

An Optical Study of Mixture Preparation in a Hydrogen-fueled Engine with Direct Injection Using Different Nozzle Designs

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ABSTRACT

Mixture formation in an optically accessible hydrogen-fueled engine was investigated using Planar Laser-Induced Fluorescence (PLIF) of acetone as a fuel tracer. The engine was motored and fueled by direct high-pressure injection. This paper presents the evolution of the spatial distribution of the ensemble-mean equivalence ratio for six different combinations of nozzle design and injector geometry, each for three different injection timings after intake-valve closure. Asymmetric single-hole and 5-hole nozzles as well as symmetric 6-hole and 13-hole nozzles were used. For early injection, the low in-cylinder pressure and density allow the jet to preserve its momentum long enough to undergo extensive jet-wall and (for multi-hole nozzles) jet-jet interaction, but the final mixture is fairly homogeneous. Intermediately timed injection yields inhomogeneous mixtures with surprisingly similar features observed for all multi-hole injectors. Fuel is concentrated near the cylinder wall, an unfavorable scenario were the engine to be fired. Results for late injection depend more on the particular injector configuration. The 13-hole injector shows complete merging of all jets, consistent with results in the literature. The influence of intake-induced bulk-gas tumble is minor for the current injector and combustion-chamber configurations.

INTRODUCTION

Hydrogen-fueled internal combustion engines (H2ICEs) can be highly efficient power plants in vehicles, meeting present and future emissions regulations at reasonable cost [1, 2]. A key element of advanced H2ICEs is direct injection (DI) of the hydrogen fuel into the cylinder [3, 4].

With DI it is possible to mitigate pre-ignition and backfire, increase power density, and recover part of the energy stored in the form of high fuel pressures. Most importantly, the engine developer can devise injection strategies to improve the trade-off between efficiency and NO_x. However, this requires knowledge about the injection event, in-cylinder mixing, and the resulting pre-combustion mixture distribution. Much can be learned from careful parametric studies on single-cylinder research engines [5]. Ideally, these metal-engine studies are complemented by laser-based measurements in optically accessible engines and numerical simulations to gain physical insight into these processes. As in optical gasoline and diesel engines, Planar Laser-Induced Fluorescence (PLIF) of a fuel-tracer can be used in DI-H2ICEs to make two-dimensional measurements of the instantaneous fuel distribution.

Using optical diagnostics in a fully optically accessible engine, we aim to provide some physical understanding of the in-cylinder processes that will be necessary to design future DI-H2ICEs. Previous studies on this engine, albeit at operating points different from the ones studied here, included OH* chemiluminescence imaging [6] and measurements of velocity and fuel distribution [7, 8]. The aim of the current study is to investigate in detail the influence of injector location and geometry and injection timing on mixture preparation. To this end, the equivalence ratio was measured in the motored engine in several horizontal planes for a series of crank angles, up to the MBT spark timing from a very similar all-metal engine at Argonne National Laboratory [5, 9]. The high quality of the PLIF data can be used to evaluate several aspects of in-cylinder air/fuel mixing, but for brevity we will here restrict the analysis to a description of the evolution of the ensemble-mean fuel distribution.

Bore	92 mm
Stroke	85 mm
Displacement	560 cm ³
Compression ratio	11
Speed	1500 rev/min
Intake pressure	1 bar
Fired IMEP	2.5 bar
Global equiv. ratio	≈ 0.25
Injection pressure	80 - 116 bar (depending on injector)
Injection duration	18.5 – 22 °CA (depending on injector)
Intake valve timing ¹	IVO: 346° CA / IVC: -140° CA
Exhaust valve timing	EVO: 130° CA / EVC: -356° CA

Table 1: Specifications of engine and operating point.

EXPERIMENT

OPTICAL ENGINE AND INJECTION CONFIGURATION

The engine under consideration is a passenger-car sized single-cylinder research engine with optical access of the Bowditch type, *i.e.*, through parts of the liner and pent-roof as well as through the flat-topped piston. Hydrogen fuel is delivered directly into the cylinder through an injector developed by Westport Inc. For all experiments here, the engine was motored and supplied with nitrogen in the intake. Table 1 summarizes essential engine and testing parameters and Figure 1 shows the general upper engine geometry. The intake system is omitted for clarity. It consists of two separate intake ports, one for each intake valve, both straight and parallel to each other. The ports form an angle of 45° with respect to the fire deck. The design serves to create tumble motion without any swirl in the combustion chamber. The engine head is a single-cylinder GM research head, which had previously been used for gasoline-fueled operation. It has not been modified or optimized for hydrogen fueling in any flow-relevant parts

Six combinations of injector-tip designs, injector locations, and jet targeting were investigated. They are (except for the 13-hole nozzle, see below) part of the same set of configurations used in previous performance studies [5, 9]. The different nozzle designs are shown in Figure 2a and are briefly described below.

- A single-hole nozzle with a 1.46 mm diameter hole at an angle of 50° with respect to the injector axis.

- A 6-hole nozzle with symmetric hole placement, a hole diameter of 0.54 mm, and an included cone angle of 90°.
- A 5-hole nozzle with asymmetric hole placement on one side of the transverse axis, a hole diameter of 0.61 mm, and a cone angle of the outer 4 holes of 70°.
- A 13-hole nozzle with 12 holes distributed symmetrically in two concentric circles with six holes each one plus the one at the center. The hole diameter was 0.38 mm, and the cone angle of all off-axis holes was 60°.

Multiple configurations were possible with respect to injector location and jet orientation. The following six configurations were used for this study:

- The single-hole injector in central location with the jet pointing along the top edge of the pent roof (1-hole central) as shown in Figure 3.
- The 6-hole injector in side location (6-hole side)
- The 6-hole injector in central location (6-hole central)
- The 5-hole injector in side location with the holes pointing upwards, along the pent roof (5-hole up)
- The 5-hole injector in side location with the holes pointing towards the piston top (5-hole down)
- The 13-hole injector in central location (13-hole central)

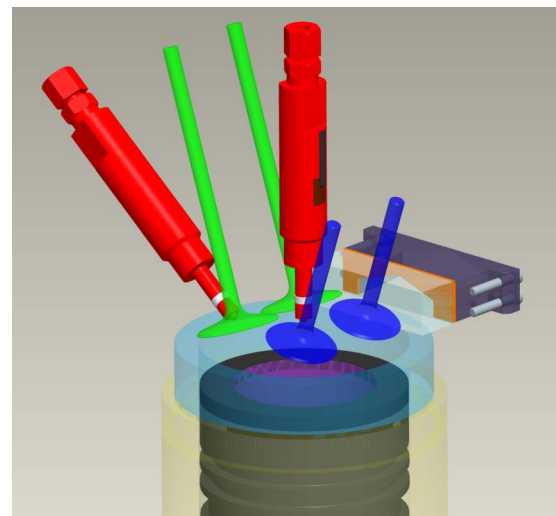


Figure 1: Selected parts of the head assembly. The injector is shown in both side and central location.

In the side location, the injector was oriented tilted 40° with respect to the fire deck, as shown schematically in Figure 2b. When mounted in the central location, the injector replaces the spark plug via a custom adapter

¹ The crank angle convention is -360° CA to 360° CA, with 0° CA corresponding to top dead center of the compression stroke.

sleeve. The orientation is vertical, *i.e.*, parallel to the cylinder axis. Because the spark plug is not in place when central injection is used, fired engine operation (for performance testing) is not possible for this

configuration. The jet orientation for the single-hole injector is shown in Figure 3, and in the same schematic the relative size of the field of view with respect to the cylinder diameter is shown.

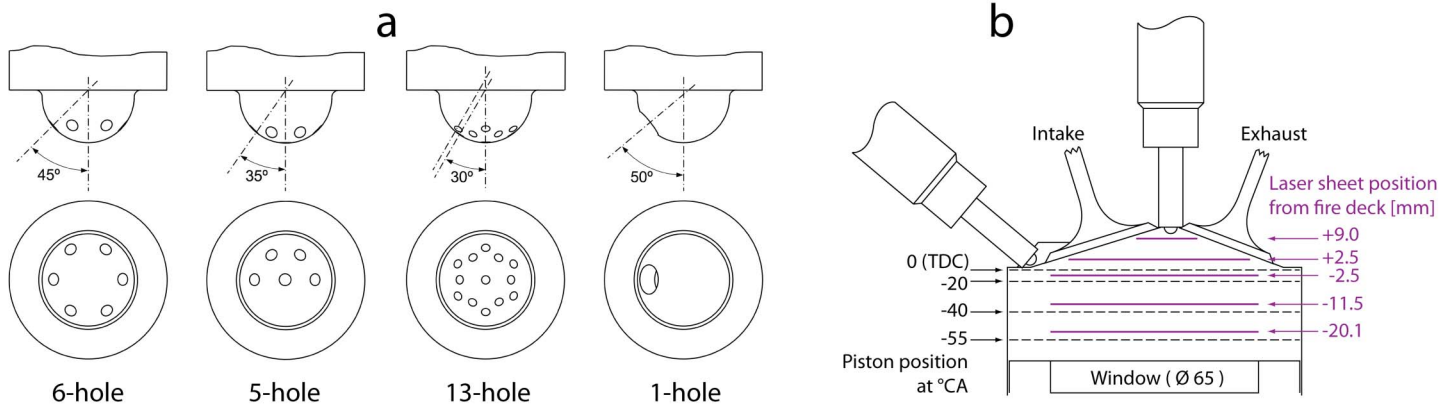


Figure 2: (a) Injector tip designs. (b) Schematic of the combustion chamber with positions of measurement planes and piston at a few crank angles.

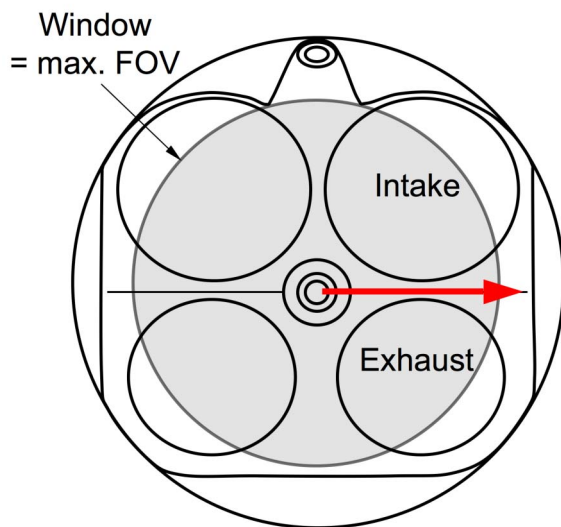


Figure 3: Schematic of the cylinder head showing field of view (shaded area) and the jet direction for the single-hole injector (red arrow).

DIAGNOSTIC TECHNIQUE

The PLIF imaging technique used to measure the in-cylinder fuel distribution is described in detail in reference 10. Briefly, acetone is seeded as a tracer into the hydrogen fuel by a high-pressure bubbler. At 100 bar and room temperature, a volume concentration of 0.33% can be reached. A quadrupled Nd:YAG at 266 nm laser excites fluorescence in a plane parallel to the piston. Laser energies of about 100 mJ/pulse and a sheet-forming lens combination with $f = 1500$ mm were used. An $f = 85$ mm, $f/1.4$ camera lens focuses the visible part of the resulting acetone fluorescence onto an unintensified, back-illuminated CCD. Standard background and flat-field corrections are performed to quantify the measurements. For the latter, a nearly homogeneous charge is prepared by DI during the

intake stroke. Inhomogeneities in the temperature field, induced by mixing of cold hydrogen and hot bulk gas, are corrected for based on known spectroscopic properties of the tracer [11, 12] and the assumption of adiabatic mixing between fuel and bulk gas [10, 13, 14, 15]. The overall typical maximum error in the ensemble-mean equivalence-ratio fields is estimated to be 25%.

EXPERIMENTAL CONDITIONS

In this study, we concentrated on pre-combustion fuel/bulk-gas mixing. In a combustor mixture, PLIF measurements after start of combustion are possible and can deliver interesting qualitative information [for example, see reference 16]. However, after spark, quantification of the signal becomes very challenging. An estimate of the applicable spark timing for each configuration was obtained as the maximum brake torque (MBT) spark timing in a very similar all-metal DI-H2ICE at Argonne National Labs [5, 9], and is referred to in this paper as “spark”, “ignition”, etc. These experiments also gave an indication as to what injection timings would yield practically useful, stable engine operation. Except for the injection pressure, that engine was operated under identical conditions (*i.e.*, those of Table 1) as the optical engine. The injection pressure in the optical engine had to be adjusted somewhat to yield the same equivalence ratio and injection duration as in the metal engine. The overall equivalence ratio was calculated from steady-state nitrogen and hydrogen flow rates, taking nitrogen to be a substitute for air (21% O_2 / 79% N_2).

For each injector configuration, three different injection timings (as given by the start of injection, SOI) were investigated:

- -140°CA , the earliest possible SOI after intake valve closure (IVC)
- -80°CA , the latest timing for which the fired metal engine operated stably for *all six* injector configurations
- -40°CA , the latest timing for which the metal engine operated stably for *at least two injector* configurations (6-hole side, 1-hole central)

Measurements were made for several crank angles ranging from midway through the injection ($\text{SOI} + 10^{\circ}\text{CA}$) to the presumed spark timing. Depending on the crank angle at the time of imaging, PLIF data were taken in up to 5 planes spaced throughout the upper part of the cylinder and pent-roof, as shown in Figure 2b. The central 65 mm of the 92 mm bore were visible through the piston window. Images from 135 fueled cycles were acquired per measurement plane.

RESULTS AND DISCUSSION

In this section the evolution of the mixing process is studied. Several injection configurations (from single-hole to multi-hole injectors) are analyzed. The section closes with a comparative analysis of the fuel distribution at “ignition” for the intermediate injection timing.

1-HOLE CENTRAL

The single-hole injector was studied to gain physical insight into the mixture formation process while avoiding the complexities of jet-to-jet interactions and multiple jet-wall interactions associated with a multi-hole nozzle. An additional benefit of this configuration is the flexibility to point the jet at any polar angle; however, for the present study the jet direction was kept at the fixed position indicated in Figure 3. This particular orientation was chosen based on the performance testing reported in reference 9, which showed that this direction provided the best performance and the widest range of stable operation. Other orientations may be evaluated optically in the future.

The images of the ensemble-mean equivalence-ratio in Figure 4 show the evolution of the fuel distribution for different injection timings. For image timings later than -70°CA the piston top is drawn schematically to indicate the lower boundary of the combustion chamber at each time. This is also to remind the reader visually that a significant portion of the cylinder volume –the near-wall regions and everything more than 20 mm below the fire deck– cannot be imaged and is not shown. The first image set in each time series essentially shows where the injector’s jet is aimed. The lag between injection command and start of needle lift is about 3°CA or 0.33 ms at 1500 rev/min, hence the first image set is taken 7°CA after the jet start.

For early injection ($\text{SOI} = -140^{\circ}\text{CA}$), Figure 4 shows that within these 7°CA , corresponding to 1.1 ms at 1500 rev/min, the jet has penetrated through the optically accessible region of the cylinder. Due to the horizontally and vertically restricted field of view, it is not clear if the jet has impinged on the cylinder wall. At -100°CA the injection process has ended (the injection duration is 18.5°CA), and the top planes are devoid of fuel except at their borders where fuel coming from jet-cylinder wall interaction is seen. It is remarkable how little fuel remains near the injector after the injection event is over. This “leaning” of the near-nozzle region is quite generic in transient jets, and it has also been observed in transient single-phase liquid jets [17] and the gas phase of diesel-like jets [18]. Musculus [19] uses a simple model to explain the associated enhanced entrainment of ambient bulk gas.

At -100°CA , the two bottom planes show a region of high fuel concentration near the cylinder wall opposite from where the jet is pointing, indicating that the impinged fuel has already “rolled over” the piston and cylinder walls. As the fuel cloud moves along the walls it entrains air and becomes leaner. The border between rich and lean sides fluid is well defined, not only in the ensemble mean of Figure 4, but also in single shots not shown here. This sharp boundary is characteristic of penetrating free and wall jets.

The roll-over of the fuel cloud continues throughout the remainder of the compression stroke such that at “spark” (i.e., MBT spark timing from the metal engine) the highest concentration ends up again on the side where the fuel was injected. The jet convection slows down significantly late in the cycle. Between -130°CA and -70°CA the jet has penetrated to the piston top and then propagated along the opposite side, but between -70°CA and -20°CA the resulting fuel-rich cloud only shifts along the pent-roof by about half the piston diameter. This slowing of convection may be due to dissipation of the original jet momentum and enhanced entrainment at the higher pressure at later crank angles. Similar to the well-known late-cycle breakdown of intake tumble there could also be break-down of the large vortex induced by the injection into smaller ones. Direct velocity measurements, planned for future work, would help clarify the evolution of the jet-induced flow. The sharp gradient in the horizontal direction convects and dissipates to become a shallower vertical gradient at -40°CA , with a lean bottom plane near the piston top. However, by -20°CA the remaining weak gradients are mostly vertical again. Over the entire jet “round-trip” the fuel distribution becomes only slightly asymmetric in the transverse direction, indicating weak influence of the bulk gas’s tumble motion, which would tend to push the fuel to one side.

When the fuel is injected at $\text{SOI} = -80^{\circ}\text{CA}$ (intermediate timing), the initial fuel distribution (at -70°CA) appears to show a reduction in the jet-spread angle. This is even more pronounced at $\text{SOI} = -40^{\circ}\text{CA}$. However, Figure 4