Natural background oriented schlieren and multiscale visualizations of overpressure wave resulting from vapor cloud explosion

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NATURAL BACKGROUND ORIENTED SCHLIEREN AND MULTISCALE VISUALIZATIONS OF OVERPRESSURE WAVE RESULTING FROM VAPOR CLOUD EXPLOSION

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ABSTRACT

Considerable research efforts are focused to forecast consequences of aerial overpressure and impulse due to fuel-air explosions. Statistics indicate that some two-thirds of the financial loss is attributable to explosions. Previous work of the authors [1] was done on propane-oxygen stoichiometric clouds ignited by SEMTEX™ high explosives. In this second study, stoichiometric mixture of methane and oxygen filled a polyethylene envelope with a total volume of the mixture of 5.5 m3. Different image processing was performed to visualize simultaneously the propagation of combustion flame in the envelope and the overpressure in ambient air, outside the envelope. To represent realistic conditions, the shape of the gas envelope was elongated like the dispersion shape from an accidental leak with wind. An electric spark ignited the mixture gas volume on one side. Both flame propagation velocity and overpressure in open-air were recorded with direct visualization. Near field scene (10 m x 6.9 m i.e. about 1.7 times the envelope length and 6.2 times the envelope diameter) was recorded with direct illumination from the flame propagation through the use of a 20 kfps (fps, frame per second) camera. Far field scene (32.4 m x 17.3 m i.e. about 5 times the envelope length and about 16.8 times the envelope diameter) was recorded with direct lighting of the scene through the use of a 9.4 kfps camera. The mixture envelope and the camera were positioned in order to use far-field vegetation as contrasted natural background. In order to visualize the overpressure wave, natural Background Oriented Schlieren (BOS) was applied as image processing [2,3]. Because of the light fluctuation due to the explosion, the reference image for a frame corresponds to the previous frame. Direct visualization shows the combustion of the mixture with increasing velocity. A transition from deflagration to detonation is identified while the combustion front reaches the middle of the envelope. Analysis of the BOS images shows the presence of two overpressure waves of decreasing velocity outside the envelope. Evolution of the global dynamics of the phenomenon is achieved through the use of synchronization of near and far field in a composite image where RGB image layers are respectively set with the BOS image, the global view and the flame view scaled to fit the far field view.

INTRODUCTION

In case of vapor cloud explosions, velocities of both the combustion front and the blast wave are essential to correctly understand the whole phenomenon, including when deflagration to detonation transition is involved.
Trinitrotoluene (TNT) equivalency method is still widely used by industrials to determine consequences of vapor cloud explosions. However, TNT equivalence method assumes that the equivalent blast source is punctual. When a Vapor Cloud Explosion (VCE) occurs, it is important to determine the volume of the explosive cloud and thus the point source assumption may be discussed. Moreover, the dynamics of the phenomenon can vary as well. The turbulent flame moves at various velocities, depending on the turbulence produced and the nature of the incoming gas oxygen mixture.

Improvements in high speed imaging technology (frame rate, sensors sensitivity, resolution…) give the opportunity of better understanding fast phenomenon such as explosion. When interest in measuring overpressures arises, it is possible to combine pressure sensors couples with high frame rate recording. This leads to highly accurate measurements of peak overpressure and impulse at one discrete point, using e.g. piezoelectric. High speed imaging is complementary to these measurements and contributes to enhance the spatial and temporal resolution. In case of combustion, the phenomenon to investigate is visible and thus the overpressure front is relatively easy to capture. Visualization of the overpressure front without combustion required special techniques to be set up. In this study, the size of the phenomenon to investigate is large. It is therefore required to use easy to set up technique for large field experiment.

STATE OF THE ART

The literature is abundant of review of visualization techniques for fluid flows. Versluis [4] explains different applications depending on the characteristic length and temporal scale and velocity. A list of available techniques is given in order to capture overpressure wave. While classical shadowgraphy and schlieren techniques require special devices such as mirrors and powerful lighting, some others techniques are easier to set up, except the need to high frame rate recording.

Background Oriented Schlieren requires only a high speed camera. This technique consists in recording the variation of the refractive index due to target phenomenon between the camera and a contrasted background [5, 6, 7]. This background can be made from printer for example. Special pattern are drawn on a screen. The interested refractive index modification, located between the background and the camera, deviates the light rays recorded by the camera. In order to retrieve what have moved, it requires little numerical computing: the target image is subtracted to a reference one, without refractive index variation as in equation (1).

$$new(i,j) = \frac{(flow(i,j) - tare(i,j))^2}{\frac{flow(i,j)+tare(i,j)}{2} + 1} \quad (1)$$

tare is the reference image, *flow* is the considered image, *new* is the BOS image result, *i* and *j* represents respectively raw and columns index of the image.

As mentioned by [3], this method reveals the overpressure wave location by distorting the background. Once these calculations have been made, it is possible to use a cross-correlation to measure the pixel shift between images, because the pixel shift is related to the magnitude of the density gradient.

Hargather [8] has compared several natural backgrounds that can be used to reveal refraction index modification. Generally, the background is not chosen and results from the selection of the test facility with safety criteria. In [2], Mizukaki uses a background composed of soil, grass, trees and clouds. The soil, grass and the sky are not perfectly contrasted and do not provide qualitative results whereas the trees allow identifying shockwaves. Both subtraction and cross-correlation are used in these works. Subtraction gives qualitative information on the shockwave. The reference image can be a frame before the beginning of the phenomenon. Doing this, every modification in the brightness between the two images is clearly enlightened. Therefore, using reference before phenomenon can lead to soften the shock wave in the resulting image. Hargather showed that subtraction might be simpler and give higher resolution for the shock leading edge location in certain situation.

METHODS

In order to reproduce the effects of a vapor cloud explosion in the near field at an intermediate size, a 5.5 m^3 envelope of stoichiometric mixture of methane and oxygen was used. The cloud geometry parameters are defined in table 1. The free vent distance L_{FV} is defined as the minimum of the cloud height H and half the cloud width W. The cylindrical distance L_{Cyl} is introduced to measure the maximum distance a cylindrical flame front can travel before reaching the edge of the cloud. The flame travel distance L_f is the distance from ignition to the flame front, with a maximum value equal to the distance to the edge of the cloud.

Table 1. Cloud geometry parameters

Parameter	Definition	length (m)
Free vent distance L_{FV}	$min\,(H, \frac{W}{2})$	0,6
Cylindrical distance L_{Cyl}	$max(H, \frac{W}{2})$	1,2

As described by [9], the cloud is considered as elongated if the ratio of the cloud length ($L = 6{,}5m$) to the free vent distance L_{FV} is larger than 10 and the ratio of the cylindrical distance to the free vent distance $\left(L_{Cyl}/L_{FV}\right)$ does not exceed 2. These parameters were respected in this study:

$$\frac{L}{L_{FV}} = \frac{6.5}{0.6} > 10.8\ ;\ \frac{L_{Cyl}}{L_{FV}} = \frac{1.2}{0.6} = 2 \quad (2)$$

The envelope was made of 200 µm thin polyethylene. Due to plastic welding, it was not a perfect cylinder as one can see on the following picture:

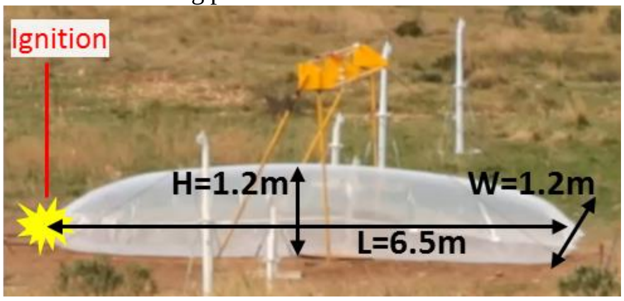

Figure 1: polyethylene envelope on the test field

The apparatus is unfolded on a military site due to safety requirements. 1.83 m^3 of methane and 3.67 m^3 of oxygen are premixed (T_{amb}: 299 K ; P_{amb}: 1013 mbar). The mixture filled the envelope of 5.5 m^3.

Fourteen PCB 137A23 blast pressure sensors were disposed around the envelop at 3, 5, 10.3 and 20 m from the center of the envelope at both axial and longitudinal directions as shown in figure 2. Data acquistion for blast sensors was achieved with HBM Genesis GEN7T at 200kHz.

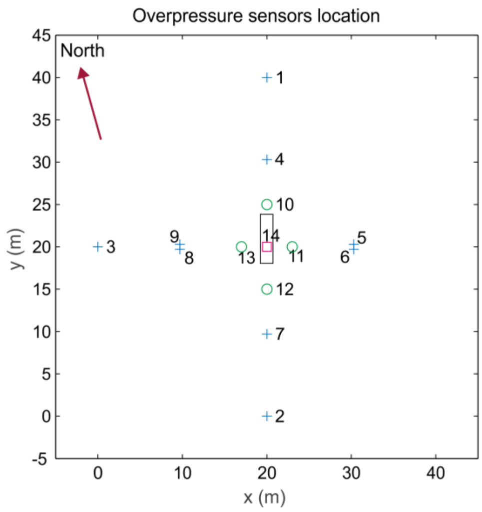

Figure 2 : Location of overpressure sensors
Altitude of the sensors is respectively 0.88 m, 1.80 m, and 1.95 m for ○, + and □.

As overpressure signals recorded by these sensors are punctual, visualizations techniques were added.

Three high speed cameras were synchronously used. The first one, a Phantom V2512, was set to visualize the flame front inside the envelope. With the same direction of sight, another camera, Phantom V711, was set to capture the overpressure wave using natural BOS. Because of the 3D aspects expected from the overpressure wave, a last camera, Photron SA-3, was set with an angle of 45° with respect of the axis of the envelope. The cameras implementation is presented in figure 3.

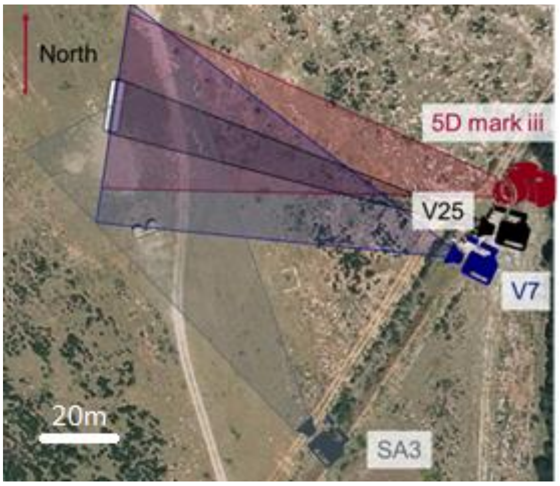

Figure 3: location of visualization

Specifications of the viewing setup are listed in Table 2:

Table 2. camera specifications

Camera	V2512	V711	SA3
Technique	Direct visualization	NBOS	NBOS
Resolution	1024 * 704	1200*640	768*512
Frequency (fps)	20 000	9 400	3 800
Magnification (mm/pxl)	9.6	28	25
Field of view (m.m)	9.8 * 6.8	33.7*18	19.2*12.8
Exposure Time (µs)	0.4	20	167

Location of both the experimental apparatus and recording location were imposed for safety reasons. Therefore, the background pattern was composed of natural bushes and trees, by different orientation for example. As shown on figure 4, several zones can be noticed:

- The direct environment of the envelope was mostly composed of sand, soil and grass with few bushes.
- As also seen on satellite view, bushes were mostly present in a second plan. Contrast was more important.
- Due to meteorological conditions, the cloudy sky was not contrasted. Global lighting of the scene was influenced by the sunshine.

Figure 4: Natural background pattern, as seen by Phantom V711

Analysis of the general background can be done quantitatively. The normalized gradient of this image figures the local contrast. It is computed and displayed on figure 5:

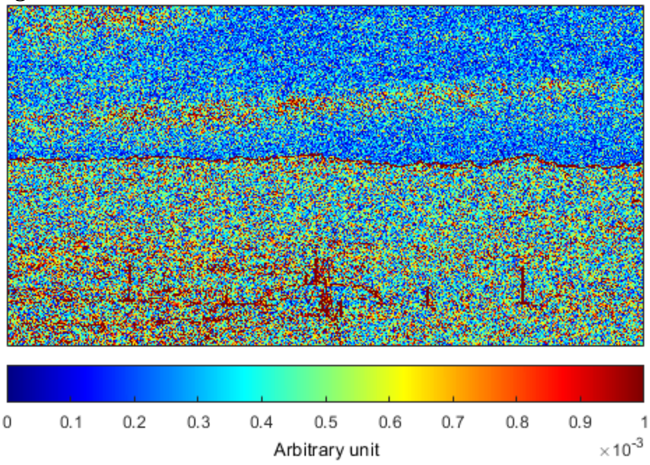

Figure 5: Normalized image gradient of the initial background before explosion

Values near to zero (dark blue) represent low local contrast. As expected, the contour lines are enlightened. Envelope, sensors base, earth-sky interface have the best local contrast values (red). Globally, bushes and soil give better results than sky. Blast wave between the camera and the background should be less visible when the sky is reached, except at the earth-sky interface.

RESULTS AND ANALYSIS

The characterization of combustion regime requires the flame velocity measurement. Visualized images of the flame in the gas mixture are shown in figure 6.

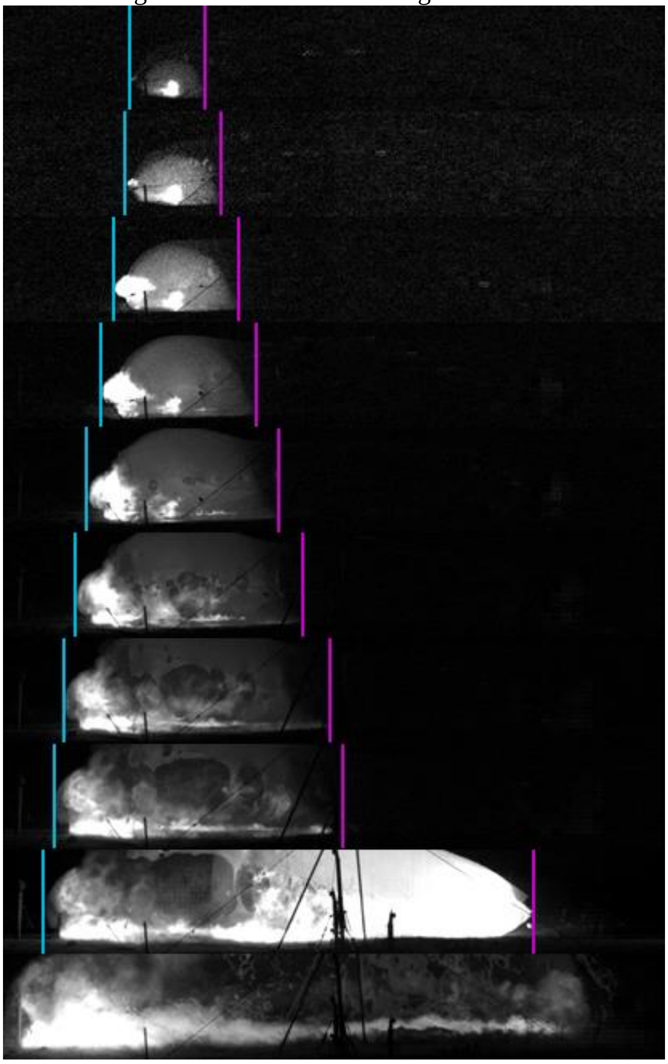

Figure 6: Flame propagation from ignition (left) to right corner in the envelope from V2512.

In this figure, each image is separated by 1.25 ms. Violet line points the combustion front of the mixture inside the envelope. On the left side, the blue line shows the split of the envelope due to expansion burning gases. In addition, an increase in light intensity is noticed when the flame front reached the middle of the envelope. It corresponds to creation of a hemispheric front, and a velocity of approximately 2390 $m.s^{-1}$. This corresponds to a detonation of the methane-oxygen mixture in stoichiometric quantities. After investigations, it appears that the location of the starting detonation corresponds to the location of the filling fitting connection to the envelope.

This accelerating front is emphasized in figure 7:

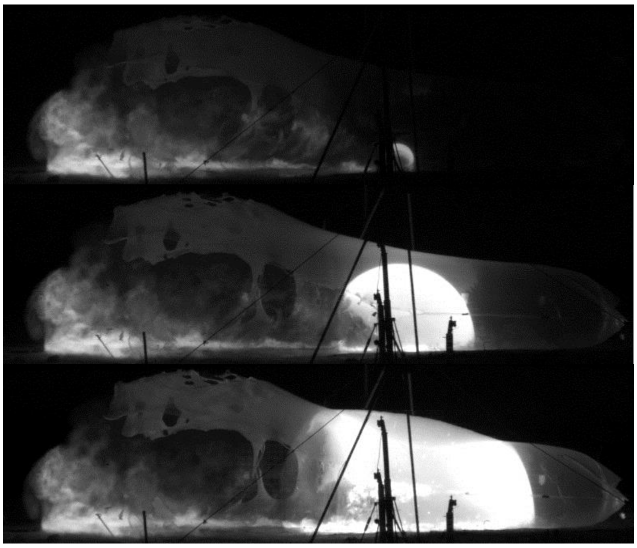

Figure 7: transition in the combustion front from V2512. Time step between images is 300 µs

This reaction front creates an aerial blast wave as it is transmitted to the air outside the envelope. This blast wave is not visible with this camera because no luminous combustion process is then realized. BOS processing is done on the phantom V711 pictures as seen on figure 8. In addition to equation (1), image values are mapped in the whole accepted interval to increase contrast. As mentioned previously, best results are obtained in the bushes/soil area.

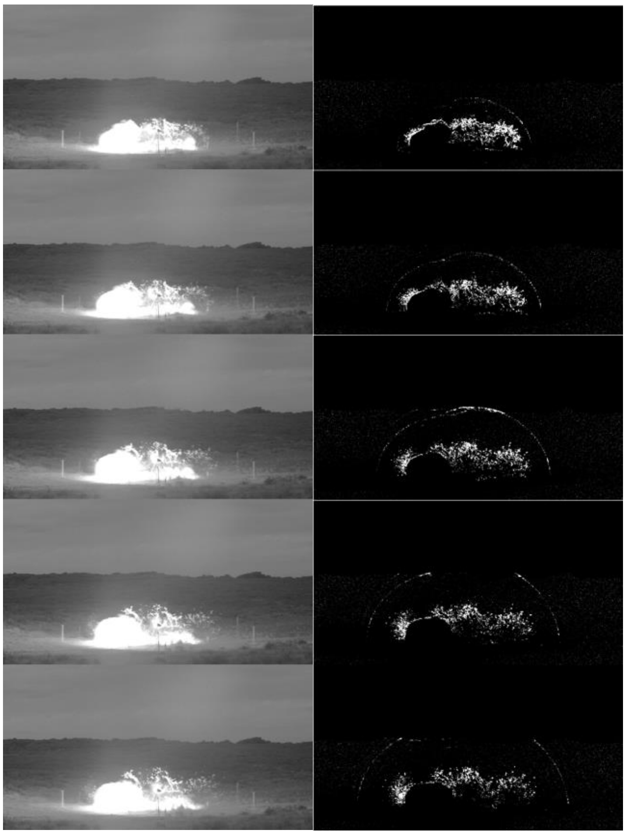

Figure 8: Blast wave in the free field – left: Original images – right: BOS processing. 106 µs between images.

The blast wave is more visible in the third BOS image at the cloud-bushes interface, as contrast is very high in this area. Initial deflagration wave is slightly visible on the left side of the envelope. Main difference with shock waves from explosives is the shape of the overpressure wave: no symmetry is reached. No classical hemispherical shape is retrieved.
Positions of the envelope and the different pressure sensors are lost with BOS image. Moreover, with the high light intensity generated by the combustion, it is impossible to see overpressure wave inside. Nevertheless, these images give useful information on the velocity of the overpressure wave in the near field of the cloud.
Understanding the whole phenomenon in the near field is made easier with by synchronizing all the data from image sensors and pressure gauges. The whole phenomenon is reconstructed by creating RGB composite image superposing original image in green layer, BOS image in red layer and dimensioned v2512 image on blue layer (figure 9). The last one is reduced in resolution. Because of the differences in recording frame rates, images of blue layer are displayed at 2.1 times the final frame rate.

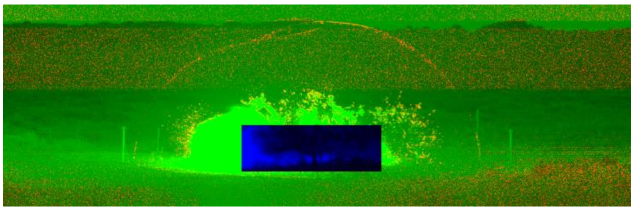

Figure 9: Composite RGB image at t=25 ms with original image in green layer, BOS image in red layer and dimensioned v2512 image on blue layer. All images are compiled in video to visualize the whole phenomenon at once.

All the data can be displayed and discussed on x-t diagram (figure 10).

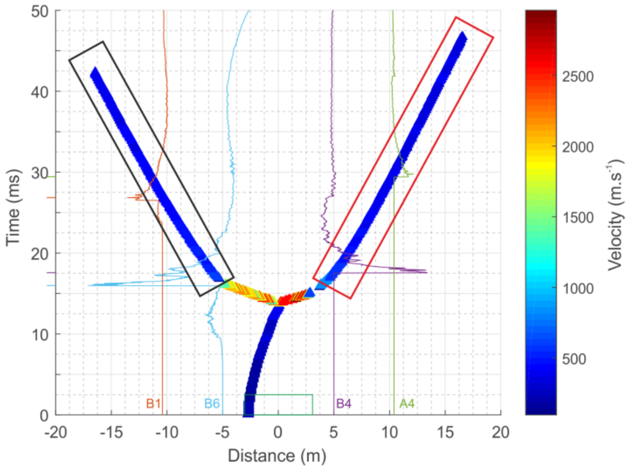

Figure 10: x-t diagram of the explosion. X-axis represents the axial line of the envelope with the origin centered on the envelope. t = 0 corresponds to the ignition of the electric spark. Overpressure signals of B1, B4, B6 and A4 sensors are represented at their respective locations with the same dimensionless scale.

On the first 13 ms, the combustion front is reported until the transition happens from v2512 images. Then, both left and right fronts are reported. It corresponds to detonation of the mixture, traveling at a speed of about 2390 $m.s^{-1}$. Limits of the envelope are reported in the green rectangle at bottom of figure 10. A slight gap in the measurements of the velocity is visible when using V711 images, due to light intensity of the combustion. Outside the envelope, the blast wave slows down rapidly (figure 11).

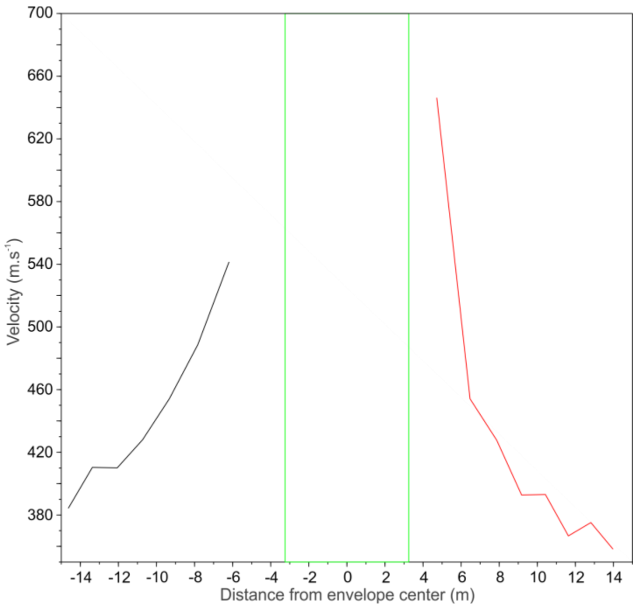

Figure 11: Blast waves velocity outside the envelope. Colors refer to corresponding rectangle in figure 10. In order to smooth uncertainties on blast wave position at each time step, velocity is computed between 30 images. Green lines illustrate geometrical the limits of the initial envelope.

Velocity of the blast wave decreases as traveling far from the envelope, from about 650 $m.s^{-1}$ to 360 $m.s^{-1}$ at the end of the visualization of the right side blast wave (end of the image). Gaps visualized at +/- 13 m are due to the lower distance traveled by the blast waves, increasing uncertainties on the velocity.

CONCLUSION

Combustion dynamics on methane-oxygen stoichiometric mixture and ignited by an electric spark was investigated. Quantitative analyses of different overpressure wave velocities resulting of the combustion of the methane-oxygen mixture of the cloud was done, both by direct visualization and natural BOS algorithm. Quality of the background has been evaluated before recording. Local contrast map have been created and showed agreements with results in BOS processing. Near field and far field were characterized and recorded synchronously. The near field, recorded by direct visualization of the phenomenon shows a transition in the combustion front, at the middle of the envelope. The resulting detonation regime propagates at about 2390 $m.s^{-1}$ while decelerating as combustion stops outside the envelope and the front becoming an aerial blast wave. These temporal data obtained by BOS imaging techniques are in perfect accordance with pressure synchronized sensors. BOS images also give the velocity decrease of the blast waves outside the envelope. Post processing consists in creating composite images of both the direct zoomed visualization of the combustion, the direct visualization of the aerial shock wave and the BOS processing, allowing better knowledge of the phenomenon on one solely video file. In a future work, algorithm like Optical flow or Particle Image Velocimetry (PIV) will be used in order to access information about the intensity of the overpressure captured by the cameras. Quality of the background has to be investigated in order to avoid important noise that can results in wrong values. Moreover, the intensity change due to the light generated by the mixture combustion in the background has to be taken into account.

ACKNOWLEDGEMENT

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NOMENCLATURE

L_{FV} Free vent distance, m
L_{Cyl} Cylindrical distance, m
H Cloud height, m
W Cloud width, m
L Cloud length, m
Lf Flame travel distance, m

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