AN IMPROVED SMALL CLOSED DRIFT THRUSTER WITH BOTH CONDUCTING AND DIELECT RIC CHANNELS

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Abstract

An improved stationary plasma thruster (SPT) was developed for operation at a power level of 100-160 W. The thruster was tested with both conducting (graphite) and dielectric (borosil) discharge channels. Integral, or overall, characteristics were obtained with both channel materials using Ar and Xe as the working gas. Ionization proccesses take place with the same intensity with both channel materials. However, the discharge current at otherwise similar operating conditions is higher by about (20÷30)% with the conducting channel compared with the dielectric one. This phenomenon is explained in the paper.

Introduction

Stationary plasma sources based on the stationary plasma thruster (SPT) are widely used both in space propulsion and technological applications. In recent years, there have been requirements in both applications for small, light plasma sources that can operate at a power of about 100÷150 W with low levels of erosion. An original approach based on the SPT [1] was used for the ion source. The general design approach used for this ion source was described previously [2]. The improved version described herein uses an improved magnetic field that results in reduced ion-beam cosine losses and reduced erosion of the discharge channel. Both conducting (graphite) and dielectric (borosil) discharge channels were used in this source. The source is shown in Fig. 1. Its dimensions are:
- external diameter is 55 mm;
- length is 34 mm;
- inside diameter of the channel at the exit is 24 mm;
- channel width at the exit is 4 mm;
- channel length, anode to exit, is 14 mm.

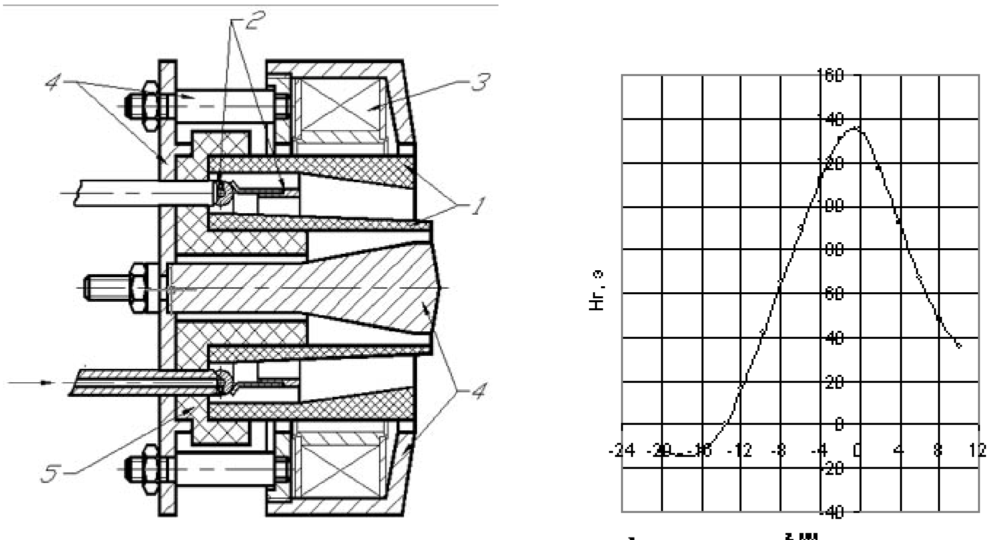

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Fig.1. a - Small ion source: 1 - discharge chamber walls; 2 - anode; 3 - magnetic coil; 4 - magnetic path; 5 - insulator. b - Magnetic field distribution, Hr, in Gauss at the mean radius of the discharge channel.

The cathode-neutralizer for most of the tests was a hot filament (HF)($\dot{m}_k = 0$) made of tungsten wire with a diameter of 0.28 mm. The HF was located 35 mm from the source exit plane. The magnetic field distribution is shown in Fig. 1b. The testing was carried out in a vacuum chamber with a diffusion-pump capacity of $21x10^3$ l/s. The cylindrical chamber has a length of 2.5 m and a diameter of 0.8 m.

A hollow cathode (HC) was used for thruster performance and endurance tests. The xenon flow through the HC was 0.1 mg/s during those tests.The vacuum chamber had a thrust scale with a laser motion indicator. The thrust error was less than 3%. The chamber has a probe actuator that permits beam profiles to be obtained at various distances from the exit plane. The plasma flow parameters such as directed ion current and ion flow divergence were obtained with a probe having two collecting surfaces oriented normal to each other and with the area of each surface equal to 0.28 mm^2. One surface of the probe was normal to the plasma flow to measure the directed ion current. The second surface of the probe was oriented parallel to a flow. The value of the ion current to the second surface characterized the chaotic current in the vacuum chamber and was utilized in the calculation of flow divergence. The directed energy of the ions was measured by a separate three-electrode, retarding-potential probe with an external diameter of 6 mm.

Integral characteristics of the sources

Conducting channel, argon working gas.

In this test series the discharge channel was made of graphite, with the channel electrically isolated from the anode. The potential of the channel during operation was close to that of the cathode. The tests showed that the source can operate without overheating the discharge channel at a discharge voltage, $U_d \leq 400$ V and argon mass flows, $\dot{m}$ =(0.42÷0.7)mg/s (14-23.6 sccm) . The maximum discharge power, W, was 170÷180 W. Increasing the discharge voltage up to 600 V at the same applied power resulted in the decrease of mass flow to (0.29÷0.40)mg/s (9.8-13.5 sccm).

The integral plasma flow characteristics are given in Figs. 2b and 3b. The volt-ampere characteristics in Fig. 2b are vertical, showing generally efficient operation and good utilization of the working gas.

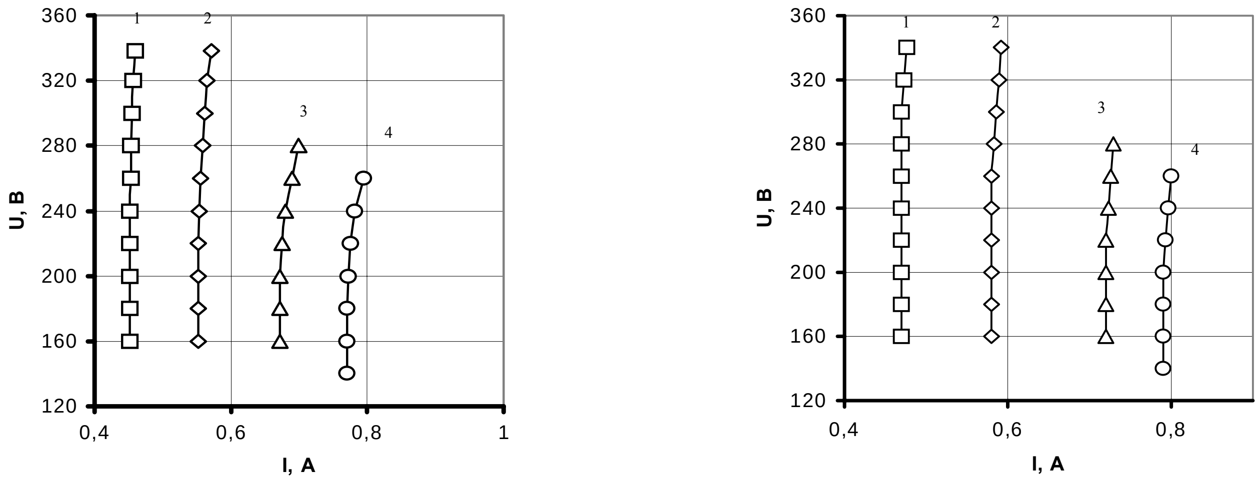

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Fig. 2. Volt-ampere characteristics of the discharge with argon as the working gas: a - dielectric channel (1 - $\dot{m}_a$ = 0.36 mg/s, 2 - $\dot{m}_a$ = 0.44 mg/s, 3 - $\dot{m}_a$ = 0.55 mg/s, 4 - $\dot{m}_a$ = 0.63 mg/s); b - conducting channel (1 - $\dot{m}_a$ = 0.42 mg/s, 2 - $\dot{m}_a$ = 0.51 mg/s, 3 - $\dot{m}_a$ = 0.63 mg/s, 4 - $\dot{m}_a$ = 0.7 mg/s). HF cathode; vacuum chamber pressure, P, was $1*10^{-4}$ Torr.

Dielectric channel, argon working gas.

The integral characteristics of the source with the borosil channel were obtained at discharge voltages, U_d=(160÷320)V, argon mass flows of 0.36÷0.63 mg/s and W < 160 W. These characteristics are shown in Figs. 2a and 3a. The volt-ampere characteristics are again vertical. From the ion beam profiles in Fig. 3, the maximum ion current density is decreased and the divergence is increased for the borosil channel, as compared to that for the graphite channel.

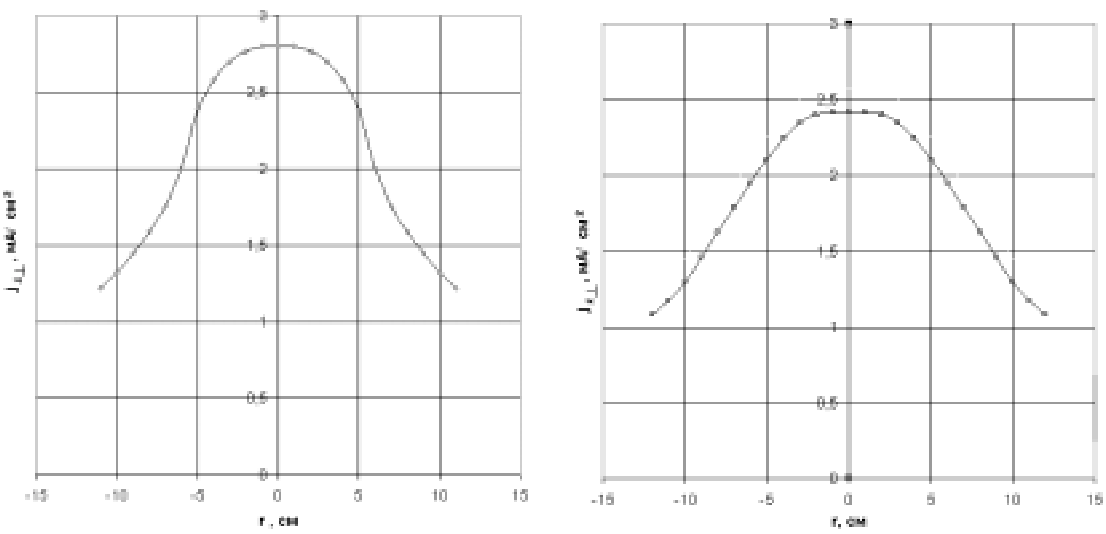

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Fig. 3. Ion beam profiles with argon working gas: a - with dielectric channel and- $\dot{m}_a$ = 0.63 mg/s; b - with conducting channel and- $\dot{m}_a$ = 0.7 mg/s. Both with HF cathode; P = $1*10^{-4}$ Torr, U_d = 200 V, z = 15 cm.

Detailed performance parameters.

A variety of performance parameters are shown in Table 1 for both shannel materials and both working gases. The best comparisons between conducting and dielectric channels are shown for xenon, where most of the parameters are nearly the same. The most significant difference is in discharge current, I_d, where that current is substantially larger for the conducting channel.

Table 1

Working gas	**Ar**	Ar	Xe	Xe
Channel	C	BNC	C	BNC
$\dot{m}$, мг/с	0.29	0.63	0.35	0.3
U_d	600	200	200	200
J_d	0.31	0.77	0.41	0.32
J_i	0.27	0.69	0.24	0.2
J_i/J_d	0.87	0.896	0.58	0.62
J_i/J_m	0.39	0.46	0.92	0.90
$J_p/J\dot{m}$	0.44	0.51	1.58	1.45

The energy distributions of the beam ions using the two channel materials are shown in Fig. 4. The most-probable energy is about 10% lower for the conducting channel.

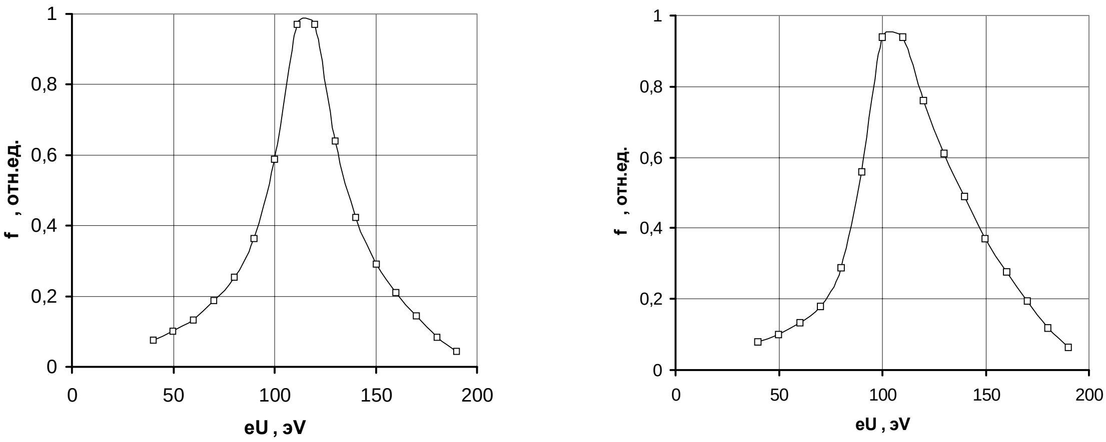

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Fig. 4. Energy distributions of the beam ions with argon as the working gas: a - dielectric channel, $\dot{m}_a = 0.63$ mg/s; b - conducting channel, $\dot{m}_a = 0.49$ mg/s. Both with HF cathode-neutralizer at a vacuum chamber pressure, P, of $1*10^{-4}$ Torr, a discharge voltage, U_d, of 200 V, and at 15 cm from the thruster exit.

Lifetime tests

Life tests with durations of 100 h were carried out using both graphite and borosil channels. After each two hours of operation, the source was turned off for 5÷10 minutes, after which it was restarted. While operating, the operating parameters were held constant at the values given in Table 2.

Table 2

Channel	U_d	J_p	$\dot{m}$
BNC	200	0.77	0.63
C	200	0.79	0.7

The lifetime of the HF cathode-neutralizer was 9÷12 hours. It was replaced when the vacuum chamber was open. The ion source was not cleaned during a life test.The channel_s dimensions and mass were checked before and after the 100 h tests. The following results were obtained during these tests:

External Channel

Material	Width of erosion band,mm	Mean erosion rate, mm/h	Mass, g
BNC	7	0.5	0,057
C	6	1.2	0,110

Internal Channel

Material	Width of erosion band,mm	Mean erosion rate, mm/h	Mass, g
BNC	5÷6	1,7	0,106
C	9	1,6	0,150

Comparing the experimental results with dielectric and graphite channels, the following conclusions can be drawn:
- sources with both channel materials operated stably and reliably in the selected ranges of discharge voltage and anode mass flow at a vacuum-chamber pressure of $1*10^{-4}$ Torr;
- the maximum discharge power without overheating source components was slightly lower with the dielectric channel (160 W) than for the graphite channel (170÷180 W);
- the ion current density on the source axis was 10÷20% higher with the dielectric channel than with the graphite channel for the same discharge current;
- the maximum divergence half-angle with the dielectric channel is slightly less (a/2≈38÷40°) than for the graphite channel (a/2≈40÷42°);
- the mean energy of beam ions was about 10÷15% higher with the dielectric channel than it was for the graphite channel;- the mean erosion rate of the external dielectric channel wall is substantially less than for that of the graphite channel (0.2 versus 1.2 mm/h).

Using the erosion rates measured in the 100 hr tests, a lifetime of about 1000 hr can be projected for either a borosil or a graphite channel. However, measured erosion rates usually decrease substantially with operating time, so that this linear projection can be excessively conservative.

The erosion rates of the inner and outer walls are approximately the same for the graphite channel, but substantially different with the borosil channel. This difference is believed due to graphite being an electrical conductor. Because the graphite is a conductor, its potential must be the same over the entire channel length. The secondary electron emission at electron energies of about 20 eV is absent. There is also no current transmission due to the near-wall conductivity. As shown experimentally, the potential of the graphite channel is close to cathode potential. Such a potential attracts ions and destroys the acceleration of ions along most of the channel length. Due to the symmetry of these processes in the radial direction, the erosion must be about the same for the external and internal walls, and the ion current density upstream of the exit plane must be low.

The situation is different in the dielectric channel. The wall potential varies along the length of the channel. At a sufficiently high electron temperature, secondary electrons are emitted from the external insulator, and the anomalous Debye layers appears [3]. The external wall is charged negatively and repulses ions toward the internal insulator. Due to the orientation of the adiabatic invariant [4], near-wall conductivity doesn_t take place at the inner wall, the Debye layer is the classic one, and there is a symmetry to the observed flow over most of the flow cross section.

Due to the above reasons, erosion on the external and internal walls of a graphite channel will be practically the same. Erosion of the inner and outer walls of a dielectric channel, however, will be quite different. As another result, there will be a difference in the ion beam profiles for graphite and dielectric channels, and a corresponding difference in thruster characteristics.

Thruster characteristics of the sources with xenon.

Dielectric channel.

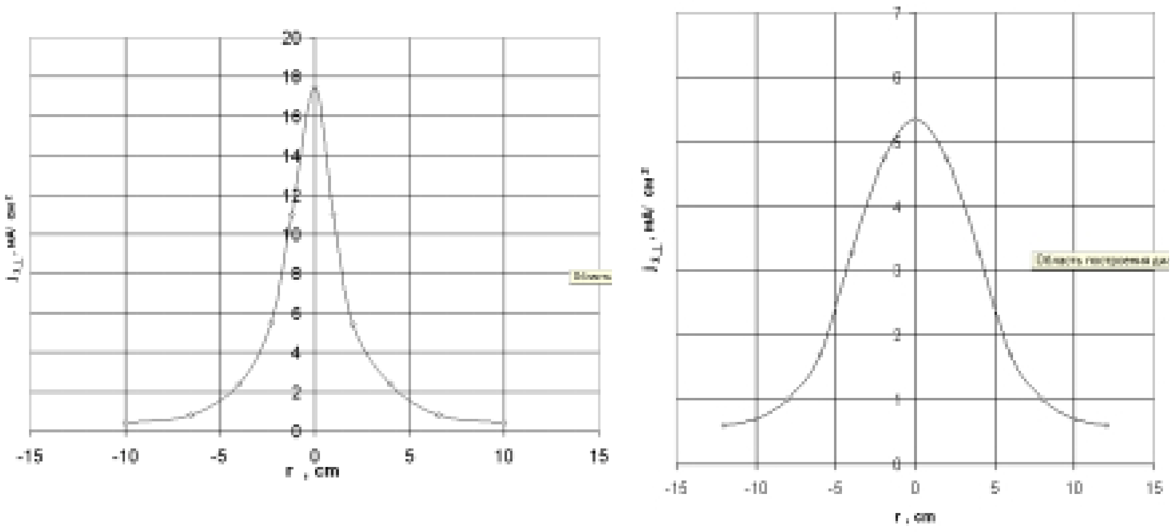

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Fig. 5. Ion beam profiles with xenon as the working gas: a - dielectric channel, ma = 0.54 mg/s; b - conducting channel, ma = 0.7 mg/s. Both with HF cathode-neutralizer at a vacuum chamber pressure, P, of 1x10-4 Torr, a discharge voltage, U_d, of 200 V, and at 15 cm from the thruster exit.

At an applied power, W< 250 W the source operates stably at xenon mass flows of 0.3-0.5 mg/s (3.1-5.1 sccm). Tests were carried out with a hollow cathode (HC) as the cathode-neutralizer and with a xenon mass flow through the HC equal to 0.1 mg/s. The neutralizer mass flow was included in the calculations of thruster efficiency and specific impulse. The ion current profile and the thruster characteristics for this combination are given in Figs. 5a and 6. The mean divergence half-angle was equal to 27°.

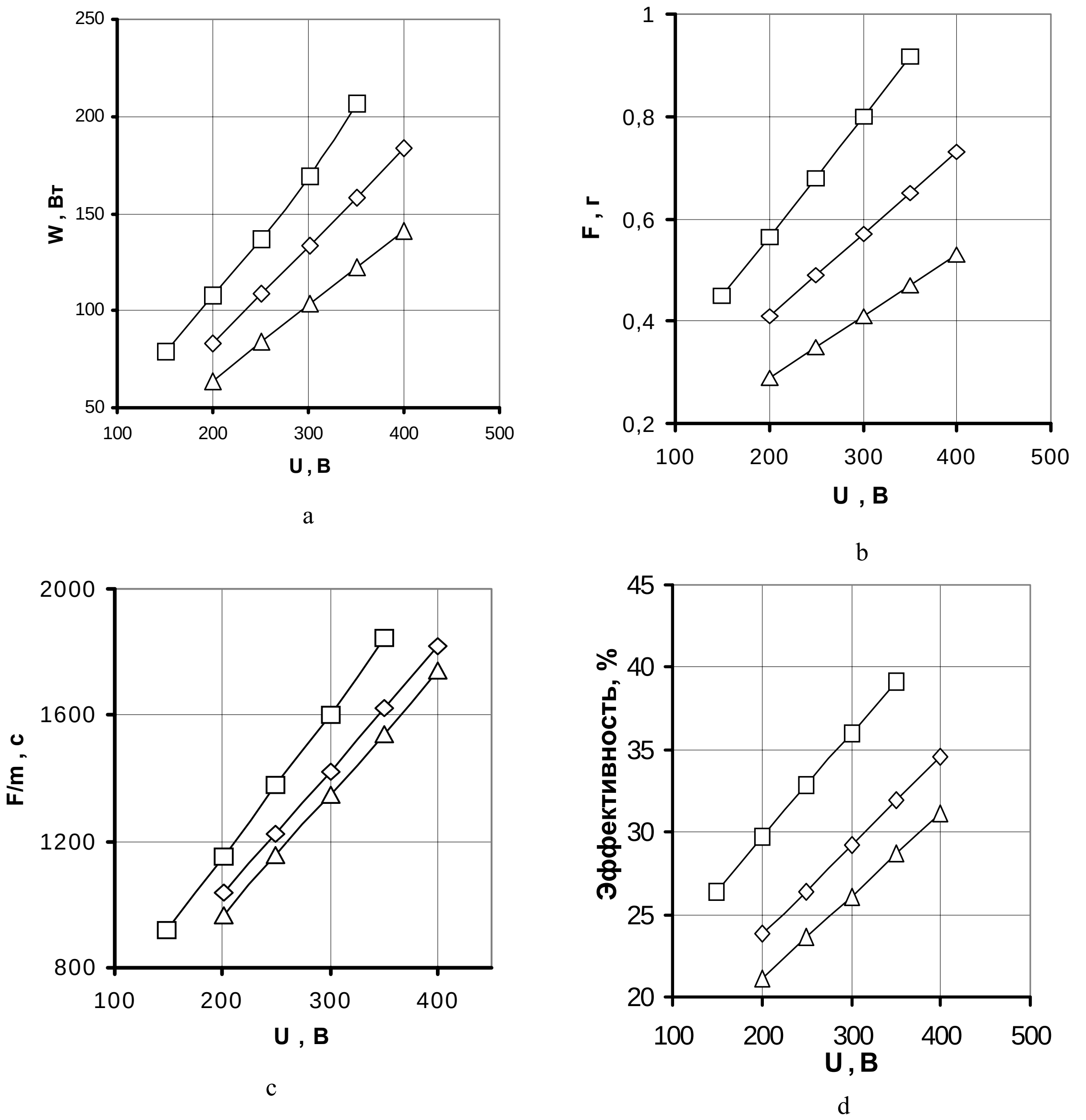

Fig. 6. Integral characteristics of the source with dielectric channel operating on xenon: a - discharge power; b - thrust; c - specific impulse; d - thruster efficiency, all as functions of applied voltage (□ - ma = 0.3 mg/s, ▱- ma = 0.4 mg/s,△ - ma = 0.5 mg/s).

By comparing Fig. 5a with Fig. 3a, one can see that the absolute value of ion current density, ji , is sharply increased with xenon in comparison with the similar result for argon. The volt-ampere characteristics (not shown) were found to be almost vertical. The thruster efficiency with a dielectric channel has a maximum value of 39% at a mass flow of 0.5 mg/s and a discharge voltage of 350 V.

Conducting channel.

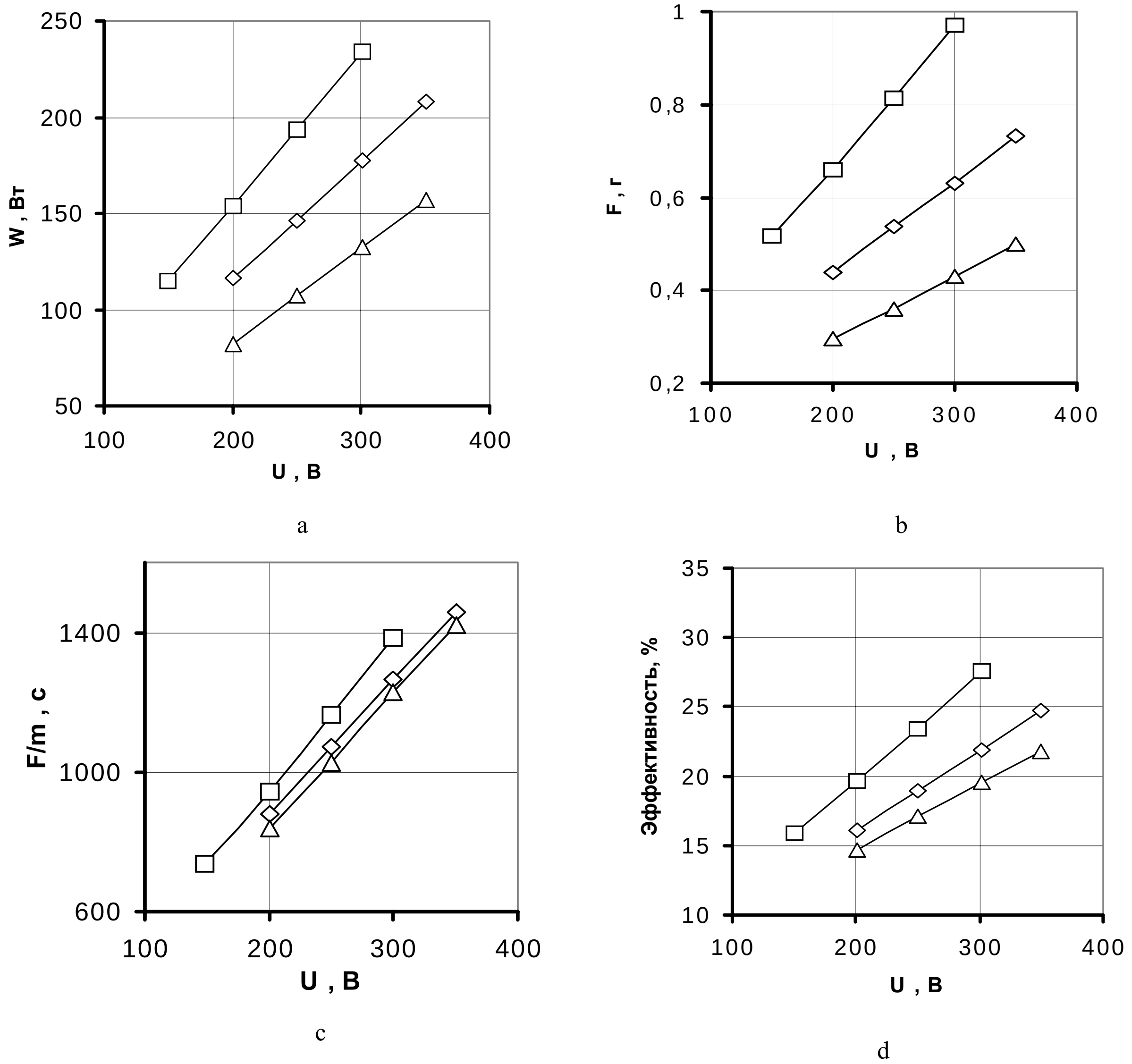

Fig. 7. Integral characteristics of the source with conducting channel operating on xenon: a - discharge power; b - thrust; c - specific impulse; d - thruster efficiency, all as functions of applied voltage (□ - $\dot{m}_a$ = 0.35 mg/s, ◇ - $\dot{m}_a$ = 0.5 mg/s, △ - $\dot{m}_a$ = 0.7 mg/s).

In this case, the xenon mass flow through anode was equal to 0.35÷0.7 mg/s for the range of discharge voltages equal to 150÷350 V. These tests were also carried out with a HC cathode-neutralizer with a xenon flow of 0.1 mg/s. The ion current profile and the thruster characteristics are shown in Fig. 5b and Fig. 7. The volt-ampere characteristics (not shown) were again found to be almost vertical.The thruster efficiency with a graphite channel has a maximum value of 28% at a mass flow of 0.7 mg/s and a discharge voltage of 300 V.

Conclusions

An improved small thruster has been operated with both conducting and dielectric discharge channels. On the basis of 100 hr tests, a conservative lifetime of at least 1000 hr is projected for both channel materials. For the dielectric channel, the thruster efficiency was as high as 39% at a specific impulse of about 1800 sec. The thruster efficiency with the conducting channel was more than 10% less.The decreased efficiency with a conducting channel was attributed to increased wall losses, by mechanisms described in the paper.The superior performance with a dielectric channel confirms once more that the excellent performance of the SPT with dielectric channel walls is dependent on the dielectric properties of those walls.

References

1. Bugrova, A.D. Desiatskov, H.R. Kaufman, V.K. Kharchevnikov, A.I. Morozov, and V.V. Zhurin, U.S. Patent 6,456,011, Sept. 2002. Other patents pending
2. A.I Bugrova, A.D. Desiatskov, H.R. Kaufman, V.K. Kharchevnikov, A.I. Morozov, and V.V. Zhurin, IEPC-02-344, Pasadena, CA, Oct. 14-19, 2001.
3. Reference for anomalous Debye layer.
4. Reference for the adiabatic invariant.