INDUCTIVE PULSED THRUSTER WITH SUPERCONDUCTING ACCELERATING ELEMENTS

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The inductive method of magnetic bodies accelerating by the superconducting accelerating system is considered. On the base of the suggested model it is possible to create a new type of thruster for the superprecise orientation of spacecraft. The electrodynamics calculation of the thruster characteristics is conducted. The problem of the effective transformation of electromagnetic energy into the kinetic one is considered

Introduction

The inductive method is considered to be one of the most effective methods of accelerating of magnetic bodies [1–5] . The special sense the method makes when superconducting accelerating systems are applied [6] . The main advantage in this case is the absence of losses of ohm resistance and the possibility of use the high levels of energy supplied into the accelerating system. On the base of the suggested model it is possible to create a new type of thruster for the super precise orientation of spacecraft. It might realize the exhaust of small solid magnetic bodies of a precise mass or plasmoids with a high precise velocity. The certain scheme of the Inductive Pulsed Thruster with further acceleration of the plasmoid in the field of the superconducting coil in the regime of non-decaying current circulation is considered. Electrodynamics calculation of the thruster characteristics is conducted. It revealed a number of advantages of this scheme comparatively to "warm" systems. The analysis of power expenses of cryogenic providence is carried on and the losses of the present scheme are estimated in the pulse regime of acceleration. The problem of the effective transformation of electromagnetic energy into the kinetic one is considered [7] .

Theoretical Part

One can consider the scheme of the induction impulse electric rocket thruster with reacceleration in the magnetic field of the superconducting ring in the regime of the undamped current circulation. The electro-dynamic calculation of the thruster could reveal the advantages of this scheme in comparison with “warm” systems. Besides, one can analyze the power expenses for the cryogenic providence and losses in the impulse regime of the accelerating system. The circuit of the induction impulse electric rocket thruster with superconducting accelerating elements is presented in Fig.1.

The working substance is supplied to the impulse quick-acting valve 1 and injected in the fore-part of the accelerating channel. Simultaneously with the working substance supply starting the discharge is initialized in the channel from the capacitor or the inductive energy accumulator through the phase shifter 2 (its necessity is shown below). The igniter circuit and the phase shifter are adjusted so that the discharge current in the coil-inductor 3 reaches maximum in the moment of maximum gas density distribution in the accelerating channel fore-part.

At that instant the avalanche ionization process begins at the sufficient value of the field induction variation. The induced currents appear in the ionized plasma. These induced currents are formed by movable electrons, which interact with the rotational magnetic field of the discharge current and, therefore, are accelerated in the direction of the superconducting ring 5. At that ions are carried away by the self-coordinated electric field of the plasmoid. Further the acceleration in the magnetic field of the superconducting coil 5 being in the regime of the undamped current circulation occurs. The plasma velocity reaches maximum in the superconducting coil plane. After that the plasmoid appears in the zone behind the shield 6. Thus, one can note the two acceleration stages in the suggested scheme: I – acceleration at the discharge from the accumulator through the coil-inductor; II – acceleration in the magnetic field of the superconducting coil. The equivalent electric circuit of the electric rocket thruster is shown in Fig.2 (in the case of the capacitor use as the energy accumulator). Its equivalent mechanical circuit is presented in Fig.3.

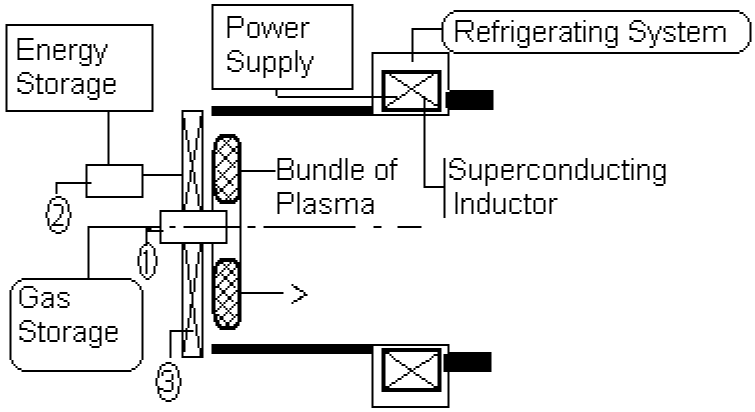

Fig.1 The scheme of the impulse thruster with superconducting inductor

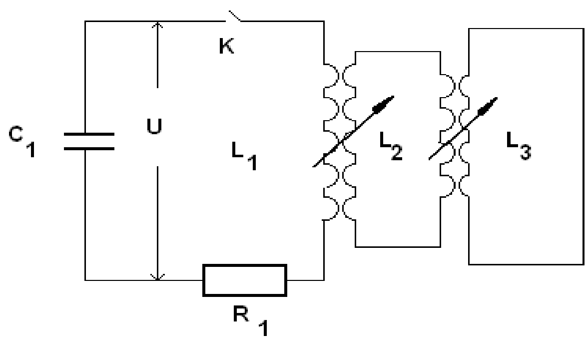

Fig.2 The electric scheme

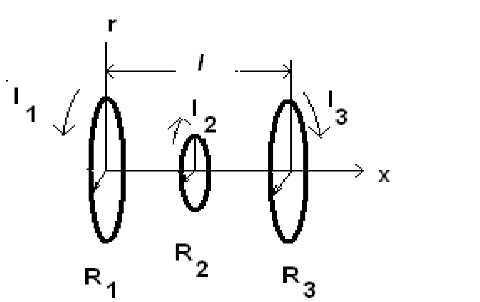

Fig.3 .The equivalent mechanical circuit

To consider the accelerating process one can observe the Lagrange function designating the discharge circuit I position as the initial coordinate:

$$L = \frac{m\dot{x}^2}{2} + \frac{L_1 I_1^2}{2} + \frac{L_2 I_2^2}{2} + \frac{L_3 I_3^2}{2} + L_{12} I_1 I_2 + L_{13} I_1 I_3 + L_{23} I_2 I_3 \qquad (1)$$

$L_{ij}-$ the reciprocal induction values of the rings 1,2,3; L_i- the induction values of the rings; I_i- the current values of the rings correspondingly. The charges in the rings $q_1, q_{2,} q_3$ and the plasma filament coordinate X can be designated as the generalized coordinates.
Considering the Relay's function

$$Q_i = \frac{d\bar{R}}{d\dot{Q}_1}; \qquad \bar{R} = \frac{1}{2} R_1 \dot{Q}_1^2 \tag{2}$$

and differentiating (1) with respect to the generalized coordinates and velocities, one can obtain the equations, which describe the equivalent circuit of the thruster in Fig.2.

$$\begin{aligned}
& m\frac{d^2x}{dt^2} = I_1 I_2 \frac{dL_{12}}{dx} + I_2 I_3 \frac{dL_{23}}{dx}; \\
& L_1 \frac{dI_1}{dt} + \frac{d}{dt}(L_{12} I_2) + \frac{d}{dt}(L_{13} I_3) + R_1 I_1 = U; \\
& L_2 \frac{dI_2}{dt} + \frac{d}{dt(\;)}(L_{12} I_1) + \frac{d}{dt}(L_{23} I_3) = 0; \\
& L_3 \frac{dI_3}{dt} + \frac{d}{dt}(L_{13} I_1) + \frac{d}{dt}(L_{23} I_2) = 0; \\
& I_1 = -C_1 \frac{dU}{dt}.
\end{aligned} \tag{3}$$

In the system (3) the first is the equation of motion, the three others are Kirhgoff's equations, which describe the variation of the electric parameters in the circuits 1, 2, 3.
One can introduce the following designations:

$$\begin{aligned}
& [x] = \left(\frac{2}{k_1} - k_1\right) \cdot K(k_1) - \frac{2}{k} \cdot E(k_1), && k_1 = \frac{4r_1 r_2}{(r_1 + r_2)^2 + x^2}; \\
& [1-x] = \left(\frac{2}{k_2} - k_2\right) \cdot K(k_2) - \frac{2}{k} E(k_2), && k_2 = \frac{4r_3 r_2}{(r_2 + r_3)^2 + (1-x)^2}, \\
& [l] = \left(\frac{2}{k_3} - k_3\right) \cdot K(k_3) - \frac{2}{k} E(k_3), && k_3 = \frac{4r_1 r_3}{(r_1 + r_3)^2 + l^2}.
\end{aligned} \tag{4}$$

where $l-$is the distance between the rings 1 and 3.; x – the plasmoid coordinate (Fig.3).
In this case the plasma inductances are written as:

$$L_{12} = m_0\sqrt{r_2 \cdot r_1}\,[x], \quad L_{23} = m_0\sqrt{r_2 \cdot r_3}\,[1-x], \quad L_{13} = m_0\sqrt{r_3 \cdot r_1}\,[l] \tag{5}$$

To denote the derivatives of the reciprocal inductances one can introduce the designations:

$$\begin{aligned}
& \{x\} = \frac{x}{\sqrt{(r_1 + r_2) + x^2}} \left[-K(k_1) + \frac{r_1^2 + r_2^2 + x^2}{(r_1 + r_2)^2 + x^2} \cdot E(k_1)\right], \\
& \{1-x\} = \frac{1-x}{\sqrt{(r_3 + r_2)^2 + (1-x)^2}} \left[-K(k_2) + \frac{r_3^2 + r_2^2 + (1-x)^2}{(r_3^2 + r_2^2) + (1-x)^2} E(k_2)\right], \\
& \{l\} = \frac{1}{\sqrt{(r_3 + r_1)^2 + l^2}} \left[-K(k_3) + \frac{r_3^2 + r_1^2 + l^2}{(r_3^2 + r_1^2) + l^2} E(k_3)\right].
\end{aligned} \tag{6}$$

The inductances of the thin rings are expressed by the dependences[8]:

$$L_1 = m_0 r_1 \ln\left[\frac{8r_b}{r_1} - \frac{7}{4}\right]; \quad L_2 = m_0 r_2 \ln\left[\frac{8r_b}{r_2} - \frac{7}{4}\right]; \quad L_3 = m_0 r_3 \ln\left[\frac{8r_b}{r_3} - \frac{7}{4}\right], \tag{7}$$

where $r_b -$ the ring width; $r_1, r_2, r_3 -$ the radiuses of the rings 1,2,3 correspondingly

Therefore

$$\frac{\partial L_{12}}{\partial t} = -\frac{dx}{dt} m_0 \cdot \{x\}; \qquad \frac{\partial L_{13}}{\partial t} = 0; \qquad \frac{\partial L_{23}}{\partial t} = \frac{dx}{dt} m_0 \cdot \{1 - x\} \tag{8}$$

For the numerical calculations it is convenient to convert the system of equations (3) into the dimensionless form. For this one can introduce the following dimensionless variables:

Dimensionless currents:

$$N_1 = \frac{I_1}{U_0}\sqrt{\frac{L_1}{C_1}}; \qquad N_2 = \frac{I_2}{U_0}\sqrt{\frac{L_2}{C_1}}; \qquad N_3 = \frac{I_3}{U_0}\sqrt{\frac{L_3}{C_1}};$$

Dimensionless coordinates:

$$\tilde{l} = \frac{1}{r_1}; \qquad \tilde{x} = \frac{x}{r_1}.$$

Dimensionless time :

$$\boldsymbol{t} = \frac{1}{\sqrt{L_1 C_1}}; \tag{9}$$

Dimensionless voltage :

$$\tilde{U} = \frac{U}{U_0};$$

Dimensionless radiuses of rings:

$$n_2 = \frac{r_2}{r_1}; n_3 = \frac{r_3}{r_1}.$$

One can obtain the dimensionless system of equations:

$$\frac{d^2 y}{d\boldsymbol{t}^2} = qN_1 N_2\{x\} + qN_2 N_3\{1 - x\};$$

$$\frac{dN_1}{d\boldsymbol{t}} - \frac{1}{\boldsymbol{c}} \cdot \frac{dv}{d\boldsymbol{t}} \cdot \{x\} \cdot N_2 + \frac{\sqrt{n_2}}{\boldsymbol{c}} \cdot [x] \cdot \frac{dN_2}{d\boldsymbol{t}} + \frac{\sqrt{n_3}}{\boldsymbol{c}} \cdot [l] \cdot \frac{dN_3}{d\boldsymbol{t}} + \boldsymbol{a}_1 N_1 = \tilde{U};$$

$$n_2 \frac{dN_2}{d\boldsymbol{t}} - \frac{1}{\boldsymbol{c}} \cdot \frac{dy}{d\boldsymbol{t}} \cdot \{y\} \cdot N_1 + \frac{\sqrt{n_2}}{\boldsymbol{c}} \cdot [y] \cdot \frac{dN_1}{d\boldsymbol{t}} + \frac{\sqrt{n_2 n_3}}{\boldsymbol{c}} [\tilde{l} - y] \cdot \frac{dN_3}{d\boldsymbol{t}} + \frac{1}{\boldsymbol{c}} \cdot \frac{dy}{d\boldsymbol{t}} \{\tilde{l} - y\} N_3 = 0; \tag{10}$$

$$n_3 \frac{dN_3}{d\boldsymbol{t}} + \frac{\sqrt{n_3}}{\boldsymbol{c}} \cdot [l] \cdot \frac{dN_1}{d\boldsymbol{t}} + \frac{\sqrt{n_2 n_3}}{\boldsymbol{c}} \cdot [\tilde{l} - y] \cdot \frac{dN_2}{d\boldsymbol{t}} \cdot + \frac{1}{\boldsymbol{c}} \cdot \frac{dy}{d\boldsymbol{t}} \{\tilde{l} - y\} N_2 = 0;$$

$$N_1 = -\frac{\partial \tilde{U}}{\partial \boldsymbol{t}}.$$

In the system of equations (10) the parameter $q = \frac{m_0}{m} \cdot \frac{U_0^2 C_1^2}{r_1} -$ is the analogous of the Artsimovitsh´s parameter[1]. It represents the relation of electromagnetic and inertial qualities of the system. The value $\boldsymbol{a}_1 = R_1\sqrt{\frac{C_1}{L_1}} -$ is the dissipational parameter of the coil-inductor.

$$\boldsymbol{c} = \ln\left(\frac{8r_b}{r_1} - \frac{7}{4}\right) \text{-}$$

The initial data for the system (7.39) are as follows:

$$\tilde{U}\Big|_{t=0} = 1; y\Big|_{t=0} = y_0; \boldsymbol{t}\Big|_{t=0} = 0; N_1\Big|_{t=0} = 0; N_2\Big|_{t=0} = 0; N_3\Big|_{t=0} = N_{30};$$

$$\left.\frac{dN_1}{d\boldsymbol{t}}\right|_{t=0} = \left.\frac{dN_2}{d\boldsymbol{t}}\right|_{t=0} = \left.\frac{dN_3}{d\boldsymbol{t}}\right|_{t=0} = 0. \tag{11}$$

In the present case to evaluate the acceleration parameters it is convenient to prescribe the initial current N_3 corresponding to the equation of the initial stored energies in the capacitor and the superconducting coil:

$$\boldsymbol{e} = \frac{\Psi_3^2}{L_3 C_1 U_0^2}, \qquad (12)$$

where $\Psi_3 -$ the magnetic flow through the superconducting ring 3.

Therefore, the initial current N_3 is defined by the formula:

$$N_3\big|_{t=0} = \sqrt{\frac{\boldsymbol{e}}{n_3}}. \qquad (13)$$

Thus, the main parameters characterizing the considered electric rocket thruster are:

$q -$ the relation of the accumulated energy and the inertial forces;

$\boldsymbol{e} -$ the relation, which determines the energy distribution in the system between the capacitor and the superconducting coil;

$\boldsymbol{a}_1 -$ the parameter, which determines the value of energy losses for the resistance.

The simple evaluations of these parameters for plasma indicate, that

$$q \approx 1...50; \quad \boldsymbol{a}_1 \approx 10^{-3}...10^{-7}.$$

Due to the numerical calculations the following results are obtained: the expressions for the discharge and induced currents in the plasma; the expression for the current in the superconducting coil. As the result of the numerical experiments one general peculiarity is revealed. It will be considered first of all. It turned out that the scheme of the induction acceleration can provide two regimes. In the first one when the acceleration starts at the phase $N_1\big|_{t=0} = 0$, the degree of the stored energy conversion into the bunch kinetic energy is small and the acceleration efficiency does not exceed few percent. In the second regime when the acceleration begins at the moment of maximum current distribution $N_1\big|_{t=0} = \max$, the efficiency rises considerably and can reach dozens of percent.

To clarify the dependence of the acceleration on the initial phase the equation is calculated for the energy conversion efficiency in the considered type of thrusters:

$$\boldsymbol{h}_{en} = \frac{mv^2}{C_1 U_0^2} \qquad (14)$$

or in the dimensionless form:

$$\boldsymbol{h}_{en} = \frac{y'}{q\boldsymbol{c}} \qquad (15)$$

The denominator of the formula (14) does not contain the consideration of the energy introduced into the superconducting ring. It can be explained that the constant energy conservation is correct at any external field changes in the circulation regime of the undamped current for the superconducting coil. Thus, the superconductor energy is not consumed but conserved according to the law of the magnetic flow $\boldsymbol{y}_3$ constancy (since the superconducting ring energy ~$\boldsymbol{y}_3^2$). It is clear that the superconducting coil will have the losses while functioning in the impulse regime.

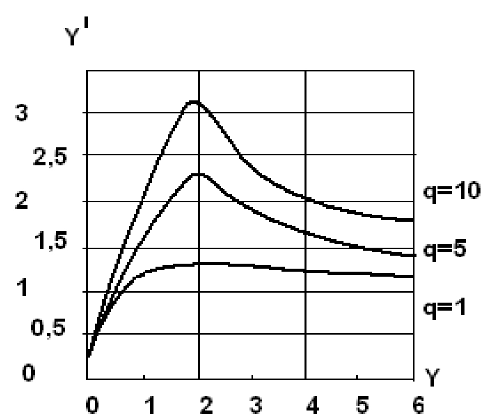

Fig.4. The dependences of the movable element velocity on the distance at different values of the Artsimivich's parameter q.

Fig.4 shows the dependences of the movable element velocity as the function of the distance at different values q (at $e = 1.0; n_3 = 1.0; n_2 = 0.8; y_0 = 0.2; a_1 = 0.01; l = 1.8$). The point $y = 0$ corresponds to the coil-inductor position; the point $y = 1.8$ corresponds to the superconducting coil position.
Obviously, that the rising of q corresponds to the energy content increase in the system that provides the velocity growth.
The research showed that the free magnetic body (plasmoid) acceleration can be realized in the system of the coaxial superconducting coils. In this case the Lagrange function is written as follows:

$$L = \frac{1}{2} M\dot{x}^2 + \sum_{i,j=1}^{5} I_i I_j L_{ij} \tag{16}$$

where the summarizing i,j=1…5 correspond to the number of the rings.
The generalized coordinates are $x, q_1...q_5$ and the velocities $\dot{x}, I_1...I_5$. One can obtain the equation of the free plasmoid motion:

$$M\frac{d^2x}{dt^2} = \sum_{j=1}^{5} I_5 I_j \frac{dL_{j5}}{dx} \tag{17}$$

By the differentiating on the correspondent currents $I_1...I_5$ one can define five motion integrals, which reflect the conditions of the magnetic flow constancy law:

$$\sum_{j=1}^{5} L_0 I_j = \Psi_i, i = 1,...,5 \tag{18}$$

The equations for the mutual inductances of the system can be written in the form:

$$L_{j5} = m\sqrt{r_j r_5}\left[\left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k)\right], ...j = 1,...,4, \tag{19}$$

where $K(k)$ and $E(k)$- the complete elliptic integrals of the module

$$k^2 = \frac{4r_j r_5}{(r_j + r_5)^2 + (x-l)^2}.$$

The derivative of the mutual inductances with respect to x is:

$$\frac{dL_{j5}}{dx} = \sum_{j=1}^{4} m \frac{x - l_j}{\sqrt{(r_j + r_5)^2 + (x - l_j)^2}}\left[-K(k) + \frac{r_j^2 + r_5^2 + (x - l_j)^2}{(r_j - r_5)^2 + (x - l_j)^2} E(k)\right]. \tag{20}$$

Taking into account the equation (20) the motion equation can be written as:

$$M\frac{d^2x}{dt^2} = \sum_{j=1}^{4} I_5 I_j \cdot m \frac{x - l_j}{\sqrt{(r_j + r_5)^2 + (x - l_j)^2}}\left[-K(k) + \frac{r_{ji}^2 + r_5^2 + (x - l_j)^2}{(r_j - r_5)^2 + (x - l_j)^2} E(k)\right]. \tag{21}$$

One can introduce the dimensionless parameters:

$$y = \frac{x}{r_1} - \text{the dimensionless coordinate;} \tag{22}$$

$$n_j = \frac{r_j}{r_1} - \text{the rings radiuses ratio;} \tag{23}$$

$$\frac{\Psi_j}{\Psi_1}, - \text{the magnetic flows ratio;} \tag{24}$$

$$\boldsymbol{h}_j = \frac{L_j}{L_1} - \text{the inductances ratio;} \tag{25}$$

$$\boldsymbol{t}^2 = \frac{t^2 \cdot \Psi_1^2}{\boldsymbol{p}^2 m M r_1^3} - \text{the dimensionless time;} \tag{26}$$

$\tilde{l}_j = \dfrac{I_j}{r_1}$ – the dimensionless coordinate of the j superconducting ring.

One can introduce the new designations:

$$b_j = m\frac{r_1}{L_j}; \qquad q_j = p^2 b_5 b_j, \qquad j = 1,...,5 \tag{27}$$

$$\{\ \}_j = \frac{y-\tilde{l}_j}{\sqrt{(n_j+n_5)^2+(y-\tilde{l}_j)^2}}\cdot\left[-K(k)+\frac{n_j^2+n_5^2+(y-\tilde{l}_j)^2}{(n_j-n_5)^2+(y-\tilde{l}_j)^2}E(k)\right]; \tag{28}$$

$$g_{ij} = \sqrt{n_i n_j}\cdot b_j\left[\left(\frac{2}{k_{ij}}-k_{ij}\right)\cdot K(k_{ij})-\frac{2}{k_{ij}}E(k_{ij})\right], \qquad i, j = 1,...,5 \tag{29}$$

$$g_{ji} = \sqrt{n_i n_j}\cdot b_i\left[\left(\frac{2}{k_{ji}}-k_{ji}\right)\cdot K(k_{ji})-\frac{2}{k}E(k_{ji})\right],$$

$$k_{ij}^2 = k_{ji}^2 = \frac{4n_i n_j}{(n_i+n_j)^2+y_{ij}^2}.$$

It being known that $g_{ij} = g_{ji} = 1$ in the condition $i = j$; and the parameter y_{ij} is the distance between the rings i and j correspondingly, expressed through the parameters y and l_j.

After the substitution one can write the system of equations in the dimensionless variables describing the ring motion in the system of the superconducting rings.

$$\frac{d^2y}{d\tau^2} = \sum_{j=1}^{4} N_5 N_j\cdot q_j\cdot\{\ \}_j; \tag{30}$$

$$\sum_{j=1}^{5} g_{ij}\cdot N_j = \frac{\Psi_i}{\Psi_1}, \qquad i = 2,...,5)$$

The system (30) is the initial for the numerical integration.

The Analysis of the Numerical Integration Results

The experimental results are shown in Fig.5. One can see the sequential growth of the ring velocity when it passes through the multiple-turn superconducting system for various ratios $\dfrac{y_5}{y_1}$ at

$n_2 = 1; n_3 = 1; n_4 = 1; n_5 = 0.5; y_0 = 2.0; y_2/y_1 = y_3/y_1 = y_4/y_1 = 1.$

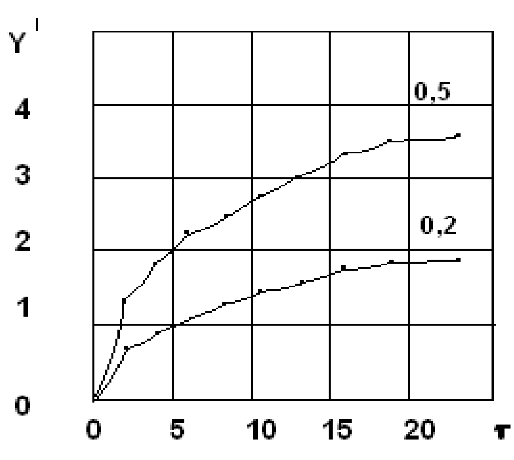

Fig.5. The dependences of the ring velocity growth on the ratio of the magnetic flows.

The analysis shows that in this system the movable ring velocity increases in three times comparatively to the case when the movable ring is accelerated in the field of the superconductive ring. Obviously that the velocity growth reduces by its passing through every subsequent ring. It evidently occurs because of the motion velocity growth and the reduction of the interaction time with every subsequent element. In order to conserve the constant velocity growth one can change the system geometry so that the distance between the rings increases in the direction of the motion. The same result can be obtained by the acceleration in the ring system of unequal radiuses or unequal magnetic flows. The obtained results are evidence of the effective acceleration possibility of solid bodies or plasma in the system of coaxial rings. To avoid acceleration losses it is suggested to adjust the relative position of the fixed coils or to vary the distribution of the initial magnetic flows along "the solenoid" length.
The equation for the energetic efficiency in the dimensionless form is:

$$\eta_{en} = \frac{\chi}{\pi^2}(y')^2 \cdot \frac{1}{\left\{1+\sum_{j=1}^{5}\left(\frac{\Psi_j}{\Psi_1}\right)^2 \cdot \frac{1}{n_i} + \frac{\sigma}{\chi}\cdot\sum_{i,j=1}^{5}\frac{\Psi_i\cdot\Psi_j}{\Psi_1^2}\right\}} \qquad (31)$$

where $\chi = \ln\left(\frac{8r_b}{r_1} - \frac{7}{4}\right) \approx 3;\quad \sigma = \left[\left(\frac{2}{k-k}\right)\cdot K(k) - \frac{2}{k}E(k)\right];\quad k \approx 4/5.$

The efficiency for various values of flow ratios ψ_5/ψ_1 calculated by formula (31) is shown in Fig.6

(at $n_2 = 1; n_3 = 1; n_4 = 1; n_5 = 0.5; y_0 = 2.0; \psi_2/\psi_1 = \psi_3/\psi_1 = \psi_4/\psi_1 = 1$).

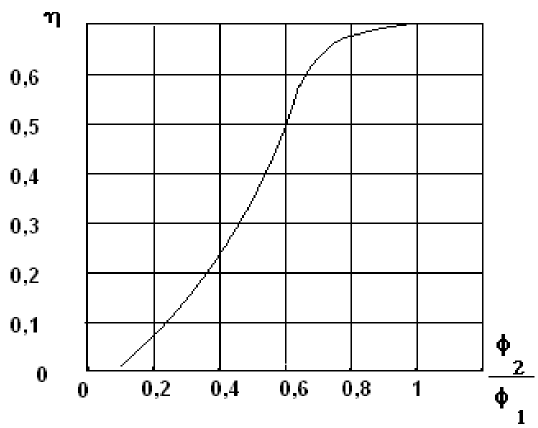

Fig.6. The dependence of the efficiency for various values of the flow ratios.

It is clear that when the energy introduced into the accelerating plasmoid increases the efficiency rises and

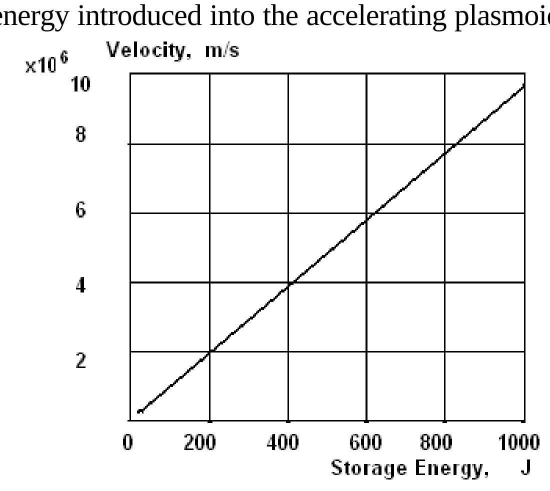

Fig.7. The velocity growth depending on the stored energy

can reach considerable values (~0.7). The obtained velocity of the accelerated mass 10^{-9} kg in the considered thruster can reach the level ~10^6 m/s at the following parameter values: the superconducting coil inductance ~10^5 Hr; the stored energy~1kJ (Fig.7).

Conclusions

The research confirmed that the use of the superconducting accelerating elements permits to elaborate the propulsion systems of the magnetic bodies and plasmoids with high efficiency of the magnetic energy transformation into the kinetic energy.

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