ISSN 1063-7850, Technical Physics Letters, 2014, Vol. 40, No. 1, pp. 81–83. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © A.I. Bugrova, G.E. Bugrov, V.A. Davydov, A.V. Desyatskov, M.V. Kozintseva, A.S. Lipatov, A.A. Safronov, P.G. Smirnov, V.K. Kharchevnikov, M.I. Shaposhnikov, A.V. Pil'nikov, 2014, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2014, Vol. 40, No. 2, pp. 68–74.

Experimental Investigation of a Low-Power Stationary Plasma Thruster

A. I. Bugrova, G. E. Bugrov*, V. A. Davydov, A. V. Desyatskov, M. V. Kozintseva, A. S. Lipatov†, A. A. Safronov, P. G. Smirnov, V. K. Kharchevnikov, M. I. Shaposhnikov, and A. V. Pil'nikov

Moscow State Technical University of Radio Engineering, Electronics, and Automation (MIREA), Moscow, 119454 Russia
Central Research Institute of Machine Building, Korolev, Moscow oblast, 141070 Russia
**e-mail: bugrov@mirea.ru*

Received August 2, 2013

Abstract—Integral characteristics of a laboratory model of the new-generation α-40 stationary plasma thruster (SPT) designed to operate at a total consumed power of 150 W have been studied. Integral parameters of the SPT prototype, including thrust, discharge current, specific impulse, and efficiency, determined on the test stands of MIREA and Fakel Special Design Bureau proved to be virtually identical. At a deposited power of ~150W, discharge voltage of 210 V, and consumption rate of propellant (xenon) of 0.7 mg/s, the thrust reached 9.4 mN, the anodic specific impulse was ~1370 s, and the anode thrust efficiency (with allowance for the power consumed by magnetization coils) was about 41%. In a different regime with a greater thrust (9.7 mN) but lower specific impulse (1240 s) at the same deposited power (~150 W), which was observed at a propellant-consumption rate of 0.8 mg/s and a discharge voltage of 190 V, the efficiency was ~40%. The jet semidivergence angle was ±25°. The predicted SPT service life is 2500 h. The obtained data show that the efficiency of α-40 SPT is higher than that of the known analogs.

DOI: 10.1134/S1063785014010179

Stationary plasma thrusters (SPTs) are now widely used onboard modern spacecraft. In recent years, there was increasing interest in using low-power (below 200 W) SPTs both in Russia [1–5] and abroad [6–9]. This interest is related primarily to active work on developing a new generation of small-scale spacecraft that can be used in solving problems concerning telecommunications and remote sensing of the Earth. The functions of SPTs onboard spacecraft include the orbit correction, maintaining the vehicle on a preset orbit, and retention of a desired spatial orientation.

The creation of modern low-power SPTs proceeds via scaling of classical engines and modifying their magnetic system. The first of these areas is being developed in Russia at the Fakel Special Design Bureau (SDB) in cooperation with the Keldysh Research Center [1, 4]. Work in the second area is being carried out by the Fakel SDB in collaboration with the Research Institute of Applied Mechanics and Electrodynamics [2]. Numerous experimental data that have been reported in the publications cited above showed that the thrust efficiency of classical SPTs decreases with the deposited power and does not exceed 30% at a power of 100–200 W. This is illustrated in Fig. 1, which presents a plot of anode thrust efficiency η_a versus deposited power N for plasma thrusters of the SPD series (SPD-25, 35, 50, 60, 70, and 100) constructed at the Fakel SDB. The first point corresponds to the SPD-25 thruster, and the last one corresponds to the SPD-100 thruster. As can be seen from this plot, the efficiency of SPD-25 is about 30% lower than that of SPD-100.

In developing low-power SPTs, MIREA specialists also used both the scaling approach based on the Malikov–Morozov criterion [10, 11] and the method of magnetic-field optimization patented in 1999

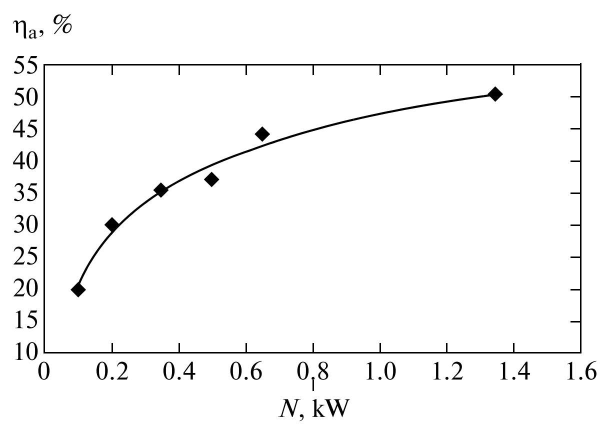

Fig. 1. Plot of thrust efficiency vs. deposited power for plasma thrusters of the SPD series developed at the Fakel SDB.

†Deceased.

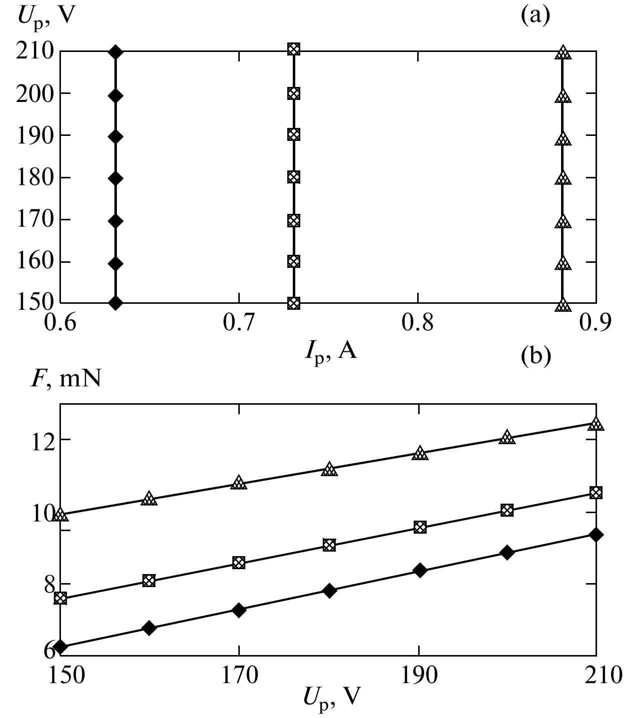

Fig. 2. (a) I–U characteristics of discharge and (b) plots of thrust F vs. discharge voltage U_p for α-40 SPT operating at different values of xenon-consumption rate, $\dot{m}_a = 0.7$ (◆), 0.8 (■), and 0.9 mg/s (▲), as measured on a test stand of the Fakel SDB at a residual pressure of 1×10^{-4} Torr in the vacuum chamber and cathode xenon mass flow rate $\dot{m}_k$ = 0.27 mg/s.

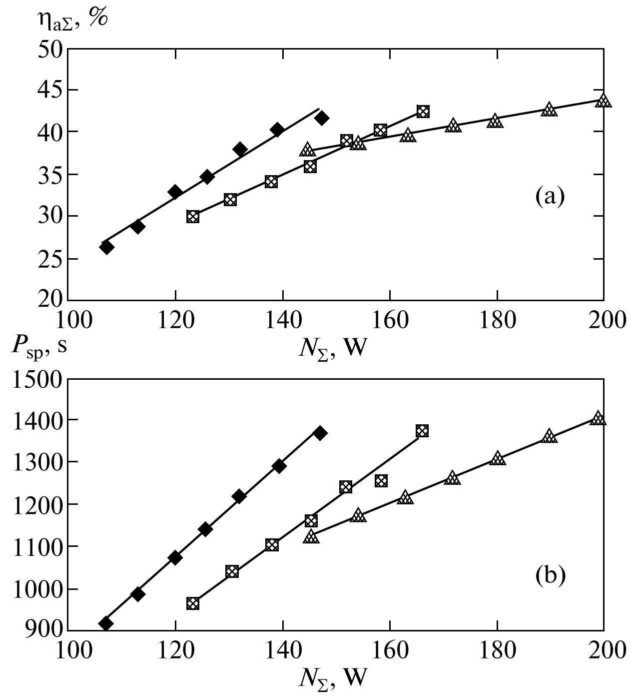

Fig. 3. Plots of (a) thrust efficiency N_Σ and (b) specific impulse P_{sp} vs. total consumed power N_Σ for α-40 SPT prototype operating at different values of the xenon-consumption rate, $\dot{m}_a = 0.7$ (◆), 0.8 (■), and 0.9 mg/s (▲).

[12, 13]. The present work was aimed at experimental assessment of the possibility of increasing the anode thrust efficiency in low-power SPTs by these methods. As a result, a laboratory model of the new-generation α-40 SPT has been designed and constructed. The SPT prototype has a diameter of ~70 mm and a length of ~60 mm. The prototype was studied on test stands in both the MIREA and Fakel SDB. The integral parameters of the SPT prototype obtained in both tests virtually coincided.

The integral parameters of the α-40 SPT prototype were measured on test stands with vacuum chambers evacuated by diffusion pumps. Let us first consider the results of experiments performed on the test stand of the Fakel SDB. The propellant (xenon) consumption rate was varied from 0.7 to 0.9 mg/s at a dynamic pressure not exceeding 1×10^{-4} Torr (for air). The deposited power (with allowance for the power consumed by magnetization coils) was varied from 125 to 200 W.

The current–voltage (I–U) characteristics and thrust developed by the SPT were measured for three values of the anodic xenon mass flow rate, $\dot{m}_a = 0.7$, 0.8, and 0.9 mg/s. The currents in magnetization coils were selected so as to ensure a minimum discharge current. It was found that currents in the internal and external magnetization coils for all $\dot{m}_a$ values are the same, $I_i = I_e = 5$ A. The anode thrust efficiency (with allowance for the total consumed power of the anode unit, $N_\Sigma = N_p + N_k$) and the specific impulse were calculated using well-known formulas.

Figure 2 shows (a) the typical I–U characteristics of discharge and (b) plots of thrust F versus discharge voltage for three values of the propellant consumption rate indicated above. As can be seen from Fig. 2a, the I–U plots of discharge for all $\dot{m}_a$ values represent almost vertical lines, which is evidence of a good degree of ionization of xenon atoms. The thrust and specific impulse exhibit linear growth with increasing discharge voltage. The maximum values of thrust at $U_p = 210$ V were 9.4, 10.6, and 12.5 mN for $\dot{m}_a = 0.7$, 0.8, and 0.9 mg/s, respectively. The corresponding values of specific impulse at this voltage were 1370, 1380, and 1410 s, while the thrust efficiency reached 43.8% at $\dot{m}_a = 0.9$ mg/s. However, the power consumed by the SPT in this regime exceeded 150 W. This can be seen from Fig. 3, which presents plots of total thrust efficiency N_Σ and specific impulse P_{sp} versus total consumed power N_Σ. Figure 3 shows that, at a xenon-consumption rate of $\dot{m}_a = 0.7$ mg/s and a discharge voltage of 210 V, the total power does not exceed 150 W, the efficiency is ≥41%, the specific impulse reaches P_{sp} = 1370 s, and the thrust is 9.4 mN. A different regime with N_Σ =150 W at $\dot{m}_a$ = 0.8 mg/s and U_p = 190 V is characterized by efficiency $\eta \approx 40\%$, P_{sp} = 1250 s, and F = 9.7 mN.

One important characteristic of SPTs is the output jet divergence, which is characterized by a solid angle in which 90% of a directed ion flow propagates. For classical thrusters of the M-70 and SPD-100 types, the semidivergence angle amounts to ±45°.

In order to determine the jet divergence in the α-40 SPT model, we have measured the profiles of directed ion current to a double probe. Processing of these profiles gave a semidivergence angle of ±25°, which is significantly smaller than in classical thrusters. A decrease in the jet divergence in thrusters of the ATON type (to which the α-40 SPT belongs) is explained by a shift of the center of gravity of the ionization region in the depth of the channel. This is achieved due to a buffer volume, which ensures isotropization of the flux of neutral atoms and creates a focusing geometry of magnetic-field lines in the channel. It should be noted that a decrease in the jet divergence angle may be accompanied by an increase in the width of erosion belts in both external and internal channels of the discharge channel. This implies the possible influence of jet divergence on the thruster service life.

According to criteria formulated at the Fakel SDB, the thruster service life is determined by the time of continuous operation upon which the thickness of insulators at the thruster output edge decreases to zero. In order to evaluate the insulator wall thickness, it is necessary to determine the rate of erosion in the radial direction at the edge. For this purpose, we have performed short-term tests on an α-40 SPT prototype operating at U_p = 210 V, $\dot{m}_a$ = 0.7 mg/s, and N_Σ = 150 W for 50 h. These experiments showed that the average rates of erosion at the edge of α-40 were 3 μm/h on the internal wall and 2.25 μm/h on the external wall. According to these data, the ceramic layer thickness for a thruster service life of 2500 h must amount to 2.9 and 2.2 mm for the internal and external wall, respectively.

Thus, the obtained experimental data show that the efficiency and predicted service life of a low-power α-40 SPT developed at the MIREA are better in comparison to the parameters of known analogs.

Acknowledgments. This study was supported in part by the Ministry of Education and Science of the Russian Federation within the framework of the federal targeted program "Scientific and Pedagogical Personnel for Innovative Russia (2009–2013)," project no. 14.B37.21.1840.

REFERENCES

1. O. A. Gorshkov, V. A. Muravlev, and A. A. Shagaida, in *Hall and Ion Plasma Thrusters for Spacecrafts*, Ed. by A. S. Koroteev (Mashinostroenie, Moscow, 2008) [in Russian].
2. K. N. Kozubskii, V. M. Murashko, Yu. P. Rylov, Yu. V. Trifonov, V. P. Khodnenko, V. Kim, G. A. Popov, and V. A. Obukhov, Plasma Phys. Rep. **29**, 251 (2003).
3. G. E. Bugrov, A. V. Desyatskov, M. V. Kozintseva, and A. S. Lipatov, Kosmonavt. Raketostroen. **3**, 69 (2008).
4. M. B. Belikov, O. A. Gorshkov, E. N. Dyshlyuk, et al., Kosmonavt. Raketostroen. **3**, 131 (2008).
5. A. I. Bugrova, A. V. Desiatskov, H. R. Kaufman, et al., *Proceedings of the 27th Intern. Electric Propulsion Conf. (IEPC-2001)*, p. 344.
6. J. Polk, *Proceedings of the 30th Intern. Electric Propulsion Conf. (IEPC-2007)*, p. 368.
7. K. A. Polzin, T. E. Markusie, B. J. Stanoev, et al., *Proceedings of the 29th Intern. Electric Propulsion Conf. (IEPC-2005)*, p. 011.
8. L. Biagioni, U. Cesari, and M. Saverdi, *Proceedings of the 41st AIAA Joint Propulsion Conf. (AIAA-2005)*, p. 3875.
9. H. Tahara, T. Fujioka, T. Kitano, et al., 28th International Electronic Propulsion Conference, 2003, IEPC-2003-015.
10. A. I. Bugrova, N. A. Maslennikov, and A. I. Morozov, Sov. Phys. Tech. Phys. **36**, 612 (1991).
11. A. I. Bugrova, A. V. Desyatskov, A. S. Lipatov, A. S. Sigov, A. I. Koryakin, V. M. Murashko, and A. N. Nesterenko, Plasma Phys. Rep. **36**, 365 (2010).
12. A. I. Bugrova, A. I. Morozov, N. N. Evtikhiev, et al., Plasma Thruster with Closed Electron Drift, RF Patent No. 2139647 (1999).
13. A. I. Bugrova, A. S. Lipatov, A. I. Morozov, and S. V. Baranov, Tech. Phys. Lett. **31**, 943 (2005).

Translated by P. Pozdeev