

PIV-LIF study of different hydrogen injectors for mixture preparation comparison

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ABSTRACT

Green hydrogen is increasingly considered as a promising solution for reducing greenhouse gas emissions in the transport sector. Among the different hydrogen-powered technologies, hydrogen internal combustion engines offer a rapid pathway toward the decarbonization of heavy-duty and off-road applications. However, their performance and pollutant emissions strongly depend on mixture preparation during the injection process. Owing to the low density and high diffusivity of hydrogen, understanding the interaction between the fuel jet and the surrounding airflow is essential for optimizing injector design and operating conditions. In this study, the development of hydrogen jets issued from three medium-pressure injectors is investigated in a constant-flow chamber. Simultaneous Laser-Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV) measurements are employed to characterize both the concentration field and the surrounding flow structures. The combined diagnostics provide detailed information on jet penetration, air entrainment mechanisms, vortex formation, and the resulting mixture distribution. The results highlight significant differences in the flow dynamics generated by the investigated injector geometries. The single-hole injector produces a highly penetrating jet that preserves a coherent core over a longer distance, leading to deeper fuel transport into the chamber. In contrast, outward-opening injectors generate stronger shear-layer instabilities and vortical structures in the vicinity of the jet. These flow structures enhance air entrainment and promote the deformation of the fuel-air interface, accelerating the mixing process. The simultaneous LIF-PIV measurements reveal a clear relationship between vortex dynamics and mixture homogenization. These findings provide valuable insights into the influence of injector design on hydrogen mixture preparation.

1. Introduction

With the transport sector representing around 25% of the world's emissions [1], decarbonation of the sector has become a priority in order to limit climate change [2]. In the transportation sector, Internal Combustion Engine (ICE) represents the main powertrain of the existing fleet. It is then necessary to find alternative powertrains such as electric motor (for instance Battery Electric Vehicle (BEV) or Fuel Cell Electric Vehicle (FCEV)), or alternative fuels which are low-carbon or carbon free. Different technologies are proposed, and among them hydrogen combustion engines (H2ICE) present numerous advantages which make it an appealing candidate, especially for heavy-duty or off-road applications [3-5]. Direct-injection (DI) was shown to achieve higher performances compared to Port Fuel Injection (PFI) [5-7]. Even though hydrogen possesses remarkable characteristics as a fuel, the mixing process of hydrogen with the air requires further understanding in order to achieve higher performances and near zero emissions. Mixture preparation in hydrogen ICEs is inherently different from conventional fuel engines because of the gaseous nature of the fuel that reduces momentum and momentum transfer compared to liquid fuels, and because of the very high diffusivity of hydrogen. It was shown that both combustion efficiency and NO_x production depend greatly on the quality of hydrogen/air mixing [5,8]. With a DI configuration, mixing is influenced by both in-cylinder aerodynamic and injection event. Indeed, contrary to H₂-PFI, H₂-DI creates injection-induced momentum and turbulence, that will interact with the general cylinder aerodynamics, leading to a different mixture formation. This interaction of the jet from the injection event and the surrounding air is an essential step for understanding and designing more efficient hydrogen engines. Furthermore, with Direct Injection, the time allowed for mixing is shortened compared to Port Fuel, and thus requires more characterisation to attain optimal mixture conditions.

Mixture formation can then be studied either experimentally or numerically. Experiments can be conducted in chambers or in optically accessible engines. Engines offer the major advantage that they reproduce the conditions of application, but they are more complex and usually less precise than chamber experiments. The latter allows for studying a more specific part of the mixing process and are greatly usable for CFD validation. This study focuses on gaseous jet development and its interaction with the surrounding gas. The development of gaseous jets has been studied by numerous researchers using experimental measurements or CFD simulations. The Schlieren technique is used to characterize the overall jet development, focusing on the jet structure, penetration length, cross-sectional and jet angle [9-15]. The geometry of the injector (inward-opening or outward-opening) and the pressure ratio between injection and ambient pressure were shown to have a significant impact on the jet morphology. However, internal structure of the jet

is still far from being understood. Background Oriented Schlieren is able to provide a refractive index field as well as a density field for axisymmetric jets. [16,17]. Hydrogen mole fraction is often obtained from Laser Induced Fluorescence: Laichter et al [18] seeded the hydrogen in order to study the initial jet evolution in a heavy-duty optical engine while Quintens et al [19] and Peters and al [20] performed a negative Planar Laser Induced Fluorescence (PLIF) to quantify the hydrogen concentration in the hydrogen jet.

Even though the jet itself has been the subject of many research, the interaction of the hydrogen jet with the ambient gas was not broadly studied. This research work proposes a characterization of the air entrainment and mixing behaviour of medium pressure hydrogen jets using coupled LIF and PIV measurement. A comparative study of the impact of the injector geometry is also carried out.

2. Methodology

In order to study the ambient air entrainment by the hydrogen jet and the mixing behaviour of the jet, two optical diagnostics are used simultaneously to capture the velocity field and the molar fraction field of the same jet: the Particle Image Velocimetry for the air entrainment and the Laser Induced Fluorescence for the molar fraction distribution in the jet.

a. PLIF

In this experiment, the ambient nitrogen is seeded with acetone tracer to capture the local nitrogen concentration and therefore, the local hydrogen concentration. The seeding of the ambient nitrogen was chosen to ensure that the tracer follows nitrogen compared to hydrogen at high velocity and high diffusion rate. Acetone was chosen as the tracer for a multiplicity of reasons, one of which being its high vapor pressure. This allows for appropriate seeding of the nitrogen in ambient conditions. It also presents good stability of absorption and emission against pressure and temperature variations, ensuring the isothermal assumption used for post-treatment is as representative as possible. Moreover, acetone has an absorption spectrum in the UV-Visible region centred around 270-280nm, and an emission spectrum located between 350 up to 550nm. This allows for the use of visible camera and lenses. Furthermore, this limits the self-absorption phenomenon, contrary to several other tracers [22-25].

The 120NL/min nitrogen flow is seeded with 3% acetone by volume and crosses the chamber ascending vertically. The chamber is then illuminated using a Quantel Q-Smart 850 Nd:YAG laser

at 266nm (100 mJ /pulse) and 10Hz. The acetone fluorescence is captured using a Princeton Instruments Kuro back-illuminated camera (2048x2048 pixels², binned to 1024x1024pixels²) with a ZEISS Makro-Planar T* 100mm f/2 ZE lens.

b. PIV

In parallel to the LIF, oil droplets are introduced in the air flow for PIV. A 532nm dual head Nd:YAG laser (Litron Bernoulli B-PIV 145) at 10 Hz, synchronized with the LIF laser, is used to form laser sheets using the same optics as for the LIF laser. The displacement of the droplets is observed between two very close instants by observing the scattering of the lasers at the two instants, then matching small identifiable structures of droplets. The Mie scattering signal is recorded using a CX3-25 Lavision camera (5312x4608 pixels²) equipped with a 100mm lens f2.8. In this experiment, the two laser shots are 10 μ s apart. This allows for quantification of the speed of the flow around the jet but not the core of the jet. This choice was made because the mixing process is predominantly governed by the shear-layer dynamics at the interface of the jet rather than at the core that will mainly remain unmixed.

A PIV image is considered to be constituted of a pair of PIV frames. The duration of the laser pulses is of the order of 10ns, essentially giving access to an instantaneous image of the flow in a given position each time. The PIV allows for the characterization of the flow in the chamber and around the jet. The movement of the particle-filled nitrogen next to the jet gives precious insight on the entrainment of air by the hydrogen jet, a crucial characteristic for mixing. The PIV and LIF are observed by the two cameras through the same optical access of the chamber and are separated by a 532nm dichroic mirror. They are also observed at the same instant, with the first image of the PIV taken just before the LIF one and the second one taken just after. This ensures that the movement seen on the PIV imaging is the movement that was happening in the chamber at the time of the LIF. It must be noted that since the LIF camera has a long exposure time, the PIV signal will appear during its exposure. The dichroic mirror and 495nm lowpass filter reduce that signal massively but the shot-to-shot fluctuations of the PIV laser still must be taken into account. For this purpose, the dual-head PIV laser is fired both during Flat Field and Jet LIF images.

c. Experimental set-up

A quiescent nitrogen-filled constant flow chamber (CFC), provided with 2 square optical accesses of 20x20 cm is used to study the jet development. The ambient pressure was set at 1 bar and the temperature at 293 K. A continuous flow of 120 NL/min is set to clear the vessel from the injected

hydrogen between injection events. The clearing flow is in the direction normal to the plane of Figure 2. The injector is located at the centre of one face. It is mounted in a custom-made adapter screwed to the chamber and protrudes very slightly inside the chamber to limit Coanda effect impact on jet development. The injection duration was set to 2ms. A plenum was installed just before the injector to reduce pressure fluctuations. The hydrogen injections are performed with 3 different injectors:

- a PHINIA DI-CHG injector. This injector operates at medium pressure and can provide a mass flow rate of 10 g/s with a hydrogen injection pressure of 41 bar. This injector is outward-opening and can be equipped with a cap. The CHG10 with a cap will indifferently be called CHG10 w cap or CHG10 with cap. Similarly, the CHG10 with no cap will be called CHG10 wo cap or CHG10 without cap.
- a single hole Bosch HDEV1 inward-opening injector. The injector's hole has a diameter of 0.55mm.
- a Bosch HDEV4, outward-opening Gasoline Direct Injection (GDI) injector that has been adopted by the Engine Combustion Network (ECN) as the first standard hardware for collaborative hydrogen jet research. The hydrogen flow rate obtained is of approximately 2 g/s at 160 bar nominal pressure and less than 1 g/s at 35 bar. Hao Wu et al. [21] measured a steady state value of 0.4g/s at 20 bars injection pressure.

The timings of the different lasers and cameras are as follows (Figure 1):

- injection frequency is 1Hz.
- for the LIF, one JET image is taken at each injection. The corresponding FF is captured 0.1s before.
- for the PIV, one PIV image is captured for each injection. Since the PIV laser impacts the signal of the JET image, it has to be fired during the LIF FF image as well, to account for shot-to-shot laser variability.

By changing the trigger of the camera relative to the injection trigger, different stages of the jet development can be visualised. The injection rate is set at 1 Hz to ensure the absence of hydrogen in the chamber for the next injection event, while the image rate is set at 10 Hz.

It is important to note that in this study, since the laser frequencies are 10Hz and one injection lasts much less than 0.1 second, only one jet image is taken for each jet, meaning that no jet development of one singular jet can be observed.

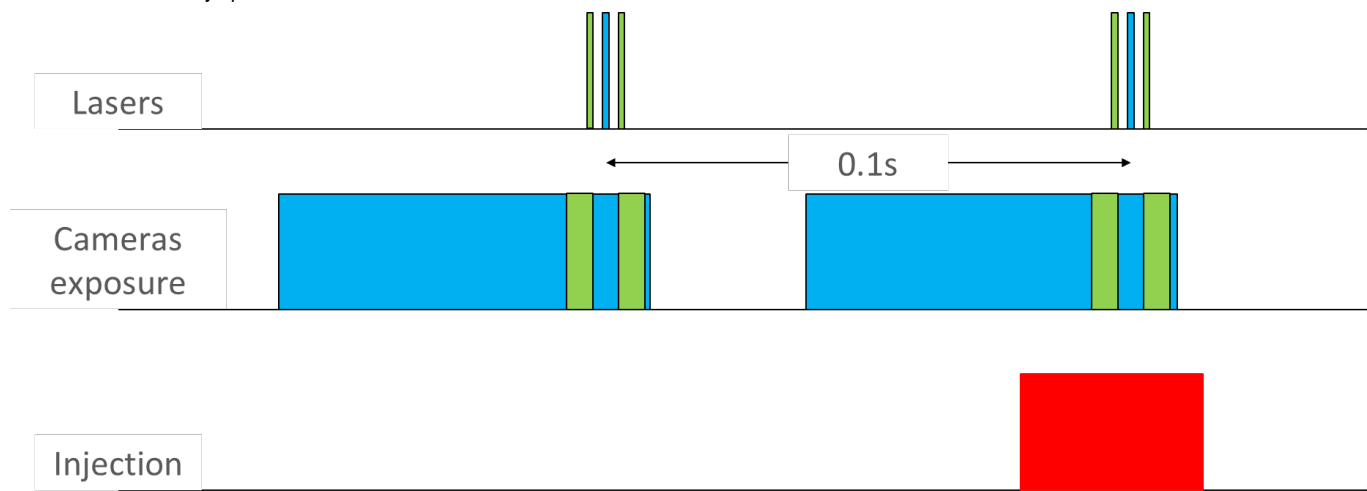


Figure 1: Timing diagram of the experiment. Green is PIV-related, blue is LIF-related. Width of the events is not to scale.

As shown in Figure 2, the LIF and PIV signals are separated with a 532 nm dichroic mirror. The scattering on the droplets being so much more intense than the acetone fluorescence, the camera used for the LIF imaging additionally uses a 495nm lowpass filter to cut-off the 532nm PIV signal.

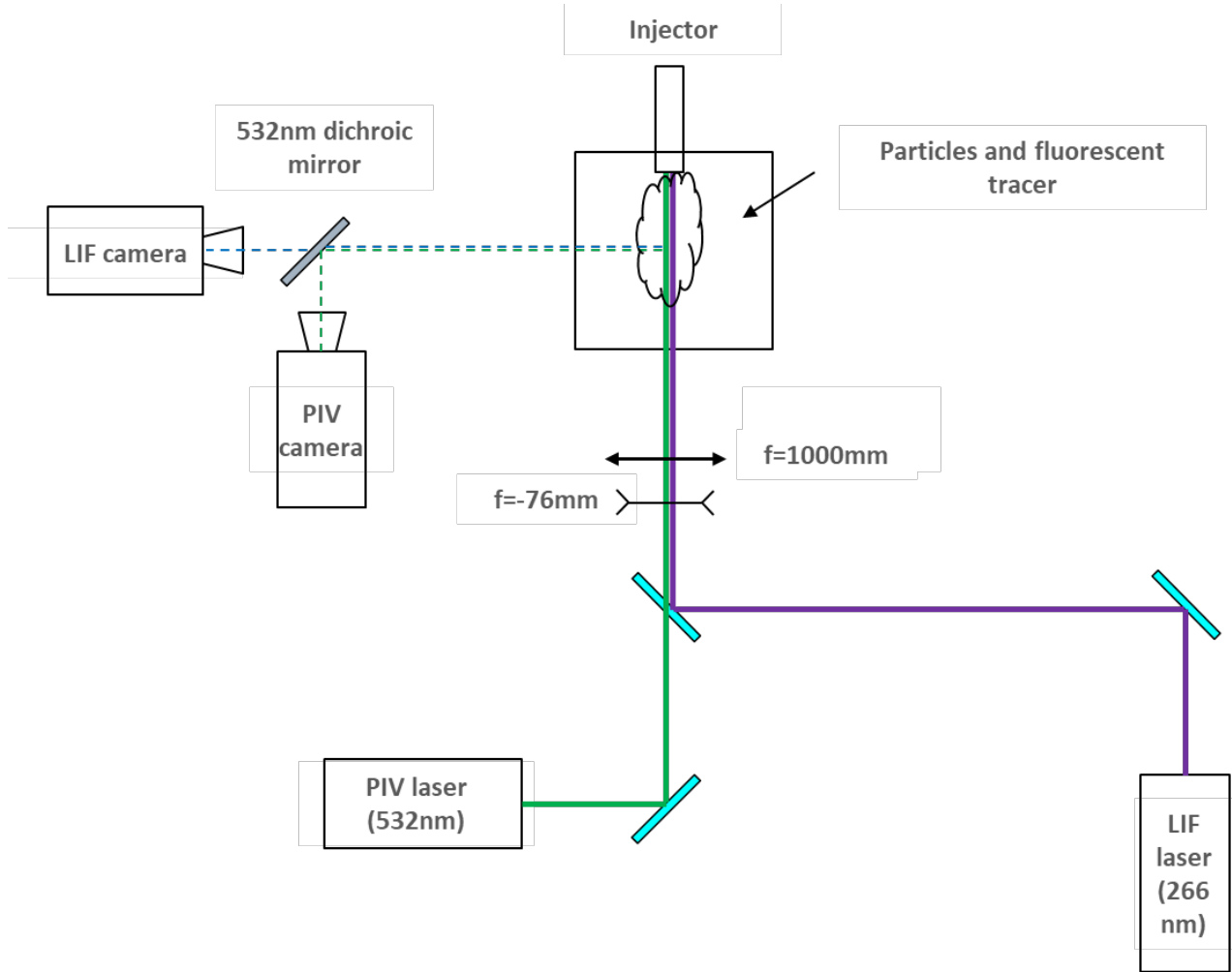


Figure 2: Schematics of the experimental setup

Furthermore, the laser sheet placement is followed at all times by a visible camera positioned facing the injector, so that the fluorescence of the metal surrounding the injector can be observed. This allows for an optimal placement of the sheet compared to the injector and a thickness indicator. Indeed, the hole of the HDEV1 injector used is only 0.55mm wide in diameter and a sheet too wide or displaced by even a tenth of a millimetre leads to an important loss of information on the early spatial development of the jet.

d. Post-processing

From the raw LIF images, the first step of processing is to remove the Sensor Noise (SN) from both the Flat Field (FF) and the Jet image. The FF is then removed from the Jet image, and the shot-to-shot laser energy variation is accounted for by selecting a Region Of Interest (ROI) fixed outside of the jet for all shots and averaging the power over that region for each image. This ensures that different images can be compared. At this point, the jet is still represented by a void area, so the

image is “inversed” to make the jet appear. Then, the conversion to mole fraction is calculated with an isothermal assumption. Finally, the treated LIF and PIV images are superimposed to show both the hydrogen mole fraction and the movement of the nitrogen around the jet.

The PIV images are analysed with multi-passes of the cross-correlation technique. The first interrogation window is of size 128x128, all the way down to 32x32 with 75% overlap. The spatial resolution of the camera is $24 \times 24 \mu\text{m}^2$, leading to a PIV resolution of $0.77 \times 0.77 \text{mm}^2$.

Both averaged and instantaneous results are obtained. The mean result gives important information for CFD simulations that use averaging methods such as Reynolds Averaged Navier-Stokes (RANS). On the other hand, instantaneous images can be compared with Large Eddy Simulations.

3. Results and discussion

a. Jet development comparison

Figure 3 depicts the development of hydrogen jets exiting the four different injectors studied. Focusing on the overall jet development, two behaviours can be identified: a single hole development and a hollow-cone development.

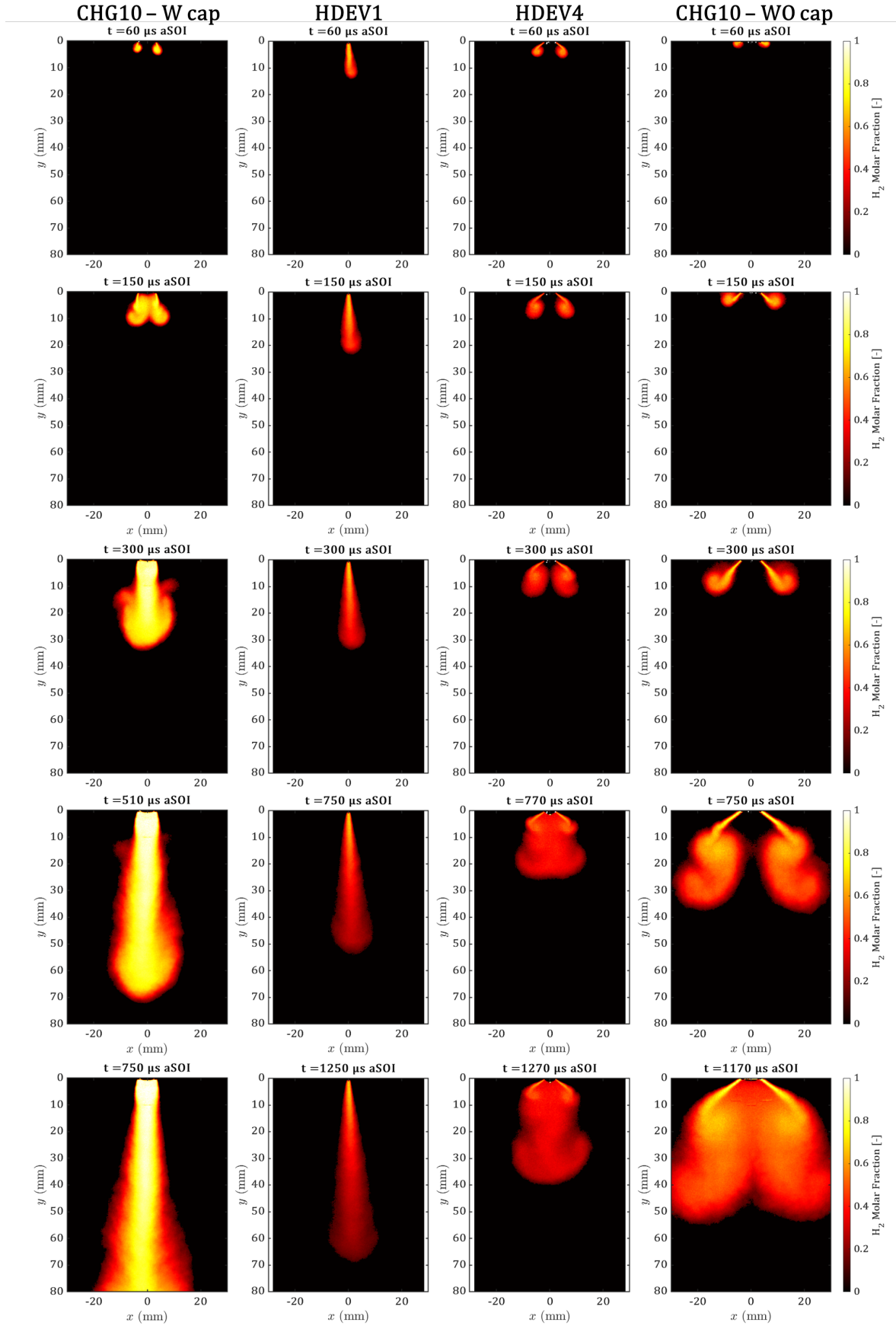


Figure 3 : Jet development for 4 different injectors. Injection pressure of 21 barA

The HDEV1 injector presents as expected a single hole jet geometry with a single jet exiting the injector, and a mainly axial development. As the jet develops, the width of the gaseous jet increases at the jet tip. Both HDEV4 and CHG10 without cap exhibit a hollow-cone structure induced by the geometry of the outward opening injector. The annular shape of the valve leads to the conical shape of the jet, of which the intersection by the laser sheet is the double jet visible. This hollow-cone shape is visible at early timing, then a collapse of the jet is visible in both cases. The centre zone undergoes a pressure loss as it exchanges momentum with the surrounding jet [10,11,14]. The pressure difference between the inside and the outside of the hollow-cone leads to the collapse of the jet. After this collapse timing, the jet propagates mainly axially with a gain in axial momentum and velocity. This phenomenon is particularly visible on the CHG10 equipped with a cap at early timing. The geometry of the cap leads to an early collapse of the jet ($150\ \mu\text{s}$ vs $900\ \mu\text{s}$ between CHG10 w cap and CHG10 wo cap), leading to an almost fully axial development similar to a single hole jet development for higher timings.

However, the four hydrogen jets exiting the studied injectors cannot be compared blindly. Indeed, as HDEV1 and HDEV4 presents similar mass flow rates, a direct comparison can be done. On the other hand, the two CHG10 jets (with and without cap) can be compared directly as the mass flow rate is identical, the nozzle geometry being the only changed parameter. Then HDEV4 and CHG10 without cap might be compared because of the similar outward-opening geometry. It is also interesting to notice the similarity between the HDEV1 jets and CHG10 with cap ones. Once the collapse of the hollow-cone has happened, they create jets that look similar even though they are geometrically different.

Figure 4 illustrates four parameters detailing the hydrogen jets development: the axial penetration which is the distance between the nozzle and the tip of the jet, the area which is the area detected, the volume of the jet calculated from the cross-sectional area and an axisymmetric assumption and the width which is the maximum distance between the left and right pixel of the detected jet. As visible on Figure 3, CHG10 with cap presents the fastest jet development compared to the other injectors studied. HDEV1 injector shows a higher axial development at early timing (before $300\ \mu\text{s}$), however, after the collapse that leads to an acceleration of the jet, CHG10 with cap produces a faster jet. In this case, the higher mass flow rate of the CHG10 also explains the faster jet. Focusing on the HDEV1 and HDEV4 injectors which presents a similar mass flow rate, it is clear that the single hole geometry enhances the axial penetration compared to the outward opening geometry (Figure 4a). Even though the HDEV1 presents a higher penetration, the cross-sectional area detected (Figure 4b) is similar for both low-flow injectors. Indeed, as visible on Figure 3 and Figure

4d, the HDEV4 injectors shows a larger jet from the beginning. Because of its outward opening geometry, the hydrogen jet develops as a hollow cone with a mostly radial development. Indeed, the outlet section of the HDEV4 points towards a radial direction where the HDEV1 one points towards the axial direction. With a lower penetration but a larger cross-sectional area, the jet exiting the HDEV4 shows a larger volume (Figure 4c) compared to the one exiting the HDEV1.

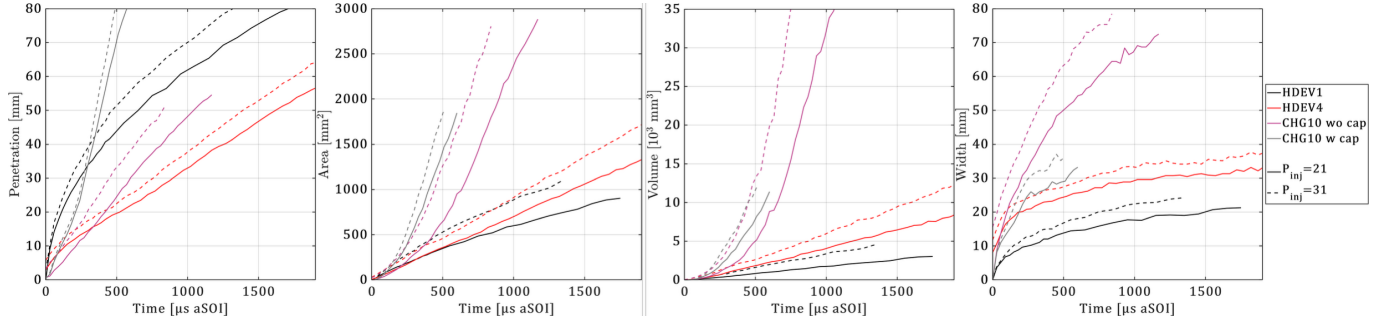


Figure 4 : Axial penetration, Area, Volume and Width of the hydrogen jets

Focusing on the CHG10 development, the presence of the cap induces important changes in the morphology as depicted in Figure 3. Indeed, the jet exiting the injector with cap presents a higher jet velocity (Figure 4a) and a similar temporal development of the area and volume (Figure 4b and c). However, it is clear that the hydrogen jet will present a higher volume for the same penetration length without the cap. The jet without the cap will then presents a larger jet. The injected mass being equal, the geometry without a cap will lead to lower average molar fraction and thus a better mixing.

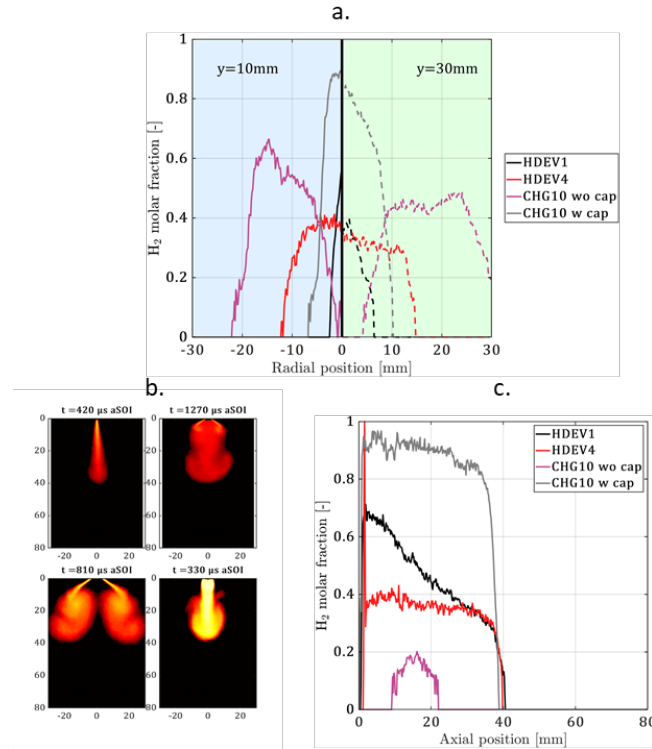


Figure 5: a- Radial H₂ molar distribution for a 40mm penetration length jet
 b -Hydrogen jets at 40 mm penetration length, Injection pressure = 21 barA
 c- Axial H₂ molar distribution for a 40mm penetration length jet

Figure 5 depicts the hydrogen molar concentration measured with the LIF for the 21 bar hydrogen jets exiting the 4 studied injectors. The distribution is studied for jets with a similar penetration length of 40 mm. The jets and the associated timing are visible on Figure 5b. The different jet morphologies are visible at this penetration length: a hollow cone before its collapse for the CHG10 wo cap, a hollow-cone after collapse for the HDEV4, a single hole jet for the HDEV1 and finally a hollow-cone transitioned to a single hole morphology for the CHG10 w cap.

Focusing on the axial distribution of the hydrogen, Figure 5c, two behaviours are visible: the hollow cone jets with a lower hydrogen concentration close to the nozzle ($y = 0$ mm) such as the HDEV4 or the CHG10 wo cap, and the single hole like development with high concentration in the near nozzle region such as the HDEV1 and the CHG10 with cap. For the HDEV1, the hydrogen is directly injected in the axial direction of the injector, leading to the high concentration. Then the hydrogen starts to mix with the ambient nitrogen and to diffuse, reducing the hydrogen concentration in the centreline. As the jet develops, the hydrogen distribution of the HDEV1 remains similar for later timing (Figure 6). As far as the CHG10 with cap is concerned, after the collapse, the injected hydrogen follows the injector centreline where the density is lower, therefore, where the friction is lower. Further from the nozzle, the concentration is reducing as ambient

nitrogen is incorporated through hydrogen diffusion and air entrainment. It is noticeable that the reduction of hydrogen concentration in the centreline is lower for the CHG10 with cap, with a reduction of 12% where the HDEV1 presents a reduction of 60% before the hydrogen concentration drop at the jet tip. As the CHG10 presents higher mass flow rate, velocity in the jet centreline is higher leading to lower diffusion and higher shear stress between the high and low concentration zone reducing the air entrainment and, therefore, a lower concentration drop. Focusing on the radial distribution (Figure 5a), the diffusion and mixing of hydrogen with the ambient nitrogen while the distance with the nozzle increases is noticeable for both HDEV1 and CHG10 with cap. Indeed, when the axial position goes from 10 mm (left part of Figure 5a) to 30 mm (right part of Figure 5a), the maximum concentration value, at $x = 0$ mm, drops while the half-width of the jet increases from 5 mm to 10 mm for the CHG10 and from 2.5 to 6.5 mm for the HDEV1. It is also noticeable that both HDEV1 and CHG10 with a cap show a thin layer between the concentrated heart of the jet and the surrounding nitrogen. This creates a central canal of low friction and the jet from the HDEV1 or the CHG10 with cap is able to penetrate much further than the HDEV4 or the CHG10 without cap, respectively. This effect is particularly remarkable on Figure 5a for the CHG10 injector for which the layer is only around 2mm thick. The CHG10 injector with cap is believed to disadvantage hydrogen-air mixing in favour of the axial propagation.

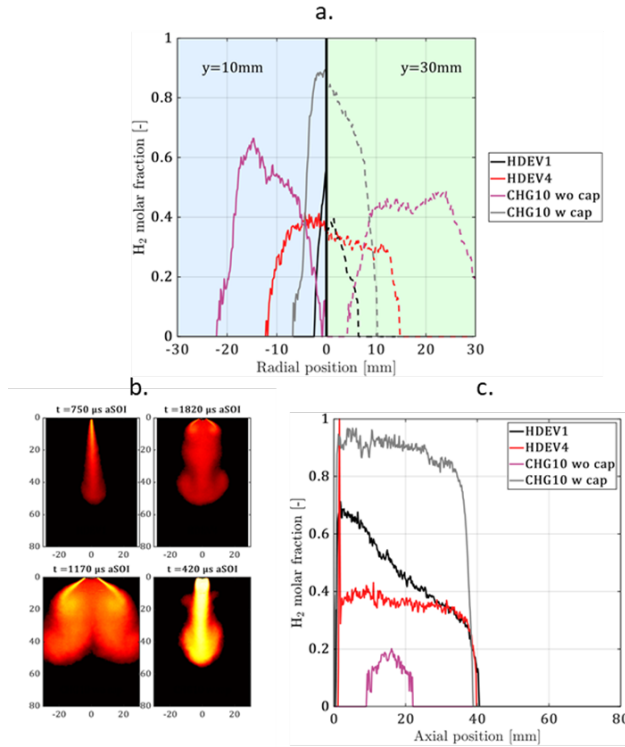


Figure 6: a- Radial H₂ molar distribution for a 60mm penetration length jet
 b- Hydrogen jets at 60 mm penetration length, Injection pressure = 21 barA
 c- Axial H₂ molar distribution for a 60mm penetration length jet

As far as the hollow cone jets are concerned, it is visible on Figure 6a and b that the HDEV4 presents a homogeneous jet contrary to the other studied injectors. Indeed, the concentration in the jet axis goes from 0.4 to 0.3 whereas the HDEV1 one goes from 0.7 to 0.3. In the radial direction, a slight increase of the half-width is visible, from 11.7 mm to 14.7 mm while the hydrogen concentration goes from 0.4 to 0.3. Unlike HDEV1, HDEV4 presents a lower radial expansion moving away from the injector nozzle a lower drop in the hydrogen concentration. With its hollow cone development, the mixing is mainly induced by the wide early development leading to high quantity of air trapped in the jet centre whereas the single hole HDEV1 injector jet mixing is induced by hydrogen diffusion and air entrainment off the sides of the jet.

For the CHG10 without cap, moving away from the injector nozzle leads to a larger jet (Figure 6c) with a lower concentration. It is also noticeable that the jet is close to collapsing 10 mm from the injector nozzle. However, at 30 mm, a gap of 9mm is visible between the two sides of the jet. Looking at the jet with a penetration length of 55 mm on Figure 6 the collapse of the jet is now visible at the two locations (10 and 30 mm from the nozzle). The collapse of the jet will occur as the jet develops. Moreover, the concentration of hydrogen slightly increases as the jet moves

forward. With this geometry, CHG10 without cap promotes the mixing with ambient nitrogen at the expense of axial velocity.

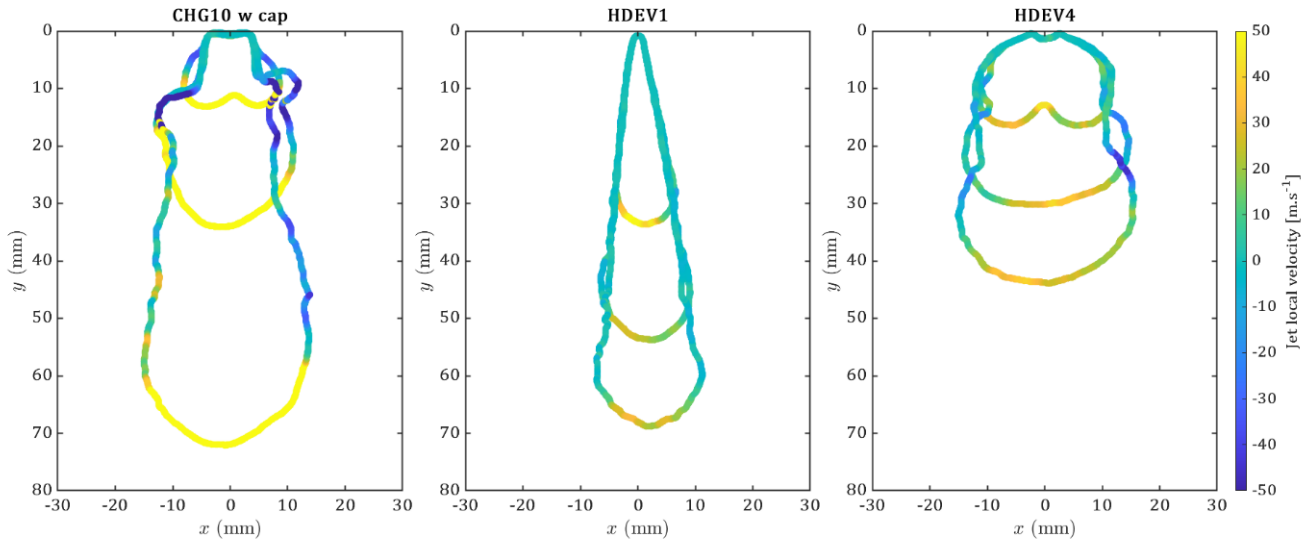


Figure 7: Jet local velocity calculated from jet boundary, Injection pressure = 21 barA

a: CHG10 with cap (150, 300 and 510 μs aSOI)

b: HDEV1 (300, 750 and 1250 μs aSOI)

c: HDEV4 (390, 920 and 1420 μs aSOI)

The movement of the envelope of the jet can be calculated using the boundary detected between two time steps, giving an access to the local speed of the jet boundary. The calculated velocity represents the displacement normal to the boundary, between two time steps. For the CHG10 with cap, the mainly axial development visible on Figure 3 and Figure 4 can also be seen Figure 7a. Indeed, it is noticeable that the boundary of the jet tip presents high local velocity above 50 m/s (peak velocity around 130 m/s). On the lateral boundary, the local velocity is lower; close or lower than 0 m/s, highlighting low radial expansion or shrinking of the jet. Focusing on the HDEV1 injector, the radial part of the boundary shows local velocity close to 0 m/s emphasizing the stability of the single hole jet. The tip of the HDEV1 jet presents positive velocity between 20 and 50 m/s highlighting the mainly axial development, as shown on Figure 4a. As for the HDEV1, the HDEV4 shows a higher tip velocity between 20 and 50 m/s, while the radial velocity of the jet boundary remains close to 0 m/s, with some areas showing a reduction of the jet width, with a negative local velocity.

b. Air velocity field

After calculating jet movement, the interaction between the expanding jet and the movement of the surrounding gases gives an idea of mixture preparation. The quantification of the air entrainment allows for a ranking of different injector geometries and injection conditions, in order to spot the trends that will go towards a maximal mixing. The simultaneous PIV and LIF allows for visualisation of the structures of the jet in correlation with nitrogen movement.

Figure 8 illustrates the temporal reconstruction of a hydrogen jet, with an injection pressure of 21 barA and a back pressure of 1 barA, for the CHG10 injector with a cap.

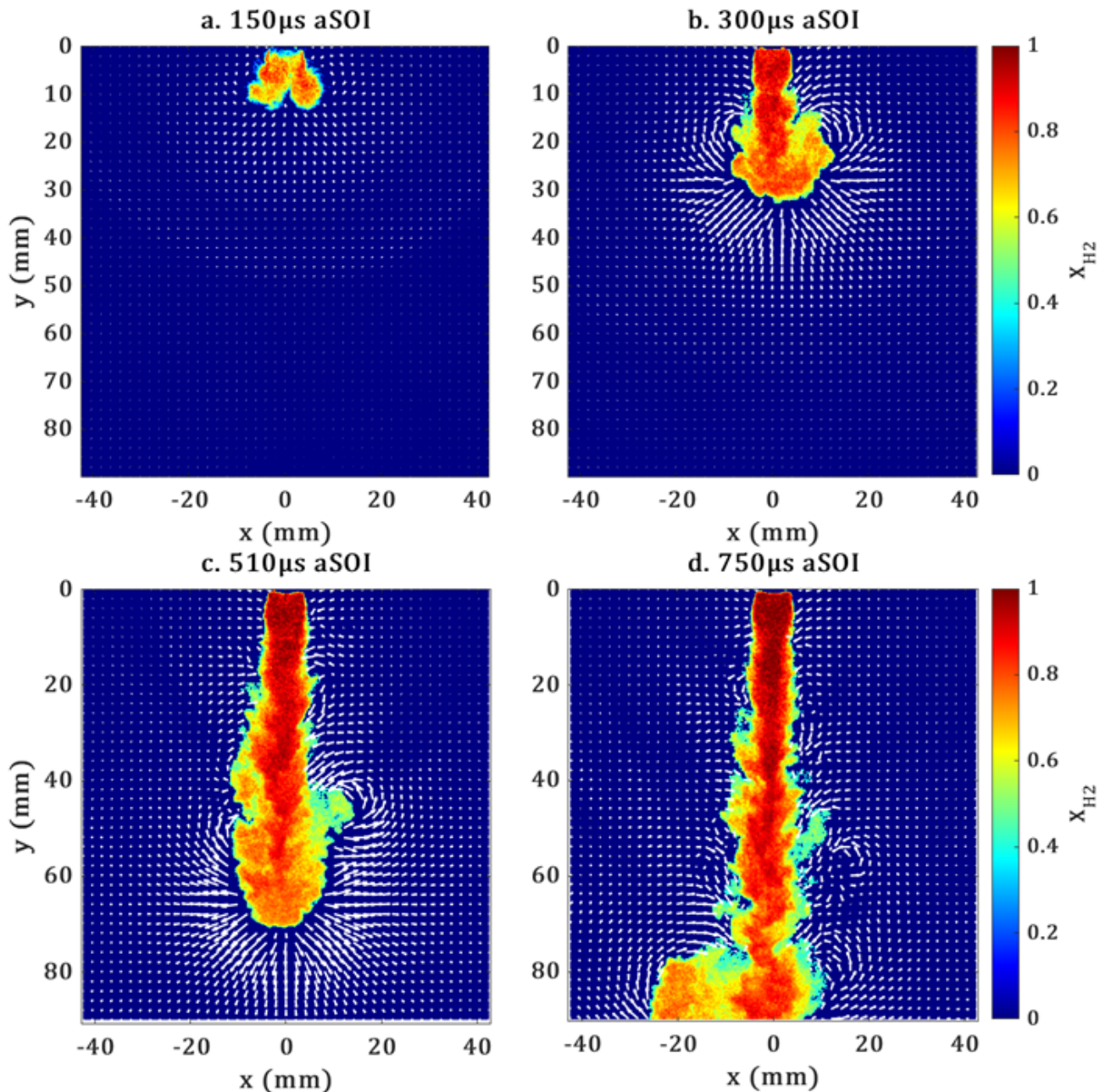


Figure 8 : a, b, c, d: Instantaneous images of jets from the CHG10 with cap for different timings.

$$P_{inj}=21\text{barA}, P_{back}=1\text{barA}$$

Figure 8a shows the collapse of the narrow hollow cone of the CHG10 with cap. Some radial development of the jet can still be observed, but it is very limited and this injector quickly forms a single jet developing in the axial direction. Figure 8a also shows a pressure wave, emitted when the injector opens, propagating in the nitrogen surrounding the tip. 300 μ s after the start of injection, in Figure 8b., the hollow cone shape is no longer visible and the jet has already collapsed into a central structure that will then propagate in the injector's axial direction. The jet axial propagation is then very fast. Clear recirculation can be seen on the sides as the structure of the jet emerges. In Figure 8c and d, the central line of the jet shows a very high concentration of H₂. The jet tip appears to push nitrogen axially and radially. Also, the location of vertices visible on the PIV correlates very well with the shapes that would be associated with vertices on the LIF. For instance, on Figure 8c, at x=10mm, y=50mm, the vortex visible on the PIV correlates with a zone of lower hydrogen mole fraction. The vortex is promoting local mixing.

For each timing, an averaged jet is also studied, to show both the general movement inside the chamber, and to offer a comparison to CFD codes that will rely on averages such as RANS methods. The average for the CHG10 injector with a cap, at 450 μ s after the start of injection is shown in Figure 9a.

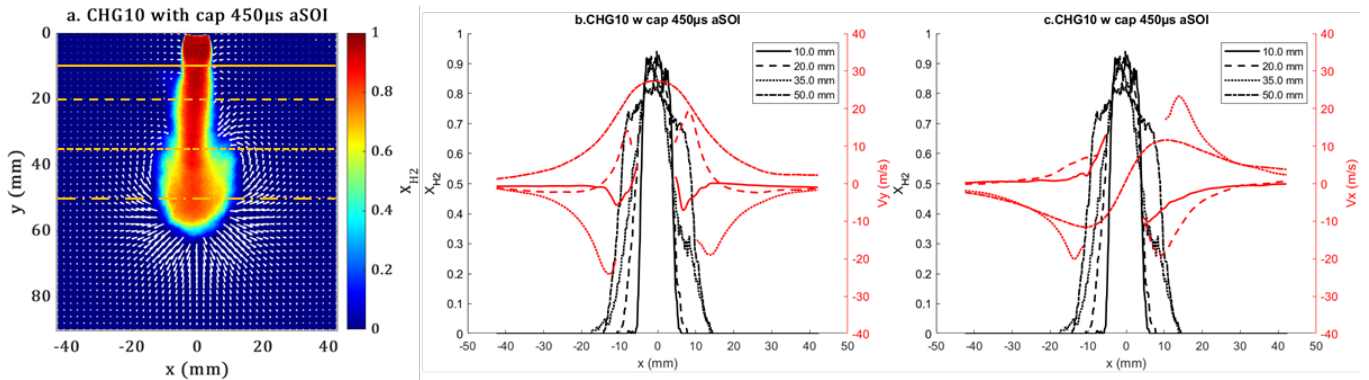


Figure 9: a: Average image of a CHG10 with cap jet observed 450 μ s aSOI. The orange lines are axial distances. b: averages of hydrogen molar fraction (black) and radial velocity (red) for different axial distances, 450 μ s aSOI. c: averages of hydrogen molar fraction (black) and axial velocity (red) for different axial distances, 450 μ s aSOI. Injection pressure is 21barA.

Very low diffusion of hydrogen happens at the jet tip and lateral boundary. Indeed, the shear layer visible between the high concentration zone in the centre and the ambient nitrogen is relatively

thin. It is clear that the axial momentum is still driving the mixing process at this instant. A nitrogen recirculation is observable on each side of the tip as the jet pushes the nitrogen asides. Small vortices appear on the sides of the body of the jet, showing nitrogen entrainment by the jet, leading to local mixing and lower hydrogen mole fractions, for instance around $x=10\text{mm}$; $y=35\text{mm}$ in Figure 9a.

On Figure 9b and c, no velocity is shown for the heart of the jet with very high hydrogen concentration. On Figure 9b, at 50mm, the negative axial velocity around $x=-15\text{mm}$ and $x=+12\text{mm}$ shows that the air is recirculating upwards at a velocity of up to 20m/s. This correlates well with the presence of hydrogen, with the hydrogen mole fraction dropping at the same radial distance. On Figure 9c, the negative radial velocity for negative x shows that the nitrogen is pushed to the left by the jet, while the positive radial velocity for positive x shows that nitrogen is pushed to the right. From that, it is clear that for $y=50\text{mm}$ the jet is pushing nitrogen on both sides, creating a recirculation that is visible on Figure 9a. But notably, for $y=10\text{mm}$ and $y=35\text{mm}$, nitrogen is clearly moving towards the centre of the jet, showing entrainment by it.

For later development of the jet, a comparison is made between the setup with a cap and the one without. Figure 10 compares the average flow fields obtained with the CHG10 with cap on top and without cap on the bottom.

The jet surrounding flow behaviour is very different: the CHG10 with cap promotes nitrogen entrainment towards the axis of the jet, both axially and radially. The axial velocity is positive for the considered axial distances, showing that the jet is creating mixture through a shear stress layer. The core of the jet is once again extremely concentrated in hydrogen, reaching molar fractions above 0.95. This unmixed hydrogen propagates very quickly along the axis of the injection. It is isolated from the surrounding gas by a gradual mixing layer. This behaviour contrasts sharply with the CHG10 wo cap injection: the gases mix nearly everywhere in the jet. 10mm down from the injector, the hydrogen mole fraction is already down to 0.5. As shown earlier, the jet penetration is massively reduced but jet width is increased. This promotes friction between the injected hydrogen and the surrounding nitrogen, leading to entrainment by the jet. Notably, the axial velocity of the surrounding gas is equal if not higher than the CHG10 with cap, even though axial jet speed is less. For $y=50\text{mm}$, the jet has not yet arrived and is only pushing the air downwards with a velocity of up to 20m/s. The jet structure exhibits important vortices centred around $y=35\text{mm}$ and $x=20$ and -20mm . This results in an important circulation of nitrogen outside of the hollow cone, with upwards velocities up to 10m/s. Inside of the cone, the movement is nearly

axial directed towards the injector. This is due to nitrogen entrainment inside of the cone, leading to a low-pressure zone. The nitrogen entrainment by the jet exiting the injector can be seen in the area surrounding the injector, between $x=-20$ to $x=20$ mm, and between $y=0$ up to $y=10$ mm. The velocity vectors of the PIV converge towards the jet exiting the injector. The mixing resulting from that main toroidal vortex is a lot more homogeneous than the axial development resulting from the CHG10 w cap injection.

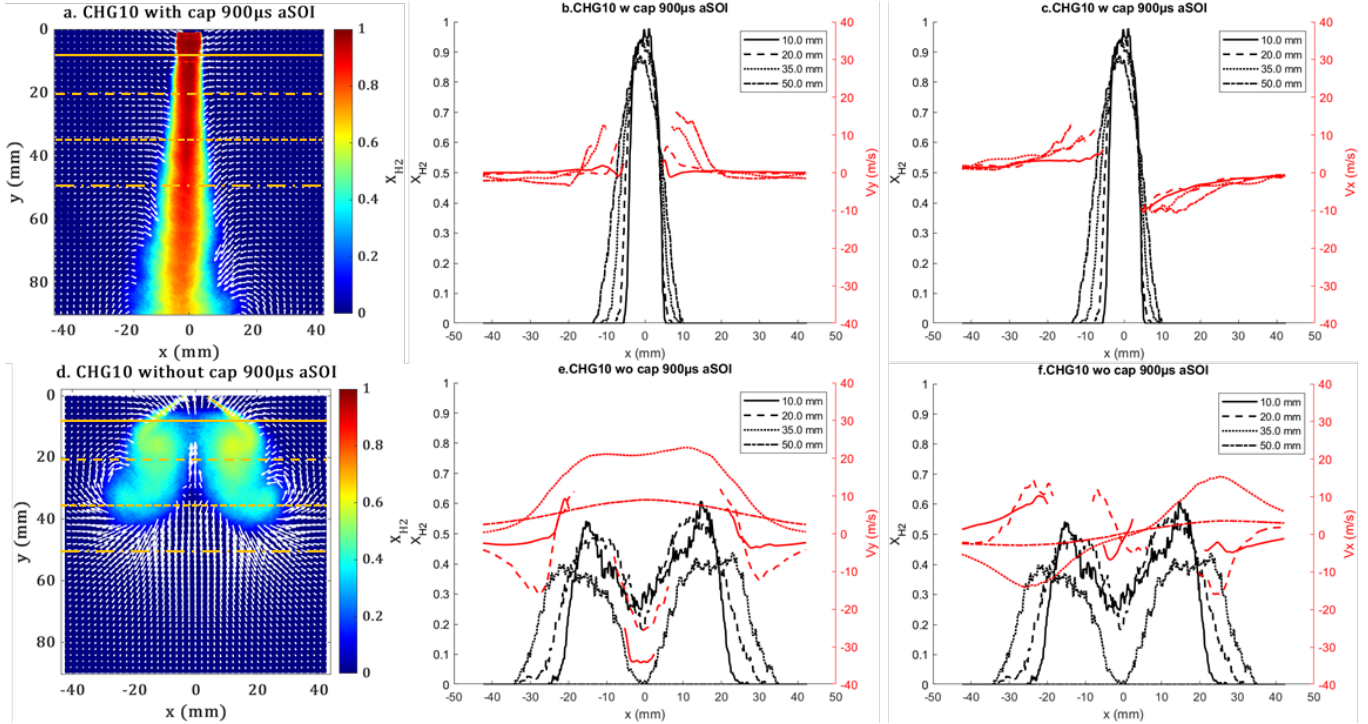


Figure 10: a: Average image of a CHG10 with cap jet observed 900 μ s aSOI. The orange lines are axial distances. b: averages of hydrogen molar fraction (black) and radial velocity (red) for different axial distances, 900 μ s aSOI. c: averages of hydrogen molar fraction (black) and axial velocity (red) for different axial distances, 900 μ s aSOI. d: Average image of a CHG10 without cap jet observed 900 μ s aSOI. The green lines are axial distances. e: averages of hydrogen molar fraction (black) and radial velocity (red) for different axial distances, 900 μ s aSOI. f: averages of hydrogen molar fraction (black) and axial velocity (red) for different axial distances, 900 μ s aSOI. Injection pressure is 21 barA.

Air entrainment is more important for the version with no cap, and the resulting mixture is more homogeneous, at least for the pure injection part.

The nitrogen entrainment is visible not only radially, but also axially, and in the case of outward opening injectors, important movement is created upwards. Figure 11 compares the flows that are created around the hollow cone portion of the jets.

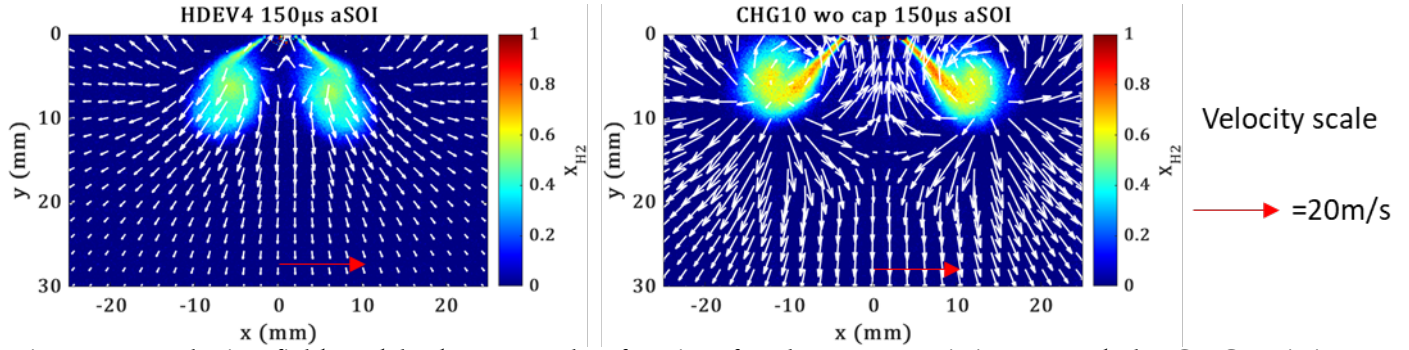


Figure 11: Velocity field and hydrogen molar fraction for the HDEV4 injector, and the CHG10 injector without cap, 150 μ s aSOI. $P_{inj}=31\text{barA}$. This figure is still under analysis

Both injectors show a flow of the nitrogen towards the injector on the vertical axis $x=0$. They however exhibit different behaviours towards air movement around the y limit of the hollow cone. They both exhibit a point of zero nitrogen velocity on the axis of the injector, but the distance from the injector is radically different. The HDEV4 has this point very early on, around $y=4\text{mm}$, but the CHG10 has it around $y=14\text{mm}$, outside of the cone. At 150 μ s timing after start of injection, the HDEV4 hollow cone structure is already collapsing and the upwards movement of the air is already limited to the very top of the inside of the cone. On the other hand, the CHG10 creates an important upwards axial movement everywhere inside its hollow-cone structure.

The toroidal vortex at the head of the jet is visible on both the PIV images and the LIF ones. That vortex is a cause of mixing for the jet, leading to a zone of lower hydrogen concentration.

4. Conclusions

This simultaneous PIV–LIF investigation enables a detailed characterization of nitrogen–hydrogen mixing under aerodynamically controlled conditions, governed solely by the momentum imparted by the hydrogen injection. Nitrogen is seeded with oil droplets to characterize the mean velocity field surrounding the hydrogen jet, and with acetone as a fluorescent tracer to quantify the ambient concentration entrained into the hydrogen jet. The simultaneous measurements allow a direct comparison between the entrained mass flow rate estimated from the PIV data and the local mixing determined from the LIF images. The proposed methodology is shown to be applicable across the four injector configurations and the two flow-rate conditions investigated. This enables direct comparison between different injectors in terms of mixing in the chamber.

Considering the similarities between the CHG10 with cap and the HDEV1 jet development on one side and the CHG10 without cap and the HDEV4 geometries on the other, general conclusions considering the mixture obtained from different injectors can be drawn. It can be seen that a hollow cone injection with a limited collapse will create more vortices and a better mixture homogeneity compared to single-hole injectors. It can also be seen that a cap that promotes the quick collapse of an outward-opening injector diminishes the vorticity and that this leads to a trade-off between axial penetration and mixture homogeneity. Furthermore, by calculating the jet and the air movement, we could highlight the areas of a given jet that incorporates more air into the jet and improves homogenisation. We conclude that in order to favour a more homogeneous mixture, a hollow-cone injector is better than a single hole injector.

Nevertheless, the injector isn't the only factor in the mixture preparation of H2ICE, and different in-cylinder aerodynamics or piston impingement could modify that conclusion.

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