Propellant Energy Flux Measurements in Pulsed Plasma Thruster

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Abstract

The Ablative Pulsed Plasma Thruster (APPT) performance is essentially dependent on propellant behavior. Understanding of physics of energy transfer from electrical discharge to propellant is necessary for adequate modeling of APPT and its design and optimization. In the APPT, the considerable energy fraction absorbed by the propellant surface may be transferred not only by particles but ultraviolet radiation from discharge. In this paper the density of the energy flux absorbed by propellant surface in the APPT was measured with a small size temperature probes. APPT model works at 60 –300 J bank energy with average mass flow rate of order $10^{23}cm^{-2}s^{-1}$. Heat flux and mass flow rate measurements were analysed on the base of propellant ablation model, accounting kinetics of polymer thermal degradation. Degradation energy and of mass flow rate values are estimated. Relative shares of conductive and irradiative energy fluxes delivered to propellant from APPT discharge, and the effect of propellant behaviour on thruster efficiency are discussed.

Introduction

Ablative Pulsed Plasma Thrusters (APPT) were the first application of electric propulsion in space almost 40 years ago [1]. The basic operation of the APPT consists of repeated discharge pulses across a solid propellant surface. Useful thrust is mainly produced by the electromagnetic acceleration of the ablated mass that has been ionized. The similar technique automatically provided the matching of a propellant feed with the APPT parameters and allows one to produce relatively effective plasma acceleration. The applications ranged from control propulsion for larger satellites to primary propulsion for small satellites. Currently, APPTs are considered as an attractive propulsion option for stationkeeping and drag makeup purposes of mass and power limited satellites.

However, the potential use of APPTs for formation-flying applications require longer-life components and lower system mass to meet mission requirements. Moreover, application of APPTs to orbit raising maneuvers of power-limited spacecraft require higher performance than has been previously demonstrated. External circuit resistance, mass loss at low speed, non-matched propellant flow rate multiply to provide a total thruster efficiency of less than 10%. By applying each of the inefficiencies in turn, it should be possible to improve the performance of the PPT substantially [2].

In the 90's, the low thrust capabilities of APPT have been reopened, thanks to the tendency to decrease satellite mass. As the same time the experiments on improving of APPT performance have given noticeable results. APPT developed in RIAME demonstrated efficiency on the level 20 –30% for bank energy range 60 – 150 J [3-4]. The use of alternative propellants with replacement of the Teflon propellant offers a perspective option to improve and enhance thruster performance. APPT developed in NASA based on carbon-impregnated Teflon realized mode of operation when Teflon has the highest fraction of its ablated mass accelerated electromagnetically. For 2%-carbon Teflon and 60 J bank energy, efficiency obtained up to 18% [5]. Nevertheless in order to incorporate any new propellant into APPT system, necessary service life tests must be completed.

It is practical to consider directions for improving APPT performance so that it may be applied to a greater range of space applications. Improving of APPT performance for less bank energies, for example in 30 – 60 J range, promises real APPT competitiveness as onboard propulsion system for mini satellites.

Modeling [6,7] shows that the APPTs can enhance their efficiency, when one manages to control the propellant flow rate, because the discharge parameters are strongly dependant on boundary conditions in the inlet of accelerating channel. Therefore the understanding of propellant ablation and ionization is very important for adequate numerical simulation of a discharge in APPT acceleration channel and thrusters development [8]. Our previous modeling of APPT used experimentally obtained dependencies of

propellant flow rate. As a whole, such boundary condition present useful approach for numerical modeling of APPT. However, it is necessary to have adequate understanding of propellant ablation and ionization at the inlet of APPT to control this for APPT discharge optimization.
Present paper presents last experimental efforts intended to the study of energy fluxes transferred from plasma onto propellant surface. Experiments were produced on APPT stand at Kurchatov Institute with bank energies 60- 300 J. The method of energy flux measurement and some results are presented. Attempts to split particle flux and radiation flux are described. The results of energy flux measurements together with Teflon mass loss and current and voltage measurements are presented.

Experimental Facility

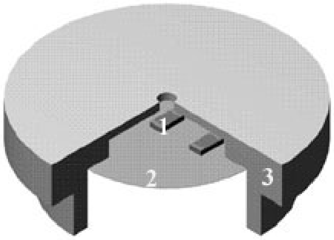
The quasi-steady APPT is housed in a rectangular stainless steel tank of volume near 1.2 m^3. Prior to thruster ignition, the tank is evacuated down to approximately $3x10^{-5}$ Torr by an oil diffusion pump and mechanical pump. The evacuation velocity is equal 5000 l/s under the pressure 10^{-4} Torr. The pulsed power supply was assembled of capacitors with the total capacitance up to 300 μF. Maximal initial voltage is up to 5 kV. The capacitor bank is connected with the feeder through the low inductive cable bridge composed of 48 high current coaxial cables. The estimated cable bridge inductance is $3\ 10^{-9}$ He. The inductance of vacuum feeder is 10^{-8} H. So, bank and feeder can simulate pulsed power source of APPT in wide range of circuit inductance and capacitance. The thruster (Figure 1) consists of a cylindrical copper anode and a tungsten cathode. The accelerating coaxial channel is near 9 cm long and 10 cm and 2 cm in diameter respectively. Outer electrode is anode. Teflon is the solid propellant. The main high current discharge in accelerating coaxial channel is triggering by low power breakdown plasma moving through the holes in the inner electrode to the outer electrode


a


b

Figure 1. Coaxial APPT. a- face view, b – photo of the discharge in the APPT.

Diagnostics
Electrical measurements include the discharge current, voltage and the magnetic field measurements. The discharge current was measured by the Rogowski coil connected to low inductance and low resistance shunt. The voltage across the capacitor bank and at other points was measured by capacitive voltage dividers. The high-speed photography of the discharge is produced with a high-speed photo camera. Maximal time resolution of the camera in streak mode is $2\ 10^{-8}$c.
Energy flux propagated to propellant surface was measured with the tool based on low dimensions (1 mm scale) thermistor. Sensor is located into hole of the propellant bar. It is glued to thin mica plate, serving as a support. A layout of involved elements is shown in Figure 2. Energy flux through small hole in the propellant bar impacted with the sensor. So, sensor stored integral flux, which produced temperature increase and a change in the resistance. A comparison bridge circuit is used to measure resistance change due to temperature increase. Temperature increase occurs after near 1 s after shot. Heat transfer from the sensor to the outer space have typical time of 1 minutes. Sensor is adjusted on azimuthal direction for maximal energy flux signal.



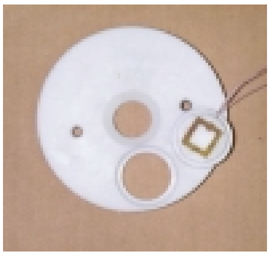


Figure 2. Draft of the measuring tool located into Teflon insert (a) and propellant bar with Teflon insert (b).

Energy flux can be transferred to propellant by particles and by radiation. To outline the energy flux content a number of filters were used. Data on filters are shown in Table 1. Absorbance dependencies on radiation spectrum are shown in Figure 3. Filters are placed on the surface of propellant bar closely to the hole.

Table 1. Used filters

Material	Thickness, μm
Teflon	4, 10,20
Polyether	6
Nitrocellulose	0.1

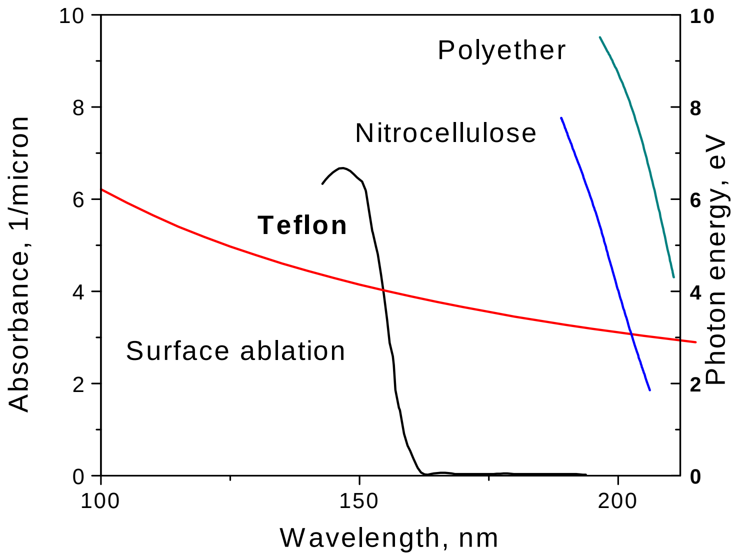


Figure 3. Absorbance of used filters. Absorbance of Teflon and polyether is given from [9], absorbance of Nitrocellulose was accounted.

Results of Experiments

Experiments were carried out on APPT stand at Kurchatov Institute with pressure $3x10^{-5}$ Torr. At this pressure a discharge in APPT under consideration have not symmetric current distribution. Figure 1-b presents the discharge image, the image shown a discharge as non-symmetric. Such a discharge is similar as in breach fed rail geometry thrusters.

For this discharge, results obtained include current and voltage distributions, light intensity registration from fiber inserted near energy flux registration point. Current and voltage data are obtained for bank energies 60 –500 J.

Teflon mass loss measurements were performed in full range of bank energies. Teflon mass loss per single pulse was obtained for not less than 300 pulses and each stored energy. Mass loss dependences on bank energy are shown in Figure 4.

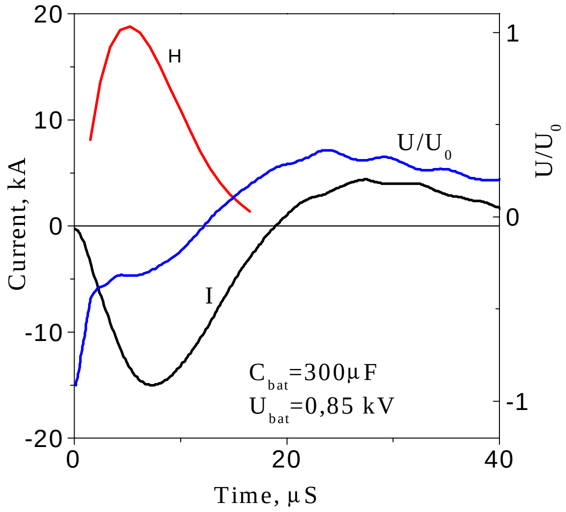


Figure 4. Time dependencies of the discharge current I, voltage on the bank U and radiation flux density, H (visible wave range, optical fiber signal, ab. units).

Calibration of energy flux measurements was produced by introducing to the sensor known quantity of heat. It is realized by means of electrical discharge through platinum foil glued on thermistor. Calibration signal was similar working one. Typical voltage – time dependency of the sensor for 180 J bank charge is shown in Figure 5. Layout of sensors are give in Figure 6.

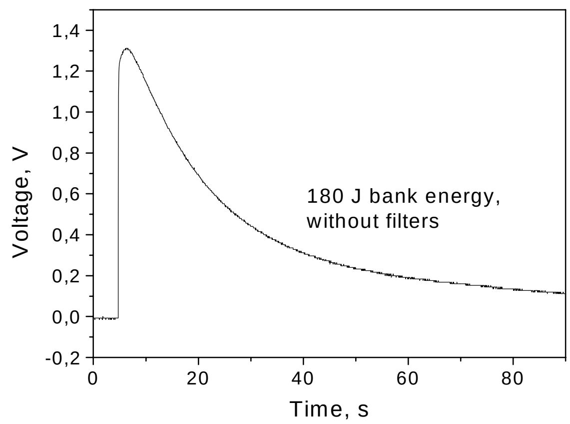


Figure 5 Sensor voltage for 180 J discharge.

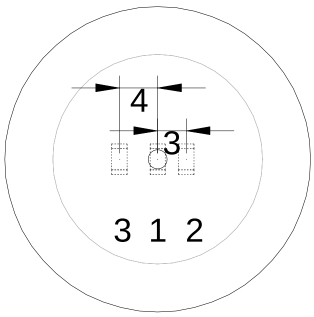


Figure 6.Placement of sensors, face view

Radiation flux determined with polyether and nitrocellulose filter were not more than 1% of energy flux measured without filters. Installation of 6 μm, 10 μm, and 20 μm Teflon filters produced the signal at level 5% of total (particle +radiation). Teflon filters were not destroyed. Nitrocellulose filters were usually destroyed in the discharge after one shot.

Measured energy fluxes are shown in Figure 7. Curve "1" show energy flux measurements from centered sensor position (Figure 6, #1). In this case all particle and radiation flux should impact with sensor. Curves "2"and "3" obtained with radial displacement of the sensor. "2" - surface of the sensor located in 1 mm from side of hole. "3" - surface of the sensor located in 3 mm from side of hole. In position "3" sensor does not see area of plasma. So, as seen from figure 7, conductive energy transfer to the propellant exceed 10% of total transferred energy.

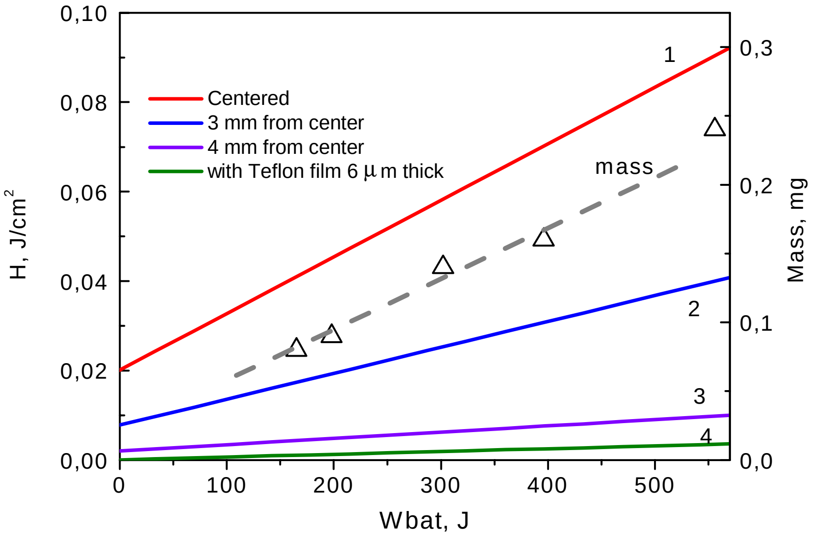


Figure 7. Measured energy fluxes propagated onto propellant (1-4) and mass loss in dependence on the bank energy. 1- without filter (centered); 2- without filter, 2 mm displacemet from hole, 3 - without filter, 3 mm displacemet from hole. 4 – 6 µm Teflon film filter.

The electron density of plasma in the near propellant surface area was measured with Mach-Zehnder interferometer. The ruby laser - in a quasi-continuous generation mode with wavelength 0.69 µ - was used as an illuminator. The propellant plane 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. Streak photo interferogram of near propellant area are given in Figure 8.The time resolution was 5 10^{-8}s. Electron density depended on the input voltage and measured at the level of 10^{16}cm^{-3} for 0.5 kV (inter-electrode gap voltage) with some deviation due to shot-to-shot changes in thruster firing.

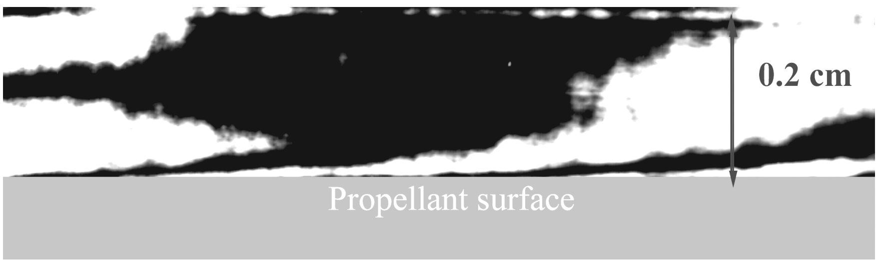


Figure 8. Streak photo interferogram of near propellant area. Time of streak is 1.5 µs. Estimated electron density is 10^{16}cm^{-3}. Voltage on electrodes is near 0.5 kV (4 cm inter-electrode gap).

It is seen from Figure 8, that there are oscillations in electron density at a distance – near (0.2 –0.3) mm from propellant surface. Period of these oscillation (instabilities) is 70 ns.

Discussion of Results

In the APPT, the considerable energy fraction released on the propellant bar surface may be transferred not only by particles but ultraviolet radiation in the wavelength range 100 nm. The absorption depth of this radiation in polymers does not exceed 10^{-5} cm [10], meanwhile the thickness of an propellant material heating due to the heat conduction is about 10^{-4} cm. Schematic of the energy transfer in APPT is shown in Figure 9. At present, the relative role of conductive and radiation mechanisms for energy transfer to the propellant is not exactly determined. Now conductive mechanism is more expanded and developed [11]. Probably the main mechanism of energy transfer to propellant depends on propellant and thruster operation mode.

In considered experiment we measure energy flux through a low dimensions hole in propellant bar. Most probably this hole destroys boundary layer near the propellant surface, because its thickness exceeds significantly the thickness of boundary layer. In this case we measure energy flux falls on boundary layer. For this reason experiments with use of Teflon filters are more reliable.

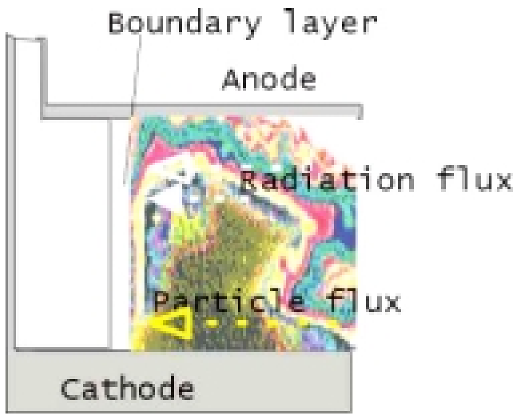


Figure 9. Schematic of the energy transfer in APPT

On the basis of obtained values of energy flux and assumption that this has sinusoidal dependencies in time one can model the interaction of flux with propellant. Calculations were produced with use of Teflon ablation model [12].

Solving the problem for the experimentally measured energy flux onto the propellant surface used value H_{tot} = 0.1 J. Needed for modeling the calculation curve was extrapolated by the function:

$H(t) = H_o e^{-\delta t} \mathrm{Sin}^2 \omega t$. ($\int_o^\infty H_o e^{-\delta t} \mathrm{Sin}^2 \omega t\, dt = 0.1$ J/cm^2). The maximal ablation rate, $\overset{*}{m}_{max}$, in a given case, is attained somewhat later than the energy flux density maximum, being equal ~ 0.4 10^{23} cm^2/s, the maximal insulator temperature is equal 1200 K. The calculation Teflon- mass loss from 1 cm^2 of the insulator surface during the whole process is 20 μg/cm^2. This value corresponds to the experimentally measured mass m_o = 200 μg, when the ablation takes place from the insulator surface which has an effective area of 10 cm^2. This value is in agreement with the frame and streak camera pictures of the discharge. Temperature dependency of Teflon degradation energy is shown in Figure 10. Degradation energy obtained from experiments is in the level of (4.5 –5) kJ/g. This value correspond degradation energy related to temperature 1200^{o}K in Figure 10.

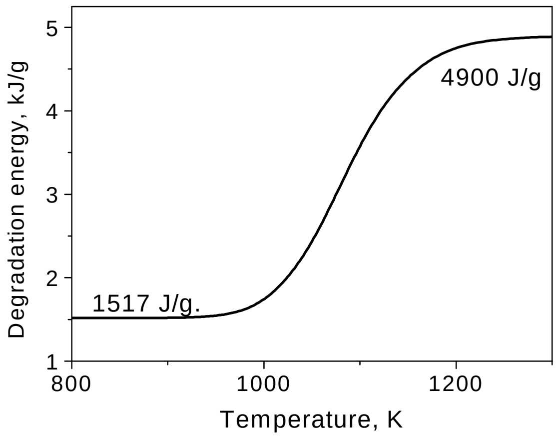


Figure 10. Teflon degradation energy accounting high temperature branches of degradation [13].

The electron density of plasma is observed in the near propellant surface area. In spite of boundary layer is relatively thin, it can significantly decrease UV flux and control particle flux onto propellant. Therefore propellant evaporation can be strongly dependent on boundary layer behavior.

Conclusion

The results of experimental measurements of and estimates of the propellant ablation in the APPT are considered. Energy flux measurements together with Teflon mass loss, current and voltage measurements presented. Experiments were produced on APPT stand with bank energies 60- 300 J.

The energy fraction released from the discharge region upon the propellant surface in the APPT is $\leq 10^{-2}$ of the energy stored in the power supply source. It is shown that near 5% the energy flux contain radiation flux located in wave range from visible to 160 nm. More than 10% of measured flux transferred by particles.

Degradation energy obtained from experiments is in the level of (4.5 –5) kJ/g. This value have a good agreement with degradation energy related to temperature 1200^{o}K. Calculated from heat flux measurements Teflon propellant losses and measured in experiments are in a good agreement.

Near propellant electron density depends on the input voltage and measured at the level of $10^{16}cm^{-3}$ for 0.5 kV (inter-electrode gap voltage) with some deviation due to shot-to-shot changes in thruster firing. Thickness of boundary layer is order of 0.1 mm

For further work any new filters has to be tested in order to share more correctly particles and radiation in energy transfer to propellant. Also angular distribution of energy flux could provide data for determining the value of UV energy flux.

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