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TRACKING OF ALUMINUM PARTICLES BURNING IN SOLID PROPELLANT COMBUSTION GASES BY FOCUSING SCHLIEREN TECHNIQUE

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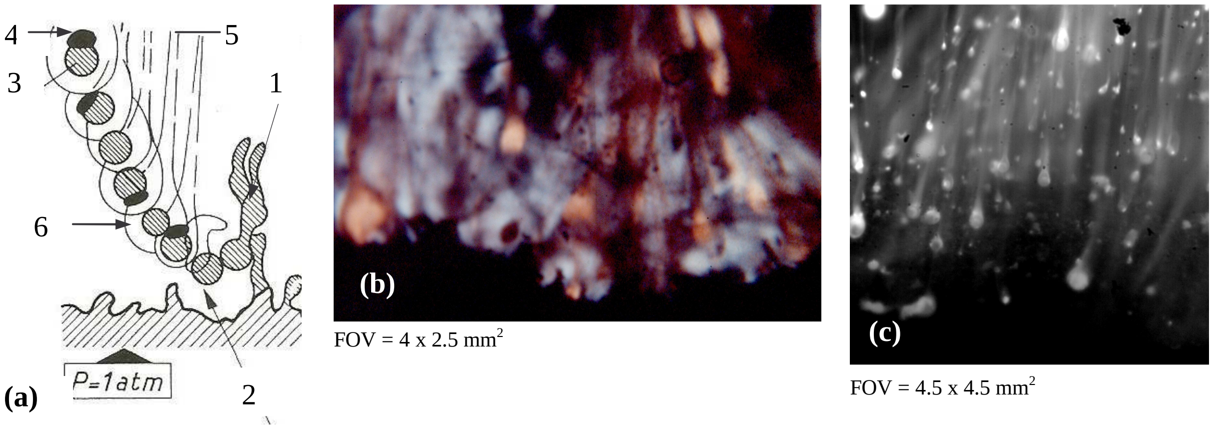
ABSTRACT: This paper describes an analysis of the behavior of aluminum (Al) particles burning in solid propellant combustion gases. Aluminum particles are added to solid propellants in order to increase the gas temperature and, in the end, the specific impulse of the propellant. It allows for a higher thrust level for the booster or missile. The Al mass fraction is quite high (15-20%) meaning that there is a lot of particles burning at the same time in the gas volume above the surface. The radiative emission level (T>3000 K) does not allow for “classical” visualization techniques application. Instead we have implemented the focusing schlieren technique (FST). FST creates in the same way as a laser, an optical thin sheet normal to the regression surface (at a few mm/s). Its depth of focus is very limited depending upon the optical arrangement (from 0.25 to 0.5 mm). The deviation of the external light by the optical indexes provides information about oriented optical gradients and particle “shadows”. Results are excellent in terms of image quality and, we also obtained clues for a better understanding of the particle burning process. The fitting of the image acquisition is not simple; it is related to pressure changing the local equivalent optical indexes. Once we get “good” images, tracking particles is quite challenging. We are seeking velocity profiles, particle diameters or features, and particle state evolution (inert, melted, burning, or burnt). A specific tracking code has been developed named “EMOTION” (French for estimation of the object movement by Onera image analysis). Examples of particle behavior and tracking are presented in the paper. FST applied to combustion phenomena is very promising due to the drastic reduction of the combustion self radiation. All the details and pieces of information are able to be sought such as those that validate the Al particle behavior models. This work was supported by ONERA, and by CNES, the French National Space Agency.

1. Introduction

The behavior of aluminum particles depends on several parameters: Al mass fraction (15-20 %), Al particle size (5 to 40 µm), flame temperature and a specific process occurring at the regression combustion surface: the aggregation process which generates particle networks of higher volume and various features called aggregates. These aggregates evolve into spherical agglomerates once the fusion temperature has been reached. Particles burn in the volume of the motor combustion chamber and are able to trigger an instability regime of the flow. Knowing particle sizes close to the burning surface (a few millimeters) is of major interest for numerical simulations of a solid rocket motor.

Particle temperature stands above 3000 K rising up to 3600 K for alumina, the combustion. Using classical camera operating in visible light domain, it is not easy to extract the diameter of any particle burning in solid propellant combustion hot gases. This is due to the high level radiative emission of the particle. The mass ratio of Aluminum particle is close to 20% in solid propellants: there are too many ejected particles at the same time in the gas volume above the burning surface. Tracking each of them is quite impossible.

Fig.1a shows how aluminum particles usually aggregate at the burning surface (1), then heated by the heat flux coming back from the flames, the particles melt (2), and become agglomerates which burn (3), before being ejected from the surface by the gas flow rate. Agglomerate burns as lifting up from the surface. At that step, the burning particle or agglomerate is composed of a melted aluminum core (3), it has an alumina cap (4) and it generates alumina smoke (5) which is taken away by the gas flow. [1]



FOV = 4 x 2.5 mm^2

FOV = 4.5 x 4.5 mm^2

Fig. 1. Visualisation in visible domain : (a) sketch of the agglomerate formation cycle [1], (b) 16mm argentine camera image at 3 MPa [2] et (c) high speed video camera image [3]

The radiative emission of particles lowers the quality of the images as soon as the test pressure level is higher than a few atmospheres. The combustion zone (6 in Fig. 1a) around the burning particle becomes opaque at 3 MPa (Fig.1b) and the aluminum solid particle diameter cannot be determined. The field of view covered in Fig.1b is 4 x 2.5 mm^2. The spatial resolution of such image allows to track particles having at least a diameter of 40 µm. The high speed digital B/W video cameras allow for a better freezing of the scene thanks to their very short exposure time but the particle surface is hidden in the hot combustion bulb (Fig.1c). In the framework of the InCoME program (Investigations in Energetic Material Combustion) we selected a light deviation based technique, one of the numerous schlieren variations, named Focusing (or Converging) Schlieren Technique (FST). The idea was to eliminate the combustion self emission which is the issue of the visualizations.

2. Focusing schlieren technique

The focusing schlieren technique (FST) proposed by Weinstein [4,5], creates an optical thin sheet normal to the regression surface. There is no integration of deviation all along the optical path; the particles are seen only in a thin volume limiting the interaction between particles which are coming out from the surface more and more numerous as the burning rate increases with respect to the pressure (i.e. a few to ten mm/s). Its depth of focus (DW) is very limited depending upon the optical arrangement, mainly the height of stripes in the grids (Fig.2). In our case, DW is limited to 0.25 or 0.5 mm.[6]

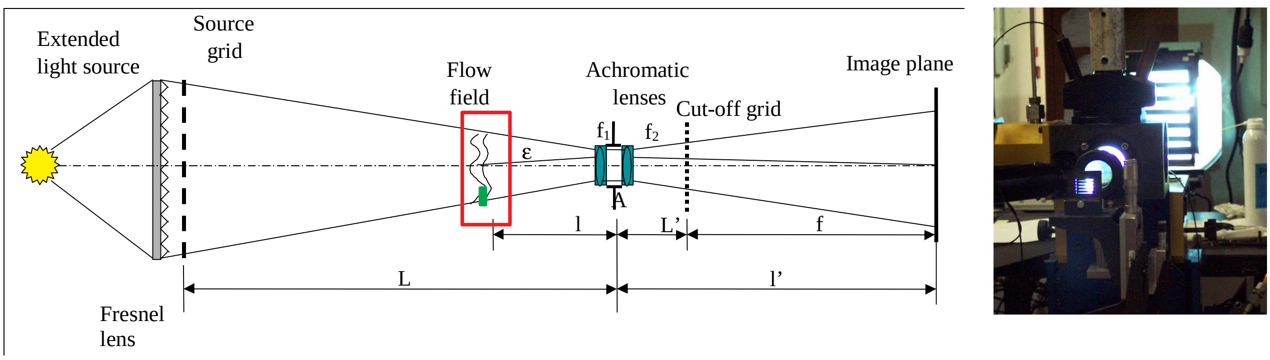


Fig. 2. Schematic and view of the FST optical system

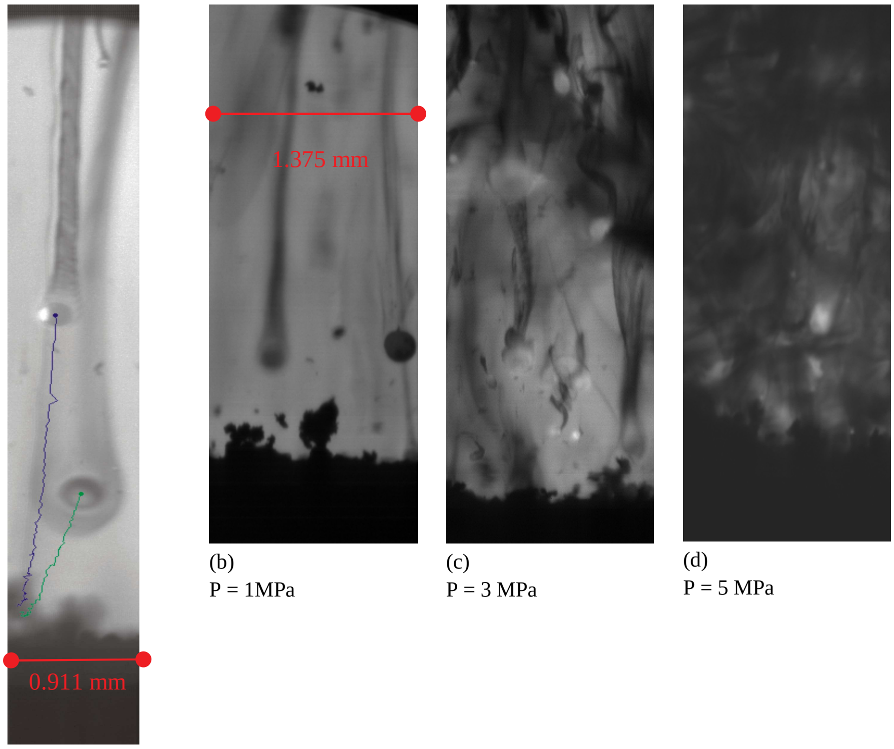
The deviation of the external light by the optical indexes allows us to obtain oriented optical indexes gradients for the gases and particle “shadows”. This also acts like a high pass light filter because part of the radiation emitted by particles, not cut by the grids, is received by the high speed camera at the same time as the white light deviated rays. The frame rate is fitted from 10,000 fps to 30,000 fps depending upon the FOV in term of pixels. It has to be selected taking into account a few parameters such as the expected particle size (optical magnitude), the particle speed in the FOV (each particle seen in a number of images), the displacement of the particle between two images (identification of each particle), and maximum allowed data flow rate to the camera memory which modifies the pixel number and/or the frame rate.

3. Application to aluminum particle tracking

In this chapter, examples of image sequences illustrate how to fit the FST images and what happens in the gas a few millimeters above the solid propellant burning surface. Then, the specific software will be presented: its principle, first validations on inert particles (instead of aluminium) mixed in the propellant batch. Finally we present results of particle tracking.

3.1 FST application domain

The **influence of the gas density** via the equivalent optical indexes is an issue: it is difficult to analyze images when the pressure is higher than 2 MPa and it depends on the propellant mixture and the initial size and mass ratio of aluminium. The FOV is generally 192 x 1024 pixels. The magnitude depends upon the particle size. In the examples in Fig.3, the magnification factor is 7 µm/px. The images are extracted from movies recorded at different operating pressures. The propellant used in the tests in Fig.3 carries out some agglomeration process. Quite large agglomerates are seen in pictures independently of the pressure level.



(a)
P = 0.5 MPa

(b)
P = 1MPa

(c)
P = 3 MPa

(d)
P = 5 MPa

Fig. 3. Images of the same propellant combustion at various pressures

In the image (a), taken at low pressure, the particles were easily tracked because there are only a few per image and the background grey level was uniform. Many pieces of information were available such as the diameter of the particle and its displacement, its alumina cap seen thanks to the high pass filter effect of FST, its rotation speed following the cap rotation, the combustion bulb and the alumina smoke. At 1 MPa (b), aggregates leave the surface and have some specific features which make their shape deviate from a sphere, the background grey level becomes non uniform. At 3

MPa (c), the number of particles increases; their smokes and the gradients generated by the diffusion flames (AP/HTPB) exhibit drastic variations in grey level. Some particles are pointed out due to their own emission (saturated white level). At 5 MPa (d), the situation is worse because the scene background has become darker.
This leads to a limited application domain in term of operating pressure. FST has to be adapted to each propellant: the DW will limit the number of particles seen at the same time in images. The cut-off level will change the grey level. With Al particles, the gases temperature is higher and the optical indexes and, consequently, as the light deviation decrease with temperature, the cut-off level has to be kept equal to zero. FST becomes shadowgraphy!

Particle size depends upon the initial aluminium size and upon the aggregation process at the surface. The diameters of particles leaving the surface require an adapted magnification; we need a few pixels to describe the particle feature. As magnitude is increased, the actual FOV is reduced leading to a short path for each particle in the FOV limiting the number of corresponding images. The velocity profile becomes difficult to be determined.

3.2 Software

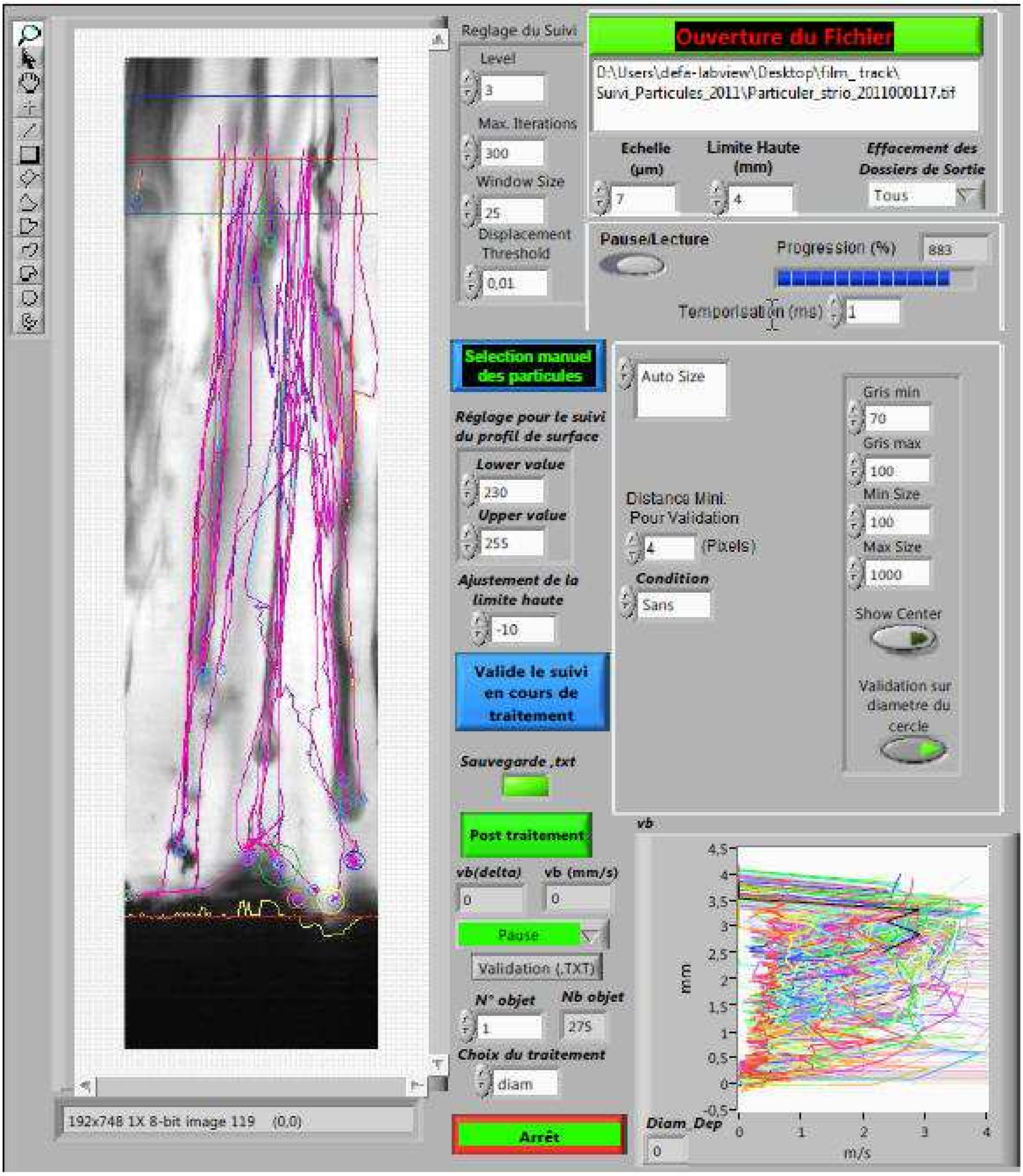
Pertinent data, included in the FST images, are of high interest for the research scientist but they are less interesting for software designer because we are far from industrial scene images which are well lighted and with a high level of contrast. A few research software's have been tested on our "easiest" images.[7,8] No significant results were obtained. We decided to write our own software using LabView VIs tool boxes. There are specific tools devoted to image processing from Alliance Vision, NI group. As there are many issues, the final goal of this study which is the tracking of particles (velocity profile and diameter evolution) seems far from to be achieved.

Principle of the software

The ONERA tracking software was named EMOTION (French acronym) standing for Evaluation of the Movement of Objects by ONERA Image Processing. Each particle has to be tracked individually. The frame by frame displacement of each particle leads to a velocity profile. The determination of the diameter frame by frame leads to the consumption of aluminium during the combustion of each particle.
The main structure of the software must use 8-bit images because all the VIs do not accept 16-bit format. A first selection module allows us to fit the tracking conditions on the first image having each particle,. The notion of first image in which the particle is detected is very important. At the combustion surface, particles are not spherical, are not burning and stands as an aggregate. The first capture of particle is not obvious. Far from the surface in the upper part of images, most of particles are spherical, burning with alumina smoke plume towards the top of the FOV. The sequences are analyzed backwards. The detection is performed in a specific zone at the top of the image and particles are tracked back to the surface.
A module is activated for determining the conditions for extracting the zone of the image including each particle. This zone, like a small "stamp", is kept in an output directory. A second level processing could be used based on morphology for instance.[9] The coordinates of the centre of each particle allows to define its displacement frame by frame but we have to make sure that this is the same particle; there are some regulation data selected by the user. This is related to the repetition rate and the mean flow rate. The velocity is determined using 3 or 5 coordinates of the particle; it means at least each particle sought on 4 to 6 images for two values of velocity which is the minimum for a profile. We got trouble with the small particles moving at the gas flow rate. 10,000 fps is the minimum value of the frame rate; 20 to 30,000 fps could be an answer for these small particles but the distance on which they could be tracked is lower due to the FOV size limitation induced by the frame rate increase.
The first step is the choice of an image sequence. The number of images is linked to the quantity of particles we could track in. This is related to the memory allocation required. We use a 4-core PC with 6 Go of memory running under 64-bit Windows. We are able to track up to 10,000 particles in a sequence.
A working zone centered at the burning surface is defined: the burning surface profile is determined and tracked frame by frame. It allows to refresh, at each frame, the particle distance to the burning surface. A second working zone is placed at a given distance from the sample surface. In this zone, the particles will be detected once entered from the top of the image for the first time. When a particle is detected, a circle overlaps the contour providing the initial diameter. Then, a "stamp" is created. The notion of "continuity" is important: we make sure that a particle is not considered twice or more.

Category of particle size (min, max) and grey level range (min, max) are two very important parameters but they are not easy to select because the size of actual particle covers a range from less than 10 µm to 200 and more µm. The contour of each particle is defined by a grey level change depending upon the burning level of the particle. For example, when an alumina cap is seen at the surface of a particle which rotates, it is an issue for the tracking and the diameter determination. The saturated white level is not considered in the fitting values of the tracking. The gravity centre and the diameter of the circle are shifted drastically.

The front panel of the software is shown in Fig. 4. Trajectories of particles are seen in the main graph but their tracking is under progress. They disappear when their tracking is ended. Velocity profiles are obtained in a second graph. All data and "stamps" are recorded in specific files and directories.



Reglage du Suivi
Level: 3
Max. Iterations: 300
Window Size: 25
Displacement Threshold: 0,01

D:\Users\defe-labview\Desktop\film_ track\Suivi_Particules_2011\Particuler_strio_2011000117.tif

Echelle (µm): 7
Limite Haute (mm): 4
Effacement des Dossiers de Sortie: Tous

Progression (%): 883
Temporisation (ms): 1

Auto Size

Réglage pour le suivi du profil de surface
Lower value: 230
Upper value: 255
Ajustement de la limite haute: -10

Distance Mini. Pour Validation: 4 (Pixels)
Condition: Sans

Gris min: 70
Gris max: 100
Min Size: 100
Max Size: 1000

vb(delta): 0
vb (mm/s): 0
N° objet: 1
Nb objet: 275
Choix du traitement: diam
Diam_Dep: 0

192x748 1X 8-bit image 119 (0,0)

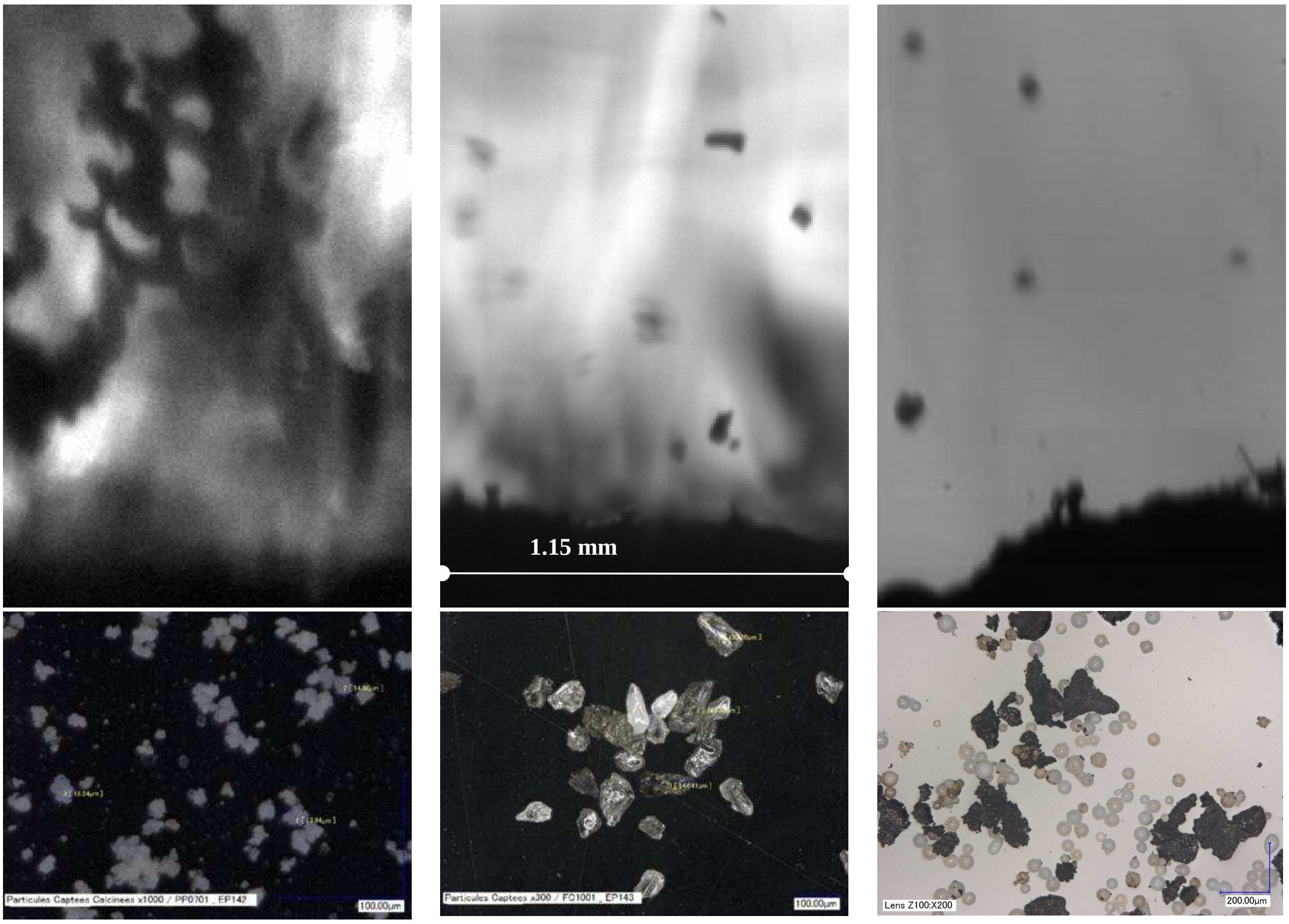
Fig. 4. Front panel of the software (actual propellant with aluminum)

Validation of the algorithms

The main issue of image processing is checking the software ability to track particles. We tested the EMOTION code directly on actual solid propellant combustion images under high pressure with background grey level variation such as those due to alumina smokes. The first step of validation should be based on the analysis of images obtained for specific propellants including inert solid particles with a known diameter distribution. First, two inert particle types were tested: alumina ($Dn_{0,5} = 30$ µm) and ZrO_2 ($Dn_{0,5} = 11$ µm). The mass ratio was chosen low at 6% aiming at limiting the aggregation if any occurred. Fig.5 shows images obtained by FST for each inert particle type (top) and the particles collected after sample combustion and burning of the binder degradation residue embedding the particles (bottom).

The result was unexpected with an aggregation of ZrO_2 particles forming flakes or pancakes (a) and individual particle of alumina having oblong shapes (b). We did not manage to track the alumina particles due to their shape features and to the inability of the software to track non spherical objects at that time.

A new formulation including spherical particles named “Microblast” (mixing of silica, alumina and zirconium) was tested recently ($Dn_{0,5} = 43$ µm). There was still some aggregation of particles leaving the surface in FST images. Most particles were identified clearly as spheres as shown in Fig. 5c.



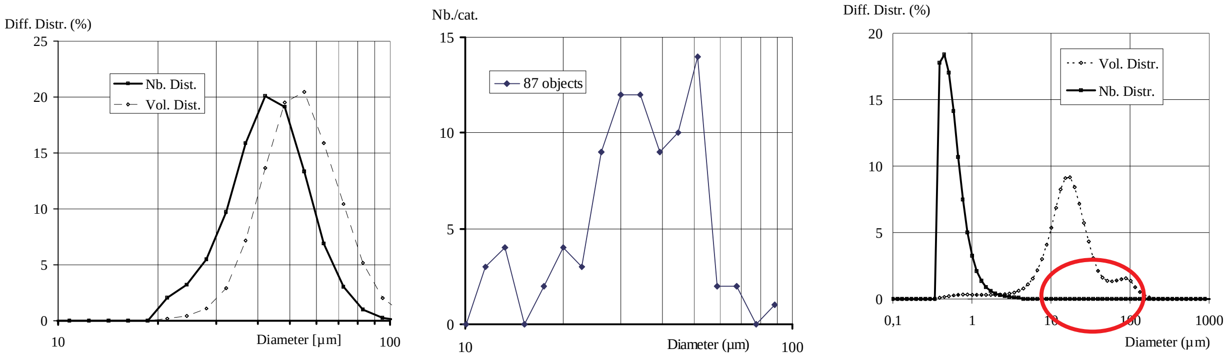
(a) ZrO_2 propellant (b) Al_2O_3 propellant (c) “Microblast” propellant

Fig. 5. Inert particles above the burning suface by FST (top) and after collection and heating (down)

3.3 Example of image analysis

The only example of tracking and sizing of particles presented in this paper concerns the “Microblast” particles. Using the movies obtained with “Microblast” propellant, we expected to check the ability of the code to find the size distribution (in number) of the particles included in the batch. The diameter of each particle was the one determined when the particle was detected for the first time it enters the working zone. The velocity profile was also obtained for most of them.

The initial size distribution in number is shown in Fig. 6a; the Dn $_{0,5}$ value is 43 µm. The FST images (192 x 1024 px) analyzed by EMOTION (Fig.6b) were obtained with a scale of 6 µm/px, the FOV was 6.14 x 1.15 mm^2 and the frame rate was 10,000 fps. The sequence duration was limited to 1,000 frames corresponding to 228 detected objects. Only 87 of them were validated; it means an initial diameter was determined, and the tracking of the particle was obtained at least from 5 frames (velocity from 5 positions). The particle size distribution was defined in number per category of the classical size distribution of the Horiba analyser (Fig.6c). This has to be compared to the initial distribution in Fig. 6a. The particle total number could be higher aiming at exhibiting the same size distribution. This validates the process and the EMOTION software.



(a) (b) (c)

Fig. 6. "Microblast” size distribution: initial (a), from FST images (b) and after collection (c)

The size distribution was quite difficult to obtain from the collected particles once the saple was burned. This was due in part to the small quantity of propellant used in the test bomb. But it was due mostly due to the residues agglomerated in pockets (black bodies in Fig.5c). Some of them embedded the “Microblast” particle as shown in Fig.6b. After 3 hours of heating at 610°C and shaking by ultrasound during a few minutes, we obtained tiny and numerous particles. It led to volume distributions shifted towards smaller diameters (Fig. 6c). Turning this volume distribution into a distribution in number was a major issue. The “Microblast” size distribution is hidden inside the distribution of unburned residues.

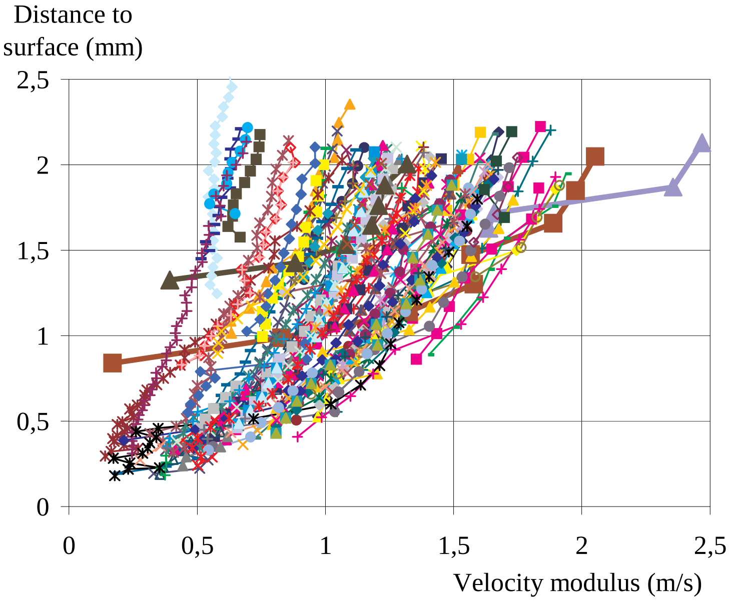


Fig. 7. "Microblast” velocity profile: 87 particles detected in a time sequence duration of 0.1 s

The velocity profiles of the 87 objects detected in a 1,000 frames sequence are presented in Fig.7. There is no link between the modulus of velocity and particle size. All are accelerated after they lift off. At a distance of 2 mm above the burning surface, the velocity modulus varies from 0.5-0.6 to 2 m/s. Only one particle moved at a higher velocity; it was one of the three underlined in the graph which entered the FOV from one lateral side of the image. They were trapped by the gas flow rate. This result obtained for less than 100 particles provides the first level of software validation.

4. Conclusion

Thanks to the focusing schlieren technique, a new route has been opened for analyzing the aggregation and agglomeration processes close to the burning surface for an industrial solid propellant. This was a major opportunity because the FST image does not include all the light emitted by the combustion. It acts as a high pass filter providing more pieces of information in each frame. The optical gradients are not integrated along the light path through the test chamber. The quality and the accuracy of the details seen in the field of view are notably enhanced.

The EMOTION software is still under development but, at the present time, it allows to extract information about diameters or features of the detected objects and also their velocity profile. We have to improve our understanding of image analysis conditions which depend upon the shape of the objects and mainly of the background grey map (smokes, flames … leading to refraction index gradient variation wrt time and location). The work already performed has to be strengthened. A strategy for software validation had to be built and inert “Microblast” particles were one way to achieve this goal.

The FST does not solve all the requirements in the field of particle tracking and sizing. A compromise has to be established between particle velocity (FOV, fps) and spatial resolution (minimum particle size). Limitations and operating conditions are conflicting with particle diameters obtained above a minimum diameter limit and with the velocity profile determination requiring a much larger spatial scale. The working zone has to be changed or adapted as the FOV and software should have to main options: diameter and profile. The particle distribution has to be described in number. This also leads to analyze the sizes of the particles collected in a test chamber from static images taken using a microscope (optical digital or MEB).

FST exhibits a high potential because the FST images are full of useful information required by the numerical simulations and models.

Acknowledgments

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