

Influence of the In-Cylinder Flow Field (Tumble) on the Fuel Distribution in a DI Hydrogen Engine Using a Single-Hole Injector

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Victor M. Salazar and Sebastian A. Kaiser
Sandia National Laboratories

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ABSTRACT

This paper examines the interaction of bulk flow and jet-induced fuel convection in an optically accessible hydrogen-fueled engine with direct injection. Planar laser-induced fluorescence (PLIF) of gaseous acetone as a fuel tracer was performed to obtain quantitative images of the hydrogen mole-fraction in the operating engine. With the engine motored, fuel was injected into inert bulk gas from a centrally located injector during the compression stroke. The injector had a single-hole nozzle with the jet angled at 50 degrees with respect to the vertical injector axis. Two parameters were varied in the experiments, injector orientation and tumble intensity, and for each of these, the injection timing was varied. Image series of the mean fuel mole-fraction between injection and near-TDC crank angles capture the mixture-formation process for each configuration and injection timing. Variation of the injector orientation shows that with the unmodified low-tumble engine-head the influence of bulk flow on fuel convection is subtle, but clearly detectable. Counter-flow from tumble-enhancing, modified ports retards the progress of injection-induced fuel convection and thereby causes significant changes in the final mixture distribution.

INTRODUCTION

Increasing oil prices and environmental concerns are demanding cleaner and more energy-efficient engines for automotive applications. Consequently, engine manufacturers are facing stringent emission and fuel-economy regulations that are motivating the use of alternative fuels. Hydrogen, with its excellent properties as fuel [1] has shown promising benefits for applications in internal combustion engines and fuel cells. So far, fuel cells offer the highest well-to-wheels benefit in terms of efficiency and emissions [2]. However,

due to their high cost and the lack of a hydrogen-refueling infrastructure, many experts believe that their deployment to the market is at least 10-20 years away [2,3,4]. Conversely, hydrogen-fueled internal combustion engines (H2ICEs) can take advantage of the current engine-manufacturing infrastructure to be mass-produced cost-effectively. Equally important, recent system studies show that advanced H2ICE-powered vehicles can outperform gasoline vehicles and are very competitive with fuel cells [3]. For these reasons, hydrogen engines are seen as a bridging technology that will help to accelerate the development of hydrogen based infrastructure.

Advanced hydrogen-engine concepts are based on direct-injection (DI) fuel systems. In contrast to port-injection, DI not only avoids loss of power due to low volumetric efficiency, but also can mitigate combustion problems such as knock, backfire, and pre-ignition, which have detrimental effects on engine performance and emissions [5]. DI can also reduce heat transfer losses, which in hydrogen engines, due to the low flame quenching distance, are relatively high [6]. Different studies in DI-H2ICEs [7,8,9,10] show that the extent of benefit from DI depends in great degree on the injection strategy and the details of the subsequent mixture formation process. Therefore, understanding the details of the injection process is an imperative step to improve the efficiency of future hydrogen engines. Previous optical measurements by the authors [10] suggest that jet-wall interactions dominate the mixing process. However, the role of intake-induced charge motion in mixture formation is unclear, mainly because its effect is superimposed onto the momentum from the fuel jet. Tumble, conventionally defined as rotational motion of the in-cylinder flow perpendicular to the cylinder axis, has significant effects on mixture formation and engine performance in gasoline engines [11]. It is believed that the large-scale tumble vortex generated during

intake initially strengthens during compression, but then breaks down near top dead center (TDC). This breakdown transfers the kinetic energy stored at the integral scale to the smaller scales of turbulence, increasing turbulence intensity at TDC and consequently the flame speed [12, 13].

In DI-H2ICEs, due to the wide flammability limits of hydrogen, the load can be controlled over a wide range by the amount of fuel injected into the cylinder. At high loads (richer mixture), the flame propagates very fast, but at low loads (leaner condition) the flame speed decreases [14, 15] to the point where combustion duration is too long for optimal efficiency. This is somewhat contrary to the generally maintained notion that “hydrogen burns very fast”. That is certainly true at stoichiometric conditions. However, while hydrocarbon-fueled engines have to operate relatively close to stoichiometric, it is possible to run H2ICEs lean enough to reach idling conditions unthrottled. Homogenous low-load operation is not desirable due to high cycle-to-cycle variability and long combustion duration. It is then important to understand how the charge motion influences the final state of stratified fuel-air mixtures in a hydrogen engine at low loads.

As in commercial diesel and some modern gasoline direct injection (GDI) engines [26], hydrogen injectors for production vehicles will most likely have multi-hole nozzles to aid rapid fuel/air mixing. However, to gain a fundamental understanding of the physical processes involved in mixture preparation and as a bench mark for initial simulation validation, single-hole injectors have proven very valuable [8, 10]. In the current study, an angled single-hole nozzle allowed adding momentum to the in-cylinder flow in different directions, depending on the nozzle orientation. The influence of injection direction and in-cylinder bulk flow on mixture formation is studied by planar laser induced fluorescence (PLIF). Three jet orientations were investigated: the jet in cross-flow, counter-flow, and co-flow with the intake-induced tumble. Also, tumble was increased by modifying the intake port geometry. We examine the changes in mixture formation due to both the changes in geometry and the in-cylinder flow. Besides understanding the physical processes in mixture formation, a complementary objective of this study is to add to a broad database that can be used to validate numerical simulations.

EXPERIMENT

OPTICAL ENGINE

Experiments were performed using a passenger-car sized optically accessible single-cylinder engine adapted to operate with hydrogen. The engine uses a four-valve four-stroke single-cylinder GM research head with a pent-roof

combustion chamber. The main modification to the head consists of two flat windows that provide optical access to each side of the pent-roof. This head was previously used for gasoline-fueled operation and it has not been modified or optimized for hydrogen fueling in any flow-relevant parts. The intake system consists of two intake ports, one for each valve, both straight and parallel to each other forming an angle of 40° with respect to the fire deck (horizontal). This port configuration is not designed to create any swirl. Some engine parameters are given in Table 1 while a schematic of the engine and imaging geometry is shown in Figure 1b.

In addition to the pent-roof windows, optical access is created by a Bowditch-type extended piston with a window covering the central 65 mm of the 92 mm bore. Also, parts or all of the liner can be replaced by fused-silica sections as required. Hence laser-based imaging can be performed in planes both parallel and perpendicular to the cylinder axis. The piston used in this study is flat-topped. Gapless compression rings made from graphite-impregnated Teflon provide sealing with very little blow-by. A drop-down liner allows for quick cleaning of the optical components.

Table 1. Engine specifications

Bore	92 mm
Stroke	85 mm
Displacement	565 cm ³
Conn. rod length	167 mm
Compression ratio	11
Intake valve timing	IVO: 346°CA ¹ / IVC: -140°CA
Exhaust valve timing	EVO: 130°CA / EVC: -356°CA

HYDROGEN INJECTOR

Hydrogen from a high-pressure vessel was supplied directly into the combustion chamber via a solenoid-driven injector developed by Westport Inc. As shown in Figure 1a, the injector has a single hole-nozzle with a hole diameter of 1.46 mm. The hole is at a 50° angle with respect to the vertical injector axis. The injection event is controlled via an injector driver supplied by the same manufacturer. A single injection pressure of 100 bar is used in this study. The average fuel flow was measured by a Brooks thermal mass flow meter. Originally, the engine operated with side injection only. To perform the experiments with central injection reported here, the injector is placed in the spark-plug hole via an adapter. This does not allow for fired operation for performance tests with this configuration. As it is shown in Figure 1b, the injector and the cylinder axis are parallel, but the injector (i.e., the spark-plug hole) has an offset of 3.2 mm towards the exhaust side due to the asymmetry of the pent-roof. This asymmetry is common in 4-valve engine heads because of the larger size of the intake valves compared to the exhaust

¹The crank-angle convention used here assigns 0°CA to combustion top-dead-center (TDC), i.e., crank angles throughout the compression stroke are negative.

valves. The injector can be rotated freely to point the single-hole nozzle in any direction.

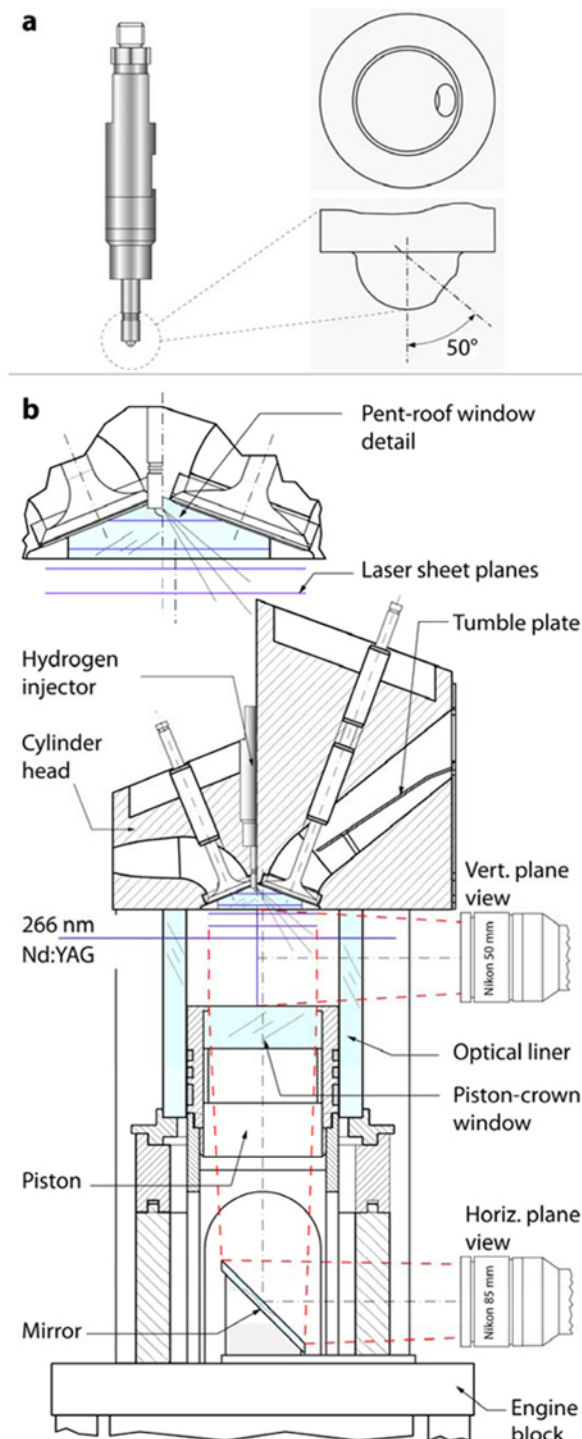


Figure 1. Schematics of the engine hardware. (a) Hydrogen-injector body and angled single-hole nozzle, (b) the upper engine with the tumble plates in the intake ports as well as the imaging geometry for both horizontal and vertical planes. Imaging in either plane was performed separately from the other one.

DIAGNOSTIC TECHNIQUE

Planar laser-induced fluorescence (PLIF) of gaseous acetone as a fuel tracer was performed to obtain quantitative images of the hydrogen mole-fraction in the operating engine. The imaging technique used to measure the in-cylinder fuel distribution is described in detail in previous work [16] and is therefore discussed only briefly here. Acetone was 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. For current purposes, differential diffusion of tracer and fuel is estimated to be insignificant due to the large spatial structures examined here and the high Reynolds number of the post-injection flow. A quadrupled Nd:YAG at 266 nm laser excited acetone fluorescence. Laser energies of about 100 mJ/pulse and a sheet-forming lens combination with $f = 1500$ mm were used. As shown schematically in Figure 1b, images were separately acquired in both a set of horizontal planes as well as in a vertical plane through the axis of symmetry of the injector. For the horizontal imaging planes, an $f = 85$ mm, $f/1.4$ camera lens focused the visible part of the acetone fluorescence onto an unintensified, back-illuminated CCD camera. For the vertical plane, an $f = 50$ mm, $f/1.2$ lens was used. Both were fitted with an achromatic $f = 500$ mm “close-up” lens. Rejection of elastically scattered UV laser-slight by the glass lenses was sufficiently good to omit a long-pass filter.

Standard background and flat-field corrections are performed to quantify the measurements. For the latter, a *nearly* homogeneous charge was prepared by injecting in the middle of the intake stroke [16], relying on the high turbulence levels in the combustion chamber to achieve more or less complete mixing before images are taken in the subsequent compression stroke. For the homogeneous case the fuel was injected from -300 to -240°CA . In previous work [16], the accuracy of this calibration by pre-IVC injection has been studied for an imaging timing of -30°CA . Typical accuracies were found to be within 5%. However, the current study includes earlier timings, which means spatial mixture inhomogeneities in the mean field upon pre-IVE injection may be greater, causing greater bias in the corrected images. Nevertheless, visual inspection of the underlying single-shot images showed only barely discernible gradients, which would be evidence of still ongoing fuel/air mixing. These gradients vanish in the mean. This is different, for example, for lower injection pressures where much greater inhomogeneities can clearly be observed.

Inhomogeneities in the temperature field, induced by mixing of cold hydrogen and hot bulk gas, were corrected for based on known spectroscopic properties of the tracer [17, 18] and the assumption of adiabatic mixing between fuel and bulk gas [16, 19,20,21]. Due to the liner's curved surfaces, the images in the vertical plane were distorted laterally. This mild distortion was easily corrected for in post-processing. The

overall typical maximum error in the ensemble-mean equivalence-ratio fields is estimated to be 25% in the horizontal plane. Small regions in the vertical plane, in particular for early crank angles, may have larger errors because window fouling and signal reflections are more severe for this imaging configuration.

EXPERIMENTAL CONDITIONS

Since the present study is focused on the mixture-preparation process prior to ignition, fired operation was not performed. The engine was motored at a constant speed of 1500 rpm. For most experiments, nitrogen was supplied as a bulk gas to render the intake charge inert and to avoid some spectroscopic complications. For some experiments, a mixture of 90% nitrogen and 10% oxygen was used to suppress acetone phosphorescence. The bulk flow-rate was metered upstream using a sonic-orifice arrangement. The pressure in the surge tank upstream of the intake runner was 1 bar, the intake temperature just upstream of the engine head was 36°C.

The hydrogen fuel was injected at 100 bar for 17.5°CA in a single injection per cycle, which results in a global equivalence ratio of 0.25 ($\lambda = 4.0$) or a hydrogen mole-fraction of 0.095. In fired operation at typical efficiencies, this represents a low load condition with about 2.5 bar IMEP. Calculation of the overall equivalence ratio was carried out from steady-state bulk-gas and hydrogen flow rates, taking nitrogen to be a substitute for air.

With the injector in the central position the jet was oriented at three different angles as indicated in Figure 2. For this intake geometry, estimates of the intake-induced flow field from separate particle-image velocimetry (PIV) measurements at BDC (not shown here) indicate a tumble ratio of 0.24, i.e., weak tumble. Hence the following description of the three injector orientations with respect to the intake-induced flow may be given:

- The jet pointing along the top edge of the pent-roof ($\beta = 0^\circ$), i.e. jet and tumble are in cross-flow.
- The jet pointing between the two intake valves ($\beta = 90^\circ$), i.e. jet and tumble are in counter-flow.
- The jet pointing between the two exhaust valves ($\beta = 270^\circ$), i.e. jet and tumble are in a co-flow.

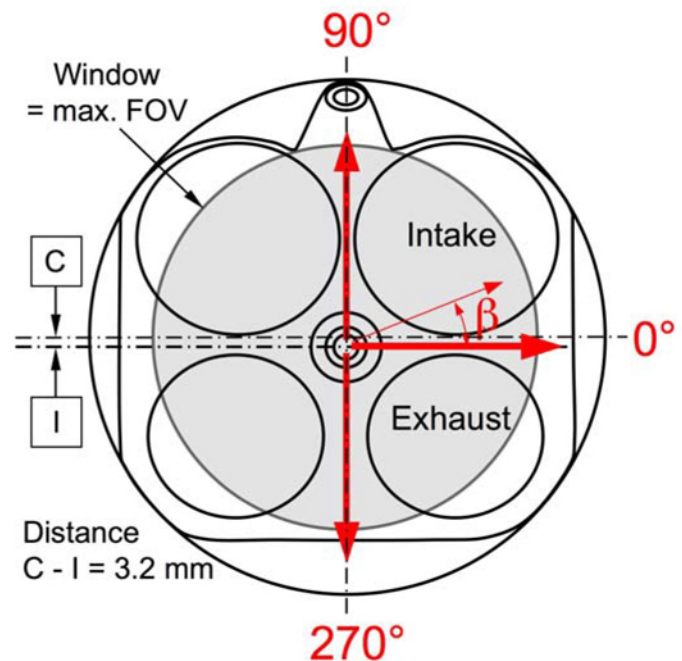


Figure 2. Schematic of the cylinder bore showing the jet orientation (red arrows) characterized by the angle β , the field of view in the horizontal plane (shaded area), and the offset between cylinder-bore centerline (C) and injector centerline (I).

It is not trivial to assure exact and repeatable orientation of the injector nozzle with respect to the engine and to align the vertical laser sheet precisely with respect to the injector axis. The former is important because this study will investigate rather subtle asymmetries in mixture stratification that could easily stem from slight errors in injector orientation. Lack of the latter will underestimate the fuel concentration in the narrow jet during injection. Proper injector orientation was achieved by inspection of ensemble-mean images in a suitably positioned horizontal imaging plane during the injection event. To align the vertical sheet, fluorescence from the sheet was imaged through the piston at small aperture with just enough background light to also see the injector tip. Our experience shows that after visual inspection (without imaging) had indicated proper injector orientation and sheet alignment, often laser imaging would reveal that the jet impinged on the liner several millimeters off ideal orientation and that the laser sheet could be a nozzle-hole diameter away from the injector axis.

In a second part of this study, the intake-induced flow was modified to induce strong tumble, and the effects of this modified flow on mixture formation after injection towards the intake valves ($\beta = 90^\circ$), i.e. against the tumble, was observed. There are several well-documented ways to increase the tumble ratio in an engine [11, 22-23]. Here we inserted tongue-like plates into the intake ports, gradually reducing the cross-section of each port to its upper half.

thereby directing the intake flow more along the pent-roof than would be the case without modifications. PIV measurements of the in-cylinder flow field show that the modified intake configuration results in a strong tumble vortex and an increase in the tumble ratio to 0.95 at BDC. The engine head with tumble plates is shown in part of [Figure 1b](#). In the following, when comparing operation with the unmodified head to that with tumble plates inserted, the former will be addressed as “low tumble” and the latter as “high tumble” operation.

For the variation in injector orientation, three timings for start of injection (SOI) were studied:

- Early, SOI = -140°CA
- Intermediate, SOI = -80°CA
- Late, SOI = -40°CA

For the comparison of high to low tumble, only the two earlier timings were investigated.

For each injection configuration imaging was performed in a series of timings that started several crank-angle degrees after SOI until the time of “ignition” in order to closely keep track of the mixture-preparation process. At low-tumble conditions, PLIF data were taken in both horizontal and vertical planes, while for the high-tumble case measurements were limited to the vertical plane. Horizontal imaging was performed in up to five “stacked” planes that covered the pent roof and the top 20 mm of the quartz liner as shown in [Figure 1b](#). With the current optical arrangement, imaging in the pent-roof was not possible in the vertical plane; consequently the fuel distribution was measured below the fire deck only. At each crank angle, 100 phase-locked shots were acquired. The 100-cycle ensemble-means are presented in the sections below.

Wallner et al. [8] report on performance testing of a similar DI hydrogen engine with the identical injector but a much greater array of operating conditions and jet orientations. Their operating speed was 2000 rpm, and due to this difference as well as subtle differences in engine geometry exact correspondence between thermodynamic and optical results is not expected. However, some trends described in that reference are consistent with our results and will be noted below. Also, from that study the maximum brake torque spark timing (MBT) for each operating condition, typically between -30 to -10°CA , was taken as representative “ignition” timing for our motored engine, indicating when mixture formation could be viewed as complete. In the following, “ignition” or “spark” timing refers to this crank angle from above performance testing.

RESULTS AND DISCUSSION

In this section the fuel distribution in the horizontal and/or vertical planes are discussed for the different conditions. The

results are presented in the following order: First, a brief overview of the mixture formation process for the injector orientation of $\beta = 90^{\circ}$ at different injection timings is given. Second, a comparison of the fuel distribution for three different injector orientations is studied. Third, the effects of low and high tumble for $\beta = 90^{\circ}$ are compared.

MIXTURE FORMATION FOR $\beta = 90^{\circ}$

Previous work [10] contains an overview of the general evolution of the mixture formation when injecting from the angled single-hole injector in the central location. To orient the reader, part of this description will be repeated here, augmented by new information available from additional images in the vertical plane. [Figure 3](#) shows image sets from vertical and horizontal planes arranged in their positions and orientations with respect to the engine geometry for three injection timings. The injector orientation is $\beta = 90^{\circ}$, i.e., towards the intake valves, consequently for this configuration the injection jet and the intake tumble have opposite effects on the charge's angular momentum. Piston top and engine-head geometry are shown schematically with the crank angle of the measurement indicated above each image assembly. Note that due to the wide dynamic range in mole fraction across each crank-angle series, the color scale was not kept fixed but varies with crank angle. For each image assembly, blue corresponds to zero mole fraction and red corresponds to the value indicated below that image assembly. Similar dynamic scaling of the color palette will also be used in figures below.

For SOI = -40°CA , data were only acquired in the horizontal planes since the field of view in the vertical plane is very limited after -30°CA . Combining the two orthogonal data sets provides fairly complete visualization of the mixing process. As will be seen, during and shortly after the injection, measurements in a vertical plane intersecting the injector's axis capture most of the relevant details. Late in the compression stroke, with the geometry of the remaining cylinder volume now much wider than tall, most of the information can be captured by an array of horizontal planes. In between, both sets of planes are necessary to understand the convection and dispersion of the fuel cloud.

The vertical plane covers the width of the cylinder bore and extends to the piston top when relevant, which allows seeing the jet-wall interaction. In [Figure 3](#), the vertical dimension has been stretched by about a factor of three for better visualization of the stacked horizontal planes. 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 in the horizontal plane and is not shown. Similarly, for the vertical planes, the pent-roof region cannot be imaged. The schematic on top of

the first time step orients the data with respect to the cylinder head.

SOI = -140°CA

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 (SOI = -140°CA), Figure 3 shows that within these 7°CA (0.77 ms) the jet has penetrated through the cylinder and has impinged on the cylinder wall². Due to the oblique angle of impingement, most, but not all of the fuel is directed downwards. The redirected downward jet has a mushroom-shaped head like that of a free jet. The smaller portion of the jet that experienced upward redirection can be seen more clearly in the upper right corner of the vertical plane at -100°CA. At this time the injection process has ended (the nominal injection duration is 17.5°CA with a little less than 3°CA lag between controller command and actual closing), and the top horizontal planes are devoid of fuel except at their borders where fuel from the upward redirection 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 [24] and the gas phase of diesel-like jets [25].

<figure 3 here>

At -100°CA, the impinged fuel has already “rolled over” the piston and has formed a wall-jet vortex structure that continues to roll over the injector-opposite cylinder wall. As the fuel cloud moves along the walls it entrains air and becomes leaner. The border between rich and lean fluid is well defined, not only in the ensemble mean of Figure 3, but also in single shots not shown here. This sharp boundary is characteristic of penetrating free and wall jets. At this point the fuel distribution is still nearly two-dimensional and could be characterized fairly well by imaging in the vertical plane only.

The roll-over of the fuel cloud continues throughout the remainder of the compression stroke such that at “spark” (i.e., MBT from the Wallner's performance testing [8]) the highest concentration ends up again on the side where the fuel was injected. 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 is due to wall friction and dilution of the original jet momentum by entrainment of nearly stationary bulk gas. Similar to the well-known late-

cycle breakdown of intake tumble there could also be breakdown of the large vortex induced by the injection into smaller-scale turbulence. Direct velocity measurements, planned for future work, will help clarify the evolution of the jet-induced flow.

At -55°CA there is some indication of the emergence of a fully three-dimensional pattern in the fuel distribution -the second to bottom-most plane shows fuel moving along the lateral sides of the cylinder-, but the main feature is still the broad tumble-like fuel convection. The sharp gradient in the horizontal direction convects and dissipates to become a shallower vertical gradient at -40°CA. However, by -20°CA the remaining weak gradients are mostly vertical again. Contrary to expectation, there is a slight asymmetry in the fuel distribution along the pent roof with higher fuel mole-fractions in the topmost plane on the right, towards the observer. Since the injector was aligned to point precisely towards the central point between the intake valves and because images in the horizontal plane showed the jet cross-section to be symmetric, this asymmetry could imply a corresponding asymmetry in the intake flow.

SOI = -80°CA

For SOI = -80°CA, throughout the data sequence the convection pattern is much more three-dimensional than for the earlier timing. At -55°CA, fuel impinging on the cylinder and piston walls can be seen in a pair of roll-up vortices near the cylinder walls outside the injector symmetry-plane. Instead of rolling over the piston top as for earlier injection, the presence of the piston now deflects fuel sideways along the cylinder walls. The data in the vertical plane at -55°CA indicate that there is some fuel spreading along the piston top, but the next image set at -40°CA shows that this part of the jet has made no further progress. Instead, the entire central part of the cylinder volume remains very lean.

Much of the fuel convection towards the wall opposite from the injector takes place near the cylinder liner, outside of the field of view of the horizontal PLIF images. This can clearly be seen comparing the images at -100°CA for early injection to those at -40°CA for intermediate injection, each image set being 40°CA after SOI. Later in the compression this fuel is pushed out to the very lean center of the combustion chamber. However, due to the reduced time available, by -20°CA the fuel barely reaches the spark plug region; consequently this injection strategy may not be optimal for stably-firing engine operation. In previous work we found that throughout a range of injector configurations, mostly with multi-hole nozzles, none was suitable for placing the fuel near the center of the combustion chamber. It seems the time between injection and “ignition” is just sufficient for the

²The light blue streak in the otherwise dark blue region away from the injector corresponds to fluorescence signal from the jet that has been reflected by the quartz liner into the camera. As verified by inspection of images from the horizontal planes this region is completely devoid of fuel. Similarly, the vertical “yellow” stripe in the bottom left of the image at -70°CA for SOI = -140°CA is due to reflection-induced errors in the background correction.