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Aluminium droplets combustion and SRM instabilities

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Abstract

This paper presents the effects of the combustion of aluminium droplets in the context of solid propulsion. A focus is made on the specific case of pressure oscillations. After a brief presentation of the characteristics of aluminium combustion, interaction with the acoustics of the motor is introduced. The unsteady phenomenon referred to as 'ITHAC' is studied through the analysis of the "Stelis Calypso" test firing. The results show that aluminium combustion is the driving mechanism that leads to a strong instability of several bars. This analysis is supported by numerous two-phase flow simulations that prove the role of aluminium droplets in the instability triggering which is characterised by high pressure oscillation levels. A second instability is also addressed. Solid rocket motors are subject to surface vortex shedding (SVS) for which pressure oscillation levels can drastically be modified by aluminium droplets combustion. Depending on the motor geometry and particles size, combustion increases or dampens the hydrodynamic instability and can be considered as an explanation to the pressure oscillations observed during tests of aluminized propellants.

Introduction

For decades, many studies have been dealing with instabilities in solid rocket motors (SRM). Many of them (see for example Ariane 5 MPS, Space Shuttle, Titan or P80 of the European Launcher Vega) exhibit pressure oscillations. It has to be noticed that most propellants contain aluminium in order to increase propulsive performances of the engine. Efforts have been done to explain their origin and a considerable amount of knowledge has been acquired. From a general point of view, a thrust oscillation is related to a pressure oscillation produced by the presence of vortex structure into the combustion chamber. This kind of instabilities is commonly referred to as vortex shedding (surface, obstacle or angle) [1][2]. They are characterised by a frequency that may differ from the longitudinal acoustic modes and present a specific evolution with time (bursts associated with jumps in frequency evolution). They result from a coupling between the acoustic of the chamber and the flow hydrodynamics. Besides these widely studied sources of instability (by both theoretical and experimental means), a coupling between acoustics and the combustion of propellant has early been suspected by authors like Culick [3] or Beckstead [4][5]. However, very few studies address the effect of aluminium combustion as a driving mechanism of instability. This phenomenon is further called "ITHAC" for Instabilités THermo-ACoustiques in the present study. As a manifestation of this effect, Beckstead suggested that aluminium combustion could be responsible of the Sentry Motor [6] strong pressure oscillations and many instability phenomena were actually solved by modifying characteristics of aluminium load in the propellant. Some other motors, reported subject to pressure oscillations and whose interpretation is not supported by standard oscillations sources (vortex shedding), could be examined from this point of view.

An interesting review of such behaviours is proposed by Blomshield [6] where many types of instability in SRM are examined, but none of them clearly describe the ITHAC phenomenon in details. That is the reason why, ASL, in a framework of a dedicated study supported by CNES, started in 2009 to investigate the possibility of such a coupling in solid propulsion. Previous studies dealing with the effects of aluminium combustion on acoustics are presented in [3] where a Rijke burner academic configuration is considered. Culick [3] suggested a similar effect in SRM. A first

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work based on both theoretical and numerical considerations was proposed by Gallier *et al.* [7], and subsequently confirmed by Onera studies [8].

Based on the acquired results on the ITHAC instability, coupling between aluminium combustion and parietal vortex shedding is also studied. Unlike ITHAC, a theoretical framework is missing to explain the possible coupling between aluminium combustion and hydrodynamics. Many works deal with the theoretical development of such instability, but there is a lack on the two-phase flow effect on pressure oscillations in presence of PVS.
Despite their own characteristics (frequency evolutions are totally different), acoustics and hydrodynamics are subject to be notably modified by the combustion of aluminium droplets.

1. Aluminium combustion

Aluminium particles are generally added to solid composite propellants in order to increase performances. The proportion of aluminium can reach the value of 20% of the overall propellant mass and they are located between the ammonium perchlorate particles. Such a configuration may yield to the formation of large aluminium globules resulting from the agglomeration of the initial population. This phenomenon is observed and can be described according to a so-called “Cohen pocket-model”[9]. The result is a distribution of aluminium droplets that can be completely different from the one introduced during propellant manufacturing. The following pictures show the formation of such agglomerates for a typical composite propellant. It can be noted that the effect of pressure is to increase the density of gases which results in lower gas velocity. As it can be seen on the figure 1, the droplets burns in the gas phase and a correct description of the physics located at propellant surface should take into account a two-phase flow description.

1.1. Aluminium combustion phenomenon

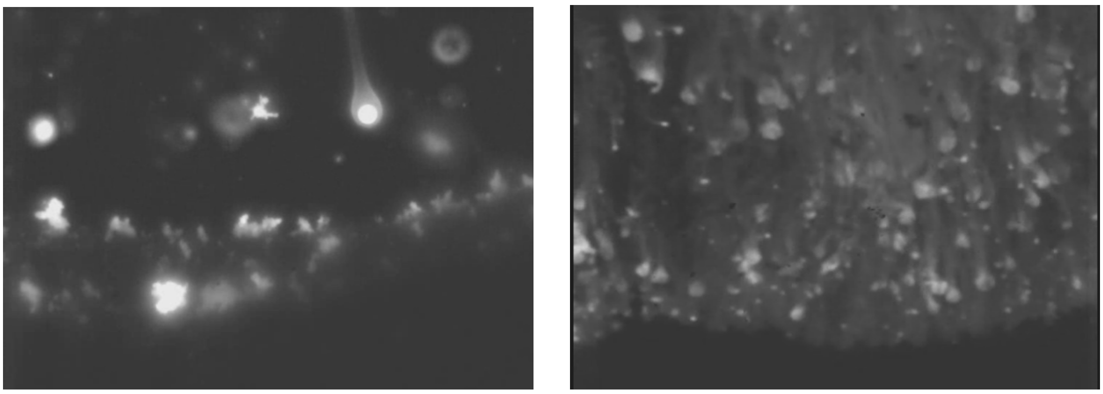

Figure 1 : Visualization of aluminium droplets burning at a pressure of 0.1 MPa (left) and 5 MPa (right)

Once ejected, aluminium particles or agglomerates react in the gas flow, in the vicinity of propellant surface, and finally lead to the formation of an inert oxide residue. Alumina comes mainly from the initial alumina layer that covers each individual aluminium particle and prevents them from further oxidation. When temperature reaches the value of 2300K, the protective alumina layer melts and allows the particles to ignite. Then a diffusion flame developsand controls the combustion rate of the droplet. Small alumina particles are formed in the flame and can be assimilated to oxide smoke with a standard diameter lower than 1µm. Some larger alumina particles can be associated to residual alumina on the droplet surface on combustion. This alumina cap results from initial protecting layer that covered aluminium particles of the agglomerate. The resulting diameter may reach 100µm [9] according to the size of the agglomerate. However, some interactions (coalescence) between particles may occur in the combustion gas and then increase the residue diameter.

Dedicated studies deal with the understanding of aluminium combustion in order to determine accurate combustion time (see [10][11][12] or [13]). In [12][11], Orlandi *et al.* present a numerical study of the combustion of a single droplet in a propellant gas environment where the unsteady response of the droplet is also addressed. Preliminary results suggest that for moderate frequencies, the steady assumption is still valid. Such a result was found in the case of combustion in air by Gallier *et al* [11] and can be extrapolated to solid propulsion gas environment. On the basis

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of these results, the standard d^2 law is used for the two-phase simulations presented in this paper. The combustion rate is then expressed as:

$$\dot{\omega} = \pi N_p (2 + 0.6 Re_p^{0.5} Pr^{0.33}) d_p \frac{\mu}{Pr} \ln(1+B) \quad (1)$$

where the Ranz-Marshall term insures the coupling between the gas and the condensed phases.

1.2. Aluminium combustion characterisation

The study of the coupling of aluminium combustion with instability requires the knowledge of the size of the droplets that are ejected from the propellant. A direct visualisation of the combustion can provide interesting data such as diameter distribution, or droplet velocity in a limited pressure range: droplets can only be identified and tracked down with a good precision for pressures lower than 3MPa. A second set-up consists in studying the combustion condensed products in order to assess the occurrence of agglomeration. This assessment is generally carried out through a specific rotate quench bomb where a propellant sample burns. The sample is located at the centre of the vessel and the test pressure is around 45 bar which is closer to the pressure in a SRM. The vessel contains a specific liquid which will quench combustion. Rotation makes the liquid climb the vertical vessel walls where the condensed products are collected. An example of results is reported on fig. 2 where the size distribution of combustion residues is plotted. The diameters are nondimensionalized by the initial particles diameter. As it can be seen, only smokes and a small amount of initial particles that did not completely burn can be observed. The presence of unburned initial particles is confirmed by the measurement of a small quantity of metal aluminium. If large agglomerates were produced, coarse combustion condensed products should be found in the size distribution.

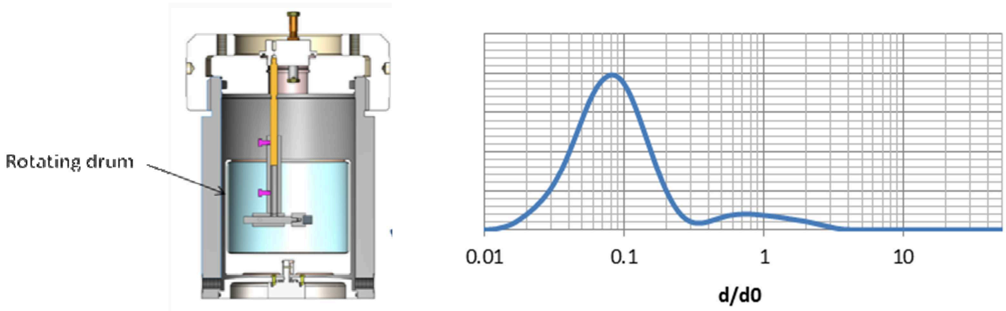

Figure 2 : Quench bomb and size distribution of the condensed product

Once we know the droplets size at the propellant surface, their interaction with an acoustic field can be tested with a specific test bench used at ASL Research Centre (CRB). This test bench was first developed by Beckstead [5] and consists of a variation of a classical T-Burner modified by adding propellant sample in the middle of the two branches where acoustic velocity is maximum (Velocity Coupling T-Burner configuration - VCTB). The figure 3 presents a view of this device which was successfully used by testing different HTPB/AP/Al composite propellants.

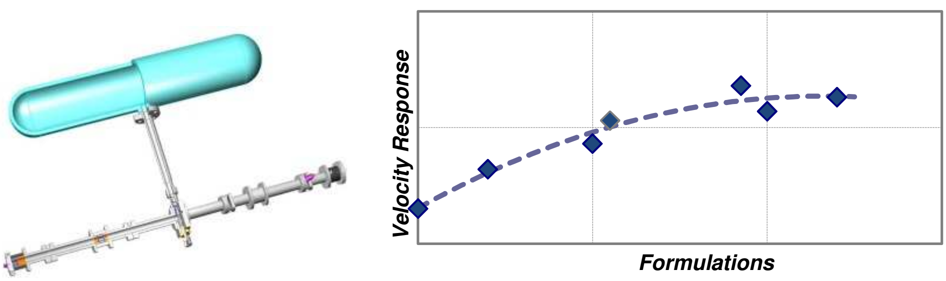

Figure 3 : ASL modified T-Burner and velocity responses for VCTB experiments

By varying propellant compounds, different velocity responses have been obtained for a given frequency. All the propellants were designed to avoid, or at least limit, the formation of large aluminium agglomerates. Hence, considering the propellant tested with the quench bomb, particles ejected from the propellant surface were mainly the

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same as the initial powder. As shown on the graph, a tendency can be found according to the considered propellant and the particles size. An optimum is found as predicted by numerical simulations. This specific device shows that there exists a clear interaction between the droplet combustion and acoustics and can help calibrating the particles size that responds to a selected frequency.

2. ITHAC in SRM

In order to obtain an experimental evidence of the ITHAC instability, ASL developed an original methodology based on theory, detailed numerical simulations and accurate experimental characterisations (aluminium powder, combustion products and propellant burning characterisation). This study was founded by CNES and carried out beside the "Instabilités De Combustion" (IDC) project which aims to design a SRM without pressure oscillations [14].

The first step was to define a motor geometry that may exhibit the ITHAC instability. The maturity of digital models, especially for aluminium droplets burning, allows now such an approach. Secondly, an important work was dedicated to the propellant formulation and characterisation of aluminium combustion. The coupling of aluminium powder was selected by numerical simulations of the Beckstead T-burner. Finally, aluminium combustion with acoustics is experimentally examined through a T-burner test. Based on the confirmation of these elements, a dedicated motor could be designed.

Since aluminium droplets burn in the gas phase near the propellant surface, the whole combustion energy is released in that region. The thickness of this combustion layer will depend on aluminium droplets size and their velocity. On the other hand, combustion chamber may be considered as a resonant cavity where a longitudinal acoustic wave may develop. A very specific acoustic layer takes place in the wall zone. It is characterised by rapid variations of the acoustic velocity near the wall or for a propellant grain, near the burning surface. For aluminised propellants, droplets are ejected from the surface and then dragged by the hot gases. They burn in a thin zone and the heat released by the combustion of these droplets interacts with the acoustic layer rather than with the planar wave (see Figure 4).

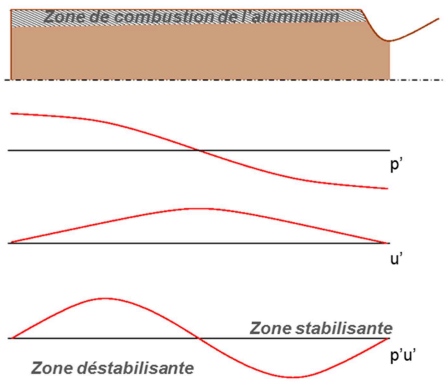

Figure 4 : Schematic view of interaction between the combustion of aluminium and acoustics (1st longitudinal mode)

In such a configuration, a Rayleigh criterion can very easily be constructed. A thermo-acoustic instability may develops only in the case of a positive Rayleigh integral value:

$$\int_{\Omega} \overline{p'Q'} \mathrm{d}V > 0 \tag{2}$$

Based on previous works of Culick [3], Gallier and Godfroy [7] proposed a theoretical framework derived from standard conservative laws of fluid mechanics. They used a linearization of fluid equations by assuming small amplitude pressure fluctuations. This leads to an analytical expression of the growth rate of harmonic modes taking into account the contribution of droplets combustion. Taking into account the other acoustic gains and losses, one can then state on the linear stability of the motor. It was also demonstrated, that the fluctuation Q' of the released heat is closely related to the velocity fluctuation u' through a transfer function that can be evaluated considering only the averaged flow field.

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As shown on Figure 4, two distinctive contributions can be identified: the front part of the combustion chamber has a destabilising effect and the rear part is stabilising. We insist on the fact that the overall stability estimation should consider all the acoustic gains (mainly due to aluminium combustion) and losses (inert particle damping, flow turning, nozzle losses…) that take place in the combustion chamber.

2.1 Experimental demonstration of ITHAC

The “Stelis Calypso” grain was fired on the 1st of April, 2015, at the Onera Fauga-Mauzac centre in order to provide a clear demonstration of the existence of ITHAC in a SRM configuration. The aluminium size was selected through a parametric study of the test bench T-bruner for which several numerical simulations were performed varying the droplets diameter. An optimal size maximizing the response of aluminium combustion was found and the propellant was formulated with aluminium particles close to this size.

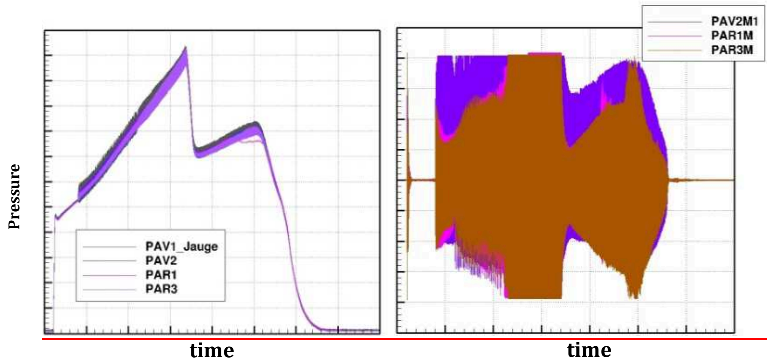

Figure 5 : Stationary pressure history of “Stelis Calypso” firing test

The unsteady behaviour recorded during this firing test clearly meets the objectives the motor was designed for. This result was possible thanks to a propellant formulation for which a specific aluminium powder is used (size was carefully selected) and the choice of a dedicated grain geometry that was designed to reinforce the resonance of the chamber.

Just after the ignition, a first burst is observed. Its amplitude is limited and its duration is a few milliseconds. A second instability takes place after a small period of stability and stretches out over almost the entire test duration. Even the presence of a pressure drop does not strongly affect the phenomenon and the instability can be observed until the end of the firing.

2.2 Analysis of the major instability

The second instability stretches out on almost all the firing. Figure 6 shows the instability amplitude which is of several bars and the associated frequency spectrum.

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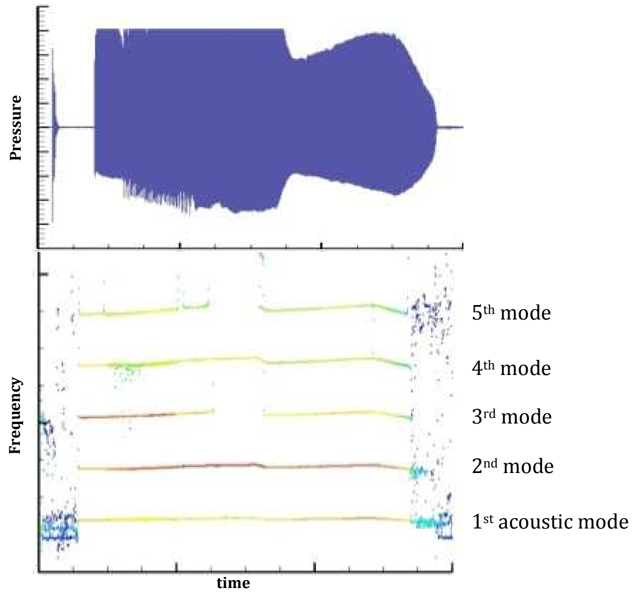

Figure 6: Amplitude and frequency evolution of the second instability of the firing

The analysis shows a rich spectrum with the presence of several longitudinal modes which can be observed during the whole time of the instability occurrence. Main energetic modes are 3L, 2L and 1L. Only the relative amplitude of each mode may vary with time. At the beginning of the instability, the instability is mainly set on a 3L mode associated with 2L and finally 1L. After the 1st third of the firing, the 2L becomes predominant, and at the end of the firing, the first mode is reinforced with regard to the 3L mode. Figure 7 illustrates this modification by considering two instants during the instability.

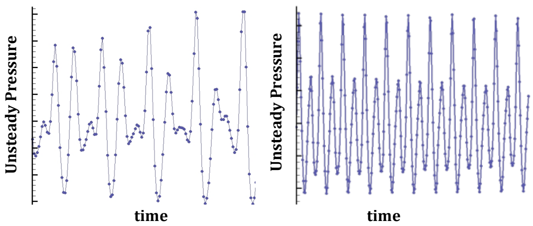

Figure 7: Evolution of the unsteady signal at two different times (same scale in time)

2.3 Possibility of a pressure response

The pressure response of the propellant could be a plausible explanation of the observed instability. The possibility of a pressure response driven instability thus needs to be studied. Culick proposed a theory to analyse such behaviour (see [3] for application to solid propulsion) and a modelling of the propellant response to pressure oscillations. It can be expressed as:

$$R_p(f) = \frac{\dot{m}'/\bar{\dot{m}}}{p'/\bar{p}} = Re\left(\frac{n.A.B}{S+\frac{A}{S}-(1+A)+A.B}\right) \qquad (2)$$

$$S = \frac{1}{2}(1+\sqrt{1+4i\omega} \text{ and } \omega = \frac{2\pi fa}{V_c^2} \qquad (3)$$

where Vc is the propellant regression rate, a the thermal diffusivity, n the pressure exponent, f the considered frequency and A and B two constants to be determined.

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Thanks to experiments carried out with the modified T-Burner on the propellant formulation used for the test, values of the pressure response are available for two frequencies. A third one is available at low frequency since response takes the value of the pressure exponent n when frequency tends to zero. With these results it is possible to build a pressure response as presented on the Figure 8. Indeed, two types of pressure response can be found according to the location of the maximum with regard to the experimental values (these two solutions are given by two distinct sets of values for parameters A and B I n Eq. 2 and 3). Frequencies associated to longitudinal modes encountered during the firing are also plotted on Figure 8. Note the very low pressure response for both the 2L and 3L modes.

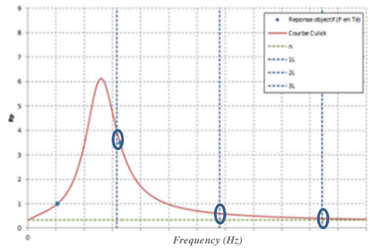

Figure 8: Example of pressure response curve

A study of the potential acoustic gains and losses of the motor was performed. It showed that the motor is stable from a point of view of the linear stability theory. The possibility to develop instability on a 1L, 2L on 3L modes as it was observed during the firing is now considered. Given the acoustic losses on this mode, the required pressure response should be much larger than the value given by the response function to trigger the instability. Hence, the pressure response, considering the Culick's approach, cannot explain the presence of the modes of the observed instability.

2.4 Effect of aluminium combustion

If one now considers that the instability can be induced by a mechanism that involves aluminium droplets combustion, a reasonable explanation to the firing behaviour can be proposed. Numerical simulations are considered as a powerful tool to confirm this assumption. Many calculations were performed considering a two-phase flow with the ASL in-house code CPS. It considers an Eulerian approach for the gas and condensed phase. A well-known d^2 law is used to model the combustion of aluminium particles. The convective effect of the gas on the droplet combustion rate is taken into account by the use of a Ranz-Marshall law.

An example of a 2D simulation is illustrated on Figure 9. The corresponding time is ~20% of the grain burning. At that moment, oscillations are experimentally fully developed. The mesh contains 95000 cells with a particular refinement at the propellant surface in order to correctly capture the physical phenomena in the aluminium combustion zone. The particles are injected on the central bore surface with a diameter close to the mean diameter used for the propellant formulation. Results indicate the formation of a stratified structure of the gaseous flow near the propellant surface (acoustic boundary layer) and no vortices can be observed. This structuration of the aerodynamic field is typical of ITHAC calculations in SRM.

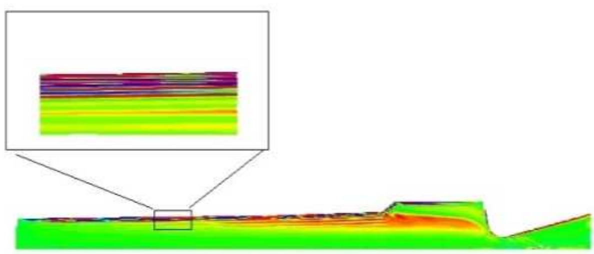

Figure 9: Gas phase rotational structure due to the droplet combustion

In order to highlight the effect of the droplets combustion on the instability, a second simulation is performed where aluminium particles are supposed to burn instantly at the propellant surface: a single phase flow is then considered for which thermodynamic properties of the gas phase are adjusted to take into account aluminium combustion. The pressure history of the gas phase simulation is presented on fig. 16 and is compared with the pressure oscillations found in the two-phase flow simulation. The pressure is nondimensionalized by the mean pressure which is the same

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for both simulations. Although the two-phase flow simulation exhibits strong pressure fluctuations that can reach in amplitude 7% of the mean pressure, in the one phase simulation, the pressure remains constant with no oscillation (cf. Figure 10).

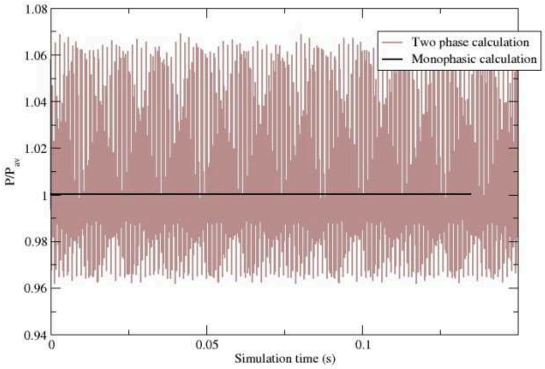

Figure 10: Pressure history for simulations with and without droplet combustion

The rotational field is presented on Figure 11. It shows a classical structure for a steady flow without vortices. Since the flow is stable, stratification of the flow is not observed unlike the two-phase flow simulation. These results clearly indicate that combustion of aluminium droplets is the driving mechanism of the instability in the previous calculation.

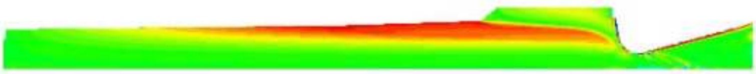

Figure 11: Gas phase rotational structure due to the droplet combustion

A study of the frequency evolution during the firing is proposed on Figure 12. Pressure measurement is analysed thanks to the HRogram method [15]. Continuous lines represent the frequency corresponding to the first mode and higher order modes. The beginning of the oscillatory behaviour appears clearly. The spectrum exhibits five modes even if the first three ones are the most energetic. This frequency evolution is compared with the theoretical acoustic frequency which is plotted with the dotted black lines. A good agreement is obtained for the second and the third mode. For the first mode, the theoretical frequency seems to be slightly lower than the one measured. The coloured dots correspond to the exploitation of the two phase calculation. As it can be seen, a good agreement is found between the computed frequencies and the measured ones. A third simulation was performed at a time in the middle of the test. The fairly good agreement is found even if the first mode is not observed in the calculation. Even if the fourth mode tends to be overestimated, the evolution of the different mode levels is correctly predicted by the two calculations with the same model of the droplets combustion.

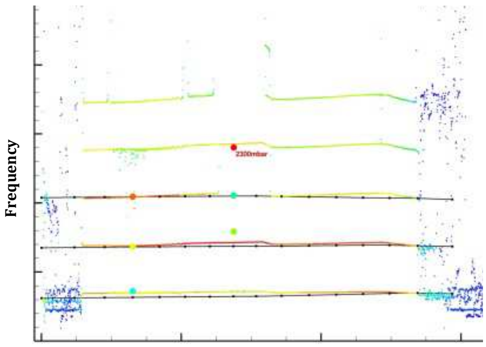

Figure 12: Frequencies study in the case of oscillatory flow

The “Stelis Calypso” grain firing demonstrated the effect of aluminium combustion on the acoustics field. A strong instability developed with huge pressure oscillations levels that are objectively driven by aluminium combustion. In this configuration, neither hydrodynamics instabilities nor a standard pressure response of the propellant can explain these results.

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3. Effect of aluminium combustion with the hydrodynamics instability

Hydrodynamic instabilities can develop in a SRM (example of Surface Vortex Shedding (SVS)). In a first step, only the effect of inert combustion products on the motor stability is considered as in [16][18]. The effect of combustion will be addressed in the following paragraph.

3.1 effect of inert combustion products

Relying on classical Temkin-Dobbins linear theory [17], such inert particles are reported to dampen acoustic instabilities and are widely used for that purpose, especially in small tactical motors. However, this approach only holds for a homogeneous and non-rotational medium which is not the case in most SRM's where vortex shedding is occurring.

The LP6-7 configuration (1/15 scale) is selected as a reference for the following calculations. Propellant containing no aluminium particles was fired and exhibited a SVS. Single phase numerical simulations yielded a similar behaviour and confirmed the ability of numerical tools to predict such phenomena. In the following computations, geometry is chosen at the time when pressure oscillations are the largest. The parametric study only deals with the diameter of injected particles. It appears that the Stokes number (St), defined as the time of particle relaxation to vortex time, is a relevant parameter to follow the inert particles effects in such a configuration. Its expression is:

$$St = \omega\tau_u = 2\pi f \,.\, \frac{\rho_P d_P^2}{18\mu} \qquad (4)$$

As described on Figure 13, the presence of vortices due to SVS induces a modification of the condensed phase concentration in the combustion chamber. All the calculations are performed with a particle mass fraction of 6% injected at the propellant surface. The most important effect consists in a sharp concentration of particles in the area between two vortices, leaving the centre of the structure nearly empty. This phenomenon comes out to be preponderant for a Stokes number close to unity. As reported in the literature [18][19][20], particles are centrifuged and preferentially rearrange at the outer edge of structures when the characteristic time of the vortex is equivalent of the characteristic time of the particle τ_u, leading to a St number of one. This effect is shown on next figure where the centrifugation is optimal for a Stokes number equal to one. On the opposite, for a small Stokes number, some particles reach the centre of the vortices and their distribution seems more regular in the combustion chamber. Largest particles come across the vortices and reach the centre of the combustion chamber where they accumulate although some of them concentrate between vortices but in a less important proportion than for St~1.

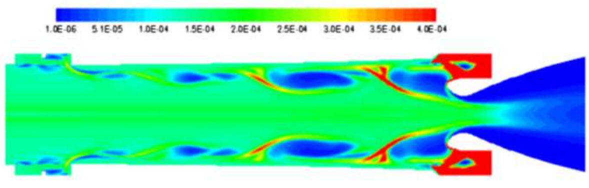

Figure 13 : Particle concentration for St~1

Until now, calculations were performed assuming an injected aluminium mass fraction issued from the supposed formation of agglomerates (i.e. 6% of the propellant overall mass). If we now consider only combustion products, the total amount of the condensed phase is dramatically reduced to 0.667%. The same parametric study is carried out with this new injected mass fraction and the pressure oscillations levels collapse even if the same bell shape is observed: the maximum level is obtained for a Stokes number shifted from one to a little larger value close to 2. For that Stokes number, the amplification is just under 20% compared to 110% in the case of 6% in mass. In any case, it is shown that the introduction of inert particles reinforces the pressure oscillations levels in the case of the presence of a SVS hydrodynamic instability.

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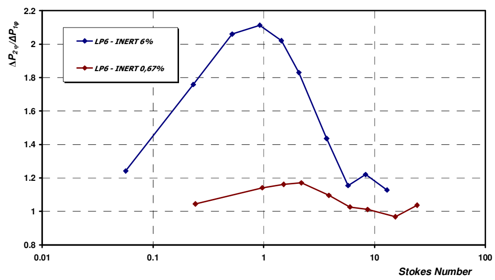

Figure 14 : Amplification level in function of the Stokes number

In order to have an experimental evidence of this phenomenon, a specific propellant was designed to be fired in the Onera experimental set up. This sub-scale motor consists of a 1/35 reduction of the MPS/P230. The dedicated composite HTPB/AP propellant was loaded with inert Zirconium oxide particles whose diameter ensures a Stokes number close to unity. Their overall mass is 7% of the propellant mass. The pressure measures during the two firing tests are presented on Figure 15. For the purposes of comparison, results obtained with an equivalent unloaded propellant (single phase configuration) are added to the graph. As it can be seen, the mean pressures are quite similar and both firings exhibit a serial of bursts corresponding to unsteady pressure evolutions.

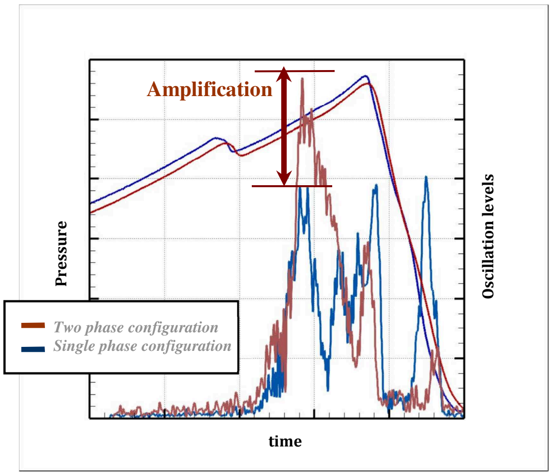

Figure 15 : Experimental results of pressure oscillations level (courtesy of Onera)

As suggested by numerical calculations, a significant increase of pressure level is observed on the first two bursts until 2.6s. However, a damping of oscillations appearing with the last burst must be noted. This burst takes place during a rapid evolution of the grain shape (end of combustion for 3rd grain segment) which needs a dedicated study to examine the preponderant unsteady geometry effects.

Two series of more than 20 computations of that configuration (scale of 1/35 Ariane 5 SRM P230) were performed in order to analyse the pressure oscillations evolution with time. Each calculation corresponds to a fixed time of the grain evolution which defines the combustion chamber geometry. Pressure levels of the instability are studied and compared with experimental data as shown on the next figure. As expected, both approach's (numerical and experimental) exhibit similar behaviours during the presence of instability. The maximum of oscillation levels is obtained at the same time followed by a gradual decrease of the oscillations levels until the apparition a new burst. The internal flow suggests that important changes occur during the level falloff. Particles are packed between structures although such an organisation seems to have disappeared a few times latter.

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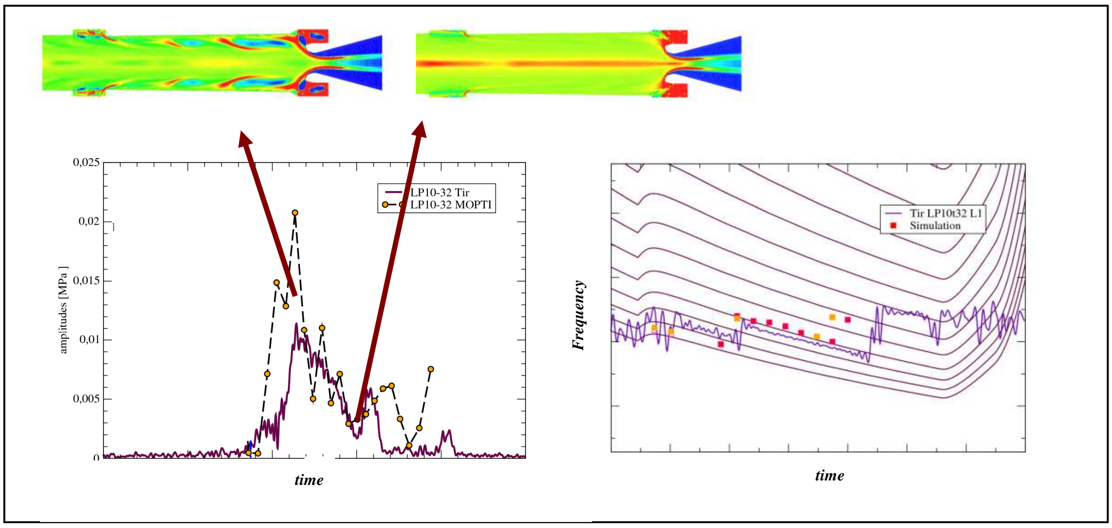

Figure 16 : Comparison of pressures oscillations levels evolution
between firing and calculations in the two phase configurations

However, simulations do not accurately estimate pressure oscillations levels: on the major burst, a factor of 2 is observed between the numerical values and the experimental ones. Likewise, the last simulated burst is characterised by an overestimation of its developing time. Such differences are related to the geometry sensibility. At such a small scale (1/35), minor variations in the grain geometry induce dramatic changes in the pressure oscillation levels. The study of the frequency evolution shows that the bursts are characterized by a serial of gradual decreases of the frequency. On the Figure 16, the experimental frequency is plotted on a theoretical network of frequency evolution. This set of unstable modes is obtained on the basis of Casalis and Chedevergne theory [21] which considers the intrinsic unstable modes of the Taylor's flow. As shown, the experimental and simulated frequencies are in good agreement and for each burst, the frequency jumps to another mode as theoretically predicted.

3.2 Effect of the combustion of aluminium droplets on SVS

Even if the effect of inert combustion products is relatively well understood, the combustion of aluminium particles can lead to more ambiguous and complex phenomena. The next figure presents the pressure unsteady evolution for three AP/Al/HTPB composite propellants fired in the same 1/15 Ariane 5 MPS/P230 mock-up configuration (segmented geometry). Reference propellant is a non-aluminized propellant, and the two others contain the same amount of aluminium. The main difference consists in the combustion process that leads to low agglomeration for propellant Butalane #1and high agglomeration for propellant Butalane #2. Agglomeration leads to a different size distribution of the aluminium droplets in the combustion layer. As it can be seen, aluminium combustion can modify the instants of bursts occurrence and their pressure oscillations levels in comparison with the non-aluminized propellant.

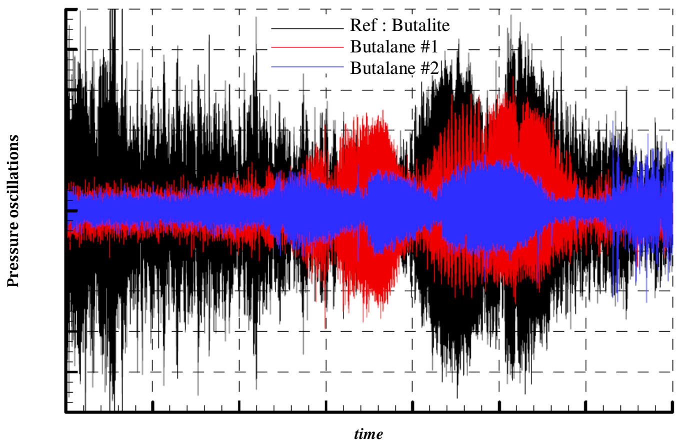

Figure 17: Unsteady pressure of three LP6 tests (courtesy of Onera)

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In order to explain these results, preliminary calculations were performed at the instant of the maximum of the third burst. Simulations consider a two-phase flow and a parametric study is carried out on the particle diameter dependence. An amount of 6% in mass of aluminium is considered for a residual mass of 0.67%. Results exhibit a peculiar effect of the pressure oscillation due to the combustion. Contrary to inert products, combustion of droplets can either strengthen or reduce pressure oscillations levels. A first amplification phase is observed for smaller droplet diameters then followed by a drastic collapse of the levels. Stokes number is built based on the final residue size. However, if we consider the effect of inert products resulting from the droplets combustion (residues), the obtained amplification is not sufficient to explain the levels reached when aluminium droplets burn. A 6% amount of aluminium burning will form only 0.66% of inert particles. As a consequence, effect of inert residues is very limited and no reduction is observed. The increase level and diminution of the levels thus cannot be explained by the sole effect of inert particles presented in the previous paragraph.

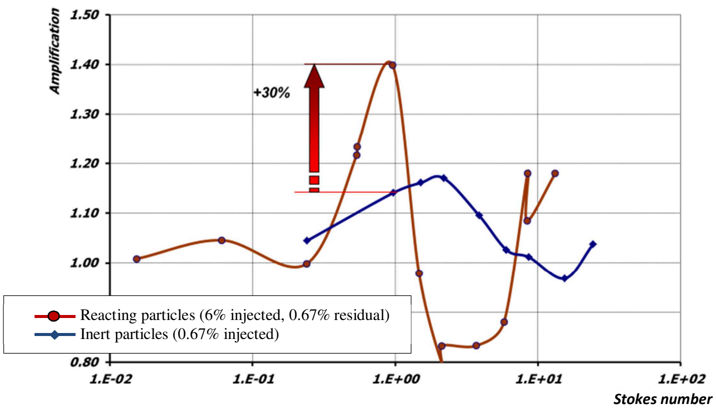

Figure 18: Combustion effect on pressure oscillations levels

In order to better understand this phenomenon, a numerical study was performed on a simplified geometry. Combustion chamber is limited to a pipe-like geometry and the L/R ratio is large enough to allow the development of a SVS. The refinement of the mesh is adapted to correctly describe the droplet combustion thickness. A parametric study is performed by varying the droplet diameter and the amount of injected aluminium. For each case, the characteristics of the gas are modified to keep the same thermodynamics of the final combustion gases. On Figure 19 one can observe that amplification is maximal for the higher aluminium rates whereas the decrease seems to be less dependent to the rate. The implication is characterised by the development of large vortices structures.

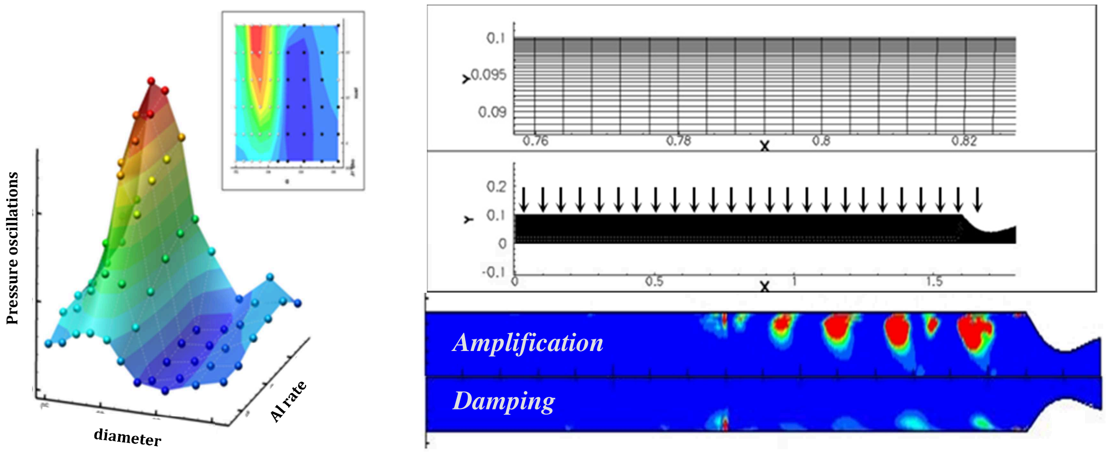

Figure 19: Effect of aluminium combustion of the SVS oscillation levels

3.3 Effect of the combustion location

Since a “ITHAC-like” mechanism is suspected to occur, complementary simulations are performed to study the coupling between combustion and hydrodynamics. .. First we note that coupling between aluminium combustion and the fluctuations present in gas phase is mainly insured by the Ranz-Marshall correction term in Equation (1). In the reference simulation, coupling is activated in every part of the motor. Two other cases are then considered where

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coupling is respectively deactivated in the front and rear part of the motor only. This is done by imposing an average value of the vaporisation rate computed in a first preliminary simulation. This methodology possesses the advantage to keep the average gas field unchanged, simplifying interpretation of the results. The results of the parametric study are presented on Figure 20. When the vaporisation rate is averaged on the rear part of the chamber only, combustion of droplets provides a systematic increase of the pressure oscillation levels. On the opposite, when averaging is done on the front part only, no amplification is observed compared to the reference case. All these elements contribute to clearly show that aluminium combustion is a driving mechanism that can dramatically change the pressure oscillations levels. Moreover, numerical simulations show that coupling between aluminium combustion and flow fluctuations operates differently whether it is located at the front or rear end of the motor: it will reinforce pressure oscillations on the front part and dampen the instability on the rear part. We also show that the extent of amplification/dampening depends on the size of the aluminium particles. However, some dedicated experimental data should now be acquired to further investigate this phenomenon.

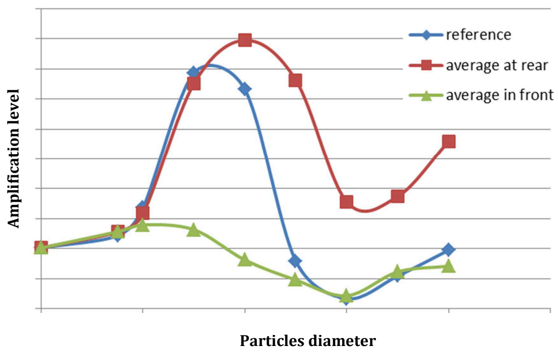

Figure 20: Effect of the location

Conclusion

This paper presents some aspects of the coupling between combustion of aluminium droplets and intrinsic instabilities that may be encountered in a solid rocket motor. Two examples highlight the modification of the pressures oscillations characteristics due to aluminium combustion.

We first focused on the interaction of combustion with the acoustic field in the combustion chamber. Aluminium droplets combustion interacts with the acoustic boundary layer yielding to a significant increase of the pressure oscillation levels. This phenomenon, referred to as ITHAC, is analysed and experimentally demonstrated through the firing test of the Stelis Calypso grain that was specifically designed for that purpose. The test results, added to T-burner velocity characterisations, provide clear evidence of the existence of ITHAC in SRM.

The focus is then set on the interaction of aluminium combustion with hydrodynamic instabilities. It is well-known that for long central bore grains, a SVS may develop creating rotational structures in the rear part of the chamber. Two effects of aluminium combustion are identified in the presence of SVS. The first one is due to inert condensed products that are concentrated at the outer edges of the vortices of the instability. These 'particle bundles' reinforce pressure oscillations when they pass through the nozzle sonic line. This amplifying effect is supported by experimental evidence. The second effect exhibits an even more complex behaviour and is related to the coupling between heat release and flow fluctuations induced by the SVS instability. Numerical studies yield precious indications on this phenomenon: depending on the aluminium size, one can observe either an amplifying effect due to coupling in the front part of the grain or a damping of the oscillations due to coupling operating at the rear end. This phenomenon may explain the difference in pressure oscillations levels observed for aluminized and non-aluminized solid propellants.

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