THE ROLE OF THE FLOW FIELD GENERATED BY THE VENTING PROCESS ON THE PRESSURE TIME HISTORY OF A VENTED DEFLAGRATION

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ABSTRACT

Vented deflagrations are one of the most challenging phenomenon to be replicated numerically in order to predict its resulting pressure time history. As a matter of fact a number of different phenomena can contribute to modify the burning velocity of a gas mixture undergoing a deflagration, especially when the flame velocity is considerably lower than the speed of sound. In these conditions acceleration generated by both the flow field induced by the expanding flame and from discontinuities, as the vent opening and the venting of the combustion products, affect the burning velocity and the burning behaviour of the flame. In particular the phenomena affecting the pressure time history of a deflagration after the flame front reaches the vent area, such as flame acoustic interaction and local pressure peaks, seem to be closely related to a change in the burning behaviour induced by the venting process. Flame acoustic interaction and local pressure peaks arise as a consequence of the change in the burning behaviour of the flame. This paper analyses the video recording of the flame front produced during the TP experimental campaign, performed by UNIPI in the project HySEA, to analyse qualitatively the contribution of the generated flow field in a vented deflagration in its pressure-time history.

1. INTRODUCTION

Vented deflagrations are a very complex phenomena. The pressure time history depends on many parameters such as the mixture composition, initial pressure and temperature, pre-ignition turbulence, the size and shape of the vessel, the position of the ignition, the location, number, size and shape of the vents, the presence of obstacles and confinement inside the vessels and outside the vents.

The mechanisms that can contribute to the pressure build-up during vented explosions are summarised, among the others, in the papers by Bauwens et al. [1] and [2] which include flame–acoustic oscillations, Helmholtz oscillations, turbulence–combustion interactions, the external explosion, and flame instabilities [3].

An important effort was made during the second part of the 20th century to develop models able to calculate precisely the vent size. Initially based on simplifying assumptions [4], these models try to take into account a number of physical phenomena like the evolution of the flame shape as function of the geometry of the vessel [5,6], the hydrodynamic instabilities [7], the turbulence of the flow ahead of the flame [8], the characteristics of the vent cover (inertia, discharge coefficient) [9].

Although they become more and more predictive, these analytical and phenomenological models cannot be generalized to all the situations [10], suggesting several phenomena may not yet be well understood or correctly accounted for.

During the experimental campaign of homogeneous hydrogen deflagrations performed at UNIPI G. Guerini laboratory for the HySEA project [11], video analysis of the flame front was performed to characterize the burning behavior of the flame front during the different stages of the deflagrations.

The objective of the present work is to investigate the changes in burning behavior during a vented deflagration originated by the two major discontinuities that characterize the phenomena, namely the burst of the vent and the venting of the combustion products. In fact the burst or deployment of the vent abruptly changes the flow field inside the enclosure, which before was affected only by flow field generated by the flame expansion and its interaction with the geometry, while after the deployment is characterized by an acceleration of the gases, burned and unburned, towards the venting area.

The second discontinuity is represented by the burned gas exiting the vent. When the burned gas reaches the vent the volumetric flow rate of gas exiting the chamber is abruptly increased due to the decrease in density of the vented gas. The initial effect of this discontinuity is to accelerate the gases towards the vent, than, due to the inertia of the outflow Helmholtz oscillation are triggered. These two discontinuities and their related accelerations fields play a role on the changes in the burning velocity and in the burning behavior of the flame.

2. EXPERIMENTAL SETUP

UNIPI 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 enclosure consists of a solid steel frame, built using L-Shaped Cross-section steel bars (50x50x4 mm), that supports the main components of the measurement system, faces of the frame are closed with various combinations of walls, doors, and vent panels.

The dimensions of the facility are: 0.92m width, 0.66m depth and 2m height. Different obstacle configuration were tested; the empty enclosure, 1 and 3 bottles inside the enclosure (see figure 1).

The top face is designed to host different types of vent: FIKE panel (dimension 500 mm x 800 mm) or a plastic sheet. When the front vent is used the top face is closed with a 5mm thick steel plate bolted to the frame.

Figure 1 SSE obstacle configuration

The front face is divided into two parts: the upper part can be fitted with a FIKE vent panel, a plastic sheet panel, or be closed with a steel plate when the top vent is used. The lower frame holds a test plate, which can be replaced to test different material or thicknesses with respect to structural response during the tests. Two steel thicknesses have been tested, namely 2mm and 5mm. The plate displacement measurement is performed using a mechanical method or a laser sensor, results from the displacement measurement as well as capabilities of CFD codes in reproducing the phenomena will be discussed in another publication.

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

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

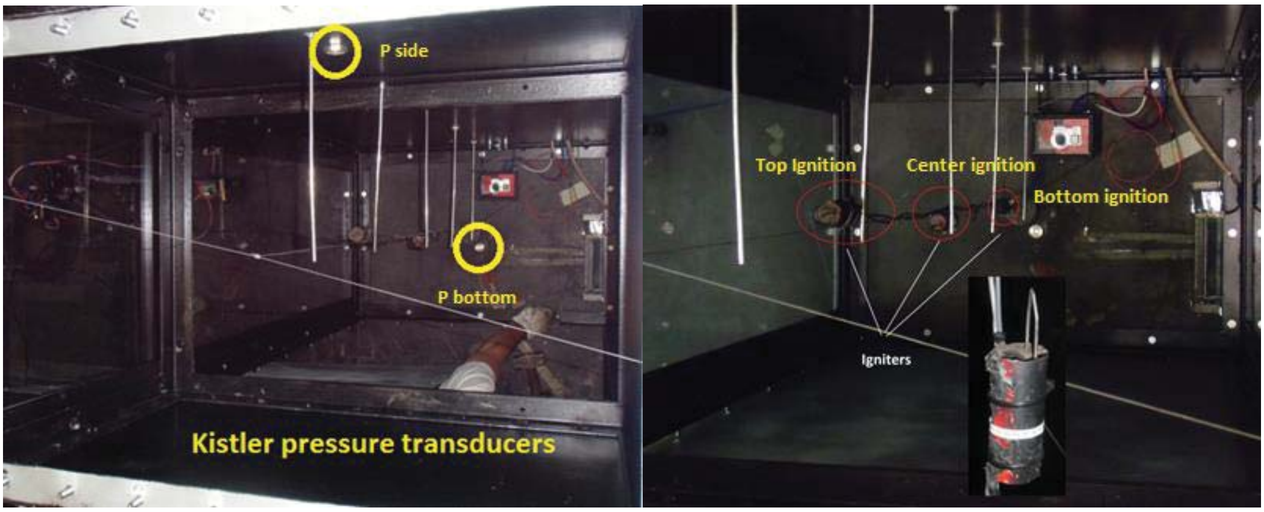


Figure 2 Inside view of the SSE, pressure transducers and ignition locations.

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

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

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

Two cameras are used to record the deflagrations, 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 used to video record the flame inside the facility when salty spray was injected to visualize the flame.

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

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

A detailed description of the experimental setup, as well as complete lists of results (filtered and unfiltered pressure time history graphs) are provided in the related HySEA deliverable [12].

3. RESULTS AND DISCUSSION

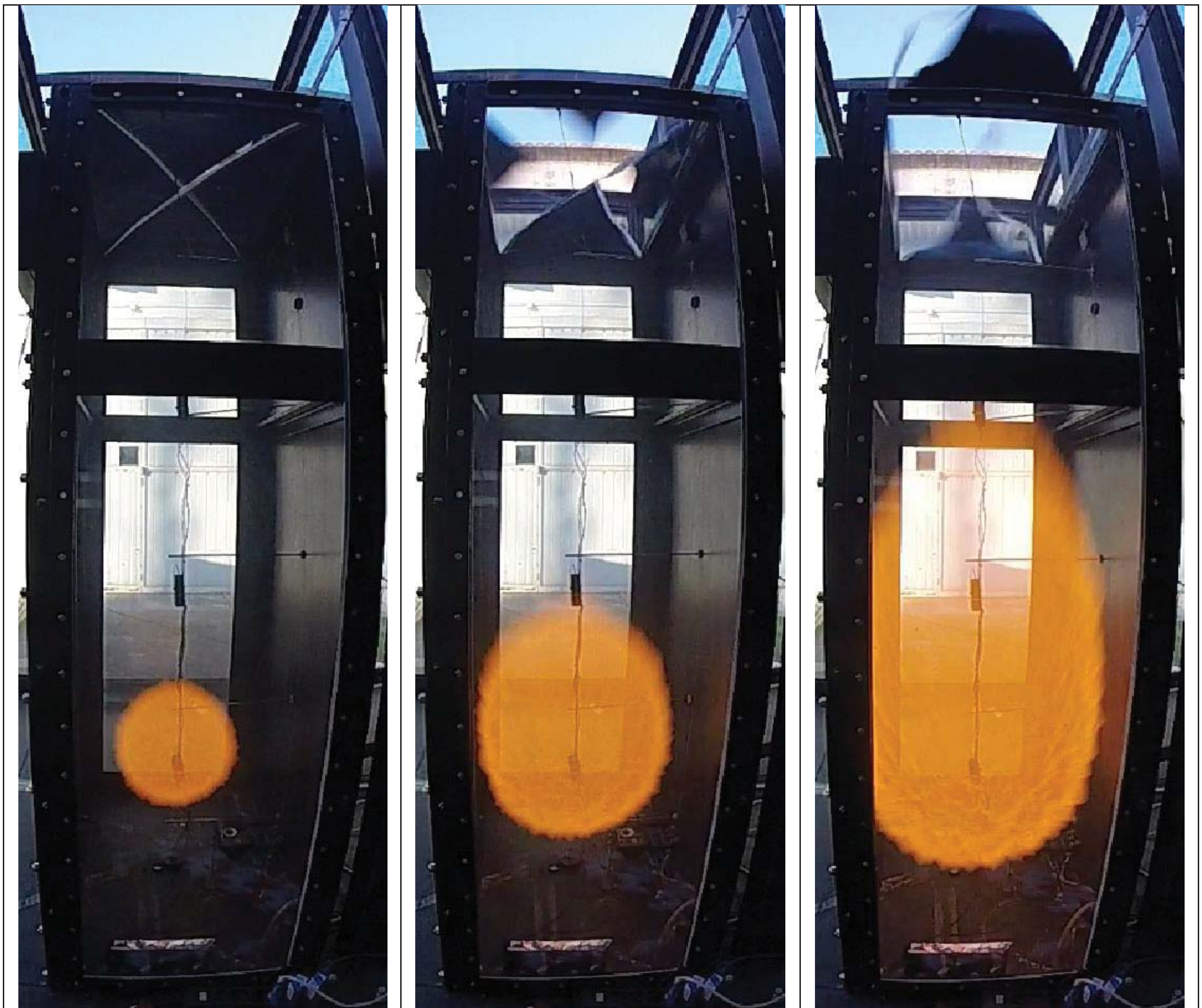
Flow field self-generated from the expanding flame front as well as produced by the discontinuities that characterize a vented deflagration affect the flow field and the local turbulence and hence the burning rate of the expanding flame front.

Two discontinuities are always present during a vented deflagrations, the first generated by the burst of the vent panel, which generates a flow field directed towards the vent area, the second generated by the abrupt enhance of the flow rate when the flame front reaches the vent area.

Both the described discontinuities produced a variable acceleration field directed towards the vent area.

After ignition the flame front expand with a spherical shape and self generates turbulence and instabilities, as well described in the literature, increasing its burning rate.

After the vent opens a flow field is generated inside the vented enclosure directed towards the vent area, when the generated acceleration field reaches the flame front expanding towards the vent it enhance the turbulence and the burning rate, dragging the flame front towards the vent itself.



(a) Frame 584	(b) Frame 587	(c) Frame 590 -

Figure 3: Frames from video recording of test TP73 (average hydrogen concentration 18%vol.)

The effect of this phenomena on the flame bubble is to stretch the part of the flame directed towards the vent enhancing its burning and expansion rate (see figure 3). In figure 3 three frames of the video recording of test

TP73 are shown, as can be seen from the naked eye the flame front towards the vent expands faster than the part directed opposite the vent, furthermore the images show the differences in the burning behavior of the flame front expanding in the two directions. In this phase the deflagration is still creating a positive overpressure inside the enclosure event though after the vent opening pressure gradient are created inside the enclosure and a difference starts to arise on the value of pressure measured in the two locations. The flame bubble is still expanding and the produced combustion product expansion accelerates the flame front towards the unburned products, but the symmetry of the phenomenon, affected in the first phase of the deflagration only by the influence of the gravitational acceleration field and the boundary conditions, is lost (see Figure 3b).

The part of the flame front expanding opposite the vent continues to burn with a rate close to the initial one and maintaining the same flame structure, while the flame front directed towards the vent is clearly subjected to an accelerated flow field, the flame structure changes and traces are visible of the activated salty particles accelerated towards the vent.

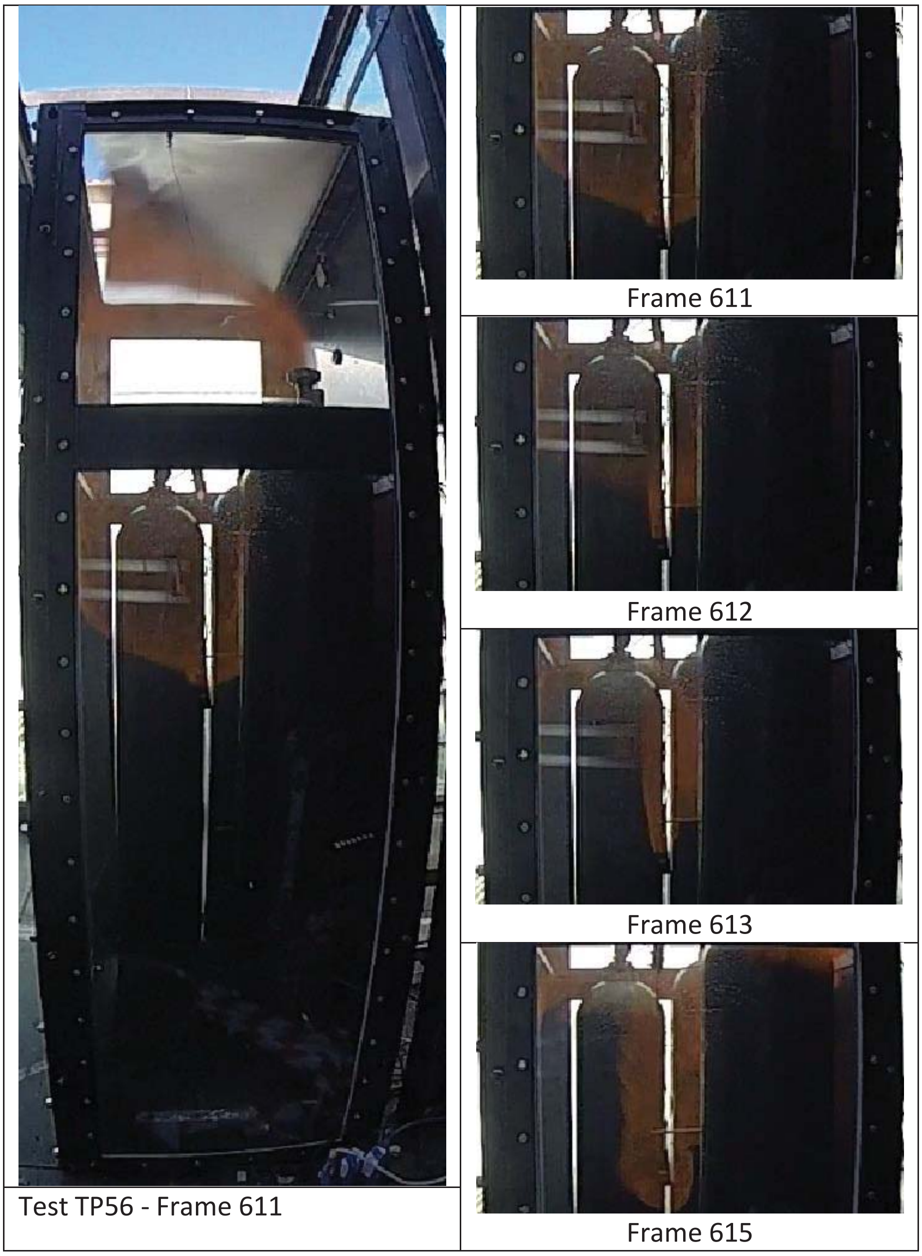


Figure 4: Frames from video recording of test TP56 (average hydrogen concentration 14%vol.)

A second, stronger, discontinuity is created when the combustion products reach the vent area. In this moment the flow rate of gas exiting the chamber is greatly enhanced as a consequence of the density differences between unburned mixture and combustion products [13]. When the combustion products reach the vent area a second acceleration field is generated inside the enclosure. The effect of this acceleration field is visible on the flame front expanding opposite the vent area after a delay dependent of the speed of sound, which correspond to the velocity at which a discontinuity propagates in the media, and the distance from the flame front and the vent area. After a delay of time in fact the flame front expanding opposite the vent is affected by the flow field (acceleration field) generated by the increased flow rate at the vent area, the following figure 4 shows the effect of the accelerating flow field on the flame front expanding opposite the vent. The flow field acceleration is dependent on the pressure difference across the vent area.

Figure 4 shows screenshots taken from the video-recording of test TP56 performed with an average hydrogen concentration of 14%vol., the ignition was given in location 3, close to the vent, while the vent used was a commercial FIKE vent.

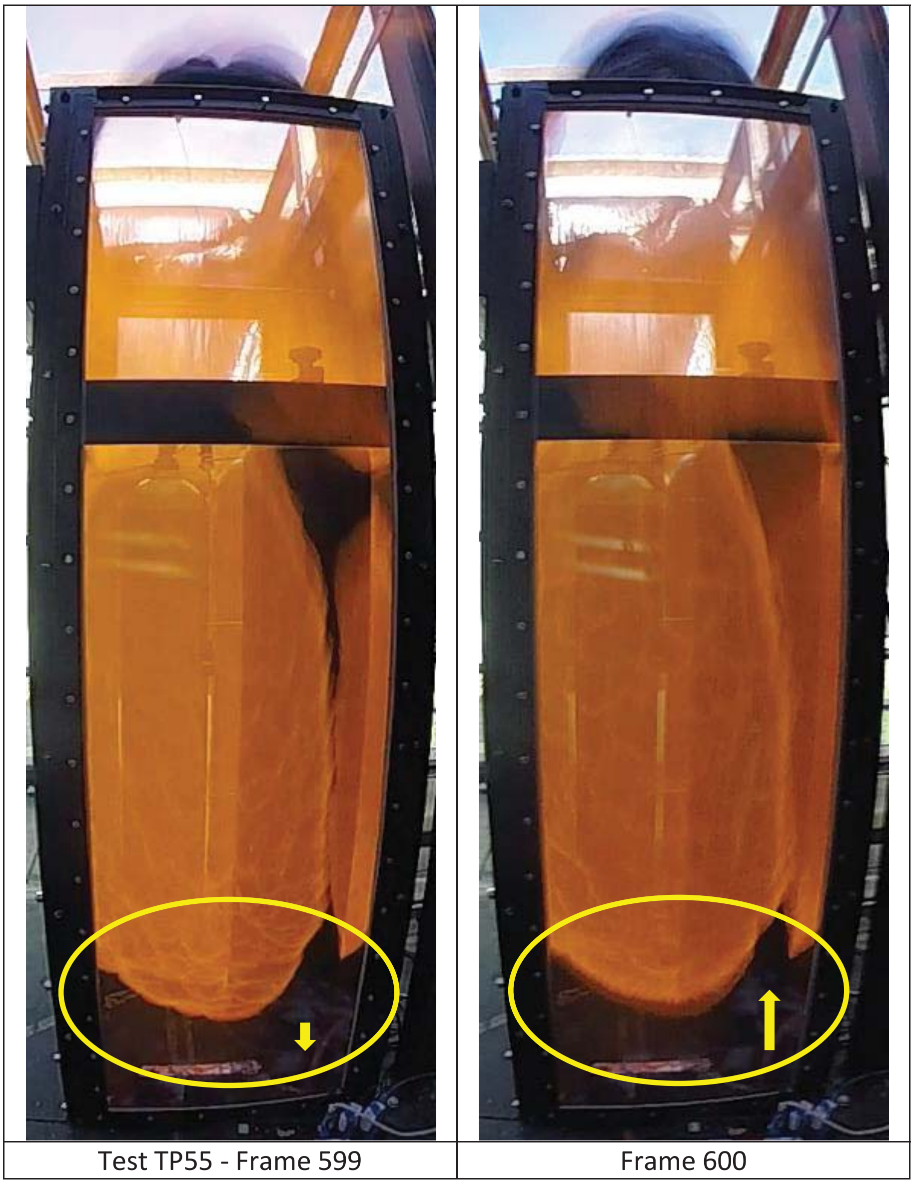


Figure 5: Frames from video recording of test TP55 (average hydrogen concentration 17.8%vol.)

In this condition the effect generated by the venting process on the flame front expanding in the opposite direction is maximized. As a consequence of the flow field generated during the venting process the flame front travelling in opposite direction is dragged back towards the vent area. It can be noticed that in the volume above the igniter, where the flow field is affected by the presence of the igniter itself and the velocities are lower, the combustion is still sustained while in the surrounding volume, where the flow velocities are higher, the flame front is dragged towards the vent area.

As a consequence of top ignition the flame front is very close to the vent during its opening, frame from 611 to 613 show how the flame front directed opposite the vent is dragged back towards the vent area with exception of the central area which flow field is perturbed by the presence of the igniter. When the acceleration field reverse itself as a consequence of the alternate air flow through the vent area (Helmholtz oscillation) the flame front starts again to expand towards the bottom of the facility with a flame shape completely different from the moment before the upper flame front reached the vent area.

This extreme case has been taken as an example because the low average concentration and the proximity of the flame front to the vent maximize the effects of the described phenomena, in other tests the flame front directed opposite the vent maintained its geometrical shape being only subjected to oscillation in the flame position as a consequence of the flow field through the vent area (Helmholtz oscillation).

Figure 5 shows two consecutive frames taken at the end of the test TP55 performed with average concentration 17.8%vol. The comparison between the two pictures shows the accelerations to which the flame front expanding opposite the vent is subjected as a consequence of the flow field produced by the venting of the burned products.

In lot of tests, after the flame front reached the vent, producing the “external explosion”, commonly referred as P_{ext} or P_2, and abruptly increasing the flow rate through the vent area, a third pressure peak is generated inside the enclosure. In some of the performed tests the third recorded peak is higher than the second, which is unusual.

The third peak presents itself before than the pressure acoustic oscillation start to arise, and can clearly be identified even in filtered pressure time history. The third peak is a local pressure peak, always higher at P_{bottom} than at P_{side}, in fact the overpressure measured at P_{bottom} is higher than the second peak, while the third peak measured at P_{side} is not higher than the second peak (see figure 6).

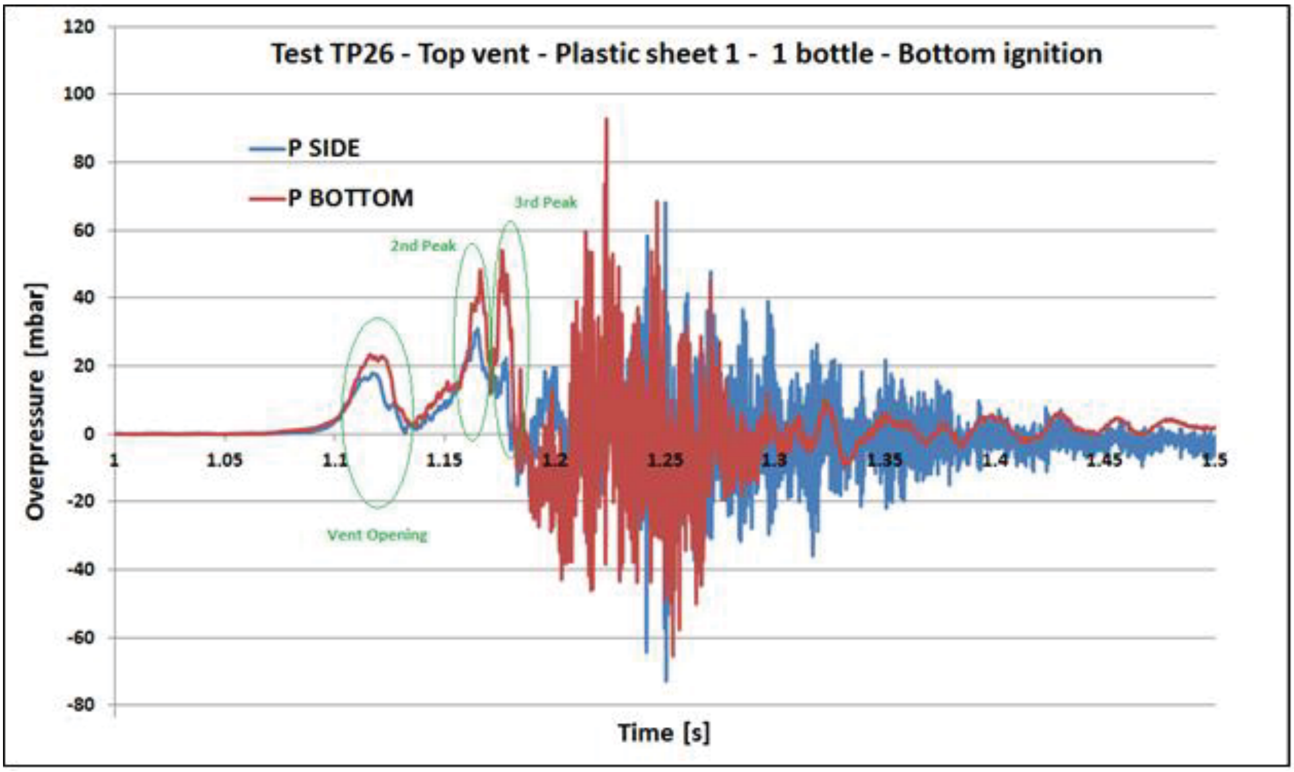


Figure 6 Unfiltered pressure time history for test TP26 (Top vent - Plastic sheet configuration 1- 1 bottle – Bottom ignition)

The generation of the described third peak may related to the huge vent area, compared to the enclosure dimension, which allow a big flow rate oscillating in and out as a consequence of the venting process.

In fact the described third peak seems to be generated after the external explosion, when air starts to flow back inside the enclosure, pushing the combustion products downwards towards the unburned mixture. When obstacles are present inside the facility the generated flow field directed inside the enclosure after venting produces flow streams with high velocities, for example in the congested volumes between the bottles and the walls of the facility. If the flame front is carried by these high velocity streams high combustion rates are generated locally which in turn produce local high overpressures.

Figure 7 shows two consecutive frames taken at the end of tests TP55 where the flame front emerging behind the bottle is carried by the flow stream and accelerated; in 1/240 of a second it burns a considerable volume while the rest of the flame front directed towards the bottom of the facility advance of a negligible distance.

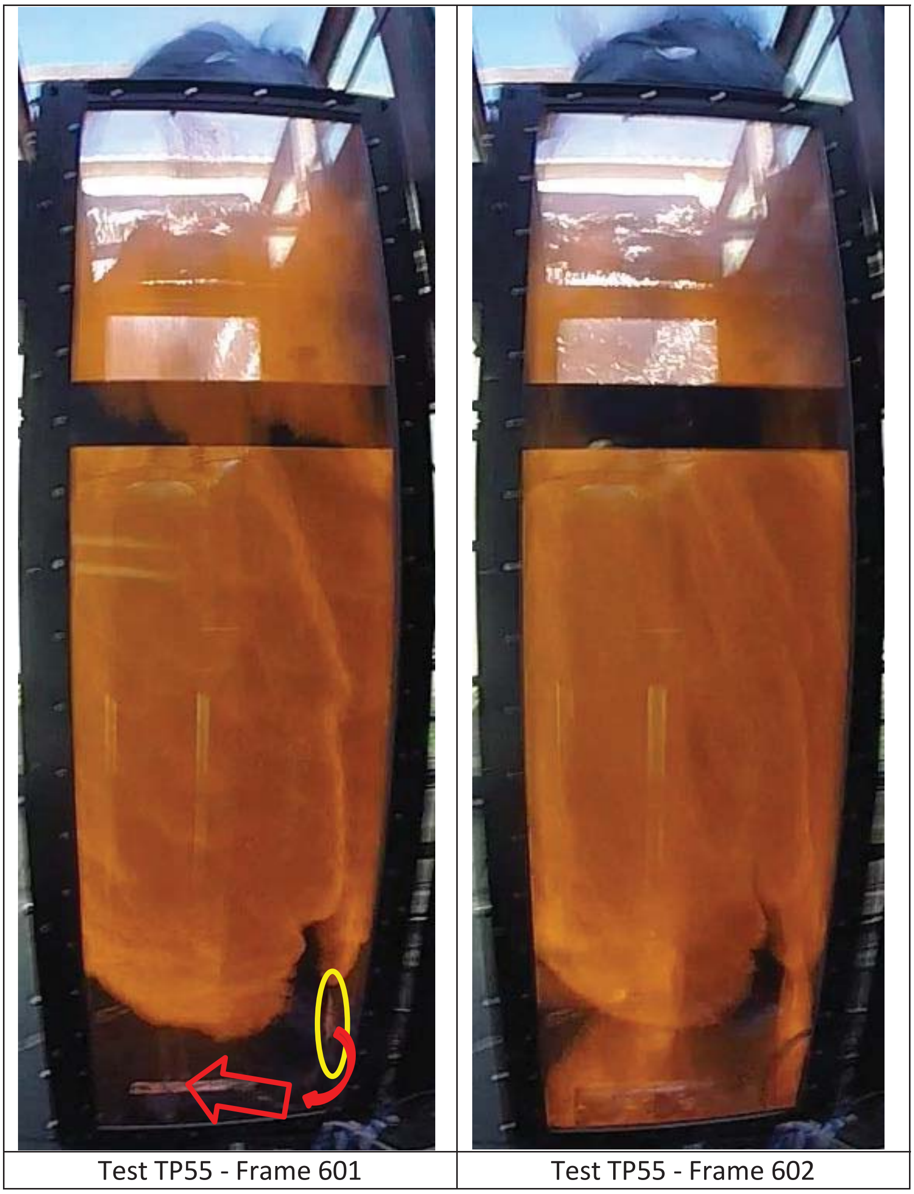
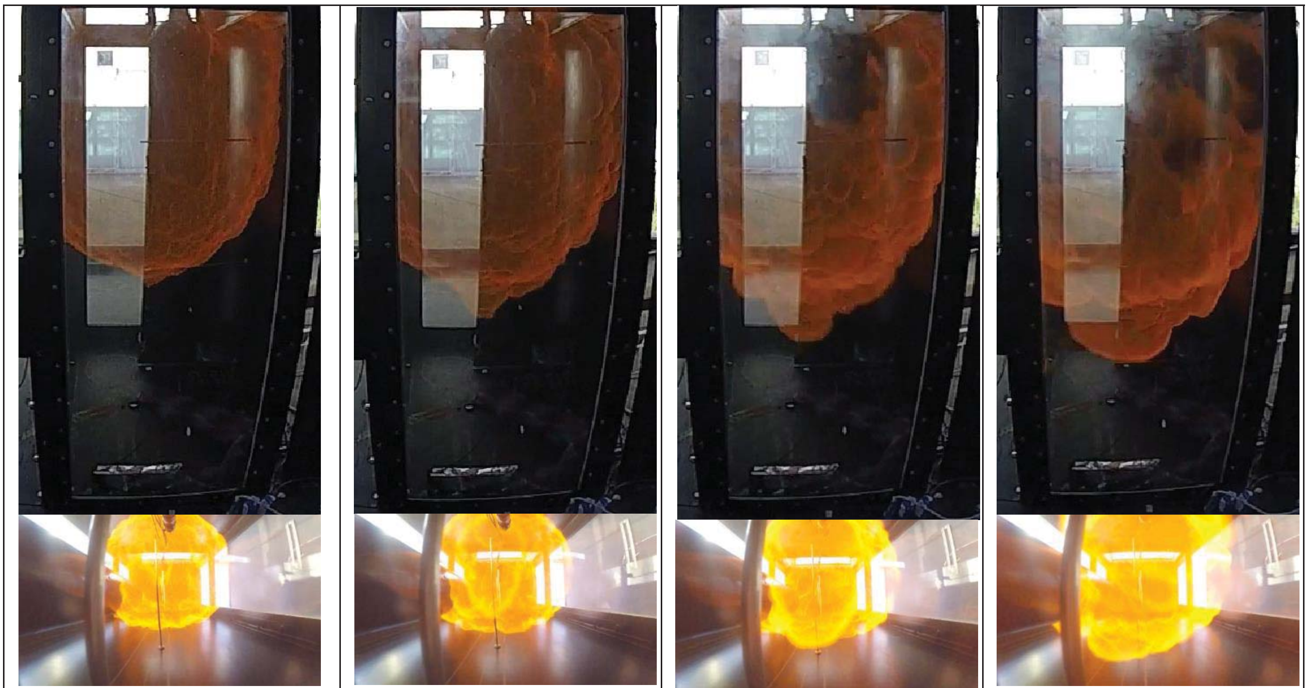


Figure 7 Frames from video recording of test TP55 (average hydrogen concentration 17.8%vol.)

Figure 8 shows four frames taken from the video recording of test TP66 in the time interval indicated on the unfiltered pressure-time history. The first of the frames is taken after the "second peak". P_{ext}, when the burned products are already vented and the pressure inside the enclosure dropped back to values close to atmospheric. In this phase of the deflagration the flame front loses the accelerations created by the expansion of the combustion products and its more prone to interact with acoustic oscillation [14].

The images show the change in burning regime of the flame front expanding towards the bottom of the facility during the interaction with acoustic oscillation generated after the venting. It is interesting to notice that, supposing we could neglect the history of the deflagration before this moment and the generated flow field, the described situation, where the flame front freely advance towards the bottom of the enclosure at a pressure close to atmospheric, is very similar to the setup of the experiment carried by Searby [15] in his study on acoustic instabilities on premixed flames. In the cited experimental setup a premixed flame was burning towards the bottom of a cylinder open at its top and closed at the bottom. In experiments performed by Searby the frequency of the acoustic oscillation could be related to the acoustic response of the cylinder itself, while in the present experimental campaign the acoustic frequencies interacting with the flame front can be related to the acoustic response of the chamber in the two directions (width and depth) perpendicular to the venting direction.



(a) Frames 601/517	(b) Frames 605/521	(c) Frames 609/525	(d) Frames 613/529

(e) Test TP66 Pressure time history (Average concentration 15.8%vol.)

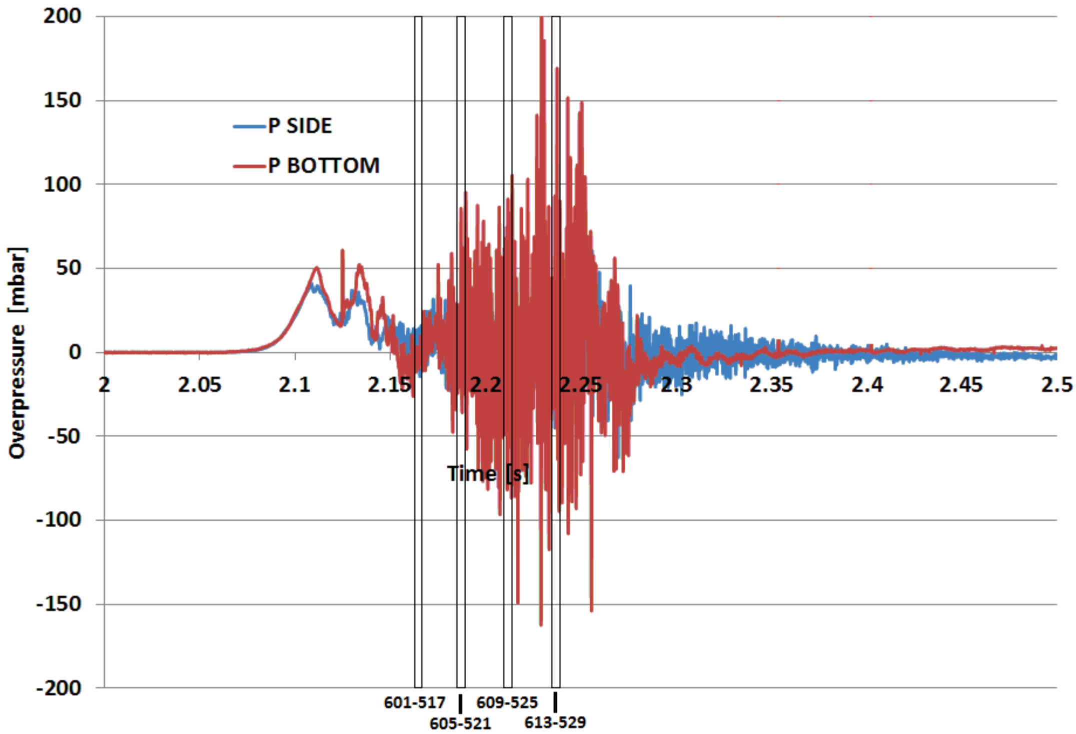


Figure 8 Frames from video recording of test TP66 (average hydrogen concentration 15.8%vol.)

4. CONCLUSIONS

Video analysis was performed to investigate the burning behavior of the flame front during homogeneous concentration hydrogen deflagration of test performed for the HySEA project by the University of Pisa.

Results show the response of the flame burning behavior to the different conditions of the flow field inside the enclosure. In the first moment after ignition the flame starts to expand and self generates turbulence and instabilities, as well described in the literature, increasing its burning rate. During this phase there are no pressure gradients inside the enclosure and the flow field ahead of the flame front is generated only by the expansion of the combustion product.

A first discontinuity in the flow field is generated during the burst of the vent. Following the vent opening a first flow field directed towards the vent area is generated. The superimposition of the flow field to the expansion of the combustion products accelerates the surface of the flame bubble facing the vent in a runaway reaction where combustion rate is increased and the higher production of the combustion product continue to accelerate the flame front. During this phase of the deflagration the flame front travelling towards the vent and the one advancing in the opposite direction undergo different burning regimes and velocities.

A second and major discontinuity in the flow field is introduced when the flame front reaches the vent area increasing the venting flow rate and producing the external explosion. As a consequence of the flow field generated during the venting process the flame front advancing in direction opposite the vent, in the present case towards the bottom of the enclosure, may be dragged back towards the vent, this effect being dependent on the velocity of the flame front itself as well as on the velocities/accelerations of the flow field generated by the venting process.

After venting the flame front burning behavior is less affected or not affected at all by the expansion of the generated combustion products which contribute to accelerate the burning regime at the beginning of the deflagration. The flame burning behavior becomes more close to a free standing flame as the one investigated by Searby in his study on acoustic instabilities on premixed flames. This is the condition in which acoustic oscillation may arise which interact with the flame front.

After venting, due to the inertia of the system which prompts Helmholtz oscillations, the air flow field may produce local flow streams in congested areas where unburned mixture is still present generating relatively high spatially localized pressure peaks.

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