Ablation-Fed Discharge Characteristics

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Abstract: Quasi-steady operation of Ablative Pulsed Plasma Thruster (APPT) in millisecond range of discharge time has been developed. Coaxial breach-fed APPT was used. Produced tests show that quasi-steady ablation-fed discharge can exist for a millisecond times. Millisecond range APPT has high thermal (more than 50%), thrust efficiency and specific impulse (5300 s). Analyzed data cover bank energy in a rage of (0.1- 80) kJ for Teflon propellant. APPTs behavior is interpreted on the base of developed single fluid plasma acceleration model and modeling of propellant heating and evaporating, based on Teflon degradation kinetics. The comparison of the calculated results with integral experimental data has a conditional nature. 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.

I. Introduction

ABLATIVE Pulsed Plasma Thruster (APPT) is a well known electric propulsion device that was the first one placed to spacecraft Zond-2 more than 40 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[1, 2].

Main space APPT 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 APPT. 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 APPT. The similar technique automatically provided the matching of a propellant feed with the APPT parameters and allows one to produce 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.

Currently three directions seem could improve thruster performance: decreasing post-discharge evaporation or late-time ablation, increasing energy density in accelerating channel, optimization of energy transfer. Last two items have been studied in detail. Late-time ablation experimental study meet difficulties due to small scale of interesting area and a number of essential processes: energy transfer, propellant ablation and ionization. So, modeling is very important here. Developed models 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

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case measured energy is an average value and can be significantly lower than local values of energy flux. One of the important measurements of energy dissipated in thermal skin-layer of a propellant surface developed in[3]. An analysis is based on degradation energy accounting and measurements of mass flow rate together with data of energy dissipated in a thermal skin-layer in the Teflon propellant per one discharge. It has been proposed that relative input of late-time ablation decreases with bank energy increasing. 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 Teflon- ablation goes on, depends on time. A change in the ablated area affects to 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 especially for high bank energy discharges.

Last experiments with low bank energy thrusters show that high density, ablated neutral gas stays near the propellant surface, and only its fraction is converted into plasma and electromagnetically accelerated, leaving the residual neutrals behind[4]. So, non-accelerated neutrals appear in accelerating channel for the duration of a discharge decreasing thruster characteristics.

As a result of the experimental study of APPT operating processes and the simulation of physical phenomena in discharge channel, the problem of APPT thrust efficiency increasing has been solved, but for relatively high bank energies, more than 20 J[5]. Naturally, there are many processes responsible for low APPT efficiency[6,7].

In this work we present APPT model with millisecond discharge time. The analysis of the APPTs behavior in dependence of power supply source parameters, propellant ablation and heating etc. to understand the physics of a discharge for improvements of thrust characteristics is given on the basis developed earlier numerical models[5,9]. Analyzed data cover bank energy in a rage of (0.1- 80) kJ for Teflon propellant.

II. Quasy-Steady Ablation-Fed Discharge

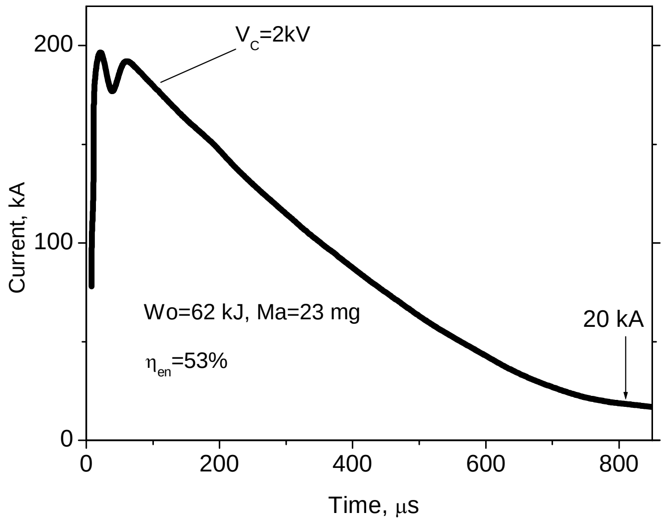

Figure 1. Ablation-fed millisecond range quasi-steady discharge. Energy of power source is 82 kJ.

Usually APPT discharge current has expressive pulsed form. So, seems, this concern many physical processes in a discharge in accelerating channel. But, estimates, modeling and experiments with high power APPT show that a number of phenomena were characterized with very shot times[8,9] . Consequently, the times of electrical breakdown, ionisation, and acceleration of particles are below than time of main discharge. However, quasy-steady operation of APPT presents doubtful because of unpredictable behavior of Teflon propellant in high energy flux conditions for milliseconds.

A. Millisecond discharge APPT

To study quasy-steady operation of APPT in wide range of discharge time, coaxial breach-fed APPT was used. External and internal electrodes having 10 cm and 2 cm in diameters were manufactured from copper. APPT was placed in the vacuum chamber, with pressure equal $5x10^{-5}$ mm Hg. It described in detail in[10]. APPT was connected to power source formed with two capacitor banks. First one is 30 kV with capacitance equal 97 μF. Second has capacitance of $3\ 10^{-2}$ F with maximal charging voltage equal 5kV. In beginning the discharge arises after switching on high voltage bank discharge. Time of increase of a current in a discharge is near 10 μs. At the time of maximum of a current second bank was connected to APPT by means of high current switches. Such a way we could realize experimentally ablation-fed discharge with high maximal current and millisecond discharge time.

Discharge current was registered by means of magnetic probes with the subsequent integration of a signal from a probe. Voltage on electrodes of the accelerating channel was measured by means of a high-voltage divider. APPT

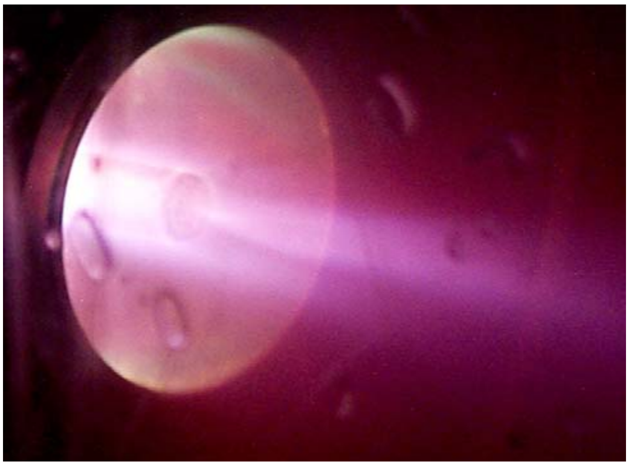

Figure 2. Millisecond range in quasi-steady APPT.

generate quasy-steady plasma flow within discharge currents in a range of 15 kA – 200 kA. During a discharge near 70% of energy stored in power source was transferred to APPT that made 62 kJ.

High speed photo registration near APPT outlet show that plasma flow with diameter of 2 cm is formed. This has lifetime near 1 ms. Divergence of plasma flow corresponds to a temperature of plasma near 2 eV. Calorimetric measurements have shown, that plasma flow contains, at least, 30 kJ, that makes about 53 % of the energy transferred to the discharge. Integral mass flow rate attains 23 mg. Discharge current in APPT is given in Fig. 1. Photo of plasma flow is shown in Fig. 2.

Teflon behavior does not prevent long time (1 ms) existence of ablation-fed discharge more than for 100 firings.

III. High power APPTs characteristics analysis

Last test completes the data base of high power APPT given in Table 1. All modes of operation shown in the Table have relatively high transfer efficiency from power source to APPT. Some decreasing in efficiency for the last model could be explained by the losses in current switches and a cable bridge of main high capacitance capacitor bank.

Table 1. High power APPT characteristics

V_0, kV	Wbat, J	Thermal eff.	Pbit, mNs	Isp, s	Mass bit, mg
2	182	0,84	4	3600	0.11
2,5	284	0,83	7.3	3100	0.24
3	410	0,88	11.7	2800	0.41
3,5	557	0,85	16.7	2700	0.61
4	728	0,87	21.8	2800	0.79
4,5	921	0,81	26.4	2700	0.99
1.5	1050	0.6	30	3000	0.7
10	6000	0.7	100	5000	2.2
2^*	82000	0.53	-	5300	23

* -initial voltage for decreasing part of current curve

From the very beginning electrical discharge in accelerating channel has no axial symmetry, and then discharge became symmetric. Dynamics of a plasma flow and integral parameters of high power APPT are well described by two-dimensional numerical model[9]. Calculated distribution of plasma in APPT (6 kJ discharge) is shown in Fig. 3.

A. Optimization of electric circuit

Optimization in APPT performances have been done due to finding the optimum relations between the electric circuit parameters and the discharge channel dimensions, realizing the quasi-aperiodic discharge in the thruster and optimising the current distribution in the discharge channel[11]. For further APPT efficiency increasing as well as for retaining the achieved efficiency under APPT manufacturing it is necessary to understand more clearly the physical processes in thruster discharge channel. Modeling is used also to optimize APPT.

B. The late-time ablation

Measurements with a thermal sensor show that the energy flux onto propellant surface is practically interrupted by the end of first half period of the discharge current. Moreover, it turned out that the average plasma velocity measured by various techniques (Doppler shift, photomultiplier, and interferometry) is somewhat higher than that found from the measurements of the plasma pulse and of the ablating mass. This difference in the plasma velocity can be explained, if one assumes that propellant ablation is continued after termination of the energy flux incident onto the propellant surface or only part of evaporated propellant is ionized and accelerated. So, the velocity of that

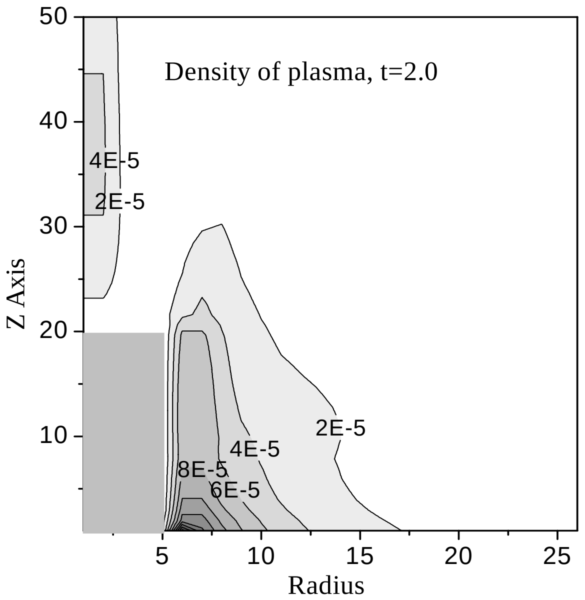

Figure 3. Plasma density (ab.units) distribution in accelerating channel for quasy-steady mode.

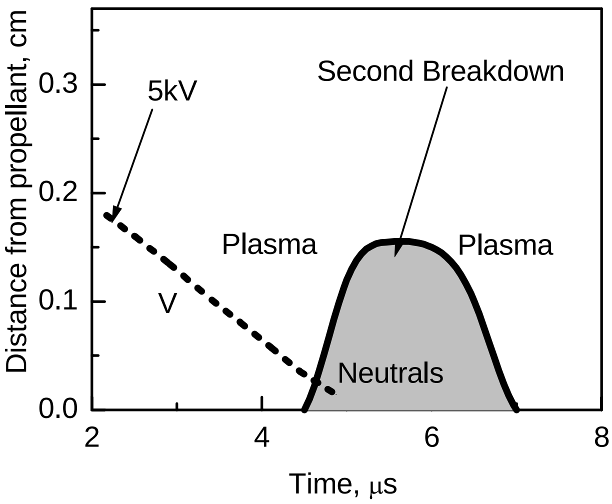

Figure 4. Late time ablation dynamics. V- voltage on the discharge

fraction is low, it reduces the average plasma flux velocity. It is natural that this effect results in deterioration of the APPT parameters. This late-time ablation or after-ablating effect which is observed in operation of APPT can be explained of elevated Teflon surface temperature or expansion of high density boundary layer. Last experiments Koizumi et al with low bank energy thruster[4] have shown that high density, ablated neutral particles stay near the propellant surface, and only a fraction of neutrals is converted into plasma and electromagnetically accelerated, leaving the residual neutrals behind.

Accordingly, late-time ablation process is not clear, especially for low bank energy thrusters. In single pulse operation of APPT under consideration evaporated mass exceeds accelerated mass up to 40%. To study this effect thermal and interferometric measurements were used. The plasma electron density in the thruster was measured with Mach-Zehnder interferometer. The thruster propellant bar was aligned in parallel to the optical interferometer axis. The interference pattern shift was registered with a streak camera. The time resolution was $5\ 10^{-8}$ s.

During the main time of a discharge the measured refraction at the APPT - entry is negative and electron density is 10^{17}- 10^{18} cm^{-3}. The average electron density distribution at the APPT- entry is changed in time. This time is characteristic for changes of a current and voltage values. Taking into account that the time of flight of 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 steady one. Since the spatial resolution was about 10^{-2}cm and the refraction nearby the propellant bar is negative, one can make a statement that the plasma ionization degree is no less than 1% at the distance 10^{-2}cm from propellant 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- 7μs fringe shift near propellant bar is positive. Maximal positive shift area thickness is near 2 mm. This is a result of neutral component existence in this area. This area begins to be visible when the electric field in the propellant surface and the total current moves to zero. Apparently acceleration of this ablated mass is small effective. Outlet plasma flow have velocity is significantly lower than this in the first half-period. When second half-period voltage increases up to 100-200 V second break-down of neutral gas is well visible. Neutral gas layer thickness dynamics is shown in Fig. 4. Quantity of neutral particles have been determined in assumption that neutral layer consist from products of Teflon degradation. The average refractive index weakly depends on molecular contents of these products. Estimates of neutral layer particles maximal quantity have given near 0.6 mg for C, 2F particles for total ablated mass of 2 mg. Note that such a picture has been obtained for high power discharge with maximal power more than 10^8 W.

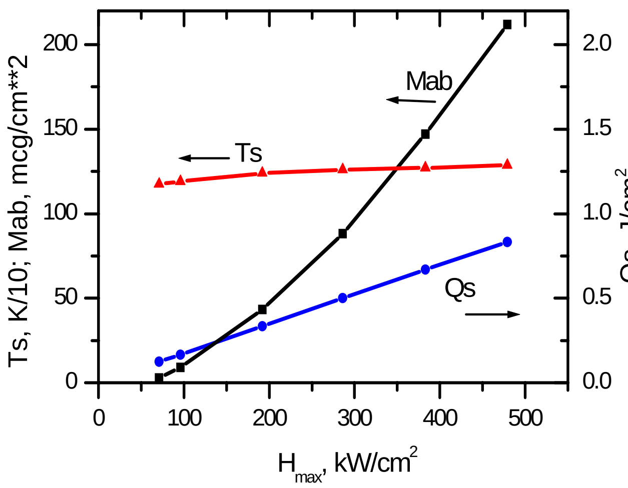

Figure 5. Dependence of M_{ab}, T_s and Q_s from H_{max}.

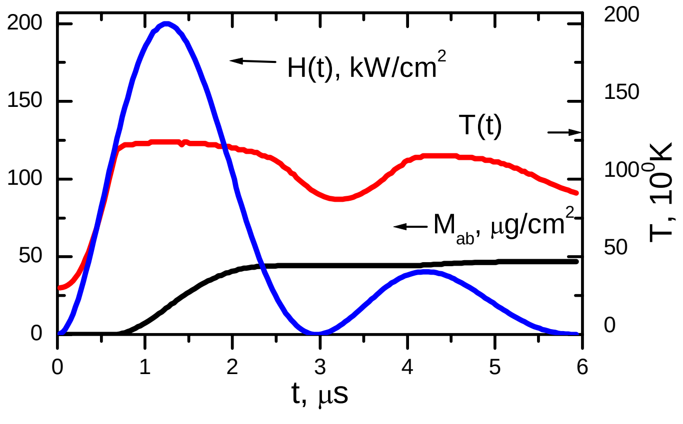

Figure 6. Time dependencies of H(t), T_s(t) and M_{ab}(t) for H_{max} =200 kW/cm^2.

C. Ablation and Ionization Modeling

The examples of calculation shown below used model developed earlier[10]. Parameters determining the value and time dependence of a heat flux onto Teflon surface were taken as following: H_{max}=2.10^{5}W/cm^2, δ = 4.5 10^5 s^{-1}, ω=1.0^{6}s^{-1}. In Figure 5 the computational dependence of full propellant flow rate, evaporating from 1 cm^2 during discharge, on maximum value of heat flux H_{max} is shown. In the same figure the maximum temperature of Teflon surface Ts and value of energy Q_s, coming to 1 cm^2 during process are also presented.

Maximum temperature of Teflon surface in a range of H_{max} = 10^5÷5 10^5 W/cm^2 changes weakly and is frozen at a level 1200 ^{o}K. At H_{max} > 250 kW/cm^2 M_{ab} depends linearly on maximum value of an energy flux density. In this case almost all energy going to Teflon is spent for a sublimation.

In Figure 6 the time dependencies of energy flux coming to the propellant surface H (t), temperature of a surface T_s and propellant flow rate M_{ab} for H_{max} = 200 kW/cm^2 are presented. In a given statement of the problem, the intensive Teflon depolymerization is beginning after surface temperature reached ≈ 1190 ^{o}K.

In Figure 7 the dependence of ionization degree have been calculated with use of semiphenomenological approach[12]. Ionization degree dependence from the distance to the propellant surface is adduced for different electric fields. The presented curves correspond to the following parameters - H_{max} = 2.10^5 W/cm^2, t = 2 μs. The calculations display dramatic expansion of ionization area at decreasing of applied electric field.

1. Direct Heating of a Propellent from a Discharge Measurement

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[3], where the breech-fed model was studied. 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

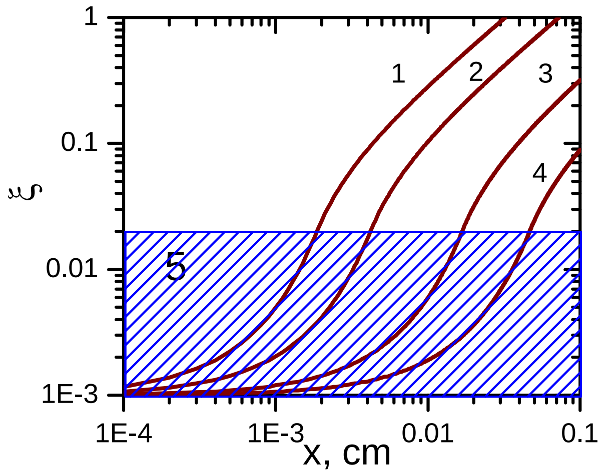

Figure 7. Dependence of ionization degree, ξ on the distance to the propellant surface. 1 –1500 V/cm, 2 – 1000 V/cm, 3 – 500 V/cm and 4 – 300 V/cm; 5 - area of a positive refraction

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. Accounted values are close to experimentally measured and weakly dependent on energy flux dissipated from a discharge. So, calculated energy transferred to heating of propellant bar attains 0.23 J/cm^2 and does not change with further increasing of total energy flux density.

IV. Conclusion

Produced tests show that high power quasy-steady electrodynamic ablation-fed discharge can exist for a millisecond times.

Millisecond range APPT has high thermal (more than 50%), thrust efficiency and specific impulse (5300 s).

High Power APPT performance data is analysed on the base of numerical models. The comparison of the calculated results with integral experimental data has a conditional nature. However, there is a sufficiently good quantitative and qualitative agreement between the experimental data and the calculations.

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