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Расчёт параметров и характеристик вращающегося лунного реактивного пенетратора

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Целью работы является определение параметров внутренней баллистики реактивного двигателя твёрдого топлива, установленного на реактивном пенетраторе, входящем в грунт с высокой скоростью вращения вокруг собственной оси. Методы исследования: для определения величины давления в камере вращающегося двигателя обычно используют известные уравнения баланса прихода и расхода газа, что и в случае невращающегося реактивного двигателя твёрдого топлива. Отличие внутренней баллистики вращающегося реактивного двигателя твердого топлива состоит в том, что влияние вращения на рабочий процесс учитывается коэффициентом расхода газов из камеры вращающегося двигателя, изменением скорости эрозионного горения твёрдого топлива при вращении реактивного двигателя твёрдого топлива, коэффициентом тепловых потерь. Результаты: установлено, что на параметры внутренней баллистики вращающихся реактивных двигателей твёрдого топлива основное влияние оказывают коэффициент расхода газов из камеры вращающегося двигателя, эффект эрозионного горения твердого топлива и изменение коэффициента тепловых потерь. Приведены основные расчетные зависимости для определения давления в камере сгорания вращающегося двигателя твердого топлива для периодов выхода давления на стационарный режим работы двигателя, работа двигателя на стационарном режиме и в период свободного истечение газов из камеры реактивного двигателя твёрдого топлива. Представлена методика выбора линейных и угловых размеров сопла вращающегося двигателя. Приведена оценка силы тяги для одинарного сопла, вращающегося реактивного двигателя твёрдого топлива. Установлено, что величина силы тяги вращающихся двигателей (при прочих одинаковых условиях в камере сгорания) в 1,1–1,36 раза меньше, чем у невращающихся реактивных двигателей твёрдого топлива. Проведённые опыты показали уменьшение степени закрутки газового потока вращающихся двигателей твердого топлива при увеличении количества топливных шашек в заряде двигателя. Заключение: результаты, изложенные в статье, могут быть полезны для научных работников, аспирантов и инженеров, занятых созданием и эксплуатацией авиационной и ракетно-космической техники, а также студентов технических вузов, обучающихся по соответствующим специальностям.

Ключевые слова: пенетратор, параметры и характеристики, вращение вокруг оси.

Calculation of the parameters and characteristics of a rotating lunar jet penetrator

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The purpose of the work is to determine the parameters of the internal ballistics of a solid propellant jet engine mounted on a jet penetrator entering the ground at a high rotation speed around its own axis. Research methods: to determine the pressure in the chamber of a rotating engine, the known equations for the balance of gas inflow and consumption are usually used, as in the case of a non-rotating solid propellant jet engine. The difference between the internal ballistics of a rotating solid propellant jet engine is that the effect of rotation on the operating process is taken into account by the coefficient of gas flow from the chamber of the rotating engine; a change in the rate of erosive combustion of solid propellant during rotation of a solid propellant jet engine; heat loss coefficient. Results: it was found that the parameters of the internal ballistics of rotating jet engines of solid propellant are mainly influenced by the coefficient of gas flow from the chamber of the rotating engine; effect of erosive combustion of solid propellant and change in heat loss coefficient. The main calculated dependencies for determining the pressure in the combustion chamber of a rotating solid propellant engine are presented for periods when the pressure reaches a stationary mode of operation of the engine, operation of the engine in a stationary mode and during the period of free flow of gases from the chamber of a solid propellant jet engine. A method for selecting the linear and angular dimensions of a rotating engine nozzle is presented. An estimate of the thrust force for a single nozzle rotating solid propellant jet engine is given. It has been established that the magnitude of the thrust force of rotating engines (under other identical conditions in the combustion chamber) is 1.1–1.36 times less than that of non-rotating solid propellant jet engines. The experiments carried out showed a decrease in the degree of swirl of the gas flow of rotating solid propellant engines with an increase in the number of propellant pellets in the engine charge. Conclusion: the results presented in the article can be useful for scientists, graduate students and engineers involved in the creation and operation of aviation and rocket and space technology, and can also be useful for students of technical universities studying in relevant specialties.

Keywords: penetrator, parameters and characteristics, rotation around an axis.

Introduction

Theoretical and experimental studies on embedding solid bodies into the ground at the expense of kinetic energy accumulated outside the ground section of the trajectory show that the section of motion in the ground sometimes has a niticeable curvilinear character, in which a significant departure from rectilinear motion is possible, up to a complete turn of the penetrating body and movement of its bottom part forward. The character of motion is significantly influenced by forces, which in turn depend both on the shape of the body and on the initial conditions of penetration, determined by the presence of the angle between the velocity vector and the axis of symmetry, as well as the angular velocities of precession, nutation and proper rotation.

When a jet penetrator with a running engine is embedded in the ground, its stability is affected (in addition to the above-mentioned factors) by such factors as the thrust magnitude, its eccentricity and the possibility of swirling motion.

The purpose of this paper is to determine the internal ballistics parameters of a solid propellant jet engine mounted on a jet penetrator entering the ground with a high rotational velocity around its own axis.

To determine the pressure value in the chamber of a rotating engine, the well-known equations of the balance of gas inflow and outflow are usually used, as in the case of a non-rotating solid propellant jet engine. The difference between the internal ballistics of a rotating solid propellant jet engine is that the effect of rotation on the working process is taken into account [1]:

– by the flow coefficient of gases from the rotating engine chamber

$$A_{rot} = A_0 \left(\frac{1}{1 + \frac{k}{k+1} \alpha_{cr}^2} \right)^{\frac{1}{1-\upsilon}}; \tag{1}$$

– by change in the rate of erosive combustion of solid propellant during the rotation of a solid propellant jet engine

$$\varepsilon_{rot} = 1 + Bn^{0.5}; \tag{2}$$

– by the heat loss coefficient

$$\chi_{rot} = \frac{1 - 0.16\left(1 + \tan\alpha_{cr}{}^2\right)^{0.4}}{1 + 2\psi}, \tag{3}$$

where A_0 is a flow coefficient of gases from the combustion chamber of a non-rotating solid propellant jet engine.

The value of the gas flow coefficient is determined according to the folloing dependence

$$A_0 = \frac{\dot{M}_0}{\dot{M}_T} \leq 1, \tag{4}$$

where $\dot{M}_0$ is a real (experimental) mass flow rate, taking into account all possible types of losses that reduce the gas flow rate through the nozzle; $\dot{M}_m = \frac{p_{cr} f_{cr}}{\sqrt{\chi R T_0}}$ is theoretical gas flow rate through the nozzle; p_{cr} is braking pressure at the nozzle inlet; f_{cr} is a critical cross-sectional area of the nozzle; χ is a coefficient of heat loss; RT_0 is a reduced force of solid propellant; B = $3.7 \cdot 10^{-6}$ at $n \leq 10^3 \ \frac{rot}{\min}$; k is an adiabatic value; α_{cr} is angle of swirl of gas flow in the critical section of the engine nozzle; n is a number of revolutions of the rotating ground jet penetrator; υ is a degree exponent in the propellant combustion rate law; ψ is a relative fraction of burnt charge.

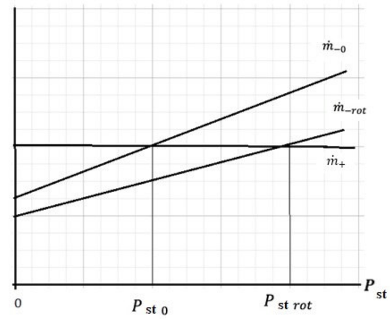

Рис. 1. График, иллюстрирующий принцип стационарности

Fig. 1. Graph illustrating the principle of stationarity

The algorithm for determining the pressure in the combustion chamber of a rotating solid propellant engine

1. Steady-state pressure at the stationary operation section of the solid propellant jet engine.

Fig. 1 graphically depicts the principle of stationarity of the operation of the rotating solid propellant jet engine.

Here $\dot{m}_{+}$ is gas supply into the combustion chamber of the solid propellant jet engine; $\dot{m}_{-0}$ and $\dot{m}_{-rot}$ are gas flow rate of the non-rotating and rotating engine, respectively.

The graph shows that a decrease in the gas flow rate of a rotating engine leads to an increase in the steady-state pressure in its combustion chamber, i.e. $P_{strot} \geq P_0$.

In this case the following equation is used for the calculation of P_{strot}

$$P_{strot} = \left(\frac{1}{N_1}\right)^{\frac{1}{1-\nu}}, \tag{5}$$

where $N_1 = \frac{N}{\varepsilon}$; $\varepsilon = \frac{P}{\rho_m \chi_{rot} R T_0}$; $\chi_{rot}(\alpha)$ is from (3); $N = \frac{\varphi_2 A_{rot} p_k f_{cr}}{S_g U_m \rho_m \sqrt{\chi_{rot} R T_0}}$; $U_m = f_1(T_3) f_2(p_c) f_3(\alpha_{cr}) f_4(\chi_0)$ – $U_m = f_1 f_2 f_3 f_4$ is solid propellant burning speed depending on the charging temperature $(f(T_3))$, pressure in the combustion chamber $f_2(p_c)$, degree of swirl $f_3(\alpha_{cr})$ of gas flow and the Pobedonostsev criterion $f_4(\chi_0)$ [2; 3].

Fig. 2 shows the dependence of the steady-state pressure in the chamber of a rotating solid propellant jet engine on the degree of swirl of the gas flow.

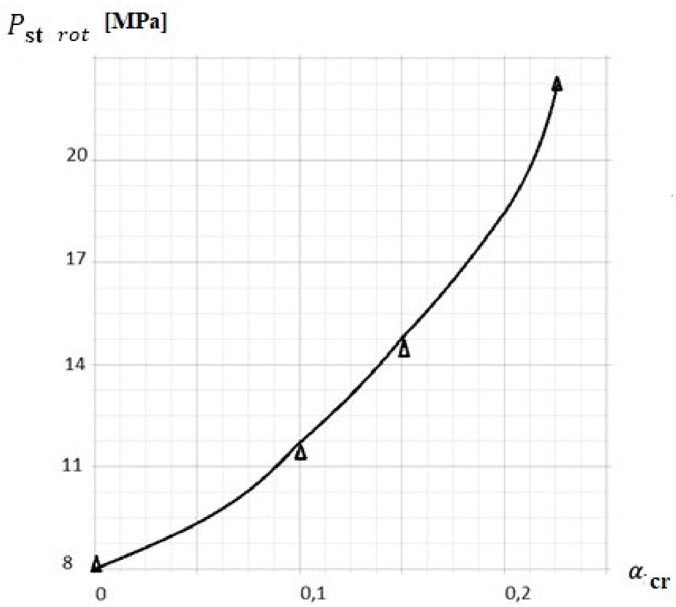

Рис. 2. Зависимость величины установившегося давления в камере сгорания от степени закрутки газового потока

Fig. 2. Dependence of the steady-state pressure in the combustion chamber on the degree of swirl of the gas flow

The calculations P_{strot} were performed for a real engine of a 40 mm diameter model ground jet. Here Δ marks are used to indicate experimental values of steady-state pressure. A good agreement between the calculated and experimental data can be seen.

Thus, the steady-state pressure in the chamber of solid propellant jet engine varies depending on the speed of its rotation around its own axis. In this case, with the increase in the degree of swirl of the gas flow, the value of the steady-state pressure increases, the rate of pressure build-up in the process of the engine entering the steady-state mode of operation decreases, and at a given propellant mass, the engine operation time decreases (Fig. 3).

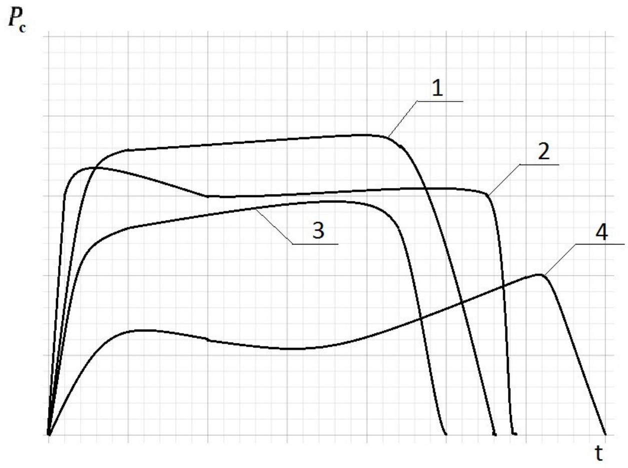

Рис. 3. Типовые зависимости давления в камере сгорания для вращающихся РДТТ:
1 – для вращающегося РДТТ; *2* – для невращающегося РДТТ; *3* – отмечается некоторое увеличение установившегося давления в камере для вращающихся двигателей при $n < 10^3 \frac{\text{об}}{\text{мин}}$;
4 – показана возможность появления второго максимума, величина которого больше первого

Fig. 3. Typical pressure dependences in the combustion chamber for rotating solid propellant rocket engines:
1 – for a rotating solid propellant rocket engine; *2* – for a non-rotating solid propellant jet engine;
3 – there is a slight increase in the steady-state pressure in the chamber for rotating engines at $n < 10^3$ rpm/min;
4 – shows the possibility of the appearance of a second maximum, the value of which is greater than the first

It should be noted that the pressure in the combustion chamber of a rotating engine can be corrected either by using an afterburning volume in its design, which increases the free volume of the combustion chamber, or by changing the thermal and hydraulic loss coefficients. The hydraulic loss coefficient can be calculated using the following formula

$$\xi = \xi_0 \left(1 + \mathrm{tg}\alpha_{cr}{}^2\right)^{1.375}, \tag{6}$$

where ξ_0 is a hydraulic loss coefficient at one-dimensional gas flow through the pipe at $\alpha_{cr} = 0$.

The calculations show that α_{cr} value due to hydraulic losses to the values $\alpha_{cr} \approx 0{,}2$ is almost unchanged, Therefore, its reduction should be taken into account at $\alpha_{cr} > 0.3 - 0.4$, when α_{cr} is reduced by 13–35 %.

2. Switching of a rotating solid propellant jet engine to steady-state mode

When calculating the pressure-time dependence of the rotating solid-propellant engine on the steady-state mode of operation, as in the case of the flow rates of a solid propellant jet engine [3; 4], the following parameter is determined

$$a = \frac{\varphi_2 A_{rot} b f_{\mathrm{cr}} \sqrt{\chi_{rot} R T_0}\,(1 - \upsilon)}{W_g}, \tag{7}$$

where rotation is taken into account by introducing the coefficients A_{rot} and χ_{rot}; b and ν are coefficients in the propellant combustion law; $W_g = \rho u S_g$ is gas supply to the combustion chamber; u is a combustion rate; S_g is a combustion surface of the propellant charge.

After that, the total time for the solid propellant jet engine to reach steady-state is calculated

$$\tau_p = \frac{1}{a} \ln \frac{1 - p_b^{1-\upsilon}}{1 - \overline{p}^{1-\upsilon}}, \quad (8)$$

where $\overline{p}$ = 0.99 is limit relative pressures in the combustion chamber in the process of the solid-propellant jet engine reaching the steady-state mode of operation; p_b is pressure in the chamber when the charge is ignited.

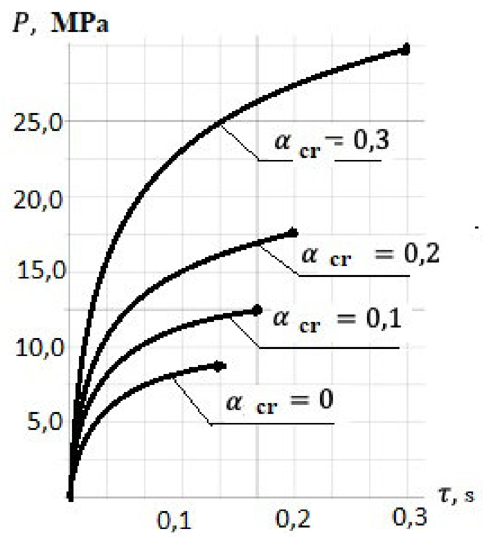

Рис. 4. Зависимость давления в камере сгорания от времени при выходе двигателя на установившийся режим

Fig. 4. Dependence of pressure in the combustion chamber on time when the engine reaches steady state

The calculations given for a 240 mm diameter rotating ground jet penetrator at swirl angles α_{cr} = 0.1; 0.2; 0.3 showed that: 1) engine steady-state time increases by 23 % with increasing rotational speed at α_{cr} = 0.1, by 46 % at α_{cr} = 0.2 and by 130 % at α_{cr} = 0.3, i.e. from 0.13 s to 0.3 s; 2) increases the steady-state pressure compared to a non-rotating engine.

In order to obtain the dependence (Fig. 4), τ_p was first defined using the fomula (8), then three following values were chosen τ_1, τ_2, τ_3, which are in the interval between τ_p and 0, and according to the value of these times the relative pressures $\overline{p}_1$ $\overline{p}_2$ $\overline{p}_3$ were determined by the formula

$$\overline{p}_i = \left[1 - \left(1 - p_b\right)^{1-\upsilon} e^{-a\tau_i}\right]^{\frac{1}{1-\upsilon}}, \quad (9)$$

Then $\overline{pi}$ were recalculated into real design pressures according to the dependence:

$$\overline{p}_i = p_{strot}\ \overline{p}_i, \quad (10)$$

where p_i is calculated up to $\overline{p}$ = 0.99.

3. Calculation of pressure during the period of free flow of gases from the chamber of a solid propellant jet engine

As in the case of calculation of the after-effect period for a non-rotating engine, the end of charge combustion time is determined by the formula [3-5]

$$\tau_k = \frac{e}{u}, \tag{11}$$

where e is a burning vault thickness; for a tubular charge burning on the outer (D) and inner (d) surfaces it is, in particular, equal to

$$e = \frac{D-d}{4}. \tag{12}$$

Taking into account the dependence of the charge burning rate on the pressure in the combustion chamber, it is evident that the end of combustion time for the rotating engine will be less than the end of combustion time for the charge of the non-rotating engine, because the steady-state pressure of the rotating engine is greater than the steady-state pressure of the non-rotating engine.

The time of full flow of gases from the combustion chamber after combustion of solid propellant is calculated by the following formula

$$\tau_{fr} = \frac{1}{B}\left[\left(\frac{p_{krot}}{1.8}\right)^{0.1} - 1\right], \tag{13}$$

where $B = \frac{K-1}{2}\frac{\varphi_2 A_{rot} f_{cr} b\sqrt{X_{rot} R T_0}}{W_{km}}$; p_k = 1.8 bar is the pressure in the combustion chamber up to which the supercritical flow formula is valid.

The pressure dependence on the free gas flow time is determined in the following sequence:

1) time τ_{fr} is divided into three intervals, where τ_1, τ_2 and τ_3 are less than τ_{fr};

2) p_1, p_2 and p_3 are calculated by the formula $p_i = \dfrac{p_{krot}}{(1+B\tau_i)^{\frac{2k}{k-1}}}$.

The curve passing through the calculation points describes the period of free gas flow from the rotating solid propellant jet engine.

Fig. 5 shows the graph of dependence of the free flow time from the rotating engine chamber on the degree of swirl of a 240 mm diameter ground jet penetrator.

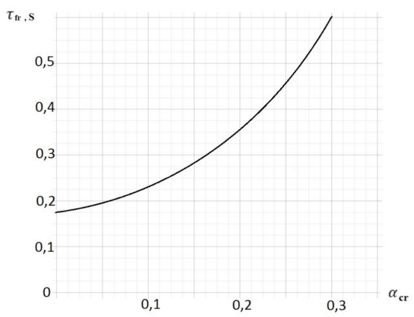

Рис. 5. Расчётная зависимость времени истечения от угла закрутки газового потока РДТТ

Fig. 5. Calculated dependence of the exhaust time on the swirl angle of the gas flow of a solid propellant jet engine

It was obtaned at $\alpha_{cr} > 0$, $\tau_{fr} = 0.173$ s; at $\alpha_{cr} = 0.1$, $\alpha_{cr} = 0.2$ and $\alpha_{cr} = 0.3$, $\tau_{fr1} = 0.22$ s, $\tau_{fr2} = 0.32$ s and $\tau_{fr3} = 0.55$ s, respectively.

It can be seen from the graph (Fig. 5) that the time of free flow of gases from the combustion chamber after the end of propellant combustion increases with the increment of swirl parameters and, consequently, the number of revolutions of the jet penetrator.

Selection of linear and angular dimensions of the rotating engine nozzle

The dimensions of a single nozzle or nozzles of the nozzle block of a rotating solid propellant jet engine are selected according to the same dependences as for a transforming engine, but taking into account the previously established dependences and coefficients.

Using dependences (5) for calculations of steady-state pressure in the chamber of a rotating engine, it is possible to find the area of the critical cross-section of the engine nozzle using the formula [1]

$$f_{cr} = \frac{s_r U_\tau \rho_\tau \sqrt{X_{rot} R T_0}}{\varphi_2 A_{rot} b p_{rot}^{1-v}}, \tag{14}$$

$$d_{cr} = \sqrt{\frac{4 f_{cr}}{\pi n}}, \tag{15}$$

where n is the number of nozzles; $A_{rot}(\alpha_{cr})$, $X_{rot}(\alpha_{cr})$ are coefficients; p_{rot} is a design pressure at the engine chamber wall.

The comparative analysis of the calculations of the supersonic nozzle part of rotating and non-rotating engines showed that the optimum angle of the supersonic part of the rotating engine corresponds to the optimum angle of the nozzle of a non-rotating solid propellant jet engine and is equal to 20°. The experimental data presented in [1] confirm this conclusion and also show that it is necessary to choose a larger nozzle entrance angle in the presence of flow rotation than for a nozzle with one-dimensional flow.

Fig. 6 shows the experimental dependence of the single impulse J_{un} on half of the nozzle entry angle α. The graph shows that J_{un} reaches a maximum at 2α = 180°, i.e., at a flat wall of the nozzle block. This effect is explained by the fact that the flat wall completely dampens the axial component of the gas flow velocity and increases its radial component, which increases the gas flow rate through the nozzle.

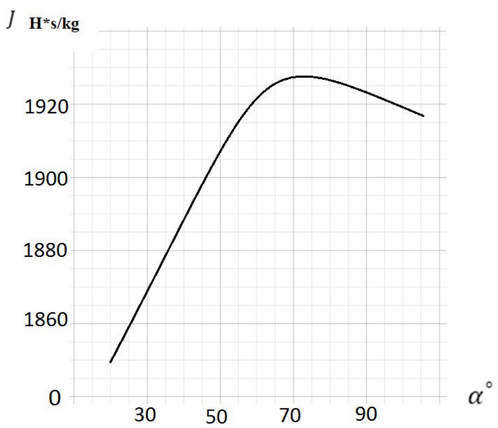

Рис. 6. Зависимость величины единичного импульса
от половины угла входа в сопло двигателя

Fig. 6. Dependence of the magnitude of a unit impulse
on half the angle of entry into the engine nozzle

For a single nozzle, the thrust formula can be written as follows

$$P_{rot} = K_d p_{rot} f_{cr} \varphi_1 \varphi_2 A_{rot}, \tag{16}$$

where K_d is a thrust coefficient; f_{cr} is a nozzle critical cross-sectional area; φ_1 = 0.95–0.98 is a velocity coefficient; φ_2 is a nozzle flow coefficient at gas flow without swirling; $A_{rot} = f(\alpha_{cr})$ is a flow coefficient for rotating gas flow.

Thus, knowing the laws of pressure change in the combustion chamber of a rotating a solid propellant jet engine and using the above formulae for thrust force, it is possible to graphically construct $P_{rot}(\tau)$ dependences for any type of a rotating engine [6-8].

The analysis of dependences for the thrust force of rotating ground jet vehicles allows us to state that the thrust force value of such engines will be less than that of non-rotating ones, all other conditions being equal.

The difference in thrust forces will be determined by the following ratio

$$\frac{A_0}{A_{rot}} = \left(\frac{P_{rotcr}}{P_{0\text{cr}}}\right)^{\frac{1}{1-\nu}} = \left(1+\frac{k}{k-1}\alpha_{cr}^2\right)^{\frac{1}{1-\nu}}, \tag{17}$$

then

$$\frac{P_0}{P_{rot}} \approx \left(1+\frac{k}{k-1}\alpha_{cr}\right)^{\frac{1}{1-\nu}}. \tag{18}$$

For real solid propellants υ = 0.5–0.67 at α_{cr} = 0.1–0.15 the value of thrust relations is within $\frac{P_0}{P_{rot}}$ = 1.1–1.36, i.e. the thrust of a non-rotating engine is 10-36 % greater than that of a rotating engine [9–11].

The experimental studies of rotating solid propellant jet engines equipped with multi-ball solid propellant charges have shown that (unlike solid propellant jet engines with single-ball charges) pressure nonuniformity in the combustion chamber is observed only in the pre-nozzle chamber. Herewith, the more draughts in the charge, the less is the degree of swirl both in the channel of a single draughts and in the pre-nozzle block as a whole [12-15].

Conclusion

Within the framework of the conducted research the following tasks have been solved:

1. It has been established that the internal ballistics parameters of rotating solid propellant jet engines are mainly influenced by the coefficient of gas flow rate from the rotating engine chamber, the effect of erosive combustion of solid propellant, and the change in the heat loss coefficient.

2. The basic calculation dependences for determining the pressure in the combustion chamber of a rotating solid propellant engine are given for the periods of pressure release on the stationary mode of engine operation, engine operation on the stationary mode and during the period of free flow of gases from the chamber of a solid propellant jet engine.

3. The methodology for selecting linear and angular dimensions of the nozzle of a rotating engine is presented, which allowed a comparative analysis of the calculations of the supersonic part of the rotating and non-rotating engines.

4. An estimate of the thrust force for a single nozzle of a rotating solid propellant jet engine is given. It is found that the thrust force of rotating engines (with other identical conditions in the combustion chamber) is 1.1–1.36 times less than that of non-rotating solid propellant jet engines.

5. The conducted experiments showed a decrease in the degree of swirl of the gas flow of rotating solid propellant engines with increasing the number of propellant draughts in the engine charge.

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