the clearance between the tip of pent-roof and piston Top-Dead-Centre (TDC) position, which as illustrated, around 5 mm below the spark plug. While this means that the measurement area will not cover the entire 54 mm field-of-view of the piston-top quartz, it allows for observation the flow field during earlier flame development period, which has been shown to be critical. The camera captures the measurement area via the 45° mirror.

Raw images and data were initially processed using commercial PIV software (Dantec Dynamics Studio) and then further analysed using in-house MATLAB code. As explained in Ref. [13], in order to maximize the valid vectors and minimize the errors while still keeping a good spatial resolution, the interrogation area was set to 32×32 pixels, which equals 1.5×1.5 mm. Furthermore, for effective analysis of in-cylinder flow-field, it is necessary to determine the velocity and turbulence conditions. Traditionally, this was done by a Fourier transformation of the instantaneous velocity data to separate a low frequency component u_{low} , which represents the mean velocity and a high frequency component u_{high} , which represents the

turbulence u' . In order to select the appropriate cutoff frequency, power spectrum analysis as per Ref. [13] was done. A frequency of 300 Hz was selected for the data in this study. Flow velocity and turbulence kinetic energy (TKE) was derived for discussion. HS-PIV measurements was performed for 19 continuously firing cycles of each conditions listed in Table 2. Continuous firing was selected over skip firing mode to retain the effects of residual gas in actual production engines.

HS-PIV as High Speed Flame Tomography Imaging

The same HS PIV setup described in the previous section also enables high-speed flame tomography imaging on the same laser plane simultaneously. While other simultaneous imaging of flow field and flame using high speed PIV and PLIF or high speed PIV and chemiluminescence has been documented previously in literature [10, 11, 12], this setup allows the flow and flame to be captured essentially at the same time, in the same image from the same camera, and eliminates potential errors that can be the result of misalignment, timing delays or line-of-sight integration. This drastically improves the accuracy when the interactions between flow and flame is concerned. With an appropriate selection of seeds, seeding amount, the density gradient between burned and unburned gas can be reflected in the density of the seed particles inside the combustion chamber. Under the exposure of an optimum laser intensity, the differences in seed density can be observed as an intensity gradient. Therefore, the burned and unburned region can effectively be distinguished and identified in the PIV image by monitoring the contrast gradients. As a result, the flame front can be estimated and derived to determine flame geometrical parameters such as flame growth speed, area, centroids, etc. Advantageously, suitable seeds and seeding method will still allow the PIV data in both burned and unburned region to be measured.

In this study, the special in-house developed seed mixture, seeding procedures and optimised laser fluence enables this simultaneous high-speed PIV and flame tomography. Due to the nature of this simultaneous technique, images captured using the HS-PIV setup and experiment is also used for flame analysis. The 527 nm bandpass filter mentioned in the PIV setup is also critical in avoiding the uncontrolled random interferences. For flame analysis, the PIV image is put through an in-house developed algorithm which contains a series of image processing steps, including inverting, background subtraction, histogram equalization, display range optimisation. The final flame front boundary is extracted via binarisation with thresholding based on Otsu's method [15] and visual inspection. This flame front boundary enables the calculation of flame growth speed, flame area and other geometrical properties. Figure 2 contains some sample of the original images and the processed images of the PIV flow field data and flame analysis data. These sample images were captured in both the vertical and horizontal planes for the $\phi = 0.72$ with a fully open intake port condition at 23° CA aIT (after ignition timing). For each imaging plane, an original image, an image (display range optimized) with flame front boundaries plotted, a vector and contour image for flow velocity and a contour image for TKE are displayed. Both images that contain PIV flow field data have the flame boundary overlaid on top for ease of interpretation. The same presentation style will be used in all the relevant figures of this report.

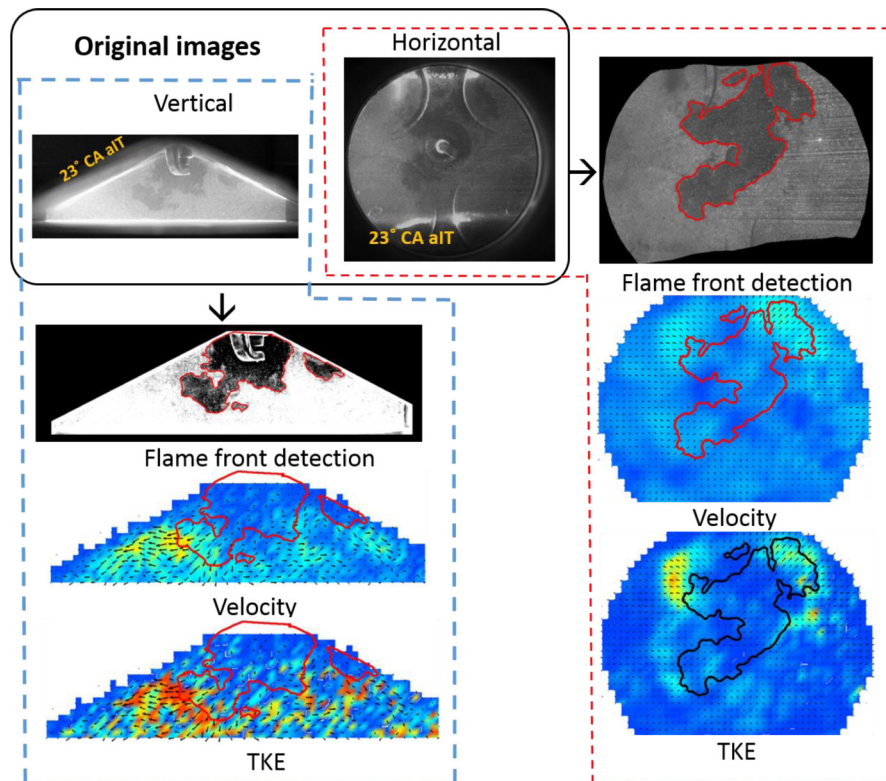


Figure 2. Sample of the original result images from HS-PIV capturing of the vertical and horizontal plane. Shown for each image configurations are the processed images for flame front detection together with plotted images of derived PIV data for flow velocity and turbulence kinetic energy (TKE)

RESULTS AND DISCUSSIONS

Mass Burnt Fractions

Figure 3a displays the mass burned fractions derived from the incylinder pressure measurements of all the operating conditions tested in this study. The bold thick lines represent the ensemble averaged traces for each condition. The black lines are for stoichiometric condition with fully open intake port, the red lines are for lean condition of $\phi = 0.72$ with fully open intake port and the blue lines are lean condition of $\phi = 0.72$ with 50% blocked intake port. With the ignition timing kept constant at -19° CA aTDC, the stoichiometric case can be seen to have a much advanced combustion-phasing compared to the lean condition, as expected. Furthermore, the variance is also significantly lower for the lean conditions. Figure 3b indicates that the 50% blocked intake does indeed greatly enhance tumble velocity, as confirmed in the stoichiometric burning condition. While, there is not much change in the CA10 values of the two lean conditions at different tumbles, CA50 values indicate that higher tumble results in faster propagation. Tested cycles for the higher tumble lean condition also have less variance in its mass burnt fractions in comparison to lower condition, suggesting strong tumble does have an effect in stabilizing lean combustion [16, 17, 18].

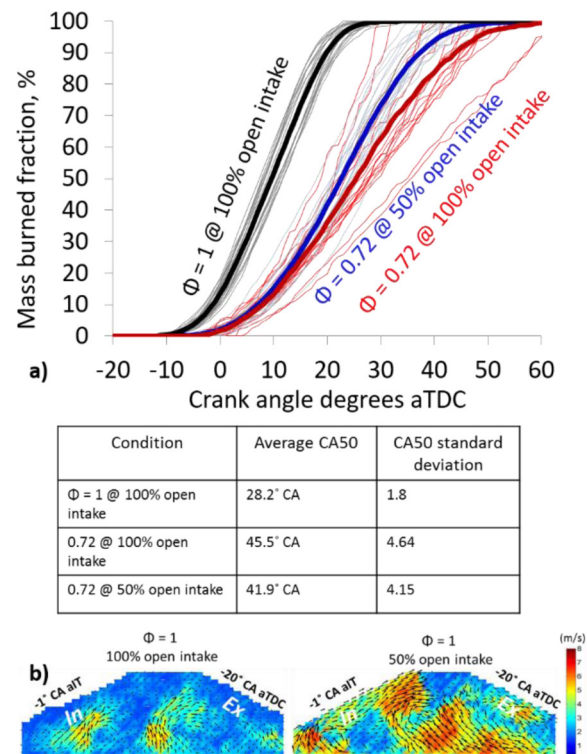


Figure 3. a) Mass burned fractions of the operating conditions tested in this study. The black traces are for stoichiometric condition, blue traces are for lean condition at 50% open intake and red curves are for lean condition at 100% open intake. b) The effect of blocked intake port on charge motion seen in stoichiometric case: tumble motion is greatly enhanced.