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SOLID PROPELLANT ROCKET MOTOR THRUST CORRELATION WITH INITIAL TEMPERATURE OF PROPELLANT CHARGE

Gheorghiță TONCU[1], Virgil STANCIU[2], Dana-Cristina TONCU[3]

Motoarele rachetă cu combustibil solid (MRCS) sunt utilizate în principal pentru vehicule de unică folosință, din cauza limitărilor tehnologice, de siguranță şi cost. Caracteristicile funcționale ale MRCS sunt influențate de condițiile inițiale, necesitând corecții pentru tracțiune şi presiune internă constante. Pentru configurația motorului şi compoziția încărcăturii date, temperatura inițială a procesului de aerdere are influență asupra propulsiei prin intermediul vitezei de combustie şi presiunea din camera de ardere, care condiționează dependența tracțiunii de acest parametru. Controlând secțiunea critică a ajutajului de reacție, s-a putut stabili dependența forței de tracțiune de temperatura inițială a combustibilulu cu suficientă precizie. Aplicarea aspectelor teoretice trebuie completată pentru fiecare rețetă de combustibil în parte.

Solid propellant rocket motors (SPRMs) are generally applied to single use vehicles, due to technological, security and cost constraints. Working characteristics of SPRM are significantly influenced by the starting conditions, imposing corrections for required constant thrust and internal pressure. For a given motor configuration and charge composition, initial combustion temperature has showed great influence on propulsion by affecting burning rate, and thus chamber pressure, which determines thrust dependence on the above mentioned internal ballistic parameter. By controlling the critical nozzle section, the thrust dependence on the initial propellant temperature can be accurately established. The implementation of the theoretical model must be completed with given solid propellant characteristics.

Key words: solid propellant motor, thrust, initial burning temperature, chamber pressure

Symbols

a = pre-exponential factor in *Saint Robert – Vieille* law;
A = geometric coefficient in Eq. (9); c^* = characteristic exhaust velocity, [m·s^{-1}];
C_D= flow coefficient; d = internal diameter, [m];

[1] Senior Researcher, Department of Aerospace Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: ctoncu@yahoo.com
[2] Professor PhD. Eng., Department of Aerospace Engineering, University POLITEHNICA of Bucharest, Romania
[3] PhD Student, Department of Aerospace Engineering, University POLITEHNICA of Bucharest, Romania

D = external diameter , [m]; k = isentropic exponent = c_p/c_v;
L = length, [m]; m = weight (mass), [kg];
M = molecular weight, [kg·kmol^{-1}];
n = pressure exponent in *Saint Robert – Vieille* law; p = pressure, [Pa];
$\widetilde{p}$ = reverse of discharge ratio through the nozzle = p_e/p_c;
r_b = linear burning (regret-ssion) rate, [m·s^{-1}]; S = area, [m^2]; t = time, [s];
T = temperature, [K]; R = perfect gas constant, [J·kmol^{-1}·K^{-1}];
w = tangential flow velocity, [m·s^{-1}];
x = axial displacement of the central body of the nozzle, [m];

Greek Letters

β_T = thermal sensibility of burning rate, [K^{-1}];
β_w = cinematic sensibility of burning rate, [s·m^{-1}];
ζ_F = nozzle efficiency; η = mass ratio (participation);
ω = thickness of burned layer from solid propellant, [m];
ρ = density, [kg·m^{-3}]; Ω = volume, [m^3];

Super- and sub- scripts

b = burning; c = combustion; chamber; ca = burning chamber;
cb = propellant; cr = critical; D = flow; e = exit; equivalent; F = force;
i = numbering; T = of temperature; w = cinematic; 0 = initial.

1. Introduction

The propulsion with chemical rocket engines is mainly used for the vehicles having unique usage, their reuse being very rare (see space shuttle) because of technological, security and cost limits. Even more rarely is the reuse of solid propellant rocket motor (SPRM), because it has all propellant charge placed in burning chamber from the very beginning (from fabrication), with all advantages and disadvantages raising from here [1][2]. Much more, the working characteristics of this type of rocket engine are strongly influenced by the conditions from which propellant consumption starts, so corrections are significantly necessary to maintain both thrust and internal pressure constant.

Theoretical and experimental studies showed that, except for the engine structural configuration and composition and burning configuration of the propellant charge, a special influence on working conditions (propulsion conditions) of SPRM is exercised by the initial temperature of burning process and gas-dynamics conditions on burning surface of charge. For a given solid propellant, this influence appears through burning (regression) rate [3][4]. The most important factor of interest which is influenced by the initial temperature of the combustion process is the pressure in the burning chamber which, in turn, influences the thrust force level of the engine [5][6][7]. The dependence on temperature of chamber pressure, which is given by the process of combustion of solid propellant (geometrical burning rate or regression rate), makes the thrust to depend on this internal ballistic parameter [8].

For a given SPRM, and a certain propellant charge, external intervention at/after the start in order to maintain the thrust force constant, can only be done by modification of (critical) throat section of the nozzle. This can be easily achieved by means of a central body placed in nozzle [9][10]. By axial displacement of the central body, the critical surface is modified, influencing the value of pressure in the combustion chamber and of the thrust force [11][12].

The main problem which appears in this case consists in establishing the correlation between initial temperature and critical surface area to maintain the SPRM thrust under desired limits. Because of the difficulty in creating an accurate direct analytical relationship, the determination of the law of variation for the critical surface of the nozzle as a function of initial burning temperature of the propellant charge is experimentally made.

This study presents the results of such an approach for a SPRM having a multiple propellant charge from unrestricted elements with internal central profiled channel. The main achievement is the application, for large ranges of initial propellant temperatures, of thrust dependence, so that both lather and pressure inside combustion chamber lay inside given limits.

2. Problem formulation

Assuming a SPRM having a nozzle with full expansion and isentropic flow, the generated thrust can be written in the following form:

$$F = \zeta_F \cdot S_{cr} \cdot p_c \cdot f(k, \tilde{p}), \qquad (1)$$

where $f(k, \tilde{p})$ is a function of the isentropic exponent and the expanding degree of the nozzle:

$$f(k, \tilde{p}) = \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\tilde{p}^{\frac{k-1}{k}}\right]}. \qquad (2)$$

As it appears from equation (1), the thrust force generated by SPRM depends on the nozzle configuration (through the geometry and flow type), and also on the combustion pressure. At the same time, the maximum pressure in the combustion chamber depends on the nozzle configuration by the following relation:

$$p_c = \left[\frac{\rho_{cb}}{C_D} \cdot a \cdot \frac{S_b}{S_{cr}} \right]^{\frac{1}{1-n}}, \tag{3}$$

Therefore, the variation of the pressure in SPRM chamber can be evaluated with the equation:

$$\frac{dp}{d\omega} = \frac{R \cdot T_c}{M \cdot \Omega_{ca}} \cdot \left[\rho_{cb} \cdot S_b - S_{cr} \cdot \left(\frac{p_c^{1-n}}{a \cdot c*} + \frac{M \cdot p_c}{R \cdot T_c} \right) \right], \tag{4}$$

in which the thickness of burned layer is given by the relation:

$$d\omega = r_b \cdot dt \tag{5}$$

For linear burning rate of solid propellant, the *Saint Robert – Vieille* relation can be admitted with adequate correction:

$$r_b = a \cdot p^n \cdot (1 + e^{\beta_T \cdot T + \beta_w \cdot w}), \tag{6}$$

thermal and kinematical sensibilities of linear burning rate being experimentally determined characteristics for the type of propellant, conditions and burning configuration effective studied.

Admitting that gas products of burning are perfect, and the volume of condensed phase in all burning products generated in SPRM chamber both in the ignition period and post combustion can be neglected (isochoric processes), the chamber pressure can be calculated with the following relations:

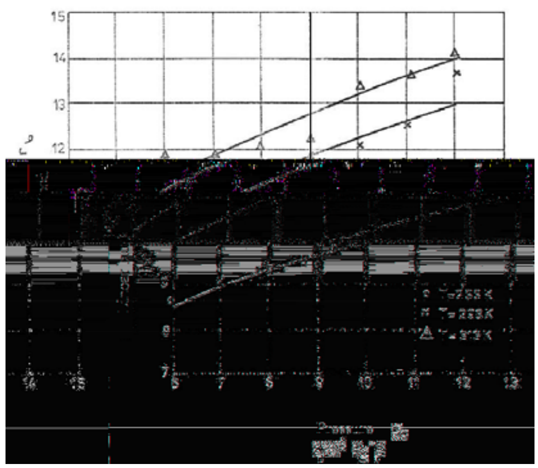

Fig.1. Linear burning rate of solid propellant

- for ignition:

$$\frac{dp}{dt} = \left(\frac{R \cdot T_c}{M} \right)_{ig} \cdot \frac{\eta}{\Omega_{ca}^0} \cdot \frac{dm_c}{dt}; \tag{7}$$

- for post combustion:

$$\frac{1}{p} \cdot \frac{dp}{dt} = -\frac{R \cdot T_c}{M \cdot \Omega_{ca}} \cdot \frac{S_{cr}}{c^*}. \tag{8}$$

As the combustion pressure and implied thrust force of studied SPRM depend on the critical section of the nozzle and the burning rate, and compensation of influence of the geometric burning rate variation on SPRM working characteristics can be made by "adapting" the nozzle, it is necessary to know the variation of nozzle geometry in order to limit the thrust variation.

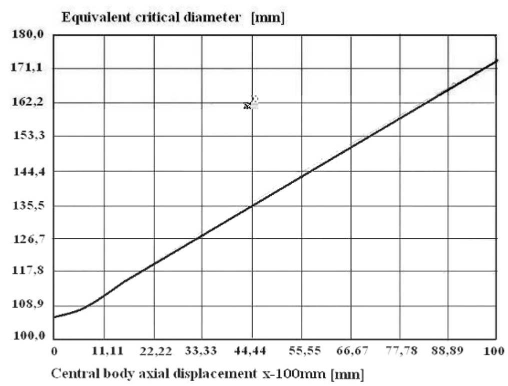

Fig.2. Variation of equivalent diameter of critical section evaluated with equation (9) for SPRM in Fig.3.

The easiest way to modify the nozzle geometry is to use a configuration having a mobile central body, which is moving along the symmetry axis. For a conic nozzle having fixed external geometry, the configuration can be modified in accordance with the following form of variation for the critical section:

$$S_{cr} = \sum_{i=0}^{2} A_i \cdot x^i . \tag{9}$$

For the conic nozzle with central body with double – cone form with constant configuration, the coefficients A_i are constant. Contrary, they will depend on the central body position (x – variable) for which the evaluation is made. Thus defined, the form for evaluating the critical section of the nozzle assures the entire domain of interest.

The variation of the equivalent critical diameter of the nozzle with central body function of a given axial displacement is shown in Fig. 2.

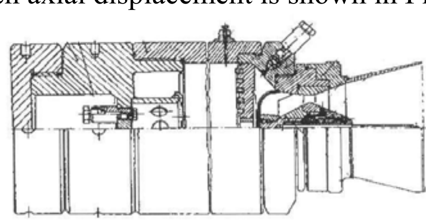

Fig.3. Solid propellant rocket motor for stand tests

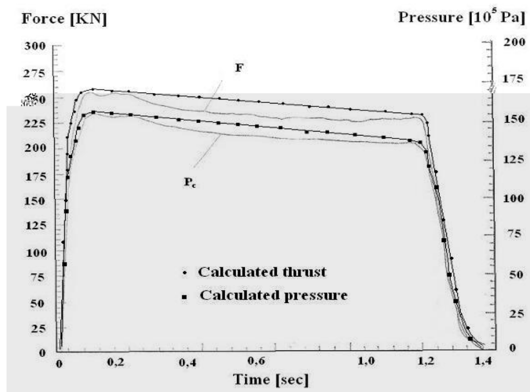

Fig.4. Time variations of pressure and thrust for initial temperature T_0 = 253K

For unrestricted combustion, the burning surface area of solid propellant charge varies according to the following law:

$$S_b = S_b^0 - 3\pi \cdot \left(D + d_e\right) \cdot r_b \cdot t \, , \tag{10}$$

For SPRM with multiple unrestricted charges the result will be multiplied by the number of identical elements from burning chamber.

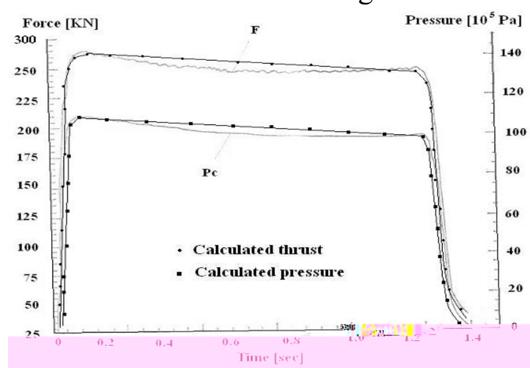

Fig.5. Time variations of pressure and thrust for initial temperature T_0 = 273 K

3. Experiments and Discussions

Experiments were carried out on static test stand using a SPRM as in Fig. 3. The “shots” procedure implied previous conditioning (tempering), 36 hours long, of SPRM fully equipped. Determinations involved multiple type propellant charges consisting of seven cylindrical identical elements with unrestricted burning. In order to reduce the regression character of combustion and diminish the pressure peak at ignition, axial internal channel of the propellant element had been profiled in cross with eight jibs, the depth of jib being chosen so that the growth of internal perimeter compensates, as much as possible, the dimension reduction of propellant elements which formed the tested SPRM propellant charge. The solid propellant which had been used is PRTF 100.

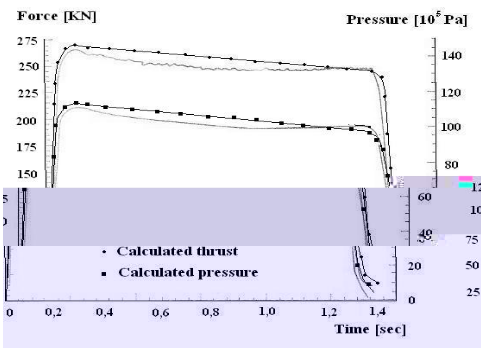

Fig.6. Time variations of pressure and thrust for initial temperature T_0 = 293 K

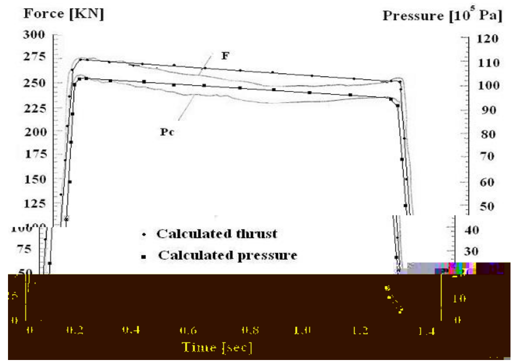

Fig.7. Time variations of pressure and thrust for initial temperature T_0 = 313 K

Because combustion takes place along the solid propellant element, the erosion cannot be cancelled, but its influence can be limited. It must be underlined that the time of burning tested SPRM (fewer than 1.5 s) limits the erosion influence, especially taking into account the compensations realized for burning surface. However, as shown by the experimental diagrams, the erosion is partially compensated by the regression of the burning surface.

The theoretical value for the thrust force (maximum thrust) is 275 KN, and it is considered constant, independent of the initial temperature of the used solid propellant. Experiments made in the initial temperature interval 253 … 313 K lead to values for thrust force between 266 and 267 KN, which indicates an experimental error less than 5 %.

Starting from the experimental data, the dependence of critical section of the nozzle on the initial temperature of propellant charge of SPRM, for tested propellant composition, could be determined. For the simplicity of practical use of tested SPRM, this dependence is expressed for the case of axial displacement of central body (see Fig. 8).

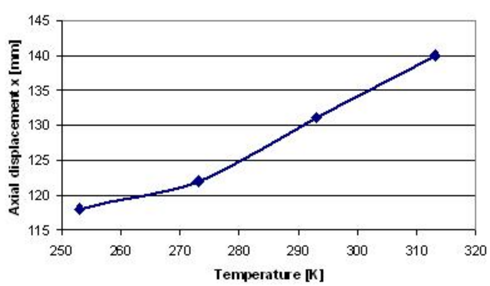

Fig.8. Axial displacement of central body as initial temperature function x = f(T)

4. Conclusions

The SPRM thrust dependence on initial temperature of the propellant may be corrected by controlling the nozzle. The experiments made on the presented mathematical model lead to expected results for the tested motor configuration and propellant composition. However, taking into account the general aspects of SPRM, the most important conclusion is that the application of theoretical aspects should be verified for each burning configuration and solid propellant composition. Also it should be underlined that experimental tests are affected by technological hazard.

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