NON-MONOTONIC OVERPRESSURE vs. H_2 CONCENTRATION BEHAVOIUR DURING VENTED DEFLAGRATION. EXPERIMENTAL RESULTS

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ABSTRACT

In industrial buildings explosion relief panels or doors are often used to reduce damages caused by gas explosion. Decades of research produced a significant contribution to the understanding of the phenomena aiming at establish an effective method by which the explosive overpressure could be reliably predicted. All the methods predict a monotonic increase of the overpressure with the concentration of the gas in the range from the lower explosion limit to the stoichiometric one. Nevertheless in few cases a non-monotonic behaviour of the maximum developed pressure as a function of hydrogen concentration was reported in the literature. The non-monotonic behaviour was also observed during experimental tests performed at the Scalbatraio laboratory at the University of Pisa, in a 25m^3 vented combustion test facility, with a vent area of 1,12m^2. This paper is aimed to present the results obtained during the tests and to investigate the possible explanation of the phenomenon.

Key words: Hydrogen, Vent, Deflagration

1. INTRODUCTION

A deflagration essentially involves an unsteady premixed flame front that develops from an ignition source and travels through a medium which may involve complex boundary conditions and obstruction of various geometries, generating an overpressure that can cause damages to personnel and structures. Venting is normally the less expensive protection method against deflagration and the appropriate design of the vent area is the key problem. In assessing plant safety, it is critical therefore, to provide correct estimates of the overpressures which may result from various deflagration scenarios.

The study of confined vented deflagrations is a very complex topic as many parameters affect the phenomena, i.e.: inhomogeneous concentration of the gas in the environment, volume’s geometry, presence of obstacles within the environment, location, size and strength of the vent, position of the ignition source, pre-ignition turbulence, etc. For hydrogen deflagration the turbulence created by the venting process and/or induced by the flow of unburnt fuel over and around obstacles has been generally acknowledged as being a major factor in the development of explosion overpressure, nevertheless the literature reports poor number of experiments with quantitative measurement of the phenomena [1,2,3,8,11].

Extensive research performed in the previous century produced a significant contribution to the understanding of the vented gas explosion in empty rooms. Harris [13] showed that the pressure as function of time can be described in terms of four distinct pressure peaks which can, but do not have to, occur (four peak model). Each peak is produced by different physical processes at successive stages during a vented explosion; the four peaks are (see Figure 1):

1. P1: The first peak is associated with the pressure drop following the removal of the explosion relief panel and subsequent venting of the unburned gases. Before the vent opens, the pressure increase is caused by the production of hot combustion products generated by the flame front travelling at the flame speed S_f. The pressure in the room is equalized by compression waves travelling at sound speed and reflecting from the walls of the room, thus, at any moment the internal pressure will be the same through the room. When the vent is removed the pressure drops generating the first peak and provoking the vent of the unburned gases and hence inducing a flow field through the vented

volume. The first peak is often followed by Helmholtz oscillation that eventually decay as the flame continues to expand.

2. P2: The second peak occurs when the flame front reaches the vent. If the vent opens early the flame front radius r_f keep increasing during a significant time after the first peak. The rate of volume generated, increased by the interaction with the turbulent flow field generated by the vent opening, become soon larger than the outflow rate, and, consequently, the internal pressure start to rise. The pressure rises until the flame front reaches the vent. When the vent is fully open the flow of gases can be calculated by the formula [13]:

$$\frac{dV}{dt} = C_d \cdot A_v \cdot \left(\frac{2\Delta P}{\rho}\right)^{\frac{1}{2}}$$

Thus a first explanation to the second pressure peak suggested that when the hot combustion products start to flow out of the vent, their density being the density of the unburned mixture divided by the expansion factor E, the outflow rate is suddenly increased by a factor $E^{1/2}$ and the outflow rate becomes again larger than the rate of volume generation, hence resulting in the second pressure peak.

However the second pressure peak may also be caused, as stated by many authors, by the external explosion caused by the ignition of the previously vented unburned mixture by the flame emerging from the vent. The unburned mixture released through the vent forms a not fully developed turbulent momentum jet, with a vortex ring at its head, consequently when the flame front emerges from the vent it proceeds to propagate in a highly turbulent flow triggering the so called external explosion which creates a back pressure at the vent that results in an higher internal pressure during the external explosion.

3. P3: The third pressure peak is caused by the reduction of the flame front area towards the end of the explosion when it reaches the walls, the flame front area has been increasing constantly until this moment, the flame front continues to propagate in the isolated pockets of unburned mixture while its area is decreasing. The third peak, caused by the decrease of the combustion products generation, usually is not the dominant one. (In the tests performed in the CVE facility with hydrogen, this peak is generated only at very lean concentrations, typically less than 9%).

4. P4: The fourth pressure peak is an oscillatory pressure peak attributed to coupling of the pressure waves generated in the combustion with the acoustic resonances in the gaseous combustion product within the room. It appears that this peak is controlled by resonant coupling between the flame and the physical response of the enclosure [14,15]. The pressure oscillations induce a cellular structure in the flame front, giving rise to very high combustion rates and creating a significant net overpressure within the vented volume. The fourth pressure peaks as the third one reaches its maximum amplitude when the flame reaches the walls, it may be the case that the two peaks are generated by the same causes, flame reaching the maximum area, with the only difference being the interaction of the flame front with acoustic oscillation.

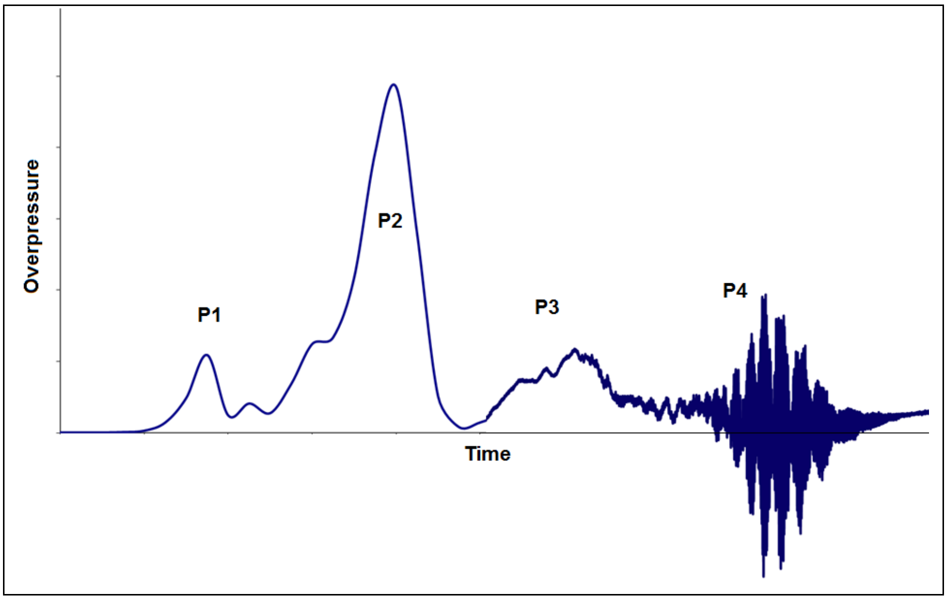


Figure 3 – Idealized pressure time history in vented explosion showing the four peaks

Based on the results obtained by the experiments, usually performed without internal obstacles, a large number of equations have been derived [5,6,7], which prediction ability had been compared [6,8]. However correspondence between predicted pressure history and experimental results still owes more to adjustable model parameters than to an exact understanding of the physics involved.

The CVE (*Chambre View Explosion*) experimental facility [9] was built at the "Scalbatraio" laboratory owned by DICI department of University of Pisa to study the confined vented explosion phenomena in real environments. With the purpose of contributing to collect experimental data, several experimental campaign of vented deflagration were performed with the presence of internal obstacles of various shapes [3,12]. In this paper some of the results will be reviewed in order to focus the attention on a non-monotonic behaviour of the developed pressure as a function of the concentration.

2. EXPERIMENTAL SET-UP

The CVE (Chamber View Explosion) apparatus is a nearly cubic structure characterized by an internal volume of about 25 m3; the roof and one side face are entirely covered with panels of glass which allow to video record the flame. All other sides are covered with steel panels having different functions. The bottom and one side faces 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 [2,3].

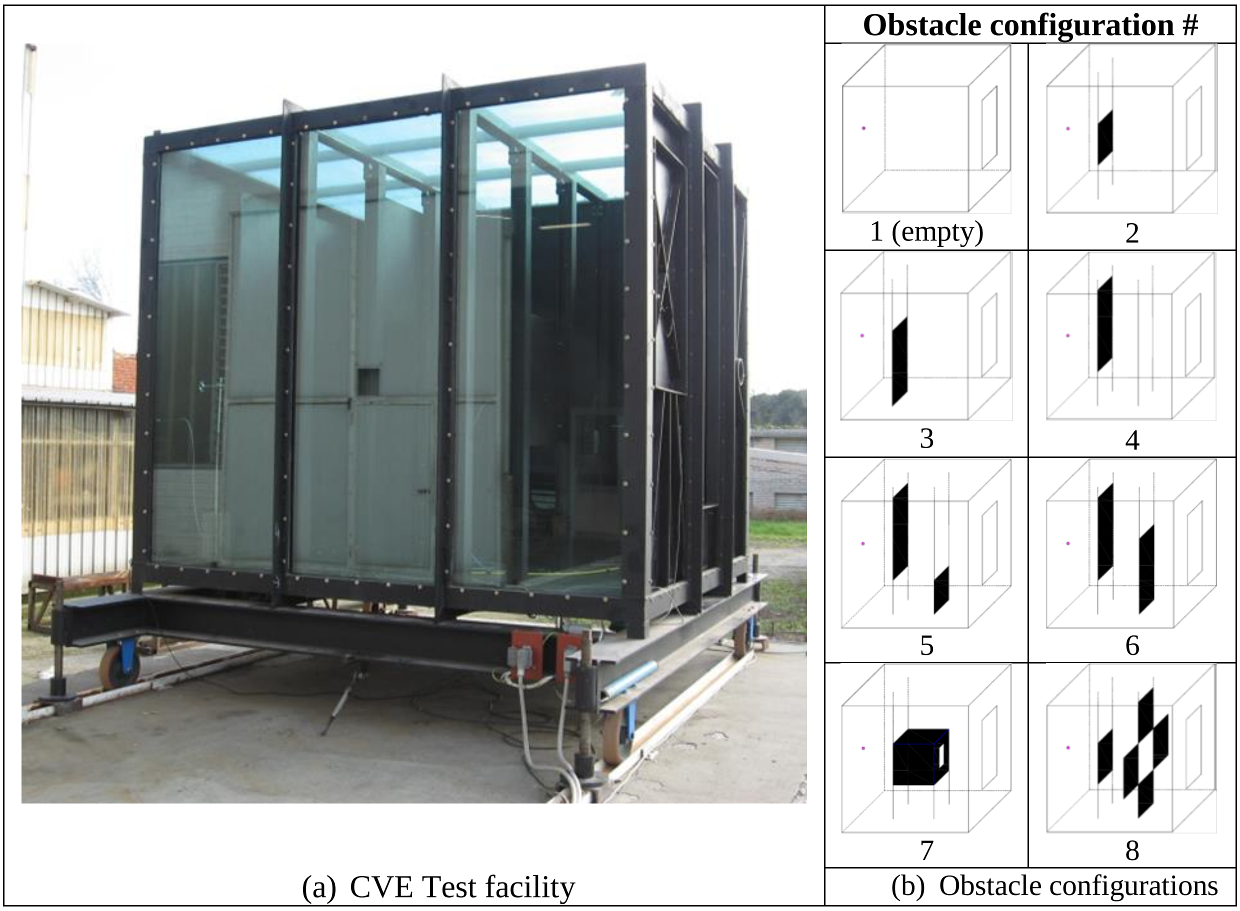


Figure 2 – (a) Photo of the CVE test facility and (b) internal obstacle configurations

CVE has been built in order to perform vented deflagration tests. The design pressure of the test facility is 350 mbar (35 kPa), while the safety vent has been designed to open at 300 mbar (30 kPa), which determines the maximum allowed internal pressure's peak value [9]. In the experimental campaigns which results are presented in this paper the vent dimensions were kept fixed and characterized by a width of 0,62 m and an height of 1,62 m (vent area 1,004 m^2). The vent area was closed with a plastic sheet characterized by an opening pressure of approximately 2.4 kPa.

Inside the CVE test facility different kind of obstacles had been placed (see Figure 2b) while the hydrogen concentration under investigation ranged between 7%vol. and 13% vol.

During the release of hydrogen inside the experimental facility the concentration has been homogenized in through the use of a fan, at the end of the release phase the fan was turned off conveniently earlier in respect to the ignition in order to prevent initial turbulence inside the vented volume. Despite of the fan, hydrogen concentration showed a stratification behavior inside the facility, with lower concentration at the bottom and higher concentration under the facility ceiling, the difference of concentrations measured between the lower and the upper sampling points was about 1,5 %vol. in every tests. Results will be presented considering the average concentration measured inside the facility in 5 different location at different heights from the floor to the ceiling.

For all the tests analysed in this paper the ignition was placed in the middle of the CVE's wall opposite to the vent at 1 m high from the floor, and it was connected to a remote driven circuit and designed to prevent accidental sparks.

Pressure transducer were placed in the centre of the wall opposite the vent and in the centre of the wall opposite the glass one. Pressure readings were recorded at with a frequency of 5 kHz.

3. RESULTS AND DISCUSSION

Results in terms of maximum overpressure measured inside the vented volume are listed in Table 1 for 92 selected tests.

Figure 3 shows the maximum peak overpressure attained in the CVE test facility as a function of average hydrogen concentration for all the tests included in this paper.

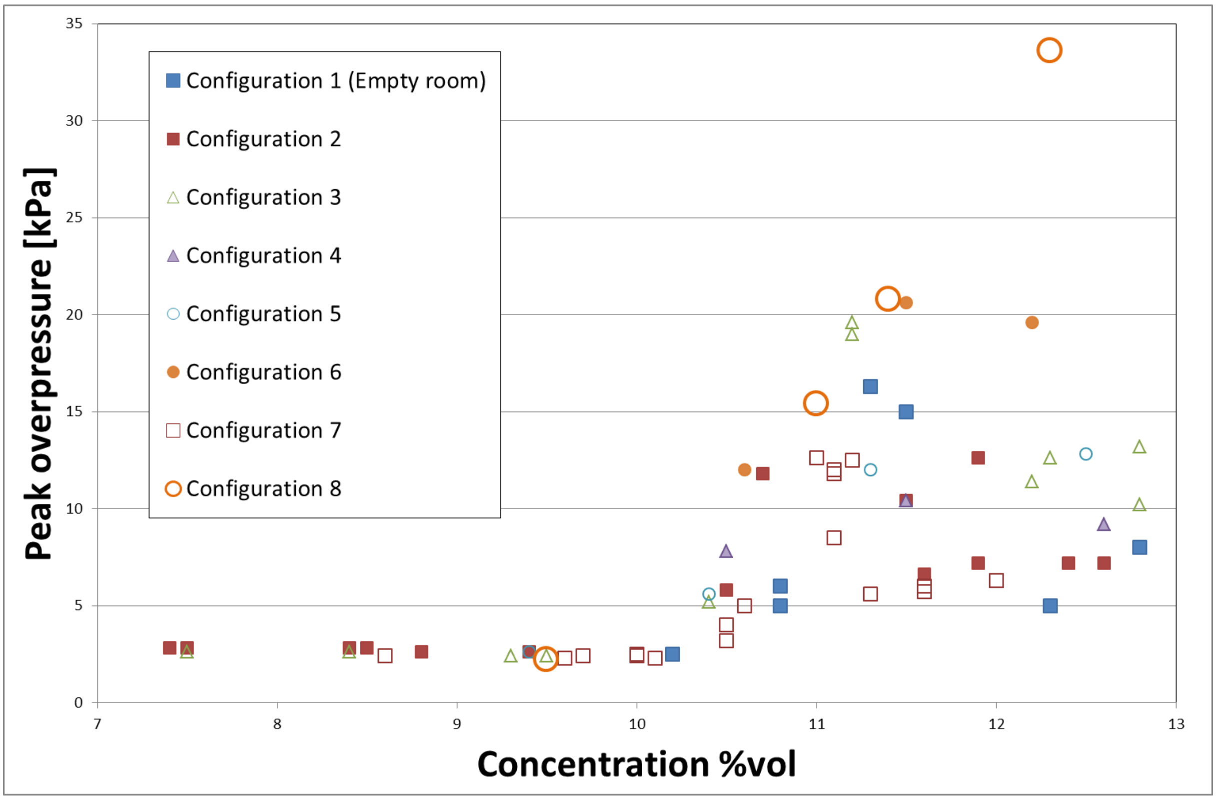


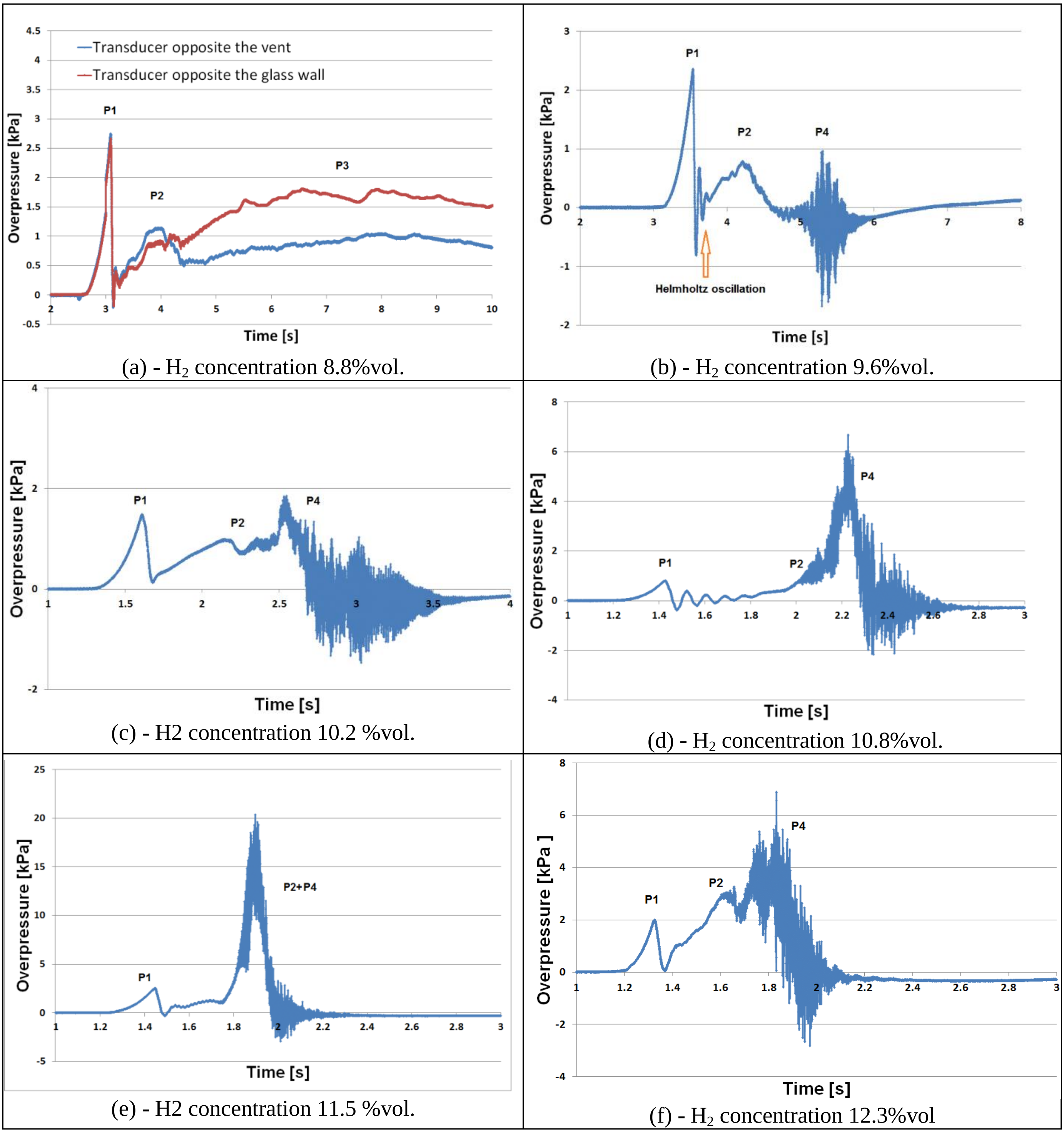
Figure 3 – Maximum overpressure's peak attained inside the CVE test facility vs. average hydrogen concentration for all the test performed.

Peak overpressure does not exceed the vent opening pressure for concentration's lower than 10% vol.

Table 1 – List of the experimental tests

#	Test ID	Obstacle config.	H2 conc. [%vol.]	Maximum overpressure [kPa][(*)]	#	Test ID	Obstacle config.	H2 average conc. [%vol.]	Maximum overpressure [kPa]
1	SM02	1	7.4	Vent	47	SM57	2	12.4	12
2	SM03	1	10.4	Vent	48	SM58	4	10.5	8
3	SM07	2	7.5	Vent	49	SM59	4	12.5	12.6
4	SM08	2	7.4	Vent	50	SM60	3	12.1	17
5	SM09	2	8.4	Vent	51	ISP25	4	11.4	12.2
6	SM10	2	8.5	Vent	52	ISP26	4	12.4	8.6
7	SM11	2	8.8	Vent	53	RED1	7	10.4	Vent
8	SM12	2	9.4	Vent	54	RED2	7	10.5	3.2
9	SM13	3	8.2	Vent	55	RED3	7	10.5	3
10	SM14	3	8.4	Vent	56	RED4	7	11.6	6
11	SM15	3	9.3	Vent	57	RED5	7	11.3	5.4
12	SM16	3	10.4	5	58	RED6	7	11.2	12.5
13	SM17	3	11.2	19.4	59	RED7	7	11	12.6
14	SM18	3	11.2	19.8	60	RED8	7	10.5	8
15	SM19	3	12.2	11.1	61	RED9	7	10	Vent
16	SM20	3	12.3	12.2	62	RED10	7	10.5	3.4
17	SM21	3	12.8	12.9	63	RED11	7	10.1	Vent
18	SM22	3	12.8	9.8	64	RED12	7	10.5	Vent
19	SM23	2	10.7	11.7	65	RED13	7	11.1	12
20	SM24	2	10.5	5.5	66	RED14	7	11.1	11.8
21	SM25	2	11.9	12.5	67	RED15	7	9.7	Vent
22	SM26	2	11.9	6.9	68	RED16	7	9.6	Vent
23	SM27	2	11.5	10.4	69	RED17	7	8.6	Vent
24	SM28	2	11.6	6.7	70	RED18	7	10.6	5
25	SM29	2	12.4	6.9	71	RED19	7	10	Vent
26	SM30	2	12.6	7.3	72	RED20	7	10	Vent
27	SM34	3	7.5	Vent	73	RED21	7	11.1	8.5
28	SM35	4	9.5	Vent	74	RED22	7	11.6	5.7
29	SM36	4	10.5	7.7	75	RED29	7	12	6.3
30	SM37	4	11.5	10.2	76	RED33	7	12	6.3
31	SM38	4	12.6	9.0	77	RED36	7	11	12.4
32	SM39	4	9.5	Vent	78	RED37	7	10.6	Vent
33	SM43	5	9.4	Vent	79	RED38	7	11.2	12.6
34	SM44	5	10.4	5.6	80	RED39	7	11.4	15
35	SM45	5	11.3	12.0	81	RED40	7	10.4	3.5
36	SM46	5	12.5	12.7	82	RED41	7	11.4	12.1
37	SM47	6	9.5	Vent	83	RED42	7	11.4	12.5
38	SM48	6	10.6	12.0	84	RED43	7	11.4	11.3
39	SM49	6	11.5	20.5	85	RED44	1	10.8	6
40	SM50	6	12.2	19.3	86	RED45	1	11.3	16.3
41	SM51	8	9.5	Vent	87	RED46	1	11.4	15
42	SM52	8	11	15.4	88	RED47	1	12.3	4
43	SM53	8	11.4	20.7	89	RED48	1	10.8	4
44	SM54	8	12.3	33.7	90	RED49	1	11	10
45	SM55	2	10.3	6.4	91	RED50	1	12.8	6
46	SM56	2	11	23.2	92	RED51	1	10.2	2.6
[(*)] Vent opening pressure is about 2.4 kPa but can slightly vary in every tests and as a general rule is slightly lower for tests at higher concentration									

For all the tests performed, except for the one in the configuration n.8, the maximum peak pressure developed inside the volume exhibits non-monotonic behaviour in the range of concentrations under investigation, it reaches a maximum in a range between 11%vol. to 11.2% vol. of hydrogen concentration, than decreases for concentrations higher than 11,2% vol. Beyond 11.5% vol. peak pressure increases again monotonically with hydrogen concentration. A similar result was described by Kumar [10] during tests of vented hydrogen deflagration in a rectangular 120m^3 facility. Kumar found that with far vent ignition the peak pressure at first increased with increasing hydrogen concentration, reached a peak at 9% vol. concentration of hydrogen, and than decreased. Beyond 10% vol. peak pressure increases again monotonically with hydrogen concentration.



(a) - H_2 concentration 8.8%vol.

(b) - H_2 concentration 9.6%vol.

(c) - H2 concentration 10.2 %vol.

(d) - H_2 concentration 10.8%vol.

(e) - H2 concentration 11.5 %vol.

(f) - H_2 concentration 12.3%vol

Figure 4 – Pressure time history observed in some of the tests

In most of the cases the maximum peak pressure in presence of obstacles results higher than in the empty chamber (blue squares in Fig.3), the only case where the maximum pressure attained in the empty facility is higher or comparable than the one obtained in configuration with obstacles is when the concentration of H2 is in the range 11%-11.5%, concentration at which the non-monotonic behaviour appears.

For each of the performed test the general shape of pressure time history can be explained with the theory developed for gas explosion and summarized in the introduction.

Unfiltered pressure time history of six different tests performed at increasing hydrogen concentration are shown as an example to discuss the main physical effects responsible for the pressure build-up in the vented volume.

In all graphs the first peak (P1) corresponds to the deployment of the plastic sheet. Before the vent opens the increase of pressure is caused by the production of hot combustion products within the room, the production depending on the laminar flame velocity and hence on hydrogen concentration. The time of vent deployment decreases with increasing the hydrogen concentration, reaching an asymptote at 0.245s after the ignition at concentrations above 12% (See Figure 5).

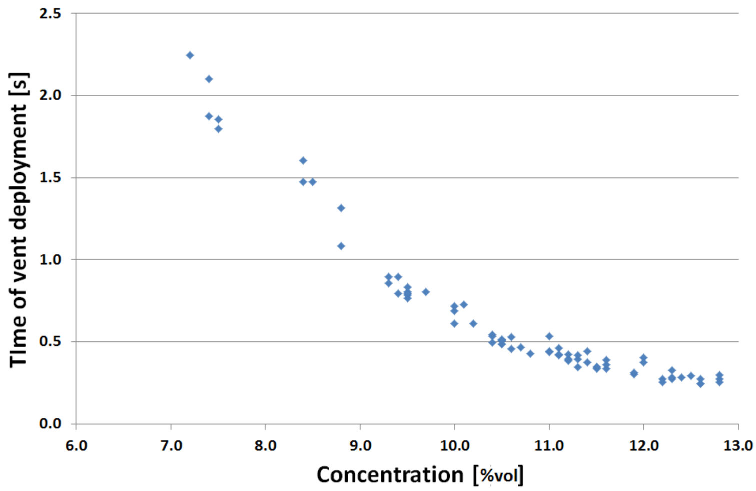


Figure 5 – Time of vent deployment after the ignition.

In tests characterized by very lean hydrogen concentrations, i.e. less than 9% vol., a second minor peak is present just after the first Fig. 4(a). At very lean H_2 concentration, when the vent is deployed the flame front had travelled considerable distance from the point where the mixture was ignited since the event occurs several seconds after the ignition. Hence the turbulent flow field generated by the deployment of the vent suddenly involves the flame front generating a fast increase of pressure as the flame approaches the vent area (P2). Fig 4(a) shows also that the pressure transducer opposite the vent records a pressure drop after the flame front reaches the vent area (P2), in fact in this moment the combustion products occupy a sort of cone which extends from the opposite wall were the sensor is located to the vent area, the unburned mixture occupies only the sides and the corners of the vented volume, so the flow of the burned mixture towards the vent produces the slight depression in the wall opposite the vent area. The slight difference of measured between the two pressure transducer, some kPa, has been observed at the end of the explosion in every test. For tests performed at higher concentration which pressure time history are showed in Fig. 4, where pressure oscillation are involved, only one pressure reading is reported to provide a more clear view.

After the flame front reaches the vent, in the rest of the volume the flame area continues to increase for a period of time due to the low burning velocity of the mixture in direction perpendicular to the vent, the reduction of the flame front area towards the end of the explosion, when its area is decreasing, as it reaches the walls and burns in the isolated pockets of unburned mixture, generates the third peak (P3) described in the introduction, caused by the decrease of the combustion products generation. In the tests performed this behaviour was observed only for very lean hydrogen concentration (i.e. under 9% vol.), at higher concentrations this peak is substituted by the oscillatory pressure peak (P4).

In tests were the flame front is not close to the vent area during the deployment, Helmholtz oscillation had been observed after the vent deployment, oscillations that eventually decay as the flame continues to expand.

After the vent deploys a flow field is introduced into the vented volume which interacts with the flame front as soon as it is close enough to the vent opening. The flame radius keeps increasing and eventually the flame stretches driven by the turbulent flow of unburned gases carried out through the vent area (see Fig.6).

In tests were concentration exceeds 11%, the rate of volume generated becomes soon larger than the outflow rate, and, consequently, the internal pressure start to rise dumping in the early stage Helmholtz oscillation generated by the vent deployment (see Fig 4 e and f). The pressure rises until the flame front reaches the vent, than due to the difference of density of the vented gases or to the external explosion a second pressure peak is generated (P2). Concerning the second peak, in tests involving lean hydrogen mixture as the ones performed in the present experimental tests, in the opinion of the author, the possibility that this may be generated by the external explosion is very unlikely since the turbulent flow of unburned gases exiting the vent should enhance the mixing with air reducing H_2 concentration outside the vent.

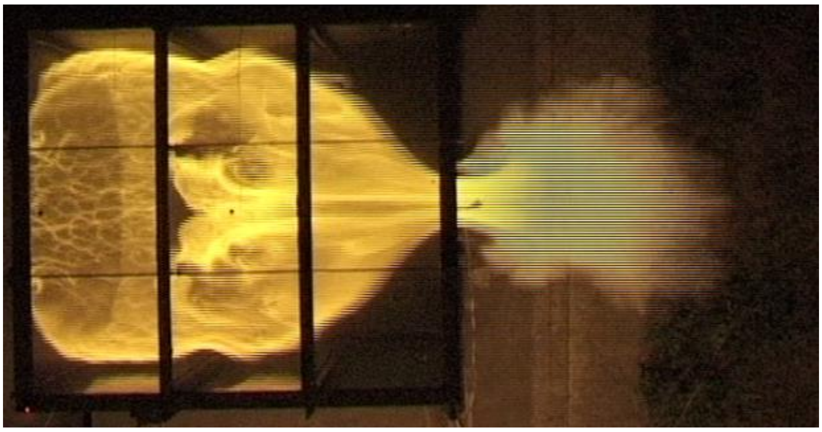


Figure 6 – Photogram of the video recorded during a test

Moreover, when the flame front approaches the vent area, pressure oscillation are triggered inside the vented volume. According to Harris formula [13], the volumetric flow rate through the vent area has a sudden increase when the unburned gases start to flow out of the enclosure, hence provoking sudden increase of their velocity, this discontinuity may be responsible of generating the physical response of the flammable envelope that changes the burning behaviour of the expanding flame front making it more susceptible to be influenced by acoustic oscillations generated inside the vented volume.

The oscillations have a variable frequency, which tends to increase as the deflagration progress, since the vented volume is progressively filled with combustion products having higher temperature and lower density compared to the unburned mixture. These oscillations, generated by the physical response of the enclosure [14,15], provoke a resonant coupling with the combustion inside the vented volume, giving rise to very high combustion rates and creating a significant net overpressure within the vented volume. The coupling of the two phenomena seems to generate stronger effects when the flame approaches the walls of the enclosure, in fact the amplitude of the oscillation increases of two order of magnitude as the flame approaches the walls.

In respect to the observed non-monotonic behaviour, the following scenario is derived: pressure oscillation are triggered as the flame reaches the vent area and the flow through it suffers a discontinuity, at the first stage acoustic waves are only superimposed to the flame front and the interaction is weak, when the flame front approaches the walls the interaction increases as so does the amplitude of the pressure oscillation generating a positive overpressure. If the flame front reaches the vent area generating the second peak and triggering the oscillations when the flame front in radial direction is far from the walls, than the oscillations that start to interact with the flame front become high enough to influence the overall net overpressure after a delay of time generating a distinctive third peak, that occurs when the effect of the overpressure generated by the second peak is already decreased (see Fig 4, b,c,d,f). Instead if the flame front reaches the vent when the flame front inside the volume is close to the walls an oscillatory peak can completely overlap to the second peak generating an higher pressure (see Fig. 4(e)).

In tests performed at concentrations between 11% and 11.5% the two phenomena take place very close one another, hence producing an higher overpressure in the facility. In tests were the concentration is higher than 12%, the flame front expands faster in direction perpendicular to the vent and reaches the walls before the oscillation are triggered, in this case more than one oscillatory peaks may be observed, each one representing an unburned pocket of gas reaching the walls.

Hence, a possible explanation to the non-monotonic behaviour observed in the tests is the superimposition of the two peak generated by the flame reaching the vent area (P2) and by the resonant coupling between the flame and the acoustic waves (P4) respectively.

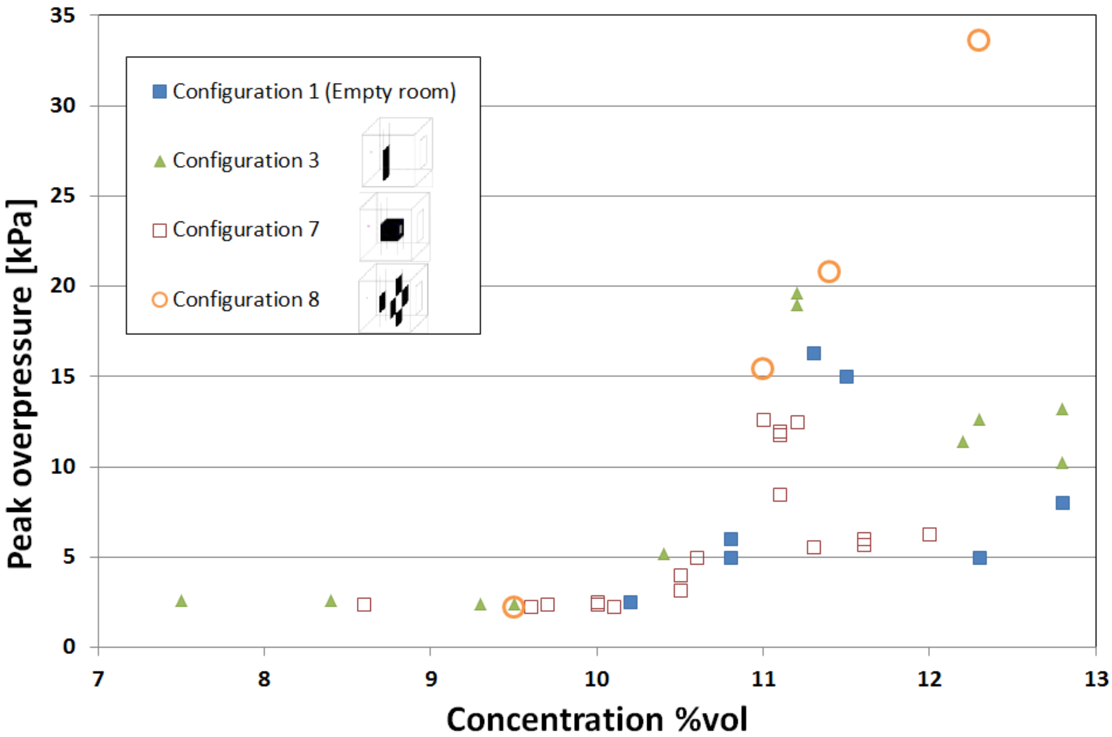


Figure 7 – Maximum overpressure's peak attained inside the CVE test facility vs. average hydrogen concentration for 4 selected setups.

As reported in the literature by some authors, the presence of the obstacles may reduce the effect of the interaction between the flame front and the oscillations produced during the deflagration, in fact the maximum peak pressure was found to be higher for tests performed in the empty room respect to the one performed with obstacles particularly at concentrations were the two peaks P2 and P4 overlap. Anyway this behaviour was found not to be true for all the configurations. In configuration 3 and 6 the maximum overpressure generated at concentration around 11%vol was comparable with the one generated inside the empty room. It should underlined that for these tests the pressure build up attributed to the second peak is higher than the one obtained in empty room or in other obstacle configuration, probably due to the fact that the flame is forced to travel towards the vent passing through the higher part of the facility were the concentration is higher. The acoustic flame interaction than generates a lower net overpressure if compared with the empty room case even though the superimposition of the two effects gives similar results.

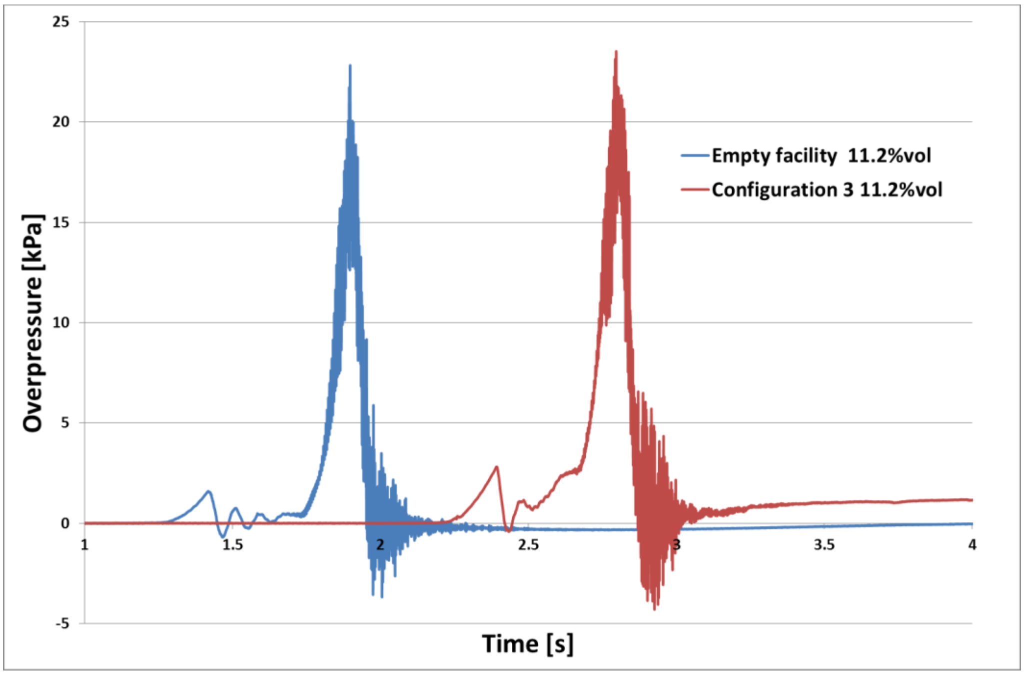


Figure 8 – Comparison of overpressure’s peak attained inside the empty CVE test facility and in configuration 3

In the configuration # 8, the flame front undergoes a stronger acceleration approaching the vent due to the obstacles configuration, this acceleration being responsible of a second peak (P2) higher than the one attained in other configuration for the same concentration. For this case the non-monotonic behaviour was not confirmed by the results. In fact in this case the turbulent flow field generated by the vent deployment generates a stronger acceleration to the flame front that reaches the vent area earlier, when in the perpendicular direction it travelled a smaller distance being farther from the walls than in other configurations at the same concentration, hence the two peaks P2 and P4 result not completely superimposed (see Fig. 8).

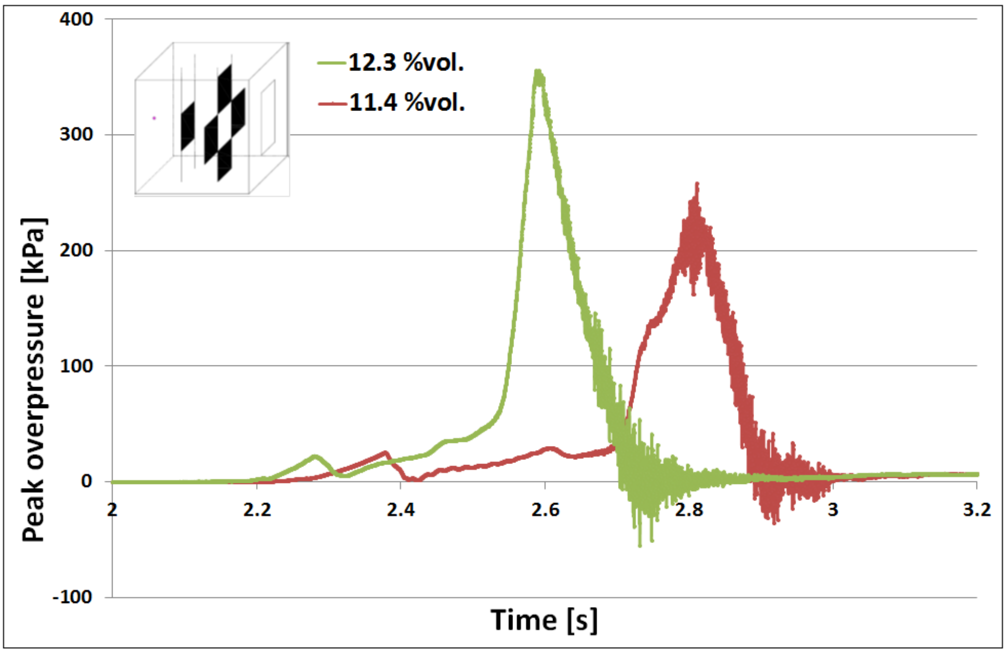


Figure 9 – Comparison of overpressure’s peak attained inside the CVE test facility in configuration #8

4. CONCLUSIONS

Experiments were performed at Scalbatraio laboratory, DICI Department of University of Pisa, in a $25m^3$ vented combustion test facility that hosted internally different obstacle configuration, to studty the combustion behaviour of hydrogen-air mixtures in vented environments.

Test facility vent dimension was constantly set to a value of $1,004m^2$, while the ignition location was in the middle of the wall opposite the vent. H_2 concentration was homogenised inside the two environments through the aim of two different fan. The study included hydrogen concentration from 8,5% to 12,5%.

A general description of the pressure-time history obtained during the tests was given following the four peak theory.

Peak overpressure developed by far-vent ignition exhibits non-monotonic behaviour in the range of concentrations under investigation, it reached a maximum at 11% vol. of hydrogen concentration, than decreased. Beyond 11,5% vol. peak pressure increases again monotonically with hydrogen concentration.

The same non-monotonic behaviour was described by Kumar [10] during tests of vented deflagration in a rectangular $120m^3$ facility, but the peak was reached at 9% vol. instead of 11% vol.

In respect to the observed non-monotonic behaviour, the following scenario is derived: pressure oscillation are triggered as the flame reaches the vent area and the flow through it suffers a discontinuity, at the first stage acoustic waves are only superimposed to the flame front and the interaction is weak, when the flame front approaches the walls the interaction increases as so does the amplitude of the pressure oscillation generating a positive overpressure. If the flame front reaches the vent area generating the second peak and triggering the oscillations when the flame front in radial direction is far from the walls, than the oscillations that start to interact with the flame front become high enough to influence the overall net overpressure after a delay of time generating a distinctive third peak, that occurs when the effect of the overpressure generated by the second peak is already decreased. In configuration 8 the non-monotonic behaviour was not observed, in this case the turbulent flow field generated by the vent deployment generates a stronger acceleration of the flame front that reaches the vent area earlier, when in the perpendicular direction it travelled a smaller distance being farther from the walls than in other configurations at the same concentration, hence the two peaks P2 and P4 result not completely superimposed.

5. ACKNOWLEDGMENTS

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