Experimental studies on the propagation velocity and temperature of flames in aluminum micro- and nanoparticle clouds

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1 Introduction

The available literature shows that Al nanopowder can significantly improve the combustion properties of some energetic materials, especially for propulsion applications. Solid propellants containing Alex nanopowders exhibit burning rates much higher (in some cases as much as 5 to 20 times higher) than the propellant formulations containing regular Al powder [1]. Further, HTPB-based solid-fuel formulations containing Alex or other nanopowders demonstrated mass burning rates in a hybrid rocket up to 50% higher than the baseline formulations with regular Al powder [2]. These superior performances of the energetic compositions containing Al nanoparticles compared to the conventional microsize particles are related to higher specific area and reactivity of nanopowders.

In the present work, the investigation is related to combustion studies of aluminum particles injected into a tube and ignited by an electric spark after the formation of a cloud. The experiments are conducted for two purposes: first to measure the flame front propagation velocities for different sizes of the Al particles, second to measure the temperature of the gas phase during cloud combustion. The experimental temperatures are compared with thermodynamic calculations.

2 Experimental setup and methods

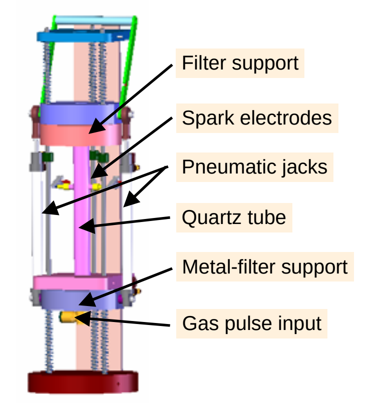

Figure 1: Combustion apparatus.

Figure 1 shows the experimental setup used for studying the combustion of nanoparticle clouds in air under normal conditions of pressure and temperature. The combustion chamber is essentially a quartz tube (inner diameter of 14 mm, height of 180 mm giving an inner volume of 27,7 cm^3), whose bottom end is closed by a porous metal plate, and the top end is closed by a thin cellulose filter. For the given reactor volume, the stoichiometric conditions in air correspond to 9.3 mg of Al mass. The present experiments are performed for different conditions corresponding to a global Al concentration from 200 to 2000 g m^{-3}.

The powder sample is placed in the bottom of the tube. Injection of particles and formation of the cloud inside the tube are achieved by a pulse air injection, using an electrical valve, to carry and disperse the particles in the tube. The injection pressure and duration are adjusted to achieve an optimum distribution of the powder inside the tube. After suspension, the cloud is stationary due to low sedimentation velocities of Al nanoparticles within

Correspondence to: escot@cnrs-orleans.fr the range of 10^{-5}-10^{-3} cm/s. The particle cloud is ignited by a spark placed on the axis at 30 mm from the top section of the tube. In these experiments, this ignition section was selected as providing the optimum ignition probability for all the combinations between the injected powder quantity, the injection time and pressure. A high-speed video camera (Phantom V5.0 with 1000 fps at a maximum resolution of 1024 x 1024 pixels, or higher frequency by reducing the resolution) is used for the flame front observations and propagation velocity measurements. The propagation velocity of the burning cloud is determined for different Al nanopowder samples by image analysis.

For the temperature measurements, particle cloud flame emission spectra are recorded using a high resolution spectrometer in the visible range. The fitting of bands $\Delta v = -1, 0, +1$ of the AlO emission is used for the determination of the gas phase temperature during cloud combustion. Equations used for the simulation of the AlO emission spectra are given below.

The specific intensity assuming that medium is optically thick, $I_\lambda(T) = B_\lambda(T)\left[1 - e^{-\alpha'_\lambda l}\right]$ (1)

The absorption coefficient corrected for stimulated emission, $\alpha'_\lambda = \dfrac{E_\lambda(T)}{B_\lambda(T)}$ (2)

Spontaneous emission with medium optically thin, $E_\lambda(T) = \left[\dfrac{16\pi^3 c N_u(T) \nu^4_{v'v''}}{3(2J'+1)}\right] S_{v'v''} S^{J'\Lambda'}_{J''\Lambda''} \times 10^{-11}$ (3)

The number of AlO molecules in the upper state is given by $N_u(T) = \dfrac{N(2J'+1)}{Q} e^{-\frac{E_u}{kT}}$ (4)

Where $B_\lambda(T)$ the Planck black body function, l the geometric path length, c the speed of light, $\nu_{v'v''}$ the frequency of emitted radiation, $(2J'+1)$ the spin multiplicity, $S_{v'v''}$ the band strengths, $S^{J'\Lambda'}_{J''\Lambda''}$ the line intensity factor, N the number density of molecules, Q the partition function, E_u the spontaneous emission in the upper state, k the Boltzmann constant and T the temperature.

In the experiments, two different Al powders: a nanopowder (250 nm) and a micropowder (6 µm) provided by SNPE Matériaux Énergétiques.

3 Flame propagation velocities: results and discussion

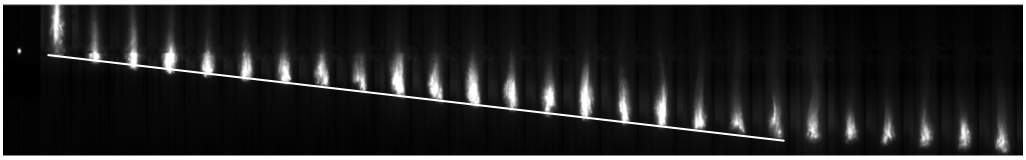

Figure 2: Sequence of Al particle cloud combustion (10 ms between frames).

Figure 2 shows a sequence of Al particle cloud combustion. In that sequence the time between frames is 10 ms. The first picture of the sequence shows the ignition point of the cloud due to the spark. Then the combustion front propagates both downwards and upwards along the tube axis. The upwards propagation ends quickly because of the expansion of the hot products. After a stabilization time, only the downwards propagation remains and can be analysed. Particle cloud flame propagation velocities are obtained by numerical the image analysis of the combustion light emission. Numerical analysis of each frame gives two parameters: time *t* and flame front position *x*. The gradient of *x*(*t*) gives the mean velocity. The experimental velocities thus obtained are collected in Figure 3.

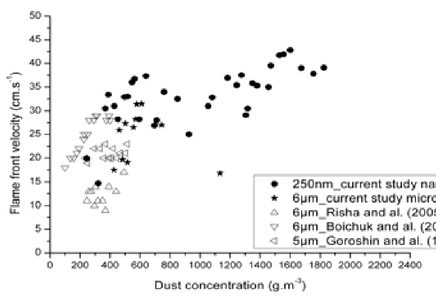

Figure 3: Flame front velocity of Al particle clouds versus dust (particle) concentration for different particle sizes.

Figure 3 compares cloud burning velocities determined for various micro-aluminum and nano-aluminum particle concentrations in air with different data from the literature. Microparticle clouds experiments are in a good accordance with the data from the literature. The results for nanoparticle clouds give two maxima: one next to the stoechiometric concentration and the second one at a higher concentration. The second maximum can be due to the increasing total area of particle surfaces when the particle concentration rises. The experiments indicate that for the same global concentration the nanoparticle clouds burn faster than microparticle clouds.

4 Flame temperature, results and discussion

Figure 4 presents different stages of the analysis of emission spectra from microparticle combustion. First is the initial spectrum obtained after the combustion, then the spectrum is divided by the apparatus function and finally the continuous spectrum is deleted to use the AlO spectrum for simulation.

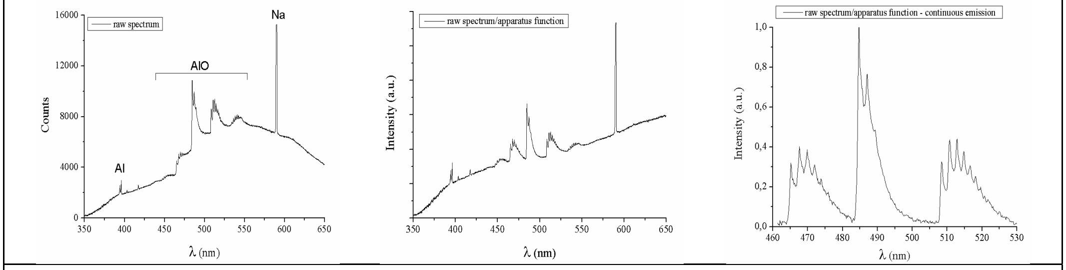

Figure 4: Different stages of the analysis of emission spectra from microparticle combustion.

The simulated AlO emission spectra are in a good accordance with the experimental spectra and give a constant value of 3300 K for the microparticle cloud combustion and 2900 K for the nanoparticle cloud combustion.

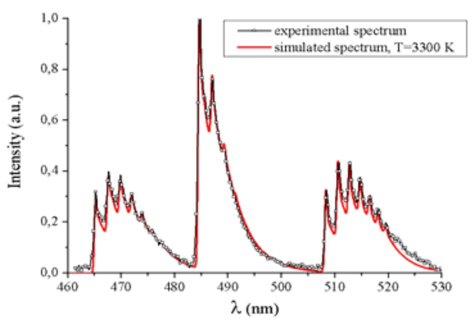

Figure 5a: Experimental and simulated AlO emission spectra during aluminium microparticle cloud combustion in air.

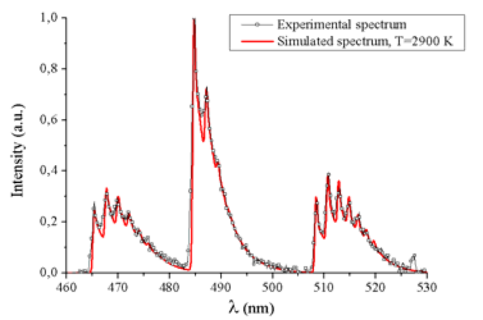

Figure 5b: Experimental and simulated AlO emission spectra during aluminium nanoparticle cloud combustion in air.

The temperature calculations are made using a 0D model including radiative heat losses. The burning time t_b is imposed. The formula used for the heat losses is $q=\sum_p \varepsilon\sigma\left(T^4-T_\infty^4\right)$ where $\sum_p$ is the surface of all particles, ε the emissivity equal to 1, σ the Stefan-Boltzmann constant, T the mean temperature of the cloud, T_∞ is considerated equal to 300K.

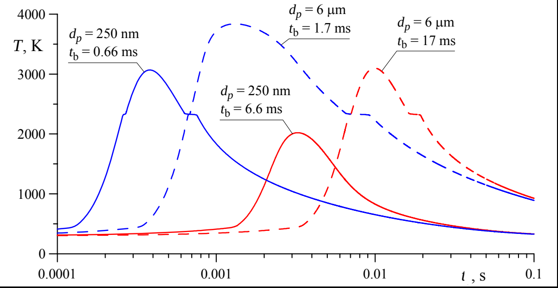

Figure 6: Flame temperature given by thermodynamic calculations including heat losses. Two sizes of particles in two different approaches are used [3].

Figures 6 shows the effect on the flame temperature of different hypothesis taken for the thermodynamic calculation during aluminum cloud combustion. The hypothesis on the combustion time t_b are taken from the results of *Parr et al* [3], which proposes two approximations $t_b(d_p)$ depending on the initial temperature.

The temperature measurements indicate a consistent value around 2900 K for all nanoparticle burning clouds and 3300 K for microparticle clouds. These results are confirmed by the thermodynamic calculations, which give the temperature between 2030 K and 3100 K for nanoparticles and between 3100 K and 3830 K for microparticle.

4 Conclusions

The present results show that nano-sized Al particle clouds burn faster than micro-sized particle clouds for the same global particle mass concentration in air. The cloud flame propagation velocity depends also on the particle concentration. The global evolution of the velocity versus concentration of nano-sized and micro-sized Al particle clouds show different trends;the nano-sized Al particle clouds show two maxima whereas the micro-sized particle clouds only one.

The thermodynamic calculations give temperature intervals in accordance with the experimental results for micro- and nanoparticles.

References

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