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WAVES PROPAGATION AND LIQUID ALUMINUM PARTICLE INJECTION IN SOLID ROCKET MOTORS

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Abstract. *A method to determine the injection of aluminium particles from the solid propellant burning surface to the core of the chamber in the presence of an acoustic wave field is developed and aluminum-droplet effects on propagation of acoustic waves in the flow of a solid rocket motor are analysed. Changes of the multiphase flow compressibility are calculated by taking into account both the translational and the pulsational motions of the aluminum droplets in consequence of the acoustic waves.*

NOMENCLATURE

c_s	sound speed
c_v	Specific heat at constant volume
c_p	Specific heat at constant pressure
p	pressure
u	velocity
T	Temperature
C_m	Particle mass loading
Q	Heat transfer
α	Attenuation coefficient
β	Dispersion coefficient
γ	Specific heat ratio
ϕ	Concentration of particles
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ	Density
σ	Density of a phase
ω	Frequency

1 INTRODUCTION

Solid propulsion is a leading technology for space missions where high thrust level is required. Simplicity, high volumetric specific impulse, high thrust with small volumes and proven experience on large-scale systems represent some of the most useful features of solid propellant motors.

During last decades, the use of aluminized propellant in solid rocket motors (SRMs) has been widely studied in terms of propellant combustion, distributed combustion, two phase flow, agglomeration, impingement, erosion and slag deposition.

The micrometric ingredients in aluminized solid propellants increment the specific impulse and their short and midterm applicability is ensured; inefficient combustion due to aluminium agglomeration and two-phase flow effects represent the drawbacks of the current technology. Moreover, the production of condensed combustion products leads to the generation of micrometric space debris which can potentially damage other orbiting space systems.

Taken into account the constant request to increase the thrust keeping the dimension of the motor, the needing of keep low the generation of combustion debris, the advent of nano-materials, is a recent impulse to the studies about the use of metal powders use in space applications.

Then the research of new energetic ingredients for novel high performance solid propellants looks to formulations embedding blends of nanometric and micrometric aluminum powders. The use of a fraction of nanometric powders instead of micrometric ingredients guarantees the reduction of agglomerate mass and an increase of burning rate. The best effect is likely to reach when only nanometric aluminium is present. Combustion features have been investigated through experimental works and models. Tests with propellant strands as well as small scale motors featuring extreme sensitivity to two-phase flow have been performed and beside the increase in specific impulse changes in acoustic combustion instability modes have been observed.

In this paper a theoretical analysis of wave propagation and liquid aluminium particles path in the combustion chamber of a solid rocket motor is presented. Some corrections in current metalized propellant rocket instability calculations accounting for the results of the analysis are proposed.

2 PARTICLE AGGLOMERATION AT THE BURNING SURFACE

The current applications of aluminized propellant use ammonium perchlorate as oxidizing agent, aluminum as solid fuel and a thermosetting polymer matrix which confers mechanical strength. Combustion process of metal powders within such propellants generates particle agglomerates featuring a diameter in the order of some hundreds of micrometers. An unburnt metal fraction is still present in agglomerates when leaving the burning surface and completion of oxidizing process takes place far from the burning surface.

Today, many scientific works connect the details of the chemical-physical composition of the propellant and the operative conditions of combustion to the final size of the produced agglomerates. In fact, both the chemical composition of the fuel and oxidizer powders and their particle size distribution play an important part in the agglomeration phenomenon. According to the original model proposed by Cohen based on the heterogeneity, when micrometric metallic powders are used, agglomeration occurs in the areas of the propellant where the combustion powders are trapped between large particles of oxidizer. These areas are called Pocket and represent regions where agglomeration is favored, and the particles tend to join together before they leave combustion surface. Has been already testified that the final size of agglomerates is highly influenced by the residence time of the metal on the burning surface, where conditions of high burning rate can be separated from the low rate ones. In the first case, smaller agglomerates are attained since original Pocket breaks into Sub-Pocket because of the low residence time and cannot agglomerate any more. In the second case the high residence time leads to the complete fusion of many agglomerates before they leave the surface of combustion, so the final size becomes larger. Reducing the particle size of the oxidizer, propellant regression rate is increased and the Pocket size is reduced, so the reduction of agglomerates size is favoured. Some analysis has been conduced about the partial substitution of micro aluminum powders with nanometric materials, showing a gradual increase of burning rate or combustion efficiency. Yet the increase in not linear and a cost-benefit compromise should be pursued. Moreover, a different agglomeration process is visible when ultrafine powders are present. In such case thin aggregates leave the burning surface in spite of spherical agglomerates.

Interpretation of the process is still open. Experimental evaluations of agglomerates produced by solid propellant rockets have been obtained in the past using two different techniques. The first one consists in gathering and quenching the agglomerates in a melting bath using ice or an inert liquid. Although this method freezes the evolution of the particles, it is invasive and the agglomerates are collected not so close to the surface. It is possible to perform a particle size analysis and a chemical composition investigation, linking the combustion efficiency to the metal content in the residuals. The second method is based on a technique of high speed and resolution cinematography, and implies the direct visualization of agglomeration, leading to the direct evaluation of the agglomerate diameter (in terms of distribution and mean volumetric diameter). It is a recent technique originated from the modern development of digital video cameras coupled with a long focal microscope. The analysis of the videos and the evaluation of the diameters of the particles are not easy because of the oxidation reaction taking place on the agglomerate surface. This is a not intrusive technique that allows the measurement immediately after the particle is released in the reacting flow. Agglomeration prediction is grounded on a new approach which takes into consideration material heterogeneity. Packing codes are used to supply computer-generated heterogeneous models which are statistically equivalent to the real material. An example of a dynamic positioning code using a molecular dynamic approach is Rocpack. The code, developed by CSAR, University of Illinois at Urbana Champaign, allows the random positioning in 2-D and 3-D space of disks or spheres of arbitrary size. This method is in use for mechanical and combustion modelling.

3 PARTICLES INJECTION IN THE ACOUSTIC FIELD

The boundary conditions for the ejecting particles constrain their trajectories, hence these affect the two-phase flow calculations, and thus significantly affect the evaluation of the slag accumulation. A method to determine the velocities of particles from the solid propellant surface to the core of the chamber in the acoustic wave field is developed in the present study. The method simulate the particle ejection from the propellant surface and the moving trajectories of metal particles in a firing combustion chamber are calculated taking into account the coupling with the acoustic wave field.

Numerical simulations with different propellant-surface boundary conditions are performed to calculate particle trajectories. By comparing two trajectories, an appropriate boundary condition on the propellant surface is referred. The present method can be extended to study the impingement of particles on a wall and other related twophase flows.

In order to calculate the trajectory of a particle in the combustion chamber, the gas flow field may be simulated first. For the present case, the mass fraction of particles in the combustion chamber is very low. There are several methods to simulate the gas flow field in a SRM combustion chamber, such as by pressure correction methods, the AF (Approximate Factorization) method, etc. In the present calculation the NavierStokes equations are solved by AF method to calculate the flow field. As the flow is transonic flow at the throat of the nozzle, the grid distribution in axial direction is attracted to the throat.

Usually there are two ways to perform the trajectory calculation: (1) Lagrangian method, in which particles are considered as a dispersed phase and each particle or particle group is followed in Lagrangian coordinate system; (2) Eulerian method, in which both gas and particles are considered as continuous phases and can be treated in an integrate method. In the present calculations the Lagrangian method is used to model the particle trajectory.

Acoustic oscillations in the internal flow of a solid propellant rocket motor provide additional mechanisms to transfer energy from periodic motions to turbulence leading to an early transition from laminar to turbulent. Turbulence induced eddy viscosity tends to suppress vortical flow motions caused by acoustic waves. Some attenuation of acoustic oscillations results from the transfer and dissipation of the acoustic energy by the particles through the momentum and heat exchange. The matching of particle thermal and momentum relaxation times and acoustic characteristic time have an important role in dictating the multiphase flow interactions with oscillatory motions. The maximum attenuation of acoustic energy seems to occur when the timescales become comparable. Current solid-propellant rocket instability calculations account for the evolution with time of acoustic energy and kinetic energy in the shear waves. The propagation of acoustic waves in fluids that contain particles is a studied subject. However instability calculation capabilities including aluminum particle effects on the propagation of waves in the combustion chamber of a rocket motor are limited. Theories for sound attenuation and dispersion on the basis of changes of suspension compressibility produced by the relative motions between the host fluid and particles have been developed. Some approaches decouple the propagation problem from the more difficult problem of obtaining an accurate description for the fluid-particle interactions. In this paper we adopt an approach of this type and this approach includes the translational and pulsational motion of the particle under the effects of the sound wave.

3 DYNAMIC COMPRESSIBILITY

The gas in the combustion chamber of a solid propellant rocket motor sustains acoustic waves changing its density. Such changes could be quantified by the medium's adiabatic compressibility defined by $K_s = (\delta\tau)^{-1} d(\delta\tau)/dp$. K_s should be computed while holding the entropy of the element of volume constant. This approach unfortunately cannot be adopted in the multiphase internal flow of a solid rocket motor. Exceptions occur at frequencies so low that equilibrium exists in the medium and it has been shown[7] that the sound speed is given by

$$\frac{c_{sf}^2}{c_s^2(0)} = \frac{1-\phi_v}{1-\phi_m}\left[\gamma_f(1-\phi_v)+\gamma_p\phi_v N_s\right] - (\gamma_f - 1)\frac{\left(1-\phi_v+\phi_v\beta_p/\beta_f\right)^2}{1+\phi_m\left(c_{pp}/c_{pf}-1\right)} \tag{1}$$

or at frequency so high that the medium can be considered frozen and the sound speed denoted by $c_s(\infty)$ can be defined in limit where the particles are essentially at rest or frozen. An expression for the sound speed is given by

$$\frac{c_{sf}^2}{c_s^2(\infty)} = \frac{(1-\phi_v)^2}{1-\phi_m} \tag{2}$$

The multiphase flow's density can be written as $\rho = \rho_f (1-\phi_v)/(1-\phi_m)$. The equilibrium compressibility $K_s(0)$ when $\omega \to 0$, for small aluminum particles concentrations, is given by

$$K_s(0)/K_{sf} = 1 - \phi_v + \phi_v\left[\gamma_p N_s + (\gamma_f - 1)\left(p_p c_{pp}/p_f c_{pf} - 2\beta_p/\beta_f\right)\right] \quad \textbf{(3)}$$

We can consider the aluminum-droplet multiphase internal flow of the rocket motor in equilibrium as an ideal medium characterized by sound speed and density. To obtain the compressibility of the multiphase internal flow at frequencies the rocket motor can show instabilities, we note that changes occur owing to non-equilibrium effects. These preclude the use of Eq. (3). Nevertheless, if the departures from equilibrium are small, it is possible to define a dynamic compressibility from K_s by considering the changes produced by the mechanisms that are active outside equilibrium. If we assume that each such mechanism contribute separately to the changes, we can express the departures of the frequency-dependent compressibility from its equilibrium as

$K_s(\omega)/K_s(0) - 1 = \left[K_s(\omega)/K_s(0) - 1\right]_1 - \left[K_s(\omega)/K_s(0) - 1\right]_2 + \ldots.$

For a given frequency, $K_s \to \tilde{K}_s(\omega) = \left[\rho_0 \tilde{c}_s^2(\omega)\right]^{-1}$, where $\tilde{c}_s(\omega)$ is a complex sound speed. Working with a complex wave number $\tilde{k} = \omega/\tilde{c}_s(\omega) = \omega/c_s(\omega) + i\alpha(\omega)$ where $\alpha(\omega)$ is the amplitude-attenuation coefficient, and $c_s(\omega)$ represents the phase velocity, we can write $\tilde{K}_s(\omega)/K_s(0) = c_s^2(0)/c_s^2(\omega) - \bar{\alpha}^2 + 2i\bar{\alpha}c_s(0)/c_s(\omega)$, where $\bar{\alpha} = \alpha c_s(0)/\omega$.

The quantity $\bar{\alpha} = \alpha\lambda/2\pi$ is a non-dimensional amplitude-attenuation coefficient, where the wavelength λ refers to waves traveling in the medium having a sound speed given by $c_s(0)$. Writing the equations in terms of $\bar{\alpha}$ we obtain

$$\frac{c_s^2(0)}{c_s^2(\omega)} - \bar{\alpha}^2 = 1 + \Re\left[K_s(\omega)/K_s(0) - 1\right]_1 - \Re\left[K_s(\omega)/K_s(0) - 1\right]_2 + \ldots \quad \textbf{(4)}$$

$$2\bar{\alpha}\frac{c_s(0)}{c_s(\omega)} = \left|\Im\left\{K_s(\omega)\right\}/K_s(0)\right|_1 + \left|\Im\left\{K_s(\omega)\right\}/K_s(0)\right|_2 + \ldots \quad \textbf{(5)}$$

Viscosity and heat conductivity through their action on the various motions that the particle can execute and on the temperature oscillations are the effects contributing to the compressibility changes.

4 EFFECTS ON WAVE PROPAGATION

The most general motion of a sufficient small aluminum vaporizing droplet in the internal gas of the solid rocket motor can be represented as the sum of a uniform translation, a rigid body rotation, and a stretching motion that can be split into a uniform expansion or contraction and a deformation of the element without a change of volume. Each of these motions can produce a change in the flow compressibility because it may affect the volume of the multiphase flow. Ignoring here shape oscillations as well as particle rotation, the only remaining particle motions are the rigid-body translation and the uniform expansion/contraction or pulsational motion and the equations for the sound speed and the attenuation can be expressed as

$$\frac{c_s^2(0)}{c_s^2(\omega)} - \bar{\alpha}^2 = 1 + \Re\left[K_s(\omega)/K_s(0) - 1\right]_{tr} - \Re\left[K_s(\omega)/K_s(0) - 1\right]_{pul} + \ldots \quad \textbf{(6)}$$

$$2\bar{\alpha}\frac{c_s(0)}{c_s(\omega)}=\left|\Im\{K_s(\omega)\}/K_s(0)\right|_{tr}+\left|\Im\{K_s(\omega)\}/K_s(0)\right|_{pul}+... \quad \textbf{(7)}$$

We consider a small volume element $\delta\tau$ having n equal particles which are allowed to pulsate, thereby changing their volume. The mass of the particles in the volume element is δM_p, and that of the fluid is δM_f. The volume element is chosen so that it always contains the same particles and the same fluid, that is, $\delta M=\delta M_p+\delta M_f$ is a constant. The corresponding volume $\delta\tau=\delta\tau_p+\delta\tau_f$ is, however, variable. We may obtain δM_p and δM_f in terms of the particle and fluid densities, σ_p and σ_f defined by $\sigma_p=\phi_v\bar{\rho}_p$, where $\bar{\rho}_p(t)=v_p^{-1}\int_{v_p}\rho_p(\mathbf{x},t)\,dV$ is the average density within one particle and $\delta M_f=\sigma_f\delta\tau_f$. Similarly, for the fluid mass, we obtain $\sigma_f=(1-\phi_v)\bar{\rho}_f$, where $\bar{\rho}_f(t)=(\delta\tau_f)^{-1}\int_{\delta\tau_f}\rho_f(\mathbf{x},t)\,dV$ is the average fluid density in the element, so that $\delta M_f=\sigma_f\delta\tau_f$. Thus the density of the suspension element is

$$\rho=(1-\phi_v)\bar{\rho}_f+\phi_v\bar{\rho}_p \quad \textbf{(8)}$$

and may also be written in terms of the mass fraction

$$\frac{1}{\rho}=\frac{1-\phi_m}{\bar{\rho}_f}+\frac{\phi_m}{\bar{\rho}_p} \quad \textbf{(9)}$$

From $K_s=(\delta\tau)^{-1}d(\delta\tau)/dp$, the contribution to the suspension compressibility arising from the translational motion as been evaluated and is given by[8] .

$$\left(\frac{K_s(\omega)}{K_s(0)}-1\right)_{tr}=\frac{C_m}{1+C_m}(V-1) \quad \textbf{(10)}$$

where $C_m=\sigma_p/\sigma_{f0}$ is the mass loading, $\delta=\rho_{f0}/\rho_{p0}$, $V=u_p/U_f$, where u_p is the complex translational velocity of a particle in a sound wave, evaluated in absence of other particles, and U_f is the complex velocity of the fluid in the sound wave, evaluated in isentropic conditions and without particles.

5 CONCLUSIONS

We have carried out a linear analysis of Aluminum-droplet effects on propagation of acoustic waves within the combustion chamber of a solid propellant rocket motor. The analysis is based on the assumption that the departures from equilibrium of the multiphase flow in consequence of the acoustic waves at frequencies the rocket motor begins to show instabilities are small. Then, changes of the multiphase flow compressibility are calculated including the effects of translational and pulsational motions of the particle resulting from the sound waves. Some corrections in current metalized propellant rocket particle trajectory calculations accounting for the results of the analysis presented here are proposed.

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