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Temperature measurement during the combustion of a single aluminium particle

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1 Introduction

Aluminum is seen as an additional source of energy that can be added to propulsion and explosive systems. Explosions are defined as phenomena that release energy into space faster than it can distribute itself, resulting in the formation of a shock wave. A common example of an explosion is the detonation of a condensed explosive charge. This phenomenon is extremely exothermic and is defined by a reactive shock wave, propagating in the solid explosive, breaking down into the product of detonation. These products, in contact with air, can in turn enter into combustion; this is the afterburning phase. This afterburning phenomenon greatly contributes to the total energy released during the explosion. The use of metallic particles in the composition of explosives makes it possible to reinforce the effects of afterburning. Aluminum has an important role in this phase, when it is used in explosives as demonstrated by Fedina [1] and Frost et al. [2]. Aluminum particles are heated by the detonation wave, then dispersed with the expansion of the gases and burn in a mixture composed of the detonation products and air. Additional heat is then produced within the fireball, making it more energetic as described by Cooper et al. [3].

Aluminum particles burn in the mixing zone which is on the periphery of the fireball. This zone is composed of air and detonation products (CO_2 , CO , H_2O). The study of the different reactions, depending on the environment of the particle, is therefore a major challenge for the understanding of aluminized explosives. In this context, the knowledge of information such as the combustion time and the temperature of the condensed phases is essential. To achieve this, we have set up a system to study the combustion of an isolated particle in various gaseous atmospheres. This study is limited to the description of the combustion of aluminum particles in air.

2 Single particle stabilization

The experimental device is mainly composed of a high-pressure combustion chamber in which an electrostatic levitation system is inserted. The particle, initially charged with triboelectric effect, is

introduced in the electric field in the center of the levitator. This single particle is isolated in the center of the chamber by modulating the different voltages of the levitator. A CO₂ LASER (power of 50 W, wavelength of 10.6 μm) is used to warm up the particle till ignition. Once the combustion is initiated, the LASER is stopped. The particle stabilized in levitation is heated almost uniformly on both sides thanks to the laser beam initially divided in two. The high-pressure chamber (up to 12 MPa by design) allows combustion experiments to be conducted in a controlled gaseous atmosphere, and with a wide variety of gas composition.

The temporal follow-up of the evolution of the burning particle is ensured by the use of an imaging device coupling a fast camera PHANTOM combined with a long-distance microscope QUESTAR QM100 focused on the particle in reaction. The camera used is the PHANTOM TMX 7510, allowing 76000 fps at maximum resolution (1280x800 px) to 78000 fps at the resolution used in this study (768x768 px). The magnification obtained with the long-distance microscope is 1.27 $\mu\text{m}/\text{px}$. The images obtained by the fast camera allow not only a phenomenological description of the combustion process, but also, after the application of a numerical treatment, the extraction of quantitative information such as for example the diameter of the initial aluminum particle after melting, the temporal evolution of this diameter, the migration speed of the alumina particles towards the drop, etc.

This device has already been described in detail and we invite the reader to consult reference [4].

3 Method for Temperature measurement

The method selected to measure experimentally the temperature is the multispectral pyrometry. This method makes it possible to determine the temporal evolution of the integrated temperature of the condensed phase during the combustion of the aluminum particle [5-7].

To achieve this, an optical system composed of 3 photomultipliers (Thorlabs PMT1002) is also set up to follow the temporal evolution of the light signal emitted by the particle during its combustion. The PMTs are operating in a wavelength range between 250 and 900 nm and at a frequency of 250 kHz. A USB-1808X acquisition card (Measurement Computing) is used to digitize the signal.

Each PMT is equipped with an interference filter (610 nm, 720 nm and 830 nm) whose wavelength has been selected to avoid the emissions of the various gaseous species produced in the reaction zone. A sketch of the pyrometer is proposed in Fig. 1.

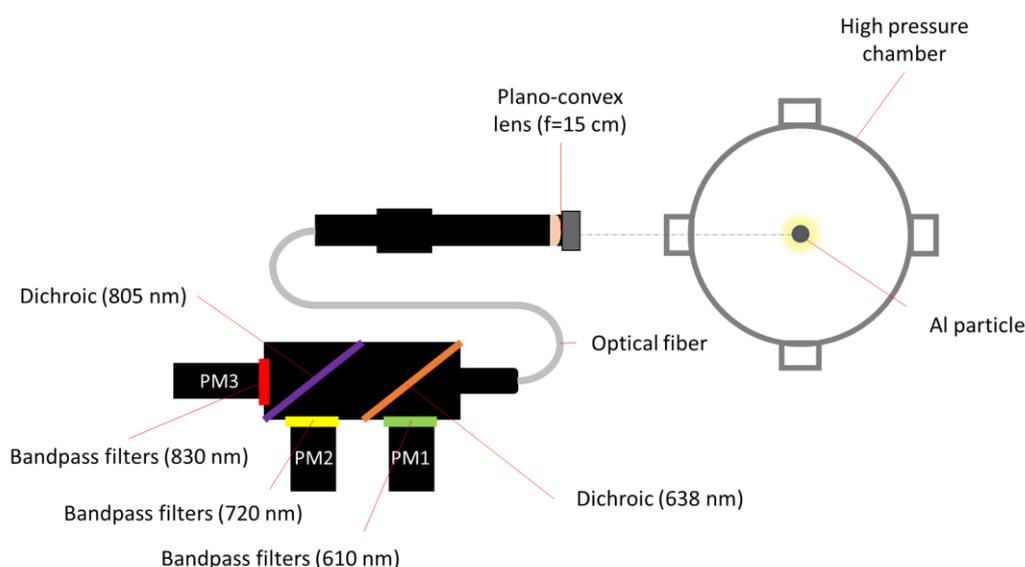


Figure 1: Schematic of the pyrometer (top view).

The pyrometer is calibrated using a calibrated black body (maximum temperature of 2000 K). This method allows to account of the optical transmission of the optical arrangement and the nonlinear response of the photomultipliers. For this study, we only used two wavelengths ($\lambda_1=720$ nm and $\lambda_2=830$ nm). We assume in the following that the emissivity of the condensed species does not vary over this wavelength range.

By evaluating the ratio of the radiant intensity measured at the two selected wavelengths, $\Gamma = L_{\lambda_1}/L_{\lambda_2}$, we obtain the expression for the temperature:

$$T(\Gamma, \lambda_1, \lambda_2) = \left[\frac{k}{h \cdot c} \cdot \frac{\lambda_1 \cdot \lambda_2}{\lambda_2 - \lambda_1} \cdot \left(\ln(\Gamma) - 5 \cdot \ln\left(\frac{\lambda_1}{\lambda_2}\right) \right) \right]^{-1}$$

With k the Boltzmann constant, h the Planck constant and c the speed of light.

4 Description of the combustion process

Aluminum particles of diameters around 70 microns have been selected for this study. They are ignited in atmospheric air. Note that the LASER is stopped after ignition.

The combustion process is illustrated in Fig. 2.

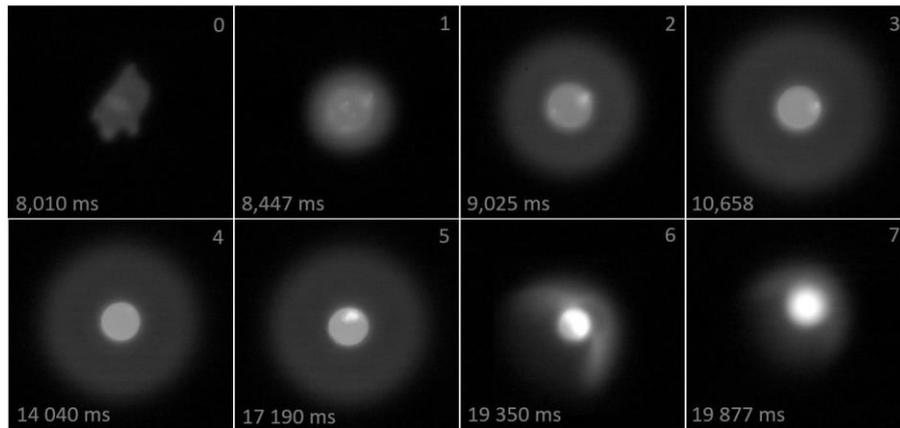


Fig. 2: Images extracted from a combustion sequence of an Al particle in atmospheric air. (initial diameter = 73 μm , sequence captured at 78 000 fps)

After ignition, gaseous aluminum is produced and react with the oxidizing environment. The combustion process starts and the laser is stopped after 8 ms. Then, a diffusion flame develops around the liquid droplet during the beginning of post ignition phase. The flame initially grows up with the reacting gaseous flow to reach an equilibrium position and become quickly established and totally spherical (from 10 ms to 18 ms), corresponding to the maximum of light emission. Thus, the aluminum burns in an almost symmetric steady vapor phase. The droplet diameter and the flame diameter gradually reduce and the emission signal decreases proportionally to the reduction of the luminous surface

The temporal evolution of the condensed phase temperature after ignition is reported in Fig. 3.

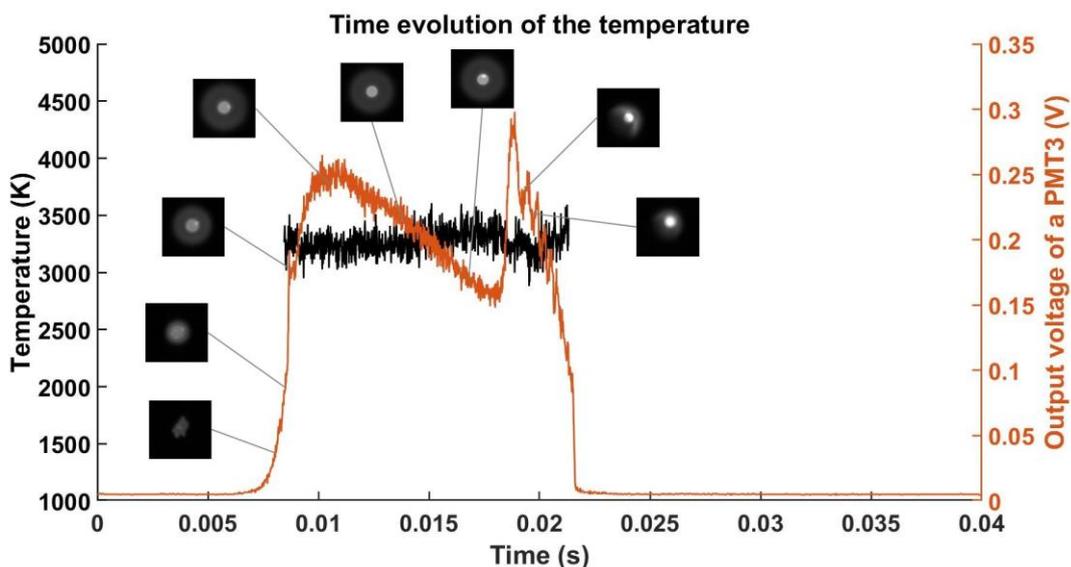


Figure 3: Time evolution of the temperature of a burning aluminum particle in air at atmospheric pressure (solid black line) and output voltage (solid orange line) of one PMT ($\lambda=830$ nm)

Fig. 3 shows in black the calculated temperature during the combustion of an aluminum particle in air. In orange, the evolution of the output voltage of a PMT ($\lambda_2=830$ nm) has been reported to facilitate the identification of the different combustion phases.

After the ignition phase (about 8 ms), an average temperature of about 3250 K is obtained. This temperature corresponds to the temperature of the alumina particles produced in the reaction zone. Similar evolutions were obtained for other particle sizes. Then, we observe that the radiant intensity gradually decreases, but the temperature remains constant. This is explained by a regression in the diameter of the particle due to the evaporation of the aluminum. The temperature remains stable all the same, because the combustion is still in progress. The peak observed before a time of 20 ms corresponds to the covering of the particle by alumina.

We have demonstrated during this study that the system set up makes it possible to precisely measure the temporal evolution of the temperature involved during the combustion of an aluminum particle. This system will now be used to detail the combustion of particles under high pressure conditions and in different gaseous atmospheres.

Acknowledgements

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