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ENERGY AND PROPULSION OPTIMIZATION OF SOLID-PROPELLANT GRAIN OF A HYBRID POWER DEVICE

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Abstract. A method of distribution of an additional solid-phase component (oxidizer) providing uniformity of grain burning for the purpose of evaluation and optimization of energy and propulsion parameters of hybrid solid-propellant motor is proposed in the paper.

1 Introduction

Non-uniform character of fuel grain burnout along its length is a typical disadvantage of hybrid solid-propellant power devices [1]. Due to oxidizer consumption for combustion reaction the density of oxidizer flow varies along the surface of grain channel. The most intensive burning takes place in the area of a front face of the propellant grain as for the area down the flow a high-temperature channel erosion takes place in parallel to combustion reaction. Therefore, a carry-over of unreacted fuel is possible due to insufficient amount of oxidizer. All of the above leads to reduction of thrust due to incompleteness of combustion of fuel mixture.

To evaluate and optimize energy and propulsion parameters of the motor we considered "fuel-oxidizer" balance equations for fuel burning rate in the form of power-law dependence on oxidizer flow density. In this case the change of oxidizer flow along the grain channel of a hybrid motor can be described by the following equation.

$$\frac{d}{dx}\left(\varrho u S\right) = -\Pi \alpha_{ox} \varrho_f a \left(\varrho u\right)^{\nu}, \tag{1}$$

where ϱ,u – oxidizer density and flow rate;
S, Π – flow area and perimeter of cylindrical channel with radius *r*;
a, ν – burning rate law constants; ϱ_f – fuel density;
$\alpha_{ox}=m_{ox}/m_f$ – ratio between "consumed" oxidizer mass m_{ox} and fuel mass m_f in the process of burning.
In case of round cylindrical channel with *S*=*const* the solution of equation (1) for oxidizer flow at an arbitrary point (section) of the channel is as follows

$$\left.\left(\varrho u\right)\right|_x = \left[\left(\varrho u\right)_0^{1-\nu} - \varphi x\right]^{1/(1-\nu)}, \ \varphi = \frac{2}{r}\alpha_{ox}\varrho_f\left(1-\nu\right)a \tag{2}$$

where $\left(\varrho u\right)_0 = m_{ox}^{in}/S$ – oxidizer "injection" mass flux (m_{ox}^{in} – total oxidizer flow rate).

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Based upon equation (2) the amount of oxidizer m_ox used for burning can be determined from the following relationship

$$m_{ox} = \begin{cases} m_{ox}^{in} - S \cdot \left[\left(\varrho u \right)_0^{1-\nu} - \varphi L \right]^{1/(1-\nu)}, \ ec\lambda u \left(\varrho u \right)_0^{1-\nu} > \varphi L, \\ m_{ox}^{in} \ , ec\lambda u \left(\varrho u \right)_0^{1-\nu} \le \varphi L. \end{cases} \tag{3}$$

The mass of fuel m_f consumed by burning process comprises $m_f = m_{ox} / \alpha_{ox}$ and, therefore, total mass of the mixture of combustion products and residual (unused) oxidizer will be equal to $m_\Sigma = m_{ox}^{in} + m_f$.

Minimal oxidizer flow density m_{ox}^{min} necessary for grain burning along the whole its length can be evaluated using equation (2), i.e. when $\left(\varrho u\right)\big|_{x=L} = 0$:

$$m_{ox}^{min} = \left(\varphi L \right)^{1-\nu} .$$

Thermodynamic characteristics of the mixture (gas constant R and isobaric heat capacity C_p) for a known value of m_{ox}^{in} are determined additively [2] using individual characteristics of gas, oxidizer (R_{ox}, $C_{p\ ox}$) and combustion products (R_f, C_{p_f}): $R = c_{ox} R_{ox} + c_f R_f$, $C_p = c_{ox} C_{p_{ox}} + c_f C_{p_f}$, where mass fractions of residual (unused) oxidizer c_{ox} and combustion products c_f are determined by the following relationships:

$$c_{ox} = \frac{m_{ox}^{in} - m_{ox}}{m_\Sigma}, \ c_f = \frac{m_f + m_{ox}}{m_\Sigma} = 1 - c_{ox} .$$

The temperature T of the mixture of combustion products and "unused" oxidizer can be determined using the law of conservation of energy

$$\frac{\gamma}{\gamma - 1} R T m_\Sigma = \left(m_f + m_{ox} \right) \left(\frac{\gamma}{\gamma - 1} R T \right)_f - m_{ox}^{in} \left(\frac{\gamma}{\gamma - 1} R \right)_{ox} \left(\tilde{T} - T_{ox} \right)$$

The first member of the right part of equation (5) describes energy input due to fuel combustion products joining the flow with temperature T_f. The last member of the right part of this equation represents energy losses associated with oxidizer gas heating from its initial temperature T_{ox} to a certain average value $\tilde{T}$. At a first approximation can be taken as $\tilde{T} = \left(T_f + T_{ox} \right) / 2$.

Then, using the mass balance between the gas fed to the combustion chamber m_{ox}^{in} in and combustion products formed m_Σ considering the fact that they are equal to flow rate G trough the nozzle cluster with throat section S_* for the case of critical flow

$$G = S_* \Gamma(\gamma) \cdot \frac{p}{\sqrt{RT}} = m_\Sigma, \quad \Gamma(\gamma) = \sqrt{\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} ,$$

pressure p in combustion chamber and P engine thrust can be determined

$$p = \frac{m_\Sigma}{S_* \Gamma(\gamma)} \sqrt{RT} \ , \ P = \left(\gamma + 1 \right) \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma-1}} S_* p .$$

In case if thrust value is less than required, the desired level can be achieved by means of increase of oxidizer flow rate m_{ox}^{in} this, however, will increase the amount of residual (unused) oxidizer. The method of adding an oxidizer component to the solid-propellant grain with the oxidizer mass fraction $z(x)$ increasing along the grain length towards the nozzle cluster according to equation [3] can be used for optimization of energy and propulsion parameters of the motor neutralizing the abovementioned disadvantage of the process.

$$z(x) = \frac{f(x)}{1 + f(x)}, \quad f(x) = \beta\left[1 - \left(1 - \varphi(\varrho u)_0^{\nu-1} x\right)^{\frac{1}{1-\nu}}\right], \tag{4}$$

where β – ratio of the mass of additional oxidizer "consumed for burning" to fuel mass.
Equation (4) was obtained by means of simple algebraic transformations of (2) and (3) to provide the uniformity of fuel burnout profile.
A hybrid power device with the following parameters: grain length L = 1 m; channel radius r = 0.1 m; oxidizer mass flow rate m_{ox}^{in} = 10 kg/s; fuel density ϱ_f = 1600 kg/m; burning rate law: a = 0.0127 mm/s, ν = 0.65 was used as an example.

Let us consider the composition containing 85 % of inert fuel-binder (FB) – butadiene rubber, plasticized by transformer oil and 15 % of Al powder ASD-4 (oxidizer – gaseous oxygen) as a solid-fuel material (SFM) for a solid-propellant grain. Data for fuels analysed with various types of additional oxidizer are given in Table 1.

Table 1. Fuel blend composition.

	Content, wt%				
	Additional oxidizer	FB	Aluminum	SFM	β
1	Ammonium perchlorate, 89.6	8.8	1.6	10.4	8.61
2	Potassium perchlorate, 89.6	11.6	2.0	13.6	6.35
3	Nitronium perchlorate 56.2	37.2	6.6	43.8	1.28

To provide uniform burning of solid-propellant grain along its length a solid oxidizer (AP, PP, NP) was added to the composition. Oxidizer component mass fraction distribution along the grain length calculated using equation (4) is shown in Fig.1 for ammonium perchlorate (AP curve), potassium perchlorate (PP curve) and nitronium perchlorate (NP curve).

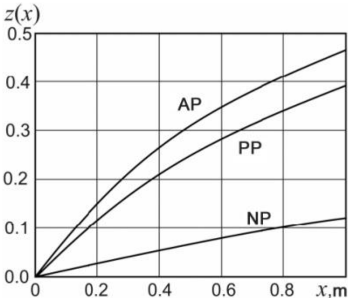

Figure 1. Oxidizer component mass fraction distribution.

As it can be seen from the graph the content of oxidizer component in solid-propellant grain composition must increase monotonically from zero (at the head section of the grain) to a maximum value (z = 0.465 – for ammonium perchlorate, z = 0.390 – for potassium perchlorate, z = 0.114 – for nitronium perchlorate) in order to provide optimal uniform burnout. In this case grain burns uniformly along the channel axis which provides high combustion completeness and, therefore, high thrust-weight ratio.

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