APPT Heat Fluxes Measurement and Calculation

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Abstract: Paper presents the results of the study of propellant performance in the electric discharge of side –fed APPT with bank energy in the range of 15 J – 60 J. 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. Results of measurements of energy dissipated in a thermal skin-layer in the Teflon propellant per one discharge are presented. Propellant flow rate calculated from heat flux measurements and measured in experiments are compared. The comparison of the calculated results with integral experimental data has a conditional nature. Really, the propellant surface area, from which PTFE- ablation goes on, depends on time. A change in the ablated area is affected on the efficiency of thruster operation and results in a change in the energy flux onto the propellant. However, there is a sufficiently good quantitative and qualitative agreement between the experimental data and the calculations. The results of energy flux measurements together with Teflon mass loss and current and voltage measurements are discussed.

Nomenclature

M_{abl}	=	ablated mass
W	=	bank energy
C_{bat}	=	bank capacitance
T	=	temperature
ε	=	degradation energy of Teflon
H_{MAX}	=	energy flux density onto the propellant (J/cm^2/s)
q	=	integral energy flux density onto the propellant trailing (J/cm^2)

I. Introduction

ABLATIVE Pulsed Plasma Thrusters (APPT) were the first application of electric propulsion in space more than 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 and thermal acceleration of the ablated mass that has been ionized. This technique automatically provided the matching of a propellant feed with the APPT discharge parameters and allows one to produce relatively effective plasma acceleration. The applications ranged from control propulsion for large satellites to primary propulsion for small and micro satellites. Currently, APPTs are considered as an attractive propulsion option for stationkeeping and drag makeup purposes of mass and power limited satellites.

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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 high performance characteristics and also necessary service life. External circuit resistance, mass loss at low speed, non-matched propellant flow rate decreased a total thruster efficiency. 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. Side –fed APPTs developed in RIAME demonstrated efficiency on the level 20 –30% for bank energy range 50 – 150 J[3]. Probably, 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%[4]. 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 J– 60 J range, promises real APPT competitiveness as onboard propulsion system for mini satellites.

APPT performance is essentially dependent on propellant behavior. Modeling[5,6] 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.

In APPT, the considerable energy fraction absorbed by the propellant surface may be transferred by particles and by ultraviolet radiation from discharge. In[7,] density of the energy flux absorbed by propellant surface in the APPT was measured in breech-fed APPT model working at 60 –300 J bank energy with average mass flow rate of order $10^{23}cm^{-2}s^{-1}$. Measurement of energy bit dissipated in a propellant bar per one firing become possible if one uses thin separated Teflon film instead of propellant bar.

Paper presents the results of the study of propellant performance in the electric discharge of side –fed APPT with discharge density at the level of 15 J – 60 J. Heat flux and mass flow rate measurements were analysed on the base of propellant ablation model, accounting kinetics of polymer thermal degradation. Results of measurements of energy dissipated in a thermal skin-layer in the Teflon propellant per one discharge are presented. Propellant flow rate calculated from heat flux measurements and measured in experiments are compared. The results of energy flux measurements together with Teflon mass loss and current and voltage measurements are discussed.

II. Experimental Facility

The thruster is side-fed APPT developed in RIAME. Teflon is a solid propellant. Results obtained for this discharge include current and voltage distributions, light intensity registration from fiber inserted near energy flux registration point, photos, energy flux values. Electrical measurements include the discharge current and the propellant energy flux measurements. Optical diagnostics include high-speed photography of the discharge.

Measurement of energy bit dissipated in a propellant bar per one firing become possible if one uses thin separated Teflon film instead of propellant bar. Method of measurement of energy dissipated in skin layer is described in[7], where the breech-fed model was studied. Discharge channel of studied side-fed model and placement of sensor is shown in Fig. 1. Side-fed propellant accelerating channel photo is shown in Fig. 2.

Energy flux propagated to the propellant surface was measured with the tool based on low dimensions (1 mm scale) thermistor.

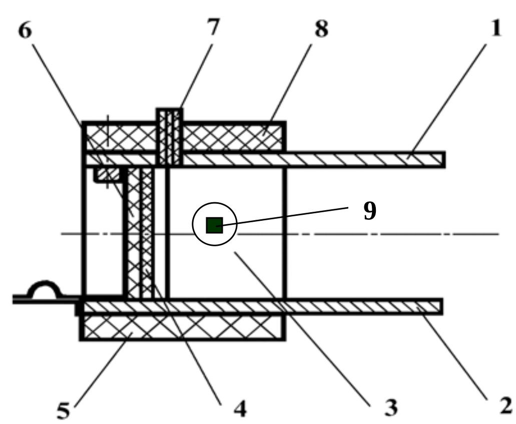


Figure 1. Discharge channel unit schematic. 1 – cathode, 2 – anode, 3 – Teflon bars, 4 – back insulator, 5 – basis, 6 – yoke, 7 – igniter, 8 – cover, 9 - sensor

The basis of the thermal sensor is made with two small-sized SMD - thermistor EPCOS with a negative resistance coefficient. One of thermistors is measuring, other is referent one. Sensor is located into the hole of the propellant bar. It is glued to thin mica plate, serving as a support. To measure energy dissipated in thermal skin layer the discharge was produced on the surface of thin Teflon film, which was closely pushed or glued to the sensor. Energy flux absorbed in the Teflon film transferred to the sensor. So, sensor stored energy bit, which produced temperature increase and a change in the sensor resistance. A comparison bridge circuit is used to measure resistance change due to temperature increase. Temperature increase occurs near 5 s after shot. Heat transfer from the sensor to the outer space has typical time of 1 minute. Sensor is adjusted on normal direction for propellant surface. In breech fed thruster 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 the platinum foil glued on the thermistor. Such a measurement were successfully used to measure propellant energy bit in breech- fed thruster[7]. A schematic of measurement of thermal energy bit dissipated in Teflon propellant per one discharge is shown in Figs. 3,4.

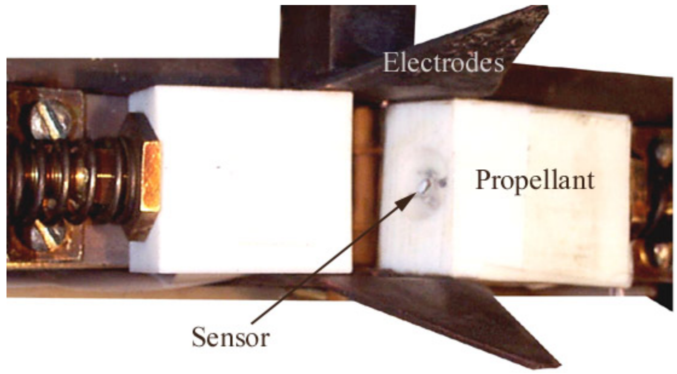


Figure 2. Side-fed propellant accelerating channel

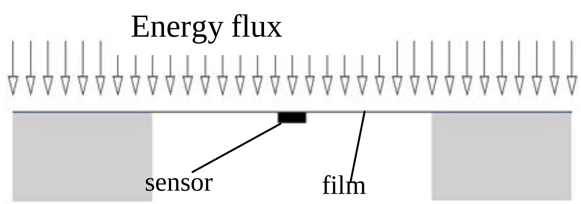
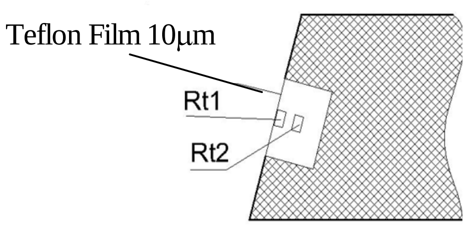


Figure 3. Method of thermalmeasurements in the skin-layer



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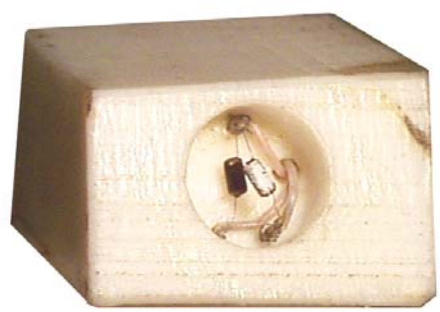

b

Figure 4. Layout of the measuring tool. a: Rt1- measuring thermistor, Rt1- comparative thermistor. b: view of the propellant bar with sensor

III. Results of Experiments

Main purpose of this experiments is to obtain data connected with energy transfer to the propellant and its ablation. These are responsible for APPT mass flow rate and plasma flow forming. So these are important not only for understanding of these devices but for parameters optimisation and thermal behavior of the thruster. Moreover, it is expected that these experiments will be useful to perform design of an improved thruster. Preliminary studies show that in considered APPT quasi- steady plasma flow are formed. It has the duration of comparable with current pulse. In this stage the distribution of parameters of plasma in the accelerating channel varies poorly.

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 thin Tungsten wire wound and pasted to the thermistor. Calibration signal was similar working one.Typical voltage – time dependences of the sensor is shown in Fig. 5.

Fig. 6 give the time dependencies of the discharge current I, from 16.2 J to 58.8 J discharges, in which the energy flux measurements were performed.

A. Results of Measurements of Energy Dissipated in a Thermal Skin-Layer

As mentioned above to measure energy dissipated in a thermal skin-layer the discharge was produced in the surface of thin Teflon film, which was closely pushed to the sensor as shown in Fig. 4a. Measured energy bit dissipated in Teflon propellant per one discharge is shown in Fig. 7. Integral energy flux dissipated in the propellant per one discharge is weakly dependent on bank energy. It is clear from the modeling, because surface temperature freezes at a value about 12000 K for H_{max} = (1÷10)10^5 W/cm^2. Thermal energy dissipated per one discharge increases on 30% with increasing of bank energy from 16 J to 60 J. Such a way propellant receives near 0.1 J/cm^2 per one shot and main energy propagated from discharge to propellant is spent for evaporation (degradation). This value is near 0.4 J/cm^2 that yields 50 μg/cm^2. The discharge width on the propellant can be varied in time. Also this can be dependant on discharge parameters. Possibly the area of discharge for low bank energy decreases significantly working surface of a propellant. Such effect is out of the description with this model, but presents important.

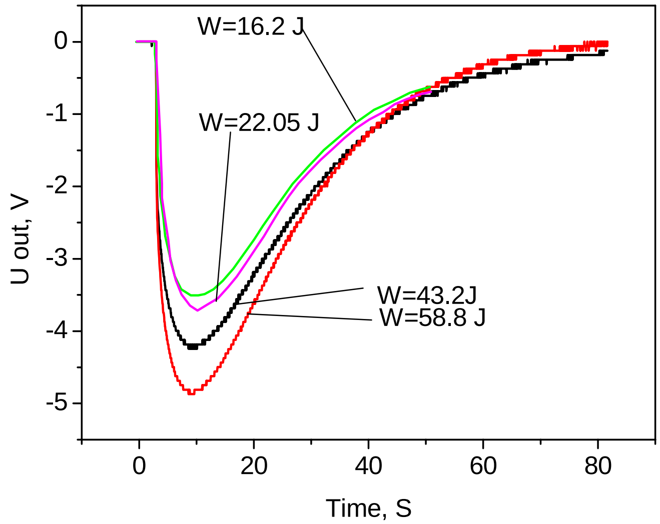

Figure 5. Sensor voltage for discharge

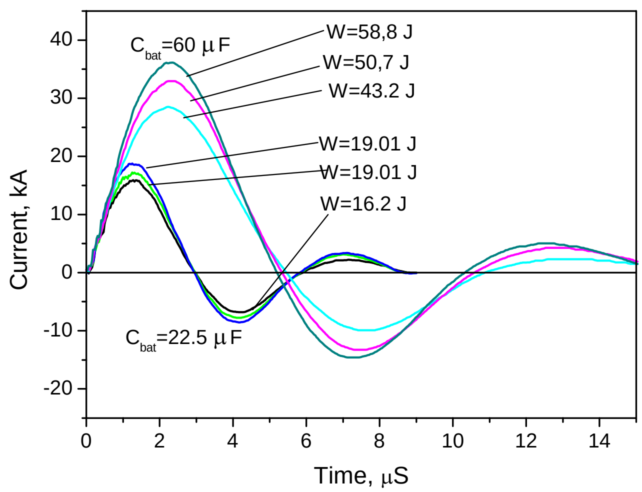

Figure 6. Time dependencies of the discharge current I, from 16.2 J to 58.8 J discharges

The measurements were done for determining the thruster operation efficiency at various propellant temperatures. Increase in propellant temperature can change mode of thruster operation. Ablation mass increase is due to decreasing temperature interval between initial temperature and temperature of propellant intensive evaporation. Usually some temperature rise occurs when APPT are working in high frequency mode of operation. With increasing propellant temperature from 300 K to 450 K mass flow rate bit (one discharge) increased on 50%.

IV. Analysis and Modeling

If one assumes that the energy flux released upon the propellant surface from the discharge zone and that the evaporated substance is instantaneously removed, the problem of propellant ablation in the APPT will be reduced to the solution of a nonlinear heat conduction equation with a moving interface. In this connection, studying the propellant ablation in these devices, one is forced to consider the kinetic of thermal degradation that considerably complicates the problem. On the other hand, the thickness of an evaporating layer in the propellant is very small, and therefore one can limit himself by a study of 1D-heat conduction equation.

Since the Teflon propellant has been more often studied in the APPT, all the quantitative data are referred to this polymer. According to [8,9,10], the following mechanism of degradation is applicable to all the polymers which undergo the thermal degradation up to a monomer, dimer and to the other oligomeric molecules produced as a result of rupture in the main chain. Details of this consideration are given in[10].

Thermal mass flow rate model and measured propellant consumption as well as energy absorbed in the propellant per one shot give the possibility to estimate surface temperature of Teflon and examine the validity of application of the model based on Madorsky approach. Energy bit dissipated in the propellant give the possibility to outline the maximal working power limited by a propellant.

The comparison of the calculated results with integral experimental data has a conditional nature. Really, the propellant surface area, from which PTFE- ablation goes on, depends on time. A change in the ablated area is affected on the efficiency of thruster operation and results in a change in the energy flux onto the propellant. However, there is a sufficiently good quantitative and qualitative agreement between the experimental data and the calculations.

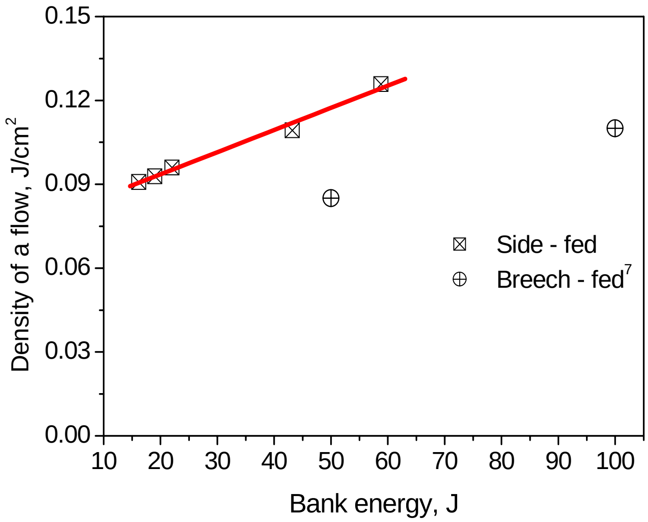

Figure 7. Thermal energy bit dissipated in Teflon propellant per one discharge in side-fed and breech-fed[7] thrusters

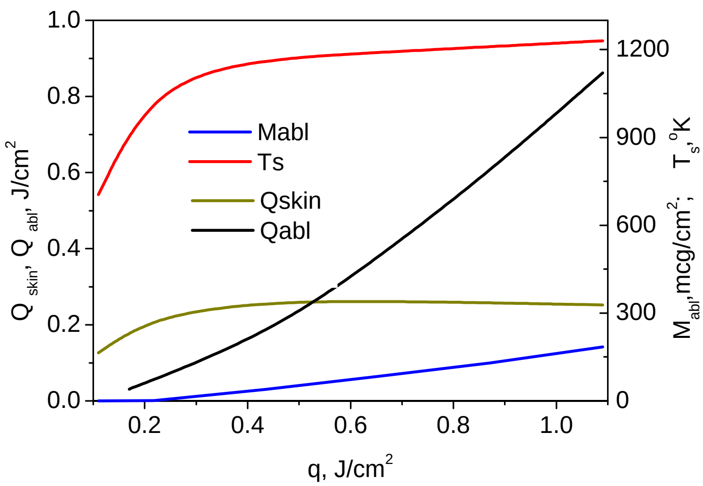

Figure 8. Results of accountings. H_{max} –maximal power of energy flux, q- total energy flux density, M_{abl} - ablated mass, Q_{skin}- energy of thermal skin layer, Q_{abl}, - Teflon destruction energy and T_s, - maximal temperature of the propellant surface

The approximation of energy flux transferred onto the propellant is similar used in[7] and presents the damping sinusoid. Time dependence of this is similar to measured energy on a propellant bar. Accounts of Teflon degradation based on thermal degradation kinetics[9,10] have been produced. The results of accounts are shown in the Fig. 8. The results of accounting show that Teflon begins to destruct intensively from surface temperature > 1100 ^{o}K. Further, temperature increases insignificantly with energy flux increasing. When the power of energy flux increases in 8 times, the temperature increases on 100 ^{o}K. For Ts= 1200 ^{o}K and for energy flux, approximated as damping sinusoid, thermal skin-layer energy contains 0.26 J. High mass loss case is demonstrated in Fig. 9, where H, M_{ABL}, T_S and ε are shown for H_{MAX}=73 kW/cm^2.

Even such relatively high fluxes of energy require a few microseconds to heat a propellant prior to the beginning of its evaporation. Really it takes high efficiency mechanism of energy transfer to explain the first time propellant flow rate. Measured energy fluxes does not exceed 0.15 J/cm^2 with stored energy up to 60 J. So it is efficient propellant surface heating without of considered description. Teflon degradation for measured energy fluxes falling onto the propellant can take place if temporal or spatial inhomogeneities in energy flux occur[11.] In this case measured energy is average value and can be significantly lower than local values of energy flux.

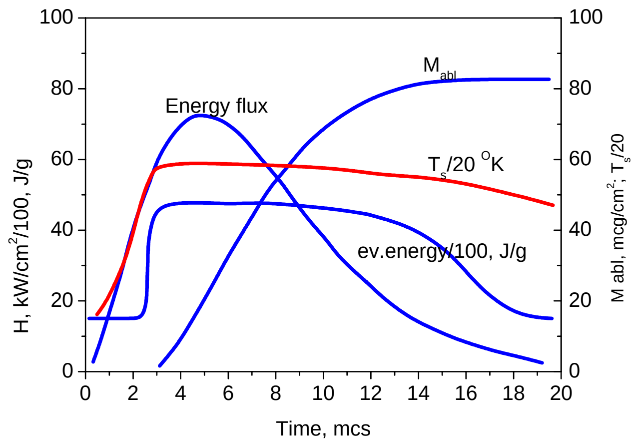

Figure. 9 Time dependencies of H, M_{ABL}, T_S and ε for H_{MAX}=75 kW/cm^2.

So, such model can explain the mass loss in a frame of thermal degradation kinetics if maximum energy flux to the propellant exceeds 30 kW/cm^2 (Integral flux more than 0.2 J/cm^2).

In the APPT, the considerable energy fraction released on the propellant bar surface may be delivered by particles and ultraviolet radiation in the wavelength range near 100 nm. The absorption depth of this radiation in polymers does not exceed 10^{-5} cm, meanwhile the thickness of an propellant material heating due to the heat conduction is about 10^{-4} cm. 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[12]. Probably the main mechanism of energy transfer to propellant depends on the thruster operation mode.

In considered experiments we measure energy flux through a low dimensions hole in the propellant bar. Perhaps 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 that falls on boundary layer.

So, in a frame of used thermal degradation model of Teflon for measured energies, degradation of Teflon propellant is doubtful. However inhomogeneities in energy flux distribution could explain observed mass flow rates for relatively low energy fluxes.

V. Conclusion

The energy flux onto the propellant surface in the range of 16 to 60 J of bank energy has been measured at stand for side – fed APPT. Propellant receives near 0.1 J/cm^2 per one shot and main energy propagated from discharge to propellant is spent for evaporation (degradation). Accounted values are close to experimentally measured. Functionability of APPT was confirmed up to 580^{o}K with significant propellant flow rate increasing.

Modelling, based on Teflon degradation kinetics can explain the mass loss in a frame of thermal degradation kinetics if maximum energy flux to the propellant exceeds 30 kW/cm^2 (Integral flux more than 0.2 J/cm^2). For low energy flux to the Teflon propellant, degradation can take place if temporal or spatial inhomogeneities in energy flux occur. In this case measured energy is an average value and can be significantly lower than local values of energy flux. For this reason, experimental data on current and plasma near propellant distribution would be very important to explain propellant ablation in low energy APPT.

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