

# STUDY OF PLASMA DYNAMICS IN THE VARIABLE SECTION CHANNEL OF STATIONARY PLASMA THRUSTER

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## Abstract

The outcomes of numerical and experimental research of influence of the change of SPT digit channel geometry on a plasma stream dynamics and the main output integral performances of a thruster are represented in the paper. The analysis of estimation results showed that the existing reduction of the channel in its input part leads to acceleration of neutral gas ionization processes, to increase of ion current density on a section of the channel and to improvement of thruster output integral performances. An optimal profile of the channel was obtained.

Experimental results confirmed results of theoretical research and testify to indubitable influence of the SPT channel profile on ion current value, and this effect is intensifying while voltage is becoming higher.

Following theoretical and experimental research a capability of management of integral parameters by profiling of discharge channel walls was shown.

## Introduction

The spent earlier numerical simulation of current of a plasma flow in SPT digit channel taking into

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account its extension in output part has shown that an extension mentioned leads to decrease a high energy ion flow towards walls in output part of the channel and to improvement of integral performances of the thruster: force of a thruster  $Ft$  and life time specified by wear of channel walls due to interaction with ion flow. An optimal value of parameter  $z_0$  has been obtained, this was at the beginning of a channel extension and  $z_0$  corresponds to the center of channel.

This paper is a continuation of paper<sup>1</sup> and is dedicated to further numerical research of the digit channel geometry variation impact on plasma stream dynamics and on main thruster parameters to optimize a channel profile. Dynamics of ion component in the channel which is narrowed in its input part with a further extension towards exit were studied. To check estimation results an experimental investigation of the plasma stream running in channels with the above mentioned profile was carried out.

## 1. Mathematical Model

At numerical simulation of plasma flowing in SPT channel a quasistationary running of plasma stream at  $\vec{E} \times \vec{H}$  fields in view of acceleration processes, digit channel geometry variation, ionization is considered, it being known that in paper only the pair collisions-collisions of atoms of neutral gas with electrons are

taken into account, because these collisions are dominating in channel volume due to a small plasma density. To describe physical processes at SPT the following system of equations is applied:

$$\begin{aligned} \vec{V} \frac{\partial f_i}{\partial \vec{r}} + \frac{1}{\xi} \vec{E} \frac{\partial f_i}{\partial \vec{V}} &= \frac{1}{\zeta} \beta n g k_p \delta(\vec{V} - \vec{V}_{0a}) \\ f_i &= n(\vec{r}, t) \delta(\vec{V} - \vec{V}_i(\vec{r}, t)), f_a = g(z) \delta(\vec{V} - \vec{V}_{0a}) \\ \vec{V}_{0a} \frac{dg}{dz} &= -\frac{g}{\zeta} \frac{k_p}{l} \int_{r_1}^{r_2} \beta n dr; n = \int f_i d\vec{V}; \vec{J} = \int \vec{V} f_i d\vec{V} \\ n_i &\cong n_e \cong n; \vec{E} = -\nabla \Phi \\ \gamma &= \Psi(r, z); \vec{H} = (0, \Psi / r, 0) \\ \Phi - T_e^*(\gamma) \ln \frac{n}{n^*(\gamma)} &= \Phi^*(\gamma) \\ T_c|_{r=r_0} &= T_c^*(z); \Phi|_{r=r_0} = \Phi^*(z); n|_{r=r_0} = n^* \\ g|_{z=0} &= g_0; n|_{z=0} = n_0; \vec{J}|_{z=0} = \vec{J}_0 \\ \Phi|_{\kappa=\kappa_0} &= \Phi^*(z); T_c|_{\kappa=\kappa_0} = T_c^*(z); n|_{r=r_0} = n^*(z) \\ \gamma &= z + A \left[ z^2 - \frac{z^3}{3} + (z-1)(r-r_0)^2 \right] \\ r_0(z) &= \frac{1}{2} [r_1(0) + r_2(0)] \\ r \in G &= \{(r, z): r \in [r_1, r_2], z \in [0, 1]\} \\ r_{1,2}(z) &= \begin{cases} r_{1,2}(0) \pm \sin Bz, z \leq z_0 \\ r_{1,2}(z_0) \pm \{\cos[C(z-z_0)] - (1-\delta_1)\}, z > z_0 \end{cases} \\ B &= \arcsin(\delta_1) / z_0 \\ C &= [\arccos(1-\delta_1-\delta_2)] / (1-z_0) \\ \delta_1 &= r_1(z_0) - r_1(0) = r_2(0) - r_2(z_0) \\ \delta_2 &= r_1(0) - r_1(1) = r_2(1) - r_2(0) \\ k_p &= \frac{r_2(0) - r_1(0)}{r_2(z) - r_1(z)} \end{aligned} \tag{1}$$

where  $\xi = \frac{mV_1^2}{e\Phi_0}, \zeta = \frac{V_1}{\beta_0 n_1 L}$  - dimensionless

parameters of a similarity, analogs of Frud and Knudsen numbers accordingly,  $L$  - length of a channel,  $g, n$  - densities of neutral atoms and ions,  $f_i$  - distribution function of ions,  $T_e$  - temperature of electrons,  $\beta = \beta(T_e)$  - factor of ionization (known function of electron temperature  $T_e$ ),  $\gamma$  - index of a magnetic force line,  $\Psi(r, z)$  - function of a magnetic flow,  $A$  - parameter of a curvature of magnetic force lines,  $G$  - two dimensional area in which the problem is considered,  $z_0$  - section where the channel has a minimum width,  $\delta_1, \delta_2$  - assigned values of a channel

width at sections  $z_0$  and  $z = 1$ ,  $k_p$  - profiling factor (Fig. 1).

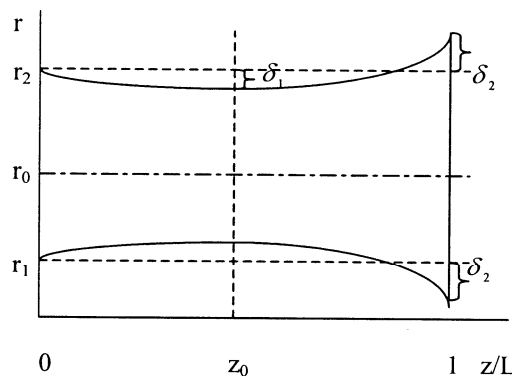


Fig. 1: Investigated Profile of discharge channel

On lateral walls of a channel  $r_1(z)$  and  $r_2(z)$  the condition of an absorption of ions is put:

$$\begin{aligned} f_i(r, \vec{V})|_{r=r_1} &= 0 \\ f_i(r, \vec{V})|_{r=r_2} &= 0 \end{aligned} \tag{2}$$

For closing of a set of equations (1) the experimental relations of a potential  $\Phi(z)$  and a temperature  $T_e(z)$  electrons on a channel axis are used.

The above mentioned set of equations at a specific magnetic field and boundary conditions allows to describe processes of ionization and acceleration of an ionic flow. It seems no possible to find any analytical solution of this system. For the solution of it the numerical algorithm combining finite difference methods with a method of "large" particles is used.

## 2. Outcomes of Numerical Calculation and Their Analysis

The calculations were conducted for SPT model with the following parameters: length of a channel -  $L = 4 \cdot 10^{-2} m$ ; external radius of a channel  $r_2 = 6 \cdot 10^{-2} m$ ; an internal radius  $r_1 = 3,6 \cdot 10^{-2} m$ ; gas flow density on input  $J_0 = 3,46 \cdot 10^{21} m^{-2} sec^{-1}$ ; gas concentration on input  $n_0 = 3,07 \cdot 10^{19} m^{-3}$ ; parameter

of a curvature of a magnetic lines  $A=5;10$ . Parameters  $z_0, \delta_1, \delta_2$  (Fig. 1) were varied.

In paper <sup>1</sup> an optimal value of a parameter  $z_0$  was obtained. It was stipulated by a minimum flow of ions on walls of a channel in this case. Therefore the geometry of a channel was set in agree with this:  $z_0 = 0,45; \delta_1 = 0,06; \delta_2 = 0;0,06;0,12$ . As working substance Xe was used.

Outcome calculation analysis demonstrated that the availability of a channel reduction in the initial area at a similar propellant flow rate leads to the acceleration of neutral gas ionization processes, to the increase of an ion flow density on a cut channel section (Fig. 2), to the decrease of an ion flow on a channel walls  $\mu$  (Fig. 3) and this leads in its turn to the increase of the thruster force  $F_t$  due to increasing of throwing out mass from a thruster (Fig. 3).

So the outcome numerical calculation analysis has shown that a selection of digit channel profile with its reduction in the initial area and extension towards a cut channel section according to (1) leads to a modification of ion current profile on a channel section and to an improvement of the thruster integral performances.

Before experimental test was performed a thruster operation estimation including a plug in the channel to define  $z^*$  parameter – section by which the channel started to be reduced by value  $2\delta$  (Fig. 4) has been made. At the variable section  $z_0=0,5$  position  $z^*$  - was varied  $z^* = 0,25; 0,45$ .

The analysis of calculation results showed that  $z^*$  position effects considerably to the dynamics of ion component: a shift of  $z^*$  towards anode leads to an acceleration of the neutral gas ionization process and to an increase of ion flow density (Fig. 5). According to the augmentation of a mass throwing out from a thruster while operating with plug the ion current  $I_i$ , thrust force  $F_t$  and thrust efficiency increase  $\eta_t$  (Fig. 6,7).

### 3.Outcomes of experimental testing

To check the calculation results an experimental test for the impact of digit channel geometry on a distribution of the ion current density on a cut channel section and on main integral performances of the thruster has been performed.

For this view some profiling plugs were introduced into the channel and they could be moved along the channel axis. A distribution of ion density was carried out by the Lengmure spherical sonde being at a cathode potential. A standard module was studied as well as a module into the channel of which profiling rings were put, they reduced it and were manufactured of the same material as the channel walls. Integral performances of the thruster were measured with existing measurement tools at varied propellant flow rates and discharge voltages.

This shows a location of plugs in the channel. Fig. 8 demonstrates relations of ion current got by integration of profiles of ion current from discharge voltage. Relations shown testify to an obvious influence of SPT channel profile on the ion current value, and it being known that the effect is intensifying at the voltage increasing. Fig. 9 snows relations of the value  $\sigma$  from discharge voltage.

The profiling of the channel leads to an important change of the discharge current. Fig. 10 demonstrates relations of the thrust force from the voltage for a propellant flow rate  $\dot{m} = 4,51 \text{ mg} / \text{s}$ .

Relationships obtained are explained apparently by inconvenient position of plugs (near the section of channel) and this has led to some loss in integral performances.

### Conclusion

The spent numerical simulation of a plasma flow current in SPT variable section digit channel has

shown that the availability of the channel reduction in its initial area leads to an acceleration of neutral gas ionization processes, to an augmentation of ion current density on the channel section and to an improvement of outlet integral performances of the thruster. The results of testing confirmed outcomes of calculations and testify to an obvious effect of the SPT channel profile to the ion current value and this influence is becoming stronger while voltage is increasing.

### References

- [1] Arhipov, B., Goghaya, E., Nikulin, N.,  
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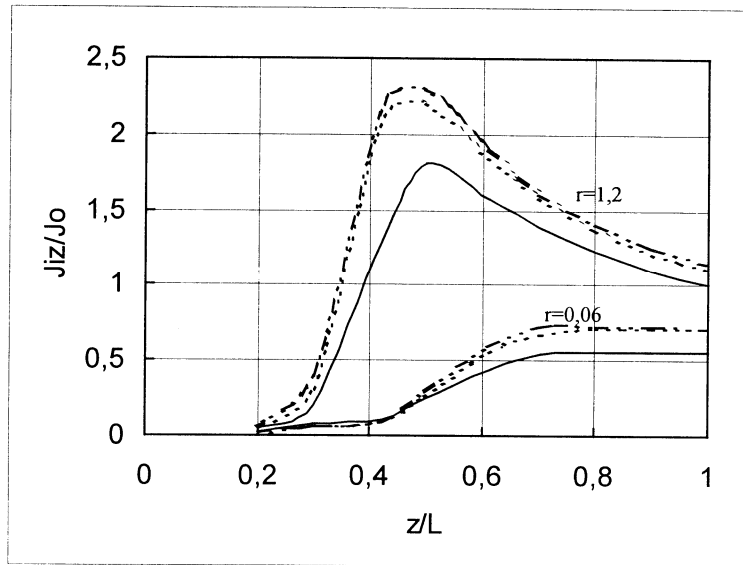


Fig. 2: Distributions of an ion flow density in a digit channel

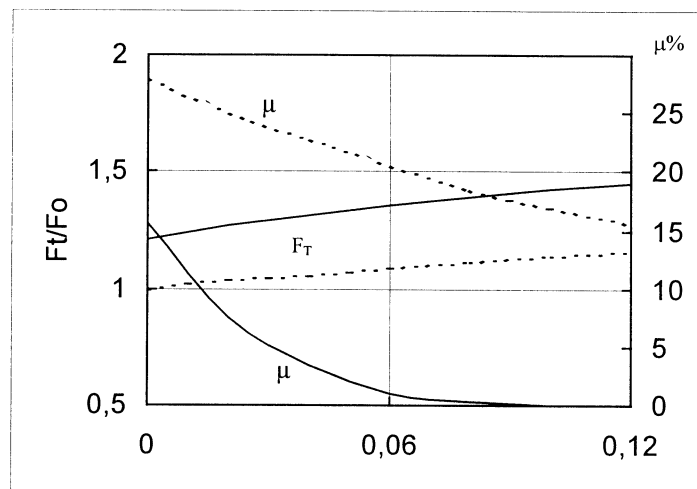


Fig. 3: Relations of a thruster force and  $\mu$  from  $\delta_2$

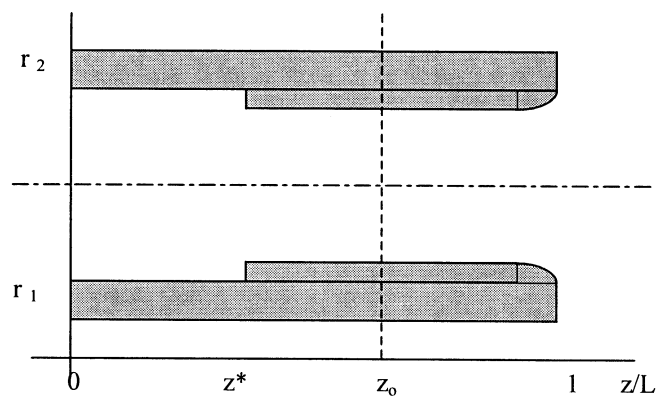


Fig. 4 : A Digit channel with a plug

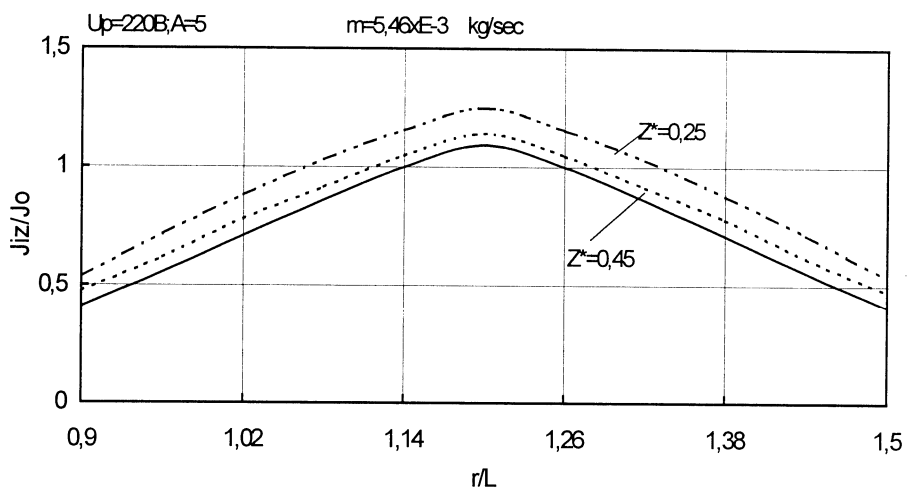


Fig. 5: Distributions of an ion flow density on a cut channel section:  
 — channel with constant section; - - - - -  $z^*=0,45$ ; ······  $z^*=0,25$

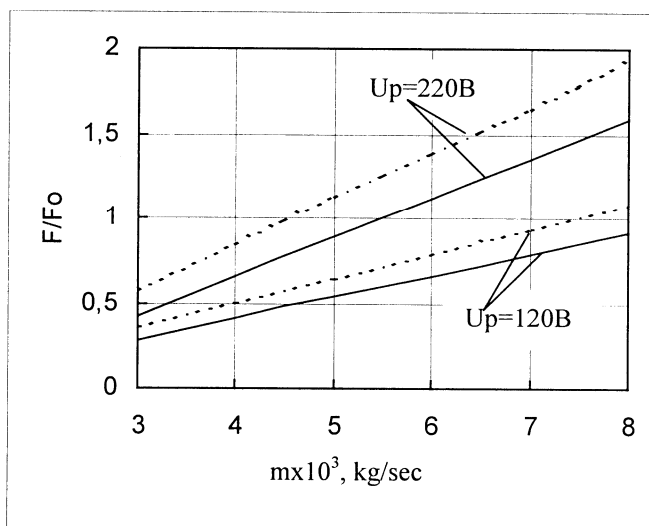


Fig. 6: Relations of a thruster force

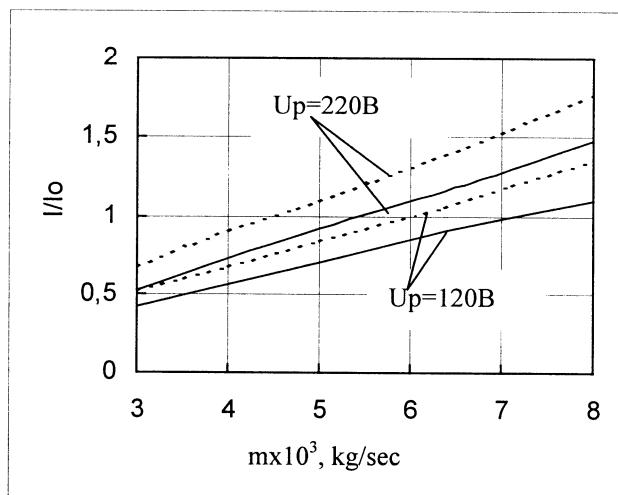


Fig. 7: Relation of an ionic

