Investigation of the Behaviour of Aluminium Particles in the Burnt Products of Heterogeneous Explosives

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In 2004 research activities on thermobaric explosives were resumed at ISL [1,2]. An understanding of the mechanisms governing the dispersion and combustion of particles during the explosion of heavily metallized explosives has been one of the main objectives. This paper focuses on the study of aluminium particle combustion. ISL's experimental investigations are conducted on reference charges containing 90% of metallized explosive mixture and 10% of explosive booster (C4). The metallized mixture is made of spherical aluminium particles (diameter of 5, 45, 100 and 315µm) mixed with a liquid oxidizer, isopropyl nitrate.

1 High Speed Imaging

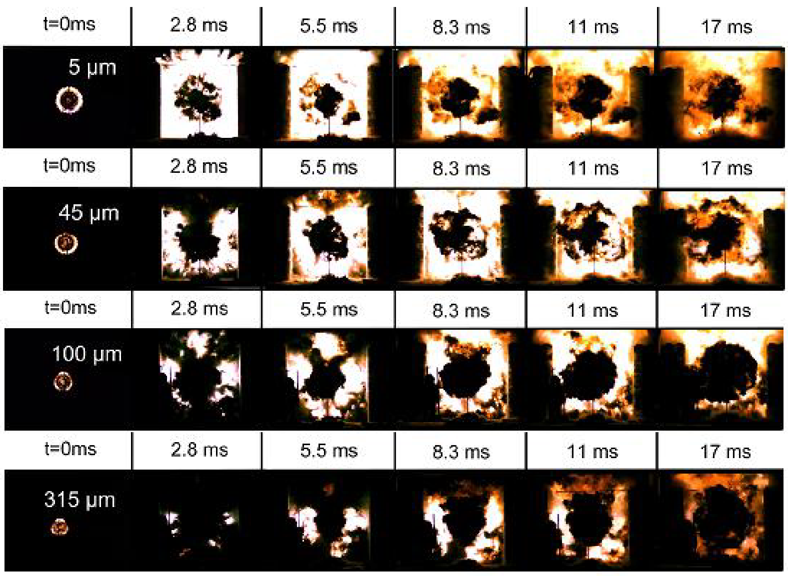

Fig.1: Effect of particle diameter on the explosion of 2kg charges in a semi-confined environment.

Metallized explosive charges were exploded in different configurations, from free field to fully confined area. A two-wall urban configuration was built using modular concrete blocks. Both the height of the walls and distance between them was 3m and the charge was suspended centrally between the walls (i.e. 1.5m from the ground and 1.5m from the wall). High speed camera filmed each explosion from a distance of 60m at 9000 frames per second, always using the same parameters for aperture and exposure. Figure 1 presents typical sequences of explosion of a 2 kg charge for different aluminium particle sizes. Present observations are in agreement with results previously reported by other researchers [3,4]: 5µm particles ignite easily, generating an intense fireball which is observed during more than 60ms. Combustion of 45µm particles occurs later but the resulting fireball is similar to that generated by 5µm particles. For 100µm diameter particles and above, the initial detonation wave is not strong enough to initiate and maintain combustion of aluminium particles during the detonation products expansion. Some local afterburning reactions can be observed near the walls, where the reflected shock waves favour local ignition and burning of particles.

2 High Speed Spectroscopy

An experimental technique of high speed spectroscopy was recently calibrated and tested with different generic explosive charges. The capability of recording one spectrum per millisecond with a maximum duration of 2 seconds allows us to detect the moment and location of the metal particle combustion. Based on a Czerny-Turner configuration, it uses a 512 pixel linear CMOS sensor, having a wavelength resolution of 1nm/pixel (in the range 400-912 nm). The spectroscopic analysis is carried out over a 1.6m high vertical band, centred on the vertical charge axis and 0.5m away from the left wall, focusing on the area where the reflected shock waves should enhance combustion reactions. Depending on aluminium boiling temperature (and also aluminium oxide boiling temperature), metal particles can burn in vapour phase (adiabatic flame temperature higher than the boiling temperature) or in solid phase (adiabatic flame temperature lower than the boiling temperature). Aluminium burning is known to yield solid oxide Al_2O_3 as final product with intermediate steps involving gaseous AlO. AlO presents characteristic molecular emission bands between 460nm and 510nm [5]. It is therefore possible to identify aluminium combustion by focusing on this range of wavelengths.

In present experiments two wavelengths were chosen for analysis:

-630 nm: this wavelength is located out of any specific atomic or molecular emission or absorption area. It also corresponds to a sensitive wavelength range of the spectroscopic CMOS sensor, minimizing the measurement error due to electronic noise;

- 487 nm: this wavelength corresponds to one of the emission bands of AlO. This could be clearly distinguished on all the recorded spectra (Figure 2). To evaluate the contribution of AlO to the total emission, we defined the ratio of the 487nm intensity (I_{487}) on the average ($I_{average}$) of the two minima either side of the peak.

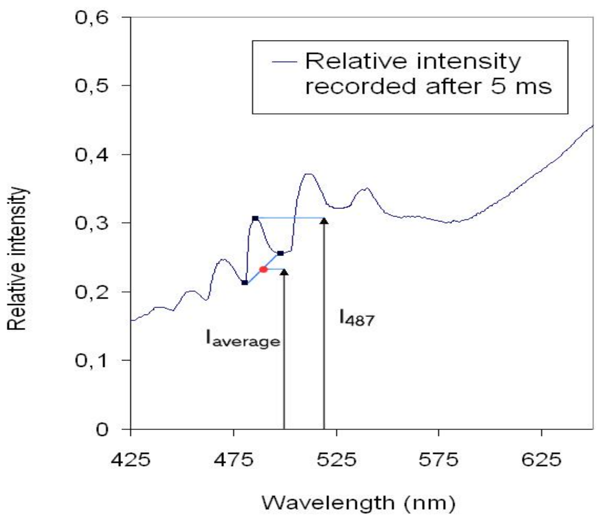

Fig. 2: Definition of I_{487} and $I_{average}$

Figure 3 represents the time evolution of the 630 nm relative intensity recorded during the explosion of 2kg charges for four different aluminium particle diameters (5, 45, 100 and 315 µm). Figure 4 compares the 487nm intensity ratio (dots) with the relative intensity.

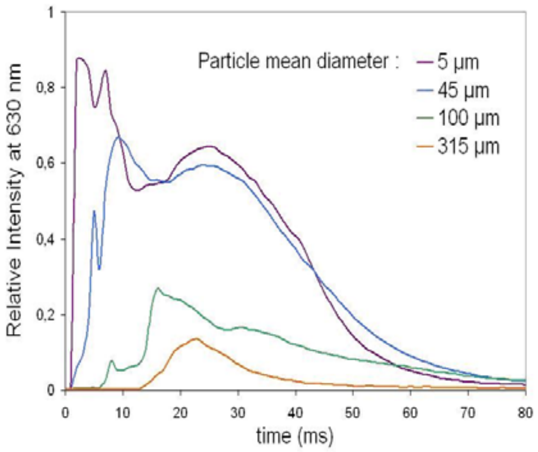

Fig. 3: Relative intensity at 630 nm for 2kg aluminized charges

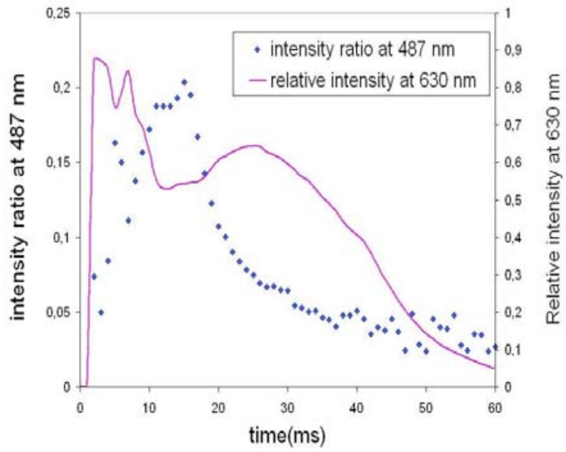

Fig. 4: Relative intensity at 630 nm and intensity ratios at 487 nm for 2kg charges containing 5µm particles.

Depending on the metal particle size, different combustion behaviour can be observed in the detonation products: 315µm particles present a delayed ignition with low and short emission, while 5µm particles react almost instantaneously and keep burning for more than 40ms. The presence of AlO at different times indicates that aluminium combustion occurs with different delays depending on the particle size and non-monotonous rates during the fireball expansion.

3 Pyrometry

By recording the light spectrum emitted by metallized explosives, it is possible to collect information on the presence of certain species during the fireball expansion. An average apparent temperature can also be determined at each integration step, using the classic method of the two-colour pyrometry. Despite it is known that this technique can generate significant errors in certain conditions [6], it does not require the determination of emissivity of the observed area. This variable is indeed hardly accessible since it depends on the wavelength and the chemical species present in the observed area. Previous studies determined the temperature of metallized explosive fireball using fixed wavelengths with better time resolution [5,6,7]. The ISL spectroscope allows choosing any pair of two wavelengths out of any specific atomic or molecular emission since all spectra are fully recorded during the explosion duration. The two wavelengths chosen for this study are 440 nm and 630 nm, corresponding to the apparent grey emission zones of the spectrum and being in a similar sensitivity range of the spectroscope sensor. Figure 5 presents the estimated fireball temperature evolution during the explosion of four 2kg charges for different aluminium particle sizes (5, 10, 100 and 315µm).

For homogeneous charges, the apparent temperature of burnt products stagnates at approximately 2500K during 15ms. In the case of a heterogeneous fireball produced by aluminized charges, the measured temperature reaches levels between 3000 and 3500K, influenced by the flame temperature of aluminium mixed with air (~3400K) [5]. Nevertheless the temperature tends to approach the value recorded with homogeneous explosive after 20~30ms, when particle combustion rate decreases. For the smallest particles (5 µm), the highest temperature (>3300K) is reached within a few milliseconds. For the 100µm particles, the temperature is at first

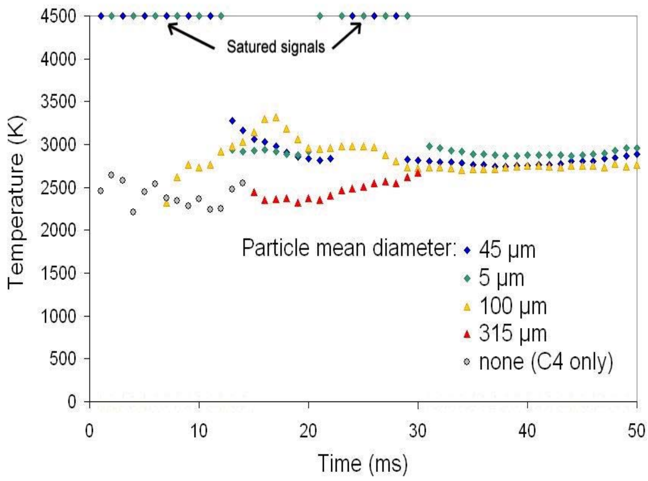

Fig. 5: Apparent temperature calculated for different explosive charges containing aluminium particles.

about 2500K, which is comparable to the value recorded for the pure booster explosion. Between 15 and 20 ms, the apparent temperature rises to 3400K, confirming the presence of delayed burning of aluminium. The late and low temperature increase observed for the largest particle fireball raises the problem of the reliability of these measurements when particles are partially reacted and projected. In this case, the observed area is not uniform, thus the error on the apparent temperature increases, as the grey body assumption may be not valid anymore.

4 Numerical simulations

In the computer model for multiphase reactive flows of the Laboratoire de Combustion et de Détonique (LCD) of Poitiers [8], the temperature of particles is assumed to be uniform. In the case of large particles this assumption may be incorrect. Therefore, a 1D model of a nonuniformly heated metal particle immersed in a hot gas has been developed in order to simulate the ignition process of a single particle of arbitrary diameter placed in the detonation products. Currently, the heat conduction problem in the particle is studied numerically and comparison is made with experimental data on ignition delays of particles of different size. A Crank-Nicholson scheme is used to solve that equation, providing second order precision in time and space. It has been demonstrated conclusively that the assumption of a uniform particle temperature is acceptable even for the largest particles considered here. Nevertheless characteristic ignition times have been assessed for aluminium particles under different boundary conditions. For instance, figure 6 presents ignition delays estimated for different particle sizes submitted to an external temperature of 2500K - which corresponds to the apparent temperature observed during the explosion of a 2kg C4 charge. It is considered that particle ignites when its external surface reaches the threshold temperature of 1000K. A flow field around the particle can also be simulated with LCD's code since this model tolerates time dependent boundary conditions.

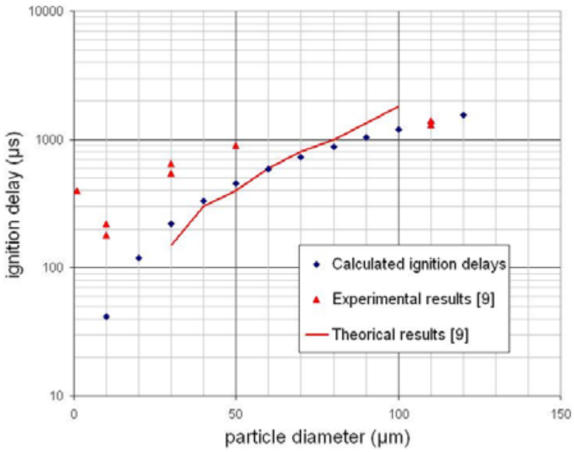

Fig. 6: Estimated ignition delays and comparison with literature

5 – Conclusions

These studies have been carried out to improve our understanding of the combustion of metal particles dispersed by heterogeneous explosive mixtures. Different reference explosive charges containing a large amount of aluminium particles have been tested in free field and semi confined environment. Depending on particle size and environment geometry, the combustion occurs with variable delays and at non-monotonous rates, with reflected shock waves enhancing the chemical reactions by compressing and mixing the reactants. An apparent temperature was evaluated using two-colour pyrometry. These data are compared with a 1D model built to estimate ignition delays of coarse aluminium particles with non uniform internal temperature. These results validate some hypothesis chosen for LCD's multiphase combustion model.

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