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Recent Advances in Aluminium Particles Combustion for Propulsion and Heat Generation

Fabien Halter[1, 2], Christian Chauveau[1]
[1] CNRS ICARE
Avenue de la Recherche Scientifique, 45071 Orléans Cedex 2 France
[2] Université d'Orléans, Orléans, France

ABSTRACT

Aluminum particles are widely used for space and military applications to significantly enhance the performances of solid rocket motors. More recently, they have been envisaged as one of the future energy carriers : they can burn to release heat without any carbon chemistry. Recent experimental information obtained both on isolated and dispersed regimes afford new insights on the burning process of an Al particles.

1. Introduction

Metal combustion has an interesting energetic potential and generates elevated combustion temperatures. According to its high energetic density (specific energy 31 MJ/kg) and its wide availability, aluminum micrometric particles are currently used in industrial solid propellants, especially to increase thrust of the solid rocket motors (SRM). The combustion of aluminum particles in SRM is a complex process. Particles leave the propellant surface and burn in a specific gaseous environment, under high temperatures and pressures, given by solid propellant combustion. The study of the aluminum combustion phenomenon has therefore been a continuous research effort. Recently, aluminium particles have been envisaged as a potential candidate as a metallic energy vector to meet global needs of a clean zero-carbon energy. Fundamental properties and structures of these Al-air two-phase flames are still poorly known compared to traditional hydrocarbon flames. However, in order to study the valorization possibilities of the energy released by an Al-air flame and therefore the viability of an energy carrier based on aluminum powders, it is essential to describe properly the combustion process of aluminum particles burning in a dispersed condition. From an energetic overview, it is also essential to evaluate the energy distribution between the radiation, convection and the energy remaining in the condensed phase.

In this context, we have developed two complementary experimental set-ups allowing to study the combustion process of both isolated and dispersed particles.

2. Method

To fundamentally analyze the combustion process of isolated aluminum particles, a specific apparatus was developed. This electrodynamic levitator (EDL) is composed of distinct electrodes supplied by AC and DC voltages which allow to set the horizontal and vertical position of the aluminum particle. This system is confined in a high pressure chamber to ensure a static and controlled gaseous environment. Partial pressures of the ambient mixture are adjusted with a high precision manometer. A 50 Watt CO2 laser beam follows a defined optical path, being successively separated, reflected and focused to symmetrically irradiate and ignite the aluminum particle. Diagnostics mainly consist in optical measurements. The light emission of the burning particle is collected and transmitted to filtered photomultipliers tubes (PM) used to transform the luminous intensity in recorded voltage signals with a rate up to 200 kHz. Dynamic sequences of the combustion process are recorded with high temporal and spatial resolution (up to 40000 fps / 2.5 µm/px) using a high-speed camera PHANTOM V1611 combined to a long-distance microscope QUESTAR QM100 focused on the isolated droplet. This set-up is described in [1].

The study of dispersed mixtures is performed with the use of a Bunsen type burner. This burner generates conical premixed metal flames in open field. A description of the experimental apparatus used can be found in [2]. The flow concentration is monitored in real time by laser attenuation using the Beer-Lambert method. The combustion is imaged by direct visualization thanks to a camera highlighting the spatial distribution of AlO(g) reaction intermediate, as illustrated in Fig. 1. In addition, an optical fiber allows a local spectral detection of the flame and a determination of the temperature of AlO(g) reaction intermediate. The radiation study of the flame / plume is carried out with a fluxmeter operating for wavelengths between 0.3 and 20 µm. Solid combustion products are sampled at different heights in the plume and a type K thermocouple provides the average temperature in the sampling zone. These samples are then analyzed by SEM and EDS in order to obtain more precise information on how aluminum particles burn in the flame by examining the shape, size, crystalline structure chemical composition of oxidized particles and studying the presence of residual unburnt.

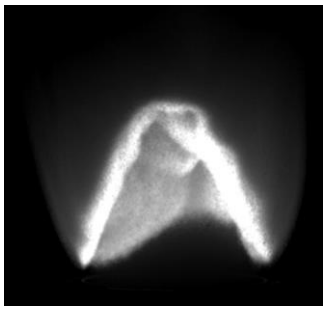

Fig. 1 Illustration of the reaction zone through the AlO(g) emission for an Al-air flame.

Corresponding author: Fabien Halter
E-mail address: fabien.halter@cnrs-orleans.fr

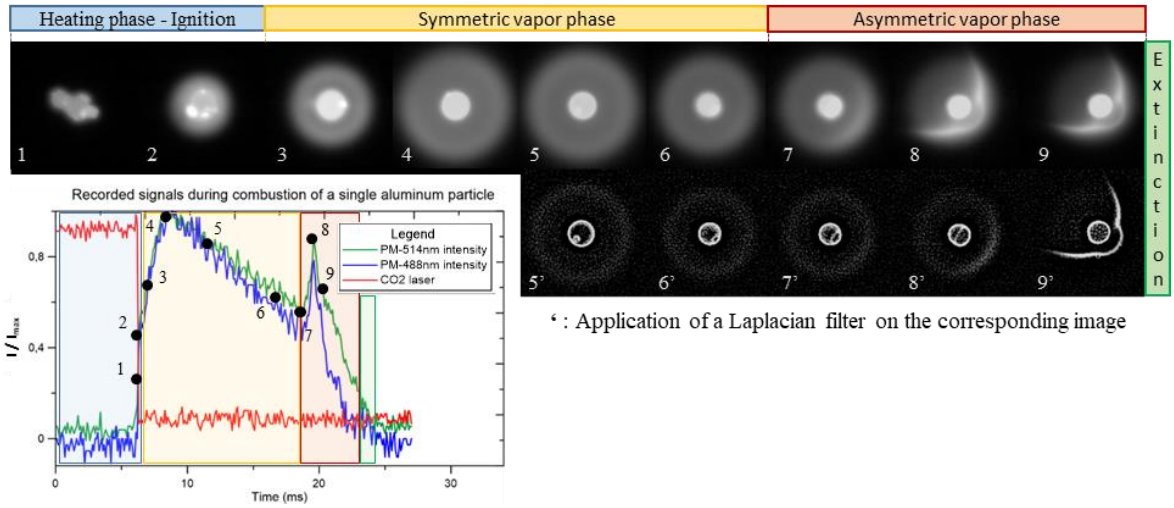

Fig. 2 Characteristic combustion sequence of an aluminum particle in air – P = 1 bar – D0 = 93 µm and temporal correlation with recorded light emission profiles.

3. Results and Discussion

The overall combustion cycle of an aluminum particle in air is complex and decomposes into an ignition phase and a chemical reaction phase. When the particle diameter is sufficiently large, the combustion takes place in a vapor phase. The liquid aluminum droplet possesses an alumina liquid lobe on its surface due to the initial passive layer covering the particle. A concentric micro-flame is detached from the droplet surface, with a constant flame diameter / droplet diameter ratio around 3.6 for an isolated particle in air as illustrated in Fig. 2. For this combustion regime in air at 1 atm, the adiabatic micro-flame temperature is around 3540 K with the presence of species such as vaporized aluminum and aluminum gaseous sub-oxides which form nanometric oxidized particles in the micro-flame. Note that nitrogen traces were also found in the combustion products.

With the particles density feeding the burner, each particle burns like an isolated particle. The temperature estimated by the AlO(g) emission spectrum is consequently only the average reaction temperature of each micro-flame. It does not correspond to the average temperature of the entire gaseous phase, that is the macroscopic flame temperature, and explains that the AlO(g) temperature does not vary according to the global equivalence ratio.

The flame radiation was measured axially for different positions using a fluxmeter. The radial coordinate of the fluxmeter is kept constant for all axial positions at 135 mm from the burner center. The setup being axisymmetric, the method for determining the total radiated power is the same as for traditional burner flames and consists in integrating the axial profile over a cylindrical surface. The maximum of the radiated power flux-density is obtained around the flame half-height. The power outwardly radiated by the flame and the plume can be measured precisely with this method and does not require any assumption on the particles emissivity. For an Al-air equivalence ratio of 0.9, the power radiated by the flame and the plume is of 5.2 kW ± 0.5 kW. As the SEM and EDS analyzes did not reveal any unburnt, the combustion efficiency can be assumed to unity. Considering that the total aluminum quantity injected at the burner exit is oxidized into alumina, the total power released by an Al-air mixture with this equivalence ratio is of 7.6 kW. In these conditions, the radiated part is evaluated at 69% ± 7%.

4. Concluding Remarks

Combustion process of aluminum/air was studied both in isolated and group regimes. With the imposed particles densities, each individual particle crossing the reaction zone (i.e. the conical flame surface) burns like an isolated particle. All particles, even the smallest ones, seem to be oxidized in a diffusion mode since nanometric combustion products are mainly smaller than 200 nm in diameter are produced. Only some micrometric spherical alumina particles were identified in the combustion products and supposed to be issued from the passive alumina covering the largest aluminum particles. The temperature evaluated with AlO(g) emissions does not seem to be representative of the average gaseous phase temperature but rather to the reaction temperature of micro-flames surrounding each particle. From an energetic point of view, the radiation contribution of the flame and the plume to the global heat release was evaluated at about 69%. However, this contribution is certainly slightly underestimated because of the detection of aluminum nitride and oxynitrides in the combustion products, formed through less exothermic reactions.

References

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