HOMOGENEOUS AND INHOMOGENEOUS HYDROGEN DEFLAGRATIONS IN 25 m^3 ENCLOSURE

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ABSTRACT

Explosion venting is a frequently used measure to mitigate the consequence of gas deflagrations in closed environments. Despite the effort to predict the vent area needed to achieved the protection through engineering formulas and CFD tools, work has still to be done to reliably predict the outcome of a vented gas explosion. Most of available data derived from experimental campaigns performed in the past involved homogeneous conditions, while, especially in the case of a very buoyant gas such as hydrogen, the most probable scenario that can follow and unintended release in a closed environment foresee the ignition of a stratified inhomogeneous mixture. University of Pisa performed experimental tests in a 25 m^3 facility in homogeneous and inhomogeneous conditions. The present paper is aimed to share the results of hydrogen dispersion and deflagration tests and discuss the comparison of maximum peak overpressure generated in the two scenarios. Description of the experimental set-up includes all the details deemed necessary to reproduce the phenomenon with a CFD tool.

1.0 INTRODUCTION

Explosion venting is a frequently used measure for mitigating the consequences of hydrogen deflagrations in confined enclosure.

Due to the high buoyancy of hydrogen, most of the real accidents that follow an unintended release 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 conducted in highly idealized conditions. Particularly, apart from a few experimental campaigns[1, 2], most tests were performed in homogeneous mixture. Furthermore few experimental campaigns were performed accounting for the presence of obstacles [3, 4, 5]. Recently, in the HySEA project, experimental campaigns were conducted in 12 foot ISO-containers by GexCon [6, 7] and in a small scale enclosure by University of Pisa, investigating both homogeneous than stratified mixtures in real volume applications with and without the presence of obstacles [8]. In those experimental campaigns most of the tests were performed venting through the roof.

Results from the small scale enclosure experimental campaign include a comparison of maximum peak overpressure achieved in homogeneous and inhomogeneous conditions [9]. For the empty enclosure results show that the maximum peak overpressure is higher in the inhomogeneous conditions for the same amount of hydrogen released. Instead homogenous mixture having average concentration equal to the higher measured concentration in inhomogeneous tests produce higher overpressures.

In order to provide more data to the scientific community and to the developers of CFD tools the present paper describes a series of experimental tests of hydrogen release and deflagration in a 25 m^3 enclosure.

Tests have been performed with different vent areas and vent cover opening pressure in homogenous and non-homogenous conditions. Results obtained from homogenous and inhomogeneous deflagration are compared.

2.0 EXPERIMENTAL SET UP

The CVE (Chamber View Explosion), see figure 1, is a nearly cubic structure characterized by an internal volume of about 25 m^3; the roof and one side face are entirely covered with glass panels. All other faces are covered with steel panels having different functions. The bottom and the side opposite the glass one are entirely made of steel strengthened panels which are not removable, while the other two lateral faces, on opposite sides, are the test vent and the safety vent respectively. The design pressure of the test facility is 35 kPa, while the safety vent has been designed to open at 30 kPa, which determines the maximum allowed internal pressure's peak.

The tests presented in this paper were conducted with 5 different vent areas, namely 0.7, 1.15, 1.5, 2 and 2.5 m^2. Two different vent cover were tested, both of them plastic sheet of different thicknesses. Tests were performed in homogeneous and non-homogenous conditions.

Hydrogen was released from a pipe placed in the middle of the floor, diameter of the pipe being ¾ of an inch, a metal sponge was placed on top of the pipe to help the dispersion of the gas. In homogenous tests, during the release, the concentration has been homogenized using a fan. The fan was then turned off at least 30 seconds before the ignition to limit the initial turbulence inside the enclosure. Since the roof of the enclosure was made of glass panels, during sunny days the heating caused by solar radiation produced an air convective movement which was affecting to some extent the stratification of hydrogen during non-homogenous tests.

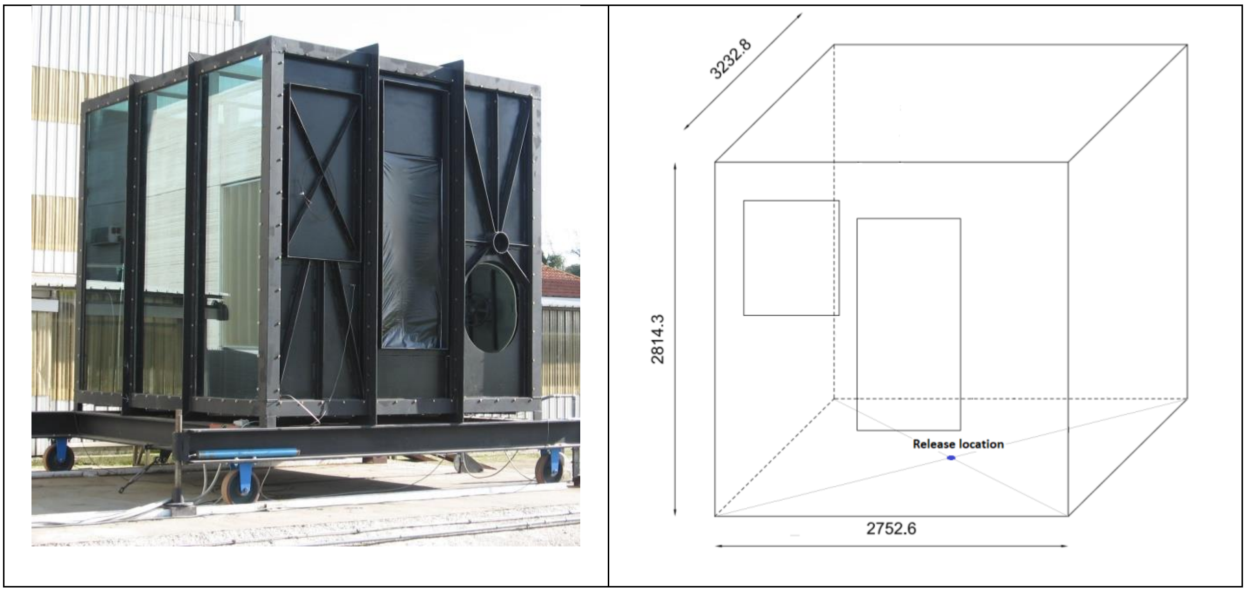

Figure 1 – Picture of the CVE test facility (left) and dimensions [mm] (right)

During the release of hydrogen the following parameters were recorded:

- Hydrogen bottles pressure and temperature,
- Hydrogen mass flow rate
- Hydrogen concentration in 5 different location inside the enclosure.

Internal atmosphere was sampled in 5 location and analysed by MSA concentration analysers having a measurement range 0-20% vol., data were recorded at 1Hz frequency. Three of the sampling lines were located on the centreline of the enclosure at different heights, 2 of the sampling lines were located on the sides of the facility to check distribution of hydrogen on planes at the same height, see Figure 2. Concentrations listed in table 1 for inhomogeneous tests are referred to the three sampling location on the centreline of the facility placed at 0.2m, 1.36m and 2.58m above the floor respectively.

Figure 2 shows the ignition location, the pressure transducer location and the hydrogen concentration sampling locations.

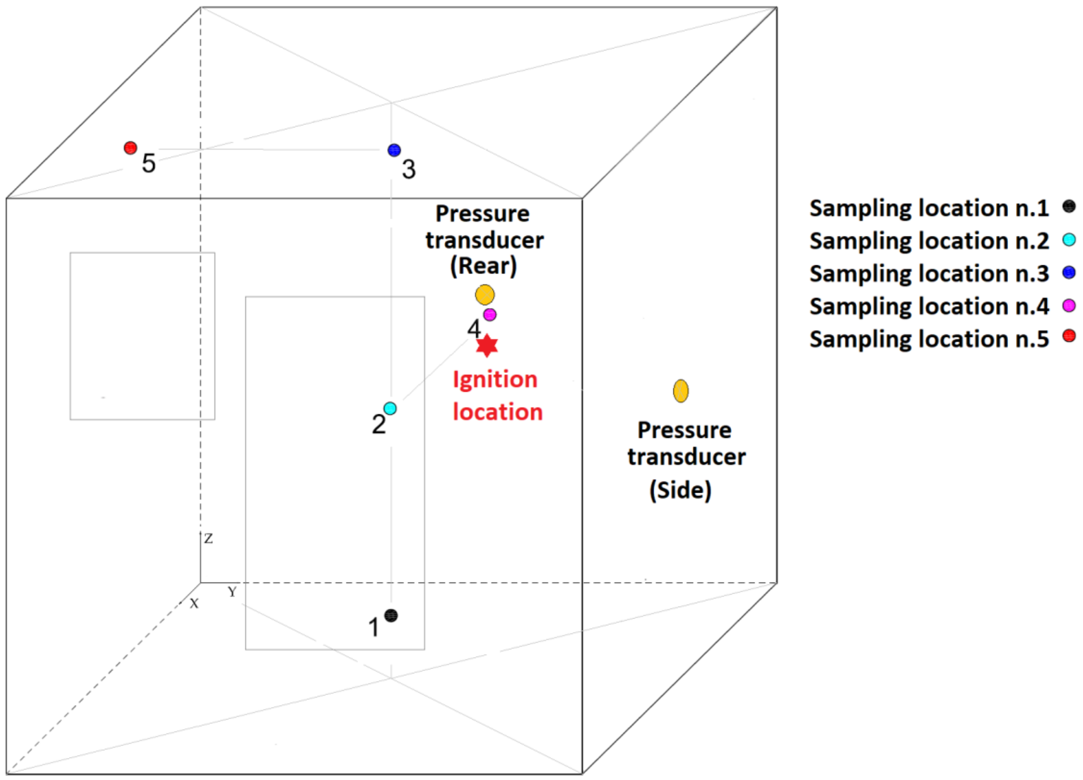

Figure 2 – Ignition, pressure transducers and internal atmosphere sampling locations

Table 1 lists the concentration sampling location coordinates, reference system being shown in figure 2.

Table 2. Concentration sampling location coordinates.

Concentration sampling point coordinates [mm]			
N.	X	Y	Z
1	1700	1440	200
2	1700	1440	1360
3	1700	1440	2580
4	190	1450	1380
5	1700	200	2580

Four different vent areas were tested, 0.7, 1.15, 1.5 and 2 m^2. Figure 3 shows the vent location and dimension for all the tested configurations.

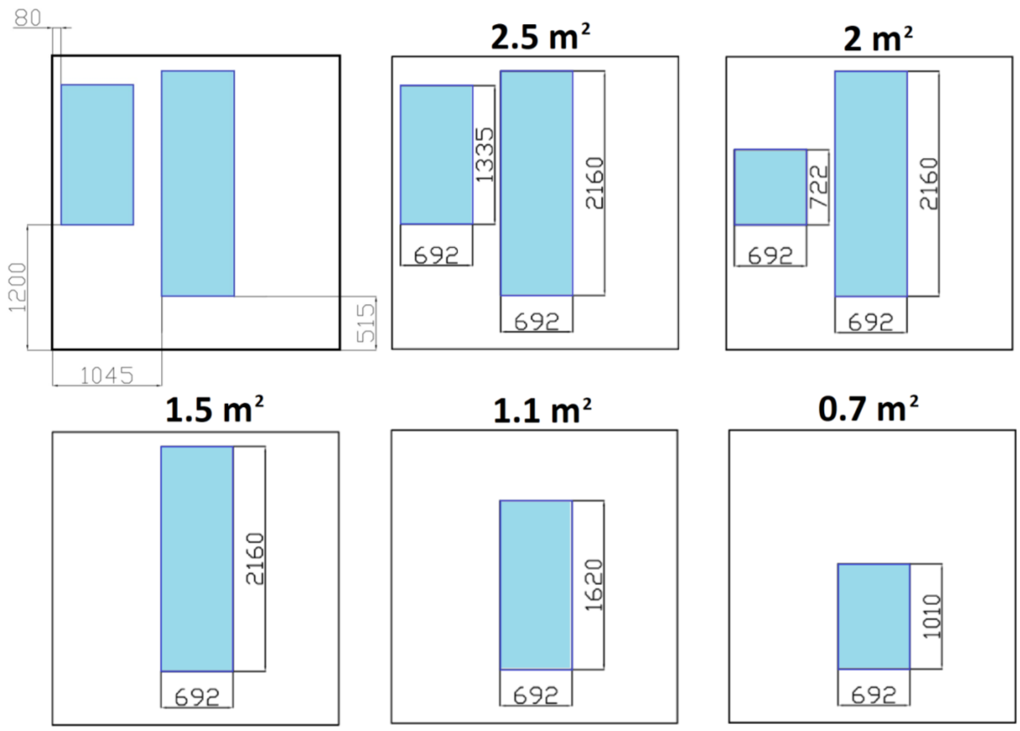

Figure 3 – Vent location and dimensions [mm]

The ignition system consisted of an electrode connected to a remote driven circuit and designed to prevent accidental sparks. For all the tests included in this paper the ignition was located in the middle of the wall opposite the vent area. Table 2 lists the ignition coordinates, the reference system being shown in figure 2.

Table 2. Ignition coordinates, reference .

Ignition coordinates [mm]			
N.	X	Y	Z
1	20	1450	1060

Time of ignition was set 2 seconds after the first recorded data in the acquisition system, pressure time history will be presented in time range 2-4 seconds, where the origin of the graphs will represent the time at which the ignition was given. Overpressure inside the enclosure was measured by two pressure transducer. One pressure transducer was located in the middle of the wall opposite the vent (Rear), the second was located in the middle of the lateral wall opposite the glass one (Side). During the deflagration pressure data were recorded at a frequency of 5 KHz.

Table 3 lists the tests included in this paper. Total mass of hydrogen released, mass flow rate and internal temperature of the enclosure are provided. High temperature of the enclosure characterize those tests were the stratification may be affected by the internal recirculation of air caused by solar radiation. Hydrogen concentration measurement refer to the recording at the time of ignition. Where only one hydrogen concentration is reported instead of the three it indicates that the tests has been performed in homogeneous conditions. Vent type “thin” indicates the thinner plastic sheet, while the vent type “thick” indicates the thicker plastic sheet.

Figure 4 shows the concentration-time history recorded close to the centreline o the enclosure. The recorded concentration in locations at 0.2 and 1.36 m are affected by the proximity of the release cone during the injection of hydrogen inside the enclosure, than they reach the “equilibrium” concentration when the release ends.

Table 3. Lists of experimental tests and H_2 release and distribution characteristics.

Test ID	T_{CVE} [°C]	H_2 released [g]	Flow rate [g/s]	H_2 conc. h=0.2 m	H_2 conc. h= 1.36 m	H_2 conc. h=2.58 m	Vent area [m^2]	Vent type
VAT10	23	253.6	1.8		12,1		2	Thin
VAT23	27	188	1.07	0.4	10.8	13.7	1.5	Thin
VAT24	28	198	0.88	0.8	11.4	14.4	1.5	Thin
VAT25	25	230	0.9	0.6	13.2	16.1	1.5	Thin
VAT26	31	186	0.85	0.4	10.8	13.7	1.5	Thick
VAT27	29	184	0.85	0.2	10.6	13.9	1.5	Thick
VAT28	32	204	0.9	0.4	11.6	14.9	1.5	Thick
VAT30	15	236	0.3		11		2.5	Thick
VAT31	14	242	0.6	0.8	13	15.2	2.5	Thick
VAT33	19	200	0.65		9.3		1.5	Thick
VAT34	19	200	0.7	0.4	11	13.8	1.5	Thick
VAT35	18	240	0.75	0.4	13	15.6	1.5	Thick
VAT36	29	251.2	0.61		12.0		1.5	Thick
VAT37	33	251.4	0.71	0.6	14.2	16.5	1.5	Thick
VAT38	29	253.2	0.75		12.0		1.5	Thin
VAT39	33	260	0.77	0.6	14.4	16.8	1.5	Thin
VAT40	24	261	0.61		12.1		1.1	Thin
VAT41	25	255.6	0.63	1	14	16.7	1.1	Thin
VAT42	27	245.2	0.88		12.1		1.1	Thick
VAT43	30	257	0.7	1.4	14.4	16.8	1.1	Thick
VAT44	33	165	0.61	0.6	9.8	12.3	0.7	Thin
VAT45	34	255	0.75		12.6		0.7	Thin
VAT46	34	239	0.83		12		0.7	Thin
VAT48	46	162	0.81	0.4	9.2	11.9	0.7	Thick
VAT49	29	205	0.9		10.4		0.7	Thin
VAT50	30	206	0.865	1.4	10.8	14.1	0.7	Thin
VAT51	35	200	0.885		10.4		0.7	Thick
VAT52	25	201.5	0.71	6.6	10.4	13.2	0.7	Thick

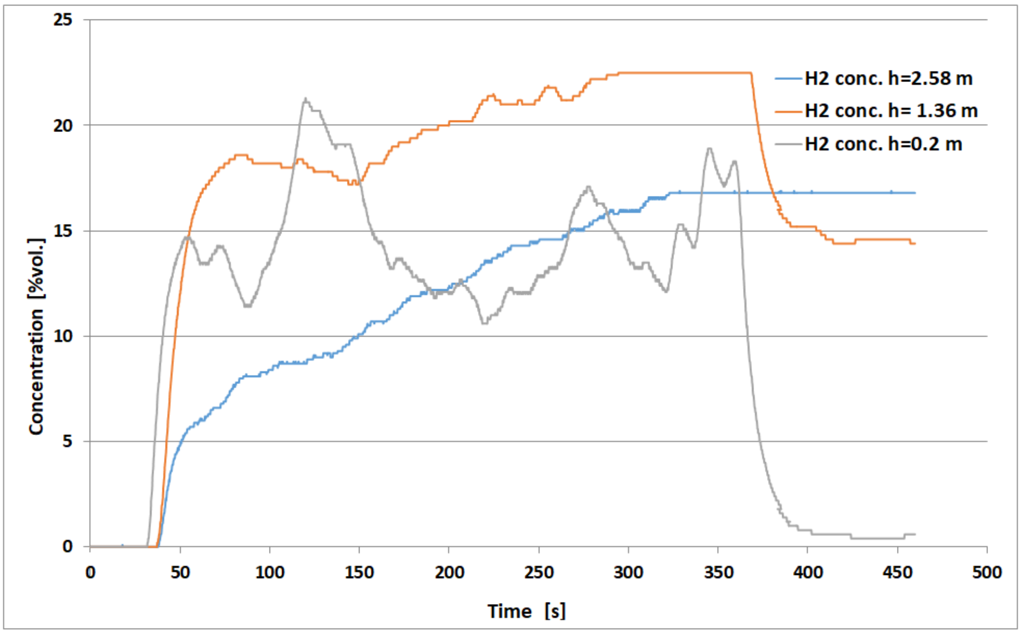

Figure 4 – Concentration time history on the sampling location along the centreline

3.0 RESULTS AND DISCUSSION

In table 4 the results of the tests included in this paper are listed. Where the maximum peak overpressure is not indicated the vent opening pressure corresponds to the maximum achieved overpressure during the deflagration. Since some of the tests presented strong oscillation due to flame acoustic interaction the indicated maximum peak overpressure has been taken from the filtered pressure time history.

Table 4. Lists of experimental tests and measured peak overpressure.

Test ID	Vent opening pressure [kPa]	Maximum peak overpressure [kPa]
VAT10	1.8	--
VAT23	1.8	1.9
VAT24	1.9	2.1
VAT25	2.3	4.7
VAT26	6.3	--
VAT27	6.7	--
VAT28	6.2	--
VAT30	7.3	--
VAT31	6.0	--
VAT33	6.1	--
VAT34	7.6	--
VAT35	8.3	--
VAT36	6.8	--
VAT37	7.5	--
VAT38	1.6	2.0
VAT39	1.9	6.0
VAT40	2.0	4.9
VAT41	2.1	8.0
VAT42	7.5	--
VAT43	7.0	--
VAT44	2.0	2.7
VAT45	2.3	12.4
VAT46	2.2	9.5
VAT48	6.9	--
VAT49	2.0	2.1
VAT50	2.0	5.3
VAT51	7.0	--
VAT52	7.5	--

The pressure-time curves show a first pressure peak, correspondent to the vent opening pressure, then a second peak which is generated when the flame front reaches the vent. Either the discontinuity in the flow rate through the vent area or the external explosion being responsible of the pressure peak in this case. Pressure acoustic oscillation generated by the interaction of the physical response of the structure with the flame front are present in the last stage of the deflagration. Flame acoustic interaction produce a third peak, never dominant in the tested geometry. Nevertheless in some tests, the third peak superimpose to the second peak. The superimposition of the second peak with the "third" peak generated by flame acoustic interaction has been experienced in this facility in homogenous mixtures and discussed in previous papers [3].

In the range of concentration under investigation the thinner plastic sheet showed a range of opening pressures between 1.8 and 2.3 kPa while the thicker plastic sheet showed an opening pressure between 6 and 7.5 kPa. Vent opening pressure of the plastic sheets being affected by both the vent dimension and rate of pressure build up inside the enclosure. Generally the smallest the vent dimension the higher the opening pressure while higher rates of pressure build up correspond to higher vent opening pressures.

In the present experimental campaign, for all the tests in which the second peak is higher than the vent opening peak, the maximum achieved overpressure increased consistently with increasing mass of hydrogen released for all the vent configurations. This is reasonable since all the tests involved lean hydrogen mixtures.

In the range of mass of hydrogen released and vent dimension under investigation the maximum peak pressure obtained when using the thicker plastic sheet as a vent cover is always limited to the vent opening pressure. In these tests the second peak was present, see red curve in figure 5, but its maximum overpressure never exceeded the vent opening pressure.

Figure 5 show the pressure time history obtained for non-homogenous tests performed in the same conditions but with different vent opening pressure. In test VAT41 the amount of hydrogen release was 255.6 g, and the recorded concentration were 1%vol. at .2m above the floor, 14%vol. at 1.36 m and 16.7%vol. at 2.58 m. In test VAT43 the amount of hydrogen release was 257 g, and the recorded concentration were 1.4%vol. at .2m above the floor, 14.4%vol. at 1.36 m and 16.8%vol. at 2.58 m.

The maximum peak pressure obtained using a thinner vent cover having lower opening pressure is higher than the maximum peak pressure obtained using a thicker vent cover characterized by higher opening pressure. The venting process is a dynamic phenomenon and the acceleration towards the vent area provoked by the flow field generated after the vent opening, which depending on the position of the flame front at the time of opening and the opening pressure, may affect the magnitude of the second peak. When the vent cover opens early, the flame front has more time and space to be accelerated until it reaches the vent area, when the vent cover opens at higher pressure the “flame bubble” is closer to the vent area when the vent opens, the lower space and time available for a flame front to accelerate towards the vent area may be responsible for the lower second pressure peak.

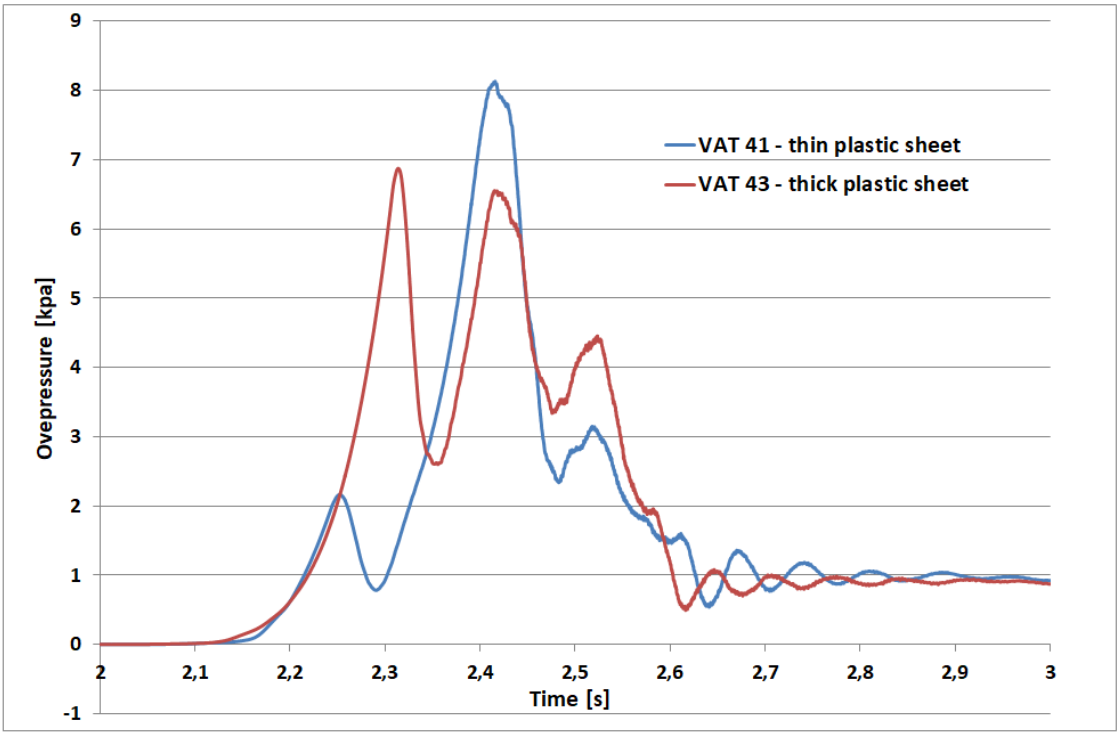

Figure 5 – Filtered pressure time history of tests performed in the same conditions but the vent thickness

Figure 5 shows also that a third minor peak that may be present in some of the tests at higher concentration or mass of hydrogen released, usually generated by flame acoustic interactions.

Concerning the dimension of the vent area, result confirm an increase of maximum peak pressure when decreasing the vent dimension as extensively reported in the literature.

Figure 6 shows the filtered pressure time history of four tests performed in homogeneous condition, 12% hydrogen concentration, with different vent areas. On figure 7 the plot shows the maximum peak pressure obtained for different vent areas. When the vent area is covered with the thin plastic sheet, for a vent area lower than 1.5 m^2 the peak overpressure linearly increase when decreasing the vent area.

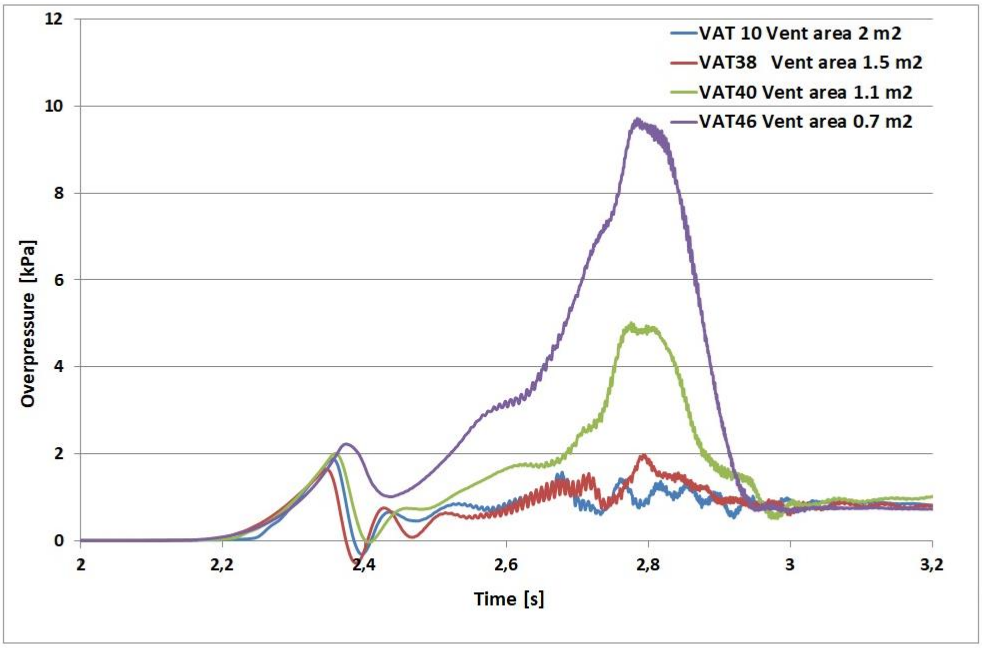

Figure 6 – Comparison of pressure time histories from tests performed in the same condition but the vent area

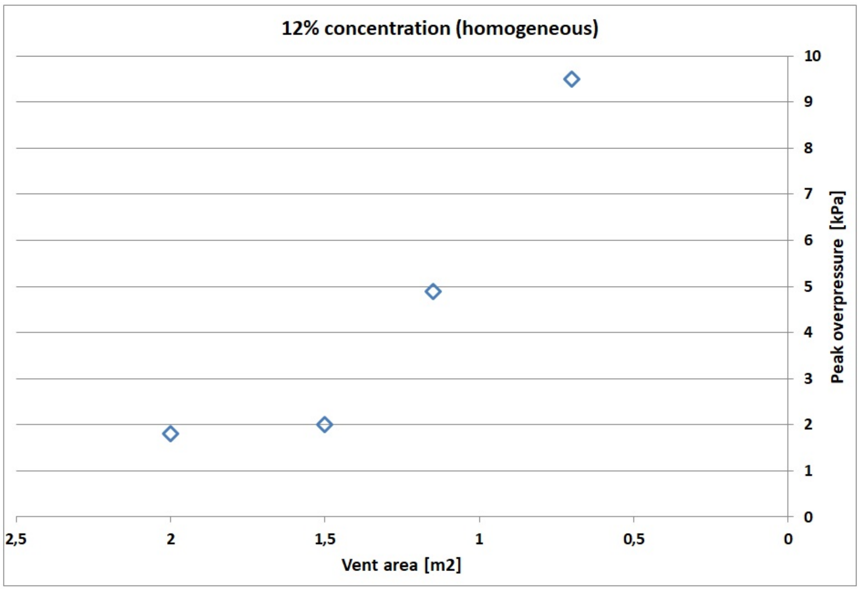

Figure 7 – Peak overpressure for homogeneous deflagrations at 12% hydrogen concentration and different vent areas

Comparison of homogeneous and inhomogeneous tests performed with the same amount of hydrogen released show higher overpressure achieved in inhomogeneous tests.

For the same amount of hydrogen released in inhomogeneous test higher concentrations are accumulated under the canopy, on the top part of the enclosure, even though ignition is always located in the center of the enclosure, were concentrations in inhomogeneous mixture are comparable to the average concentration achieved in the correspondent homogenous mixture for the same amount of hydrogen released. In test 49 and 50, the concentration at ignition location is 10.4%vol in homogeneous and 10.8%vol in inhomogeneous mixtures, but the initial pressure build up during the deflagration of inhomogeneous mixture is much faster than homogeneous mixtures.

Figure 8 shows pressure time histories generated by two tests, homogeneous and inhomogeneous, for which the amount of hydrogen released was about 205 g, which corresponds to an average homogenous concentration of 10.4%vol. Due to the higher concentrations reached close to the roof in inhomogeneous test the initial pressure build-up is faster which in turn provokes an earlier vent opening and an higher acceleration of the flame towards the vent and peak overpressure generated.

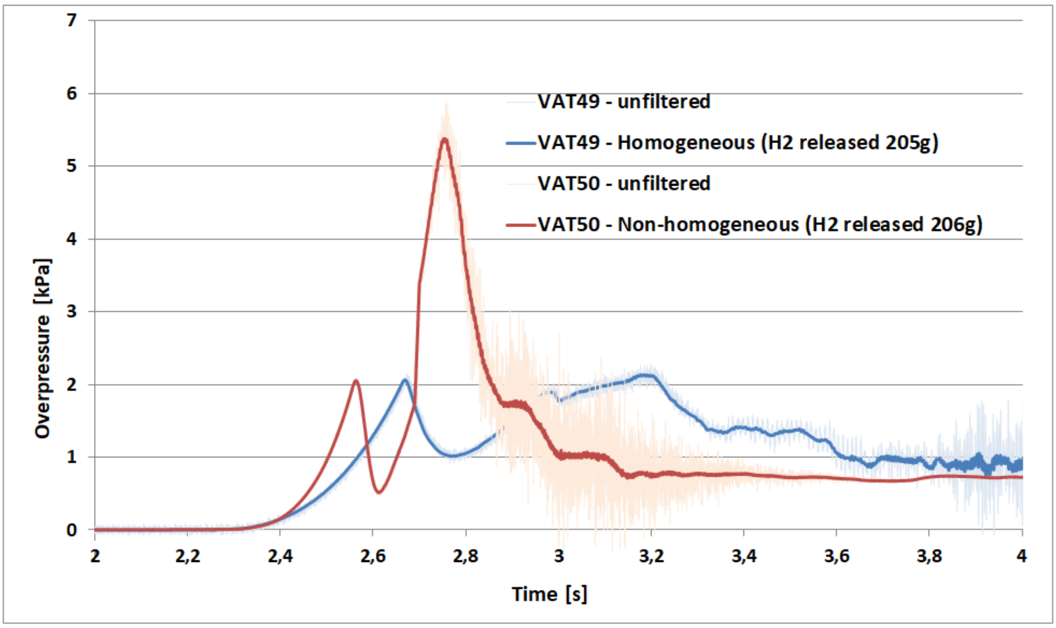

Figure 8– Comparison of tests performed in homogeneous and inhomogeneous condition for the same mass of hydrogen released (equivalent concentration 10.4%vol.)

Figure 9 shows pressure time history generated by a release of about 260 g of hydrogen in homogeneous and inhomogeneous conditions, the amount of hydrogen released corresponding to an average concentration of 12.1%vol. while the maximum recorded concentration in inhomogeneous condition being 16.8%vol.

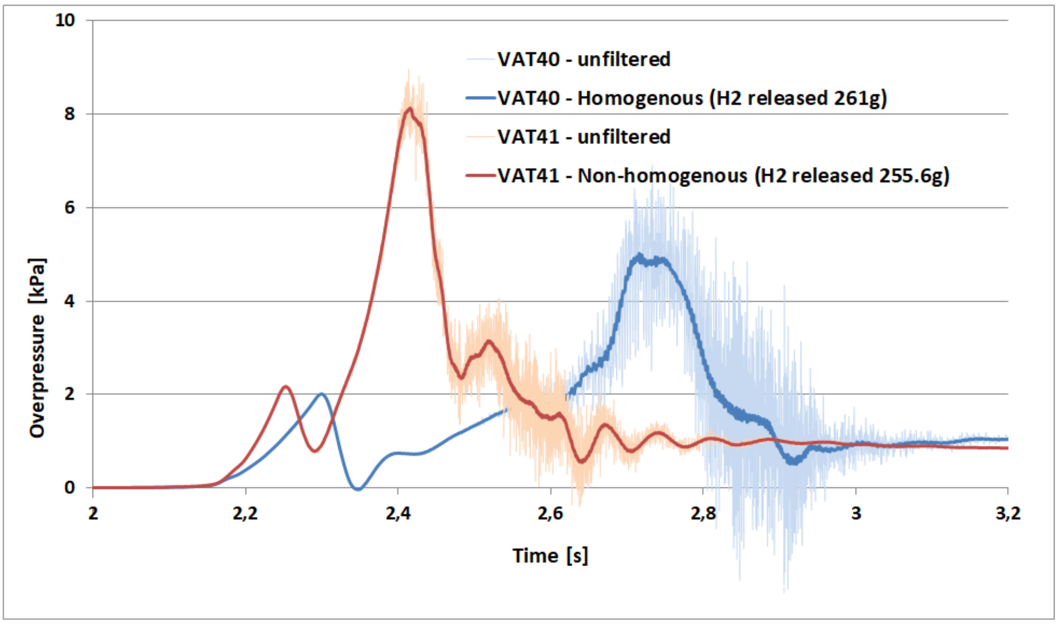

Figure 9 – Comparison of tests performed in homogeneous and inhomogeneous condition for the same mass of hydrogen released (equivalent concentration 12.1%vol.)

Figure 10 shows the maximum achieved overpressure for tests performed with a vent area of 0.7 m^2 covered by the thinner plastic sheet. If compared on the maximum measured concentration, the maximum peak pressure achieved in inhomogeneous conditions is lower than the maximum peak pressure achieved in homogeneous condition.

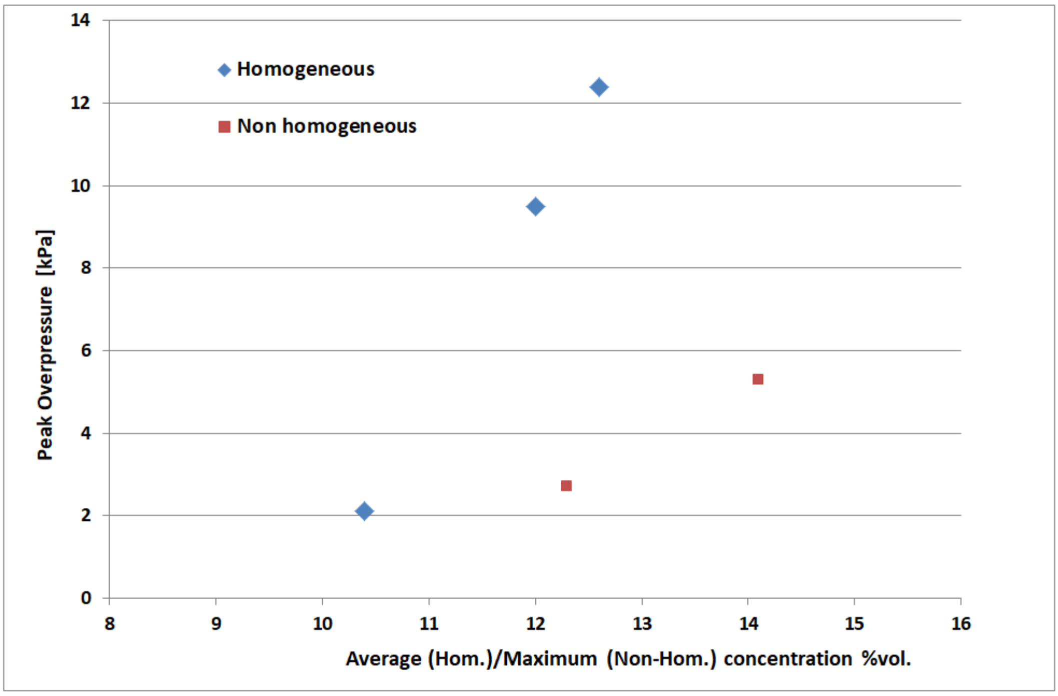

Figure 10 – Comparison of tests performed in homogeneous and inhomogeneous condition for the maximum measured concentration inside the enclosure (vent area 0.7 m^2 – thin vent cover)

4.0 CONCLUSIONS

Experimental deflagration study of lean hydrogen homogeneous and inhomogeneous mixture has been presented for a 25 m^3 volume enclosure with different vents sizes and two different vent covers.

As expected, for smaller the vent size the internal overpressures generated by a deflagrations performed in the same condition are higher.

Results show that, for the same vent size, a lower vent opening pressure can lead to higher generated overpressure with respect to higher vent opening pressure. This behavior can be explained taking into account the turbulence generated by the venting process and the larger path available for the flame front to be accelerated before reaching the vent area after the vent cover in deployed when the vent cover opens earlier.

Inhomogeneous deflagration generate higher overpressure with respect to homogeneous deflagrations performed with the same amount of hydrogen released. Nevertheless deflagration of homogenous mixture having average concentration equal to the higher measured concentration in inhomogeneous tests produce higher overpressures than the inhomogeneous.

Result are presented providing all the detail considered sufficient for modelers to reproduce gas dispersion and deflagration by CFD tools.

REFERENCES

1. M. Kuznetsov, A. Friedrich, G. Stern, N. Kotchourko, S. Jallais, B. L'Hostis, Medium-scale experiments on vented hydrogen deflagration, Journal of Loss Prevention in the Process Industries Volume 36, Pages 416-428 https://doi.org/10.1016/j.jlp.2015.04.013
2. D.Makarov, P.Hooker, M.Kuznetsov, V.Molkov, Deflagrations of localised homogeneous and inhomogeneous hydrogen-air mixtures in enclosures, International Journal of Hydrogen Energy, Volume 43, Issue 20, 17 May 2018, Pages 9848-9869
3. Schiavetti M., Carcassi M. "Maximum overpressure vs. H2 concentration non-monotonic behavior in vented deflagration. Experimental results" International Journal of Hydrogen Energy Volume 42, Issue 11, 16 March 2017, Pages 7494-7503, http://dx.doi.org/10.1016/j.ijhydene.2016.03.180.
4. C.R.Bauwens, J Chao, S.B. Dorofeev, Effect of hydrogen concentration on vented explosion overpressures from lean hydrogen–air deflagrations, International Journal of Hydrogen Energy, Volume 37, Issue 22, November 2012, Pages 17599-17605, https://doi.org/10.1016/j.ijhydene.2012.04.053.
5. L.C.Shirvill, T.A.Roberts, M.Royle, D.B. Willoughby, P.Sathiahd, Effects of congestion and confining walls on turbulent deflagrations in a hydrogen storage facility-part 1: Experimental study, International Journal of Hydrogen Energy, Volume 43, Issue 15, Pages 7618-7642, https://doi.org/10.1016/j.ijhydene.2018.02.135.
6. Skjold, et al. (2017). Experimental investigation of vented hydrogen deflagrations in containers – Phase 1: Homogeneous mixtures. Report HySEA-D2-04-2017, July 2017: 304 pp.
7. Skjold, et al. (2019). Vented deflagrations in containers: Effect of congestion for homogeneous and inhomogeneous mixtures, International Journal of Hydrogen Energy, Volume 44, Issue 17, Pages 8819-8832. https://doi.org/10.1016/j.ijhydene.2018.10.010
8. Skjold, et al. (2017). Influence of congestion on vented hydrogen deflagrations in 20-foot ISO containers: homogeneous fuel-air mixtures. Twenty-Sixth International Colloquium on the Dynamics of Explosions and Reactive Systems (26 ICDERS), Boston, 30 July – 4 August 2017.
9. Schiavetti M., Pini T., Carcassi M. "Comparison of experimental tests on hydrogen deflagration in homogeneous and non-homogenous condition" The International Symposium of Hydrogen Fire Explosion and Safety Standard (ISHFESS 2018), July 6-8 2018 Hefei, China