HOMOGENEOUS HYDROGEN DEFLAGRATIONS IN SMALL SCALE ENCLOSURE. EXPERIMENTAL RESULTS

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ABSTRACT

University of Pisa performed experimental tests in a $1m^3$ facility, which shape and dimensions resemble a gas cabinet, for the HySEA project, founded by the Fuel Cells and Hydrogen 2 Joint Undertaking with the aim to conduct pre-normative research on vented deflagrations in real-life enclosures and containers used for hydrogen energy applications, in order to generate experimental data of high quality. The test facility, named Small Scale Enclosure (SSE), had a vent area of $0{,}42m^2$ which location could be varied, namely on the top or in front of the facility, while different types of vent were investigated. Three different ignition location were investigated as well, and the range of Hydrogen concentration ranged between 10 and 18% vol. This paper is aimed to summarize the main characteristics of the experimental campaign as well as to present its results.

1. INTRODUCTION

Whereas it is preferable to locate hydrogen installations outdoors, this is not always feasible in practice. Hence, it is common to operate hydrogen energy applications, such as electrolysers or fuel cell backup systems in containers or small enclosures.

Explosion venting is the most frequently used measure for mitigating explosions in industry, but it is not straightforward to design vent systems that will reduce the explosion pressure sufficiently to prevent collapse of structures and formation of projectiles.

HySEA [1] is conducting pre-normative research to inform the European and International Standards organizations on “hydrogen explosion venting mitigation systems” and to update and harmonize the international standards for sizing and optimizing the design of venting devices for fast-deploying containerized hydrogen-energy products.

Most of the experimental tests performed in the past were carried out in the context of nuclear safety

[2, 3, 4], while only a limited number of tests were directed towards hydrogen energy applications [5,6,7].

In addition, existing experiments were largely performed in highly idealized conditions. Apart from a few experimental campaign [8, 9], most tests were performed in empty enclosures with ignition along a plane of symmetry and with walls highly reflective to acoustics.

This paper summarize the results of hydrogen deflagration experiments in enclosures having typical dimensions of a gas cabinet, and using realistic levels of congestion and obstacle layout, achieved placing a number of gas bottles inside the facility.

2. EXPERIMENTAL SETUP

UNIPI, with technical support from HySEA partners, has designed a generic experimental enclosure suitable for investigating vented hydrogen explosions in installations such as gas cabinets, cylinder enclosures, dispensers and backup power systems.

The dimensions of the enclosure had been chosen taking into account the dimensions of gas cabinets and dispensers commercially available on the market, while the dimensions of the vent were chosen to accommodate commercial vent panels provided by FIKE. Dimensions of the facility are: 0.92m width, 0.66 m depth, 2 m height.

The enclosure consists of a solid steel frame, built using L-Shaped Cross-section steel bars (50x50x4 mm), whose sides are covered with various combinations of walls, doors, internal congestion and vent panels bolted to the structure.

The back wall, closed by a 5 mm thick steel plate bolted to the frame, supports the main component of the measurement system and is fitted with holes and connections for:

- Five sampling tubes (hydrogen concentrations measurement chain)
- Cables used to power the igniters
- Cables to power the fan (to homogenise the inner atmosphere)
- Cables to control the internal camera
- Compressed air tube (to wash the inner atmosphere after the deflagration or to dilute the hydrogen concentration in case of ignition failure)
- Pipe inlet of salty water spray (used to visualize the flame)
- Pressure transducer

The top face is designed to host different types of vent: FIKE panel (dimension 500 mm x 800 mm) or plastic sheet. When the front vent is used the top face is closed with a 5mm thick steel plate bolted to the frame. Different obstacle configuration were tested: the empty enclosure, 1 and 3 bottles inside the enclosure (see figure 1).

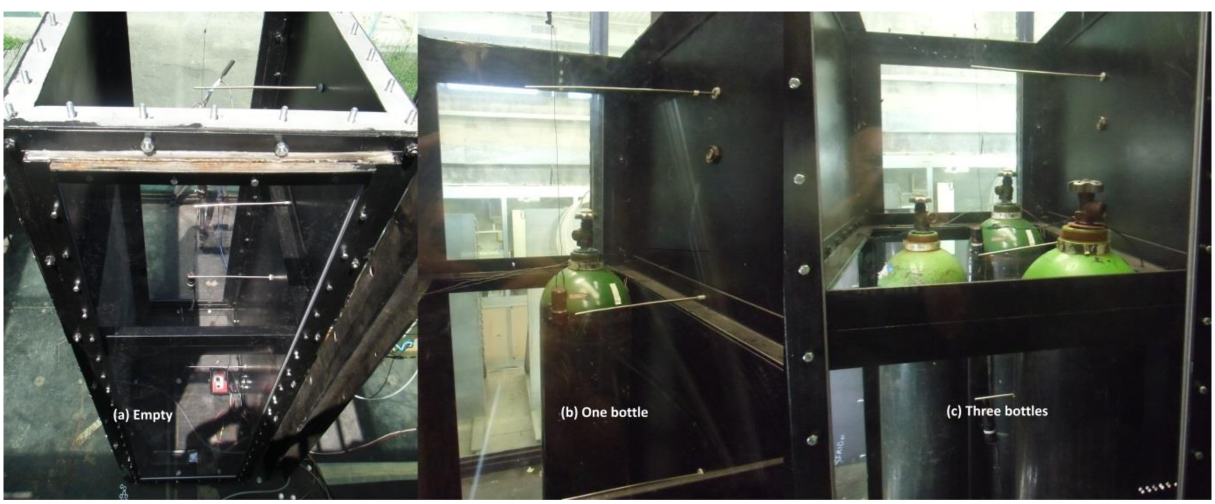

Figure 1 SSE obstacle configuration

The front face is divided into two parts: the upper part can be covered using a FIKE's or plastic sheet vent panel, or be closed with a bolted steel plate when the top vent is used.

The plastic sheet was initially applied to the frame by means of a double sided tape, than the frame bolted to the vented surface of the SSE (configuration 1). Video analysis showed that the plastic sheet in this configuration was undergoing a huge swelling before rupture, this ascertainment led to try different configuration in order to eliminate the phenomena.

A second configuration was tested, named configuration 2, where the plastic sheet was cut along the holding frame internal border and then closed using a paper tape. This configuration showed results comparable with the original configuration 1 when enough pressure was applied to the paper tape during the sealing of the cuts. Because of the difficulties in measuring and replicating the pressure applied to the paper tape to seal the performed cuts configuration 2 was abandoned and only few tests performed

In a third configuration, named configuration 3, an X shaped cut was performed in the middle of the plastic sheet and then closed using the paper tape. This configuration proved to have a lower opening pressure as well as to limit the swelling of the plastic sheet before rupture.

The lower part of the front frame holds a test plate, which can be replaced to test different materials or thicknesses with respect to structural response during the tests. Two steel thicknesses have been tested, namely 2mm and 5mm. The plate displacement measurements are performed using a mechanical method or a laser sensor, results from the displacement measurement as well as capabilities of CFD codes in reproducing the phenomena will be discussed in another publication.

The two lateral frames hold transparent polycarbonate panel (LEXAN) to allow the external deflagration video recording.

The SSE is built inside a bigger experimental facility (named CVE) that has been extensively used in the past to perform hydrogen deflagration experiments [5, 8, 9], which, in the present campaign, serves as a barrier against the projection of missiles that may occur. The frame of the small-scale enclosure has been be bolted to the floor of the CVE test facility.

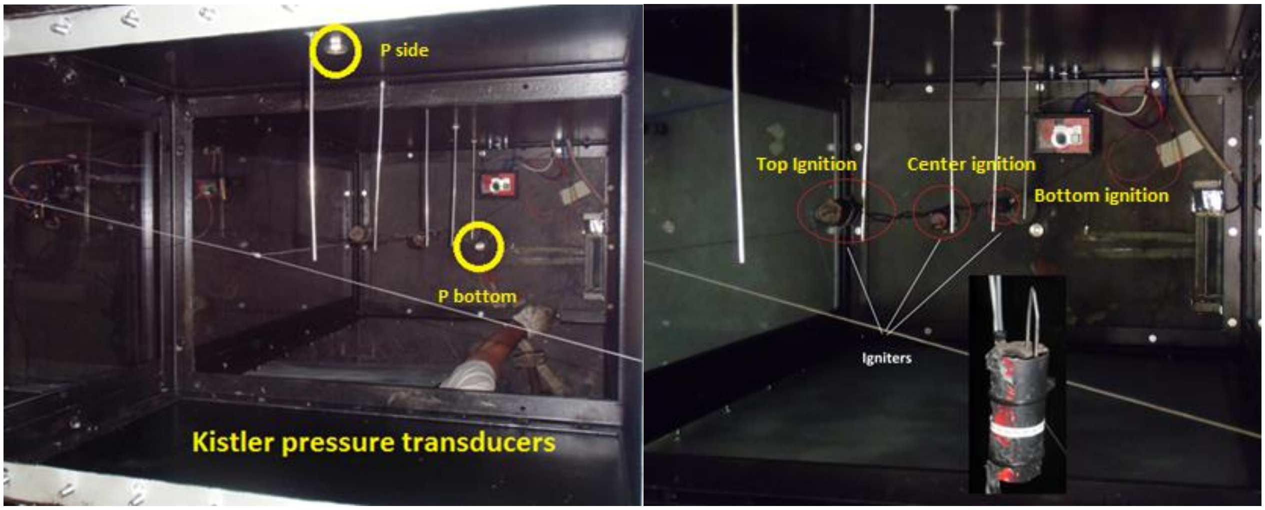

Figure 2 Inside view of the SSE, pressure transducers and ignition locations.

The main variables under investigation are: hydrogen concentration, vent type and location, ignition location, internal obstacle configuration and the thickness of the test plate.

Hydrogen is released from a pipe in the centre of the floor of the facility and mixed using a fan. During the release a number of variables are controlled and some of them recorded at a frequency of 1 Hz, among the controlled variables the most important are the measures of the concentration analysers. Concentration sampling tubes suck the inner atmosphere from a location on the centreline of the facility at 5 different heights, 0.2/0.6/1.0/1.4/1.8 m from the floor.

Pressure transducers are placed in the middle of the floor, P_{bottom}, and in the middle of the upper part of the back wall, P_{side} (see figure 2). During the deflagration the two measured overpressures and the measured displacement are recorded at a frequency of 5 kHz.

The flammable mixture can be ignited in three different positions, all the igniters are located on the centreline of the facility, bottom ignition at 0.5 m above the floor, centre ignition 1 m above the floor, and top ignition 1.5 m above the floor (see figure 2).

3. EXPERIMENTAL CAMPAIGN

A total number of 76 deflagration tests were performed during the experimental campaign, the following table summarizes the main variables investigated.

Table 1 Summary of the experimental campaign.TP

Test #	H_2 concentration range [%vol]	Vent location	Vent type	Ignition location	Obstacle configuration	Test plate thickness [mm]
1…76	10 - 18	-Top -Front	-Plastic sheet (3 configurations) -FIKE vent (3 different explosion vent)	-Top -Centre -Bottom	-Empty -1 bottle -3 bottles	2 - 5

Complete lists of results as well as filtered and unfiltered pressure time history graphs and displacement time history graphs are provided in the related HySEA deliverable [10].

4. RESULTS AND DISCUSSION

4.1 Vent type and opening behaviour

In the range of concentration under investigation, when using a plastic sheet as bursting vent, the measured maximum overpressure was achieved during the vent opening for concentrations lower than 12% vol. in every obstacle configuration. In tests performed with FIKE explosion vents the maximum measured overpressure was always achieved during the vent opening irrespective of the obstacle configuration or ignition location. For all the bursting vent tested, both plastic than commercial vents, the opening pressure was found to be increasing when increasing hydrogen concentration. Figure 3 shows the opening pressure, measured at P_{side}, as a function of average hydrogen concentration for plastic sheet in different configurations.

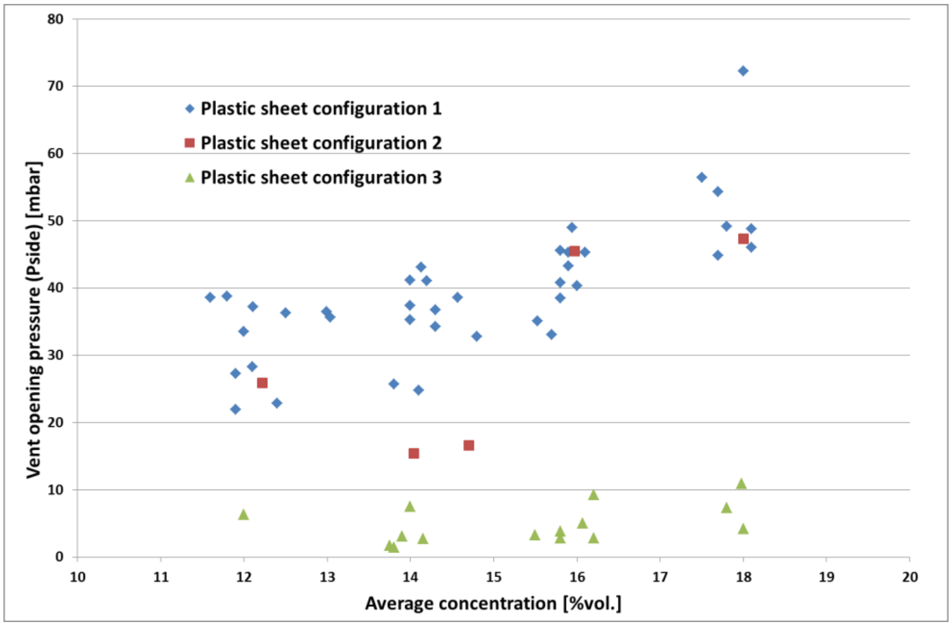

Figure 3 Opening pressure for all the plastic sheet configurations (all obstacle configuration and ignition location are included).

Opening pressure of the plastic sheet was found to be dependent also on the obstacle configuration, namely increasing the percentage of volume occupied by the bottles, the opening pressure increased, see the following figure 4.

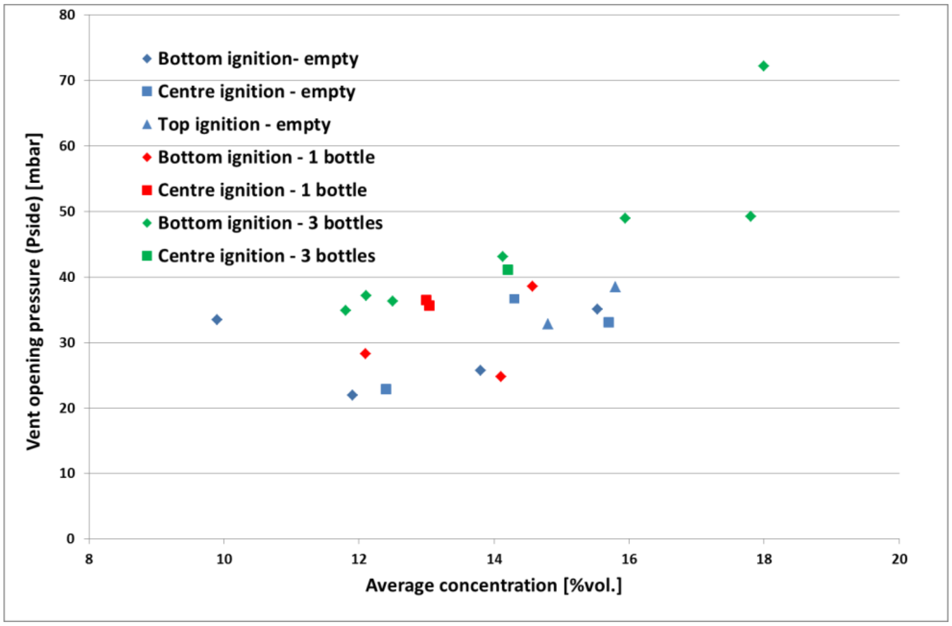

Figure 4 Opening pressure for plastic sheet configuration 1 as a function of obstacle configuration and ignition location (Top vent only).

In all the performed tests the measured overpressure during the opening of the vent was higher at P_{bottom} with respect to the one measured at P_{side}, the pressure difference being dependent on hydrogen concentration.

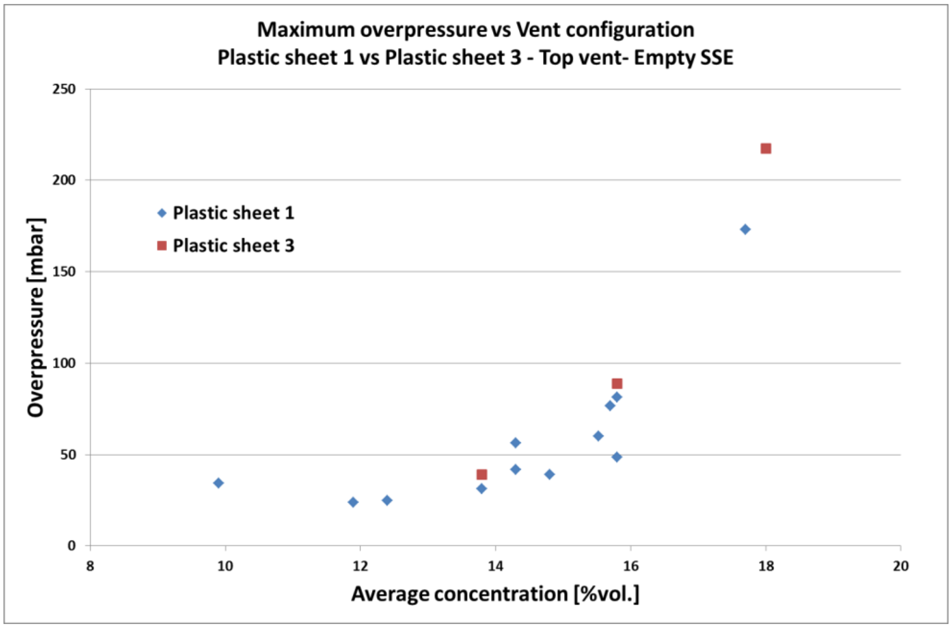

Figure 5 Peak Overpressure for plastic sheets in configuration 1 and 3 in Empty SSE, Top vent

When comparing the maximum overpressure obtained using the plastic sheet in configuration 1 and 3, despite the difference in opening pressure, results are similar for the empty facility or when one bottle is placed inside the facility (see figure 5), while the maximum overpressure is higher when using plastic sheet in configuration 1 in the case where 3 bottles are placed inside the SSE. (see figure 6)

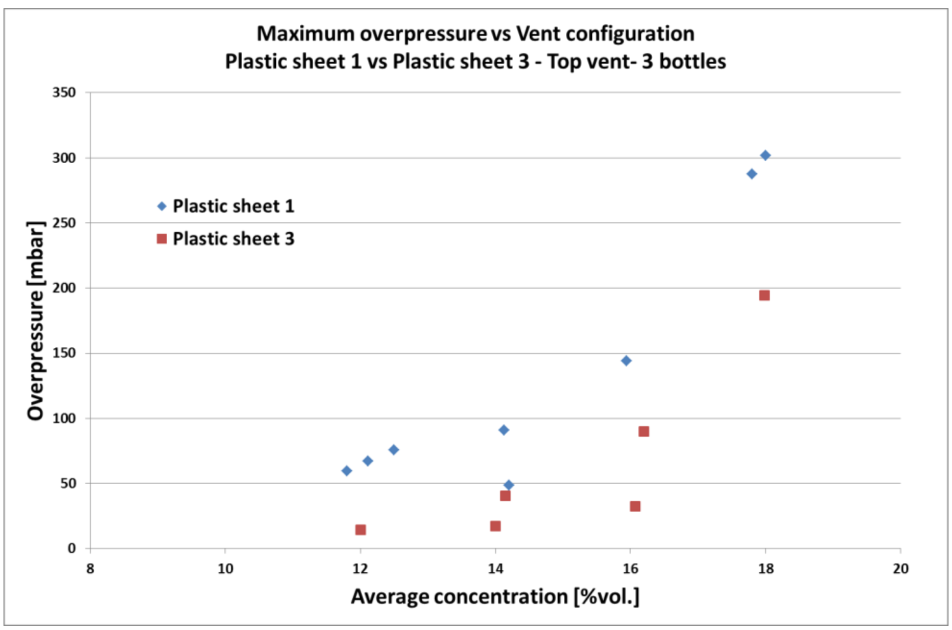

Figure 6 Peak Overpressure for plastic sheets in configuration 1 and 3; 3 bottles, Top vent

4.2 Vent location

Tests performed with the same vent characteristics and opening feature (Plastic sheet configuration 1) were compared to investigate the dependence of the maximum overpressure on the vent location.

The two vent locations seemed to be equivalent in mitigating the effect of the deflagration for the configurations of the empty facility (see Figure 7) and when 1 bottle was placed inside the SSE. In the configuration where 3 bottles were placed inside the Small Scale Enclosure, the front location produced lower maximum overpressure in all the range of concentration under investigation (see Figure 8). Despite the limited population of tests performed, the same behavior has been confirmed by the results obtained using plastic sheet in configuration 3.

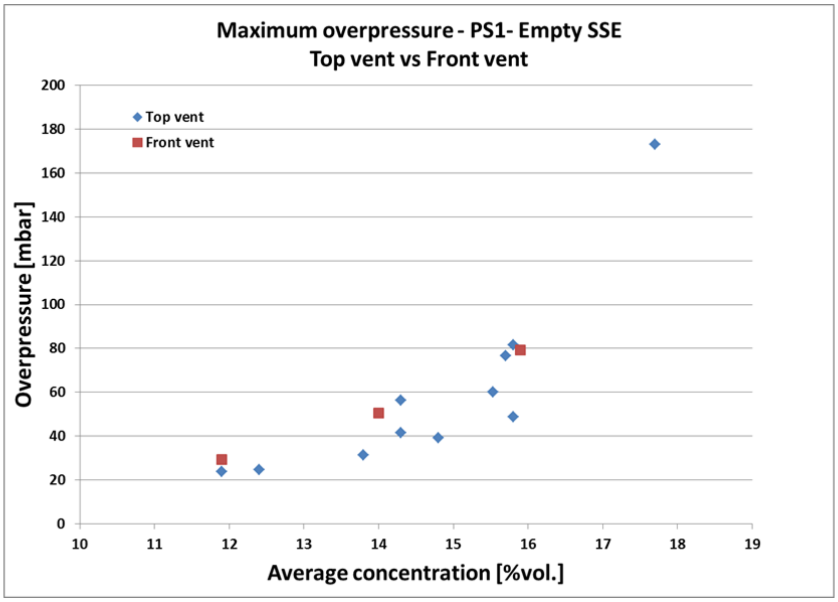

Figure 7 Peak Overpressure for plastic sheets configuration 1 and Empty SSE (top vent vs. front vent)

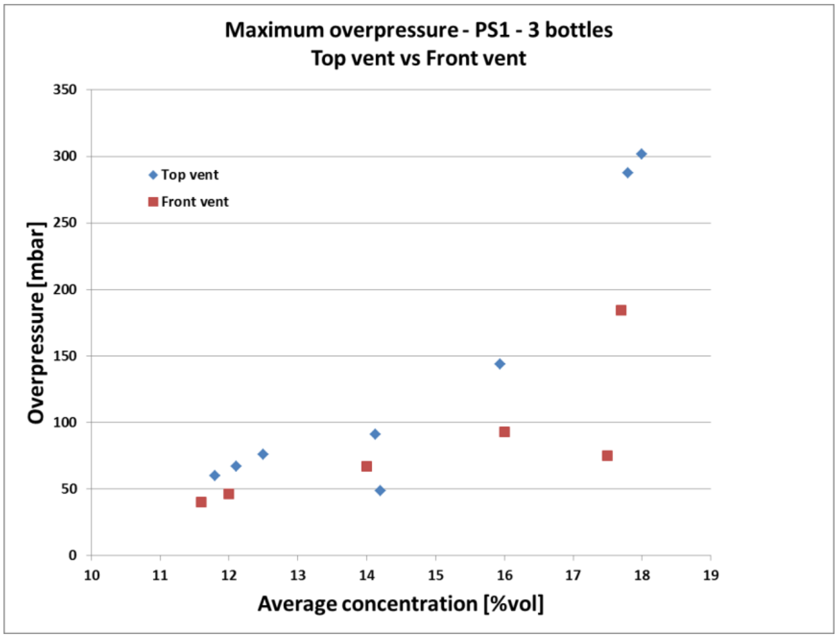

Figure 8 Peak Overpressure for plastic sheets configuration 1 and 3 bottles obstacle configuration (top vent vs. front vent)

4.3 Ignition location

Top ignition, which position is very close to both the top and front vent locations, always led to lower overpressure when compared with tests performed in the same conditions but ignited in the centre or in the bottom locations. In fact in this case the flame front is very close to the vent area during the vent deployment and the short distance does not allow the flame front to accelerate towards the vent.

Centre and bottom ignition were found to produce similar results when the top vent is used, while when the front vent is used centre ignition produced lower peak pressure with respect to the bottom ignition. This behaviour can be explained considering that with respect to the front vent location, centre ignition is a close vent ignition and the flame front cannot suffer major accelerations towards the vent as for the case of top ignition.

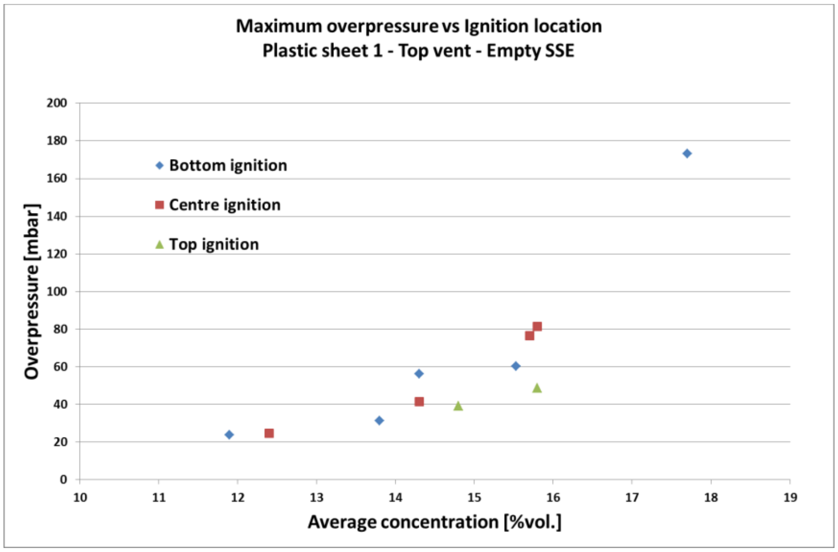

Figure 9 Peak Overpressure for test performed with different ignition location in the Empty enclosure (Vent type Plastic sheet configuration 1)

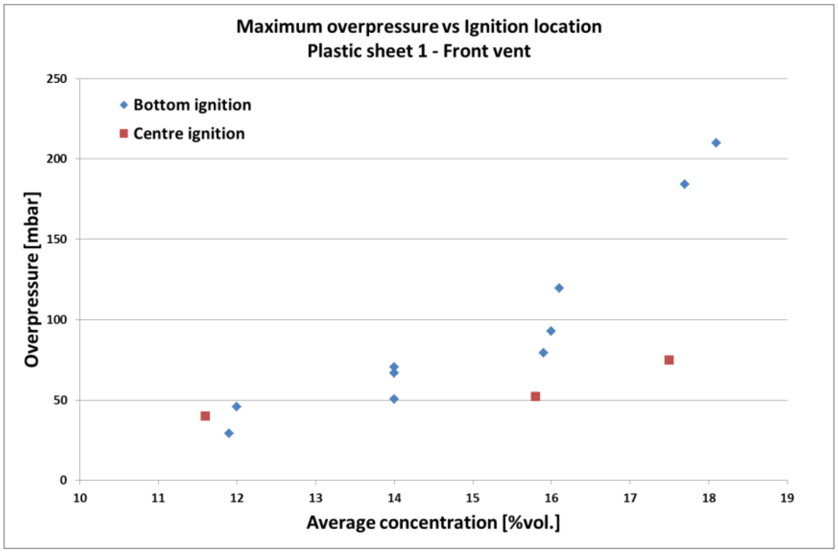

Figure 10 Peak Overpressure for test performed with different ignition location inside the SSE (Vent type Plastic sheet configuration 1 – all obstacle configurations)

4.4 Obstacle configuration

When the front vent is used, in the Empty facility the peak overpressure is lower than the one obtained in configurations where one or three bottles are placed inside the facility, nevertheless results of test performed with the latter two configurations produced comparable results, see figure 11.

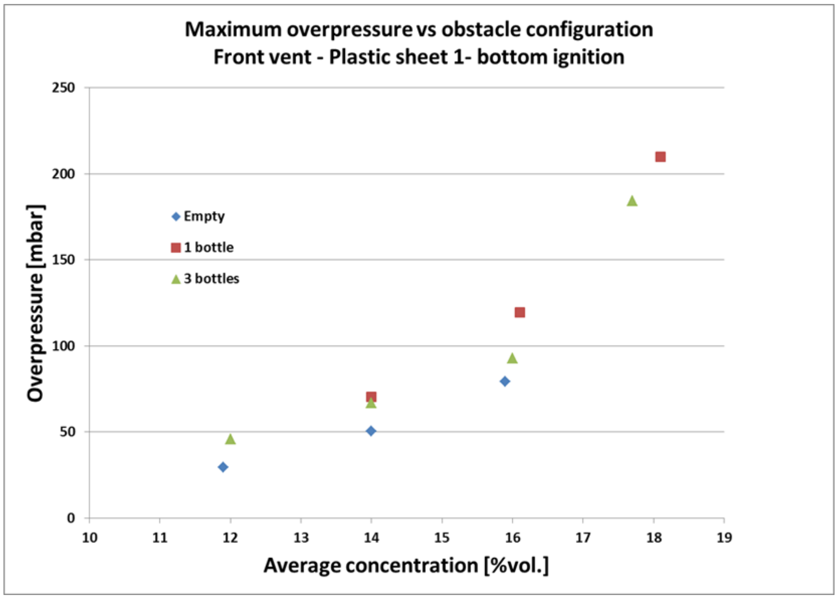

Figure 11 Peak Overpressure (Plastic sheet configuration 1, front vent, bottom ignition) vs. average concentration

For top vent location, a dependence of the maximum overpressure with obstacle configuration has been found, see figure 12. In this case the maximum overpressure increases when increasing the volume occupied by the bottles inside the facility.

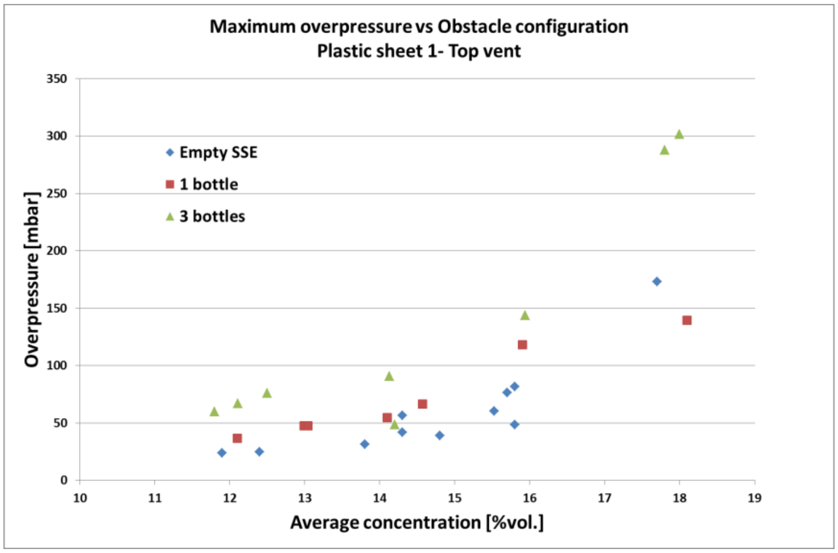

Figure 12 Comparison of the Peak Overpressure for test performed in the 3 different obstacle configurations (Plastic sheet configuration 1, top vent, irrespective of the ignition location).

Some of the tests showed a number of pressure peaks after the so called second peak generated when the flame front reaches the vent area producing a discontinuity in the venting flow rate as well as igniting the unburned mixture previously vented. Of these peaks, the first one, identified in the following with the denomination 3rd peak, may be higher than the second peak.

The 3rd peak is always higher at P_{bottom}, with respect to P_{side}, in fact the recorded 3rd peak at P_{bottom} can be higher than the 2nd peak, while the 3^{rd} peak recorded at P_{side} is often lower than the 2^{nd} peak, see figure 13. These data led to the interpretation of the 3^{rd} peak as a local peak overpressure developed in the bottom of the enclosure just after the venting of the burned gases.

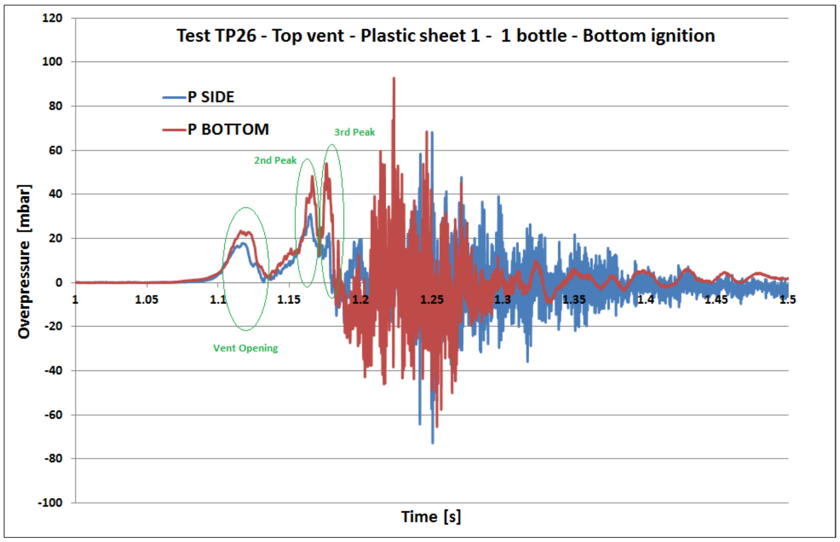

Figure 13 Pressure time history for test TP26 (Top vent - Plastic sheet configuration 1- 1 bottle – Bottom ignition)

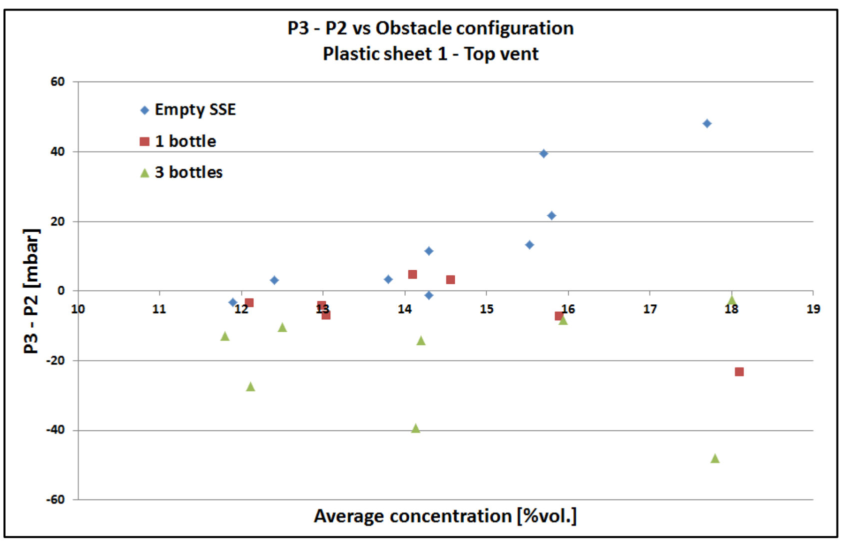

Figure 14 Pressure difference between the third and the second peak (Top vent - Vent type Plastic sheet configuration 1)

For most of the tests performed using the top vent covered by plastic sheet in configuration 1 in the empty facility, the 3rd peak measured at P_{bottom} is higher than the 2^{nd} peak. The pressure differences between the two peaks increases with hydrogen concentration. Nevertheless in configuration with 3 bottles inside the SSE, using the top vent covered by plastic sheet in configuration 1, all the test performed produced a 2^{nd} peak higher than the 3^{rd}.

As for plastic sheet configuration 1, in the empty facility or with one bottle inside the enclosure, the 3rd peak is always higher than the second and the differences increase with the average hydrogen concentration.

For plastic sheet in configuration 3, with the 3 bottles inside the SSE and average concentrations lower than 16% vol. the 3rd peak measured at P_{bottom} is slightly higher than the second pressure peak. In test performed with centre ignition the 3rd peak is higher than the 2nd also for concentration higher than 16%vol.

A possible explanation of this phenomenon may take into account the fresh air sucked back inside the facility after the venting process creating a flow field which accelerates the flame front towards the bottom of the enclosure. The strength of the phenomenon may then be related to the acceleration suffered by the flame front travelling towards the bottom of the enclosure after the flame front travelling in opposite direction reaches the vent area.

Hence the appearance of the 3rd peak may be dependent on the geometry, on the position of the flame front inside the facility, on the strength of the acceleration prompted by the discontinuity at the vent area, dimensions of the vent area etc.

5. CONCLUSIONS

Deflagration tests involving homogeneous Hydrogen air mixture were performed at the B.Guerini laboratory of the University of Pisa for the HySEA project. Tests were performed in an enclosure of $1m^3$ volume investigating the vent location, ignition location, and obstacle configuration in a range of concentrations between 10% and 18%vol. In tests performed with commercial explosion vents the maximum measured overpressure was always achieved during the vent opening irrespective of the obstacle configuration or ignition location. For all the vent cover, both plastic sheets and commercial panel the opening pressure was found to be dependent on hydrogen concentration. Results underline the highly dynamic nature of gas deflagrations and the dependence of the maximum measured overpressure over a number of factors. Ignition location closer to the vent area always leads to a lower overpressure compared with far vent ignition locations in the same conditions. The mitigating effect of the top and front vent are comparable in the empty facility or with one bottle placed inside the facility, while in test were three bottles are placed inside the enclosure the front vent seem to be more effective in mitigating the maximum overpressure generated inside the enclosure. Results showed the presence of a local 3rd peak after the external explosion, generally referred as 2nd peak or P_{ext}. The 3rd peak is often higher than P_{ext} at P_{bottom} location, but is rarely higher than P_{ext} at P_{side} location. The presence of the 3rd peak may than be closely related with the reverse air flow after venting which accelerates the flame front towards the bottom of the enclosure.

6. ACKNOWLEDGMENTS

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