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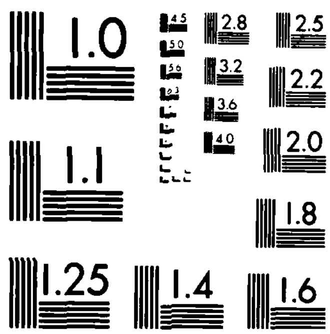

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by

Xu Wengan

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RESEARCH OF THE PROJECT FOR ADJUSTING THE THRUST OF A SOLID ROCKET PROPULSOR

Xu Wengan

ABSTRACT

This paper presented a proposed plan for a solid rocket motor with adjustable propellant. It was realized through the use of a negative pressure exponent propellant. In this paper, the feasibility and characteristics of the adjustment of this technique were discussed. It also pointed out the other advantages of the negative pressure exponent propellant.

TABLE OF SYMBOLS

A_b	surface area of combustion	P_c	pressure inside the combustion chamber
A_t	area of the throat of the nozzle	r	combustion speed
a	combustion speed coefficient	t	time
C^*	characteristic speed	$u(t)$	unit step function
C_F	propulsion coefficient	V_c	volume of the combustion chamber
$C_i(i=1,2)$	constants	a	$(=\lambda/\rho c)$ thermal diffusion rate of propellant
F	thrust	$\bar{\varepsilon}(\infty)$	static difference
F_{max}	maximum thrust	Γ	function of k
F_g	given thrust	$\lambda_i(i=1,2)$	constant coefficients
k	specific heat ratio of the combustible gas	ρ_c	density of combustible gas
$k_i(i=1,2)$	constant coefficients (including the ones with the superscripts ",",", ")	ρ_p	density of the propellant
		σ	over adjustment quantity
n	pressure exponent of the combustion speed	$\tau_{0.05}$	transition time

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I. INTRODUCTION

In the area of thrust control of a solid rocket engine, a large amount of work has been performed both here and abroad. As a result, directional control systems and thrust termination mechanism of various principles such as the "deflected flow ring", "rotating nozzle", "vibrational nozzle", "soft nozzle", "liquid suspension nozzle" and the "secondary nozzle" for liquids or combustible gases were developed. However, with regard to the adjustment of the magnitude of the thrust, there is not yet a good feasible method. Although some people had proposed some possible means such as the "layer engine" and the injection of a certain liquid to the combustion chamber and some preliminary attempts [1,2] were made using a propellant with a positive pressure exponent n, which is greater than zero and close to 1, and a mechanical rotating valve or an adjustment cone in the nozzle, however, due to the complicated structure and the poor weight and performance characteristics, these methods do not have an optimistic future.

This paper is an attempt to use a new propellant with a less than zero pressure exponent whose absolute value is greater than one. For ease of discussion, the author named it the "high negative pressure exponent" propellant as the concept to solve this problem.

II. THE FEASIBILITY OF USING HIGH NEGATIVE PRESSURE EXPONENT PROPELLANT TO REALIZE THE ADJUSTMENT OF THE MAGNITUDE OF THRUST AND ITS ADVANTAGES

Why do we have to search for this type of propellant? Can this propellant provide the adjustment of thrust? What are its advantages? Obviously, these are the questions to be answered first. As it is commonly known, when the combustion speed follows the $r=ap_c^n$ law, a sonic flow always exists at the throat of the nozzle. The equilibrium pressure and the corresponding propulsion in the combustion chamber of a solid rocket engine can be expressed by the two following formulas:

$$P_c=\left(\rho_p\cdot C^*\frac{A_b}{A_t}\cdot a\right)^{\frac{1}{1-n}} \qquad (1)$$

$$F = C_F P_c A_t \tag{2}$$

From the above equation, in order to realize the adjustment of thrust, the only effective way is to change the two parameters A_b and A_t. Among them, the only parameter to realize the random change using a simple method (i.e., the type of parameter which does not follow a pre-determined program but changes according to the need according to the circumstance) is mainly the throat area of the nozzle A_t. Therefore, we will use the following equation obtained from the simultaneous solution to (1) and (2) as the basic equations to be discussed in this paper:

$$P_c = K_1 A_t^{-\frac{1}{n-1}} \tag{3}$$

$$A_t = \left(\frac{F}{K_2}\right)^{1-\frac{1}{n}} \tag{4}$$

$$P_c = K_3 F^{1/n} \tag{5}$$

where

$$K_1 = (\rho_r \cdot C^* \cdot A_b \cdot a)^{\frac{1}{1-n}}$$

$$K_2 = C_F \cdot K_1$$

$$K_3 = K_1 \cdot K_2^{-\frac{1}{n}}$$

when the propellant is chosen and the combustion area A_b is a constant, obviously it is allowable to use K_1 as a constant to analyze the problem. Furthermore, C_F is also a function of $\frac{A_b}{A_t}$ and P_c. However, within the realm of this discussion it can be treated as a constant approximately. Therefore, in the following discussion, K_2 and K_3 are also treated as constants in approximation. Thus, by taking the logarithmic differentiation on both sides of the above equation, we get

$$\frac{dp_c}{p_c} = \frac{1}{n-1} \cdot \frac{dA_t}{A_t} \tag{6}$$

$$\frac{dA_t}{A_t} = \left(1 - \frac{1}{n}\right)\frac{dF}{F} \tag{7}$$

$$\frac{dp_c}{p_c} = \frac{1}{n} \cdot \frac{dF}{F} \tag{8}$$

From equations (5) or (8), we know that the adjustment of the magnitude of thrust will cause a pressure variation inside the combustion chamber. However, when the pressure variation becomes totally unacceptable to the practice, the adjustment of the magnitude of the propulsion becomes an empty thought. Therefore, it is necessary to minimize the variation of combustion chamber pressure during the adjustment of propulsion (consequently, the structural strength of the engine can be sufficiently utilized). At this time, the absolute value of n should be as large as possible. For example, when the pressure exponent n = 0.75, in order to increase the thrust by eight or four times, the pressure must be increased by 16 or 6.34 times. These changes are so huge that the weight performance of the engine is greatly reduced in order to ensure the engine to function under the maximum pressure. This is the fatal weakness of the experimental and development plans reported abroad. However, when n =-2, to increase the thrust by the same factors, the pressure is reduced to about 1/3.83 or 1/2 of the original pressure. Obviously, the amplitude of pressure variation inside the combustion chamber is significantly reduced.

On the basis of the above consideration, obviously, the large $|n|$ is the better. However, in order to let the engine operate stably, the n value with an absolute value greater than 1 cannot be positive. This is because when the flow rate of the engine and the formation rate of the combustible gas are equal, it will work under an equilibrium pressure (ρ_{cb}). This equilibrium, just as any other equilibrium problem, also has the stable equilibrium, unstable equilibrium and occasional equilibrium conditions. In other words, if some factor happens to affect the pressure of the combustion chamber to deviate from the equilibrium P_{cb}, then is there a tendency to decrease or increase this deviation? Or is it reaching equilibrium under new conditions? These are the differences of the three types of equilibria. For an engine to work stably, obviously we must have a stable equilibrium. The mathematical expression of this analysis may be:

$$\frac{d}{dp_c}\left(\frac{dp_c}{dt}\right)<0 \quad (9)$$

where $\frac{dp_c}{dt} = \frac{\Gamma^2 C^{*2}}{V_c}\left[(\rho_p - \rho_c)A_b a p_c^n - \frac{A_t p_c}{C^*}\right]$

therefore $\frac{d}{dp_c}\left(\frac{dp_c}{dt}\right) = \frac{\Gamma^2 C^{*2}}{V_c}\left[(\rho_p - \rho_c)A_b a n p_c^{n-1} - \frac{A_t}{C^*}\right]$

because at the equilibrium point we have $(\rho_p - \rho_c)A_b a p^n = \frac{A_t p_c}{C^*}$

By substituting into the above equation, we get $\frac{d}{dp_c}\left(\frac{dp_c}{dt}\right) = \frac{\Gamma^2 C^{*2}}{V_c} \frac{A_t}{C^*}[n-1]$

also because $\frac{\Gamma^2 C^{*2}}{V_c} \cdot \frac{A_t}{C^*} > 0$

Therefore, we have to let $\frac{d}{dp_c}\left(\frac{dp_c}{dt}\right) < 0$

(Note 1) $\frac{d}{dp_c}\left(\frac{dp_c}{dt}\right) < 0$ is the common mathematical expression $\frac{d^2t}{dp_c^2} > 0$, because the former can be converted to

$$\frac{d}{dp_c}\left(\frac{1}{\frac{dt}{dp_c}}\right) < 0 \quad \text{which is} \quad \frac{-\frac{d^2t}{dp_c^2}}{\left(\frac{dt}{dp_c}\right)^2} < 0$$

$$\frac{d^2t}{dp_c^2} > 0$$

It is necessary to let $n - 1 < 0$

which is $n < 1$

This can be intuitively observed from Figure 1.

For this reason, in order to minimize the combustion chamber pressure variation during the adjustment of the magnitude of the thrust, we should use a "high negative pressure exponent" propellant.

Simultaneously, from equations (1) and (2) as well as the logarithmic differentiation of both sides of equation (1), we get

$$\frac{dp_c}{p_c} = \frac{1}{1-n}\left[\frac{d\rho_p}{\rho_p} + \frac{dC^*}{C^*} + \frac{dA_b}{A_b} - \frac{dA_t}{A_t} + \frac{d_a}{a}\right] \qquad (9)$$

We can see that the fluctuations of parameters such as ρ_p, C^*, A_b, A_t, a caused by a certain factor will cause the fluctuations of the combustion

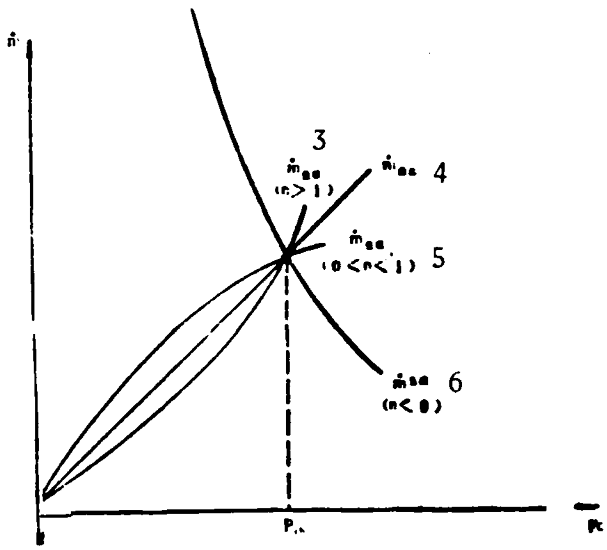

Figure 1

3--formation; 4--flow out;
5--formation; 6--formation

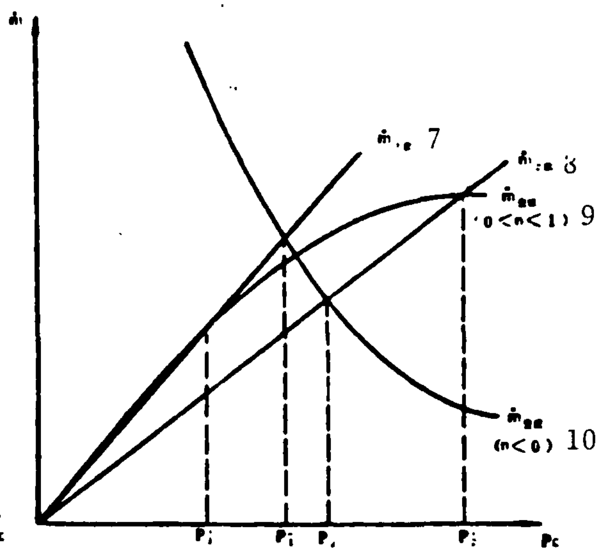

Figure 2

7--flow out; 8--flow out;
9--formation; 10--formation

chamber pressure p_c and the propulsion force F. However, when the relative fluctuation of the former is fixed, the relative fluctuation of the latter decreases with decreasing n value. In practice, the maximum fluctuation of the above parameters (such as ρ_p, C^*, A_b, A_t, a , etc.) is the combustion speed coefficient a. However, from the actual charge production requirements, it is frequently required to fluctuate in a wider range. For example, a heterogeneous propellant has two typical formulations and their $\frac{\Delta a}{a}$ are regulated to be about 0.07 and 0.02 respectively. This is already very difficult technologically. However, if n = 0.75, together with the fluctuations of other parameters, $\frac{\Delta Pc}{Pc}$ has already reached as high as 0.28 and 0.08, respectively. If n = -2, then $\frac{\Delta Pc}{Pc}$ can be reduced to 0.023 and 0.007, respectively. Its advantage is obvious. It can indeed significantly reduce the fluctuation of combustion chamber pressure and the distribution of the propulsion of the engine. In addition, the effect of $\frac{\Delta A_b}{A_b}$ on $\frac{\Delta p_c}{p_c}$ is similarly reduced significantly. Therefore, it allows the use of a high surface ratio charge design to improve the filling density of the engine.

Summarizing the above, as shown in Figure 2, after using the new "high negative pressure exponent" propellant, it is possible to adjust the thrust within a relatively large amplitude under the condition that the present structure of the present solid rocket engine might not have to be changed. In addition, it has the advantages of low combustion chamber pressure flutuation, small engine propulsion distribution and high filling density.

Obviously, in order to turn the adjustment of the magnitude of the thrust into reality, we must allow the throat area to be adjustable by a large amplitude. This can be seen from equations (4) and (7). We can see that when $n < 0$ and $|n|$ is greater than 1, in order to obtain the needed adjustment, we must be able to adjust the nozzle throat area A_t significantly. As shown in the two examples given above, for an increase in the propulsion force of eight times, A_t must be reduced by a half for $n = 0.75$. However, for $n = -2$, A_t must be increased to 22.6 times of the original value. This is not possible for the usual mechanical adjustment of the throat area of the nozzle. However, if a flow controlled "vortex value" is used, there it is no problem at all. Furthermore, with the increasing energy of the propellant, it is necessary to rely on the flow control technique to adjust the throat area of the nozzle (i.e., the flow rate) when the nozzle throat is working in such hostile conditions. Therefore, in theory, this requirement is not an obstacle to the realization of thrust adjustment based on this method. On the contrary, it provided the feasibility for the "microadjustment" of the thrust. Therefore, it can be predicted that it will have the ideal static characteristics and accuracy as a link of the automatic adjustment system.

III. CAN THE "HIGH NEGATIVE PRESSURE EXPONENT" PROPELLANT BE OBTAINED?

Due to the limited work available, the author cannot perform a quantitative analysis based on the combustion mechanism. Now, the following points are presented as the basis of discussion:

1. Not only in theory, but also in practice there are $n < 0$ propellants in existence. For example, in a certain formulation, within the pressure range from 50-70 kg/cm^2. the conditon that the pressure exponent $n = -0.825$ exists.

In the reports abroad, the so-called "mesa" effect exists in the double base platform propellant and heterogeneous propellant with $n < 0$ [3,5]. It was further reported that heterogeneous propellants with $n < 0$ or even $n = -4.0$ existed [4]. This shows that it is feasible and practical to obtain a "high negative pressure exponent" propellant.

2. In the foreign literature [1,4,5,6], the mechanism of the "mesa effect" regarding the combustion of heterogeneous solid propellants have been described.

(1) From the micrographs of the combustion surface after the fire is ceased in experiments, we can see that under low pressures (less than 30 kg/cm^2) the ammonium perchlorate (Ap) crystals are protruding on the surface. This is because under such conditions the thermal decomposition of the binder is faster than that of Ap. While under high pressures (greater than 30 kg/cm^2), the results are the reverse. There are holes indicating that the Ap crystals are consumed very rapidly [1].

(2) The pU binder is different from binders such as CTPB. It is already very fluid before reaching the rapid decomposition temperature. However, the latter is a high viscosity fluid with bubbles. Under high pressures, a local cease fire effect will appear [1,4,5,6] when the highly fluid binder flows into and covers the holes of the Ap crystals on the combustion surface.

(3) It was observed using a movie camera that there was the irregular pulsing combustion effect with local cease fire in the flat form propellants. The magnitude of the fraction of local cease fire with respect to the total area determines the extent of average combustion speed decrease on the full combustion plane. However, the

dependence of this fraction on pressure will cause the reduction of the pressure exponent n, which initiates the "mesa effect" [1,4,5] with $n < 0$.

(4) With the addition of an easily fuseable salt such as $(NH_4)_2SO_4$ as the combustion speed adjuster, it can cause a similar local cease fire affect or create a deep thermal potential base and the suppression effect of NH_4^+ on the decomposition of NH_4ClO_4 [4].

3. Reference [4] presented a physical model of the combustion process of this type of propellant which was partially verified by experimental observations. An experiment of the engine using 80 pounds of propellants with $n = -2.5$ was also reported.

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IV. PRELIMINARY ANALYSIS OF SOME ADJUSTING CHARACTERISTICS

For the large circuit of the automatic propulsion adjustment system, the adjustment of the engine is only one of the links. Its adjusting quality obviously must be analyzed.

For convenience, let us assume that the combustion speed still follows the $r = ap^n$ law during the adjustment process that: there is a sonic flow at the nozzle throat at all the times, the pressure inside the combustion chamber is equal everywhere and it is equal to the nozzle inlet pressure. Thus, from the continuity equation of the combustable gas:

$$\frac{d\rho_c}{dt} = \frac{\Gamma^2 C^{*2}}{V_c}\left[(\rho_p - \rho_c)A_b a p^n - \frac{A_t p_c}{C^*}\right] \qquad (10)$$

From the logarithmic differentiation with respect to equation (2) and by assuming C_F is a constant, we get

$$\frac{dF}{F} = \frac{dp_c}{p_c} - \frac{dA_t}{A_t}$$

or

$$\frac{1}{F}\frac{dF}{dt} = \frac{1}{p_c}\frac{dp_c}{dt} - \frac{1}{A_t}\frac{dA_t}{dt} \qquad (11)$$

By solving equations (2), (10) and (11) simultaneously, we can obtain the dynamic function of this link as:

$$\frac{1}{F}\frac{dF}{dt} = K_4\left(\frac{F}{A_t}\right)^{n-1} - K_5 A_t + \frac{1}{A_t}\frac{dA_t}{dt} \tag{12}$$

where

$$K_4 = \frac{\Gamma^2 C^{*2}}{V_c}(\rho_p - \rho_c) A_b a C_F^{1-n}$$

$$K_5 = \frac{\Gamma^2 C^*}{V_c}$$

When the input is a unity step function, i.e., $A_t = A_{t_0} + u(t)$ (A_{to} is the throat area before the unity step function), obviously, when t > 0, $u(t)=1$, $\frac{dA_t}{dt}=0$. At this time, the differential equation (12) is:

$$\frac{dF}{dt} + K_2' F = K_1' F^n \tag{13}$$

where

$$K_1' = \frac{K_4}{[A_{t_0}+1]^{n-1}}$$

$$K_2' = K_5[A_{t_0}+1]$$

The obtained unity transition differential equation (13) is the classical Bernoulli equation. Hence, through a variable separation method, we get: when n ≠ 0 $t = \frac{-1}{(1-n)K_2'}\ln(K_1' - K_2' F^{1-n}) + C_1$

From the initial condition, $t=0^+F=F(0)$, we get $C_1 = \frac{1}{(1-n)K_2'}\ln\{K_1' - K_2'[F(0)]^{1-n}\}$

$$t = \frac{1}{(1-n)K_2'}\ln\frac{K_1' - K_2'[F(0)]^{1-n}}{K_1' - K_2' F^{1-n}}$$

Therefore

$$F(t) = \lambda_1\{1 - \lambda_2 \exp[(n-1)K_2' t]\}^{\frac{1}{1-n}} \tag{14}$$

Where

$$\lambda_1 = \left(\frac{K_1'}{K_2'}\right)^{\frac{1}{1-n}}$$

$$\lambda_2 = 1 - (K_2'/K_1')[F(0)]^{1-n}$$

Also because (n-1) < 0, therefore, from equation (14) we can get when $t \to \infty$, $F(\infty) = \lambda_1$, . Simultaneously, we can get $\lambda_2 = 1 - \left[\frac{F(\infty)}{F(0)}\right]^{n-1}$ Therefore, equation (14) can be rewritten as:

$$F(t) = F(0)\left\{1 - \left[1 - \left(\frac{F(0)}{F(\infty)}\right)^{1-n}\right]\exp[(n-1)K_2' t]\right\}^{\frac{1}{1-n}} \tag{15}$$

1. In the transition period: from the definition $\frac{|F(\tau_{0.05}) - F(\infty)|}{F(\infty)} = 0.05$ can get

$$\tau_{0.05}=\frac{1}{(n-1)K_2'}\ln\frac{1-(1\pm0.05)^{1-n}}{1-\left[\frac{F(0)}{F(\infty)}\right]^{1-n}} \tag{16}$$

where the + and - signs correspond to the $0<n<1$ and $n<0$ conditions, respectively.

When the relative adjustment amount $\Delta=\frac{|F(\infty)-F(0)|}{F(\infty)}\cdot 100\%=10\%$ corresponding to the conditions of n = 0.75 and n = -2, $\tau_{0.05}$ are about $\frac{1.43}{K_2'}$ and $\frac{0.213}{K_2'}$, respectively. This also means that the transition period of the latter is about 1/7 of the former.

2. The over adjustment quantity: From equation (14), we can get $F_{max} = \lambda_1$. Therefore, according to the definition, the over adjustment $\sigma=\frac{F_{max}-F(\infty)}{F(\infty)}\cdot 100\%=0.$

3. Static difference: From the given $F_e=P_c\cdot C_F\cdot[A_{t_0}+u(t)]$ and $P_{cg}=\left[(\rho_p-\rho_c)\cdot C^*\frac{A_b}{A_{t_0}+u(t)}\cdot a\right]^{\frac{1}{1-n}}$, we can get $F_e=\left\{\frac{K_1'}{K_2'}\right\}^{\frac{1}{1-n}}=F(\infty)$. Therefore, according to the definition, the static difference $\delta(\infty)=\frac{|F_e-F(\infty)|}{F_e}\cdot 100\%=0$ (the P_{cg} above is the static equilibrium pressure corresponding to a given propulsion).

Therefore, when the pressure changes rapidly, the combustion speed is no longer a function of pressure alone. It is also a function of the pressure variation rate such as $r=ap_c^n\left(1+\frac{an}{a^2p_c^{1+n}}\frac{dp_c}{dt}\right)$ (assuming that this empirical formula is applicable to the n < 0 condition). Similarly, the dynamic equation corresponding to a unity step process can be obtained as:

$$\frac{dF}{dt}=\frac{K_1''F^{2n+1}-K_2''F^{n+2}}{K_3''F^{n+1}-K_4''}$$

when $n\neq1.0$, its solution is

$$t=\frac{-1}{(1-n)K_2'}\ln(K_1'-K_2'F^{1-n})-\lambda_1 n\int\left(\frac{dF}{F^{2n+1}-\lambda_2F^{n+2}}\right)$$

In the meantime, there are experiments which showed that the 9
combustion pressure exponent n_a of a pressure transient process is greater than the pressure exponent n under a gradual change [7]. Therefore, the assumption used above based on the $r=ap_c^n$ law in the adjustment process is obviously different from reality. This

difference can be observed from the experimental regularity shown in Figure (2) in [4]. Therefore, the above analysis is only preliminary.

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