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Non-homogeneous hydrogen deflagrations in small scale enclosure. Experimental results

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ABSTRACT

University of Pisa performed hydrogen releases and deflagrations in a 1.14 m^3 test facility, which shape and dimensions resemble a gas cabinet. Tests were performed 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 enclosures and containers used for hydrogen energy applications. The test facility, named Small Scale Enclosure (SSE), has a vent area of 0,42 m^2 which can host different types of vent; plastic sheet and commercial vent were tested. Realistic levels of congestion are obtained placing a number of gas bottles inside the enclosure. Releases are performed from a buffer tank of a known volume filled with hydrogen at a pressure ranging between 15 and 60 bar. Two nozzles of different diameter and three different release directions were tested, being the nozzle placed at a height where in a real application a leak has the highest probability to occur. Three different ignition locations were investigated as well. This paper is aimed to summarize the main features of the experimental campaign as well as to present its results.

Introduction

Due to the high buoyancy of hydrogen, most of the real accidents that can happen in closed environments foresee an accumulation of the released gas under the canopy of the enclosure and a stratification in layers at different concentrations, instead of homogeneous mixtures.

Nevertheless, most of the experimental tests performed in the past were performed at highly idealized conditions. Particularly, apart from a few experimental campaigns [1–3], most tests were performed in empty enclosures. Furthermore only few experimental campaigns were conducted investigating non-homogeneous mixtures [4–6].

HySEA project [7] conducted 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. Experimental tests were performed in 12 foot ISO-containers by GexCon [8,9] and in a small scale enclosure by University of Pisa (UNIPI), investigating both homogeneous and stratified mixtures in real volume applications with and without the presence of obstacles.

The small scale enclosure (SSE) is designed to reproduce volumes and arrangements of a gas cabinet. In a first experimental campaign tests were performed in homogeneous conditions (tests label TP) [10–12]. In the second part of the

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experimental campaign (tests label NHTP), described in this paper, the release is carried out using a buffer tank filled at the desired pressure, from a nozzle of a known diameter. The nozzle is placed at a height where the leak has the higher probability to occur in a real application, namely the area above the bottles where connections with the gas manifold are located. During the release the inner atmosphere is sampled at 5 different heights both when the release stratifies for some minutes before ignition, then when it is ignited at the end of the release. Furthermore the small scale enclosure was used to collect data on the variability of the opening pressure of commercial vent as a function of the rate of pressure rise during the deflagration. The effect of the time of ignition was investigated as well as the one of the ignition location on the maximum achieved overpressure.

A total number of 82 releases and deflagration tests, named NHTP, were performed during the experimental campaign. This paper summarizes the aforementioned aspects of the data analysis, while other collected data will be published in the future.

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, 0.92 m width, 0.66 m depth, 2 m height, 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 (see Fig. 1). FIKE is a globally recognized supplier of vent panels that protect vessels and buildings from explosions and a partner of the project HySEA. Two different obstacle configurations were tested: the empty enclosure and 3 bottles inside the enclosure (see Fig. 3). The free volume of the empty facility is 1.14 m^3, while the 3 bottles occupy 14.6% of the internal volume.

The enclosure consists of a solid steel frame, built using L-Shaped Cross-section steel bars (50 × 50 × 4 mm), bolted to the basement beams of a 25 m^3 experimental facility. The frame external faces are covered with various combinations of walls, doors, and vent panels bolted to the structure.

The back wall, closed by a 5 mm thick steel plate bolted to the frame, is strengthened around the position of a pressure transducer (P_{side}) which is located at a height of 1690 mm from the floor. The back wall is also fitted with holes and connections for the measurement system and hosts the release nozzle which axis is placed at 1520 mm height from the floor (see Figs. 1 and 2(b)).

The top face of the facility is designed to host different types of vent: commercial FIKE panel (dimension 500 mm × 800 mm) or plastic sheet. The tested FIKE vent, single element, integrated frame, was selected during the first experimental campaign involving homogeneous mixtures for its lower dependency of the opening pressure with the pressure rise rate with respect to composite layers stainless steel and fluoropolymer vents.

The front face is divided into two parts: the upper part, which height is 0.62 m, is closed with a bolted steel plate of which the displacement is measured during the deflagration; the lower part, height 1.38 m, was closed by a 5 mm thick steel plate. The location of the displacement measurement, that is the external bowing of the bolted plate provoked by the internal pressure rise inside the enclosure during the deflagration, is opposite to the pressure transducer placed on the back-wall. Two thicknesses of the plate have been tested, namely 2 and 5 mm. Results from the displacement measurement are listed in the HySEA deliverable [12], while the discussion on the capabilities of FE and CFD codes in reproducing the phenomena has been discussed in another paper [13,14].

The two lateral faces host frames with transparent polycarbonate panels (LEXAN) in order to have the possibility to video record the flame from outside.

Salty water aerosol was injected inside the enclosure before starting the release in tests were the flame front was filmed. Comparison of similar tests performed at the same H_2 concentration with and without salty water aerosol injection allowed to verify that effect of the aerosol on the resulting pressure time history was negligible.

Two small commercial cameras (Go-Pro Hero 5) are used to record the deflagrations with a recording frequency of 240 frames per second: the internal camera is placed on the bottom of the facility facing the top vent, the external camera was used to record the vent opening features in some tests and to video record the flame inside the facility when salty aerosol was injected to visualize the flame.

Hydrogen is contained in a buffer tank of a 3.785 L volume, see Fig. 2(a), that is filled to the desired pressure, the release is initiated opening a valve. Nozzle diameters are 0.5 mm, (area 0.196 mm^2), and 0.95 mm, (area 0.709 mm^2), respectively. The release has been performed in different direction: horizontally, upward or downward direction have been tested in the experimental campaign. Downward release impinges in a hydrogen sampling steel tube and in the L-shape frame of the structure, see Fig. 2(b).

Concentration sampling tubes suck the inner atmosphere from a location on the centreline of the facility at 5 different heights, 0.2 m; 0.6 m; 1.0 m; 1.4 m and 1.8 m from the floor. During the release and consequent stratification the concentration measurements were recorded at a frequency of 1 Hz.

In some of the tests the volume above the bottles was occupied by the sampling lines of the oxygen sensors. Oxygen sensors were used to measure the concentration close to the roof of the enclosure where the concentrations could exceed the reading limit of the hydrogen sensors. The presence of the sampling lines affects the distribution of hydrogen as discussed in the following paragraphs. Nevertheless the results of the oxygen sensor measurements were not considered satisfactory and their results are not included in this report. More information please refer to the HySEA report [15].

The flammable mixture has been 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 Fig. 1).

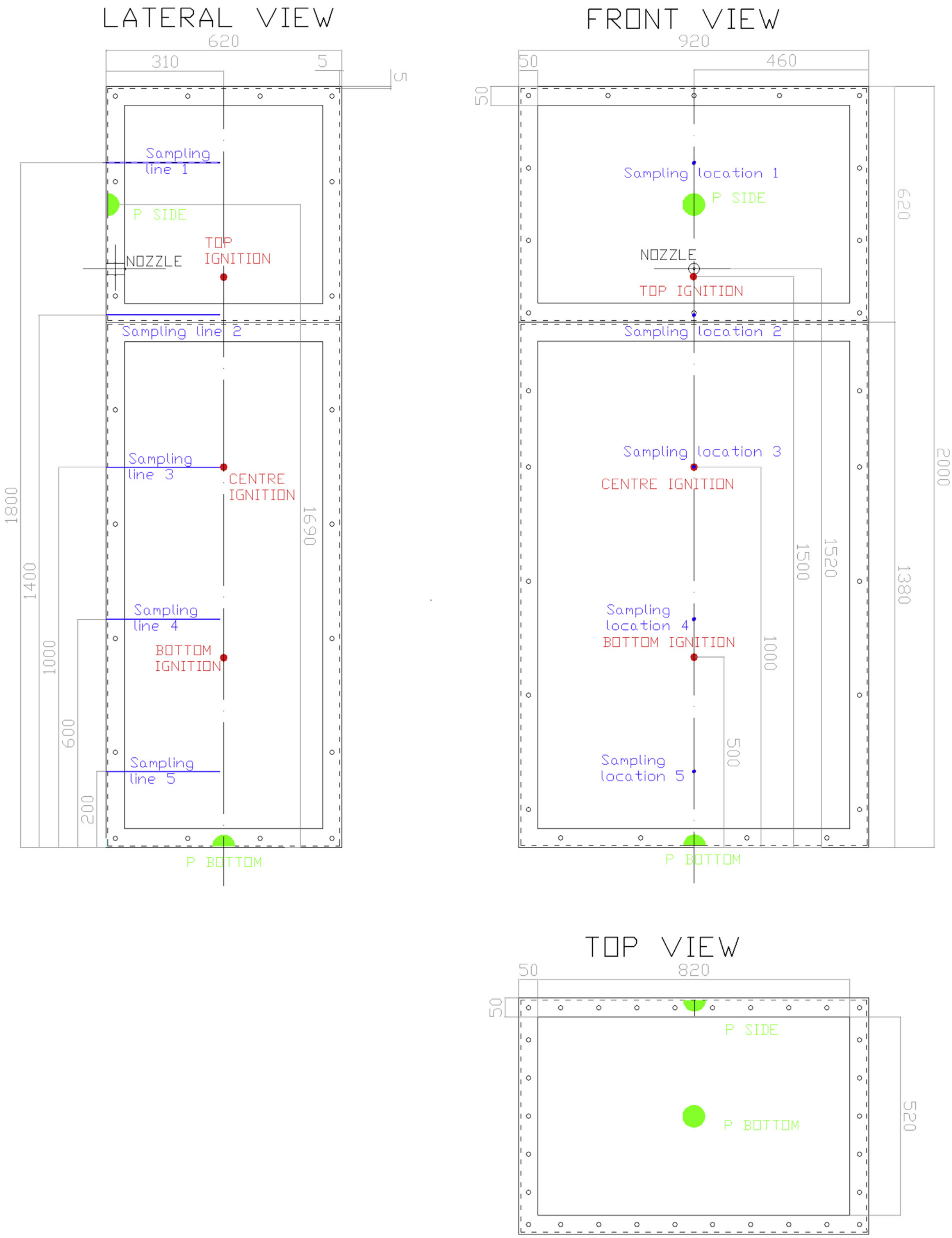

Fig. 1 – Schematic of the SSE.

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}, height 1690 mm from the floor, (see Fig. 1). During the deflagration the two measured overpressures and the measured displacement are recorded at a frequency of 5 kHz.

A number of parameters have been investigated during the experimental campaign, see Table 1.

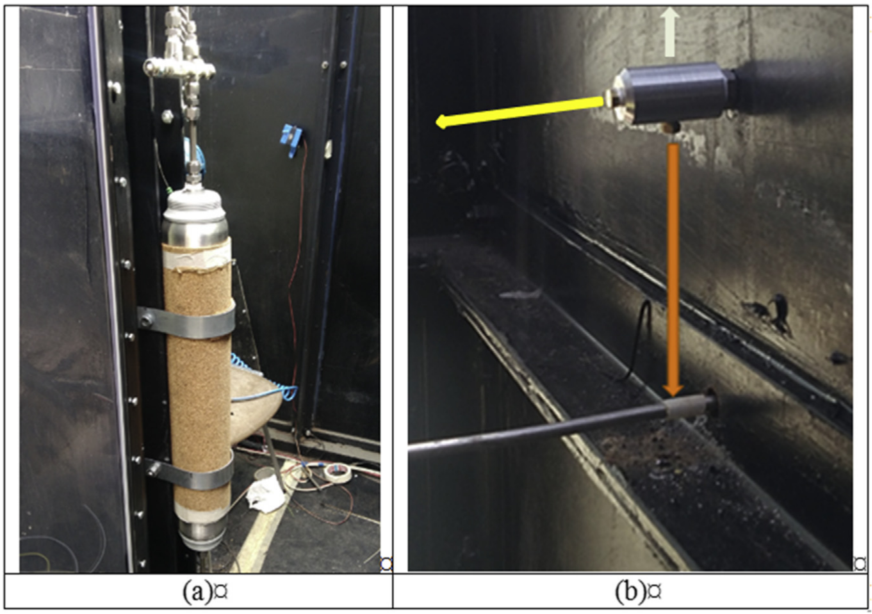

Fig. 2 – Pressurized release buffer (a) and nozzle with indication of release directions (b).

Fig. 3 – SSE obstacle configurations.

Results and discussion

Hydrogen dispersion and stratification

The stratification of hydrogen inside the enclosure is affected by both release direction and nozzle diameter as well as by the presence of obstacles. Among the obstacles present, the sampling lines of the oxygen sensors must be taken into account; results showed their effect particularly for the horizontal release performed with the smaller nozzle. The jet generated by the release performed through the smaller nozzle was partially deflected towards the bottom of the facility creating a more homogeneous mixture with respect to the same release performed without the sampling lines (see Fig. 4). Fig. 4 shows the concentration measurements at the 5 sampling heights for tests performed at different initial pressure and obstacle configuration, with and without the oxygen sampling lines but always using the smaller nozzle. The trend line of the distribution of hydrogen are also shown. The smaller image in the lower right corner shows the stratification of hydrogen following horizontal releases performed through the bigger nozzle with and without the oxygen sampling lines. Release performed through the bigger nozzle were only slightly affected by the presence of the sampling lines.

The comparisons of the effect originated by the presence of the bottles on hydrogen distribution has been performed comparing tests where the oxygen sampling lines are present in the upper part of the facility. Since the oxygen sampling lines affect the stratification of hydrogen released from the smaller nozzle, only the results obtained from the larger

Table 1 – Variables under investigation in the experimental campaign.

Obstacles	Buffer tank pressure [bar]	Nozzle diameter [mm]	Release direction	Vent type	Ignition location (T = top, C = centre, B = bottom)
Empty enclosure	15	0.5	Horizontal	Plastic sheet	T
	20	0.5	Horizontal	Plastic sheet	T
	25	0.5	Horizontal	Plastic sheet	T
	30	0.5	Horizontal	Plastic sheet	T
	40	0.5	Horizontal	Plastic sheet	T-T-C-C[a]
			Downward	Plastic sheet	C
				FIKE – SANI V	C-C[a]-T
		0.95	Horizontal	Plastic sheet	T-C-B
				FIKE – SANI V	C-B
			Downward	Plastic sheet	C-T-C[a]
	50	0.5	Horizontal	Plastic sheet	T-C
			Downward	Plastic sheet	C-B-T-C[a]-B[a]-T[a]
		0.95	Horizontal	Plastic sheet	C
				FIKE – SANI V	C
			Downward	Plastic sheet	C-C-C[a]
	60	0.95	Horizontal	Plastic sheet	C-B
3 bottles	30	0.5	Horizontal	FIKE – SANI V	T-C
	40	0.5	Horizontal	Plastic sheet	C-C[a]-B[a]-T
			Downward	Plastic sheet	C-C[a]-T[a]
			Upward	Plastic sheet	C
		0.95	Horizontal	Plastic sheet	C-C[a]-T-B
				FIKE – SANI V	C-C[a]-T-T-B
			Downward	Plastic sheet	C-C[a]
			Upward	Plastic sheet	C-C[a]
	50	0.5	Horizontal	Plastic sheet	C-C[a]-B[a]-T-T
			Downward	Plastic sheet	C-C[a]
			Upward	Plastic sheet	C
		0.95	Horizontal	Plastic sheet	C-B-B[a]-C
				FIKE – SANI V	C-C[a]
			Downward	Plastic sheet	C
			Upward	Plastic sheet	C-C[a]
	60	0.5	Horizontal	Plastic sheet	C-B-C[a]
			Downward	Plastic sheet	C
		0.95	Horizontal	Plastic sheet	C-C[a]-C

[a] Note: Indicates ignition switched on 5 s from the end of the release.

nozzle are presented and discussed to assess the effect of the bottles on the distribution of hydrogen inside the enclosure.

The comparison between tests with and without the bottles is shown in Fig. 5 for releases at 40, 50 and 60 bar. Figure shows concentration measurement at the 5 sampling heights. The different measurements obtained for the same release conditions are due to experimental variability. Despite the mentioned variability, which is reasonable to expect in real scale experimental tests, the releases where found to be reproducible. The figure shows also the trend lines of the stratification of hydrogen as a function of the height of the location from the ground. When bottles are present hydrogen is more prone to accumulate in the upper part of the facility (empty space) with respect to the empty enclosure.

Similar behavior was found for downward release, in both 0.5 and 0.95 mm release diameter. Also in these tests the presence of the bottles is enhancing the concentration in the upper part of the enclosure. Upward releases were performed only with 3 bottles inside the enclosure. More data and analysis of the performed tests can be found in the HySEA report [15].

Deflagration pressure peaks

Pressure time history of the performed deflagrations can be classified in three different categories.

The first category is represented by the tests performed using commercial vent panels which opening pressure (typically higher than 100 mbar) is higher than the opening pressure of the plastic sheets (25–50 mbar). In these tests irrespective of the obstacle configuration or ignition location, the vent burst pressure is the highest pressure achieved during the deflagration. The following Fig. 6 shows the typical pressure time history for one of the tests performed with commercial vents. This part of the campaign was focused on studying the dependence of the vent burst pressure with the rate of pressure build up. Results show that the opening pressure is dependent on the rate of pressure increase when this exceeds 2.5 bar/sec. The image of the top right corner shows the opening pressure measured at P_{side} as a function of the rate of pressure increase.

The second and third categories are generated by tests performed using plastic sheet as vent panels. In these cases, following the first peak generated by the vent burst, the pressure inside the enclosure decrease and rises up again to

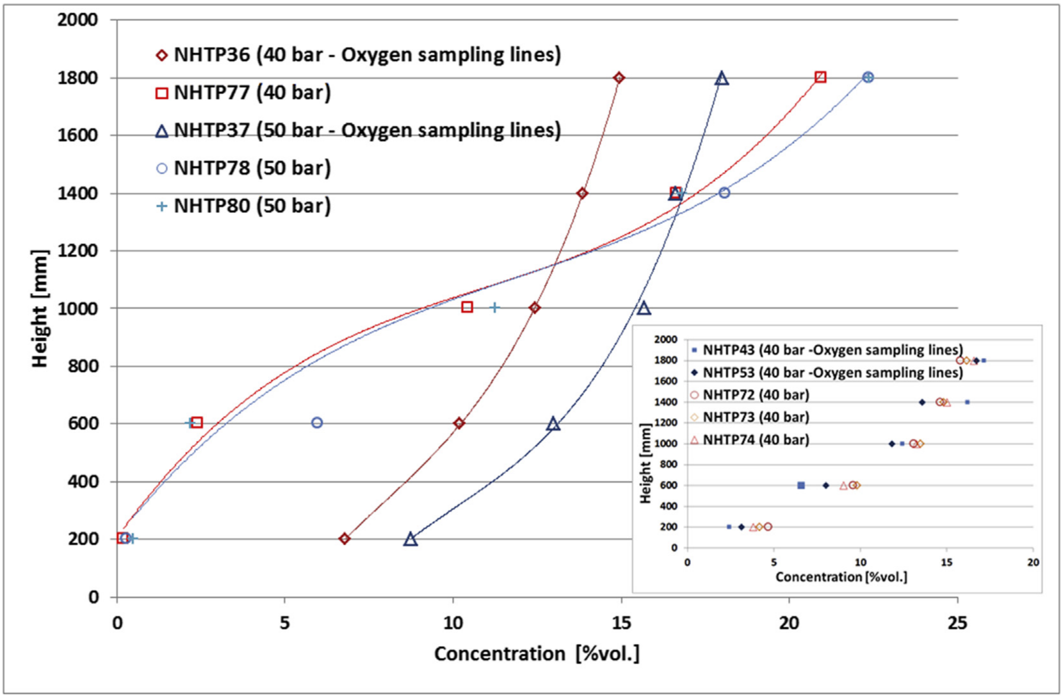

Fig. 4 — **H_2 distribution for tests performed through the 0.5 mm diameter and 0.95 mm diameter nozzle (lower left corner) with and without oxygen sampling lines.**

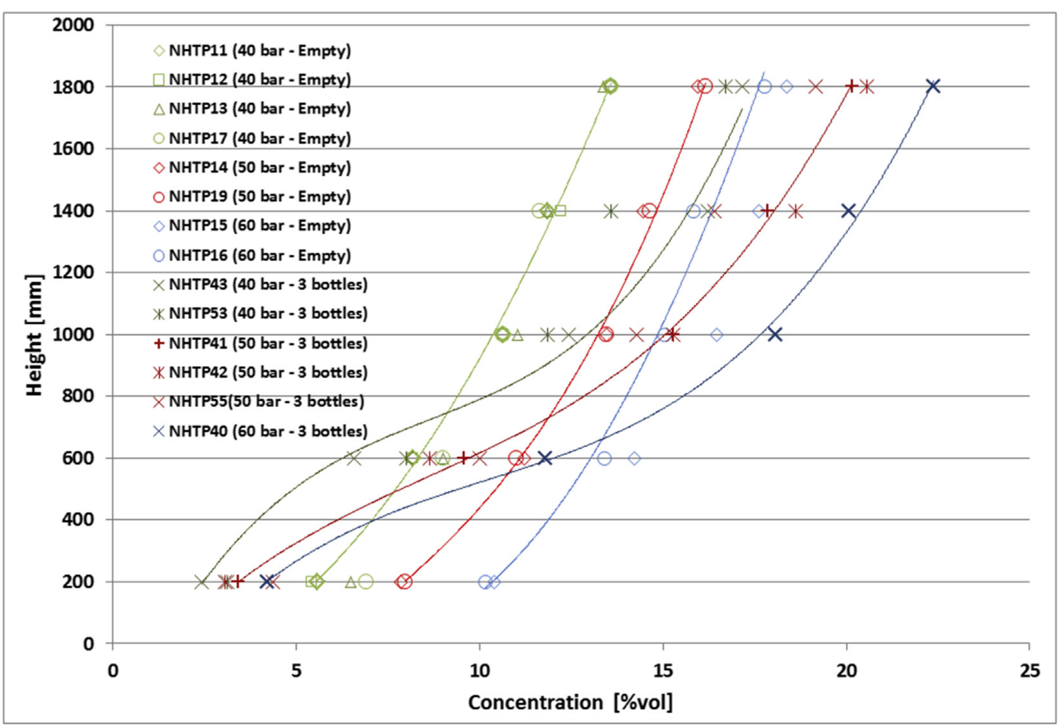

Fig. 5 — **H_2 distribution: (Empty facility; 3 bottles inside the enclosure; nozzle diameter 0.95 mm, horizontal; initial buffer pressure 40, 50 and 60 bar).**

generate the second peak, which presents itself when the flame front reaches the vent area.

Pressure time history recorded by the two pressure transducers are coupled up to the moment of the vent burst. When the vent starts to open an initial flow field is generated inside the enclosure. Pressure continues to rise for some milliseconds in the bottom, while, due to the opening of the vent, it's lower close to the vent area. When the venting of

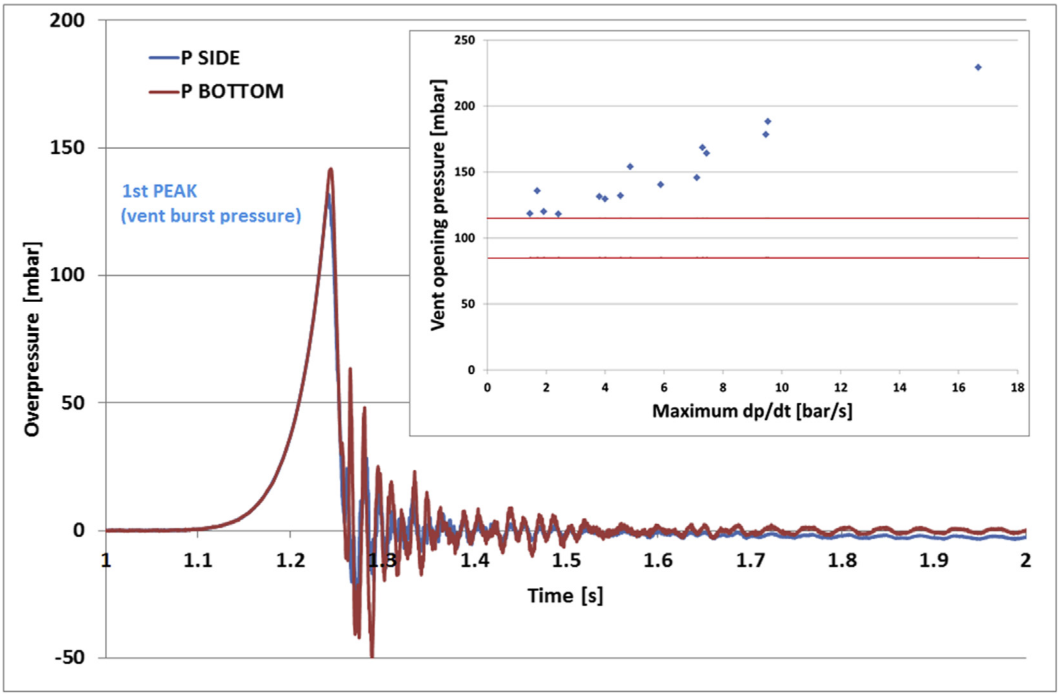

Fig. 6 – Pressure time history of the deflagration in test NHTP33.

the unburned mixture starts to be overcome by the expansion of the flame bubble the two transducer measure the same pressure again. As soon as the flame front reaches the vent generating the second peak a flow field is again generated inside the enclosure and the two pressure transducers record different values till the extinction of the perturbations. Fig. 7 shows the pressure time history of a test exhibiting this behavior. The phenomenon of flame acoustic interaction is not always present and its intensity may vary from test to test. This category of test also includes the tests at low hydrogen concentration were the second peak is lower than the vent burst peak.

The second category differs from the third in the last phase of the deflagration where an acoustic peak is generated by the interaction of the flame front with the acoustic oscillations. In the third category of tests, following the vent burst peak and

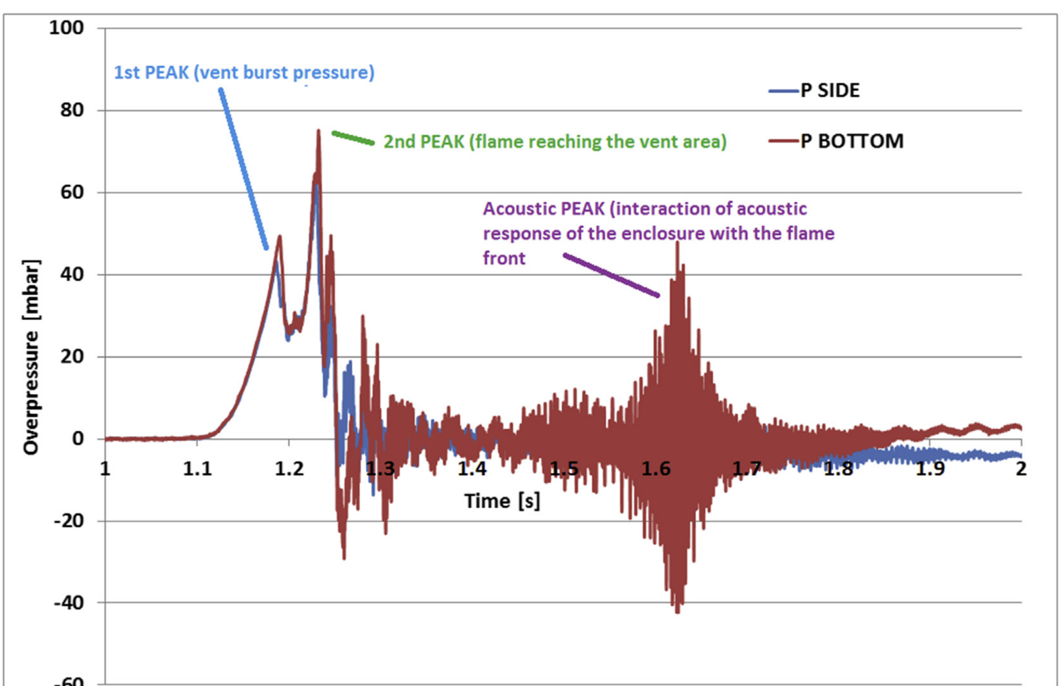

Fig. 7 – Pressure time history of the deflagration in test NHTP16.

the second peak, a third peak is generated. It is a local or directional pressure peak, since it's usually recorded at P_{bottom} with higher measurements with respect to P_{side}. The third peak is often the highest peak measured at P_{bottom} during the deflagration. Nevertheless the measure at P_{side} during the third peak is lower than the second peak. Fig. 8 shows the typical pressure time history obtained from this category of tests. The physical phenomena which lead to the generation of the third peak may be the counter wave re-entering the enclosure after the flame front reaches the vent, phenomenon enhanced by the large vent area with respect to the volume of the enclosure. In fact the third peak appear to be the first peak of the Helmholtz oscillations. Of the 66 valid tests performed with the plastic sheet as vent panel 21 showed the 3rd peak during the deflagration.

Effects of obstacles on the maximum achieved overpressure

A comparison of the maximum achieved overpressure for tests with obstacles (3 bottles) and conducted in the empty enclosure was performed taking into account the amount of hydrogen released. Fig. 9 shows the result of the described comparison for the maximum pressure recorded at P_{bottom}.

The maximum achieved overpressure doesn't seem to be affected by the presence of the obstacles when the amount of hydrogen released is below 12 g. The maximum measured concentration inside the facility for 12 g of hydrogen released ranges between 13.3%vol and 17.6%vol, while the range varies between 15%vol and 21%vol with the bottles inside the enclosure. Increasing the mass of hydrogen released above 16 g led to higher overpressures achieved during deflagration when 3 bottles are placed inside the facility. The maximum measured concentration inside the empty facility for 16 g of hydrogen released ranges between 18%vol and 19%vol, while the range varies between 21%vol and 23%vol with the bottles inside the enclosure. As discussed in the previous paragraphs the distribution of hydrogen is affected by the presence of obstacles. Changes in hydrogen distribution and concentration at the ignition location are not resolved in this analysis, nevertheless, even though top ignition often leads to higher overpressures, results are predominantly affected by the total amount of hydrogen released compared to the detailed hydrogen distribution inside the enclosure. Fig. 9 shows the maximum achieved overpressure for tests taken in the empty facility and with 3 bottles inside the enclosure as a function of the mass of hydrogen released.

Effect of the ignition location

Results from the 1st experimental campaign showed that in homogeneous condition the maximum overpressure generated inside the enclosure is dependent on the ignition location. Particularly as much as the ignition location is far from the vent, as higher is the maximum overpressure developed inside the facility.

When testing deflagration in non-homogeneous concentrations, nevertheless, the described behaviour is not confirmed. In non-homogeneous conditions the stratification leads to very low hydrogen concentration in the lower part of the facility. Even when hydrogen concentration is sufficiently high to start the deflagration, the flame velocity is still low when the pressure reaches value of the vent burst. After the vent bursts, when the flame front reaches regions at higher concentrations, lot of the rich mixture present in the upper part of the facility is already been pushed out through the vent.

Fig. 10 shows the pressure time history for 3 tests performed with the same release but ignited in different

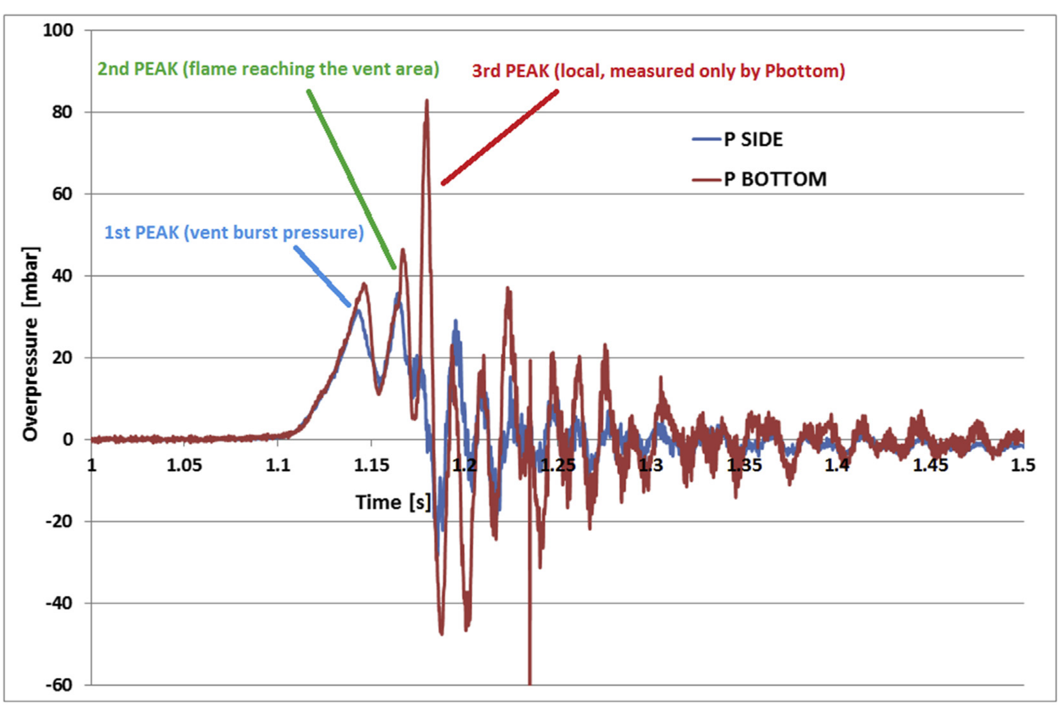

Fig. 8 – Pressure time history of the deflagration in test NHTP28.

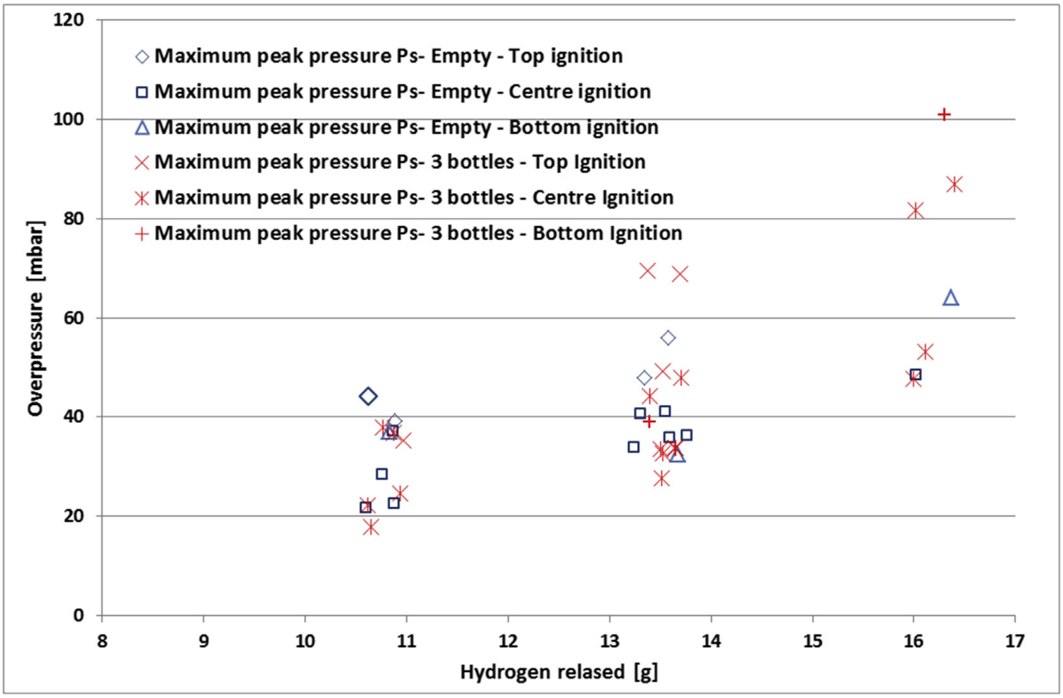

Fig. 9 – Maximum achieved overpressure at P_{bottom} for tests performed with and without obstacles.

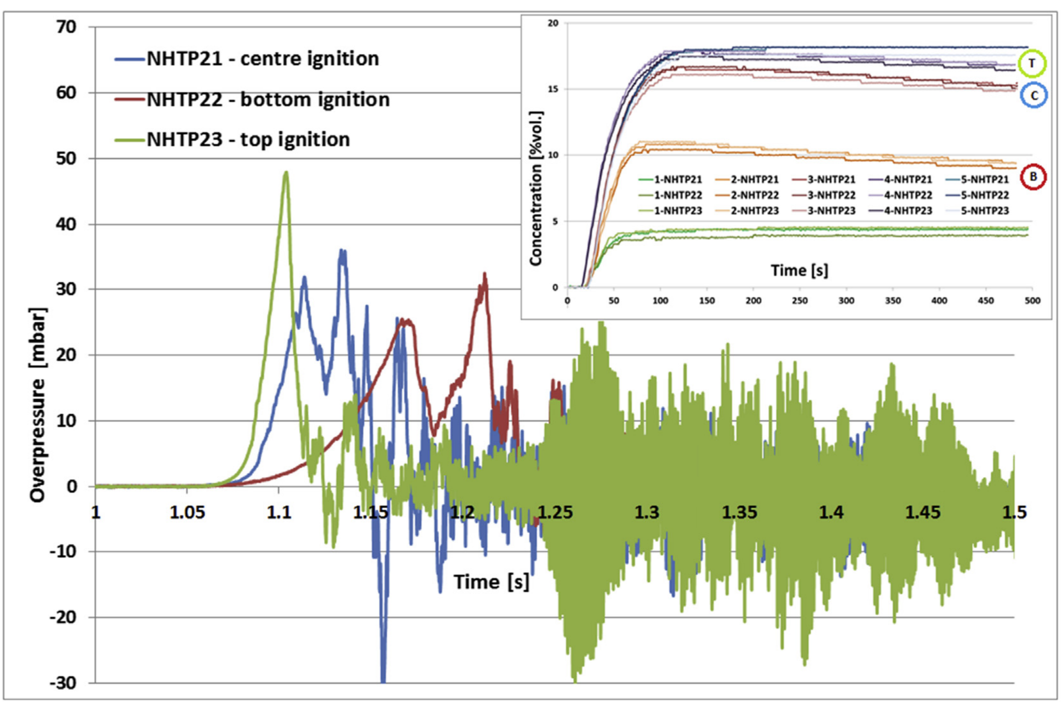

Fig. 10 – Pressure time history of repeated releases ignited in 3 different location (NHTP21-22-23).

locations. The graph in the top right corner shows the concentration time history recorded during the three releases and gives an indication of the concentration at the ignition location. The dependency of the plastic sheet opening pressure with respect to the rate of pressure rise can be also appreciated in the figure.

Top ignition corresponds to a higher concentration and initial burning velocity. Nevertheless, due to the location of the vent, the flame bubble generated from the top ignition reaches the vent as soon as it bursts. This condition prevent the second peak to be generated in this case, see the green pressure time history in Fig. 10.

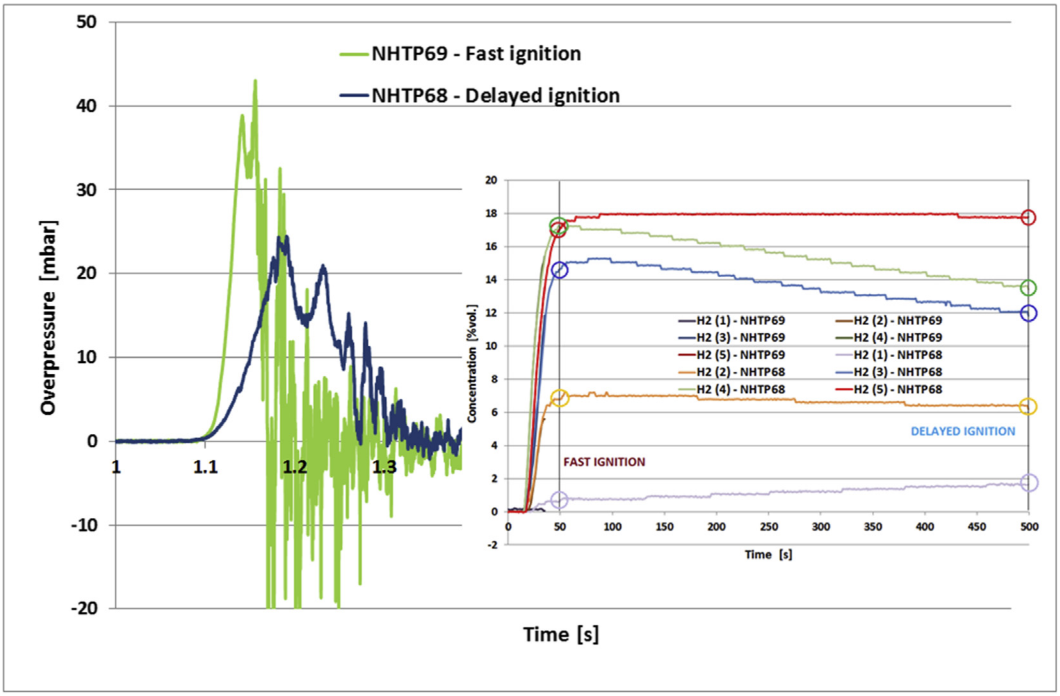

Fig. 11 – Pressure time history for tests NHTP68(stratified release) and NHTP69 ignited at the end of the release.

Effect of the time of ignition

Most of the tests were ignited after considerable time after the end of the release, 6–8 min, to reduce uncertainties on the measurement of hydrogen concentration and to assess the changes in time of the stratification of the released mixture. Nevertheless some tests were repeated in the same condition and ignited 5 s after the end of the release to investigate the effect of the jet self-generated turbulence on the maximum achieved overpressure. Results show as the overpressure developed when the ignition was switched on at the end of the release is higher, as well as faster is the pressure build-up during the first and second peaks. Fig. 11 shows a comparison of the pressure time history of tests NHTP68 and NHTP69 in which the release has been performed in same conditions (nozzle diameter 0.95 mm, upward direction, centre ignition

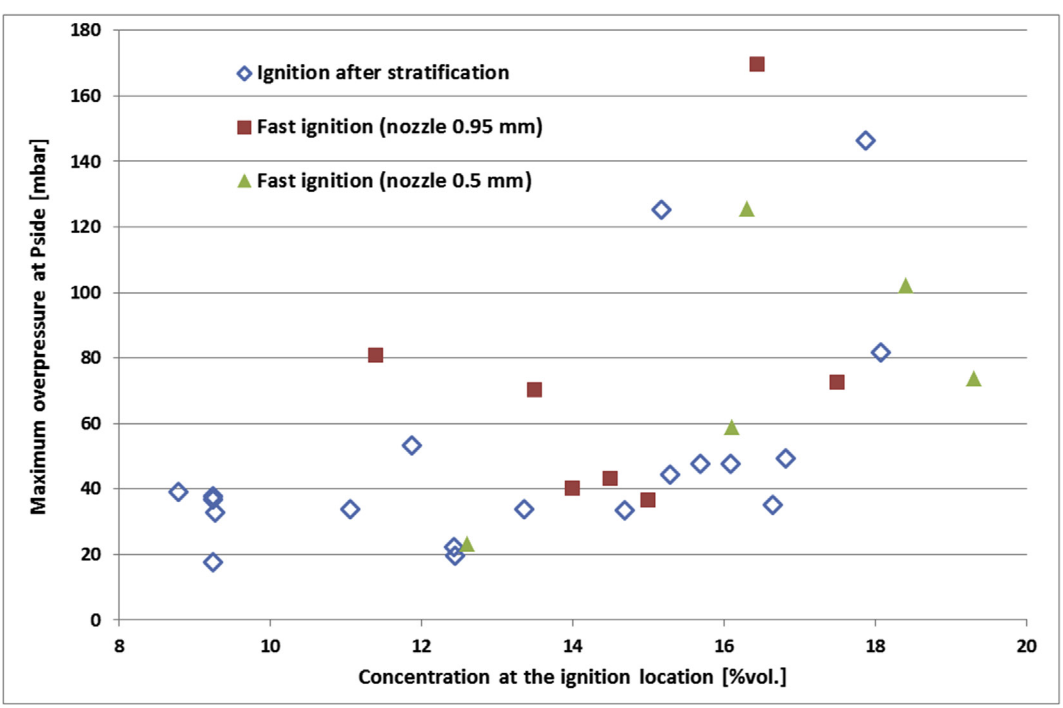

Fig. 12 – Maximum overpressure as a function of the concentration at the ignition location – Fast vs. stratified (3 bottles).

and plastic sheet as a vent). In the first, NHTP68, blue time history in Fig. 11, the ignition was switched on after 500 s, while in the second NHTP69, green time history in Fig. 11, the ignition was switched on 5 s from the end of the release. The image shows also the dependency of the opening pressure of the plastic sheet to the rate of pressure increase, being the first peak higher in the second case. The lower graph in Fig. 11 shows the hydrogen concentration time history during the tests with indication of the concentrations at the time of ignition. Centre ignition correspond to the location of the hydrogen sampling line number 3, (blue line in the graph). The highest overpressure obtained in tests ignited 5 s after the end of the release was found to be originated by the higher concentration at the time of ignition. The same results were confirmed also for tests ignited at top location which is 1.5 m above the floor, 20 mm lower than the axis of the horizontal release and 100 mm higher than the hydrogen sampling line n.4, green line on the concentration time history in Fig. 11.

Fig. 12 shows the maximum overpressure reached in the facility with 3 bottles, comparing tests in which the mixture has been ignited after the stratification with tests in which the ignition was switched on after 5 s from the end of the release. For the latter the estimated concentration at the ignition location has been considered. Information on the dimension of the nozzle are also included. Results show that for both the nozzle diameters the initial turbulence generated by the release is not strong enough to abruptly affect the maximum generated overpressure. The initial turbulence slightly affects the maximum overpressure generated in few tests performed with the bigger nozzle and ignition location close to the release location (top ignition).

Conclusions

The performed high pressure release tests are a more accurate reproduction of a real accident with respect to the deflagrations performed in homogeneous conditions. For the tested releases, results confirmed that the momentum generated by the jet is not capable to produce a homogenization of the mixture inside the 1.14 m^3 enclosure, in both the cases with the empty enclosure and with the 3 bottles.

Hydrogen distribution following an unintended high pressure leak from a system is affected by a series of factors like: initial pressure inside the buffer, leak diameter, leak direction, presence of obstacles on the path of the jet, presence of bottles inside the enclosure. Nevertheless in the presence of the bottles hydrogen is more prone to accumulate in the empty space in the upper part of the enclosure.

The presence of the bottles increased the maximum achieved overpressure only for tests where the hydrogen released was greater than 13 g (maximum concentration inside the facility ranging between 17.5%vol and 20.5%vol in the empty enclosure and between 18%vol and 22%vol with the bottles inside the enclosure). No appreciable differences with the empty enclosure were found for a mass of hydrogen released less than 12 g, (maximum concentration inside the facility ranging between 13.3%vol and 17.6%vol in the empty enclosure and between 15%vol and 21%vol with the bottles inside the enclosure).

The FIKE vent SANI-V, selected during the first experimental campaign involving homogeneous mixtures for its lower dependency of the opening pressure with the pressure rise rate, was extensively tested. Results confirm an opening pressure close to the higher value reported on the plate data when the pressure build up rate is less than 2.5 bar/s, and a linear increase of the opening pressure when rate exceeds 2.5 bar/s.

The comparison between tests ignited after 6–8 min, and tests with the same release characteristics ignited 5 s from the end of the release shows that the overpressure achieved during tests with fast ignition is always higher than the overpressure generated in the tests where the ignition was switched on after several minutes. Nevertheless results are more dependent on the changes in hydrogen concentration at the ignition location than on the initial turbulence generated by the release. This may be due to the small size of the orifices selected for this study which generate turbulence only close to the nozzle.

Tests also confirmed that locating the vent in the roof of an enclosure is the most efficient way to vent hydrogen mixtures in real applications since the mixture at higher concentration accumulated under the canopy has better chance to be vented outside before participating to the combustion.

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