но, в основном в реакции (1), а во втором, кроме того, в реакции [9]

$$NO^+ \cdot H_2O + NH_3 \rightarrow NH_4^+ + HNO_2,$$

причем только при очень малой концентрации NH_3 внешний пик больше внутреннего. Это можно объяснить тем, что при относительно большой концентрации аммиака скорость реакции передачи протона от иона H_3O^+ (или аналогичного) молекуле аммиака лимитируется концентрацией заряженных частиц, которая, очевидно, выше во фронте. Максимум концентрации NO^+, как и при отсутствии добавки, располагается между двумя максимумами $[NH_4^+]$ и растет при увеличении концентрации аммиака. Кроме того, появляются ионы NH_2O^+ и NO_2^+. Отметим, что при большой концентрации аммиака наряду с кластером $NH_4^+ \cdot nH_2O$ образуется $NH_4^+ \cdot NH_3$.

Таким образом, в данном случае, вероятно, образование NO^+ происходит по схеме:

$$NH_3 \xrightarrow[-H_2O]{+H_3O^+} NH_4^+ \xrightarrow[-H_2O]{+O_2} NH_2O^+ \xrightarrow[-H_2O]{+O} NO^+.$$

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INVESTIGATION ON ALUMINUM PARTICLES COMBUSTION IN THE FLAME OF SOLID ROCKET PROPELLANTS

Aluminum is widely used in modern solid rocket propellants for many purposes, but mainly to increase the specific impulse by raising the flame temperature. Most of the aluminum, present in powder state in the propellant, do not vaporize onto the burning surface so tending later to agglomerate into large particles difficult to burn even in the flame. The aim of this work is to study the behavior of the aluminum particles onto the burning surface and into the gaseous region of the propellant flame structure. Different diagnostic techniques have been used: SEM on the burning surface of extinguished samples, pictures taken during combustion by filtered still camera and a new developed laser diagnostic. By the use of an UV laser beam and a high speed shutter TV camera, the Al particles onto the burning surface has been visualized. A suitable Image Processor to extract information from the frames has been adopted. Tests on a HTPB.12/AP.68/Al.20 propellant in the pressure range 10—50 atm has been performed. Results show the reliability of the diagnostics here used and have contributed to a better characterization of the tested propellant.

Introduction

The modern solid rocket propellants make large use of aluminum in their composition. Besides the advantages, however, the Al particles can cause a variety of problems in the rocket motors and their combustion must be predicted as precisely as possible. As it is well known [1], most of the Al particles loaded in the propellant do not vaporize onto the burning surface and the flame, because protected by an oxide layer. The Al combustion is made even more difficult by the tendency of the Al powder to agglomerate into larger particles onto the burning surface. This effect, which starts in the reaction layer at a temperature lower than the Al melting point, is enhanced, under certain conditions, by the retention due to the molten binder tension forces [2]. Large Al agglomerates lead to low combustion efficiency, high two-phase flow losses and high nozzle erosion caused by their kinetic energy and by raising the heat flux into the walls. Also the residual thrust effect is closely joined with the agglomeration and the impinging of the agglomerated particles inside the rocket motor [3]. Very often it is made even worse by the combination of the axial and centrifugal accelerations.

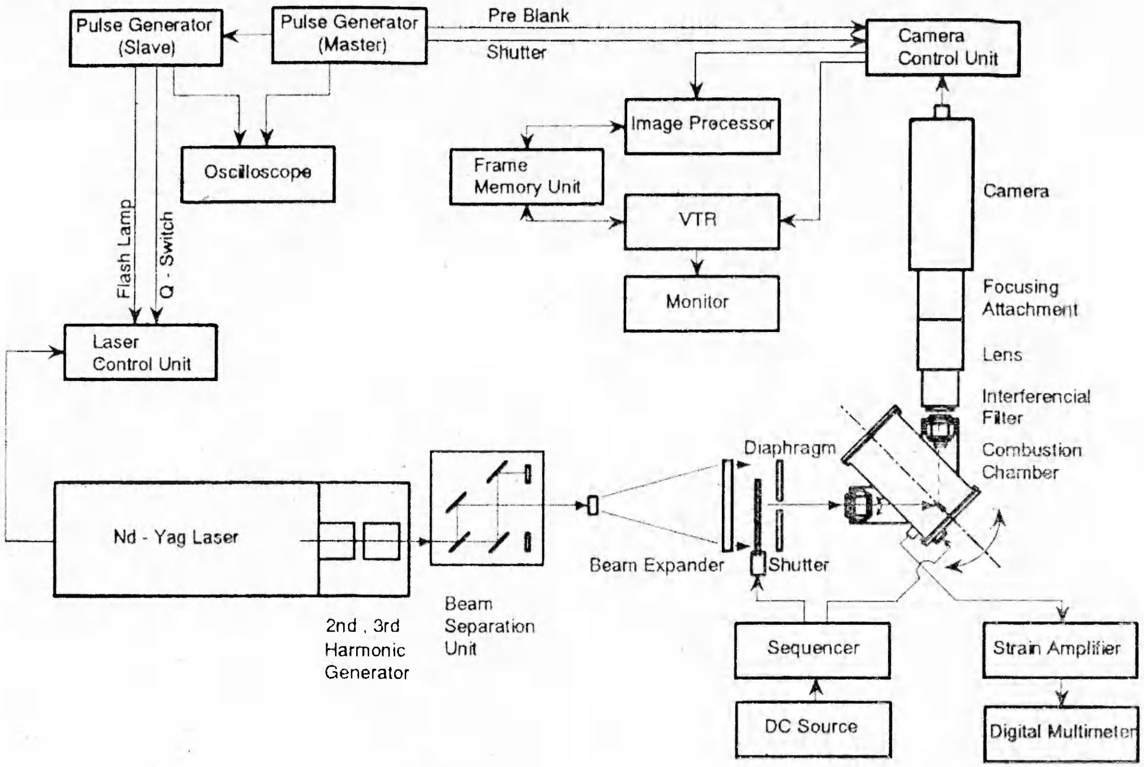
In order to visualize the individual particles and the agglomerates, many experimental diagnostic techniques has been so far developed. Large use of Scanning Electron Microscopes (SEM) has been done and pictures of the burning surface of extinguished samples are now routinely taken. Other pictures are simply obtained using still cameras equipped with proper filters in different region of the spectrum. In many cases the pictures so obtained show clear images of the Al particles in the gas flow and are suitable to determine their dimensions. More sophisticated visualizing techniques make use of high speed film camera. Many of this kind of apparatus use a laser light source in order to light up the Al particles. This choice has been demonstrated suitable in solving the motion blur problem and in better revealing the particles into the bright flame [4]. Also the diagnostic here described make use of a laser, but, by using a TV system, instead of seeking for a high time resolution, it aims to have immediate replays of the movie with consequent analysis of the frames.

Experimental Set-up

Combustion chamber. The combustion shamber is equipped with 4 optical accesses: two of them are diametrically opposite and their common axis is parallel to the burning surface if the propellant strand. The other two windows look at the burning-surface from above at 45 deg. It must be noticed that the housing of the glasses can be tilted within 10 deg or more allowing precise alignments and avoiding distortions of the laser beam passing through the window and of the image seen by the TV camera. In order to have a good rejection of the combustion products, the ratio between the chamber and the strand volume is designed to be around 330 and moreover a N_2 gas flux is maintained.

Optical system. The light source consists of a Nd-YAG laser with a 3rd harmonic generator. The beam so produced has $\lambda = 355$ nm, $E = 55$ mJ and pulse width $t - 6$ ns. Because of the procedure related to the video system, the pulse repetition rate has been reduced to 5 Hz and the laser cavity ad-hoc modified. After passing through a wavelength separator (see Fig.), the emerging monochromatic beam is expanded by a Galileian beam expander to obtain a more flat radial profile. Before impinging onto the strand burning surface, the expanded beam passes through a diaphragm (5 mm) that selects its central part; after that it is stopped by a shutter. The opening of the shutter is activated by the sequencer at a prefixed time after the propellant ignition.

Video System. The burning surface (or the condense phase particles in the flame) lighted by the laser is shot by a shutter TV camera (Ha-



Experimental set-up.

mamatsu C4053) whose CCD sensor is sensitive in the range 200—800 nm. This sensor, coupled with an image intensifier, can allow a shutter speed up to 100 ns. The standard number of frames for this camera should be 30 fr/s, but a 67 ms delay has to be set between the pre-blank and the shutter signals because the camera works in shutter external trigger mode. Moreover an accumulation time is needed resulting in a reduction of the effective number of frame to 5 fr/s. The TV camera is equipped with a Nikkor UV $f = 105$ mm lens with a focusing attachment that gets a magnification $M = 20$ and a depth of field $d = 5$ mm. An interferencial filter, whose 10 nm bandwidth is centered on the laser wavelength used in these measurements ($\lambda = 355$ nm), is placed just in front of the camera lens system. Two chained pulse generators (Stanford Research System DG 535) synchronize the laser pulse with the camera shutter opening.

Experimental Procedure and Preliminary Comments

The propellant sample ($d = 5$ mm, $h = 10$ mm) is placed in a metallic holder surrounded by a polyimide film able to adsorb UV light and to avoid UV reflections inside the combustion chamber. Assuming the gas emitting as a black body, the total power released in the spectral region of the interferencial filter (350—360 nm), during the time when the camera shutter is open (100 ns), can be roughly evaluated in $P = 0.6 W/cm^2$. Despite that the emission of the aluminum particles could increase [5] this value, it remains at orders of magnitude smaller than the shot power reflected by the burning surface. The image of this surface is therefore expected to be clearly seen by the camera even if its view angle intercepts the propellant flame.

Unfortunately many factors concur to increase the intrinsic difficulties of the hostile ambient. Among the principal ones: the laser light is often stopped by particle clouds before reaching the burning surface, individual particles can sometime scatter so much light to activate the circuit that protects the camera from overexposures, density gradients can locally change the optical path of the laser light. As a result, in order to light up properly the burning surface and to avoid that Al particles or in-chamber reflections shut the camera off, scattering losses, UV reflections and deflections have to be carefully taken into account. Therefore a good setting implies also a proper choice of the camera lens aperture and it depends on the chamber pressure. Once the desired conditions (pressure and N_2 flow rate) in the combustion chamber are set, the propellant is ignited and the beam shutter is open 0.5 s later. The laser lights up the propellant burning surface and particles in the gas phase; their images are therefore seen by the camera. The frames taken and recorded by a VTR (Sony EDV 9000) are then analyzed by using an Image Processor (Hamamatsu DVS — 3000). Patricles dimensions, burning surface area covered by molten aluminum and intensity distribution of the light scattered by the burning surface are obtained.

Results

Experiments in the pressure range 10 to 45 atm has been carried out and burning surface TV images have been examined. The formation of aluminum «streams» and «bridges» between particles is clearly seen. Agglomerates can be easily detected both in the gas phase and onto the burning surface. The average agglomerates dimensions are different depending on the position in the flame structure and such phenomenon is very clear overall at low pressure. Preliminary measurements of the agglomerates dimensions at $p = 10$ atm onto the burning surface has shown to be in the range 40—80 and 80—400 μm into the flame for the propellant used in this work.

The UV light ($\lambda = 355$ nm) scattered by the Al particles onto the burning surface during combustion show a concentration of Al particles higher (around 18 %) than the one measured without combustion. At higher pressure the behavior of the Al agglomerates becomes different and no traces of «welding bridges» can be visible; only clouds of particles and agglomerates can be seen. Attempts to measure their average dimension have given a result of 60 μm at maximum into the flame and 20 μm onto the burning surface. Moreover at $p = 45$ atm particles bigger than 20 μm can be noticed only occasionally more than 8 mm from the burning surface. In the case of large particles also the heterogeneous flame-smoke envelope can be identified and its thickness (around 100 μm for a 400 μm particle) can be measured. Individual particles not yet agglomerated, but lying in the same gas envelope are also visible.

Conclusions

The preliminary results so far obtained have demonstrated the reliability of the opto-electronic system and its usefulness in the study of the aluminum particles combustion in the flame. Some quantitative results about the Al particles dimensions onto the burning surface and inside the gas phase are in good agreement with the data previously collected by other diagnostic methods (SEM, high speed camera, ...). The main advantages of this system are in its versatility and in the immediate processing of the collected images. As the frames are shot in a very short time, the motion blur problems are almost solved and the melted Al «streams» and the burning surface are, at least at low pressure, well visible. The Al behavior at different pressure can be also charaterized.

Future Work

The definition of the image can be improved using better camera optics equipment and their processing can become more precise by using more advanced image processing systems. A better knowledge of the modulation transfer function of the electro-optical system can also accurately define the performances of the experimental set-up. Further improvements of the results are forseen by lighting up the flame with the laser beam parallel to the burning surface.

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