EXPERIMENTAL STUDY OF VENTED HYDROGEN DEFLAGRATION WITH IGNITION INSIDE AND OUTSIDE THE VENTED VOLUME

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ABSTRACT

Experiments were performed in a 25m^3 vented combustion test facility that hosted internally a 0,64m^3 vented box, called RED-CVE, which vent was left open. Test facility vent area was fixed, set to a value of 1,12m^2, while three different areas were tested for the RED-CVE vent. Hydrogen concentration was homogenised inside the two environments by use of two different fans. The study included hydrogen concentration from 8,5% to 12,5%; while three different ignition locations were used, (1) far vent ignition, (2) ignition in the middle of the rear wall of the RED-CVE box, and (3) near vent ignition. Peak overpressures generated inside the test facility as well as inside the smaller box were investigated. Experiments indicate that peak overpressures inside the CVE test facility with near vent ignition were negligible compared with those with far vent ignition and ignition inside the RED-CVE box. In experiment with far vent ignition the pressure at first increased with hydrogen concentration, reached a peak value at 11%vol. concentration, than decreased showing a non-monotonic behaviour. Overpressure produced inside the RED-CVE resulted higher when ignition location was external to the box, with the flame entering in the RED-CVE through the vent, than when the mixture was ignited directly inside.

Key words: Hydrogen, Vent, Obstacles, External ignition

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, number and strength of the vent, position of the ignition source, pre-ignition turbulence, etc. For hydrogen deflagration the instabilities and 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 only few experiments with quantitative measurement of the phenomena [1,2,3,8,11].

Based on the results obtained by the experiments, usually performed without internal obstacles, a vast number of equations have been derived [4,5,6], which prediction ability had been compared [7,8]. 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, in a previous experimental campaign, vented deflagration were performed with the presence of internal obstacles of various shapes [3].

In the present experimental campaign a smaller vented box, called RED-CVE, was placed inside the CVE test facility. The campaign was focused on the investigation of the overpressure developed in the RED-CVE box, varying hydrogen concentration and ignition position. One ignition position was placed inside the small box, opposite to the vent, while the other two ignition positions were inside the CVE facility and outside the small box. Peak overpressure inside the CVE facility was also investigated, results obtained by tests ignited from the centre of the wall opposite to CVE's vent were compared with results obtained by previous experimental campaign and characterized by same ignition position and vent size, but different configuration of the obstacles placed inside the test facility.

Experimental data will be presented and discussed for homogeneous conditions of H_2 concentration.

2. CVE EXPERIMENTAL FACILITY AND RED-CVE

The CVE (Chamber View Explosion) apparatus 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 panels of glass which allow to video record the flame. All other faces 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].

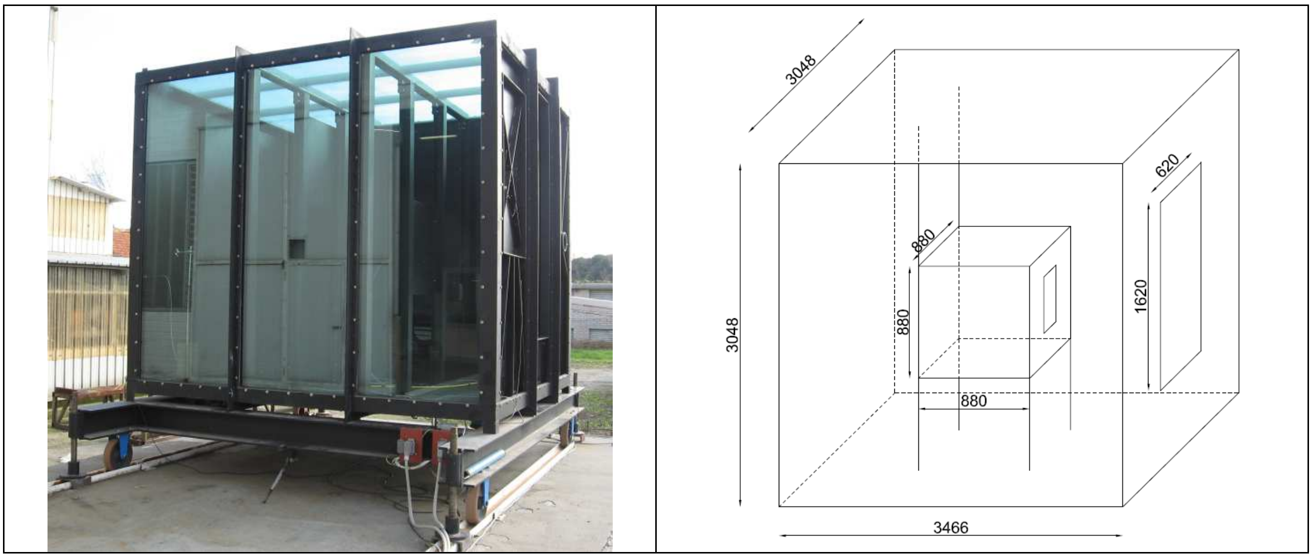

Figure 1 – Photo of the CVE test facility (left) and its dimensions [mm] (right)

CVE has been built in order to perform vented deflagration tests. In the current experimental campaign its vent dimensions were kept fixed and characterized by a width of 0,62 m and an height of 1,62 m (vent area 1,12 m^2). The vent area was closed with a plastic sheet characterized by an opening pressure of approximately 24 mbar.

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 [1].

Inside the CVE test facility a smaller vented chamber was built, called RED-CVE (see figure 2). RED-CVE has cubic shape characterized by side's dimension of 0,88 m and an internal volume of about 0,64 m^3 (see Figure 1).

The vent area of the inner box can be varied, with the width having a fixed dimension of 0,205 m, while the height can be changed. In the present experimental campaign three different vent areas has been tested 0,135m, 0,205m and 0,27m. The position of the vent of the smaller chamber was in the centre of the wall and has been left open.

During the release of hydrogen inside the experimental facility the concentration has been homogenized in the two environments through the use of two different fans, a bigger one located inside the CVE facility and a smaller one that sucks the air from the lower part of the RED-CVE and recirculates it inside the small chamber.

At the end of the release phase, the duct that connects the recirculating fan and the internal area of the RED-CVE was sealed by a plate of steel moved by an hydraulic piston (see figure 2),hence no transmission of the flame was possible through this duct. All experiments were conducted at ambient pressure and temperature.

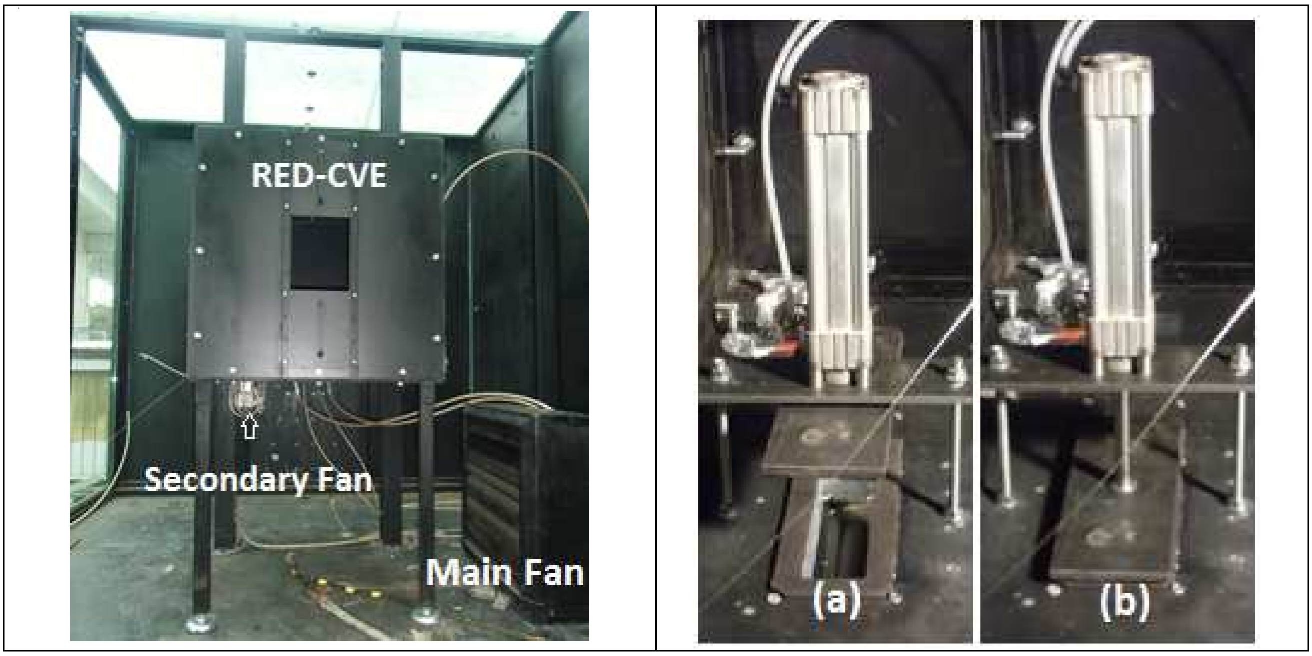

Figure 2 – Picture of the RED-CVE box and the recirculating fans (left) and ventilation duct (right) in open (a) and closed (b) positions

The data acquisition system has been designed to monitor and record the following parameters:

- hydrogen bottles pressure and temperature;
- pressure and temperature of hydrogen in injection pipeline just outside the test facility;
- concentration of hydrogen inside the CVE: four concentration sampling points (2-5 in Figure 3);
- concentration of hydrogen inside the RED-CVE: one sampling point (1 in Figure 3);
- deflagration pressure within the CVE: a piezoelectric pressure gauge was placed on the wall of the CVE opposite to the vent;
- explosion pressure within the RED-CVE: a piezoelectric pressure gauge was placed inside the RED-CVE;
- temperature inside the RED-CVE box.

During the release phase, fans were on operation with the aim to homogenize the atmosphere and hydrogen concentration inside the facility and the RED-CVE box(1).

In all the tests performed the concentration measured inside the RED-CVE reached a value close to the maximum concentration in the upper part of the facility under the ceiling, hence slightly higher than the average concentration.

The ignition system consisted of 3 electrodes connected to a remote driven circuit and designed to prevent accidental sparks.

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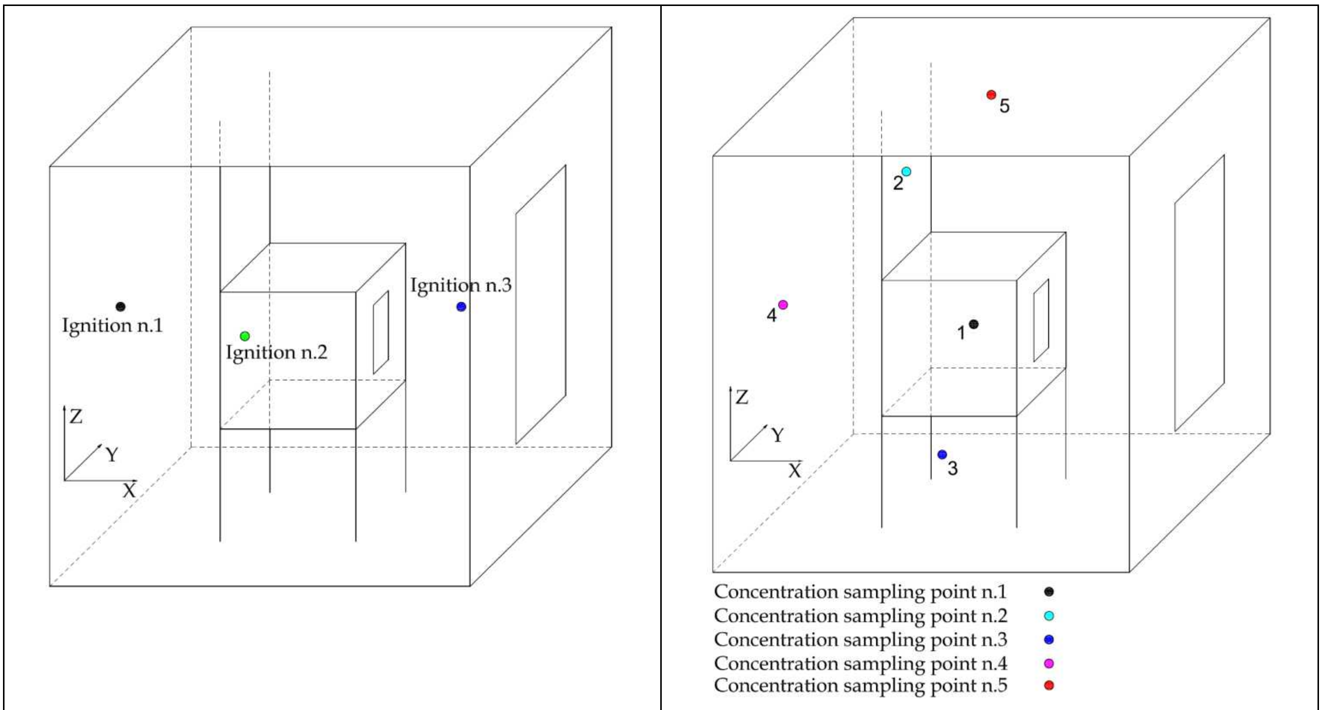
(1) Despite of the fans, hydrogen concentration showed a stratification behavior inside the facility, with lower concentration at the bottom and higher concentration under the facility ceiling, the difference of concentrations measured between the lower and the upper sampling points was about 1,5 %vol. in every tests.

The three electrodes have been placed as described below (see Figure 3):

- (1) ignition point placed in the middle of the CVE's side opposite to the vent at 1 m high from the floor;
- (2) ignition point placed in the middle of the RED-CVE's side opposite to the vent at 0.44 m high from the bottom of the box;
- (3) ignition point placed in between the CVE vent and the RED-CVE vent, 1,3 m high from the floor.

Each ignition could be sparkled independently, the ignition was given after a proper time delay (ranging from 30 seconds to 1 minute), once the fans were turned off, to ensure a low initial turbulence intensity. Time of ignition was set 2 seconds after the first recorded data in the acquisition system, pressure time history will be shown in time range 2-4 seconds, where the origin of the graphs will represent the time at which the ignition was sparkled.



Igniters coordinates [mm]			
N.	X	Y	Z
1	20	1450	1060
2	1250	1380	1380
3	2680	1390	1360

Concentration sampling point coordinates [mm]			
N.	X	Y	Z
1	1650	1380	1380
2	1440	1200	2370
3	1540	580	710
4	190	1300	1200
5	1440	1700	2800

Figure 3 – Igniters position and coordinates (left) and concentration sampling points position and coordinates (right)

3. EXPERIMENTAL CAMPAIGN

The experimental campaign was focused on the investigation of the overpressure developed in the RED-CVE box, varying hydrogen concentration, RED-CVE vent dimensions and ignition position.

Three different sizes were investigated for RED-CVE vent dimensions, as listed in Table 1. Three different ignition positions were investigated, while the average concentration was varied between 8% vol. and 12% vol. The CVE vent area was fixed equal to 1,12 m².

Table 1 – RED-CVE vent dimensions investigated

RED-CVE vent dimensions			
	Y [mm]	Z [mm]	Area [m^2]
Vent 1	205	135	0,027675
Vent 2	205	205	0,042025
Vent 3	205	270	0,05535

Peak overpressure inside the CVE facility was also investigated, particularly results obtained by tests ignited from position n.1 were compared with results obtained by previous experimental campaign and characterized by same ignition position and vent size, but different obstacles placed inside the CVE facility.

A total number of 35 experiments with different hydrogen concentrations and ignition positions have been performed, of which 31 have been included in this paper.

Table 2 lists an overview of the performed tests.

Table 2 – List of the experimental tests performed

Test ID	Vent dimesions RED-CVE	Average concentration	RED_CVE concentration	Ignition
RED5	0,135X0,205	11,3	12,2	1
RED6	0,135X0,205	11,2	11,6	1
RED7	0,135X0,205	11	11 (10,9)	1
RED8	0,205X0,205	10,56	11	1
RED9	0,205X0,205	10	10 (9,8)	1
RED10	0,205X0,205	10,5	11,3	1
RED11	0,205X0,205	10,1	10,5	1
RED12	0,205X0,205	10,5	11	1
RED13	0,205X0,205	11,1	11,6 (11,8)	1
RED14	0,205X0,205	11,1	11,7	1
RED15	0,205X0,205	9,7	10,1	1
RED16	0,135X0,205	9,6	10,2	1
RED17	0,135X0,205	8,6	9	1
RED18	0,135X0,205	10,6	11,2	1
RED19	0,135X0,205	10	10,5	1
RED20	0,135X0,205	10	10,8	1
RED21	0,27X0,205	11,1	11,8	1
RED22	0,27X0,205	11,6	12,4	1
RED23	0,27X0,205	11,2	11,5	2
RED24	0,205X0,205	11,2	11,8	2
RED25	0,135X0,205	11,2	11,8	2
RED26	0,135X0,205	11,1	11,8	3
RED27	0,205X0,205	11,1	11,5	3
RED28	0,205X0,205	10,5	11,2	2
RED29	0,205X0,205	12	12,5	1
RED30	0,135X0,205	10,5	11,2	2
RED31	0,135X0,205	10,5	11,2	3
RED32	0,27X0,205	11	11,8	3
RED33	0,27X0,205	12	12,6	1
RED34	0,205X0,205	12	12,8	3
RED35	0,205X0,205	10,5	11,8	2

4. RESULTS: OVERPRESSURE PEAKS IN THE CVE TEST FACILITY

Figure 4 shows the maximum peak pressure attained in the CVE test facility as a function of average hydrogen concentration for the 3 cases: far-vent ignition (ignition 1); ignition inside the RED-CVE box (ignition 2); and near-vent ignition (ignition 3). Near vent ignition tests (ignition 3) develop peak overpressures inside the CVE which value have always been limited by the opening pressure of the vent (approximately 24 mbar).

When the mixture is ignited inside the RED-CVE box (ignition 2) pressure rises first inside the box and later in the CVE. In this case inside the test facility only one peak overpressure is attained, it reaches its maximum during the opening of the vent, but its corresponding pressure results higher than the vent opening pressure (see Figure 5).

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

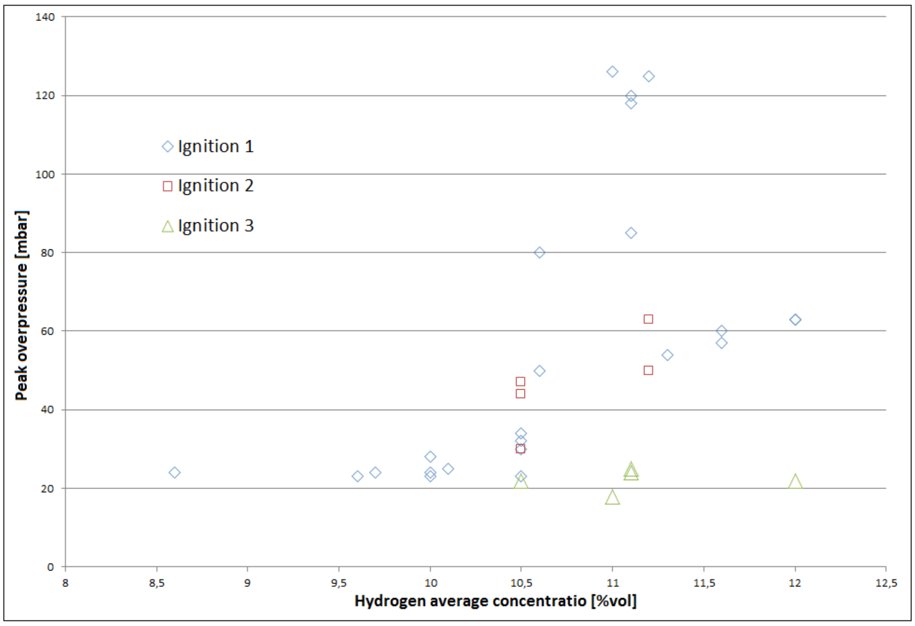


Figure 4 – Comparison of overpressure's peak attained inside the CVE test facility vs. average hydrogen concentration for different ignitions position

The measured peak overpressure inside the CVE test facility has been also compared with previous data obtained from the experimental campaign SM which investigated turbulence effects generated by different sets of obstacles placed inside the test facility. In particular tests will be compared that had a single plate as an obstacle, which position was the same that the current face of the CVE-BOX opposite to its vent. The CVE vent area in the previous experimental campaign had the same dimensions of the one used in the current campaign, also the ignition location was the same (ignition 1).

Results of the old experimental campaign are in good agreement with the ones of the current one. Peak overpressure does not exceed the vent opening pressure for concentration's lower than 10% vol. Peak overpressure behaviour in the concentration's range under investigation shows a peak around to 11% vol. of hydrogen concentration.

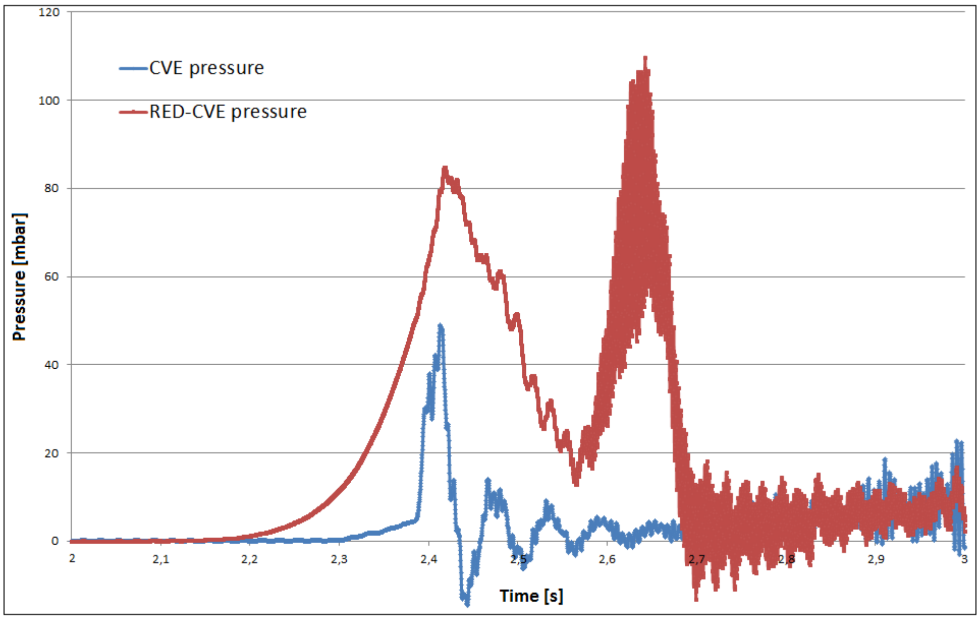


Figure 5 – Pressure time history typical of a deflagration with ignition position inside the RED-CVE box (ignition 2) Experiment RED 30.

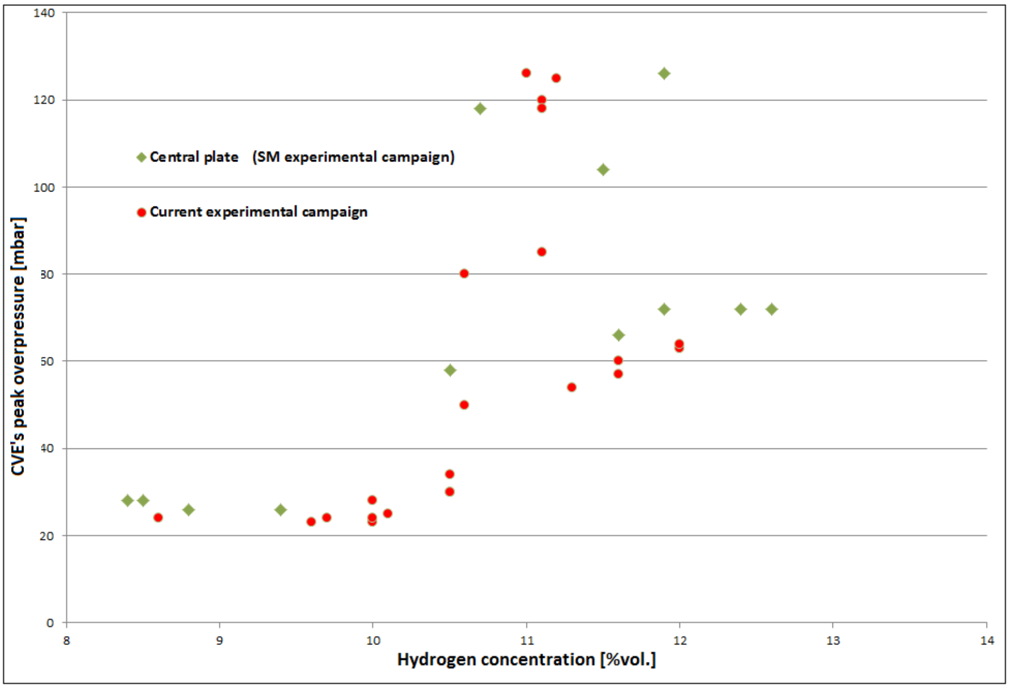


Figure 6 – Comparison of overpressure's peak attained inside the CVE test facility in the present and previous experimental campaign as function of hydrogen concentration

A similar result was described by Kumar [10] during tests of vented 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. The same non-monotonic behaviour has been found in the present experimental campaign, but the peak was reached at 11% vol. instead of 9% vol. This difference may suggest a dependence of the concentration at which the peak occurred on the parameters that influence the venting phenomena (test facility dimensions, hydrogen concentration and vent opening pressure).

5. PEAK OVERPRESSURES IN THE RED-CVE BOX

Maximum peak overpressures measured inside the RED-CVE were recorded as a function of the average concentration inside the environment (see figure 7) and as a function of the concentration measured in sampling point n.1 inside the box (see figure 8). In both cases results are scattered and no clear behaviour can be described, especially regarding tests with ignition location outside the RED-CVE chamber. Over the range of condition investigated, the highest peak pressure rise of about 700 mbar (70 kPa) occurred in the 11%vol. hydrogen mixture for vent dimensions of 0,135 mm X 0,205 mm, with far vent ignition (Figure 7,8,10).

Despite of the few number of tests performed with ignition location inside the RED-CVE box, the peak overpressure seems to exhibit a monotonic behaviour as a function of hydrogen concentration inside the box.

Results show that for a given concentration, both average in the facility (Figure 7) and measured inside the box (Figure 8), the overpressure produced inside the RED-CVE resulted higher when ignition location was external to the box (ignition 1 or 3), with the flame entering in the RED-CVE through the vent, than when the mixture was ignited inside the box (ignition 2).

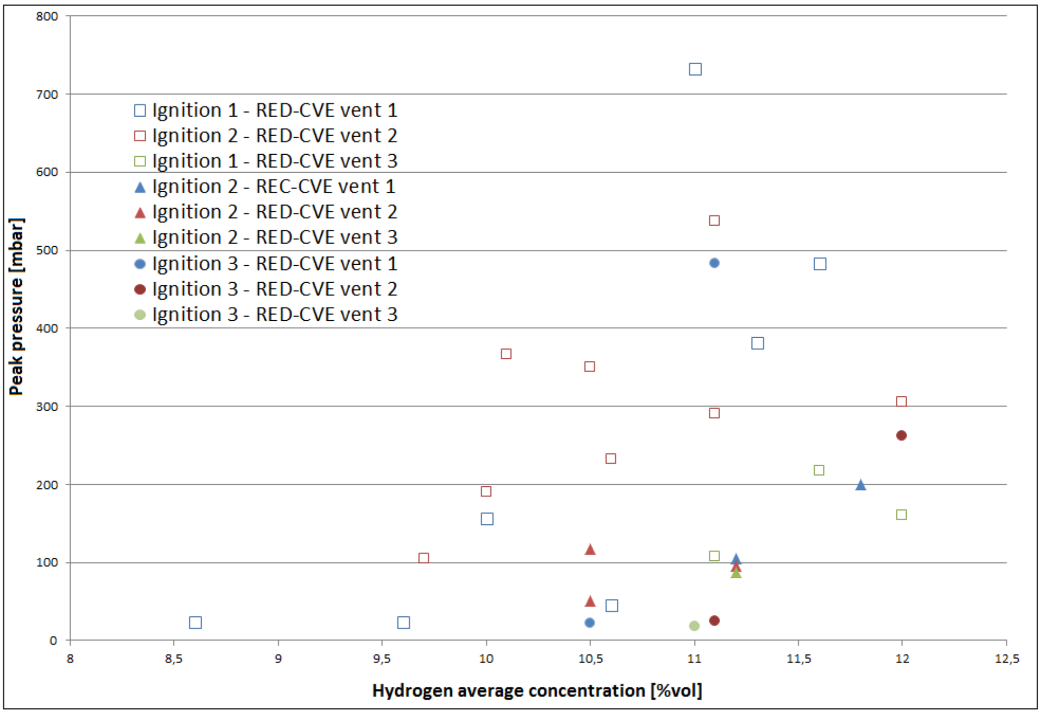


Figure 7 – Maximum peak overpressure inside the RED-CVE vs. H_2 average concentration for different ignition location and RED-CVE vent dimensions

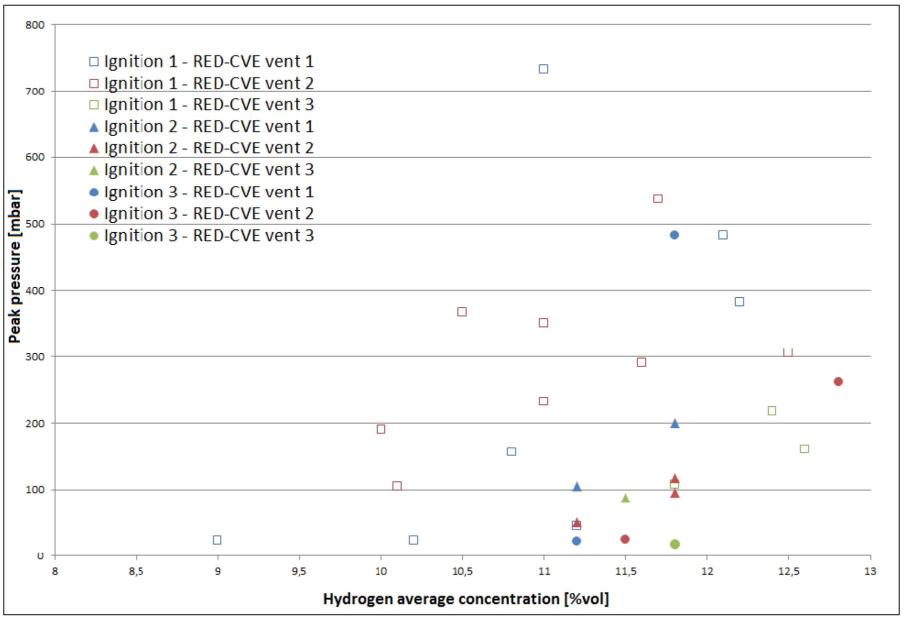


Figure 8 – Maximum peak overpressure inside the RED-CVE vs. H_2 concentration measured inside it for different ignition location and RED-CVE vent dimensions

With ignition located near the vent of the CVE test facility, in front of the RED-CVE vent, the pressure inside the RED-CVE were most of the time limited by the vent opening pressure value (figure 9) except in a couple of tests, one of which was performed with the smallest tested RED-CVE vent dimension, 0,135mm X 0,205 mm. Figure 10 shows a comparison of the pressure-time behaviour for the test mentioned above with tests performed with the same average concentration of hydrogen inside the test facility but different ignition location. The peak pressure obtained with internal ignition is lower than the one generated by external ignition location, that may indicate the dependence of the resulting peak overpressure from the flame speed and acceleration through the RED-CVE vent.

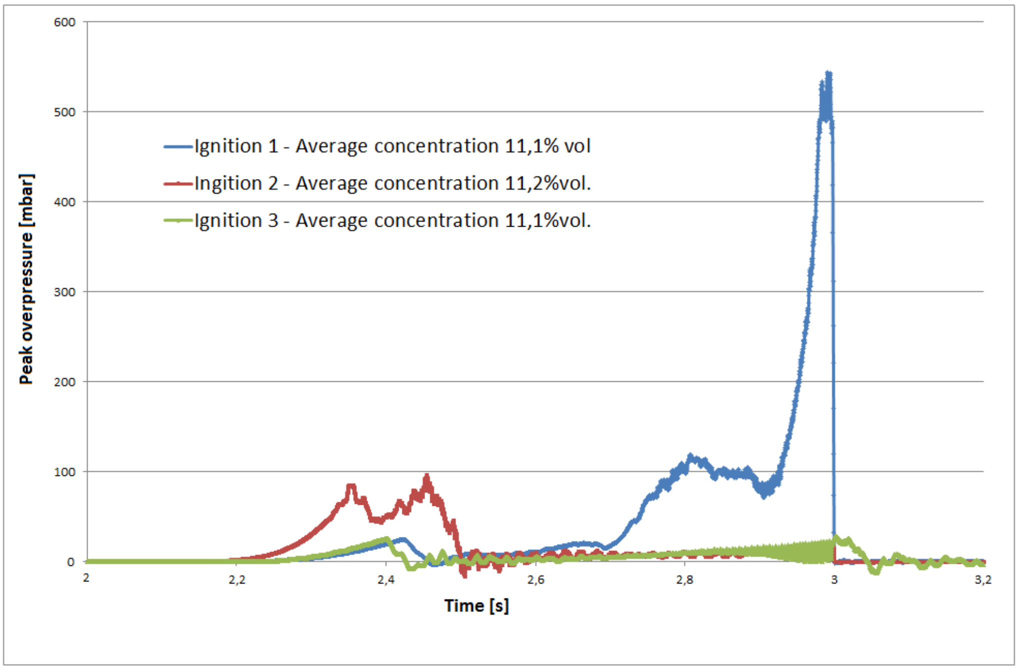


Figure 9 – Effect of ignition location on RED-CVE internal pressure vs. time history for 11,1% H2 concentration and RED-CVE vent dimensions 0,205 mm X 0,205 mm

Maximum peak overpressure generated with ignition in near vent location were generally lower than the one generated with ignition in position n.1 (Figure 9 and 10). Flame generated from ignition location 1 is subjected to a higher turbulence generated from the deflagration process after the vent opening, hence the burning velocity of the flame entering inside the RED-CVE box could be correspondingly higher.

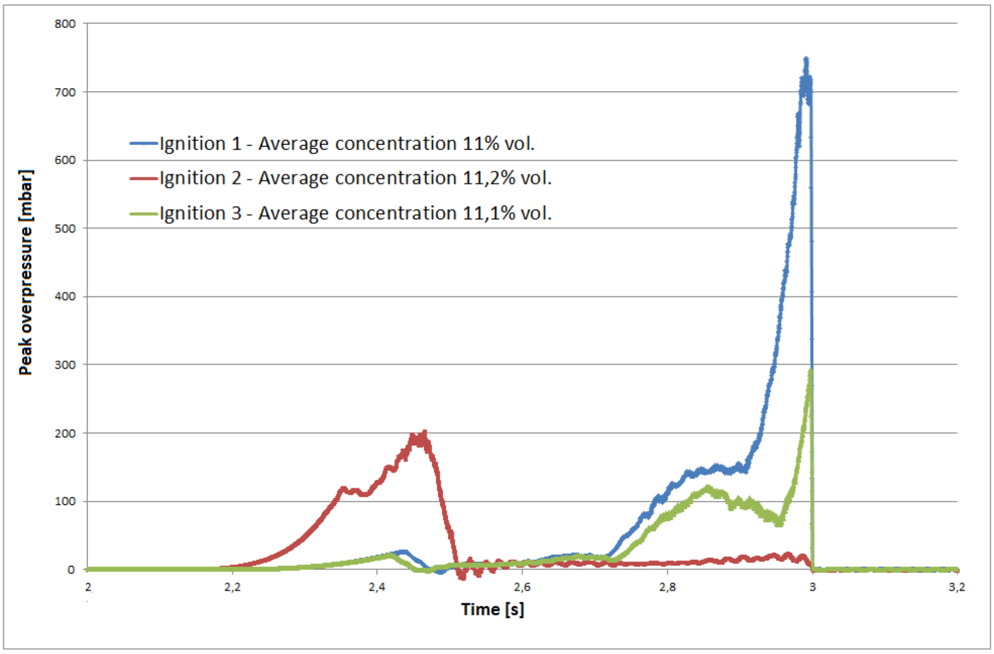


Figure 10 – Effect of ignition location on RED-CVE internal pressure vs. time history for 11,1% H2 concentration and RED-CVE vent dimensions 0,135 mm X 0,205 mm

6. CONCLUSIONS

Experiments were performed at Scalbatraio laboratory, DICI Department of University of Pisa, to determine the combustion behaviour of hydrogen-air mixtures in vented environments.

Experiments were performed in a 25m^3 vented combustion test facility that hosted internally a 0,64m^3 vented box, called RED-CVE, which vent was left open. Test facility vent dimension was constantly set to a value of 1,12m^2, while three different areas were tested for the RED-CVE vent. Hydrogen 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%; three different ignition location were used, far vent ignition, ignition internal to the RED-CVE box, and near vent ignition.

For the CVE test facility near vent ignition tests (ignition 3) developed a peak overpressures inside the CVE which value have always been limited by the opening pressure of the vent (approximately 24 mbar).

When the mixture was ignited inside the RED-CVE box (ignition 2) pressure rose first inside the box and later in the CVE. In this case inside the test facility only one peak overpressure was attained, it reached its maximum during the opening of the vent, but its corresponding pressure resulted higher than the vent opening pressure (see Figure 4).

Peak pressure rise 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.

This difference may suggest a dependence of the concentration at which the peak occur on the parameters that influence the venting phenomena (test facility dimensions, vent dimensions and vent opening pressure).

Maximum peak overpressures measured inside the RED-CVE, over the range of condition investigated, was about 700 mbar (70 kPa), it occurred in the 11%vol. hydrogen mixture for vent dimensions of 0,135 mm by 0,205 mm, and with far vent ignition.

Results show that for a given concentration, both average in the facility (Figure 7) than measured inside the box (Figure 8), the overpressure produced inside the RED-CVE resulted higher when ignition location was external to the box (ignition 1 or 3), with the flame entering in the RED-CVE through the vent, than when the mixture was ignited inside the box (ignition 2).

With ignition located near the vent of the CVE test facility, in front of the RED-CVE vent, the pressure inside the RED-CVE were most of the time limited by the vent opening pressure value (figure 9) except in a couple of test; this behaviour may indicate the dependence of the resulting peak overpressure from the flame speed and acceleration through the RED-CVE vent.

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