HYDROGEN-AIR VENTED EXPLOSIONS: NEW EXPERIMENTAL DATA

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ABSTRACT

The use of hydrogen as an energy carrier is a real perspective in Europe since a number of breakthroughs obtained in the last decades open the possibility to envision a deployment at the industrial scale if safety issues are duly accounted. However, on this particular aspects, experimental data are still lacking especially about the explosion dynamics in realistic dimensions. The purpose of this paper is to provide a set of totally new and well instrumented hydrogen - air vented explosions. Experiments were performed in a large explosion chamber within the scope of the DIMITRHY project (sponsored by the National French Agency for Research). The 4 m^3 rectangular experimental chamber (2 m height, 2 m width and 1 m depth) is equipped with transparent walls and is vented (0.25 and 0.5 m^2 square vents).. Six pressure gauges were used to measure the overpressure evolution inside and outside the chamber. Six concentration gauges were used to control the hydrogen repartition in the vessel. The hydrogen-air cloud was seeded with micro particles of ammonium chloride to see the propagation of the flame, the movement of the cloud inside and outside the chamber. The incidence of reactivity, vent size, ignition position and non homogenous repartition of hydrogen received a particular attention.

1.0 INTRODUCTION

Especially along the last decade a growing interest in the potential use of hydrogen as an energy carrier was observed. Undoubtedly, a significant impulse was given out by international organisations like IEA [1] overseas and by the European network HySAFE [2] by organizing networking, promoting research projects. Important progresses were made. Besides a number of technical achievements, the main outcome of this past effort may be that the certainty emerged that safety issues could be mastered so that a manageable hydrogen economy could appear in the near future. Today, R&D activities are still going on but in closer connection to practical applications via more industrially targeted projects like, DIMITHRY [3] and H_2E [4] in France. Safety issues still constitute the red line of these programmes but looking for practical solutions. The main purpose of DIMITRHY project is to develop mitigation techniques for stationary H_2 fuel cell systems. Explosion venting is clearly an option which needs to be efficient in case all other defence lines fail.

An important effort was made during the second part of the XXth century to develop models able to calculate precisely the vent size. Initially based on simplifying assumptions [5], these models try to take into account a number of physical phenomena like the evolution of the flame shape as function of the geometry of the vessel [6,7], the hydrodynamic instabilities [8], the turbulence of the flow ahead of the flame [9], the characteristics of the vent cover (inertia, discharge coefficient) [10]...Although they become more and more predictive, these analytical and phenomenological models cannot be generalised to all the situations [11], suggesting several phenomena may not yet be well understood or correctly accounted for.

A set of excellent papers [12, 13, 14] suggest that flame instabilities or different nature (Taylor, hydrodynamic, acoustic...) play a great role and that in particular the external combustion of the cloud in front of the vent [15, 16, 17] interacts strongly with the internal explosion. In fact, the degree of interaction is prevailing especially at large scale with large “vent” ratios [18].

Given the inherent complexity of flame instabilities [19], it is not so surprising that accurate prediction of “vented explosion” remains a difficult task even using complex CFD modelling [11, 20]. Because hydrogen tends to give out more unstable flames than with many other fuels, vent dimensioning for H_2 systems remains a particular challenging question. The difficulty is amplified by a severe lack of experimental data. Some preliminary work on this subject was proposed during the preceding ICHS [21] but many questions remained about the dynamics of the successive explosions.

In the present paper, this work is continued. An experimental parametric study is conducted about the dynamics of vented hydrogen-air explosions. The test campaign was performed during the DIMITRHY project sponsored by the French National Agency for Research (ANR) in support for the deployment of about in H_2 fuel cell systems.

Several parameters were studied: the concentration of hydrogen in the mixture, the vent size, the ignition position in the vessel and the homogeneity of the mixture.

2.0 Experimental details

The outer dimensions of the experimental chamber (figure 1) are : 2m long, 2 m high and 1 m deep, representing an inner volume of 4 m^3. Only one central vent area was arranged on one small side. Three sides are provided with large transparent plates (2 cm PPMA for the front side, the top, the small side containing the vent). The other walls are 5 mm thick steel plates. The frame is strengthened with I and T steel beams. The overall pressure resistance of the chamber is about 3 bar.

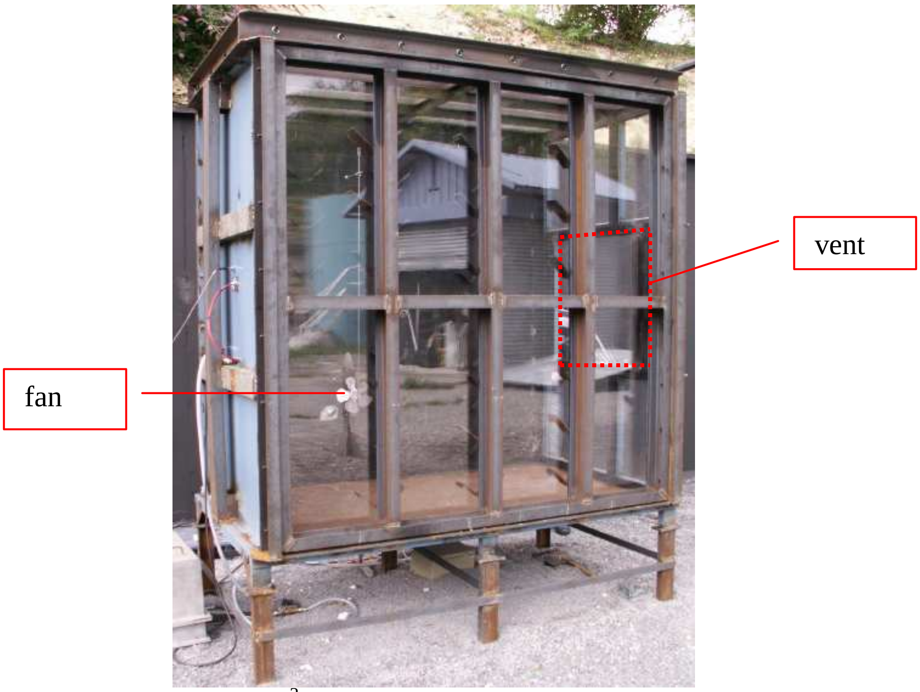


Figure 1: the 4 m^3 chamber (2 m high, 2 m high, 1 m deep)

Hydrogen is injected directly from 200 bar bottles via a 1 mm orifice located in the lower part of the chamber. An electrically driven fan is used to obtain an homogeneous mixture. The concentration distribution is controlled using 6 oxygen analyzers sampling the atmosphere long the vertical axis each 35 cm. To ease the observation of the cloud outside, in front of the vent, and of the propagating flame, the mixture is seeded by microparticles of ammonium chloride during the preparation of the mixture (consider figure 4 to get a visual impression of the result). To do this, ammonia vapors and hydrochloric acid contained in two different vials are contacted. This forms fine particles of ammonium chloride and injected in the chamber. This technique doesn’t modify the flame behavior.

The vent area is covered with a very thin plastic sheet held with magnetic tapes. Ignition is achieved using an electrical spark (10 mJ).

Three piezoresistive gauges (KISTLER 0-10 bar accuracy ± 0,1 %) are used to measure the pressure evolution inside. The first gauge (P1) is located on the small side opposite to the vent, the second one (P2) is located in the center of the large side opposite to the front transparent wall and the third (P3) is close to the vent (figure 2). Three additional piezoresistive gauges (KISTLER 0-2 bar accuracy ± 0,1 %) are used to measure the pressure evolution outside. Two pressure gauges are located on the axis of the vent at 2 m and 5 m from the vent. The last one stands perpendicularly at 5 m from the axis of the vent aligned with the vent. Further the formation of the cloud in front of the vent and the propagation of the flame are filmed using a high speed video system (PHOTRON Fastcam).

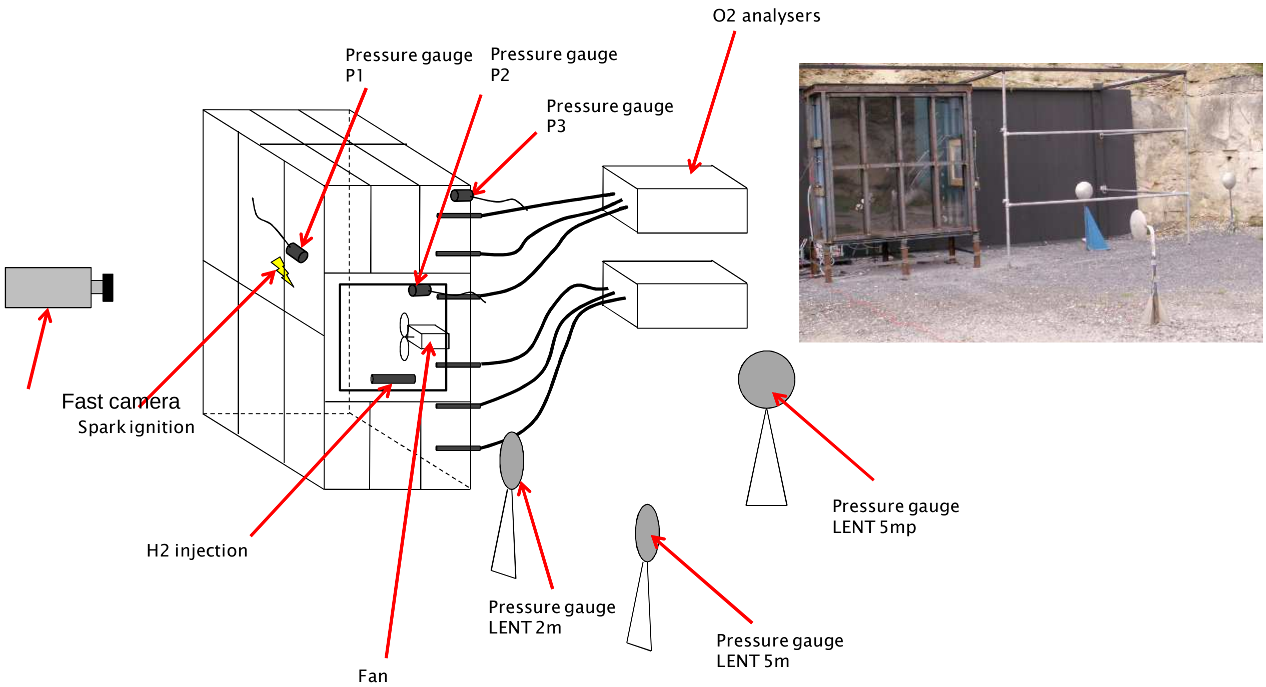


Figure 2. Instrumentation

Two vent size have been tested (figure 3) : 0.5 m^2 and 0.25 m^2.

Figure 3. Two vent size (0.5 m^2 and 0.25 m^2)

3.0 Analysis of a typical test

Test n°5 (16.5% H_2-air mixture, homogeneous, rear ignition, 0.5 m^2 vent) is analysed in details below.

The pressure signals are shown on figure 3 and some excerpts from the film on figure 4. presents the typical internal and external overpressures registered by the gauges. The maximum overpressure inside the vessel is obtained at 132 ms. Fig 4 presents the typical evolution of flame inside and outside the vessel at different times. The flame exits the enclosure 123 ms after ignition.

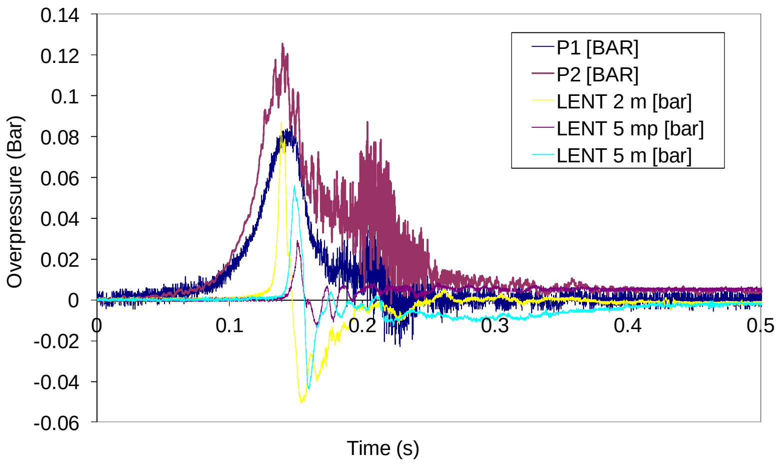
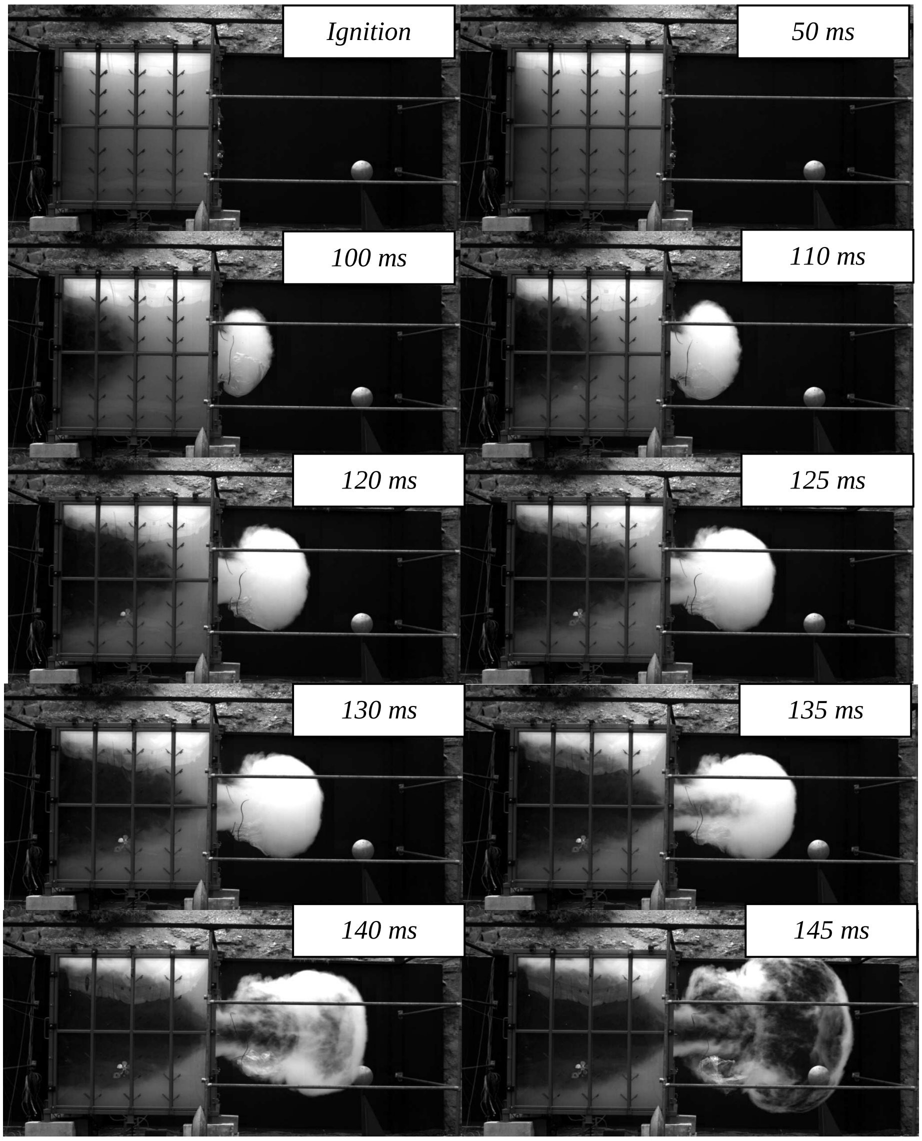


Figure 3. Internal and external overpressures (rear ignition, % H_2 = 16.5, homogeneous, vent area 0.5 m^2 – P3 gauge are not installed for this test)



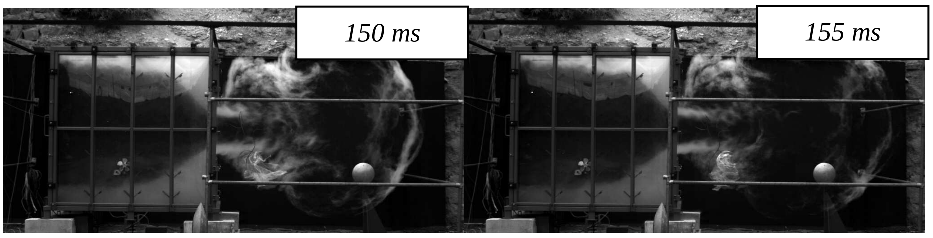


Figure 4. Formation of the external cloud and evolution of the flame at different times

3.1 Formation of the external cloud

The gaseous mixture is pushed out of the chamber by the internal overpressure and, immediately, the front border of this flow is deflected sidewise, rolls along the propagating column of gas, forming a sort of “mushroom” which turns into a sort of “bubble”. This behavior was observed before [14, 16, 18]. The border of the cloud is sharp and the optical density does not seem to differ from that of the mixture emerging from the vent, indicating a very low level of mixing with the surrounding atmosphere. This aerodynamic structure resembles strongly the “laminar vortex rings” studied by Maxworthy [22, 23, 24]..

Quite detailed information about the diameter of the bubble and velocity of the leading edge of the cloud can be made available (figure 5) The maximum diameter of the bubble is about 1 m e.g. twice the width of the vent, which is again in agreement with past experimental data [18] whereas the velocity of the leading edge correlates very well with that of the flow emerging from the vent (estimated as $\sqrt{\frac{2.\Delta P}{\rho}}$ where ΔP is the internal overpressure before the exit of the flame and ρ the density of the reactants)

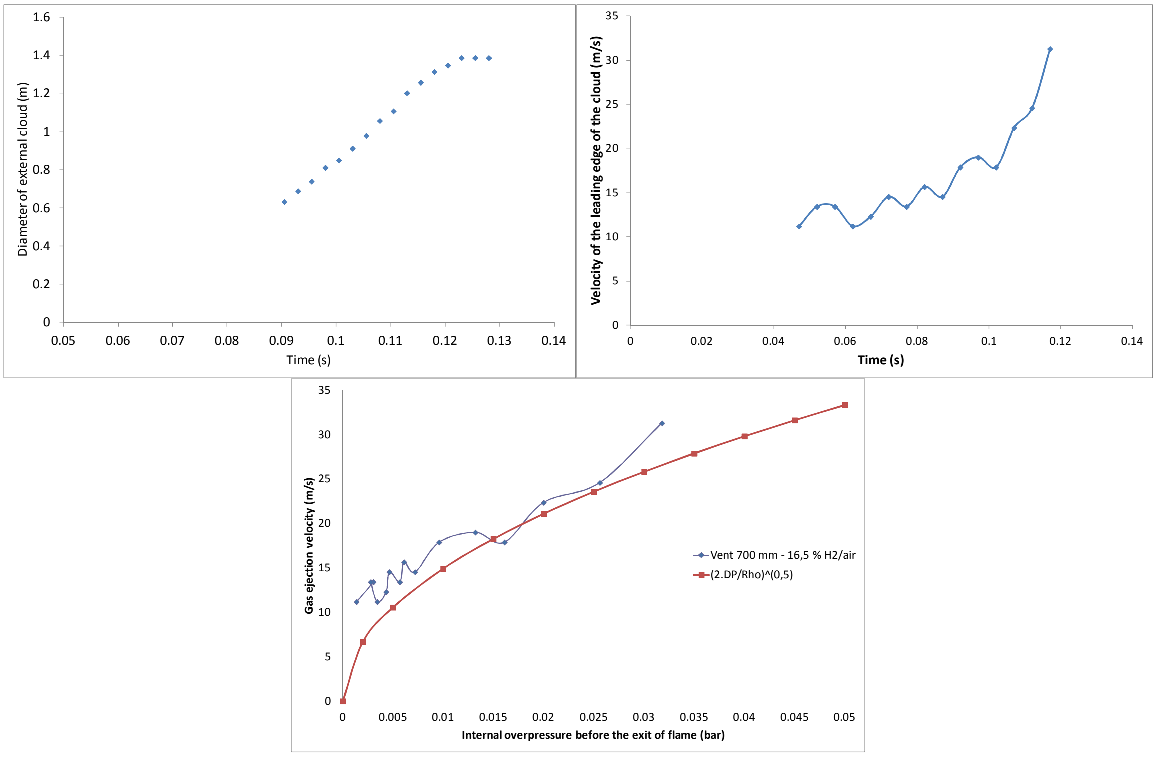


Figure 5. Correlation between internal overpressure before the exit of flame and the gas ejection velocity

3.2 Combustion of the external cloud

The external cloud is ignited when the flame, rushing out of the vent, reaches the stagnation point at the leading edge of the "bubble". Then the flame is wrapped very fast around the vortex ring and the maximum expansion velocity of the burning cloud occurs at this moment (fig 6) in typically 5 to 10 ms (140-150 ms).

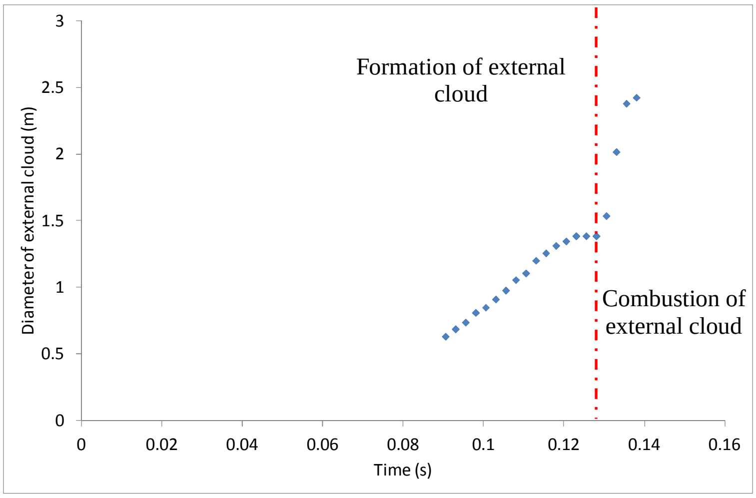


Figure 6. Diameter of external cloud

This is a very unusual mode of combustion which does not seem to have deserved much attention so far [24, 25]. A pressure pulse is observed during the combustion of the external cloud. Note the first pressure gauge is located inside the burning cloud. According to the acoustic theory applied to explosions (Leyer;, 1989), the expansion velocity of the cloud V_{flame} could be (roughly) deduced from the pressure signal $\Delta P_{\exp-cloud}$ according to :

$$\Delta P_{\exp-cloud}(t) \approx \frac{3}{2} \cdot \rho_{atm} \cdot V_{flame}^2(t)$$

This estimation corresponds to the data extracted from the high speed video films confirming the external pressure pulse results from the explosion of the external cloud ΔP_{out_cloud} . The same acoustic theory is normally applicable to the pressure field outside the burning cloud using :

$$\Delta P_{out\_cloud}(t) \approx 2 \cdot \rho_{atm} \cdot \frac{R_{flame}(t)}{r_{gauge}} \cdot V_{flame}^2(t)$$

Where ρ_{atm} is the density of atmosphere, R_{flame} is the flame radius, and r_{gauge} is the position of the gauge.

Noteworthy, a good estimation of the pressure signal measured @5m perpendicularly is obtained but is strongly underestimated @5m on axis. This is presumably the consequence of the Doppler effect for which the initial velocity of the cloud increase the velocity of the flame.

3.3 Internal combustion

If we compare the internal overpressure evolution, flame evolution and the external overpressure at 2 m (fig 7) for the test 6, the internal maximum overpressure is reached when the external maximum overpressure is reached. During the combustion of external cloud (10 ms), the increase of flame seems to be almost stopped and the internal overpressure is stabilized at the maximum value. After, the inside pressure decreases releasing combustion products.

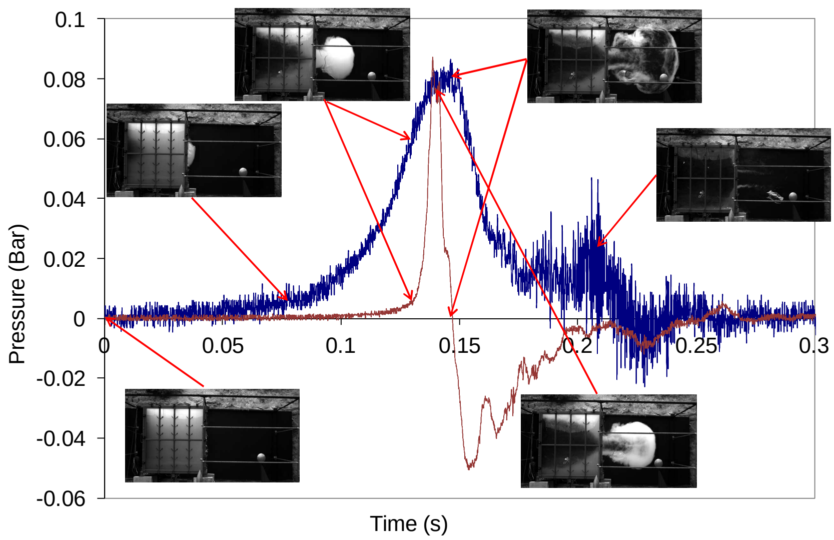


Figure 7. Internal overpressure evolution, flame evolution and the external overpressure at 2 m (Test 6 : rear ignition, % H_2 = 16.5, homogeneous, vent area 0.5 m^2)

4.0 Parametric investigations

4.1 Reactivity

Fig 8 presents the evolution of internal overpressure measured for an increase of reactivity (10,5 % vol H2/air, 16,5% vol H2/air, 21,1 % vol H2/air, 24,8 vol H2/air, 28,7 vol H2/air) for the vent area 0,5 m^2.

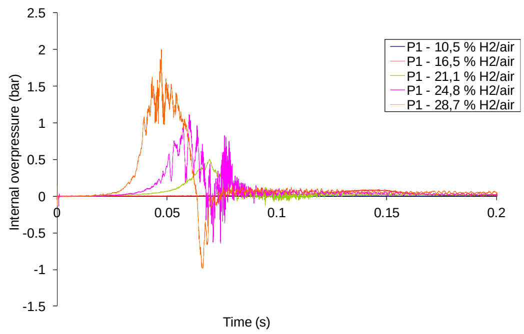


Figure 8. Internal overpressure measured for an increase of reactivity (Rear ignition, 10,5 % vol H2/air, 16,5% vol H2/air, 21,1 % vol H2/air, 24,8 vol H2/air, 28,7 vol H2/air, Vent area 0,5 m^2)

The correlation between of the velocity of the leading edge and the internal overpressure before the exit of flame is verified for other reactivities (fig 9).

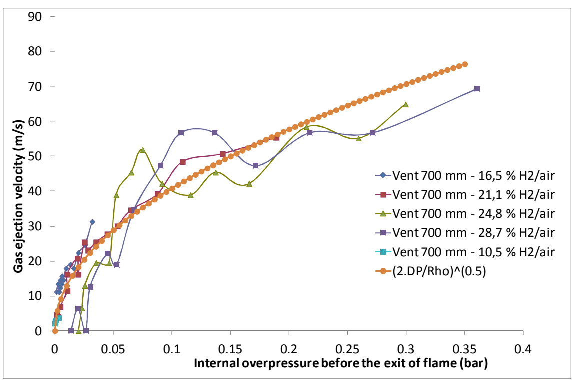


Figure 9. Correlation between the velocity of the leading edge and the internal overpressure before the exit of flame

The pressure traces due to the external explosion are presented on fig 10.

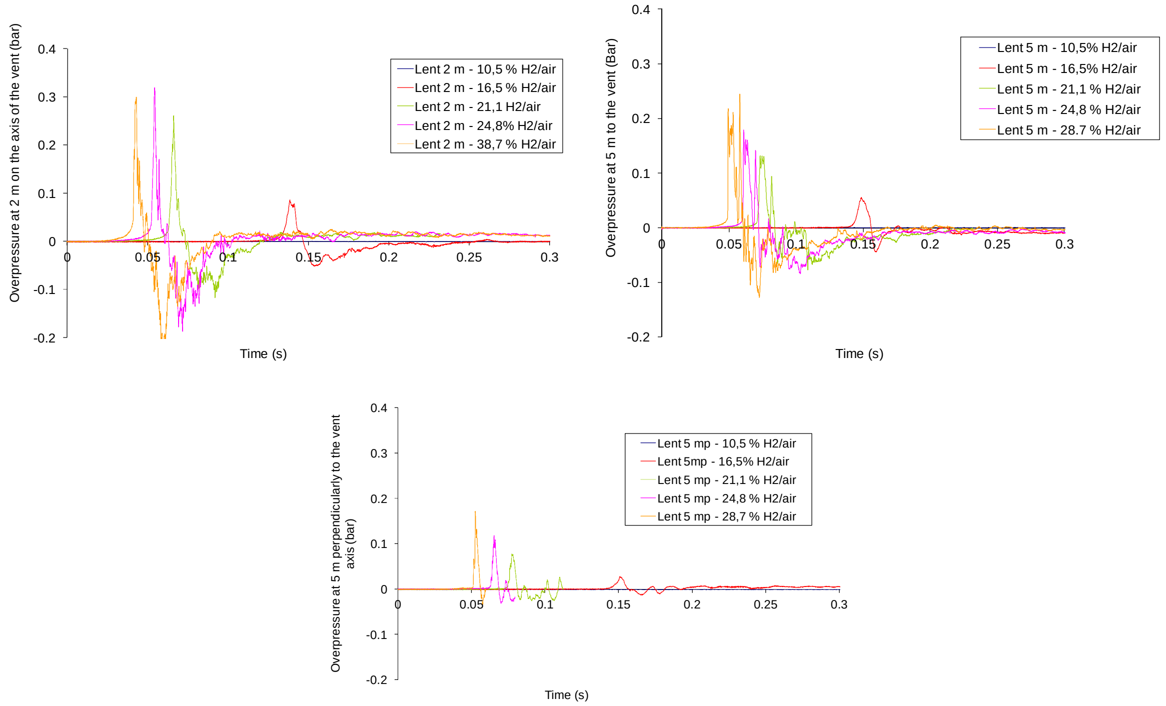


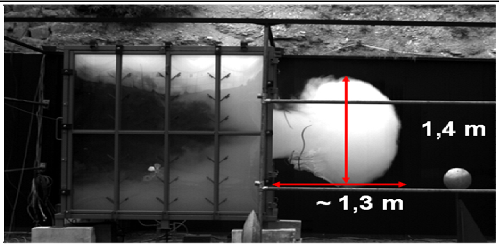
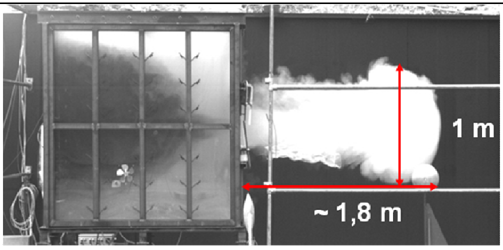
Figure 10. Overpressures measured at 2 m and 5m on the axis of the vent, and at 5 m perpendicularly (rear ignition, vent side = 0.7 m, homogeneous mixtures)

It is recalled that the gauge located at 2 m sits inside the exploding cloud and gives a direct estimation of the strength of the explosion. Surprisingly, the maximum overpressure reaches a sort of limit above 20% H_2 in the initial mixture. The maximum external overpressure is then about 0.3 bar suggesting an outward expanding velocity of about 130 m/s. Looking at the internal explosions, it appears that for the corresponding experimental configurations (% H_2 > 20), the internal overpressure is measured between 0.7 and 1 bar approaching situations where the flow should be chocked at the vent. Consequently the flow velocity is certainly very close to speed sound. We might deduce that the inner structure of the bubble should have the same velocity. Although the laminar burning velocity is very different between 21% H_2 and 28% H_2 in air, the expanding velocity of the burning bubble are pretty the same suggesting that the inner aerodynamics of the bubbles drives the external explosion to a much larger extent that the intrinsic burning properties of the mixture. For the other mixtures (below 20%), both the external and internal explosion are much weaker.

Further downstream (at 5 m from the vent location), a dependency according to the composition of the initial mixture is retrieved. Focusing on the gauge located perpendicularly, the influence of Doppler effect is less important since we noticed an increase of overpressure with an increase of reactivity.

4.2 Vent size

The size of the vent has a strong influence upon the formation of the external cloud (fig 11). When the vent size is reduced, the duration of the internal explosion increases leaving presumably enough time for the "bubble" to become unstable and force the flow to break down in a jet like structure. The pressure signature of the external explosion seems also different.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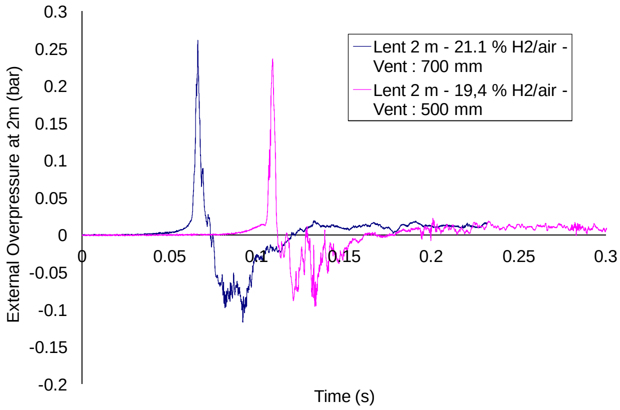

Figure 11. Comparison between external clouds for two vent sizes and similar explosion conditions homogeneous mixture H2 ≈ 20% v/v)

4.3 Position of the ignition source

Regarding the internal explosion, the position of the ignition point does not have a large impact (at the same vent size, same reactivity: Fig 13) on the maximum overpressure. This conclusion is certainly specific to this particular chamber with a relatively small vent area. The duration of the combustion process is strongly affected because the flame behavior is completely different. For the rear ignition, the flame is subjected to the thermal expansion of burnt gas, so that the flame velocity is higher than the other ignition position. For rear ignition, the flame is subjected to the thermal expansion of burnt gas, so that the flame speed is higher than for other ignition positions. For the middle ignition, the initial flame development is roughly spherical until burnt gases are discharged by the vent, and the flame speed decreases. For the ignition near the vent, all the burnt gases are directly discharged by the vent and the flame is not subject to the expansion of burnt gas..

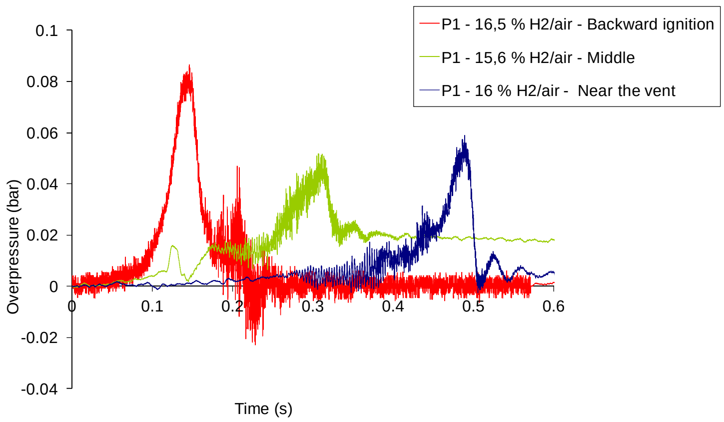

Figure 12. Inside pressure signal (homogeneous mixture H2 ≈ 16% v/v – rear ignition - ignition in the middle of the chamber and ignition at the vent)

However, the ignition position has a huge important on the external explosion, since the size of the external cloud (prior to ignition) is drastically different from one ignition location to the other. The external cloud reaches its maximum size when the ignition point is on the rear wall giving enough time for the bubble to form. When the ignition point is located close to the vent the external cloud is ignited very early while only a very small quantity of reactant has been expelled (Fig 13).

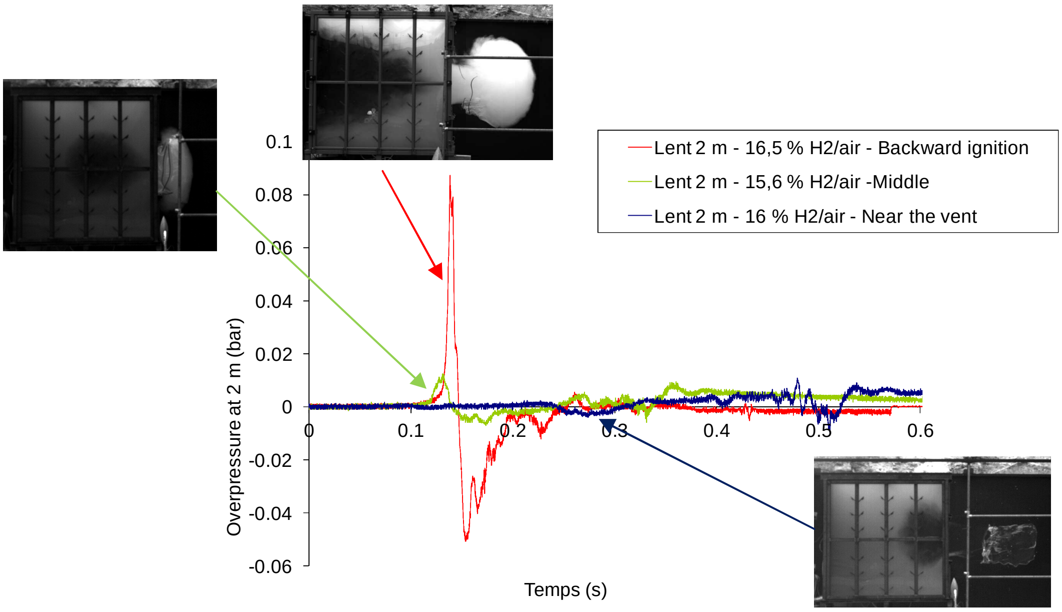

Figure 13. Flame behavior and external overpressures during test

4.4 Inhomogeneous mixture

It is possible to produce an inhomogeneous mixture inside the explosion chamber by injecting H2 close to the top wall. This way a homogeneous and rich layer is created 50 cm from the top. The fan is then switched on to create some turbulence, triggering some spreading of the layer (fig 14). On Figure 15 are compared, the explosion signals when the mixture is homogeneous and heterogeneous for the same overall quantity of hydrogen (11% v/v on average).

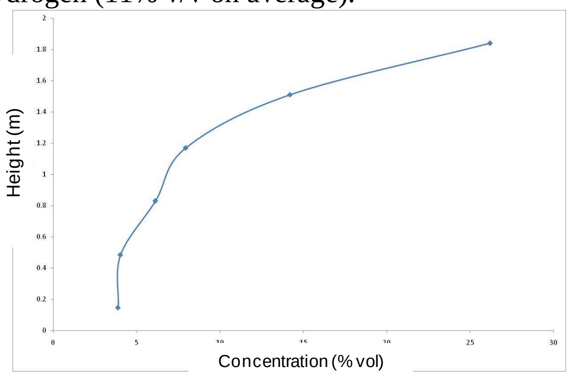

Figure 14. Vertical repartition of hydrogen during tests

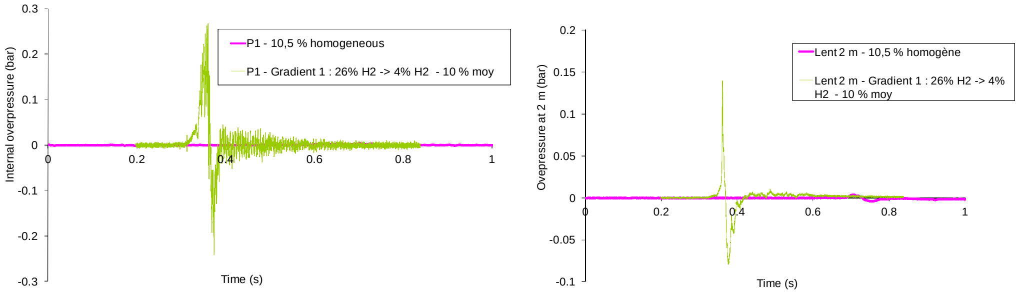

Figure 15. Internal and external overpressures (Homogeneous mixture and heterogeneous mixture)

The pressure effects are much more important when the mixture is heterogeneous. It can be understood looking at the high speed videos (fig 16).The flame does not develop spherically but follows preferentially the most reactive layer near the top with a flame speed corresponding to this local concentration

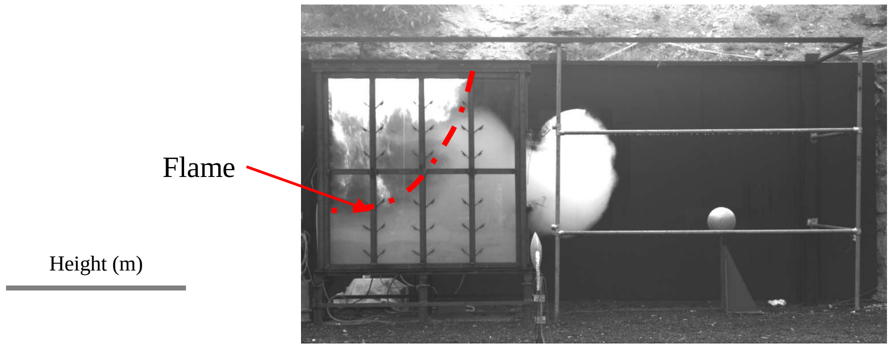

Figure 16. Flame development in an inhomogeneous mixture

5.0 Conclusion

The use of hydrogen as an energy carrier is a real perspective in Europe since a number of breakthroughs obtained in the last decades open the possibility to envision a deployment at the industrial scale if safety issues are duly accounted. However, on this particular aspects, experimental data are still lacking especially about the explosion dynamics in realistic dimensions.
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A 4 m^3 rectangular experimental chamber (2 m height, 2 m width and 1 m depth) is equipped with transparent walls and is vented (0.25 and 0.5 m^2 square vents).. Six pressure gauges were used to measure the overpressure evolution inside and outside the chamber. Six concentration gauges were used to control the hydrogen repartition in the vessel. The hydrogen-air cloud was seeded with micro particles of ammonium chloride to see the propagation of the flame, the movement of the cloud inside and outside the chamber.
The formation and combustion of external cloud are particularly studied. The velocity of expelled gas is directly linked to the internal pressure. The mechanism of external combustion seems to be a very unusual mode of combustion. An important doppler effect is noticed and it seems the inner aerodynamics of the bubbles drives the external explosion, especially revealed by the study of reactivity.
The size of the vent has a strong influence upon the formation of the external cloud, where a jet structure of expelled unburned gas can appear when the vent size is reduced.
The position of the ignition source does not seem to have a large incidence at least on the maximum overpressure, but on time of combustion where the behavior of flame is completely different according the ignition position.
The pressure effects are much more important when the mixture is heterogeneous because the flame follows preferentially the most reactive layer with a velocity corresponding to this concentration

6.0 References

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