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► **To cite this version:**

Jérôme Daubech, Christophe Proust, Didier Jamois, Emmanuel Leprette. Dynamics of vented hydrogen-air deflagrations. 4. International Conference on Hydrogen Safety (ICHS 2011), Sep 2011, San Francisco, United States. pp.NC. ineris-00973626

HAL Id: ineris-00973626

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Submitted on 4 Apr 2014

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Dynamics of vented hydrogen-air deflagrations

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Abstract

The use of hydrogen as an energy carrier is a real perspective for Europe since a number of breakthroughs now enable to envision a deployment at the industrial scale. However some safety issues need to be further addressed but experimental data are still lacking especially about the explosion dynamics in realistic dimensions. A set of hydrogen-air vented explosions were thus performed in two medium scale chambers (1 m³ and 10 m³). Homogeneous mixtures were used (10% to 30% vol.). The explosion overpressure was measured inside the chamber and outside on the axis of the discharge from the vent. The incidence of the external explosion is clearly seen.

All the results in this paper and the predictions from the standards differ greatly meaning that a significant effort is still required. It is the purpose of the French project DIMITRHY to help progressing.

Introduction

Especially along the last decade a growing interest in the potential uses of hydrogen as an energy carrier has been observed. A significant impulse was given 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 safety issues could be mastered so that a manageable hydrogen economy could appear. Today, R&D activities are still going in close connection to practical applications via more industry targeted projects like HyPE [3], DIMITRHY [4] and H₂E [5] in France. Safety issues still constitute the red line of these programmes but looking for practical solutions. DIMITRHY, in particular targets on the development of explosion mitigation techniques for stationary H₂ fuel cell systems. Explosion venting is clearly an option which needs to be efficient if all other defence lines fail. The subject of explosion venting has received a large attention during the second part of the last century. The flame theory was applied to this matter and equations, graphs were issued [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Some appear in official documents [17, 18]. However, the models developed for this purpose are based on simplifying assumptions and even if a number of physical phenomena are tentatively introduced like the evolution of the flame shape as function of the geometry of the vessel [7, 9, 14], the hydrodynamic instabilities [11, 15], the turbulence of the flow ahead of the flame [10, 12, 15], the characteristics of the vent cover (inertia, discharge coefficient) [16]... Despite these refinements, venting equations are numerous tend to produce conflicting results [19] suggesting several phenomena may not yet be well understood or correctly accounted for. A set of excellent papers [20, 21, 22, 23, 24] 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 [25, 26, 27] interacts. In fact, the degree of interaction is very strong especially at large scale with large “vent” ratios [28].

Given the inherent complexity of flame instabilities [29], it is not so surprising that accurate prediction of “vented explosion” remains a difficult task even using complex CFD modelling [30]. Because hydrogen-air flames tend to be more unstable than many fuels, vent dimensioning for H₂ systems is a challenging question. The difficulty is amplified by a severe lack of experimental data.

The purpose of the present paper is to provide additional experimental results about vented hydrogen-air explosions in vessels of industrial sizes.

Available data

To the knowledge of the present authors, only a few articles present experimental results about vented hydrogen-air explosions [30, 31, 32, 33] and even a more limited number are directly usable ([30, 31, 32]: table 1) within the scope of vent dimensioning (controlled experiments).

| ref | Volume | Dimensions | % H2 in air (v/v) | Ignition | Vent area (m ²) | Pred (barg) |
|------|-----------------------------------|---|-------------------|------------------|-----------------------------|-------------|
| [30] | BOX : 64 m ³ | Height = 3 m Length = 4.6 m Width = 4.6 m | 18 | opposite to vent | 2.7 | 0.32 |
| | | | | | 5.4 | 0.13 |
| | | | | center | 2.7 | 0.23 |
| | | | | | 5.4 | 1.25 |
| [31] | CYLINDER : 0.95 m ³ | Length: 1.5 m Diameter: 0.97m | 30 | center | 0.2 | 1.25 |
| | | | | | 0.3 | 0.4 |
| [32] | SPHERE : 6.85 m ³ | Diameter : 2.3 m | 10 | center | 0.018 | 1.6 |
| | | | | | 0.049 | 0.9 |
| | | | | | 0.159 | 0.3 |
| | | | 20 | center | 0.018 | 4.8 |
| | | | | | 0.049 | 4.2 |
| | | | | | 0.159 | 3.2 |

Table 1 : some experimental data (quiescent homogeneous hydrogen air mixtures)

As mentioned before there are a number of very diverse methods to calculate vent sizes (see for instance [19]). In two recognised guidelines [17, 18], the same equations are proposed :

$$A_{vent} = \left[\left(0.127 \cdot \log_{10} K_g - 0.0567 \right) \cdot P_{red}^{-0.582} + 0.126 \cdot P_{red}^{-0.572} \cdot (P_{stat} - 0.1) \right] \cdot V^{2/3} + \frac{K_g \cdot \left[\max\left(\frac{L}{D} - 2; 0\right) \right]^2}{750}$$

- A_{vent} : vent area in m²
- P_{red}, P_{stat}, maximum (reduced) explosion overpressure and static opening overpressure of the vent panel in barg
- K_g explosion severity index ¹
- L/D length over diameter ratio of the vented vessel
- V volume of the vented vessel in m³

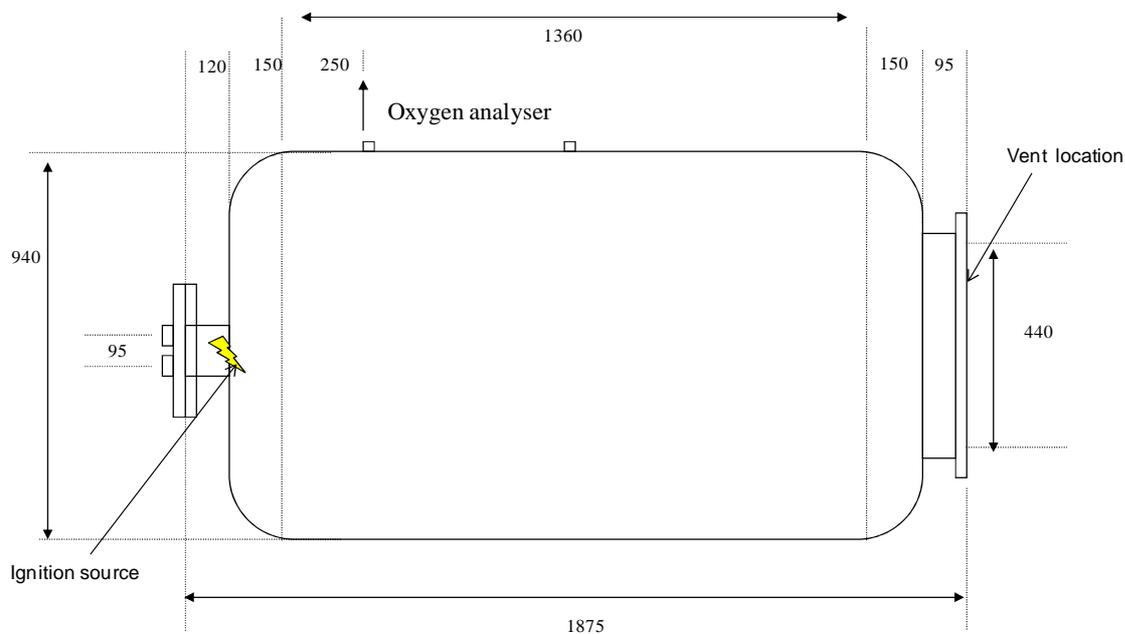
¹ K_g = 550 bar.m/s for hydrogen-air explosions [18]

Experimental details

Two experimental chambers were used (Figure 1 and 2) of 1 and 10.5 m³ with an L/D ratio of respectively 1.4 and 3.3. Only one vent area was arranged on the 1 m³ vessel leaving the flange opposite to the ignition location fully open which corresponds to a vent area of 0.15 m². Similarly, on the 10.5 m³ chamber, only one vent area was arranged by leaving the flange opposite to the ignition location totally open which corresponds to a vent area of 2 m².

The fuel-air mixture was prepared by injecting pneumatically the fuel from the content of pressurised bottles (1 of 5 l for the 1 m³ vessel and 4 bottles of 8 l for the 10 m³ chamber). The final composition was carefully checked by measuring precisely the oxygen content prior to ignition. A sheet of paper was lightly taped on the vent area in order to prevent the hydrogen mixture to escape before ignition. It was verified that the mixture was homogeneous by measuring the gas concentration at several locations into the chambers with accuracy around ± 0.5 % vol.

Ignition was performed with a pyrotechnical match², releasing 60 J, located on the axis of the chamber, at the opposite end to the vent.



² Pyrotechnical match is a good ignition source to detect the initial time and seems not to disturb flame development during the initial times



Figure 1 : sketch (dimensions in mm) and views of the 1 m³ vessel (injection device of the fuel on the right picture)

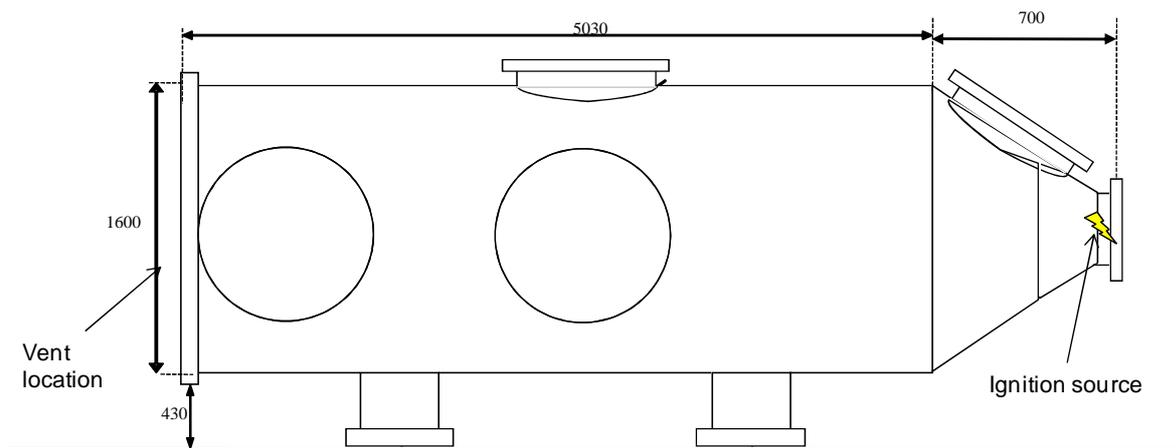


Figure 2 : sketch (dimensions in mm) and views of the 10.5 m³ chamber (injection device of the fuel on the right picture)

With the 1 m³ vessel, five piezoresistive pressures gauges were used (figure 3), 2 inside the chamber (0-10 bar \pm 0.01 bar) and 3 along the axis of the vent (0-2 bar \pm 0.002 bar). The pressure sensors located outside were mounted on special aerodynamic supports at respectively 1m, 3 m, 5 m from the vent exit. With the 10.5 m³ vessel, only two piezoresistive pressures gauges were used (figure 4) inside the chamber (0-10 bar \pm 0.01 bar). The propagation of the flame inside was traced with 6 ionisation gauges in the 1 m³ vessel and 4 ionisation gauges and 4 optical sensors (miniaturized solar panels) in the 10.5 m³ chamber.

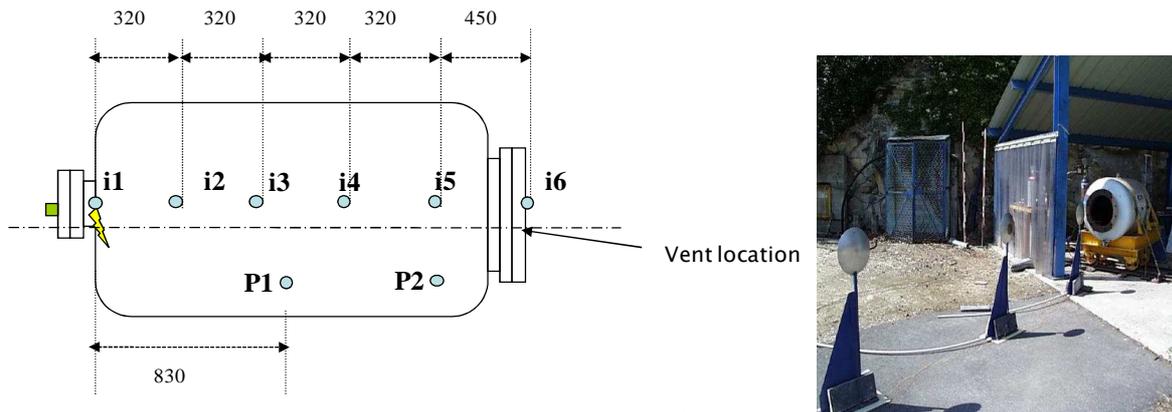
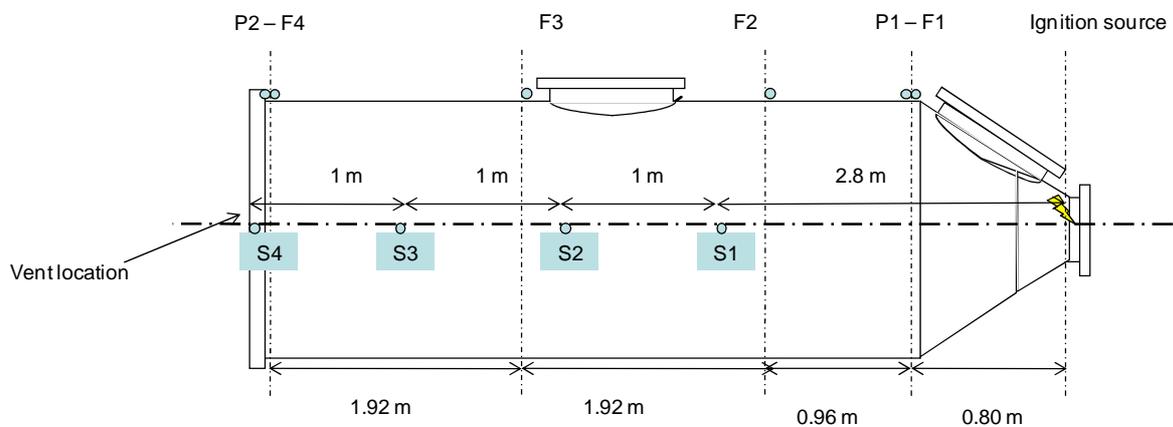


Figure 3 : instrumentation of the 1 m³ vessel (inside and outside)



P1, P2 : Pressure transducers in the chamber

| | | | |
|----|-------------------------|----|---------------------|
| F1 | } Optical flame sensors | S1 | } Ionisation gauges |
| F2 | | S2 | |
| F3 | | S3 | |
| F4 | | S4 | |

Figure 4 : instrumentation of the 10 m³ chamber (inside)

The evolution of the cloud and flame outside was recorded by high-speed video (500 to 2000 f/s). In order to ease the observation of the cloud, the gaseous mixture inside the chamber was seeded with fine silica particles (order of 1 g/m³).

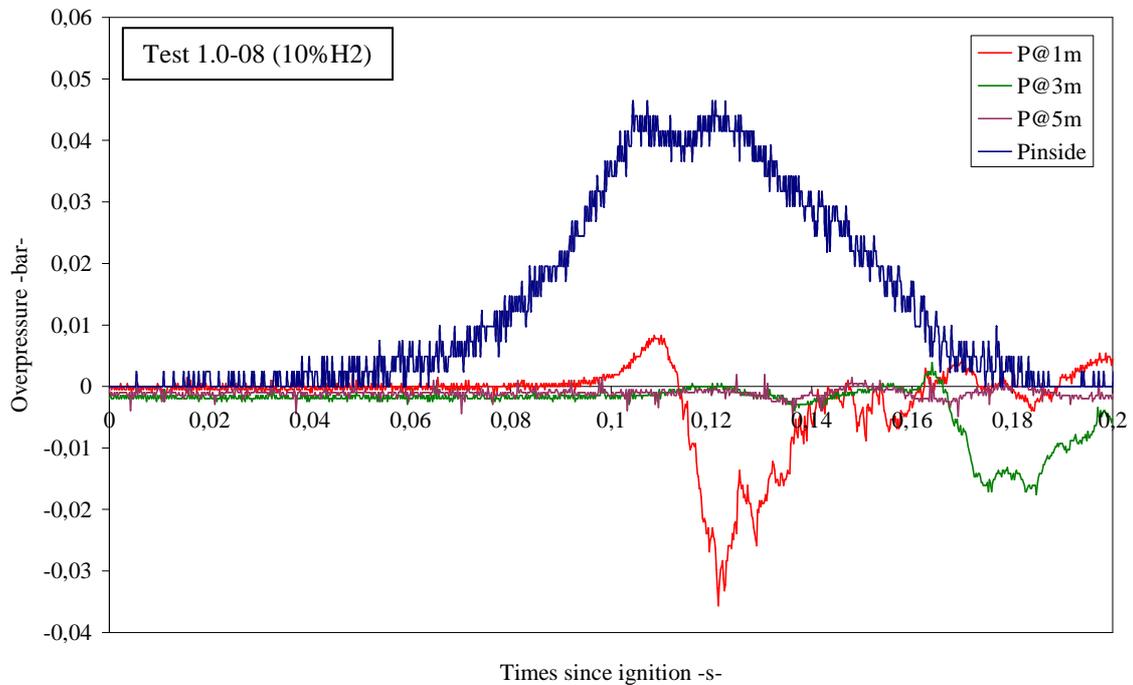
Results

Experiments were done varying the initial pressure into the dispersion reservoir. The main results are given in table 3 but some further details are given hereafter.

| Test # | Chamber | % H2 v/v | Pred (mbar) | Pmax out 1 m (mbar) | Pmax out 3 m (mbar) | Pmax out 5 m (mbar) |
|---------|---------------------|-------------|-------------|------------------------|------------------------|------------------------|
| 1.0-01 | 1 m ³ | 27 | 1400 | 630 | 380 | 145 |
| 1.0-02 | | 27 | 1220 | 550 | 360 | 135 |
| 1.0-03 | | 27 | 1440 | 600 | 340 | 150 |
| 1.0-04 | | 20 | 734 | 220 | 180 | 100 |
| 1.0-05 | | 20 | 551 | 177 | 195 | 100 |
| 1.0-06 | | 15 | 225 | 110 | 87 | 60 |
| 1.0-07 | | 15 | 240 | 60 | 40 | 28 |
| 1.0-08 | | 10 | 45 | 10 | 4 | 1 |
| 10.5-11 | 10.5 m ³ | 14 | 31 | x | x | x |
| 10.5-12 | | 14 | 50 | x | x | x |
| 10.5-13 | | 14 | 30 | x | x | x |
| 10.5-16 | | 23 | 230 | x | x | x |
| 10.5-17 | | 23 | 210 | x | x | x |
| 10.5-19 | | 23 | 200 | x | x | x |
| 10.5-20 | | 23 | 250 | x | x | x |
| 10.5-21 | | 23 | 200 | x | x | x |
| 10.5-22 | | 23 | 260 | x | x | x |
| 10.5-23 | | 23 | 300 | x | x | x |

Table 2 : main results of the experiments

The pressure traces and flame trajectories for the typical tests in the 1 m³ vessel are presented in figure 5.



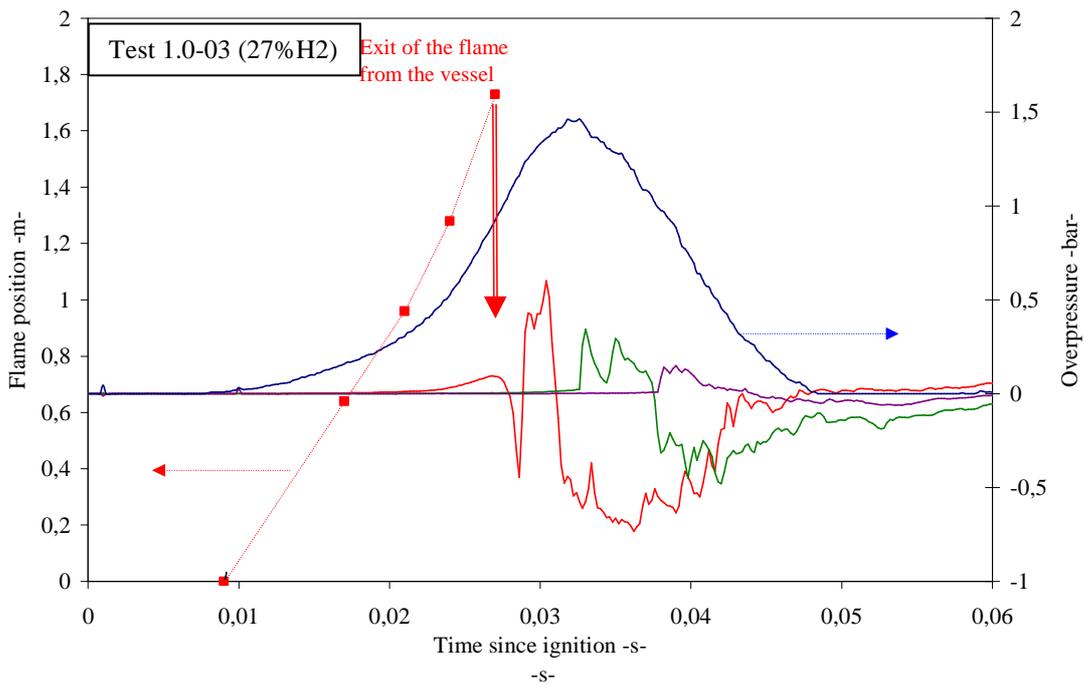
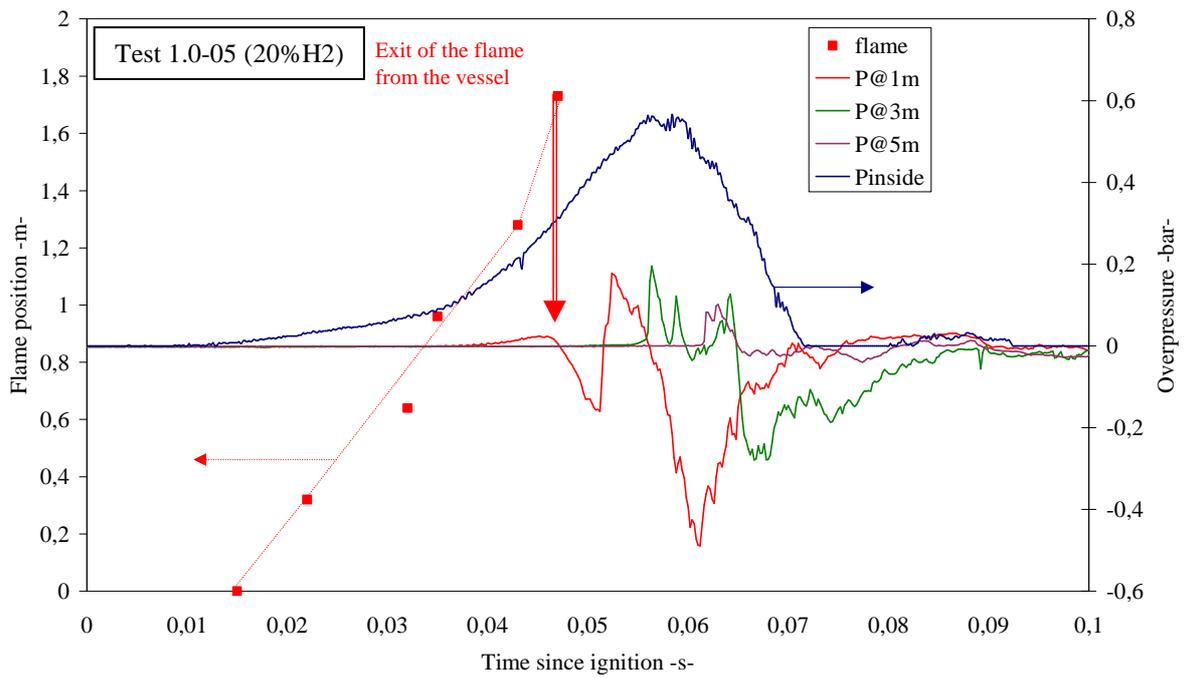
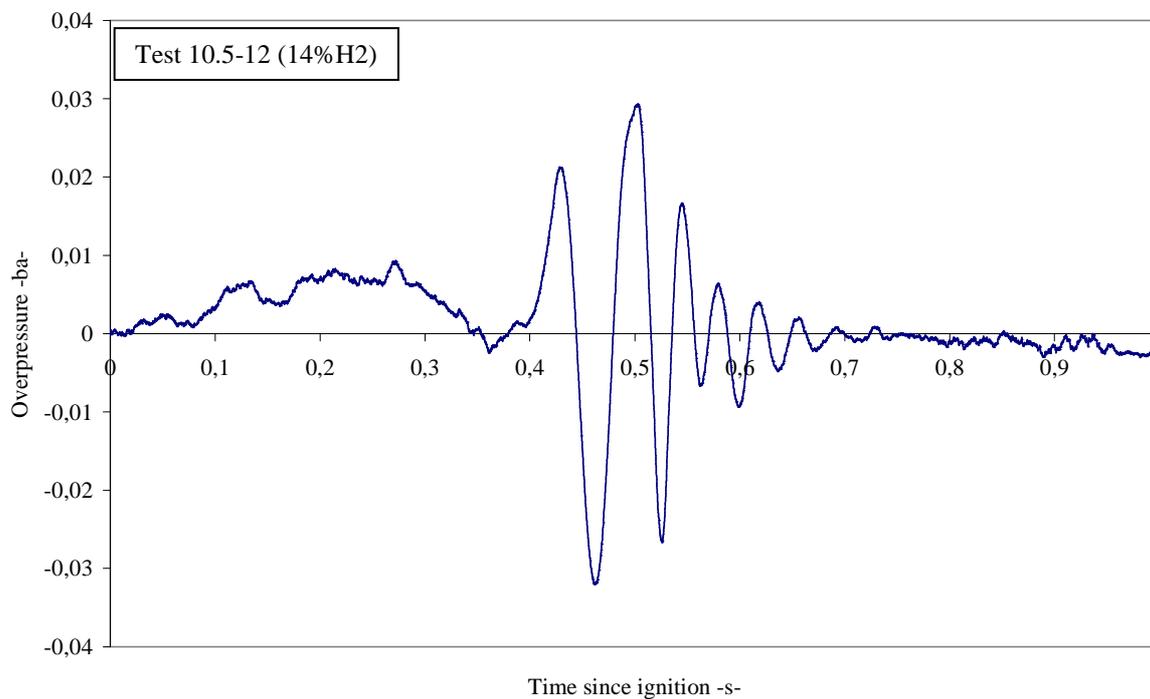


Figure 5 : Flame position, internal and external overpressures (1 m^3 vessel, rear ignition, 0.15 m^2 vent, % H₂ in air = 10; 15; 20 and 27)

The internal overpressure trace has a classical shape with a single dome. It is interesting to note that the overpressure does not drop when the flame rushes out but continues to rise. Note that as soon as the flame exits, the overpressure measured just on the axis of the vent at 1 m drops sharply. This is a local phenomenon since it does not appear further downstream. But after this initial pressure drop (at 1 m on the axis of the vent discharge) a strong pressure burst is superposed. This pulse appears also at 3 and 5 m although with a smaller amplitude (it can be verified that the time difference between these pulses correspond to the speed of the sound). The magnitude of this burst is larger the richer the mixture. It is not detectable when %H₂=10. After this pressure burst the pressure inside the explosion chambers drops (taking into account the time delay corresponding for the trailing edge of the pulse to join the pressure transducer : about 5 ms at the speed of the sound).

The pressure traces and flame trajectories for the typical tests in the 10.5 m³ vessel are presented in figure 6.



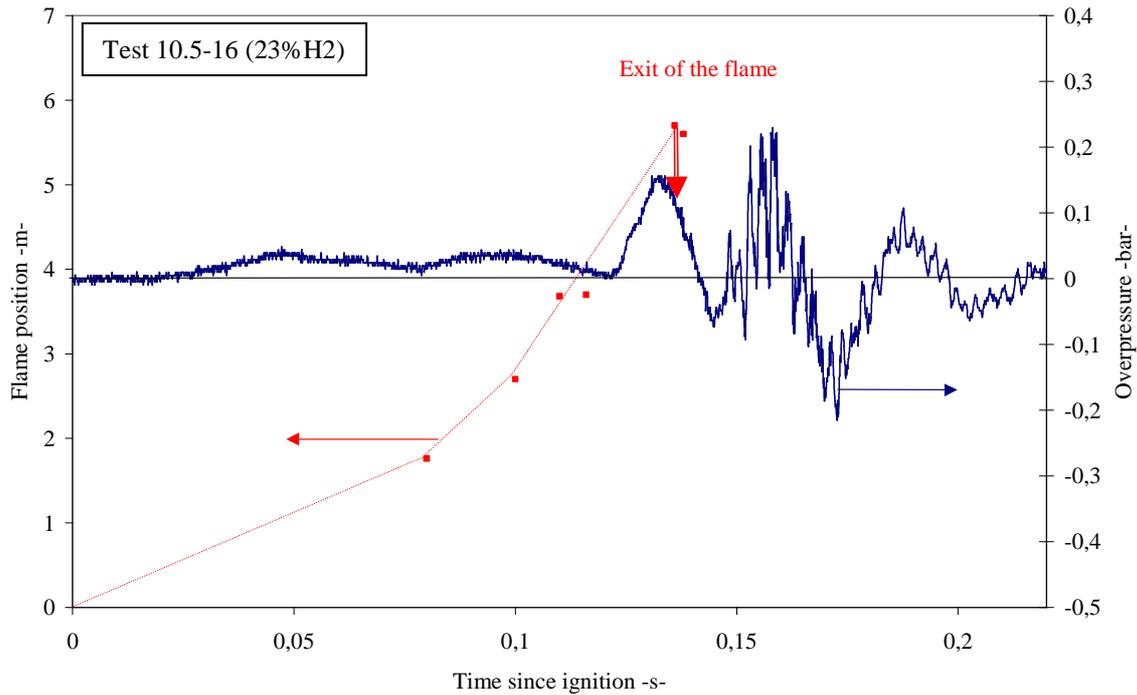


Figure 6 : Flame position, internal and external overpressures (10.5 m³ vessel, rear ignition, 2 m² vent, % H₂ in air = 14; 23)

Much more complex signals are produced : there is a first pressure bulge lasting two thirds of the propagation of the flame in the chamber (up to 0.35 s for test 13 and 0.12 s for test 16). The pressure at the end of this period drop to zero and then rises sharply just before the flame rushes out. After this several peaks appear with a period of 20-40 ms corresponding to the first acoustic mode of the chamber (“organ pipe”). Peaks with a much smaller period (2 ms) are also visible on the traces of test 16. It seems to correspond to the natural vibration of the metallic envelope of the chamber rather than to any acoustic mode of the chamber [34].

Discussion and conclusion

The main objective of this paper is to provide additional data about explosion venting of hydrogen air mixtures. Tests were performed in a 1 m³ vessel and in a 10.5 m³ totally vented at one extremity. In addition to the pressure trace presented herein, high speed films were performed which results would certainly add. For instance, the pressure bursts seen on the pressure trace measured on the axis of the vent for the 1 m³ vessel can clearly be attributed to a significant external explosion. This burning outside of the vent prevents for a while the discharge of the burned gases from the vessel as suggested earlier by Cooper at al. [22]. This combustion also occurs for the larger vessel some of the late oscillations.

Finally, it was attempted to compare all the results in this paper to the predictions from the standards (Table 3 and figure 7). As expected the actual data differ greatly from the prediction (NFPA 68) meaning that a significant effort is still required. It is the purpose of the French project DIMITRHY to help progressing. To this end another type of experimental device enabling the full visualization of the explosion is being prepared.

| Reference | Volume (m3) | Vent area (m2) | Measured (bar) |
|--------------|-------------|----------------|----------------|
| [30] | 64 | 2.700 | 0.32 |
| [30] | 64 | 5.400 | 0.13 |
| [31] | 0.95 | 0.200 | 1.25 |
| [31] | 0.95 | 0.300 | 0.4 |
| [32] | 6.85 | 0.018 | 4.8 |
| [32] | 6.85 | 0.049 | 4.2 |
| [32] | 6.85 | 0.159 | 3.2 |
| present data | 1 | 0.15 | 1.4 |
| present data | 10.5 | 2 | 0.25 |

Table 3 : Characteristics of experimental data

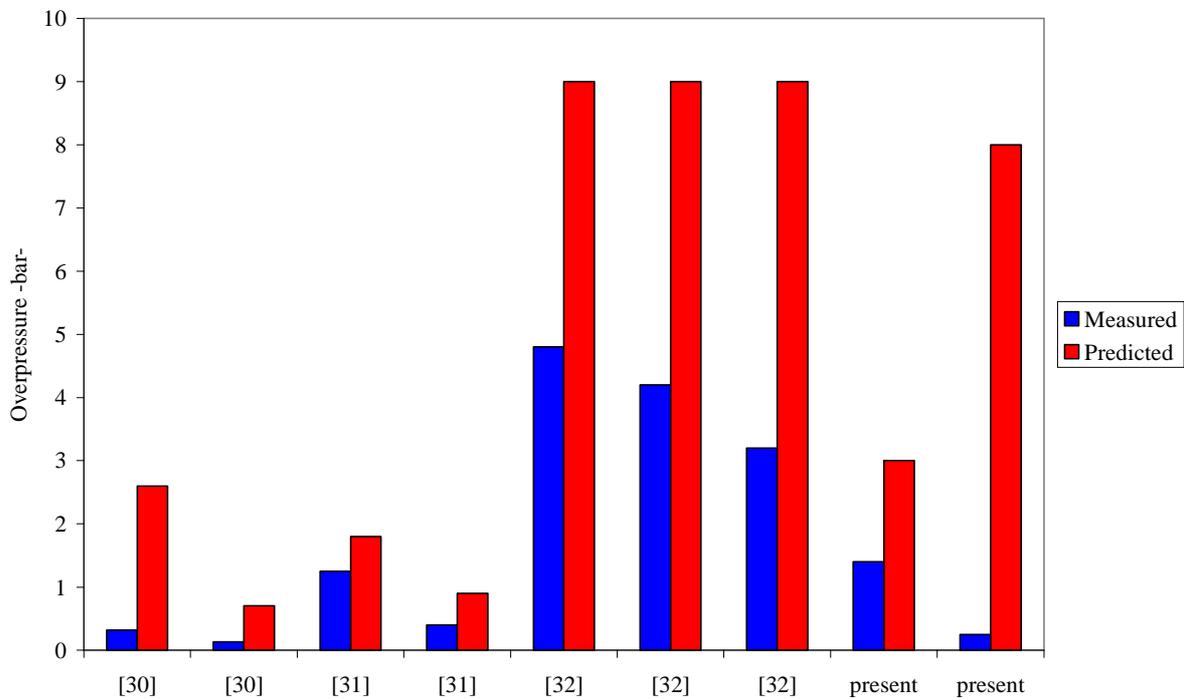


Figure 7 : experimental data and prediction with the standards

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