PERFORMANCE STUDY OF HIGH POWER ABLATIVE PULSED PLASMA THRUSTER

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Abstract

Pulsed plasma thrusters (PPT) are high $I_p$ propulsion systems, that provides repeatable, discrete impulse bits. Firstly tested on Zond-2 spacecraft in 1964 PPTs have a successful heritage. High power ablative PPT (APPT) are the effective devices to transfer the power source energy to kinetic energy of plasma flow, having an average velocity up to $10^3 \text{cm/s}$. A study to increase the efficiency of very high power, coaxial geometry APPT, working in electro-dynamic mode of operation was done. The optimisations of the thruster were performed up to the discharge power of $10^6 \text{W}$. Capacitor bank have $85 \mu \text{F}$, the inductance of the outer electrical loop $10^3 \text{H}$. Maximal initial capacitor bank voltage is $15 \text{kV}$. More than 50% of energy stored in capacitor bank is transferred to kinetic energy of plasma directed flow. It is shown that plasma acceleration take place mainly within 1-2 cm from insulator surface. Then at the channel output, the plasma flow is formed with dimension significantly less than outer electrode diameter. Maximal obtained electron density is $10^{16} \text{cm}^{-3}$. Late time ablation arises at the end of first half-period of discharge current. Estimated from interferometric measurements late time ablated mass is 30% of total mass ablated in single discharge.

Introduction

The Pulsed Plasma Thruster is a well known electric propulsion device that was the first one placed to spacecraft Zond-2 more than 30 years ago. PPTs have a successful spaceflight heritage and has exhibited a renewed interest for use in satellite station keeping, drag makeup, and orbit raising largely because of its simplicity and robustness. Main space PPT applications deal with thrusters having capacitor up to 100 J. One can discuss bank energy up to 1000 J for space applications. Higher energy PPTs have applications in technology fields. Such high energy and high discharge power devices, work usually in electro-dynamic mode of operation. This acceleration mechanism allows for high efficient power source energy transfer to plasma directed motion energy. Efficiency of working process in these is a desirable example for conventional PPT. Acceleration of the plasma produced as a result of pulsed evaporation of a solid propellant, when a high current discharge is initiated along its surface, is its distinctive feature of PPT. The similar technique automatically provided the matching of a propellant feed with the APPT parameters and allows one to produce a relatively-effective plasma acceleration. An opportunity to precisely adjust the plasma impulse, practically-instantaneous readiness, absence of some commutational facilities and fast-responsive valves for the propellant feed into the APPT - accelerating channel, storage of the working substance in a compact form etc. are advantages of such thrusters.

The main scientific problem in PPT modelling is the lack of full understanding of the process of energy transfer from discharge to solid propellants and mass ablating. In the ablative PPT the mass-flow rate depends on discharge characteristics in the accelerating channel. This makes impossible the development of self consistent numerical model without careful account of propellant behavior. For this reason, low energy (~100 J) PPTs have not yet performed at efficiencies higher than 16% and it is not clear how to increase this significantly. High power PPTs have limits in $I_p$. Because of the projected use of PPTs it is important to further investigate physical processes and develop a predictive ability that will determine the potential for future applications. Numerical simulation and experiments have found the effect of late-time ablation from the Teflon surface. This is the main contributor to the ablated mass difference with accelerated mass. The late-time ablated particles just evaporate from the Teflon surface and are accelerated gas-dynamically along the accelerating channel. Evidently, this neutral flow represents an inefficiency and results in a reduced effective specific impulse. The understanding of mass flow rate dependencies will lead to ways of improving PPT performance.

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In this paper we present the experiments on dependencies of integral parameters of the high power PPT-geometry and on the parameters of a power supply source to explain physics of discharge and allow one to improve thruster parameters. The results of experiments on energy flux transferred to insulator and near insulator interferometric measurements also presented and discussed.

**Test facility. Thruster Performance**

High power APPT have two copper coaxial electrodes with radii $R_1=2$ cm, $R_2=10$ spaced with Teflon insulator (Figure 1). The outer electrode is fabricated as a truncated cone, which small diameter is equal 8 cm. Length of electrodes of the accelerating channel is equal 10 cm. The thruster is located in the vacuum chamber, the pressure in which is $5 \times 10^{-5}$ mm Hg. Low inductive capacitor bank of 85 µF is charged up to 15 kV. Bank initial voltage is changed in a range 0-25 kV. Maximal charge voltage in this geometry is determined by surface breakdown electric field for Teflon with is equal 22 kV/cm. Maximal field $E_{max}$ should not exceed

$$E_{max} = \frac{V_0}{\ln \frac{R_2}{R_1}} \approx 16 \text{ kV/cm.}$$

Total initial inductance consisting of bank inductance, feeder one, and initial inductance of the accelerating channel, not exceed 10 nH. Electric discharge is initiated on the surface of working insulator by a small energy auxiliary spark. Initial plasma through the holes get in the accelerating channel and initiate the main discharge. A flow of energy from area of the discharge expose the surface of working insulator, that results in its ablation. Evaporated substance is heated up, ionised and accelerated along electrodes producing plasma flow. Photo of plasma flow is shown in Figure 2.

The interaction between this magnetic field and the charged particles in the plasma, the $j \times B$ interaction known as the Lorentz force, accelerates the plasma, producing plasma flow and thrust. Distribution of a current in the discharge have not axial symmetry. In the beginning current flows in the narrow channel, which then extends and fills in a significant part of space between electrodes.

![Figure 1. Schematic of High power APPT](image1)

![Figure 2. Photograph of plasma flowing from high power PPT. Image is posterised.](image2)

The dependences of a current, voltage on electrodes and energy transferred to discharge from the power supply are shown in Figure 3. The current reaches the maximal value $I_{max} = 507$ kA ($V_0 = 15$ kV) at the time $t = 2$ μc. To the time $t = 3$ μs the most part of energy from the power supply is transferred to the discharge. Ratio of the effective active resistance to wave one in the given model was equal $R_{eff}/\rho = 1 - 2$. Here $R_{eff}$ and $\rho$ - are average for the impulse active and wave resistances of the discharge. This mode of operation corresponds to the greatest power which is transferred by the power supply to plasma acceleration ($=5 \times 10^7$ W). During the discharge about 85% of bank energy is transferred to PPT. The selection of mode of operation of the PPT is carried out by a choice of capacitance, initial inductance $L_0$, and also length of working insulator $l_m$. 
Figure 3. Discharge current I, voltage on the electrodes V and energy transferred to the discharge W ($V_0 = 15$ kV, $C_0 = 85$ μF).

Output parameters of the APPT are shown in Table 1. There: $V_0$ - voltage on capacitor bank, $W_0 = C_0V_0^2/2$ - energy, stored in the bank, $m_0$ - mass ablated per pulse (is measured by weighing of insulator), $\eta_t = P/2m_0W_0$ - thrust efficiency, $P$ - impulse bit, $\eta_a = Q/W_0$ - thermal efficiency, $Q$ - total energy of plasma flow, measured out of the accelerating channel, $v_{av} = P/m_0$ - average velocity of plasma flow. It is of interest to compare parameters of the thruster working in a mode with low stored energy < 1000 J, with the considered APPT (10 kJ and higher). As it is visible from Table 1, thrust efficiency and average velocity of plasma flow is a little bit higher, than at 1000 J. Thus, velocity, thrust efficiency, ablated mass rise with increase of stored energy. In our case $\eta_t = 0.47-0.53$, i.e. is close to the thrust efficiency at energy ~ 1000 J.

The analysis of experimental data shows (see Figure 4), that about 15 % of energy is lost in the power supply; it - basically, loss in capacitors, and also loss in busbars and contacts. Main part of energy originally stored in the power supply is transferred in the APPT. Approximately 7-8 % of energy is lost in the electrodes and less than 1 % is spent on evaporation of working insulator. The energy contained in a plasma flow is 70 - 80 % from energy in the power supply.

Table 1. APPT Parameters

<table>
<thead>
<tr>
<th>$V_{in}$, kV</th>
<th>$W_{in}$, kJ</th>
<th>$m_{in}$, mg</th>
<th>$\eta_t$ %</th>
<th>$P$, N.s</th>
<th>$\eta_a$ %</th>
<th>$v_{av}$, km/s</th>
</tr>
</thead>
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<td>10</td>
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<td>2</td>
<td>0.47</td>
<td>9.2 $10^{-2}$</td>
<td>0.68</td>
<td>60</td>
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<tr>
<td>15</td>
<td>9.6</td>
<td>3.8</td>
<td>0.53</td>
<td>0.2</td>
<td>0.70</td>
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</tr>
<tr>
<td>1.75</td>
<td>1.13</td>
<td>0.84</td>
<td>0.38</td>
<td>0.027</td>
<td>0.6</td>
<td>32</td>
</tr>
</tbody>
</table>

Figure 4. Energy sinks in the thruster.

Plasma flow characteristics

After triggering for a few tens on nanoseconds the main discharge resistance decreases to 0.1-1 mOhm. Then the discharge current in the plasma source circuit is determined by the wave impedance of the power supply and by the resistance related with the plasma acceleration. As a rule, the electric surface breakdown in a vacuum (P<10^{-3} Torr) is realized in the form of a thin channel that expand with a thermal velocity corresponding to the plasma temperature (~3 eV). The focused pulsed plasma flow is formed at the accelerating channel outlet. The outlet velocity of a plasma flow was measured in several ways. First, average velocity was determined from a ratio $v_{av1} = P/m_0$. These estimations decrease average velocity of a flow, as effectively accelerated mass is appreciably less $m_0$. It is explained, in particular, that the insulator continues to evaporate after ending of the energy flow from discharge. Average velocity of plasma appreciated from the ratio $v_{av2} = 2Q/P$ a little bit higher than $v_{av1}$. Secondly, the velocity of a flow was calculated from Doppler broadening of lines FII ($\lambda = 4225$ Å) and CII ($\lambda = 4267$ Å), on shift of maxima of signals with piezoelectric probe and electrical probes. All these methods of measurement of plasma velocity with average atomic weight $\Lambda = 16$ (Teflon) give $v_{av} = 7-9$ 10^2 cm/s. Velocity of a flow front in this case makes $v_f = 2 \times 10^7$ cm/s. If polythene is used as working insulator, average velocity $v_{av}$ grows up to 2 10^7 cm/s.
Plasma acceleration take place mainly within 1-2 cm from insulator surface. The measurements have shown that the distribution of accelerated mass with respect to the plasma particle velocities during the first current half-period is rather compact: at $W_0 > 5 \text{kJ}$, the average plasma velocity is $(7-9) \times 10^6 \text{cm/s}$. The interferometric measurements show that the plasma acceleration is actually a 2-dimensional one and the plasma flow with the minimal diameter close to the diameter of a central electrode is formed at the output of the acceleration channel. The maximal electron density in a plasma flow is $10^{16} \text{cm}^{-3}$ (at the distance of 4 cm from the output). Minimal diameter of a flow is realised at a distance 2-3 cm from the thruster outlet. Than flow expands with a velocity approximately corresponding to the plasma temperature of about 3 eV.

**Mass Ablation. Teflon Behaviour**

The total mass of a substance evaporating from the insulator surface during the whole process was measured by weighting the insulator with the accuracy of about 10%. The measurement was done at various facilities. In this case, the bank capacity, energy, insulator length ($l_{\text{ins}} = R_{1} - R_{2}$), power supply source inductance were varied. Ablating mass is approximately proportional to the power supply source energy at the energies greater than a 2 kJ and depends on inter-electrode gap (insulator length). In Figure 5 the dependence of an ablating mass on insulator length is shown.

![Figure 5. Dependence of an ablating mass on the insulator length.](image)

**Measurements of the Energy Flux Density Released on the Insulator Surface**

The density of the energy flux released upon the insulator surface in the APPT was measured with a thermal probe [4]. The thermal probe (Figure 6) was installed inside the insulator so that its sensitive element - thin platinum foil heated up to about 1300°C - was located at about the insulator level. When the energy is released in the foil, its temperature is increased. A change in the intrinsic foil radiation - related with a change in its temperature - was registered with a photomultiplier (PM). The time resolution of the thermal probe is determined by the foil thickness. The thermal probe time resolution of about 0.4 µs and sensitivity about $10^{-3} \text{J}$ were realised.

![Figure 6. Principle of the thermal probe.](image)

Some typical time dependencies of the energy registered with the thermal probe, energy flux density, as well as those of the discharge current in the facility, are given in Figure 7. The thermal probe measurements were checked by the measurements of the total energy released upon the insulator surface, made with the microcalorimeter pressed within the insulator.

Analyzing the measurement results of the energy flux to the insulator in the APPT, one can make the following conclusions:
- the energy fraction released from discharge zone onto the insulator surface is $\sim 10^{-2} - 10^{-3}$ of the energy initially-stored in the power supply source.
- the energy is released upon the insulator surface, practically during the whole process of plasma acceleration. From this it follows that the insulator ablation should also occur during the whole process. This conclusion is confirmed by interferometric measurements of the plasma density near the insulator surface.
- the energy flux density to the insulator is changed in the range $10^6 - 10^8 \text{W/cm}^2$, when the thruster power is varied in the range $10^7 - 10^9 \text{W}$. One should note that the density of an energy flux to the insulator surface is proportional, within a rather good
accuracy, to the instantaneous discharge power. The dependence of the ablated insulator mass ratio to the power supply source energy is given in Figure 8. At high power source energy this parameter tends to 0.1 μg/J.

![Figure 7. Dependencies of the energy registered with a thermal probe E, energy flux density upon the thermal probe foil, H, and the discharge current, I on time.](image)

If one doesn’t undertake some special measures, the electric breakdown across the insulator surface in the majority of APPT’s and, then, the electric discharge in the acceleration channel turn out to be azimuthally-asymmetric. However, if one initiates the electric breakdown in many places upon the insulator surface the current distribution in the thruster channel turn out to be rather symmetric. In this case, one can measure the dependence of an propellant flow rate on the radius, m(R). If one excludes the places in the vicinity to the electrodes from consideration, it will turn out that m ~ 1/R, i.e. this dependence is similar to the current density distribution in the near insulator area.

![Figure 8. Dependence of the ratio between the ablated mass and the power supply source energy on power supply source energy.](image)

**Late-Time Ablation in Single Pulse APPT**

The late-time ablation or after-ablating effect which is observed in operation of APPT usually can result because of elevated Teflon surface temperatures. Evidently, the late-time ablated particles results in a reduced effective specific impulse and thrust efficiency. In single pulse operation of APPT under consideration evaporated mass exceeds accelerated mass about 30-40%. This confirm the assumption about evaporation of Teflon after ending of main discharge. To study this effect thermal probe, interferometric measurements were done.

The measurements with a thermal probe show that the energy flux onto the insulator surface is practically interrupted by the end of first halfperiod of the discharge current. Moreover, it turned out that the average plasma velocity measured by various techniques (Doppler shift, photomultiplier, interferometry) is somewhat higher than that found from the measurements of the plasma pulse and of the ablatating mass. This difference in the plasma velocity can be explained, if one assumes that the insulator ablation is continued after termination of the energy flux incident onto the insulator surface. Since the velocity of that fraction is low, it reduces the average plasma flux velocity. It is natural that this effect results in deterioration of the APPT parameters.

The plasma electron density in the thruster was measured with Mach-Zehnder interferometer. The thruster insulator was aligned in parallel to the optical interferometer axis with the accuracy up to 3°. The interference pattern shift was registered with a streak camera. The time resolution was 5 10⁻⁶ s. Typical near insulator interferogram is shown in Figure 9.

During the main time of a discharge the measured refraction at the PPT-entry is negative and electron density is 10⁻⁷ - 10⁻⁸ cm⁻³. The average electron density distribution at the PPT-entry is changed in a time. This time is characteristic for changes in the current and voltage magnitudes. Taking account of the fact that the time of flight for particles through this area, at a very modest average particle velocity value, is shorter than 10⁻⁷ s; the gas flow can be assumed to be a stationary one. Since the spatial resolution was about 10⁻⁴ cm and the refraction nearby the insulator is negative, one can make a statement that the plasma ionization degree is no less than 1% at the distance 10⁻² cm from the insulator surface. For the time gap 0-4 μs the main contribution to refractive index include electrons and fringe shift is negative. For the time 4.5-7 μs fringe shift near insulator is positive. Maximal positive shift area thickness is near 2 mm. This is a result of neutral component existence in this area. This area begin to be visible when the electric field in the insulator surface and the total current moves to zero.
Conclusions

High power PPT at power level up to $2 \times 10^8$ W having pulse duration near 5 µs produce plasma flow with particle density in up to $10^{18}$ cm$^{-3}$. Specific impulse reach 6000-7000 s. Thrust efficiency is near 50% for bank energy in the range 1 kJ-10 kJ. It is a hope to receive such efficiency for PPT with capacitor energy on the level of several hundreds Joules.

Main energy sinks for losses are in electrodes and energy source.

Experiments show that in single pulse operation, late-time ablation take place after first half-period of discharge current. Mass flow rate for late-time ablation is near 30% of mass ablated per discharge. This late-time ablation of C$_2$F$_4$ may occur due to long distance plasma irradiation of insulator and/or energy stored in thermal skin layer of insulator.

References