MINI MOTORS USING SOLID PROPELLANTS

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Abstract

The fields of applications for solid propellant mini-motors cover the propulsion of mini satellites, mini-UAV and spreading of MEMs.

Combustion in mini-chambers is driven by some effects different from these involved in larger motors. Flows are rather laminar, wall effects are important and time scales are short. In this aim, CFD computations are done with CPS code in order to illustrate these effects down to the millimeter scale. They have shown the influence of the combustion chamber dimensions on combustion efficiency and of two major effects: heat transfer and molecular diffusivity phenomena of gas combustion.

These particular conditions lead to the choice of specific solid propellants showing a strong energy and short duration of combustion. These compositions, laboratory-scale made, are first evaluated in term of sensitivity and combustion properties. Thermo-chemical calculations predict their energetic performances.

Some mini-grains of several grams are defined and made for new mini-motor design. A test bench is especially designed for this application. It is equipped to measure the internal pressure, thrust and the infrared temperature. The expected thrust is of a tenth of a Newton for a 1 second operating time.

Instrumented tests of operation are performed with a centimeter-scaled motor. The nozzle diameter is about one millimeter. The experimental results are analyzed and compared to ballistic prediction by simulation. An optimized mini motor system is using a carbon case and an adapted ignition system.

Then, these new energetic propellants contribute to the improvement of mini-motor performances and to the development of associated applications.

Introduction

The solid propellant micro rockets have been yet studied as thrusters for miniaturized engine [1]. The most common applications are smart dust deployment and Micro UAV propulsion booster or attitude control.

SNPE Matériaux Energétiques research activities propulsion are centered on the development of energetic materials for civilian and military applications [2]. The research center is linked with SNPE industrial subsidiaries as Pyroalliance which can translate laboratory works in operational devices.

New energetic material formulations are tested with standard trials performance and safety tests [3]. Their combustion and operational behaviors could be predicted and explained with CFD codes. Usually, demonstrators are performed to illustrate the interest of the new concept before industrialization.

The purpose of this paper is to show how SNPE Matériaux Energétiques propulsion research facilities and methodologies could be helpful to enhance mini rocket performances. First, CFD codes allow illustrating the scale effects induced by motor miniaturization. The propellant aluminum particles combustion in mini scale chamber is calculated for different aluminum particle sizes. New high energetic propellants issued from the latest SNPE Matériaux Energétiques propulsion research are reviewed for this application. An instrumented mini standard motor is defined to test these new formulations and to prove their performances.

Scale Factors

Theoretical aspects of scaling

In this section, some aspects of changing scale on aerodynamics and combustion are investigated.

A propulsive device, composed by a combustion chamber and a nozzle, is considered. In modelling such a simple motor, it is important to remind the limit of the hypothesis of 'continuous medium', which corresponds to a Knudsen number smaller than 10^{-2}. At these small scales, some terms of the modelling become more important. For example, we can refer to the Navier-Stokes equation in a non dimensional form,

$$St\frac{\partial v}{\partial t} + v\nabla v = -Eu\nabla P + \frac{1}{\mathrm{Re}}\mu\nabla^2 v + \frac{1}{Fr}g\ ,$$

where St is the Stroual number,

Eu, the Euler number,

$\mathrm{Re} = \frac{\rho v l}{\mu}$ the Reynolds number,

and Fr the Froude number.

Reynolds number decreases as the characteristic length l. Therefore, viscous effects become preponderant in comparison with the other terms of the equation. Such effects can also be underlined in the species transport where molecular diffusion becomes a major way for mixing (less turbulence or convection).

If we now consider a common combustion chamber, the energy released by the combustion of the premixed gas, is proportional to the volume, i.e. l^3. On the other hand, the heat losses through the structure of the chamber are dependent of the surface exposed to the hot gases, i.e. l^2. The ratio between energy generated and energy lost leads to a quantity proportional to the characteristic length l. So, reducing the scale favours the dissipation of energy through the structure. Such an approach was considered by Bruno in [4]. It is shown that the gas temperature can be estimated as following:

$T_g = \frac{A_1 l + A_3 T_i}{A_3 + A_1 l^{1/2}}$, where A1, A2, A3 are constant.

This relation shows that the temperature chamber decreases when l tends to 0. In addition, the resulting thrust of the motor is driver by l2, yielding to a drop of the thrust as l is decreased.

Combustion of aluminum in small scale chamber

The solid propulsion is characterized by an energetic material generating hot premixed gazes. The combustion flame of such material is very close from the burning surface, generally less than 100 µm. This distance decreases as the pressure increases. Considering also that the components of the propellant have a not too coarse granulometry, the hypothesis of uniform premixed gases is still valid for 1 mm characteristic length small motors. Hence, it is generally assumed that the gas is in a thermodynamic equilibrium in the chamber.

Usually, aluminum particles are added to the propellant in order to increase the performance of the motor. These particles are about 5 to 50 microns in size and their combustion generates an important increase of the temperature (about 1000K). One aspect of aluminum particles combustion is the formation of several microns diameter alumina droplets. Some very small particles, i.e. smoke, are also produced. Then, some droplets may agglomerate and obstruct the nozzle, leading to an unacceptable rise of the pressure in the chamber.

A preliminary calculation is useful to estimate the limit in diameter of aluminum particle to have a complete combustion in the chamber. The correlation proposed by Widener and Beckstead [5] is used. It gives the combustion time of an aluminum particle in a defined environment.

$$\tau_c = 1138 \frac{d^{1.8}}{T^{1.57} P^{0.2} X_{eff}^{0.39} D},$$

where τ_c is the combustion time,

d the particle diameter,

T the temperature,

P the pressure,

X_{eff} an evaluation of the oxidizer,

D a coefficient to take into account the presence of H2.

In order to show the importance of the size of aluminium particles, a modelling of a millimetric solid motor was considered with an aluminized HTPB propellant. Assuming a velocity of about 30 m/s for the gases in the chamber, the previous correlation yields to a diameter of 8 µm for a complete combustion of the particle, i.e. the combustion time is less or equal to the presence time defined by the gas velocity.

Three simulations corresponding to a defined size of aluminum particles (300 nm, 5 µm and 30 µm) were performed with the aerodynamics CPS code, developed at SNPE Matériaux Energétiques. The particles are injected with gases obtained by the thermodynamic equilibrium of the AP with the HTPB binder. The temperature value is 2800K in order to ensure the aluminum droplets ignition

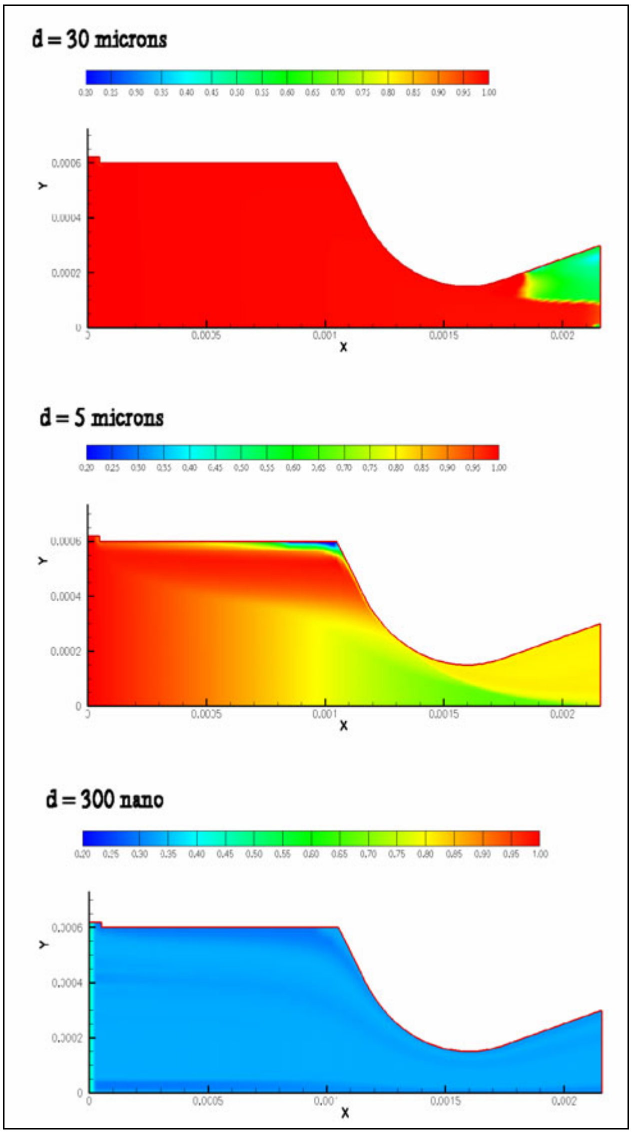

Figure 1 : Evolution of particles in the combustion chamber for three initial diameters

(ignition occurs about 2300K and the temperature of droplets is taken to 2791K during the combustion).

The Figure 1 presents the particle diameter in the chamber for the three considered cases. As it was expected, the bigger ones (30 µm in size) partially burn inside the chamber. The combustion of the 5µm particles is nearly achieved when the droplets pass through the sonic point. Although their diameter is still 50% of the initial diameter, the mass of burnt aluminum is 70%. This computation is confirmed by the preliminary estimation of the limit diameter. Another interesting result of this calculation is the presence of a boundary layer along the chamber wall. This zone is characterized by a lower temperature and particles with a more important diameter. For the smaller particles, the combustion is completed as soon as the particles are injected in the chamber. This phenomenon leads to a maximal performance. However, we have to keep in mind that this result is obtained in the ideal configuration where particles do not agglomerate.

Propellant Compositions

First, it should be reminded that the mini rocket scale effects on combustion needs higher volumic energy motor than usual full scale rocket. Few new propellant compositions could be chosen for the mini-rocket application.

Aluminized HTPB propellants are well-known as most energetic material. There are used for space and strategic propulsion. Thirty microns aluminum particle sizes are typically included in these compositions. We performed computations (see previous chapter) which confirm the experimental results issue from the bibliography [6]. This particle size is too large to lead to a full combustion in centimetric combustion chamber.

At small scale, aluminized compositions present the disadvantage to lead to unpredictable deposit on nozzle throat and so, unpredictable ballistic behavior. Nozzleless motor could be lead to better functioning with this kind of composition.

For this reason, high energetic propellants without particle are also interesting for this application.

Table 1

Compared characteristics of the main conventional and advanced oxidizers

Molecules	AP	AN	RDX	HMX	CL 20	ADN
Formula	ClH_4NO	$H_4N_2O_3$	$C_3H_6N_6O_8$	$C_4H_8N_8O_8$	$C_6H_6N_{12}O_{12}$	$H_4N_4O_4$
Molecular weight (g/mole)	117.5	80	222	296	438	124
Density	1.95	1.72	1.805	1.91	2.04	1.81
Enthalpy of formation (KJ/mole)	-296	-369	+70	+84	+372	-150
Oxygen balance (O_2/CO+H_2O) (%)	+ 34	+20.5	0	0	+11	+25.8

Among the different energetic prepolymers developed in the world, SNPE Matériaux Energétiques has chosen to manufacture azide prepolymers and plasticizers issued from GAP. Such compounds exhibit energetic properties: a high heat of formation, a high density and a high burning rate by themselves. GAP is compatible with GAP based plasticizers as well as nitrato esters like BTTN and TMETN, that would play for a better compromise energetic performances-vulnerability of the energetic materials. Added strong oxidizers as RDX, HMX or HNIW lead to high energy propellants (Table 1). In comparison with a current composite propellant, the benefit in volumic impulse is about 7% plus low signature, low toxicity and low corrosivity of exhaust products (no HCl).

The ballistic behaviors of these propellants, called AZAMITE, are now well-known. They are developed at industrial scale.

The Table 2 shows the theoretical ballistic performances of HTPB reduced smoke propellant, Azamite propellant loaded with HNIW oxidizers, and aluminized HTPB propellant. The measured burning rate at a pressure of 7 MPa is also presented.

Table 2

Ballistic properties of propellant compositions

compositions	Azamite GAP/HNIW	Aluminized HTPB propellant 17 % of micrometric aluminum
Calculated performances		
Expansion ratio 70/1		
Is P/1 (s)	256.5	259
C* (m/s)	1598	1553
Burning rate		
Ultrasonic measurement		
v 7 Mpa (mm/s)	11.92	4.57
n	0.59	0.15
Pressure range	1 to 10 Mpa	3 to 8 Mpa

Instrumented Standard Mini Motor

A large part of the activity in the solid propellant industry is devoted to burning rate measurement either during the development of a new propellant, during manufacturing (quality control) or for service life (ageing evaluation). In this aim, standard subscale static motors are used to measure solid propellant ballistic properties in controlled conditions [3]

An instrumented standard mini motor has been defined in order to compare the propellant performances at small scale. This mini motor

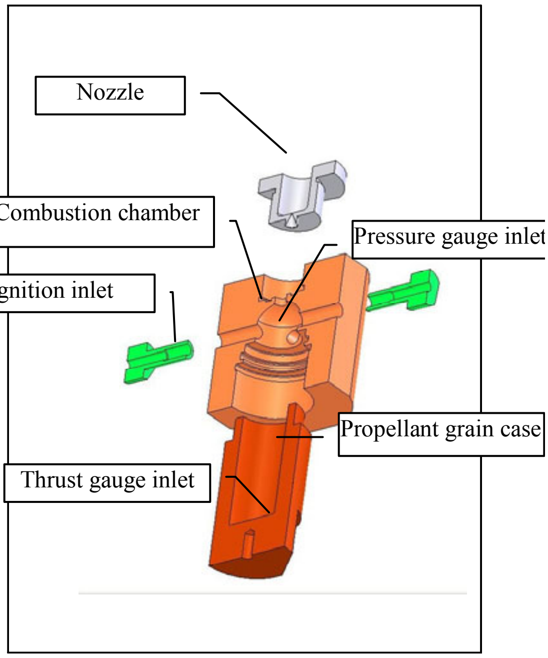

Figure 2 : Mini scale standard motor views

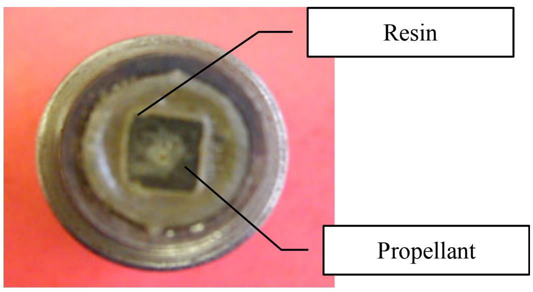

Figure 3 : View of an end burning grain for mini scale combustor.

presents basically the same design then sub-scale standard motor (Figure 2). The metallic motor main structure is in three parts composed by the nozzle, the combustion chamber and the propellant grain case. Pressure gauge inlet and safety rupture disc are mounted on the combustion chamber. The propellant ignition is carry out by a hot wire. Two sealed crossings allow to bring the ignition wire to the propellant surface. A small amount of energetic black powder past could be added on the propellant surface to enhance the ignition. The motor length is 60 mm. The nozzle throat diameter is between 0.3 mm and 0.7 mm depending of the targeted pressure. It should be notice that this very small nozzle throat dimensions need high accuracy manufacturing in order to reach the required pressure. The propellant grain dimensions are about 5× 5× 23 mm and its mass is about 1.5 g. It is embedded in a resin die casted in 12 mm diameter case. One end of the propellant grain is striped in order to ensure an end burning combustion (Figure 3).

Two gauges measure the internal pressure and the thrust generated by the mini rocket. The pressure gauge range is 250 bars, the thrust one is 0.5 or 5 N. The Figure 4 shows the bench test equipped with the measurement devices. Video and infrared camera could be also used to visualize the mini rocket exhaust plume.

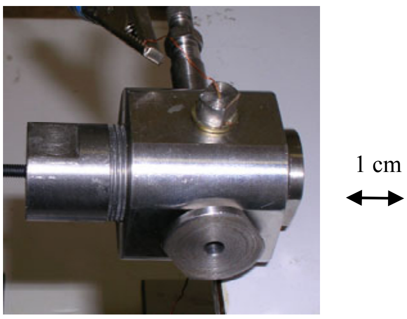

Figure 4 : View of the mini static fire bench.

Experiment Results

First experiments have been performed with Azamite and aluminized propellants. Fire

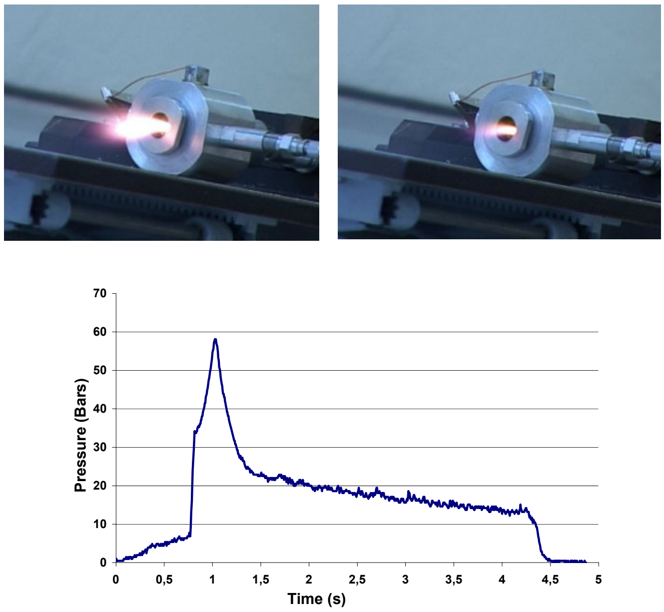

Figure 5 : Pressure and views of a mini motor fire with an Azamite propellant

pressure curves are recorded and allowed to analyze the motor behavior.

The Figure 5 shows the typical pressure curve obtained with an Azamite propellant and a view of the fire test. For this test, the nozzle throat diameter is 0.6 mm. The nozzle expansion ratio value is 1. The grain combustion surface was 25 mm^2 for a length of 20 mm. The pressure curve shows a peak after the ignition maybe due to the ejection of the ignition wire through the nozzle. Then, the pressure decreases slowly around 15 bars during 3 s. As the measurement of the throat diameter after the fire didn't show any erosion, this variation may be due to combustion surface variation. The thrust level during this quasi steady phase is about 0.5 N

The fire pressure is higher than the expected one for a 0.6 mm nozzle throat diameter. It may be due to a striction phenomenon induced by an aerodynamic boundary layer at the throat, which can be significant at this small scale.

Optimized Laboratory-Scale Mini Motor

In order to decrease the weight of the inert mass, a concept of mini motor has been designed to reduce ignition system mass and case mass. This system is showed on figure n°6.

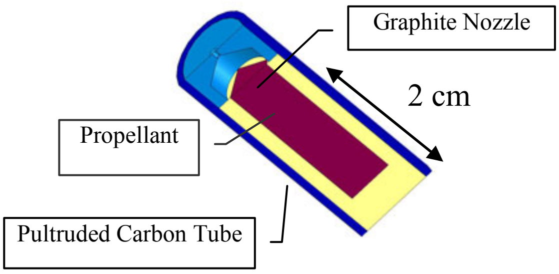

Figure 6 : Design of optimized mini motor

The main structure is a tubular-pultruded carbon-frame, the nozzle is made with graphite and the nozzle throat diameter is 0.7 mm. The grain is embedded in resin and it is stuck the tubular carbon structure. The nozzle is also stuck on the structure inside. The grain combustion surface was 25 mm for a length of 23 mm.

The ignition system is a hot wire which crosses the nozzle to the propellant surface and it is welded on the graphite chamber. The natural electric carbon conductivity is used to close the circuit. This concept is presented on Figure 7.

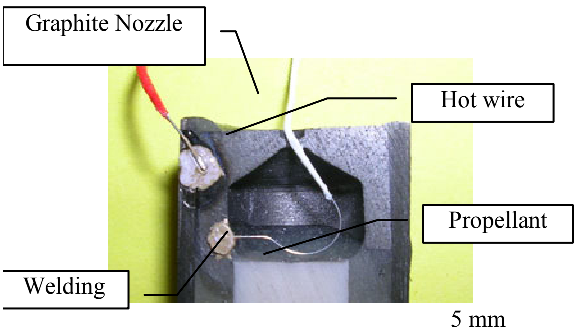

Figure 7 : Ignition System

This optimized mini motor has been tested with a thrust measurement set-up. A small amount of energetic black powder could be added in the chamber to enhance the ignition and the pressurization. The figure shows typical thrust measure obtained with an Azamite propellant and a view of the fire test.

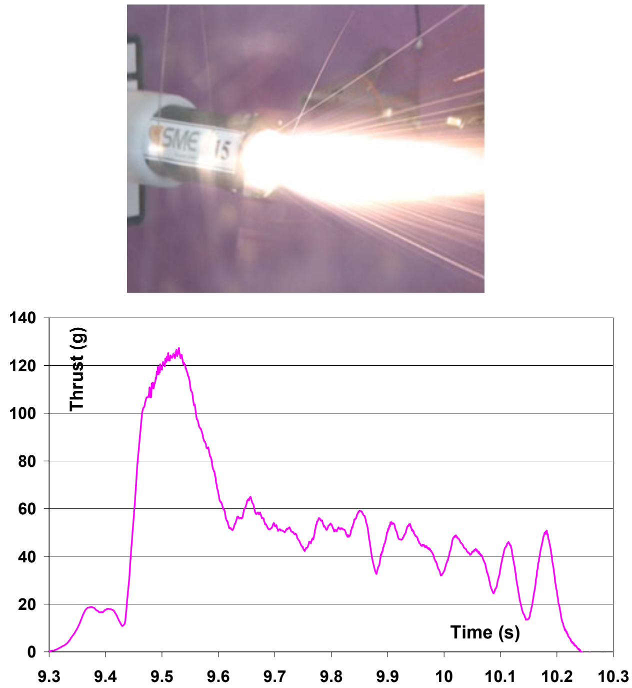

Figure 8 : Thrust and views of a mini motor fire with an Azamite propellant

The obtained total impulsion is about 40 grams, with an expansion ratio about one, and a diameter nozzle about 0.7 mm.

Conclusions

This study presents the mini motors evaluation using solid propellants and a laboratory-scale optimized mini motor. Combustion chamber modellings show the influences of the small scale which lead important heat and performance losses. In addition, the modelling shows the aluminum combustion in a mini combustion chamber. Moreover, for mini rocket application, new azide prepolymers and plasticizers issued from GAP, developed at SNPE Matériaux Energétiques, may be used. In order to characterize this product, a mini rocket with a submillimetric diameter nozzle was defined and manufactured. The first results showed the good behaviour of new smokeless energetic material for mini propulsion. An optimized laboratory-scale mini motor was designed to enhance the ignition and to test the new case concept.

Endless, the energetic materials and the systems must still be optimized to improve motor application tests, and to open new way for industrial applications.

Acknowledgements

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References

[1] B. Larangot & al. "Solid propellant Micro-Rockets – Towards a New Type of power MEMS". Nanotech 2002. 9-12 September 22202. Houston. USA.

[2] Y. Longevialle & al. "The Use of New Molecules in High Performances Energetic materials", NDIA insensitive Munitions and energetic materials technology symposium Tampa Florida 29/11, 02/12 /1999

[3] NATO/RTO – AVT – WG 16 reports, December 2000.

[4] Bruno, Chemical Microthrusters : Effect of Scaling on Combustion, 37th AIAA/ASME/SAE/ASEE, Joint propulsion Conference, Salt-Lake City, July 2001.

[5] Widener and Beckstead, Aluminum combustion modeling in solid propellant combustion products, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, July 1998

[6] Sigman. R.K & al. "Subignition heating tests for flake and powdered aluminum". Proc. 3rd annual JANNAF combustion Meeting. Monterey. CA. CPIA. November 1996.