On the Characterization of Propulsive Powders: Performance Calculation of Congolese Compositions

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Abstract: ***In this study we sought to corroborate in a comparison the calculated and / or experimental theoretical values of the solid propellant powders prepared by us with the experimental data of the few typical powders reported in the literature taken as references. It is a question of studying a possible substitution of the Chinese propellant by the Congolese propellant. Experimental trials were conducted at two levels and in two stages: 1. Initially the tests were carried out in open field, 2. In the second phase we conducted the tests in combustion chambers with the dimensional characteristics of a rocket 107 of Chinese manufacture, our reference, and Congolese manufacture. We controlled and varied the particle size of the constituents, composition by weight of constituents, propellant / engine structure ratio, aging time, combustion area, fill factor and binder nature or composition to determine or Calculate the parameters influencing propellant performance. Thus reaction time (ignition or priming), thermal energy, texture, pressure, specific pulse, volume of ejection gas, momentum, energy value and kinetic energy have Were calculated to assess physical homogeneity, stretch limiting force and elongation, compressive and deforming force, thermal expansion, thermal conductivity, diffusivity and chemical stability.***

Keywords: Propellant, Combustion, Motor, Component, Thermodynamic, Propulsion

1. Introduction

Of two major categories of known jet engines; that is to say:

Engines using air as a working fluid with dynamic compression (in ramjets) or with mechanical compression (in turbojets); and

- The engines using the gases from the combustion of the bodies called propellants stored on board the craft itself thus becoming totally autonomous;

The second category consists mainly of rocket engines used on most spacecraft as booster propellers or as an auxiliary take-off in aviation.

Our study particularly concerns this second category in that it focuses on the development of solid propellants allowing their propulsion by emission of large volumes of hot gases after combustion.

It is obvious that such a study will be concerned with the operation of these engines; which operation is dependent on aspects related to the characteristics of the propellants, which are:

- Combustion,
- The relaxation of the gases,

The evaluation of the thrust effect resulting from the ejection of high-speed gases, and

- The movement of the machine

Each of these aspects is normally an appropriate and in-depth study for characterizing and determining the performance of a propellant.

They have been the concern of chemists, physicists and powder engineers for the development and improvement of energy-sensitive powders that can provide aerodynamic performance of autonomy, lift and stability to self-propelled engines. [1][2][3][4][5].

The objective pursued by our work is that of studying the possibility of substitution of the Chinese propellant (with double base), by the Congolese manufacturing compositions (Mixed / or composite) for the propulsion of the same type of engines and for the same results.

In this study we are interested in the energy quality of our propellants based on the physicochemical parameters appreciable either on the basis of the measurements made or on the basis of the calculations according to the principles known and experimentally tested.

Our mixtures were made on the basis of binary compositions by playing on the thermodynamic and explosive properties of nitrocellulose and nitroglycerine, to which we associated black powder and powdered aluminum to make the typical Congolese solid propellants. All in a binder made from natural rubber in acetone.

In this way we have calculated and determined the optimum values for our powders, which can be applied under the conditions required to be used in engines with specific characteristics.

2. Material and Methods

2.1. Methods

The methodology used to conduct this study, consisted in a first stage, in a constitution of a statistical data base through the development of over 500 different compositions of propellants based on the physicochemical properties of individual components generally used for preparation of homogeneous or composite solid propellants one hand, and those of the constituents entering different compositions binders or binders, materials used for the improvement of mechanical properties of solid propellant other.

The second step allowed us to carry out a gradual elimination of certain formulations using blanks (outdoors) combustion tests of the propellant blocks, taking into account the gas phase reaction characterized by an Arrhenius-type expression.

$[M = AgP^n \exp(-E_g/2R\,T_{inf})]$,

coupled with the condensed phase reaction for the different combustion models proposed in different studies. [12][13][14][15][16][17][18][19][20].

Which were followed macroscopically observable or calculated parameters [6][10][11]such as:

- Reaction time or priming sensitivity
- The mechanical resistance reflecting the compactness of the block
- The length and the vivacity of the flame translating approximately the speed of combustion
- The volume of ejected gases
- The residue left by the block to assess the amount of propellant burned per unit of time.

Where, given the low ambient pressure, it has been reported that the rate of combustion (rb) is of the order of 1 mm / s and the gas ejection velocity (ω) varies from 15 to 30 m / s.

The formation of large drops of aluminum is also highlighted and their burning time (tc) is estimated at 70 ms[7].

This methodology is explained by the sensitive and strategic nature of the field of self-propelled engines where almost all research results are kept secret; and the one that is available provides superficial information. In the third step of our methodology we performed the tests in the combustion chambers insulated before the final, test in the Chinese-made rockets and / or Congolese for compositions with satisfactory results the tests in insulated tubes.

The results obtained and the behavior observed with our compositions were compared with the results obtained and with the behavior observed while using, under the same conditions and for the same engine, the Chinese propellant used for the propulsion of the rockets 107.

To do this we varied, tracked and controlled the following parameters:

1. The nature of the oxidant
2. The nature of the binder
3. The composition of the constituents
4. The particle size of the constituents,
5. The mass ratio Propergol / motor structure,
6. The aging time,
7. The combustion surface,
8. The filling factor

The purpose of the open-air tests was to make an assessment of the characteristics and performance of a propellant system in relation to the theoretical ejection velocity in a vacuum where the aerodynamic drag is ignored. While the tests in combustion chambers were conducted to compare the behavior of the latter vis-à-vis a typical composition of propellant designed for these engines and taken as a reference in order to get an idea about the quality energy efficiency and the performance of our propellant in terms of parameters such as:

1. The reaction time (ignition or priming),
2. Thermal energy,
3. The texture,
4. The pressure
5. The specific impulse,
6. The volume of ejection gas,
7. The amount of movement,
8. Kinetic energy

After varying the granulometry of the constituents, the weight composition Nitrocellulose-nitroglycerine), the mass ratio, the nature of the binder, the particle size distribution, the filling coefficient and the combustion surface as presented in Tables 1 and 2, respectively between 0 , 18 mm and 2.4 mm mesh sieves; 25% and 54% Nitrocellulose-Nitroglycerin; 0.15 and 0.25 weight structure / weight propellant; 276.32 cm 2 and 760.4923 cm 2 of combustion area of a propellant shell; 0.65 and 0.93 for the filling coefficient.

2.2. Equipment

For the preparation of propellant blocks we used:

- Sieve from 0.18 to 2.4 mm mesh.
- 2000 ml beaker
- Glass rod
- A mild steel cylinder 4000 mm long and 40 mm inside diameter.
- Stainless steel mandrels 4000 mm long and 10 to 19 mm inside diameter.
- Hydraulic press with a maximum of 4 pressure bars.
- Oven up to 250 ° C.

For the tests:

- Insulated cardboard bombs with the dimensions of the propellant blocks.
- Slow locks
- Delayed initiation system with tungsten filament.

- Electric priming system with mercury fulminate.
- Combustion chamber with the characteristics of rocket 107 Chinese manufacture.
- Combustion chamber with the characteristics of rocket 107 Congolese manufacture.
- Single-tube electric start ramp.

Table1: Composition of different binders used

Liant	Caoutchouc Naturel	Mouillant	Accélérateur	Durcisseur	Vulcanisateur	Charge
LIAC1	45	5	5	10	20	15
LIAC2	50	10	2	10	20	8
LIAC3	50	5	1	10	25	9

Table 2: Texture of the blocks according to the granulometry

Constituant	Granulométrie dans C1		Granulométrie dans B1		Granulométrie dans B3		Granulométrie dans B3M1		Granulométrie dans B3M2		Granulométrie dans B2M1		Granulométrie dans B2		Granulométrie dans DB1	
	mm	Texture	mm	Texture	mm	Texture	mm	Texture	mm	Texture	mm	Texture	mm	Texture	mm	Texture
Aluminium	0,18	Compact	0,18	Compact	0,18	Compact	0,18	Poreuse	0,18	Compact	0,18	Poreuse	0,18	Compact	0,18	Poreuse
	0,24	Compact	0,24	Compact	0,24	Compact	0,24	Poreuse	0,24	Compact	0,24	Poreuse	0,24	Compact	0,24	Poreuse
Black Powder	0,18	Compact	0,18	Compact	0,18	Compact	0,18	Poreuse	0,18	Compact	0,18	Poreuse	0,18	Compact	0,18	Poreuse
	0,24	Compact	0,24	Compact	0,24	Compact	0,24	Poreuse	0,24	Compact	0,24	Poreuse	0,24	Compact	0,24	Poreuse
Nitrocellulose	0,18	Compact	0,18	Compact	0,18	Compact	0,18	Poreuse	0,18	Compact	0,18	Poreuse	0,18	Compact	0,18	Poreuse
	0,24	Compact	0,24	Compact	0,24	Compact	0,24	Poreuse	0,24	Compact	0,24	Poreuse	0,24	Compact	0,24	Poreuse

3. Results and Interpretation

3.1. Characterization of elaborate compositions

We have obtained better results under the following conditions:

3.1.1. For blank tests

Dimensions of the blocks
Weight: 200 g
Length: 20 cm
Outside diameter: 4 cm
Inside diameter: 1 cm
Combustion area: A=2πrh+ 2πr^' h^'+2π(r^2- 〖r^'〗 ^2) = 295,7723cm^2

Conditions of preparation
The particle size of the black powder: 0.18 mm
The particle size of the aluminum powder: 0.18 mm
The granulometry of nitrocellulose: 2.4 mm
The weight composition of the constituents: 55% Nitrocellulose and 34% Nitroglycerin,
The combustion surface: 325 cm2
The nature or composition of the binder: Natural rubber, Naprex oil, Sulfur, Thiuram, Black smoke, Vulcanol.

For tests in combustion chambers

3.1.2.1. Chinese Propellant:

Type: Homogeneous propellant with double base

Table 3: Typical composition of a homogeneous double base propellant

Component*	**%in the propellant***
Nitrocellulose	25
Nitroglycerine	30
Perchlorate ammonium	20
Aluminum	20
Plasticizer	5
Stabilising	1
Physical characteristics	
Densityat20°C	0.063 lb/in^3
Thermochemical characteristics*	
Temperature of flame at constant pressure (°C)	4.000K
SpecificImpulsionat1000psi	265
Explosion Heat	1.650 cal/g
Gaz Volume	0,035 mole/g
Spécific Heat	1,20
Combustion Characteristics	
Combustion Velocity at 1000psi	0,7
Thrustat 1000-2000psi	0,5

- * composition referred to that of a propellant type double-base.

Characteristics of the combustion chamber

Inside diameter: 107 mm
Length of the room: 43 cm
Weight of the structure: 14 Kg
Propellant weight: 4 Kg
Filling coefficient: 0.93
Dimensional characteristics of the blocks
Weight: 500.72 g
Length: 40 cm
Outside diameter: 4 cm
Inside diameter: 8 mm
Combustion area: 626,9952cm^2
Number of blocks: 7
Total surface of combustion: 7 x626,9952cm^2 = 4388,9664 cm^2

3.1.2.2. Congolese Propellant

Type: Dual base mixed propellant

Table 5: Typical composition of a dual base mixed propellant.

Composition	
Constituant	% dans le Propergol
Nitrocellulose	41,5
Nitroglycérine	25,5
Poudre noire	7,5
Aluminium	1,5
Plastifiant	24
Stabilisant	-
Caractéristiques thermochimiques	
Température de la flamme à pression constante (°K)	2140,28
Température de la flamme à volume constant (°K)	2568,34
Impulsion spécifique à 1000 psi	255,3978
Chaleur d'explosion	773,4315
Chaleur spécifique moyenne	0,3472
Caractéristiques de combustion	
Poussée à 1000-2000 psi	758,09

Conditions of preparation

The particle size of the black powder: 0.18 mm
The particle size of the aluminum powder: 0.18 mm
The granulometry of nitrocellulose: 2.4 mm
The weight composition of the double-base constituents: 55% Nitrocellulose and 34% Nitroglycerin,
The mass ratio Propergol / engine structure: 0.25
The filling coefficient: 0.70
The nature or composition of the binder: Natural rubber, Naprex oil, Sulfur, Thiuram, Black smoke, Vulcanol.

3.1.3. Determination of the thermodynamic parameters of performance

Considering that all the dimensional parameters of the engine (Chinese rocket) are the same and remain unchanged in all the launch tests carried out, that is to say:
Shape and dimensions of the nozzles
Weight of the structure
Height of the combustion chamber
Filling coefficient
Internal diameter
Type of ignition (priming)

All the parameters have been calculated on the basis of the fundamental equations of relaxation of a gas in a nozzle which are [21][22][23][24][25][26]:

1. The equation of state where the mixture of gases is assimilated to a perfect gas:

$$\frac{P}{\rho} = \frac{R}{M} T$$

2. The conservation equation of matter: $\rho\omega A = C^{te}$ ou $\frac{d\rho}{\rho} + \frac{d\omega}{\omega} + \frac{dA}{A} = 0$

3. The conservation equation of energy: $dH + \omega d\omega = 0$ ou$C_p dT + \omega d\omega = 0$ and

4. The equation of conservation of the momentum for a permanent movement:

$$\omega d\omega + \frac{dP}{\rho} = 0$$

Where R, P, H, T, M, A ,, ω respectively represent the constant of the ideal gases, the pressure, the enthalpy, the temperature, the molecular weight of the gas, the area of the nozzle, the specific gravity of the gas and the rate of gas ejection.

Taking into account only the characteristics of the propellant with the following simplifying hypotheses [6][7][28]:

- Propellant contains only carbon, hydrogen, oxygen, nitrogen and aluminum as metal[9];
- Aluminum oxides are the only products formed during combustion in the presence of aluminum and are ejected at the same speed as the gaseous products[5][28] ;
- Combustion gives rise to decomposition reactions without dissociation;
- Combustion reactions are equilibrium reactions;
- The combustion gas mixture is in equilibrium (Mainly CO_2, CO, H_2O, H_2O_2);

Friction and loss of heat by cooling along prey are negligible (adiabatic transformation);

- The transformation is reversible;
- The relaxation is isentropic.

Equations for the relaxation of a perfect gas [7][22] give us:

- The ejection speed:

- The ejection speed$\omega_{ej} = \sqrt{2\frac{\gamma}{\gamma-1}\frac{R}{M}T_c[1-\left(\frac{P_{ej}}{P_c}\right)^{\frac{\gamma-1}{\gamma}}]}$

- impulsion $I = \sqrt{2\frac{\gamma nRT}{(\gamma-1)g}[1-\left(\frac{P_{ej}}{P_c}\right)^{\frac{\gamma-1}{\gamma}}]}$

- strength $F = 2\frac{\gamma}{(\gamma-1)}[1-\left(\frac{P_{ej}}{P_c}\right)^{\frac{\gamma-1}{\gamma}}$

Knowing that for a propellant composed of carbon, hydrogen, oxygen and nitrogen, it is admitted that [4]:

- gaz volume $n = (C) + \frac{1}{2}(H) + \frac{1}{2}(N)$
- *Calorific* capacity $C_v = 1{,}62(C) + 3{,}265(H) + 5{,}1493(O) + 3{,}384(H)$
- the apparent potential $Q = H_c - 67.421(2C + \frac{1}{2}H - O)$
- Relative energy $E_{2500} = H_c - 13{,}2771(C) - 40.026(H) + 51.819(O) - 6724(N)$

Where C, H, O and N are the gram atoms of carbon, hydrogen, oxygen and nitrogen per gram of propellant in which they exist.

On the basis of pre-calculated additive individual values [3][4], we have determined the different parameters of our propellants, the results of which are given in Table 6.

Table 5: Characterization of some elaborate compositions

Propellant	Composition	Mass ratio	Burning surface	Filling coefficient	thrust	t_v (°K)	Specific Impulsion	Explosion heat.	Specific heat
C1	20-20-30-10-20	0 ,25	276,32	0,75					
B1	25-25-20-10-20	0,20	276,32	0,75					
B3	30-20-20-10-20	0,25	276,32	0,75					
B3M2	41,5-25,5-7,5-1,5-24	0,25	760,4923	0,70	758,09	2568,34	255,3978	773,4315	0,3472
B3M1	50-20-20-10	0,20	760,4923	0,75					
B2M1	50--30-10-10	0,25	760,4923	0,80					
B2	40-20-9-1-20	0,20	276,32	0,75					
DB1	55-35-8-2	0,20	276,32	0,75					

3.2. Performance Calculation

From these different compositions and with regard to the parameters determined, we were particularly interested in the composition B3M2 which obviously gave us more convincing results and for which the essential characteristics are shown in the table below.

Table 6: Characteristics of Congolese B3M2 propellant

Composition		Q	n_i	E_i	C_{vi}
Component	% in Propellent				
Nitrocellulose (12,6%N)	41,5	956	0,04040	198,9	0,3454
Nitroglycerine	25,5	1.785	0,03082	951,9	0,3438
Aluminum	1,5	3.634	-	399,09	0,2150
Potassium Nitrate	5,4	1.434	0,00989	25	0,2158
Charcoal	0,75	-3.330	0,08326	-3.188	0,1349
Sulfide*	9,24	-183,707	-	-	0,0114
Natural Rubber NBR	12	-1.404	0,0814	-2.111	0,4231
Sommons in the Propellant					
Nitrocellulose		396,74	0,01676	82,5435	0,10893
Nitroglycerine		455,175	0,00785	242,7345	0,06662
Aluminum		54,51	-	5,9863	0,00245
Potassium Nitrate		77,436	0,00053	1,35	0,11653
Charcoal		-24,975	0,00062	-23,91	0,00101
Sulfide*		-16,9745	-	-	0,00105
Natural Rubber NBR		-168,48	0,00976	-253,32	0,05077
Propellant Caracteristics					
B3M2 Propellant		773,4315	0,03552	55,3843	0,3472

*n_i and E_i values have not been listed for these compounds.

From these values we can calculate:

1. Calorific coefficient: $\gamma = 1 + \frac{nR}{C_v} = 1 + \frac{0{,}03552 \text{ x } 1{,}987}{0{,}3472} = 1{,}20$
2. The heat capacity to constant pressure C_p: $\frac{C_p}{C_v} = 1{,}20 \rightarrow C_p = 1{,}20 \text{ x } C_v = 1{,}20 \text{ x } 0{,}3472 = 0{,}4166 \text{ Cal/(g)(°K)}$
3. Constant volume adiabatic temperature t_v: $t_v = 2500\text{°K} + \left(\frac{E}{C_v}\right) = 2500\text{°K} + \left(\frac{23{,}7292}{0{,}3472}\right) = 2568{,}34 \text{ °K}$
4. Adiabatic temperature at constant pressure t_p: $t_p = \frac{t_v}{\gamma} = \frac{2568{,}34}{1{,}20} = 2140{,}28 \text{ °K}$
5. Specific impulsion $\text{Iat}P_c = 100 \text{ psi} = 689 \text{ KPa}$ and $P_a = 14{,}7 \text{ psi} = 101{,}283 \text{ KPa}$

$$:I = \sqrt{2\frac{\gamma nRT}{(\gamma-1)g}\left[1 - \left(\frac{P_{ej}}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$= 13{,}153\sqrt{\frac{1{,}20 \text{ x } 0{,}03552 \text{ x } 2140{,}28}{(1{,}20-1)}\left[1 - \left(\frac{14{,}7}{1000}\right)^{\frac{1{,}20-1}{1{,}20}}\right]} = 255{,}3978 \text{ secondes}$$

6. Strength F:
$F = nRT_v = 0{,}03552 \text{ x } 8{,}31 \text{ x } 2568{,}34 = 758{,}09 \text{ Newton}$

3.3. Launch tests

With the characteristics defined in point 2., we conducted six launch trials numbered RCh1, RCh2, RCo1, RCo2, RCh3 and RCo3 in two steps at six-month intervals. This relatively large interval between stages is justified by the concern to study the behavior of propellant against aging.

RCh1, RCh2, RCo1 and RCo2 tests relate respectively to the Chinese combustion chamber with Chinese propellant, the Chinese combustion chamber with Congolese propellant, the Congolese combustion chamber with

Chinese propellant and the Congolese combustion chamber with Congolese propellant before aging while the RCh3 and RCo3 tests them, respectively relate to the Chinese combustion chamber with Congolese propellant and the Congolese combustion chamber with Congolese propellant after aging (six months later).

Table 7: Comparative Table of Congolese Propellant and Chinese Propellant Fire Test Behavior

Parameter	ChinesePropellant	CongolesePropellant
Behavior before aging		
priming	Instantaneous	Instantaneous
Lift-off	Instantaneous	Retardé (deux secondes)
Speed	Great	Low
bearing	15 Km	10 Km
Behavior after aging		
priming	Instantaneous	Instantaneous
Lift-off	Instantaneous	Instantaneous
Speed	Great	proportional
bearing	15 Km	12 Km

- The calculated additive values of B3M2, indicate that the propellant has a heat of explosion de 773,4315 Cal/g(H_2O),

It produces 0.03552 moles of gas per gram, has a relative energy at 2500 ° K of 55.3843 Cal / g and an average heat capacity of 0.3472 Cal / (g) (° K) between 2000 and 3000 ° K. The positive value of the relative energy means that there is sufficient heat to raise the temperature of the combustion gases beyond 2500 ° K:

- Instant priming of the propellant
- A takeoff delay of about two seconds compared to the Chinese propellant
- Low take-off speed of the B3M2 self-propelled engine compared with the Chinese propellant.
- Maximum range (12 Km) weak compared to that of the Chinese propellant (15 Km).

Logically explained by the small amount of gas ejected per gram of B3M2 (low gas ejection speed), thus communicating a low speed and low impulse to the engine; this being due to the low thrust force developed. Nevertheless the values of the B3M2 performance parameters remain within the range of values generally found for solid propellants. The different behavior observed before and after aging is explained by the presence of solvent before aging (slowing down, to a certain extent, combustion) and its absence after complete drying at aging.

4. Conclusion

Through this study we have been able to realize that it is possible to use fully developed propellant powders using simple techniques and easily accessible materials, for the propulsion of rocket engines of several types. In fact, by means of well-developed mixtures and the optimization of parameters such as the weight composition, the Propergol / motor structure weight ratio, the combustion surface, the filling coefficient, the nature of the binder, the particle size distribution and the weight ratio. Texture of the powder, the propellant performance is affected, such as the reaction time (ignition or priming), thermal energy, pressure, specific impulse, ejection gas volume, aging time or the amount of movement. Parameters that we had checked and verified by firing tests in combustion chambers with the characteristics of a 107 mm rocket.

The greatest difficulty for us was that of the uniform development of the propellant blocks due to the lack of a plasticizing binder available on the local market. The choice of a type of engine with well-defined characteristics will be decisive because we develop a propellant for one type of engine and not the other way around.

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