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Dynamics of ions in the plume of the stationary plasma thruster operating with Krypton

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Received November 7, 2022
Revised December 2, 2022
Accepted December 2, 2022

The results of the spatial accelerated ion flow density distribution and of the mean energy of ions exhausting thruster and moving in the different directions in the plume of the stationary plasma thruster operating with Krypton of the experimental SPT model of new scheme operating with Krypton are presented in the given paper. There are also presented the results of the directed radial and „back" ion flows in the vicinity of the mentioned SPT experimental model.

Keywords: Stationary Plasma Thruster, gas discharge, crossed electric and magnetic fields, propellant flow ionization and accleration, plume divergence, radial and „back"ion flows.

DOI: 10.21883/TPL.2023.02.55364.19416

Morozov stationary plasma thrusters (SPTs) are the most widely used electric thrusters in current space technology, and their range of application is extending even [1]. While the majority of earlier flight models of SPTs used xenon as a propellant, krypton thrusters of this kind have also been constructed and applied in recent years, since krypton is considerably cheaper than xenon and is produced in significantly greater amounts. The transition to krypton helps solve the problem of of large amounts of propellant supply needed for propulsion systems of certain spacecraft (such as the Starlink constellation that consists of several thousands of satellites [2]). In view of the above, research and development works on new krypton SPTs have intensified. Studies of processes in jets of such thrusters are of academic and applied importance: they allow one to examine the efficiency of ionization of propellant particles in an SPT discharge, the formation of accelerated ion flows, and the evolution of secondary processes in jets [3,4]. In the present study, we report the results of investigation of spatial distributions of the plasma parameters and accelerated ion flows in the jet of an experimental krypton SPT-70V thruster model of a new design (with an external accelerating channel diameter of 70 mm and an acceleration zone, within which the greater part of the potential drop is localized, shifted out of the working channel) and „radial" and „back" ion flows and parameters of plasma in the vicinity of the indicated SPT model.

The ionization of a propellant flow and the acceleration of produced ions in an SPT are made in plasma of an electric discharge with predominantly longitudinal electric and predominantly radial magnetic (crossed) fields. It is difficult to focus accelerated ions in an SPT discharge, since the distribution of the electric field, which governs the motion of ions, in this discharge is hard to control due to the presence of a great number of complex and insufficiently studied influencing processes. Therefore, accelerated flows of ions from SPTs normally have a significant divergence. This causes certain problems related to the unwanted influence of a thruster jet on the structural elements of spacecraft. In view of the above, the examination of the spatial distribution of a flow of accelerated ions and their energy characteristics in the jet of a krypton SPT-70V thruster model was set as one of the goals of the present study. Such data enable one to estimate the influence of the operating thruster jet on structural elements of spacecraft, the influence of incompleteness of the atom flow into ions conversion and the application of a discharge voltage on the acceleration of ions, as well as of the jet divergence, and the velocity spread of ions on thruster efficiency [3,4]. Another goal was to examine the motion directions of ions emerging outside the channel near the exhaust ends of the discharge chamber walls at the boundaries of the primary flow and forming „radial" flows of ions with fairly high energies [3,4] and „back" ion flows. The latter flows are induced in a jet by secondary processes. The key process of this kind is the charge exchange of accelerated ions with neutral atoms that are almost always present in a jet due to the incompleteness of conversion of an atom flows into ion flow in the primary discharge and also enter a jet from the cathode. Recharged ions have low energies and move in the jet plasma under the influence of an electric field formed by plasma density gradients. They move primarily in radial and „back" (opposite to the acceleration) directions, capture electrons, and form a plasma „near-spacecraft" environment that may alter the potential of structural elements of spacecraft contacting with it when a thruster is working and affect the operation of certain instruments.

Just as in [3], the first of the indicated goals was achieved by measuring the current density and energy of accelerated ions with an electrostatic energy analyzer; the plasma parameters were determined using a cylindrical electrostatic probe. The model SPT was positioned in these measurements on the axis of a horizontal vacuum chamber with an internal diameter of 2 m and a working length up to 6 m evacuatedby cryogenic high-vacuum and „dry" other vacuum pumps. The axis of the model was aligned with the chamber axis. Probes could be moved in a controlled manner within the jet of the working model in the horizontal plane (containing the axis of the thruster model) along a circle 0.7 m in radius with its center at the intersection between the indicated axis and the exhaust plane of the working channel. In order to determine the distribution of the current density of accelerated ions over off-axes angle β deviation of measurement directions from the model axis, the energy analyzer was moved with a constant rate within the range of angles β from -90 to $+90°$. A positive bias of $+30$ V was applied to the analyzing grid relative to the screen grid of the energy analyzer and the vacuum chamber to block off „slow" ions from plasma. Integrating the obtained current density distribution over the hemisphere into which the jet is ejected, we estimated the divergence of the flow of accelerated ions and the net current of ions outflowing from the model [3]. In order to determine plasma parameters and the energy distribution function of ions, probes were stopped at different positions within the jet in steps of 10° of the angle of deviation of measurement directions from the SPT model axis. Voltage-current curves (VCCs) of the cylindrical probe were determined in each position, and „retarding curves" of the the energy analyzer were recorded by applying 20 cycles of rippling voltage, which decelerated ions, to the analyzing grid with the probe collector current registered at each value of voltage at the grid. Differentiating these „retarding curves," we obtained the energy distribution function of ions, which could then be used to determine the mean energy of ions at a given angle of deviation of measurement directions from the SPT model axis.

To achieve the second goal, we used a planar probe, which could be rotated in a controlled manner around the vertical axis, with a normal that moved in the horizontal plane containing the thruster axis in the process of rotation. The probe was mounted on a two-axis positioning device in the vicinity of the working channel exhaust plane (hereinafter referred to as the exhaust plane). Stopping the rotation of this probe, we could determine its VCC and radial and longitudinal components of directed ion current $J_{iz} = J_{iz+} - J_{iz-}$ and $J_{ir} = J_{ir+} - J_{ir-}$ that specify directed ion current vector $\mathbf{J}_i(J_{iz}, J_{ir})$, where J_{iz+}, J_{iz-}, and J_{ir+}, J_{ir-} are the values of ion current to the probe in the direction of acceleration of the primary flow ($z+$), in the opposite direction ($z-$), away from the thruster model ($r+$), and to the model ($r-$). Measurements were performed in the horizontal plane containing the thruster axis at several points on the lines of their intersection with three planes perpendicular to this axis: the first one was the thruster exhaust plane, the second one was shifted by

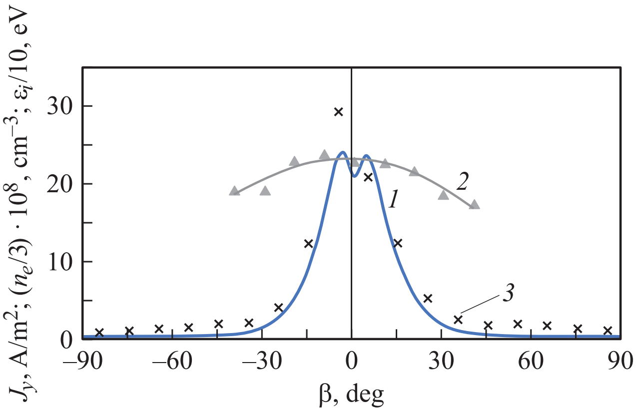

Figure 1. Distributions of current density J_y of accelerated ions (*1*), mean ion energy ε_i (*2*), and plasma density n_e (*3*) over the angle of deviation of measurement directions from the model axis.

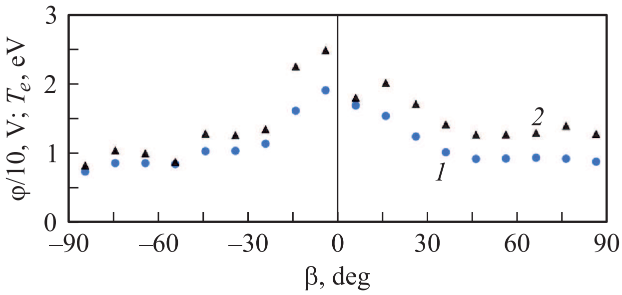

Figure 2. Distributions of plasma potential φ (*1*) and electron temperature T_e (*2*) over the angle of the measurement directions deviation from the thruster model axis.

10 cm in the $z+$ direction, and the third one was shifted by 10 cm in the $z-$ direction. The probe VCCs, which allowed us to estimate the plasma parameters and ion currents to the probe in the above-indicated four orientations of the receiving probe surface, were determined at each measurement point.

All measurement results reported in the present study were obtained in experiments with the krypton SPT-70V thruster model operated with a discharge voltage of 300 V and a discharge current of 4.5 A. The thrust efficiency (ratio of the kinetic power of the exhaust jet, which is calculated based on the measured jet thrust of the model and the mass flow of krypton through the model, to the discharge power) was $40 \pm 3\%$. The potential of the model body relative to the vacuum chamber was not measured in our experiments; in steady-state operation regimes of a krypton SPT, it normally deviates by no more than ± 10 V from the cathode potential, which was $-(15-20)$ V. Thus, the potential could assume values within the range from -5 to -30 V. According to our estimates, this had no effect on the results of measurements, since the plasma density was sufficiently high, the Debye radius and the depth of penetration of the potential of a negatively charged surface into the bulk of plasma were small, and the exterior

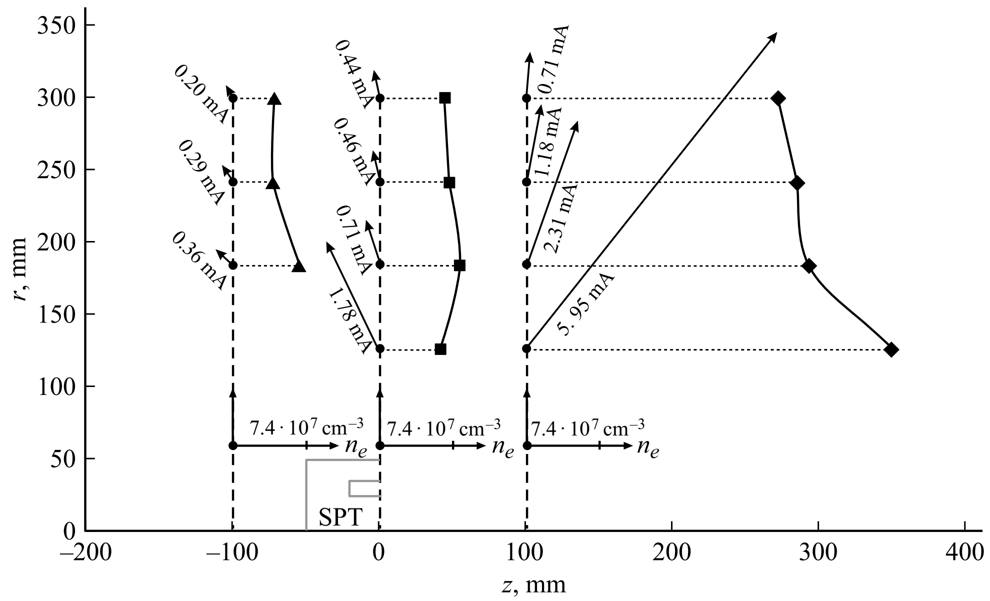

Figure 3. Fields of directed ion currents (arrows) and plasma density (points) in the vicinity of the working krypton SPT-70V thruster model.

surface of the model body was small relative to the plasma formation.

The most intriguing results obtained in the study are presented in Figs. 1–3. They indicate that the distributions of plasma parameters and the current density of accelerated ions in the jet of the SPT-70V model are similar to the ones determined for xenon thrusters (Figs. 1, 2). However, the jet divergence half-angle was approximately 58° and exceeded considerably the value corresponding to a commercial xenon SPT-100 thruster (around 45°) [3]. The ratio of the net current of ions outflowing from the thruster (determined using the measurement data) to the „consumption" current calculated based on the flow of krypton atoms through the working channel of the model under the assumption of their complete conversion into singly charged ions was approximately equal to 0.7. This value is lower than the one for SPT-100 [3]. The mean energies of accelerated ions at angles of deviation of measurement directions from the axis up to 40° were 200–240 eV (Fig. 1), which is close to the energies determined for SPT-100 [3].

The mentioned discrepancies between the data for the SPT-70V model and the SPT-100 thruster are attributable to the differences in design and size of thrusters and in atomic masses and ionization parameters of krypton and xenon. These differences also explain why the thrust efficiency of the krypton SPD-70V model is lower.

Comparing the distributions of current density of accelerated ions and plasma density (Fig. 1), one finds that they remain similar in nature at angles of deviation of measurement directions from the axis up to $\sim 20°$; i.e., accelerated ions produce the dominant contribution to the plasma density in the jet at these angles.

The results of identification of directed ion currents in the vicinity of the SPT-70V model (Fig. 3) reveal clearly the presence of fairly significant „radial" and „back" ion flows. As was already noted, the charge exchange of accelerated ions with neutral atoms is the most probable source of „back" ion flows [4].

Thus, new data on the jet characteristics, which include the first measured fields of „radial" and „back" directedl ion currents, of the novel krypton SPT-70V model were obtained. These data should be of value in further analysis of physical specifics of SPT operation.

Funding

This study was supported financially by the Ministry of Science and Higher Education of the Russian Federation (grant No. 075-15-2021-301 dated April 19, 2021).

Conflict of interest

The authors declare that they have no conflict of interest.

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