Un-ignited and ignited high pressure hydrogen releases: concentration - turbulence mapping and overpressure effects

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Abstract

Safety studies on hydrogen production industrial installations revealed the importance of accurate prediction of the overpressure effects generated by delayed explosions of turbulent hydrogen jets. Analysis of previous experimental works confirms auto-similarity correlations of concentration and velocity. It confirms also the high level of overpressure produced by the jet explosion. But, the link between turbulent structures of flammable jet and flame behavior are not well established. To deal with this particular problem, a joint industrial project was created between AIR LIQUIDE, AREVA STOCKAGE ENERGIE, and INERIS. The purposes of this experimental work are to realize un-ignited and ignited high pressure hydrogen free jets, to map hydrogen free jets in term of concentration and velocity, to measure turbulence directly in the flammable free jet, to characterize flame behavior regarding to the turbulent flow field and to compare these experimental results (dispersion and explosion) with blind FLACS modelling.

Keywords: *delayed explosions, turbulence, high pressure jet explosion, flame behaviour*

1. Introduction

Safety studies on hydrogen production industrial installations or on hydrogen fuel cell systems revealed that the most important safety perimeters are given by explosion and more particularly by delayed explosion of turbulent hydrogen jets. The estimation of these safety perimeters needs accurate prediction models in order not to be too conservative and to help the deployment of hydrogen installations.

The subject of delayed explosion of turbulent jets has not received a large attention. In the framework of the MERGE project, INERIS (Chaineaux, 1995) performed hydrogen and methane jet explosion experiments. A 5 m^3 vessel at initially 40 bar was used with release diameter from 35 to 100 mm. Measurements of concentration were performed in flammable jet. Two ignition sources were used: a pyrotechnical match of 60 J and a chemical igniter of 5000 J. The overpressures were measured at 10.8 m from the ignition point. Although high levels of overpressure (400 mbar) are measured for the explosion of most important release, all attempts to measure flame velocity (thermocouple, or videos) give inaccurate data to interpret flame behavior.

For the validation of Explojet software (Explojet, 1997) developed by INERIS, Gaz de France and Air Liquide, horizontal hydrogen releases were performed with an initial pressure of

20 bar and release point of 25 mm. The explosion overpressure was recorded by high speed pressure gauges at 3 m from the ignition source. The ignition (60 J) was realized at different locations along the jet axis. The ignition at 2.5 m from the release point gives the largest overpressure which is 135 mbar at 3 m from ignition. This experimental work gave overpressure information to “validate” Explojet Software, but brought little information about the interaction between flame and turbulence.

Hydrogen jet explosion experiments were conducted at the Tashiro testing facility of Mitsubishi Heavy Industries (Takeno, 2007). The initial pressure was 400 bars for release diameters from 0.5 to 10 mm. Measurements of concentration were realized by conventional concentration sensors and optical techniques which gave precious data about the repartition of species. However, flow velocities were not measured. Ignition was performed using an electric spark (20 mJ) set along the jet axis at 4 m away from the nozzle. The time elapsed from the start of leakage to spark ignition (from 0.5 to 5 s) was also studied. Flame velocities were measured using a high speed camera. For the 10 mm hole, the release pressure decreases strongly during to first seconds which impacts the measured overpressure. On the other hand, for the 5 mm and lower diameters, the pressure remains constant.

In the framework of the HYPER project, Willoughby and Royle (2009) have performed some jet explosions. The release device allows or not some flow restrictors (1.5, 3.2 and 6.4 mm in diameter) to be placed in the 9.5 mm piping for pressure of 205 bars. As a consequence, only the 9.5 mm experiments are real high pressure sonic jets. Overpressures have been measured at multiple locations. However, only the overpressure measured at 2.8 m from the release point, 1.5 m from the centre line of the jet and 50 cm from the floor is reported in the publication,. The ignition point was located on the jet axis at 2 m from the release point. The distance between the pressure gauge and the ignition point is 1.84 m. Royle et al have studied the effects of ignition delays and locations; the maximum measured overpressure is 195 mbar. Moreover, Background Orientated Schlieren BOS (1000 frames per second) and high speed infra-red video recordings (100 frames per second) were performed to catch the flame behavior. Yet little information is presented in the publication.

Grune et al (2011) performed unsteady horizontal hydrogen jets with an amount of hydrogen up to 60 STP dm3 and initial pressures of 5 and 16 bar at the FZK hydrogen test site HYKA. A circular release opening with an inner diameter of 10 mm was used. The free hydrogen jets were ignited at different times and different locations. The maximum overpressure recorded is around 200 mbar with 16 bar as initial pressure and the ignition source at 50 cm. A high speed movie of the jet ignition was realized to capture the flame behavior but no result of dispersion is presented.

The previous experimental works brought precious data about flow and concentration fields for hydrogen jets, and confirmed auto-similarity correlations (Birch, 1984, 1987) of concentration and velocity. It revealed also the high level of overpressure produced by a jet explosion. But, we notice a lack of experimental data to link turbulent structures of a flammable jet (u’ and Lt directly measured in the flammable jet) and the flame behaviour. For this reason, a Join Industrial Project was created between AIR LIQUIDE, AREVA STOCKAGE ENERGIE, and INERIS to realize un-ignited and ignited high pressure hydrogen free jets.

The purposes of this experimental work are:

- To map the hydrogen free jet in term of concentration and velocity,
- To measure turbulence directly in the flammable free jet,

- To attempt to determine length scale of turbulence,
- To measure overpressures when the jet is ignited at different locations,
- To characterize the flame behaviour,
- To compare these experimental results (dispersion and explosion) with blind FLACS modelling.

2. Experimental set-up

Medium scale horizontal un-ignited and ignited high pressure releases were performed at the INERIS location. The storage volume was 5 m^3 at 40 bar and the release diameter was 12 mm allowing for a quasi-constant release mass flow rate during the first 20 seconds (Figure **1**). The release point is 1.5 m above the floor.

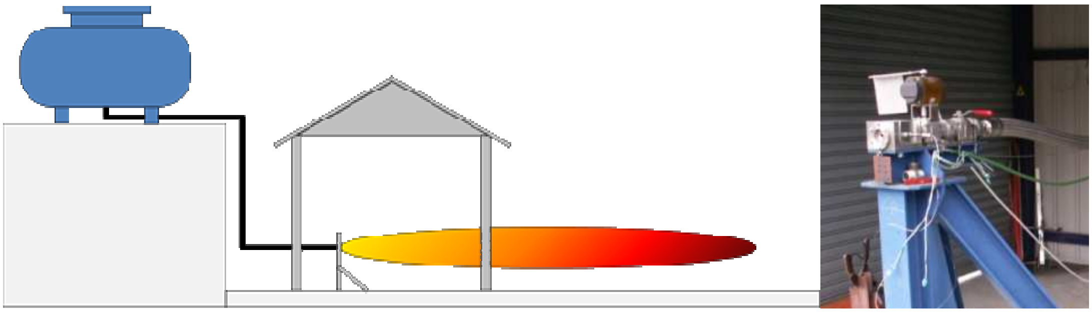


Figure 1 : Scheme of experimental device and release point

2.1 Dispersion instrumentation

Dispersion is studied by measuring the main characteristics of the flammable zone of the turbulent jet, such as velocity and concentration. An instrumented mast moved at different x positions between 1.25 and 10 m from the the release nozzle is used. A picture of the mast is presented in Figure 2, with concentration probes on the vertical axis of the support, and velocity (pressure) probes on horizontal axis.

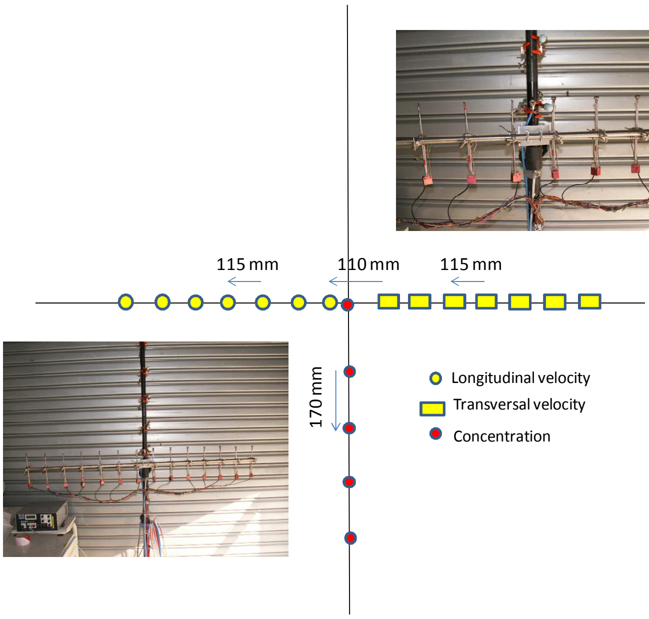


Figure 2: Support of dispersion sensors

The measurements of the H2 concentration (deduced from O2 continuous measurement) were performed using paramagnetic oxygen analysers (SERVOMEX - type PM1158 – error ± 0.02%O2 v/v). The calibration is obtained, first by injecting pure nitrogen to get the zero, and then air.

For the mean velocity field, Pitot bidirectionnal probes coupled with differential pressure sensors allowed to measure the pressure. A description of this sensor can be found in (McCaffrey, 1976). Assuming that momentum is constant along a streamline[1], it is possible to get the instantaneous dynamic pressure, and to deduce the instantaneous velocity. It is then possible to calculate the turbulence intensity (standard deviation) and the turbulence integral scale by measuring the correlation between two probes or the same probe and itself (time interval). This technique has been already used for turbulence in gas or dust cloud (Tamanini, 1990 and Proust, 2004).

2.2 Explosion measurement

2.2.1 Pressure sensors

The measurement of overpressure was realized by 3 piezoresistive pressure sensors Kistler 0-2 bar. These sensors are embedded in a lens support which allows for the measurement of incident pressure wave without any reflection effect.

Figure 3 shows the overall repartition of pressure gauges. The L1 sensor is located near the release point (20cm). The L2 sensor is located at 2.5 m of the igniter perpendicular to the jet axis. The L3 sensor is sensors located on the axis of the jet at 2 m.

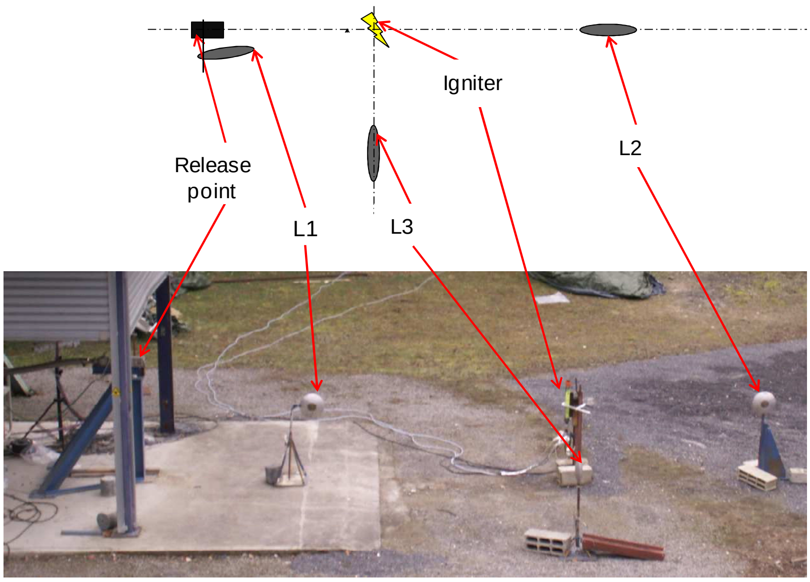


Figure 3 : Overall repartition of pressure gauges

2.2.2 Ignition source

The ignition source is a vertical steel tube (diameter: 5.5 cm – length: 50 cm) filled with H2/O2 stoichiometric mixture which is ignited by a pyrotechnical match (60 J). The igniter is a 45 cm long flame which ignites the free jet (Figure 4). Due to the jet flame length, in order to have an ignition point on the centerline, the extremity of the tube is placed at 20 cm below from the axis of the jet. The aim of this technique of ignition was to obtain reproducible tests.

[1] The flow is considered incompressible

Figure 4: Ignition source

2.2.3 High speed camera

A high speed video system was used to catch flame behavior. A PHOTRON FASTCAM was installed at 10 m perpendicularly to the ignition source. The image was centred on the igniter and visualized 3 m downstream and 2 m upstream of the igniter. The rate of capture was 2000 frames/s.

3. Results

3.1 Jet similarity profiles

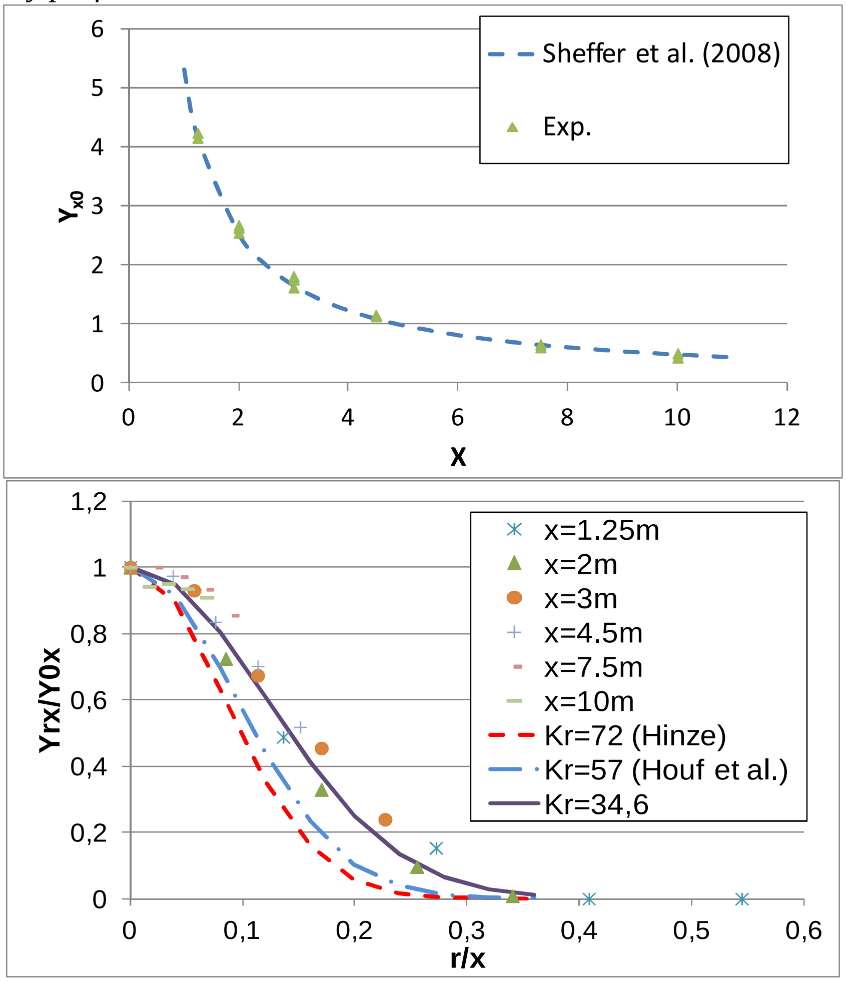


Figure 5: Mass concentration along the axis (up) and normalized mass concentration along the normalized radius (down).

The centerline variations in the mean H2 mass fraction, Yx0, are shown in Figure 5.

Yx0 decreases rapidly as ambient air is entrained into the high velocity jet where it mixes with the hydrogen. The centerline mass fraction decay for nonreacting jets can be correlated with distance from the virtual origin, x0 (Hinze 1975, Birch, 1984; ScheferSheffer, 2008). This correlation can be expressed as:

$$Y_{x0} = \frac{K_c D_{eff}}{x - x_0}$$

with Deff the effective diameter, x0 =4D and Kc=4.8 as expressed by Schefer (2008).

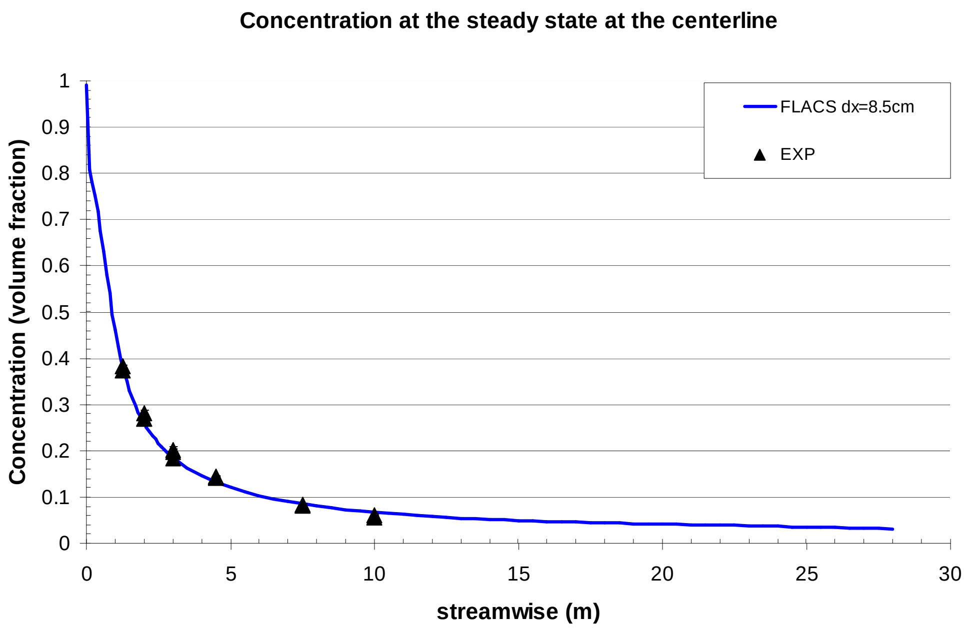
The radial profiles of Y have been replotted in terms of jet similarity variables in Figure 5 where the mean mass fraction is normalized by the centerline value, and the radial distance is normalized by distance from the origin.

The present results for hydrogen show good agreement with correlations expressed by

$\frac{Y_{xr}}{Y_{x0}} = \exp[-K_r(\frac{r}{x - x_0})^2]$, where different values of Kr can be found in the literature : Kr=72 for Hinze (1975), Kr=58 for Schefer et al., (2008), Kr=57 for Houf et al. (2008). The best value of Kr is found equal to 34.6.

Concerning velocity profiles, the same conclusions can be made. Similarity profiles are respected. Comparisons with other authors as Chen and Rodi (1980) or Hinze (1975) seems showing a good agreement.

Experimental results are also compared with FLACS v10.1 simulations. Figure 6 shows the concentration dilution vs. the distance in the streamwise direction for the comparison of FLACS v10.1 simulations with experimental measurement (black triangles).



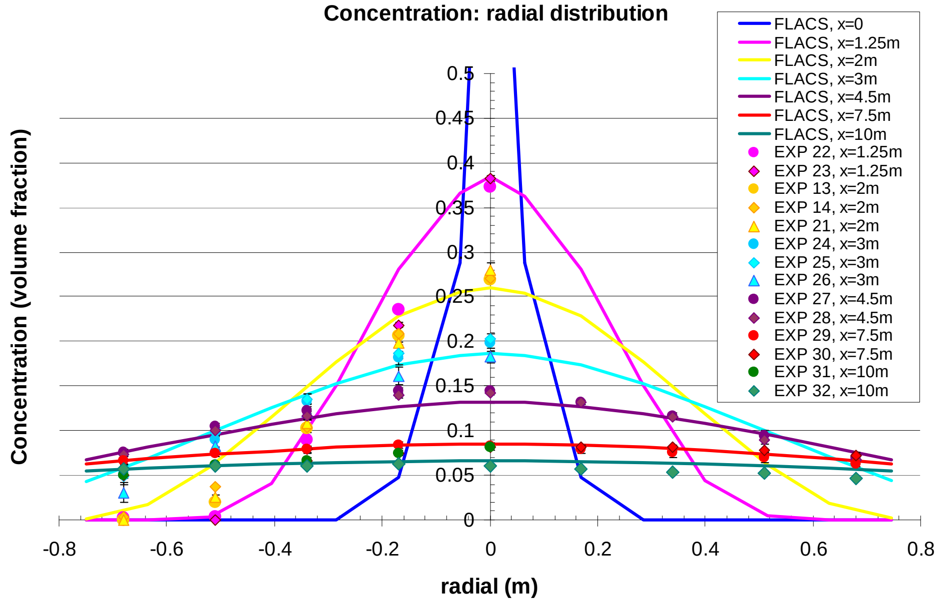
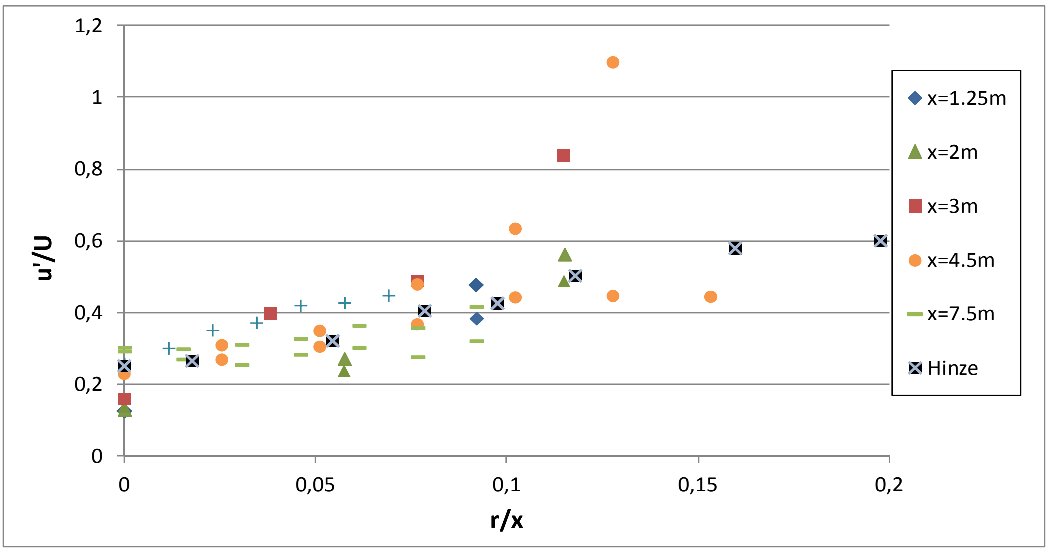


Figure 6: Concentration decay (centreline – radial) – experiments vs. FLACS

Figure 6 reveals the radial concentration distribution at various streamwise (x-direction) positions. FLACS simulations match very closely experimental results.

The relative intensity of the turbulence (standard deviation) is between 15 and 30% and exponentially increases with the normalized radial distance r/x, in a coherent way if we compare with the values proposed by Hinze (1975) for example.



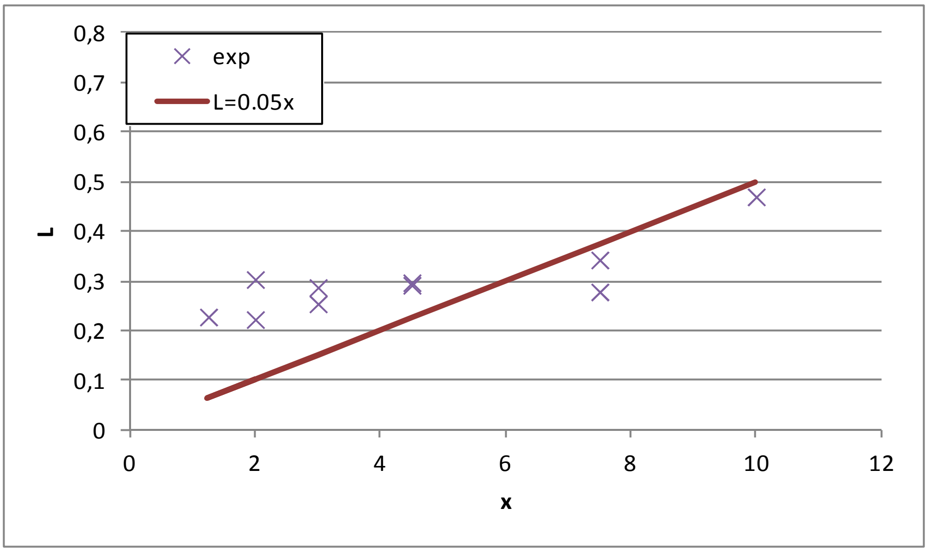


Figure7: Standard deviation along the radius (left) and turbulence scale along the axis (right)

The scale of turbulence also respects the Hinze correlation (1975), consisting in an increase of the scale respecting 5% of the distance of the origin. These results confirm the ability to get an order of magnitude of the turbulent characteristics

3.2 Explosion results

This paragraph presents typical results obtained during the experimental work. The igniter is installed at 1.8 m where the H2 concentration is around 30 % in air. Figure 8 shows the overpressure signal. The pressure signal shall be filtered using a 0.6 ms window moving average filter.

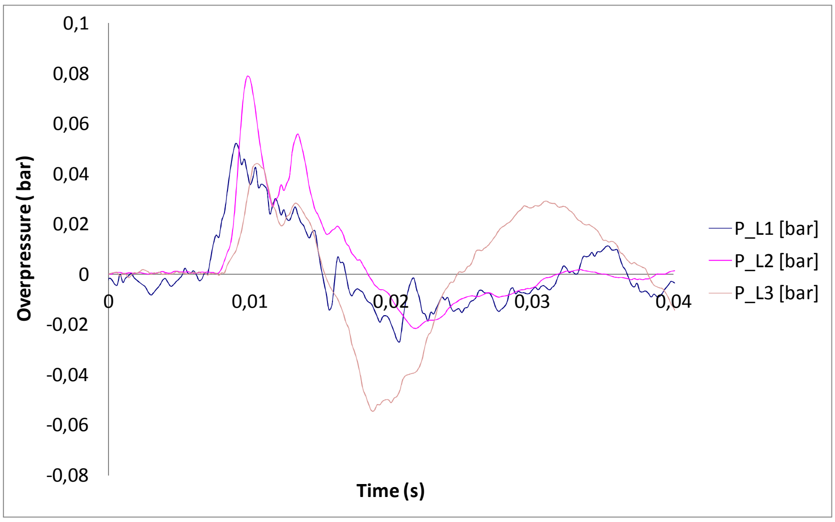
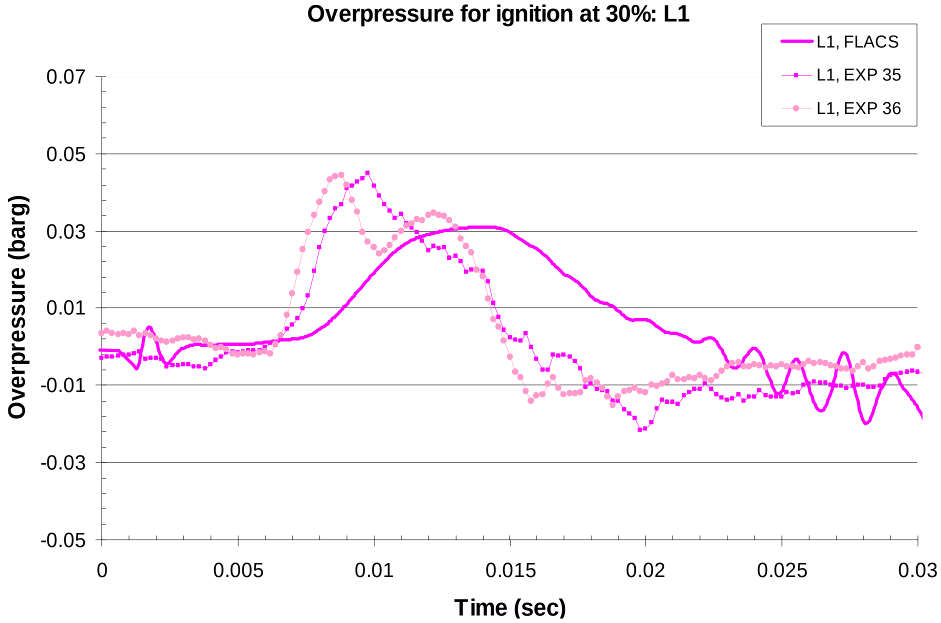


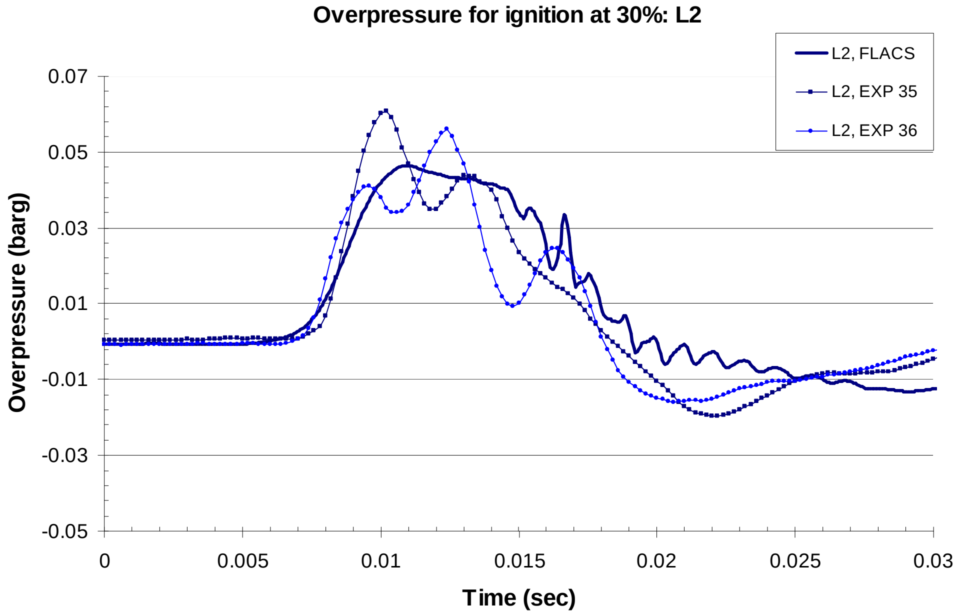
Figure 8: Overpressure

We notice the most important overpressure is measured at 2 m downstream the igniter. The maximum overpressure is around 80 mbar. The pressure rise takes around 5 ms.

The pressure level measured on L1 sensor is lower than the level on L2 sensor

Figure 9 compares the overpressure signal computed by FLACS v10.1 to the one defined from the experiments at pressure detectors (L1, L2 and L3). Similar to experiment in simulations the maximum overpressure is observed on the second detector L2, this is located closer to the ignition position. One can easily see that for ignition at 30% the overpressure is slightly underestimated by FLACS v10.1.





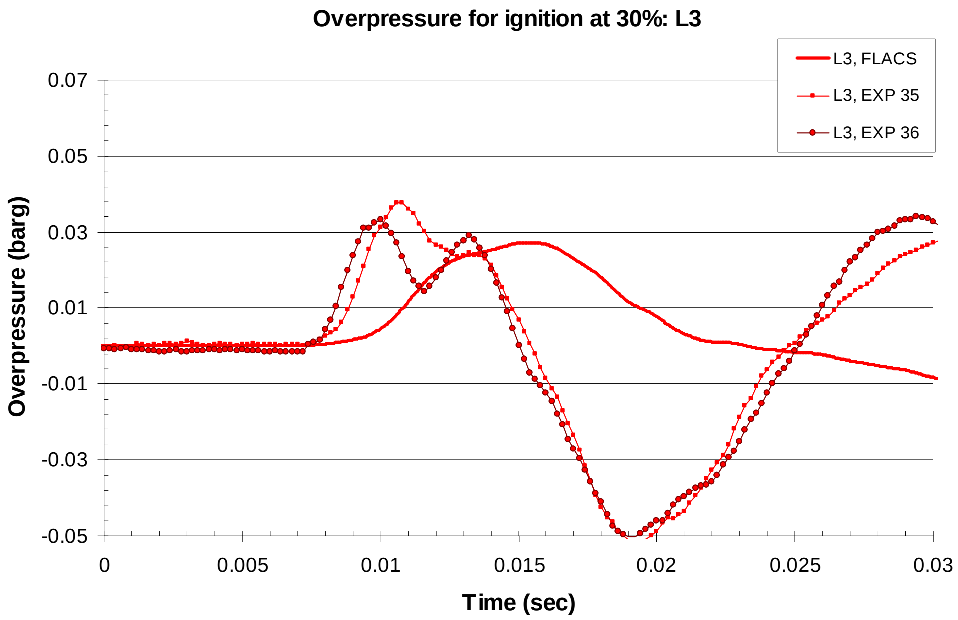


Figure 9: Overpressure evolution in time FLACS simulations vs experimental data

One can easily see that FLACS simulations shows quite good agreement with experimental data for explosion simulations.

A specific image processing was necessary to see the flame behaviour in the jet (Figure 10). A Scilab (Scilab 5.4.4) algorithm was realized and consists in subtract the first images, adjust the contrast and luminosity and detect the image pixels whose intensity is superior to a threshold define for each test. This zone defines the pocket of burnt gas.

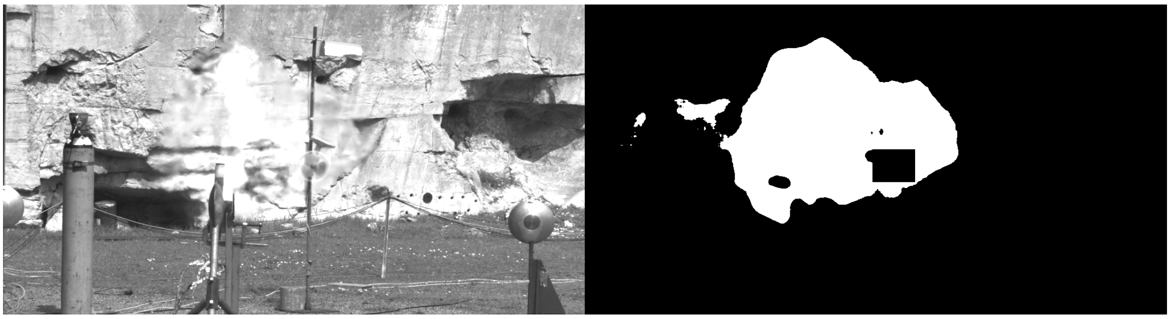


Figure 10: Image before and after image processing

At the beginning, the hydrogen flame develops vertically, which is characteristic of vertical igniter. Later the flame develops preferentially in the direction of the flow whereas the upstream advance of the flame along the jet axis is held back by the flow. We can extract the horizontal flame position from the high speed treated images and deduce the downstream spatial flame velocity (Figure 11).

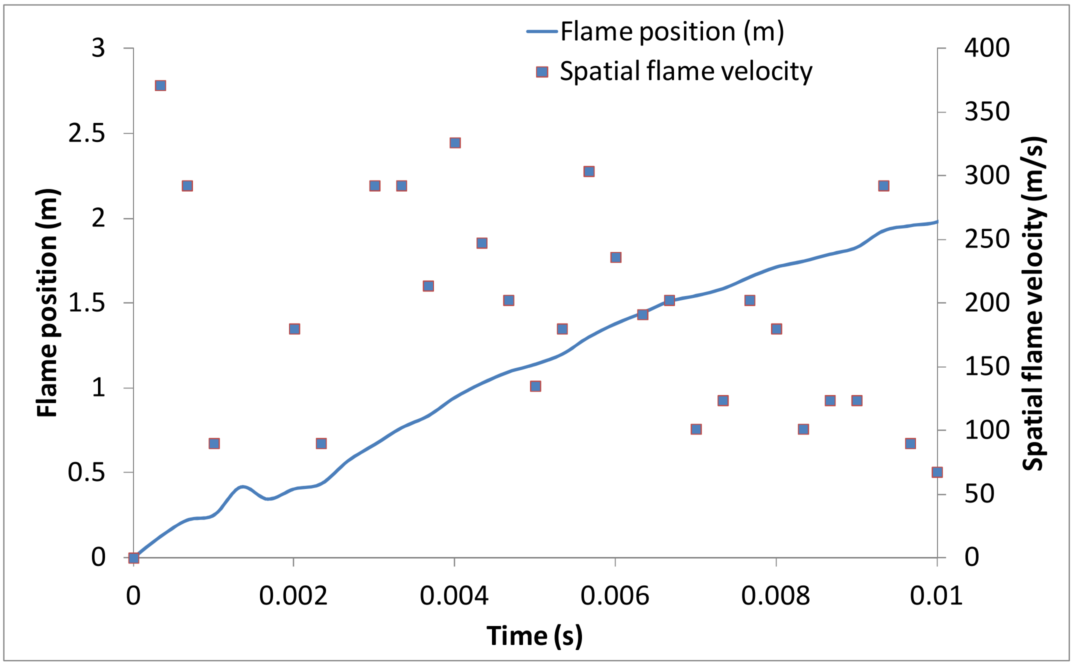


Figure 11: Flame position and downstream spatial velocity (deduced from the video treatment)

4. Conclusions

Although the past experimental works brought precious data about flow and concentration fields for hydrogen jets, confirms auto-similarity correlations and the high level of measured overpressure, we notice a lack of experimental data to link turbulent structures of flammable jet and flame behavior. A joint industrial project was created between AIR LIQUIDE, AREVA STOCKAGE ENERGIE, and INERIS to realize un-ignited and ignited high pressure hydrogen free jets.

The purposes of this experimental work are to map hydrogen free jets in term of concentration and velocity, to measure turbulence directly in the flammable free jet, and to characterize flame behavior regarding to the turbulent flow field.

A specific instrumentation is developed to measure flow field (turbulence and velocity). The measures of concentration and velocities are made at different distances from the release point. The tests are broadly reproducible. The auto-similarity correlations of concentration and velocities are confirmed. The intensity of turbulence and the typical length scale are caught by the flow field measurement and they are of the same order of magnitude as in the theory.

FLACS v10.1 simulations match very closely experimental results in terms of the concentration decay at the centreline. At short distances the radial concentration profile of FLACS is slightly larger than the experimental one, where at larger streamwise distances FLACS is in very close agreement with experimental data.

The second phases of this experimental study consists in characterize the flame behavior and evaluate the overpressure effects when the jet is ignited. A typical test is presented in this paper. The ignition source is settled at 30 % of hydrogen in air. The maximum overpressure is measured at 2 m downstream and is around 80 mbar. A specific image processing had been developed to catch the flame behavior. Downstream flame position and spatial velocity had been defined. The maximum spatial flame velocity is around 300 m/s.

Concerning the FLACS modelling, simulations shows quite good agreement with experimental data. For the ignition source settled at 30 % of hydrogen in air FLACS simulations in very good agreement with experimental data with a slight underestimations of the maximum overpressure by 20% in average.

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