Experimental Study of Closed Volume Explosion

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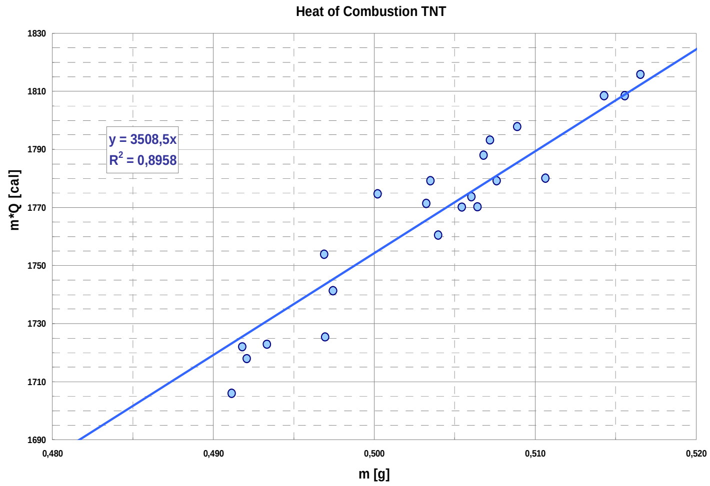
Introduction and problem statement

This paper deals with combustion effects occurring in confined explosions of condensed high explosives (HE). The explosive charge releases energy, commonly known as the detonation energy, to transform the solid phase into gaseous detonation products (DP). DP are usually fuel rich in carbon, carbon monoxide, methane, hydrogen, etc. TNT for instance is a well known HE with a negative oxygen balance (-74%). These hot gases can react when mixed with air. Then, they can release additional energy in a combustion process, usually called afterburning or post combustion with surrounding air. This process is a very specific unmixed turbulent combustion regime. Indeed, detonation products expand at high velocity, which drives a strong blast wave into surrounding air. Because of the very large density ratio across the interface DP/Air, hydrodynamic instabilities induce turbulent mixing. In a closed volume, the turbulent combustion process enhances by shock reflections from the walls. Combustion causes here an increase in pressure. Pressure measurements are widely used to quantify such constant volume combustion effects [1,3]. Overpressure measurements techniques are precisely used to link an overall thermodynamic data (the pressure) to chemical species combustion rates (burnt fuel mass). As a result, the afterburning effect of classical high explosives is a major concern for the last fifteen years in the defence community to assess mechanical and thermal effects as well as to develop blast mitigation techniques. Several authors describe simulation tools for 2D or 3D calculations of complete spherical detonation. For instance, adaptative mesh refinement techniques can be used to track turbulence in expanding DP and to determine post-combustion rate [4,7]. A.L. Kuhl studied gas-dynamic aspects of this combustion process and fuel corresponding locus in thermodynamic state spaces. These complex events are of course highly transient. The overall physics governing is controlled by characteristic time scales associated with several coupled processes. Within a closed volume, the flow dynamics is characterized first by reflected shock waves, but also by re-circulating pockets or quenching zones. S. Menon details in [6] large eddy-simulations to address these issues. In [8], A. Milne uses a multiphase Eulerian code, EDEN, to compute confined explosions within simple structures with rigid walls and gives calculation results to assess classical HE performance.

<u>CEA Gramat Studies Overview</u>

In such a problem, turbulent mixing efficiency and thermal effects are still difficult to measure. This is the reason why CEA Gramat keeps on developing several experimental configurations to characterize the “fireball” dynamics and the turbulent combustion during the course of open air or confined explosion. Both TNT and HMX-based HE (called here HMX b) were tested, in order to vary the oxygen balance, and thus the afterburning phenomena. First of all, we decided to measure their available energies - the heat of combustion- with an isoperibol calorimetric combustion bomb. HE were reduced to powder and burnt under thirty bars of pure oxygen. With such a device, we only measure constant volume combustion energy. Assuming that water exists as steam and that a total combustion occurred, we neglect gas production to determine standard enthalpy (we assume that all products are gaseous including water). We measured combustion energy of TNT of 14.689 MJ/kg in oxygen. The standard deviation is about 0.086 MJ/kg on the whole set (figure 1). This result is in good agreement with the equilibrium constant volume explosion theory and data measured by Ornellas [10] (14.958 MJ/kg). Theoretical values can be calculated with the thermodynamic equilibrium code Cheetah 2.0 [11]. Cheetah predicts a heat of detonation equal to 4.744 MJ/kg and a heat of combustion of 15.048 MJ/kg. Measured combustion energy of HMX-b is about 9.678 MJ/kg. While these tests experimentally confirmed the heat of combustion of these explosives, they only simulate a quasi-perfect combustion case and did not provide any information on the temporal evolution of the explosion energy. We then studied open air explosion and we improved classical height of burst experiment to assess characteristic times, thermal effects due to turbulent combustion and the fireball surface temperature. Results are detailed in [13,14,16]. For instance, figure 2 shows infrared cartography of a 6 kg TNT charge fireball recorded thanks to a two colour pyrometer. This picture can be directly compared with visible spectra recorded frames. The main objectives of our present studies are then to fully characterize a close volume explosion. We want to collect relevant data to validate the numerical codes we used to simulate such problem, namely Ouranos, which is an ALE Multimaterial hydrocode, or CHYMERE, our new multiphase/multispecies hydrocode, including heat and mass transfers, and simplified chemical reactions. As a result, to complete our data base, we focused on simple experimental tests to simulate enclosed systems



HE Type	E(cal/g)	E(MJ/kg)	*Total Number of test*
HMXb			
Average Value	2311,55	9,678	12
Standard deviation	17,55	0,073	
	0,76%		
TNT			
Average Value	3508,34	14,689	26
Standard deviation	20,50	0,086	
	0,58%		

Figure 1 Left: Measured heat released in calorimetric bomb during TNT combustion under pure oxygen atmosphere as a function of the sample mass – Right: experimental values of combustion energy

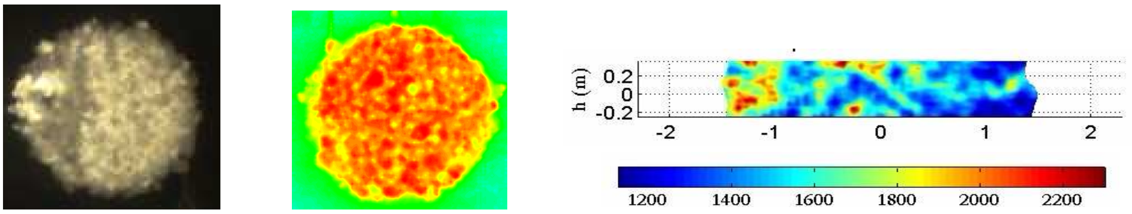


Figure 2 Fireball dynamics – Visualization of turbulent combustion (visible spectrum (left), pseudo color analysis (center) and surface temperature (right) in Kelvin (infrared pyrometer) for TNT (6 kg spherical charge)

Closed Volume Explosions Experiments - Experimental Setup

Test Chambers and Working Environment

Explosion performance of HE has been evaluated using closed chamber experiments. Three kinds of hermetically sealed room have been used to vary dynamic mixing, length ratios and also quenching or mixing rates. Three sets of experiments have been performed at CEA Gramat, namely experiments performed in the Sirocco Chamber, in the Athena Chamber and in a scaled bunker (figure 3). The bunker is a 1.875 cubic meter parallelepipedic chamber, which has several openings in order to insert sensors or glass windows. The Athena chamber is a 2.356 cubic meter sealed chamber. It is basically cylindrical, but has internal reinforcements which can amplify the mixing process. The Sirocco chamber is a 33 cubic meters cylindrical chamber with smooth walls. The experiment consists in the detonation of a spherical charge of HE. The explosive payload is detonated in the middle of the room. Shock waves induced by the explosive charge and reflected on the walls produce eddies interacting with existing instabilities. Thanks to the use of three different vessels, it is possible to cover a large spectrum of test cases: spherical charge / plane-parallel room, spherical charge / smooth cylindrical room, spherical charge / unsmooth cylindrical room. All the results below have been plotted in terms of chamber loading density W that is defined as the explosive mass per chamber volume (kg/m^3). Experiments cover a finite range of value, e.g. [0.01 – 0.12] kg/m^3. We stay thereby in the fuel-lean regime: the initial amount of oxygen is enough to burn all the fuel. Moreover, to focus on reference real cases, experiments were performed outdoor. Air temperature range was from -5°C to 35°C. Ambient hygrometry was also an important data. Relative humidity rate stayed in the range [70%, 100%]. Finally, the total number of experiments is equal to 42.

Overpressure Transducers and Typical Overpressure Time History

Piezoelectric pressure gauges (PCB Piezotronics) as well as piezo-resistive devices (ENDEVCO) allowed us to record internal overpressure time histories. Figure 4 shows typical signals. The blue curve is related to piezo resistive sensors, whereas the red one is related to piezoelectric sensors. Home made protective systems and gauges avoid classical thermal shift and pyro-electric discrepancy. Measurements chains show a very stable behavior and are able to catch continuous part of signals.

« Athéna » Chamber	« Sirocco » Chamber	Bunker

Figure 3 CEA Gramat hermetically sealed vessel dedicated to closed volume explosion

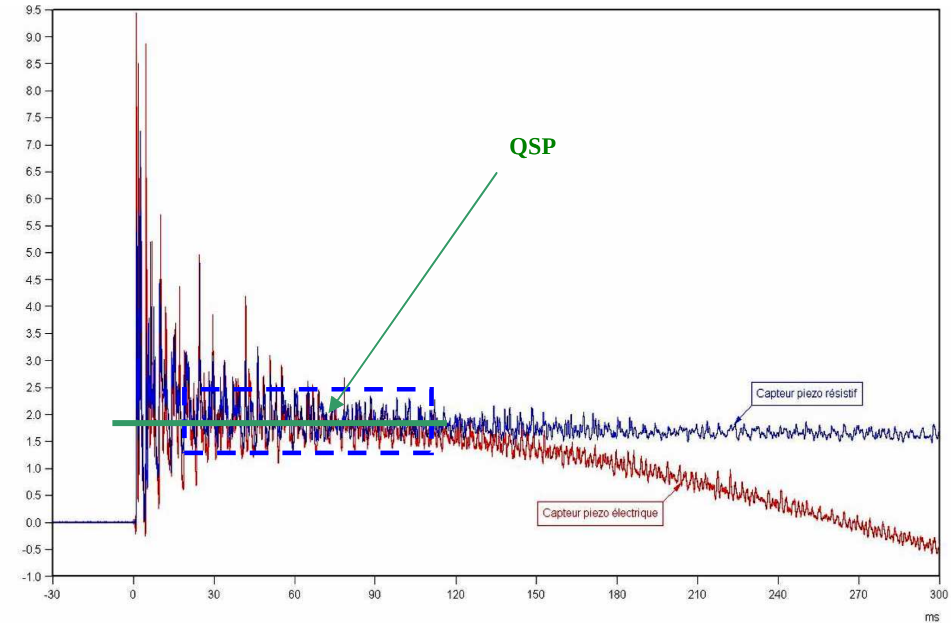


Figure 4 Typical signals: Overpressure time histories and QSP plateau (blue curve : piezpresistive transducer – red curve : piezoelectric transducer)– In blue, selected window to perform FFT

Indeed, the chosen measurement techniques are able to distinguish short-time-scale but large-spatial-gradient « blast » pressure and the long-time-scale but spatially invariant « quasi-static » pressure as described by Ames [9]. Typical total pressure time history from an enclosed explosion can be seen as a sum of a fluctuation term and a continuous term, which is illustrated by the signal figure 4.

Post-Processing of Recorded Signals

Two kinds of post-processing allowed us to measure the final quasi-static pressure reached at the end of the afterburning process (figure 4 - green line), and the continuous quasi-static pressure increase and the associated rise time: to apply a low pass filter (cutting frequency is equal to 200 Hz) is useful to highlight quasi-static pressure increase. We notice that all recorderd signals show a very stable behavior up to 100 ms after the charge detonation. The assumption of a closed system is here validated.

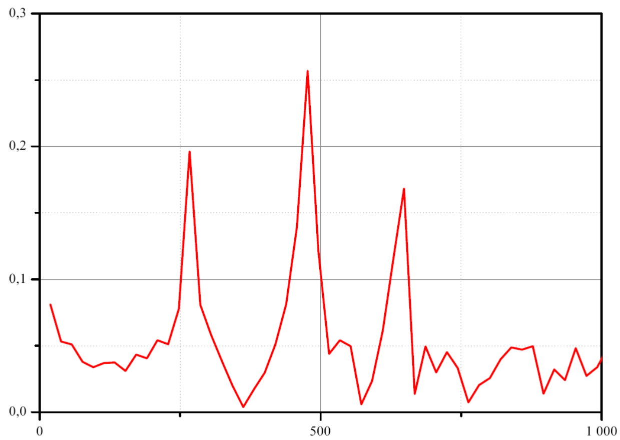
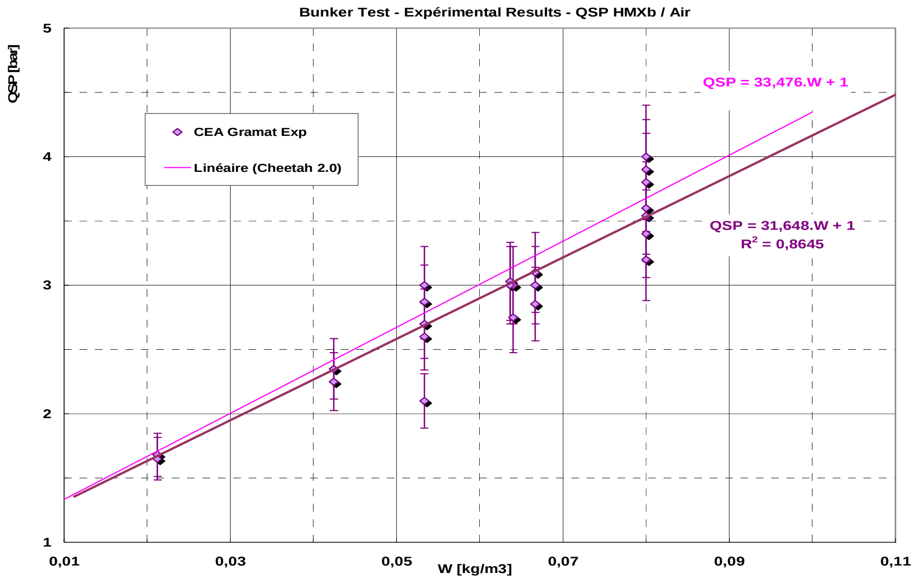


Figure 5 FFT analysis – Example of power spectrum with three main frequencies

Quasi-static overpressure and assessment of thermal effects

Figure 6 shows QSP experimental results for bunker experiments only. Error bars indicate a total error of 10 %. For both HE, QSP has a linear behaviour versus W. Experimental results are compared with theoretical values: the converted explosion energy indicates a deficit compared with the calorimetric data. Then, we can notice that the experimental values show 94 % QSP and 89 % QSP for HMX b and TNT respectively with respect to

Cheetah calculations. The combustion process is not totally achieved. These differences can be explained by non ideal boundary conditions as well as working environment. Results are also in good agreement with already published data [5, 11].



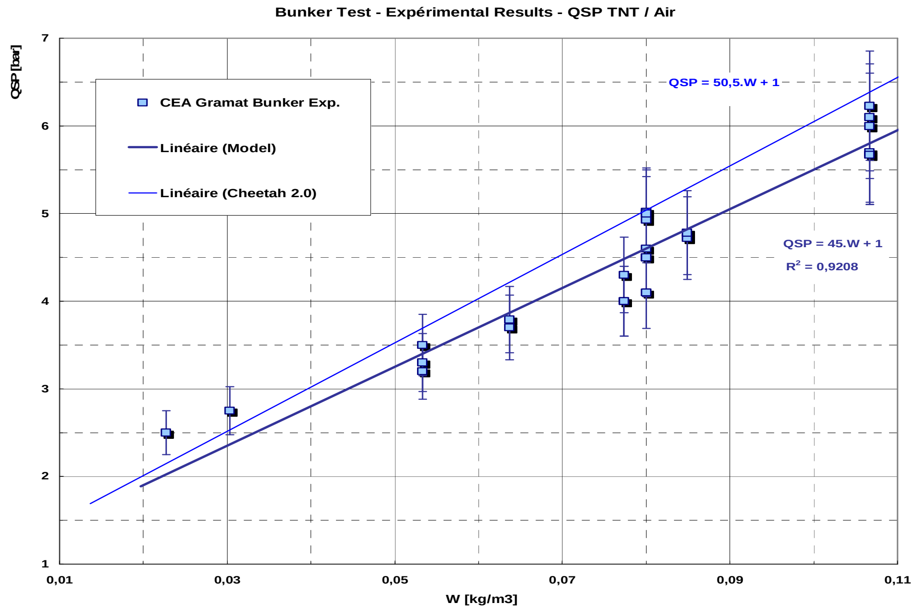
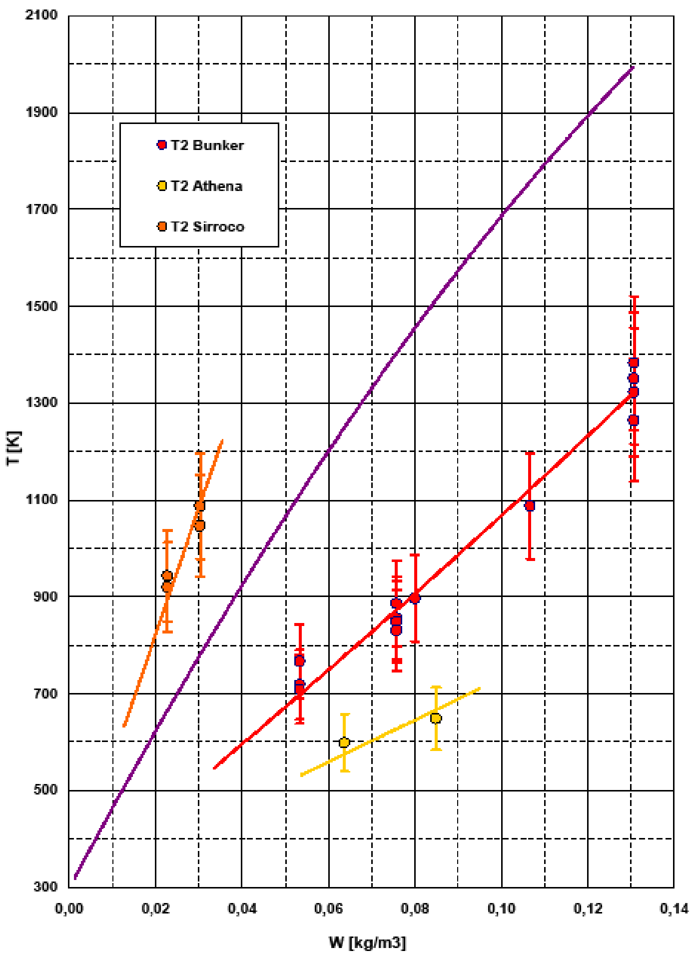


Figure 6 QSP Experimental results (absolute pressure) – Comparison with Cheetah calculations

Spectral Analysis of Recorded Signals

In order to estimate the temperature field within the room after detonation of the explosive charge, spectral analysis of pressure signal can be used. The principal task of this analysis is to provide a global interpretation of the events taking place in a closed room upon detonation of an explosive charge. DP and air induce exothermic reactions, which create hot burnt gases. The air not involved in this process has been compressed by reverberating shocks generated by the explosion and the expanding hot gases. We focused now on the final part of the process between for instance 10 and 100 ms after the detonation. In this temporal range, quasi-sonic waves propagate in the room and variations of total pressure are very small. The power spectrum of a signal is calculated by FFT over a selected window (figure 5) in order to know the mathematical composition of the signal. For each shot, we picked the main frequencies of the calculated spectrum. Then, for each mass of HE, a theoretical equilibrium chemical composition is calculated (e.g. Cheetah 2.0 constant volume explosion module). A speed of sound associated to this equilibrium state and the main frequencies values (linked to the three characteristic lengths of the room) are then calculated. At this time, gases are supposed to follow a perfect gas equation of state.



It's then possible to assess a gas temperature in which quasi-sonic waves propagate. Close to the walls, pressure gauges remain in a "cold" cells (containing compressed and heated air not involved in the mixing process) or in "hot" cells (containing DP and burnt gases), depending on their initial position. Figure 7 is an example of post processing results and allows comparing experimental values with a theoretical temperature Tqst, assuming that the remaining air (nitrogen + unconsumed oxygen) and detonation / afterburning products mix perfectly, and that a quasi-static pressure and temperature equilibrium is reached in the bunker. This assumption is obviously false, since experiments have proven that only pressure equilibrium can be obtained quickly. These experimental results show that the temperature field is complex and heterogeneous. Depending on the room volume and characteristic length, the average local temperature can be higher than Tqst. In the bunker, on the whole range of W, temperature of hot cells is lower than theoretical Tqst.

Figure 7 Estimated average temperatures of "hot" cells (violet curve corresponds to theoretical equilibrium T)

Transient Phenomena Modeling Approach – Internal Overpressure Time History

The experimental results reveal dynamic features of an exothermic process of combustion. This mechanism is here controlled by fluid mechanic transport in a highly turbulent field due to hydrodynamic instabilities and reflected shock waves. As previously described, pressures following a detonation within a structure are of the form shown figure 5, whatever the point of measurement from a rigid wall. The slow varying pressure loading term can be approximated by a time-dependent function, as detailed by A.K. Oppenheim and A. Kuhl in [2,3,4].

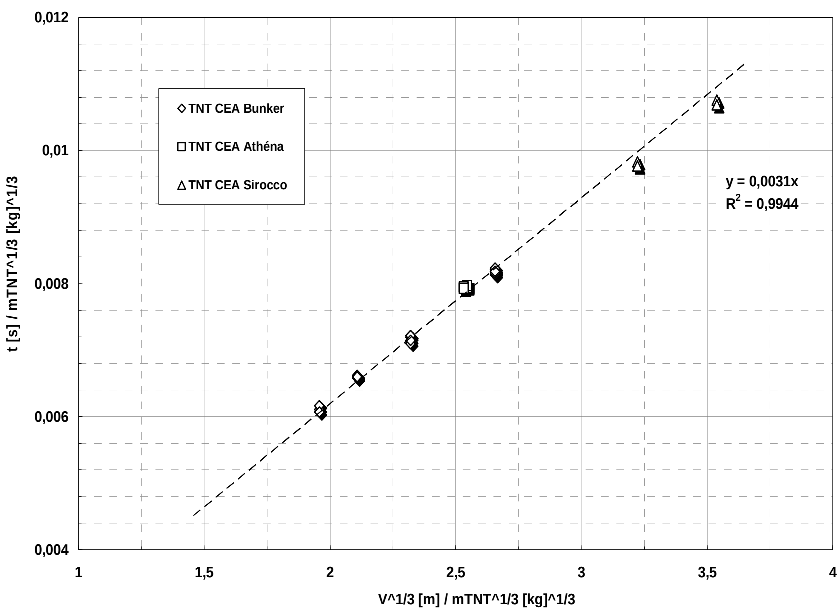


Figure 8 Time to reach 63% QSP – TNT Experiments

Indeed, A.K. Oppenheim and A.L. Kuhl described also in details in [1,2,3] the evolution of the mass fraction of fuel consumed in an enclosed system and the way to describe it thanks to very simple time dependent functions. The evolution of internal overpressure exhibits the properties of an exponential decay following a sharp initiation. For TNT and HMX based HE, all experimental data (for the three kinds of tests) allowed us to build such exponential functions:

$$\Delta P_{HMXb} = 31{,}288\frac{m_{HMXb}}{V}\left[1-\exp\left(\frac{-t}{0{,}0042V^{\frac{1}{3}}}\right)\right] \qquad \Delta P_{TNT} = 43{,}822\frac{m_{TNT}}{V}\left[1-\exp\left(\frac{-t}{0{,}0031V^{\frac{1}{3}}}\right)\right]$$

with m the HE mass in kg, V the room volume in m^3 and P the overpressure in bar. In comparison to the unconfined situation which has a theoretical infinite reaction time, Kuhl et al. showed that fuel consumption rate depends on chamber volume (figure 8). For the TNT-Air cases, some authors found that the time to reach QSP increases with loading density in the fuel-lean regime. Our results are in agreement with Kuhl and A. Milne published data [1, 15]. Rise time does not depend on the charge mass and exhibits a linear behaviour versus W.

Conclusion

Closed volume explosion experiments have been performed at CEA Gramat to assess thermal effects and to determine non dimensional internal overpressure time histories. Experimental results show that it is possible to reduce a very complex problem to simple time dependant functions. This very special unmixed turbulent combustion regime is still difficult to simulate with 2D/3D numerical codes. Indeed, final states seem to be very sensitive to working environment and initial parameters. The study of detonation products optical properties should allow us to characterize more precisely the temperature field induced by such an explosion. This work is still in progress and will be detailed in further publications.

References

[1] Oppenheim, A.K., Kuhl, A.L., Dynamic features of closed combustion systems, Progress in Energy and combustion Science, 26, 533-564, 2000

[2] Oppenheim, A.K., Kuhl, A.L., Life of Fuel in Engine Cylinder, Society of Automotive Engineers, 980780, 1080-1089, 1998

[3] Oppenheim, A.K, Sum, T-H., Inverse Problem in Explosion and Combustion, 18th International Colloquium on Dynamics of Explosions and Reactive Systems, Seattle, July 2001

[4] Kuhl, A.L., Reichenbach, H., Combustion effects in confined explosions, Proceedings of the combustion Institute, 32, 2291-2298, 2009

[5] Reichenbach, H., Neuwald, P., Kuhl, A.L, Afterburning and Combustion in Explosions in Barometric Calorimeters, 21st International Colloquium on Dynamics of Explosions and Reactive Systems, Poitiers, 2007

[6] Menon, S., Fryxell, B., Simulations of Strong Shock-Shear Layer Interactions in Complex Domains, Computational Combustion Laboratory Report 2004-015, 2004

[7] Kuhl, A. L. and Ferguson, R. E., Spherical Combustion Layer in a TNT Explosion, 17th Int. Symposium on Military Aspects of Blast and Shock, Las Vegas, UCRL-JC-143658, 2002

[8] Milne, A.M., Cargill, S., Bennett, K, Longbottom, A.W, Modelling of Enhanced Blast and Heterogeneous Explosives, 2008

[9] Ames, R.G., et al., Quantitative disctinction between Detonation and Afterburn energy Deposition Using Pressure-time Histories in Enclosed Explosions, The Thirteenth International Detonation Symposium, p.253, Norfolk, 2006

[10] Ornellas, D. L., Calorimetric Determination of the Heat and Products of Detonation for Explosives: October 1961 to April 1982, Lawrence Livermore National Laboratory, UCRL-52821, Livermore, California, 1982

[11] Zhang, Fan et al., Post-detonation energy release from TNT-Aluminium explosives, Shock Compression of Condensed Matter, American Institute of Physics, CP955, 2007

[12] Fried, L. E., Howard, W. M., and Souers, P.C.,Cheetah 2.0 User’s Manual, UCRLMA-117541 (Revision 5), Lawrence Livermore National Laboratory, California, 1988

[13] Munier, L. et al., Secondary Combustion of Detonation Products with Surrounding Air Experimental Characterization of Fireball Dynamics, 22nd International Colloquium on Dynamics of Explosions and Reactive Systems, Minsk, 2009

[14] Baudin, G., Munier, L., A simple URANS Approach for secondary combustion of HE detonation products, Shock Compression of Condensed Matter, American Institute of Physics, 2009

[15] Milne, A.M., El Mai, S., Cargill, S.B., Private communications and Analysis of closed volume experiments with octoviton, Technical Report, Fluid Gravity Engineering, TR074-06, 2006

[16] Ramel, D., Détermination optique de la température d’un volume de produits de détonation, PhD Thesis, Université Paris X Nanterre, Juin 2008