

PIV and PLIF to Evaluate Mixture Formation in a Direct-Injection Hydrogen-Fuelled Engine

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ABSTRACT

In an optically accessible single-cylinder engine fueled with hydrogen, acetone planar laser-induced fluorescence (PLIF) and particle image velocimetry (PIV) are used to evaluate in-cylinder mixture formation. The experiments include measurements for engine operation with hydrogen injection in-cylinder either prior to or after intake valve closure (IVC). Pre-IVC injection is used to produce a near-homogeneous mixture for PLIF calibration experiments and to establish a baseline comparison for post-IVC injection. Calibration experiments and a temperature correction allow conversion of the acetone fluorescence signal to equivalence ratio. For post-IVC injection with start of injection (SOI) coincident with IVC, PLIF results are similar to pre-IVC injection. With retard of SOI from IVC, mixture inhomogeneities increase monotonically, with high hydrogen concentration spatially located near the injector and within a smaller volume. For injection late in the cycle, the turbulent fuel-rich area is sharply delineated from the more quiescent fuel-lean region. The PIV vector plots suggest that the observed spatial distribution of hydrogen for SOI retarded from IVC is a consequence of the in-cylinder flow field generated by the injection event. Specifically, in the measured r - θ plane of the cylinder and in the field of view imaged, the vector plots show a large-scale mean flow towards the injector. It is conjectured that the observed flow field results from jet-wall interactions that redirect the leading edge of some of the fuel jets back towards the injector, creating a counter-flow with respect to the other fuel jets, which inhibits further jet penetration. The net result is a high hydrogen concentration near the injector. This scenario confirms that the injector tip geometry, injector location, and injection timing are critical parameters with respect to in-cylinder mixing in direct-injection hydrogen-fuelled engine.

INTRODUCTION

Hydrogen-fueled internal combustion engine (H_2 ICE) development efforts are focused to achieve an advanced hydrogen engine with peak brake thermal efficiency (BTE) greater than 45%, near-zero emissions, and a power density that exceeds gasoline engines [1-4]. With respect to these efforts, the direct-injection (DI) H_2 ICE is one of the most attractive H_2 ICE options [3-6]. The high volumetric efficiency and the higher heat of combustion of hydrogen compared to gasoline provide the potential for DI- H_2 ICE power density to be approximately 115% that of the identical engine operated on gasoline. In addition, the problems of preignition associated with port-fuel-injection (PFI) H_2 ICEs can be mitigated in a DI- H_2 ICE by timing injection to both minimize the residence time that a combustible mixture is exposed to in-cylinder hot-spots (*i.e.*, late injection) and to allow for improved mixing of the trapped residual gas with the intake air. Lastly, in-cylinder injection offers multiple degrees of freedom available for controlling emissions and optimizing engine performance and efficiency.

The challenge with DI- H_2 ICE operation is that in-cylinder injection affords only a short time for hydrogen-air mixing. For early injection, with start of injection (SOI) coincident with intake valve closure (IVC), maximum mixing times range from approximately 4–20 ms, depending on engine speed, valve timing and injection duration. In practice, to reduce the compression work of the engine [3] and to mitigate preignition, SOI is retarded with respect to IVC, and mixing times are further reduced. Since mixture distribution at the onset of combustion is critical to engine performance, efficiency, and emissions, a fundamental understanding of the in-cylinder mixture formation processes is necessary to optimize DI- H_2 ICE operation. The objective of this paper

is to evaluate mixture formation in a DI-H₂ICE using acetone planar laser induced fluorescence (PLIF) and particle image velocimetry (PIV).

Fuel-tracer PLIF is a widely used diagnostic technique to quantify in-cylinder fuel-air distribution in optical engines. An excellent review of tracer photophysics and engine-relevant applications has been given recently by Schulz and Sick [7]. Typically, the laser-excited fluorescence emission is from a tracer species that has been seeded into a non-fluorescent fuel. In general, the dependency of the fluorescence emission on tracer concentration is determined by calibration experiments performed at engine operating pressures and temperatures. The calibrations then provide for the conversion of fluorescence signal to equivalence ratio.

PIV is used to measure velocity vectors in a planar slice of the flow. In engines, the technique has been used in various studies to evaluate flow properties both in-cylinder and in the ports [8-10]. In general, the flow is seeded with small tracer particles that track the flow with adequate fidelity. Images of the tracer particles are acquired by using pulsed laser light formed into a thin sheet and a camera to image the laser light scattered by the particles. The pulse width of the laser light (~ 10 ns) is much smaller than any flow time scale, so that the particles are essentially frozen over the duration of the laser pulse. The particle displacement field in the imaged plane is determined by cross-correlating the particle images acquired for two successive laser pulses. The velocity field is then determined by dividing the displacement field by the time separation between the two laser pulses.

The utility of PLIF and PIV measurements for the study of in-cylinder mixing follows from the generic transport equation given by,

$$\frac{\partial \rho \theta_i}{\partial t} + \nabla \cdot (\rho \theta_i \hat{u}) = \nabla \cdot (D \nabla \theta_i) + S_{\theta_i}, \quad (1)$$

where θ_i is species concentration, $\hat{u}$ is the velocity vector, ρ is density, D is the diffusivity, S_{θ_i} is a source term, and t denotes time. Equation 1 demonstrates that a complete, quantitative measure of mixing requires simultaneous, spatially and temporally resolved measurements of both the species concentration and the velocity vector field. In turbulent flows, and even more so in an engine, this is very challenging. In the present experiments, acetone PLIF is used to measure the hydrogen concentration field (θ_i) and PIV is used *separately* to measure the velocity vector field ($\hat{u}$) as “frozen flow snapshots” that are uncorrelated from shot to shot.

EXPERIMENT

OPTICAL ENGINE EXPERIMENTAL SET-UP

The optical engine and a generic layout of the experimental set-up used for both PLIF and PIV are shown in Fig. 1. Optical access into the cylinder is either through an optical piston (via a 45° UV-visible mirror mounted inside the extended piston region) or through a partial quartz liner.

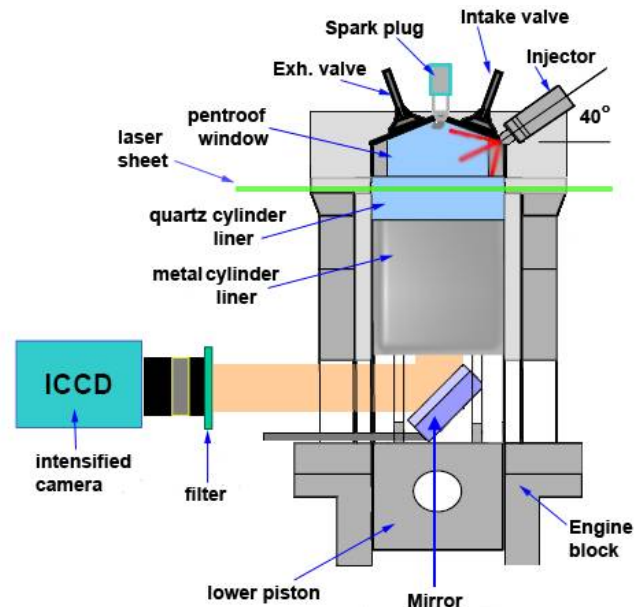


Figure 1. Optical engine experimental set-up.

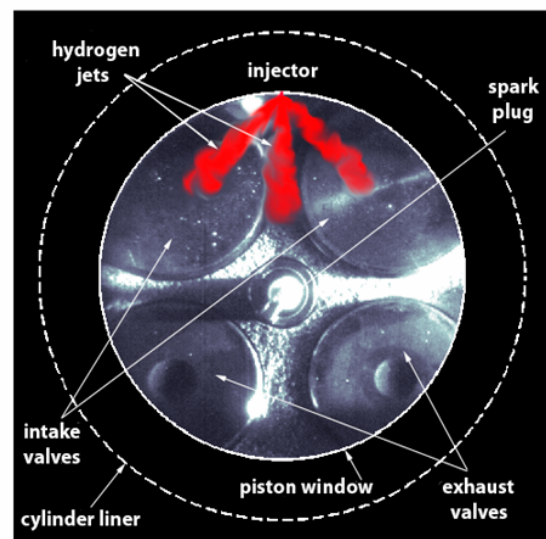


Figure 2. Field of view as imaged through the piston window. The outer dashed line and inner solid line corresponds to the diameter of the cylinder bore and piston window, respectively. The injector is located at the top of the image and the spark plug is located slightly off-center.

In the present experiments, the partial quartz liner is used for laser access and the optical piston is used for imaging. The optical piston has a center quartz window 65 mm in diameter that provides a limited field of view of the combustion chamber shown in Fig. 2. In the image, the six-orifice injector is located at twelve o'clock. The three red plumes in the figure are cartoons of the hydrogen jets as seen through the piston window.

Bore	92 mm
Stroke	85 mm
Displacement	560 cm ³
Geometric Compression ratio	9.1
Engine Speed	1200 rpm
Intake air pressure (BDC pressure)	50 kPa
Intake air temperature	298 K
Coolant temperature	363 K
Valve Timing (open/close) ¹ :	
Inlet	+344 /-112 CAD
Exhaust	+160 /-328 CAD
Maximum valve lift	9.19 mm

Table 1. Engine specifications and operating conditions.

The test engine is an automotive-sized, single-cylinder, optical research engine. The engine head is a pent-roof type, with two intake and two exhaust valves, a central spark plug, and a side injector located between the two intake valves and orientated at an angle of 40° to the horizontal. The experimental prototype injector used in the experiments has a six-orifice nozzle and an included cone angle of 90°. Each orifice diameter is 0.56 mm and the hole-pattern is symmetric about the injector axis. Figure 3 shows the orientation of the hole pattern with respect to the cylinder axis. For this particular injector and injector tip the orientation is not a matter of choice but instead a consequence of where on the injector the electrical connectors are mated and how the injector sits in the engine head. The resulting asymmetry will be seen clearly in the images presented below.

Hydrogen delivery to the injector is by compressed gas bottles. The pressure of hydrogen gas delivery to the injector is held constant by a proportional, integral, derivative (PID) pressure controller. An accumulator with a volume of 1 liter located downstream of the PID pressure controller dampens pressure fluctuations.

¹ The crank angle degree (CAD) convention used is -360 ≤ CAD ≤ +360 where 0 CAD is at top dead center of the compression stroke.

Hydrogen fuelling is controlled by varying injection pressure or the duration of the injection event. The fuel-to-air ratio is determined from measurement of the mass input of air (sonic orifice metering) and the mass input of hydrogen per cycle (calibration curves).

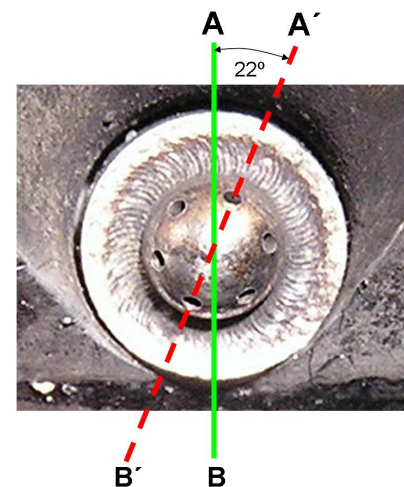


Figure 3. Photograph of the injector tip. AB denotes the vertical plane of symmetry of the engine cylinder. A'B' denotes a symmetry plane of the injector, which is rotated 22° clockwise relative to AB.

EXPERIMENTAL DETAILS

The experiments include measurements for non-fueled engine operation and for fueled operation with hydrogen direct injection either prior to or after IVC. Pre-IVC injection is used to produce a near-homogeneous mixture for the PLIF calibration experiments. In these experiments, SOI is at -270 CAD and end of injection (EOI) is at -240 CAD. Hydrogen fuelling is controlled by varying injection pressure.

Three different post-IVC injection timings are investigated, hereafter referred to as early, intermediate, and late injection. The timings are summarized in Table 2. Hydrogen injection pressure and injection duration are fixed at 2.5 MPa and 50 CAD, respectively. The hydrogen fuelling rate corresponds to a global equivalence ratio near $\phi \approx 0.55$, chosen because it is near the equivalence ratio where NO_x rapidly increases [2-3]. Nitrogen is substituted for intake air to avoid difficulties associated with combustion and with interpretation of the LIF signal due to cycle-to-cycle in-cylinder temperature variations. The last column in Table 2 is a series of schematic representations of the timings of IVC, injection, and imaging. Note that for late injection, images are taken near the end, but still during, the injection event. For both PLIF and PIV presented here, images are acquired at -32 CAD. At this crank angle, the imaged r-θ plane is located 4 mm below the fire deck and 2 mm above the piston.

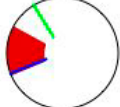
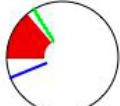
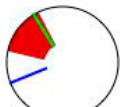
Timing	SOI [CAD]	EOI [CAD]	IVC injection imaging
early	-112	-62	
inter- mediate	-90	-40	
late	-77.5	-27.5	

Table 2. Injection timings.

Planar laser-induced fluorescence experiment

The experimental arrangement for this measurement is essentially that of earlier work [11] with some modifications to improve the signal-to-noise ratio (SNR) of the PLIF images. A compressed gas mixture of 99.5% H₂ and 0.5% acetone by volume at a bottle pressure of 5.4 MPa (750 psig) is used for gas delivery to the injector. The gas mixture is prepared by Matheson gas and certified with NIST-calibrated instrumentation.

Acetone was chosen as the fluorescence tracer due to its well-characterized photophysical behavior [12,13], low toxicity, and relatively high vapor pressure (boiling point 53.6 °C at atmospheric pressure). However, seeding acetone into gaseous flows at high pressure with sufficient concentration to produce good LIF signal levels is difficult, since the maximum concentration of acetone in a mixture is limited by its vapor pressure at the mixture temperature. It follows that for compressed gas bottles at constant temperature, the maximum concentration is limited by bottle pressure and a compromise must be made between storage bottle pressure and LIF signal strength. To avoid condensation in the bottle, its temperature is kept slightly elevated above ambient laboratory temperature by a heating jacket. Although acceptable for these initial studies of hydrogen-air mixing in a DI-H₂ICE, the combination of injection pressure and seed concentration is not ideal, since the injection pressure is lower than what would be used in practice [2, 3, 6], and the relatively low acetone concentration translates to high measurement uncertainties.

Although acetone, a ketone, was one of the first fluorescent chemicals to be used for PLIF, there are now several other groups of tracers that have been used in engine applications [7]. These include aromatic compounds (toluene, benzene) and amines

(trimethylamine, triethylamine). Both of these groups of tracers have typically higher quantum yields than acetone, which can translate into greater LIF emission. However, their emission spectrum is predominantly in the UV, while ketones emit LIF in the visible wavelength range. Most UV lens systems and detectors are not as efficient as their counterparts for the visible spectrum, offsetting this advantage to some degree. Also, with the exception of toluene, much less is known about their photophysical properties at elevated temperature and pressure. Toluene exhibits a strong decrease of the quantum yield with increasing temperature, necessitating greater temperature corrections, which may influence the measurement accuracy negatively. Hwang et al. [16] used toluene as a gas-phase fuel-tracer in an engine and performed temperature corrections using the same strategy that will be used in this paper. Triethylamine (TEA) has been used in a DI-H₂ICE [14]. The authors of that paper did not explicitly take into account the potential variation of the fluorescence signal with temperature, but an in-situ calibration was applied, which may include such dependencies implicitly. These examples show that different tracers can be successfully applied for similar tasks depending on measurement goals, equipment availability, and the current state of photophysical knowledge.

For excitation of the acetone LIF, a frequency-quadrupled Nd:YAG producing about 70 mJ per pulse at 266 nm is used. A cylindrical telescope forms the laser light into a laser sheet. The acetone fluorescence emission is imaged by a Canon 50 mm f/1.2 lens onto a Princeton Instruments intensified CCD camera. The projected in-plane pixel size is 133 x 133 μm². However, the true optical resolution is impacted by lens aberrations and blur of the image intensifier. Additionally, an 11 x 11 pixel median filter is used to suppress noise in the processed images. We estimate the overall in-plane resolution of the PLIF images to be 0.5 – 1 mm, which is also about the thickness of the laser sheet. While this resolution is not sufficient to resolve smallest scales of turbulent fuel-air mixing, it should be well suited for the analysis presented below.

Data reduction for the PLIF images includes the usual combination of background subtraction, correction for average intensity variation within the laser sheet, and for imaging train throughput. On a single-shot basis, the images are also corrected for total laser-energy fluctuation (recorded by a photodiode), but not for shot-to-shot sheet variation. 100 images are acquired for each experimental condition.

To convert the measured fluorescence signal to local fuel concentration and equivalence ratio, a series of calibration measurements with a range of global