POWER PROPULSION SETS WITH PULSED PLASMA THRUSTERS

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Dependencies of thrust, mass and dimensional characteristics of pulsed plasma thrusters (PPT) with ablation of dielectric propellants upon various PPT parameters and operating modes are studied experimentally and theoretically. Propulsion sets with PPT are developed, which comprise primary power source, pulsed plasma thrusters and control systems for PPT parameters. Successful tests of such propulsion sets were conducted on board the "Mir" high-altitude probe rocket. Effect of operating thrusters on the onboard equipment operation is defined.

Pulsed plasma thruster is a kind of electric jet engines [1]. One of the main difference of PPT from stationary plasma thrusters is the periodic character of the thruster operation, i.e. operation with some discharge repetition frequency. PPT designs with dielectric propellant ablation are presented in Fig. 1.

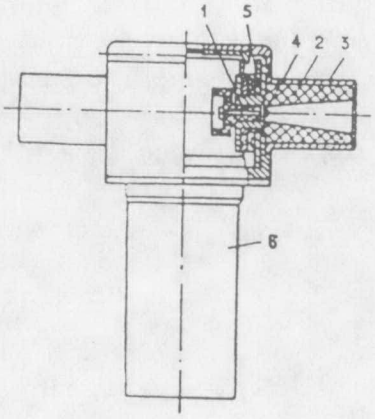

Fig.1. Design diagram of pulsed plasma thruster with dielectric propellant ablation. 1 - cathode; 2 - propellant; 3 - anode; 4 - discharge initiator; 5 - Rogovsky belt; 6 - capacitor.

Plasma in such thruster is generated by electric discharge over the surface of dielectric, separating the electrodes. Plasma is

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accelerated under the influence of electromagnetic and gasdynamic forces, produced during the discharge [2, 3]. Relation between electromagnetic and gasdynamic forces inside the PPT channel might be varied by changing the level of energy, stored before the discharge in the accumulator (capacitor in the most number of cases), and by choosing the propellant and electrodes geometry and other parameters; various thrust characteristics might be obtained as a result. Performance of PPT of medium power (with power consumption P_{el} of up to 100 kW and energy, stored before the discharge, W_o of about some kJ) and PPT of low power (P_{el} of order of kW and W_o of about some tens and hundreds of J, correspondingly) were studied. It was planned to use medium power PPT as cruise engines and low power PPT - as a part of attitude control and station-keeping systems of high-precision spacecrafts.

Medium power PPT

PPT electric circuit, comprising capacitor with internal inductance and resistance, current supplying devices and plasma accelerator with inductance and resistance, variable in time, is a system, which is very complicated for studying . That is why it is very difficult to study the effect of any electric circuit parameter independently, because other parameters will be changed in this case also. But our experience showed that improvement of capacitor parameters (reduction of internal inductance and resistance) and of parameters of the circuit as a whole leads to the thrust characteristics improvement. Such circuit parameters improvement was achieved by two ways. In the first case, batteries of capacitors connected in parallel were used. In this case we used capacitors with bad internal parameters, produced by the industry. In the second case, special capacitors were designed on the basis of industrial ones.

Values of energy W_o, stored in the capacitor, capacitance C and initial voltage U_o have very high and complicated influence upon the PPT thrust characteristics. This is connected with the peculiarities of non-stationary plasma acceleration. As our studies showed, at the given electrode geometry and propellant the

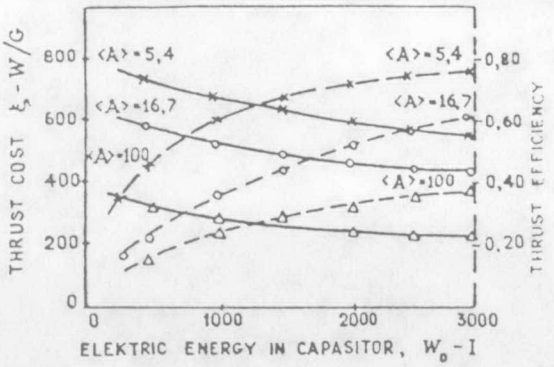

Fig. 2. Thrust efficiency and thrust/power ratio as functions of electric energy, stored in the capacitor.

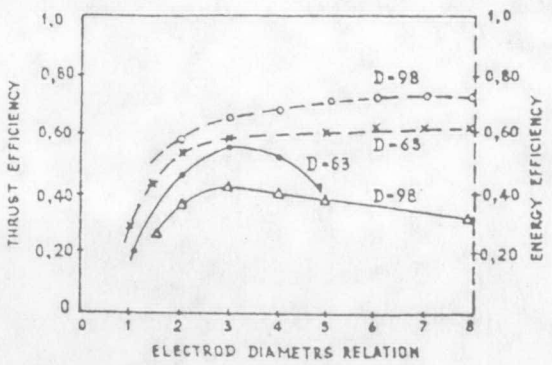

Fig. 3. Thrust efficiency and energy efficiency as functions of the relation of external and internal electrode diameters.

W_o value growth causes the increase of specific impulse I_{sp} and dielectric ablation mass per one discharge m_1 and improvement of thrust characteristics while using any electric circuit, but the form of functions $\eta_T(W)$, $I_{sp}(W)$, $m_1(W)$ and $\xi(W)$ is defined by the electric circuit parameters (Fig. 2, 4).

Geometry of accelerator electrodes has high influence upon the PPT thrust characteristics. PPT with various electrode geometries (rail, coaxial and conical) were studied and their geometrical dimensions were changed within the broad limits. Good

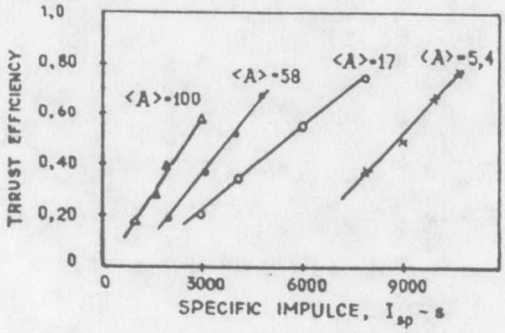

Fig. 4. Thrust efficiency as a function of specific impulse for the medium power PPT.

results were obtained in the case of coaxial geometry of electrodes. Multiple experimental studies allowed to reveal optimum relation between external electrode diameter D and internal electrode diameter d (Fig. 3). As it is seen, energetic efficiency η_{en} dependence upon the D/d ratio is smooth, while η_T

dependence upon D/D has maximum at D/d ≈ π. This might be explained by the fact that optimum conditions for plasma outflowing from the accelerator are created in the case of such relation. Existence of such optimum relation of electrode diameters is confirmed by several experimental serieses, as well as in the case of "end" PPT geometry. As the charge ignition system is located inside the central electrode, it is difficult to make the electrode diameter less than 13 mm. Thermal mode of the central electrode operation becomes worse in this case. Studies of PPT electrode length influence upon its parameters allowed to make a conclusion that it is advisable to choose the electrode length to be about the diameter of external electrode.

Choice of propellant and its thermal and physical properties has a high influence upon the PPT thrust characteristics. Analysis of conditions of propellant use in PPT allowed to choose only some (about thirty) of a large variety of dielectric materials for conducting the experiment. Due to the simplicity and convenience for operation a large number of experiments was made using solid propellants - unicomponent (fluoroplastic with average atomic mass of products of complete decomposition $\langle A\rangle=16.7$, caprone with $\langle A\rangle=5.4$, for example) and multicomponent, consisting of binding substance and one or several fillers, that allowed to change the parameters of such propellant within the broad range by varying the relation between binder and filler (mechanical mixtures, pastes, etc.). Fluorinated silicone is used as liquid or viscous binder in pastes, while cesium iodide CsJ, mercurous iodide with $\langle A\rangle=100$, etc. - as filler.

A large number of propellants was tested using PPT with optimized coaxial geometry of electrodes (D=63 mm, d=21 mm, length of both electrodes - 60 mm) and capacitive battery (C=1500 μF). Experiments were made by serieses of some minutes in duration with repetition frequency of up to 10 Hz; electric power was about some kW. It was discovered while studying the thrust/power ratio that:

$$\xi_{HgO}\sqrt{\langle A\rangle_{HgO}} \approx \xi_{fl}\sqrt{\langle A\rangle_{fl}} \approx \xi\sqrt{\langle A\rangle_{capr}} \approx \text{Const}$$

or:

$$\xi \sim 1/\sqrt{A},$$

i.e. for PPT the thrust/power ratio ξ is inversely proportional to the square root of the average atomic weight of products of propellant complete decomposition $\langle A \rangle$.

More complicated dependence for the mass flow rate per one discharge was obtained for the following ranges: $500J \leq W_o \leq 3500J$ and $10 < \langle A \rangle < 100$:

$$m_1 = C(T) \times 46 \times \langle A \rangle \times (\sqrt{W_o + 0.5} - 0.7),$$

where: $[m_1] = \mu g$, $[W_o] = kJ$; $C(T) \geq 1$ - coefficient, having different values for substances with different thermophysical properties and accounting for the mass flow rate increase as a function of the propellant bar temperature, taking place in the case of prolonged PPT operation.

Specific impulse I_{sp} grows with W_o increase for all propellants, but specific impulse is much higher in the case of propellants with low $\langle A \rangle$. Analysis of the obtained experimental dependencies showed that the following relation is valid for the studied range of parameters:

$$I_{sp} \sim K(W_o)/\sqrt{\langle A \rangle},$$

where $K(W_o)$ - semiempirical coefficient, depending on the W_o value and electric circuit parameters.

Value of thrust efficiency η_T increases with W_o growth for all propellants. Application of propellants with lower $\langle A \rangle$ results in higher η_T for the same stored energy W_o.

In addition to experiments with solid propellants, a large number of tests was made with liquid dielectrics. Special PPT designs with liquid dielectric feeding were developed and refined for this.

Generalized diagrams $\eta_T - I_{sp}$ were plotted on the basis of obtained experimental dependencies of PPT thrust characteristics on some parameters, I_{sp} values being presented along X axis and thrust efficiency η_T values, realized in this or that thruster at given specific impulse I_{sp} - along Y axis (Fig. 4, 5). Thus, generalized diagrams show, which ultimate thrust characteristics might be obtained and allow to choose PPT parameters for realizing the required thrust characteristics. For the convenience of

diagram use the lines of equal values of thrust/power ratio ξ are shown also (Fig. 5).

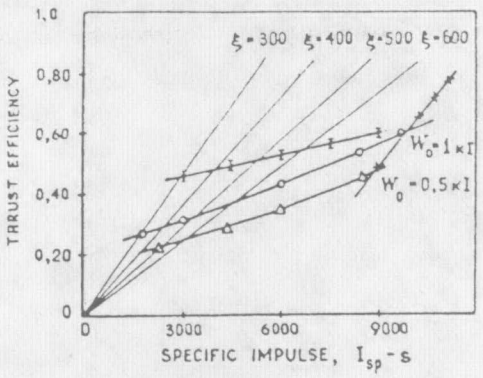

Fig. 5. Generalized thrust characteristics of medium power PPT.

Low power PPT

Analysis made by us for the optimum actuator devices of the attitude control and station-keeping systems of spacecrafts with long life-time and high accuracy of attitude control, providing high accuracy and minimum power consumption (propellant and electric energy consumption), showed that inertialess devices, ensuring low unit thrust pulse, high specific impulse, large number of startings and allowing the thrust (controlling moment) control within the broad limits, are the best. Pulsed plasma thrusters meet these requirements in full enough measure. As the electric power, meant for the electric propulsion operation, does not exceed 1 kW, as a rule, as applied to PPT this means the necessity of development and study of PPT thrust characteristics at reduced values of electric parameters: energy W_o, stored before the discharge, does not exceed 300 J; capacitance - 20-100 μF; initial voltage $U_o \leq 3000$ V; discharge repetition frequency does not exceed some Hz. Thrust/power ratio ξ is of great importance for such thrusters, that is why much attention was paid to investigations for decreasing the thrust/power ratio in PPT.

Conical, coaxial and cylinder configurations of electrodes are of the most interest for the low power PPT. Fig. 6, 7 show some of the numerous experimental characteristics of different PPT models (differing not by the electrode geometry only, but by the electric circuit, propellant, etc., also). Curve 1 is obtained using the PPT model with conical geometry of electrodes (external

electrode diameter is 25 mm, internal - 8 mm, length of electrodes is 40 mm, angle of tapper of external electrode $\alpha=60^{\circ}$); serial capacitor KIM-3-20-2 with capacitance of 108 μF was used; propellant - cesium iodide with $\langle A\rangle=130$. The following thrust characteristics were obtained at the stored energy W_o = 150 J: ξ = 178 W/g, I_{sp} = 1100 s, η_T = 0.3. Thrust produced by the thruster was 1.68 g in the case of electric power P_{el}=300 W, supplied to PPT. Unit impulse I_1 = 0.84 gs, total impulse to the thruster nozzle I_Σ=100 kgs.

Curves 2 and 3 are obtained using the PPT model with conical external electrode (external electrode diameter is 48 mm, internal - 16 mm, length of electrodes is 225 mm, angle of tapper is 60°). Capacitor KIM-3-20-3 with capacitance of 98 μF, internal inductance L_o = 43 nH and internal resistance $R_o=6\times10^{-4}$ Ohm was used. The following thrust characteristics were obtained at the stored energy W_o= 160 J and application of cesium iodide with $\langle A\rangle=130$: ξ = 270 W/g, I_{sp} = 930 s, η_T = 0.17. Unit impulse I_1 = 0.59 gs, spring system of propellant feeding to the thruster was used, total thrust impulse to the thruster nozzle I_Σ=1000 kgs. Thrust produced by the thruster was 1.78 g in the case of operation with repetition frequency of 3 Hz and electric power P_{el}=480 W, supplied to PPT. While using fluoroplastic with the same model and at W_o= 160 J the thrust characteristics were as follows: η_T = 0.22, I_{sp} = 1980 s, ξ = 435 W/g (curve 3).

Thrust characteristics of PPT with coaxial geometry of electrodes, propellant (fluoroplastic-4) bar of conical form at W_o variation from 40 to 300 J are shown by the curve 5. It is seen that at specific impulse I_{sp} = 600 s the thrust/power ratio is $\gamma \sim$ 180 W/g. Unit impulse may vary from 0.08 gs up to 3.0 gs, total impulse per one nozzle I_Σ= 200-2000 kgs. Curve 5 presents characteristics of PPT model with cylinder discharge chamber (external electrode diameter D=94 mm, internal - 20 mm, length of electrodes was changed in steps: 50, 100, 150 mm), propellant - fluoroplastic-4, standard capacitor of IMM-3-100 type was used in the circuit.

Experimental curves, presented in Fig. 6, 7, allow to determine main thrust characteristics of low power PPT, studied by us.

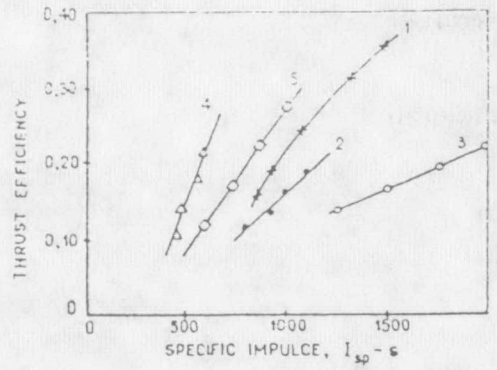

Fig. 6. Thrust efficiency as a function of specific power for the low power PPT.

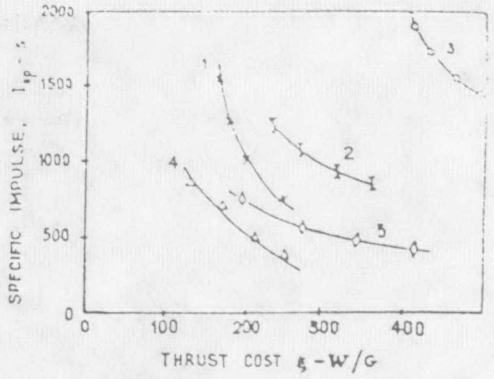

Fig. 7. Specific impulse as a function of thrust/power ratio for the low power PPT.

Test of electric propulsion set with PPT on board the high altitude probe rockets

Experiments were fulfilled on board the high altitude probe rockets of "Mir" series aimed to the comparison of PPT thrust characteristics, obtained using ground facilities, and to the determination of operating PPT influence on the spacecraft equipment [4]. Propulsion sets with PPT were developed for this in January and April, 1974. Block-diagram of one of such sets is presented in Fig. 8. The set comprises: secondary high-voltage power supply source (accumulating battery, available on board the high altitude probe, was used as a primary source), designed for converting the onboard accumulating battery voltage of 28∓4 V to the PPT operating voltage U_o=1450∓100 V and ensuring the electric energy supply to the accumulating capacitors; programme commutation device, controlling the secondary high-voltage power supply source and distributing the initiating pulses between two accelerating channels; two units of pulsed plasma thrusters, each comprising two accelerator nozzles, mounted on one capacitor; two double-channel ignition units, producing pulses initiating the PPT operation.

Cylinder external electrode (diameter 40 mm, length 60 mm) and internal electrode (diameter 20 mm, length 10 mm), between which a propellant bar of conical form is placed (Fig. 1) are the main elements of PPT design. Electrodes are mounted on the capacitor with C=30 μF, and stored electric energy was W_o=30 J at

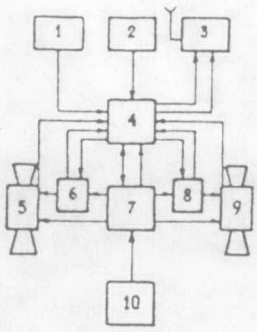

Fig. 8. Block-diagram of power plant with pulsed plasma thruster tested on board the high-altitude probe rocket. 1 - scientific equipment control system; 2, 10 - accumulating battery; 3 - radio telemetry system; 4 - programme commutational device; 6, 8 - discharge initiation systems; 7 - high voltage energy source.

operating voltage U_o=1450 V. Surface breakdown spark plug for the charge initiation in PPT was mounted inside the internal electrode. Discharge duration $\tau \approx 10^{-5}$ s, discharge current amplitude $I_d \approx 1.1 \times 10^{-4}$ A. Thruster unit and ignition unit were combined into a single unit. Commands for switching this or that PPT nozzle were generated by a control system of the probe rocket scientific equipment. Operation of above presented units of propulsion set with PPT was controlled by specially designed sensors, signals from which after conversion were transmitted to the input of onboard radio telemetry station (Fig. 8). The following parameters of power and propulsion set with PPT were registered during the flight test on the basis of onboard telemetry signals using 12 channels: power supply voltage and electric current of programme commutating device and secondary high voltage power source; voltage and current of charging in the accumulating capacitor of thrusters and capacitive units of ignition; discharge currents in the thruster channels; correlated telemetry signal of ignition unit, providing information on current presence in the circuit of ignition spark plug and on the voltage presence in the telemetry system, etc.

In the case of the first high-altitude probe rocket launch the command for starting the pulsed plasma thrusters was generated at the altitude of 200 km. PPT were operating in pairs in the

repeated mode of short duration with pulse repetition frequency of 2.7 Hz. Each pair of thrusters operated during 90 s per one cycle. Various propellants were used in thrusters: fluoroplastic-4, polyurethane with calomelol and barium chloride. Propulsion set operation stopped at the altitude of 70 km when probe entered dense atmosphere layers during the re-entry stage. Thus, plasma sets have been operating for 22 minutes within the altitude range of 70-1500 km, which corresponds to the variation of environment pressure of 10^{-3}-10^{-13} mm Hg. In the case of the second probe launch, according to the flight program the pulsed plasma thrusters were started at the ascent portion of the flight at the altitude of 800 km and their operation was finished at the same altitude at the descent portion of the flight; duration of thrusters operation was 7 min.

Telemetry data obtained during the probes flight allowed to measure thrust of each of pulsed plasma thrusters and to define all thrust characteristics. Thrust value in PPT with fluoroplastic as propellant was $F=0.43\mp0.03$ g. This value is much greater than the thrust value, measured under the laboratory conditions, but the difference is within the experiment error. Analysis of records for all telemetry channels, standard systems of high-altitude probe rockets including, showed that operation of pulsed plasma thrusters did not have any undesirable effects upon the normal operation of onboard systems, radio systems including.

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