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DESIGN OF A STATIONARY PLASMA THRUSTER

Manual

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The basic diagram and basic working processes taking place in a stationary plasma thruster are considered. The essential features required of constructional materials and the description of the SPT M-70 anode block design are given.

For the students who are taught on speciality «Spacecraft thrusters and power plants».

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TABLE OF CONTENTS

LIST OF SYMBOLS, INDICES AND ABBREVIATIONS

B - induction of a magnetic field, Тл;

DC - discharge chamber;

ERT - electro-rocket thruster;

E - strength of an electric field, B/m;

J - current, A;

PU – propulsion unit;

SFV - space flying vehicle;

SPT - stationary plasma thruster;

t - time, s;

T - temperature, K;

U - voltage, V;

W - Energy, j, eV;

ZEH - zone of electron heating;

ZCC - zone of classical electron conductivity;

ZI - zone of ionization;

ZIA - zone of ionization and acceleration.

1. The Basic Working Processes in SPT

Stationary plasma thruster (SPT) is plasma electrojet thruster of azimuthal electrons drift in which thrust is created by acceleration of ion plasma component in electric field.

The basic diagram of SPT is shown in Fig. 1. The thruster includes a discharge chamber (DC) 1 made of a dielectric material into which through the anode-gas-distributor 2 the plasma-making gas (as a rule, inert gas - Xenon) is supplied. In DC of the thruster ionization of plasma-making gas atoms by electrons and acceleration of ions take place. The magnetic system includes polar tips 3, magnetic conductor 4 and magnetization coils 5, magnetic screens 6 which allow to have a magnetic field with a big gradient along the discharge channel. The magnetic system of SPT is designed so that on the channel area where atom ionization and acceleration of ions is carried out, the magnetic field should be directed mainly on the radius with the maximum value on the edge of the discharge chamber. In practice the choice of a relative positioning of magnetic screens, polar tips, magnetization coils and matching of the amperes-coils in them is preliminary done in the form of magnetic force lines (there should be provided approximately symmetric configuration as related to the medium surface of the channel), and finally – by experimental approach according to thruster integrated characteristics [1]. The cathode-neutralizer 7 located behind the edge of the channel (a separate device in which independent gas discharge is provided), is a source of electrons necessary for keeping the main discharge and compensating the space charge of the ion jet. Part of electrons (from the plasma created by cathode-neutralizer) goes into the channel. Moving in the electric field, these electrons collect energy and ionize plasma-making gas atoms. The other part of electrons goes into the ion jet coming from DC, and compensates its space charge.

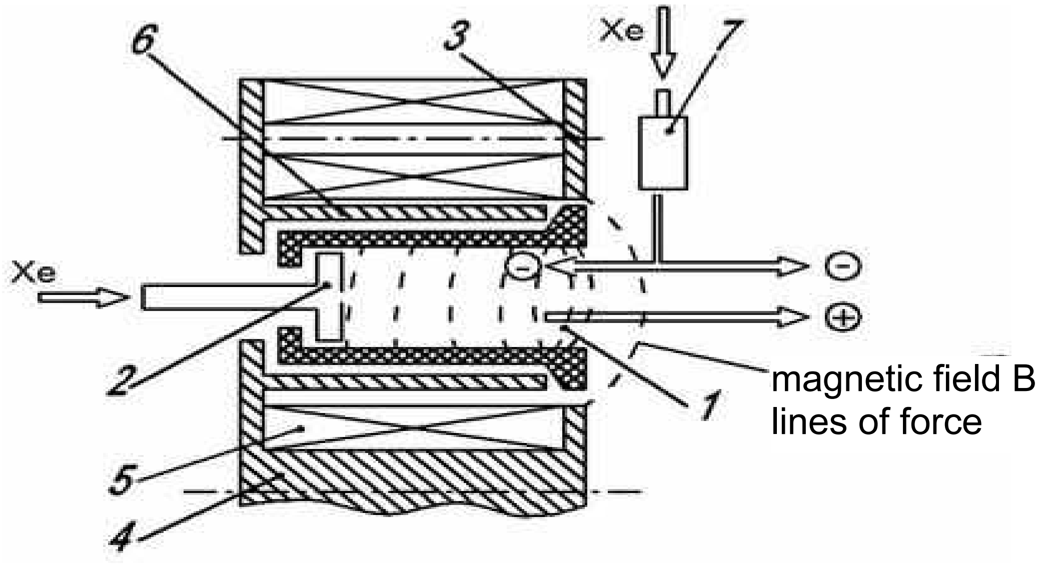

Fig. 1. The scheme of a stationary plasma thruster

As a cathode-neutralizer in SPT, discharge high-emission hollow cathodes (DHHC) are usually used. Now the most perspective as regards optimal power inputs and resource is DHHC scheme shown in Fig. 2. It has the following distinctive features [2]:

1) filling of plasma-making gas through a cathode-neutralizer working field leads to formation of a positive plasma column (in relation to the emission surface) which reduces the discharge voltage and improves surface emission properties (due to Schottki effect in thermoelectrical emission);

2) due to the presence of a diaphragm the necessary plasma-making gas pressure (required for discharge in cathode) in the working field is reached at its lower mass flow rate;

3) use of activating substances or appropriate thermo-emitter improves the working surface emission properties, as a result of decreasing the electron output potential.

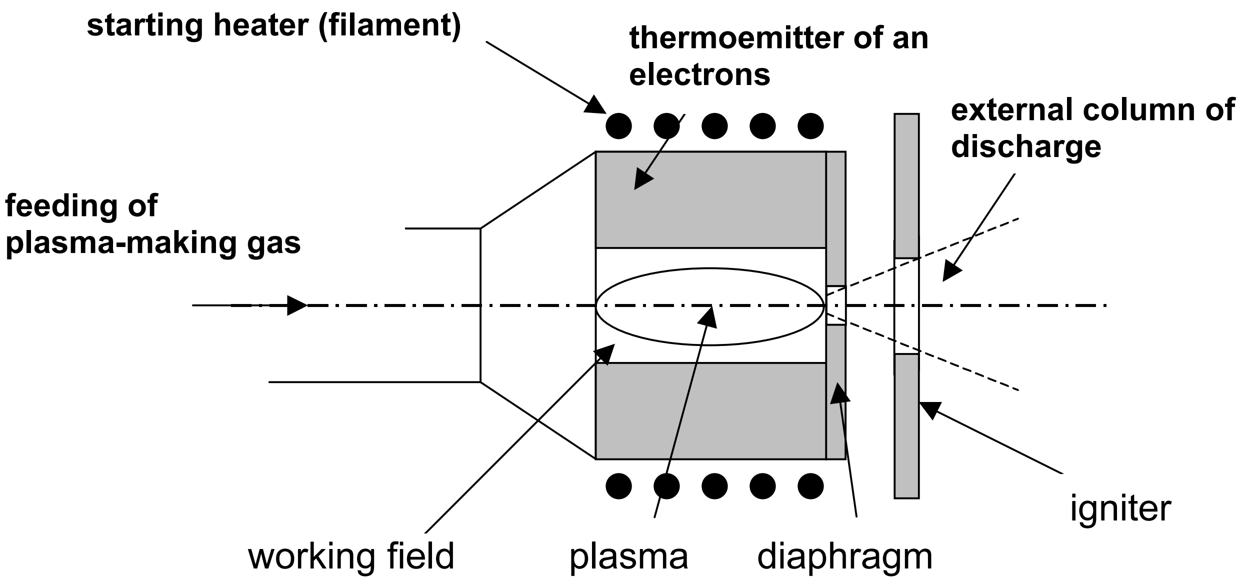

Fig. 2. The scheme of the discharge hollow high-emission cathode

To gain a better understanding of cathodes-neutralizers you may look up into the manuals [3, 4, 5].

Experimental research of an electric field formation regularity, distribution of a magnetic field induction and the directed ion current in the channel are shown in Fig. 3 [1].

Ionization of a plasma-making gas in the process of its moving to the DC outlet begins directly at the anode-gas-distributor. As plasma potential in this part of the channel is higher than the anode potential and near-wall plasma layers, the ions appearing near the anode move in the anode direction and also to the DC walls where they recombine and come back to the channel as atoms. As this takes place the energy spent on ionization and acceleration, is lost. The energy of ions recombined on the anode wall surface does not exceed 20 eV, and so the reverse ion stream does not cause dispersion of DC material (see Fig. 3).

Formation of directed ion stream which provides thrust, begins in the DC region near the edge of the accelerator where the electric field has

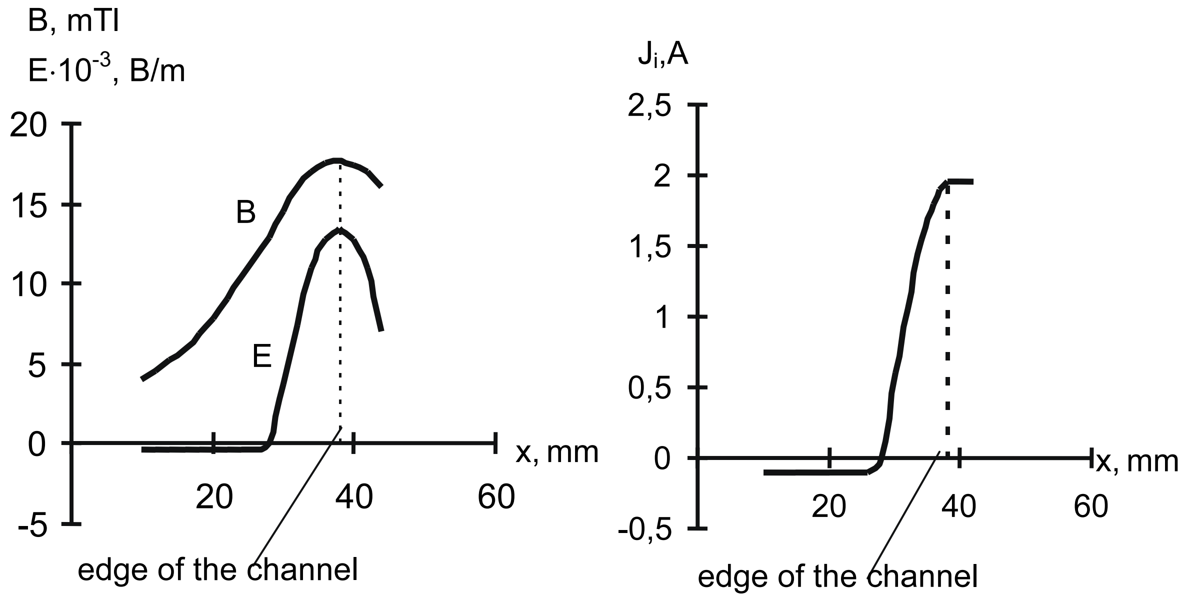

Fig. 3. The distributions of electric field intensity E, magnetic field induction B and directed ion current J_i in the SPT channel

a positive value. According to the data [1] this zone is located in DC area, where induction of the magnetic field is approximately ≈0,6 of its maximum value. This region is called a zone of ionization and acceleration (ZIA). In ZIA 3 regions [6] are usually distinguished: zone of ionization (ZI), zone of classical conductivity of electrons (ZCC) and zone of electron heating (ZEH) (Fig. 4).

The names of the zone are conventional, but they reflect some features of the processes occuring in them: intensive ionization of a plasma-making gas in the first zone, prevalence of the classical mechanism of electron conductivity in the second and gaining the energy by electrons when they move from the cathode to the edge of the channel in the third. In this region in the process of ion movement to the exit of DC, the increase of ion current, owing to ionization, gives way to its reduction as a part of the accelerated ions getting onto DC walls at the energy of $\approx 0{,}5U_p$, is neutralized and causes their sputtering.

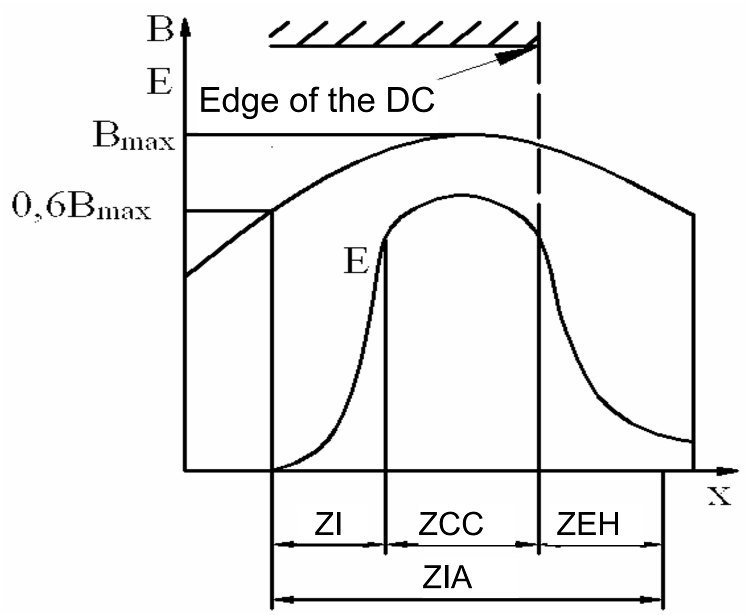

Fig. 4. A zone of ionization and acceleration (ZIA)

2. Requirements of construction materials

The basic properties of a construction material such as durability, electro-conductivity, heat conductivity, thermo-stability, etc., determine serviceability and indestructibility of a thruster at transportation and putting into orbit, and also its operation in nominal modes.

Taking into account that during the operating cycle of a thruster the anode temperature changes from the outer space cold (≈100K) up to the working temperature (≤900K), the alloyed steel 9X18H10T chosen as a material for its manufacturing, possesses high heat resistance and high threshold of cold brittleness, and also low pressure of saturated vapor that provides low speed of material evaporation into vacuum. This material is used for producing gas-feeding tubes and all fixing elements (screws, nuts, washers, etc.) as it possesses low magnetic permeability and construction elements made of it do not distort the configuration of a magnetic field.

The requirements of DC material, except for the common ones, such as durability, high melting temperature and low pressure of saturated vapor, vibration strength, adaptability to manufacturing, low cost include a number of peculiar features depending on operating conditions of the isolator in this design. They are: high electroresistance, low heat conductivity, low coefficient of ion sputtering, etc. (Table 1). Owing to ion bombardment the DC is subject to wearing and substantially determines the thruster lifetime. Nowadays nitride of boron and aluminum ("ABN – 1") is the best-investigated material for manufacturing DC, but it is also possible to use "borosil", "sialon", boron nitride (BN)$TiO_2Si_3N_4$, aluminium oxide Al_2O_3 [1] offering the lowest factor of dispersion. However its application is limited to low adaptability to machining.

Table 1

Material	α	$T_{пл}$	$\rho/10^3$	λ	C	$E/10^5$	σ_β (extension)	G
	1/K	K	Kg/м^3	W/(м·K)	KJ/(кg·K)	MPa	MPa	Kg/(м^2·s)
aluminium oxide	$9\cdot10^{-6}$	2303	3,96	2,59	1,13	3,45	240	$1{,}4\cdot10^{-8}$
beryllium oxide	$10\cdot10^{-6}$	2773	3,01	14,98	1,8	2,6	51	$1{,}3\cdot10^{-9}$
magnesium oxide	$15\cdot10^{-6}$	2773	3,58	3,48	0,78	1,91	100	$31{,}1\cdot10^{-8}$
thorium oxide		3073	9,59	5,7	0,23	1,17	100	$1{,}05\cdot10^{-9}$
zirconium dioxide	$11\cdot10^{-6}$	2973	6,27	0,72	0,7	1,18	110	$1{,}01\cdot10^{-9}$
boron nitride		3023		12,13	0,92	1,09	90	$1{,}01\cdot10^{-8}$
zirconium nitride		3273	6,88	1,4	0,55	1,11	87	-
boron carbide	$5{,}8\cdot10^{-6}$	2723	3,14	1,73	0,95	0,95	87	-

The end of the Table 1

Material	α	$T_{пл}$	$\rho/10^3$	λ	C	$E/10^5$	σ_β (extension)	G
	1/К	К	Kg/м^3	W/(м·К)	КJ/(кg·К)	MPa	MPa	Kg/(м^2·s)
flint carbide	5,2·10^{-6}	2823	4,90	0,14	1,26	0,85	49	-
tantalum carbide		4423	14,98	0,45	0,46	1,1	51	-

Nomenclature: α **-** coefficient of temperature expansion, 1/К;

T_{ml} - temperature of melting, К;

ρ - density, Кg/m^3;

λ - coefficient of heat conductivity, W/ (м·К);

C - thermal capacity, J/(Кg·К);

E - module of elasticity, Pa;

σ_β - strength, Pa;

G - speed of evaporation into vacuum (at pressure 10^{-4} Pa), Kg/ (м^2·s).

The elements of magnetic conductor made of non-retentive metals possess high magnetic permeability μ_s, low coercitive force (H_c), small losses at reversal of magnetism and a narrow loop of hysteresis (it is usually ferromagnetics). Ferromagnetics are such transitive metals as iron, cobalt, nickel.

The properties of these materials are characterized by the presence of domain in their structure. The domain is a field in which elementary magnetic moments of atoms are focused mutually in parallel and, owing to this, such material is magnetized before full saturation.

Magnetic materials should have a crystal structure, i.e. the atoms in them should be arranged in an orderly fashion. In a ferromagnetic material at temperature lower than its Curie point the values of relation of internuclear distance "a" to the radius of an electronic environment "r_d" a/r_d are given in Table 2.

Table 2

Metal	Ti	Cr	Mn	Fe	Co	Ni
$\frac{a}{r_d}$	2,24	2,36	2,94	3,26	3,64	3,96

While the temperature of a ferromagnetic increases the energy of thermal atom movement also increases, and when it reaches the critical temperature, it becomes greater than the exchange interaction energy. As a result of which the atom orderliness of the relative positioning of the nuclear magnetic moments is broken and ferromagnetic turns into a paramagnetic state.

The critical temperature compatible with transformation of ferromagnetic into paramagnetic, is referred to as **Curiy point**. Table 3 gives values of **Curiy** points (for ferromagnetics).

Table 3

Metal	Fe	Co	Ni	Cd
Curiy point, К	1041	1393	633	513

The process of ferromagnetic magnetization in an external magnetic field in coordinates of external magnetic field intensity (H) and magnetic induction (B) is shown by the curve plotted in Fig. 5.

Where H_s is a value of external magnetic field intensity at which the maximum value of induction (induction of saturation) B_s and the maximum value of magnetic permeability $\mu_m = B_s / H_s = \mathrm{tg}\ \beta$ are reached.

Attenuation of the external magnetic field leads to metal demagnetization, but the curve of demagnetization does not coincide with a curve of magnetization. This phenomenon is known as hysteresis.

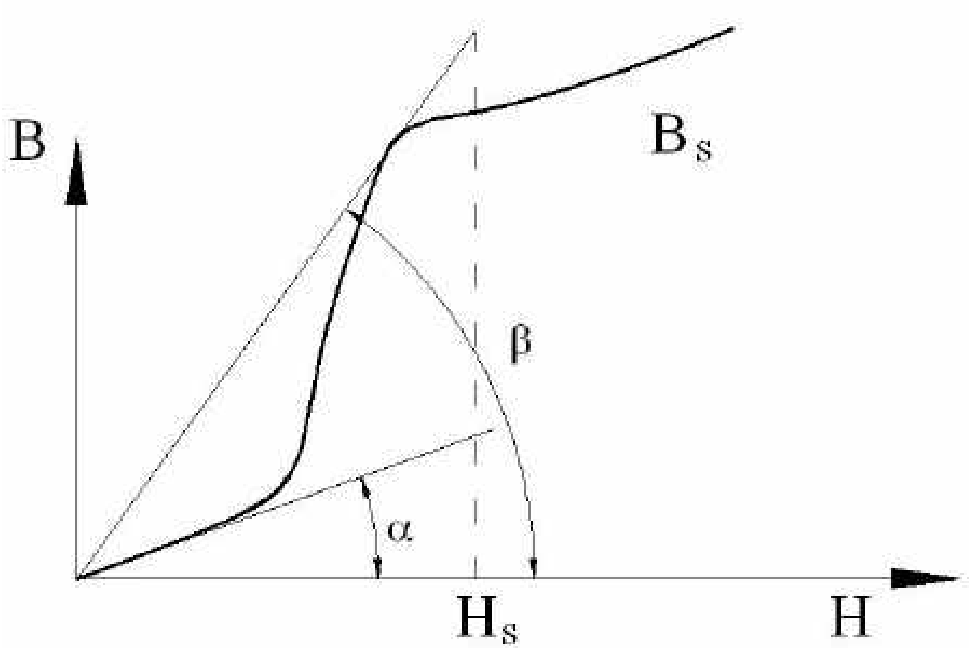

Fig. 5. Dependence of induction B on magnetic field intensity

Residual metal magnetization in this case is characterized by residual induction B_r. The value of the residual induction depends on quantity of domains of remagnetization with opposite direction of magnetization vectors. The field intensity needed for demagnetization of ferromagnetic, is refered to as coercitive force H_c. Owing to discrepancy of magnetization and demagnetization curves there is a loop of a hysteresis curve (Fig. 6).

The area of a hysteresis loop is proportional to the value of magnetic losses arising in the material at remagnetization and named losses at hysteresis. These losses are connected with the necessity in executing work to turn the domains.

Non-retentive metals used in magnetic design of the SPT, PIT, etc., are usually divided into steel and iron, taking into account the contents of carbon and technological way of its manufacturing.

Steel is iron and carbon alloys, obtained in the Martin or electric furnaces, containing no more than 0,1 % of carbon and minimum quantity of manganese, silicon, and other impurities.

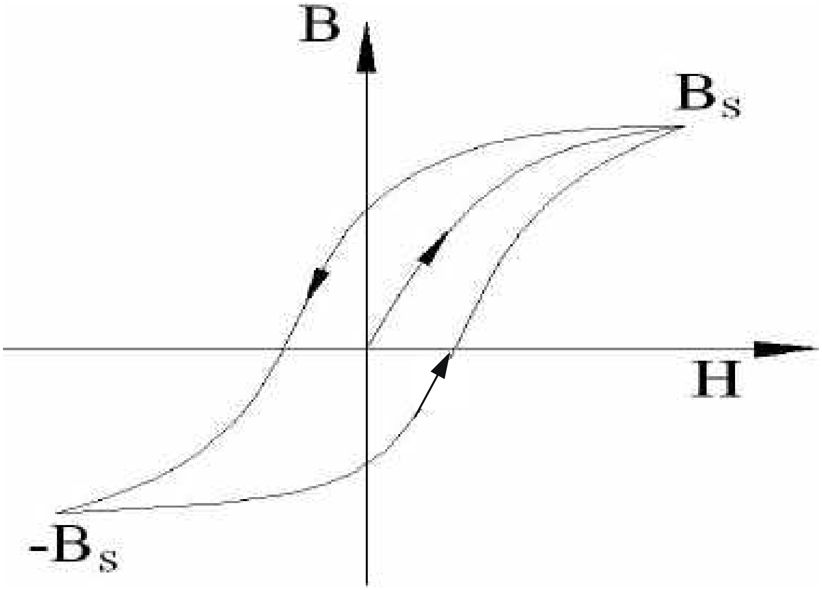

Fig. 6. The phenomenon of a hysteresis

Iron is a low-carbon steel with the contents of carbon less than 0,025%.

Table 4 gives chemical composition of these materials.

Table 4

Materials	**Chemical composition**					
	C	**Si**	**Mn**	**S**	**P**	**Cu**
«Armco-iron»	0,025	0,05	0,035	0,025	0,015	0,08
electrolytic iron	0,004	0,004	0,002	0,004	0,003	-
carbonyl iron	0,01	0,01	0,01	0,005	0,005	-

Technical iron or "**Armco**-iron" is melted in Martin furnaces. E**lectrolytic** iron is received by electrolyzing the solution of ferriferous sulfate or iron chloride, but carbonyl iron is obtained by decomposition of pentar-carbonite of iron. Table 5 shows the magnetic properties of iron of various degrees of cleanness.

Table 5

Iron	Magnetic and electric properties				
	μ_a	μ_m	Hc, А/м	Bs, Тл	$\rho \cdot 10^6, Ом \cdot м$
Technical	200	700	64	2,18	0,1
electrolytic	600	15000	28	2,20	0,1
carbonyl	3300	21000	6,4	2,17	0,1

Nomenclature: μ_a **-** magnetic permeability coefficient;

μ_m **-** maximal value of magnetic permeability coefficient;

H_c – coercive force, А/м;

B_s - maximal magnetic induction, Tl;

ρ - specific electrical resistance, Ом·м.

For winding the magnetization coils we use a copper wire in heat-resisting isolation of "ПОЖ"-type with maximum working temperatures in the range between 400 and 600^{0}C, possessing high electrical conductivity and low cost. To prevent disruption onto the case a mica dielectric spacer is inserted between the winding and the coil case.

In SPT design both soldered and glued joints are used. The essential feature required of solders and glues is retaining their electromechanical properties at peculiar operating temperatures about 300^{0}C. We use "ПСр 3 (ГОСТ19738-74)" as a solder and "K-400 (ОСТ92-0949-74)" as a glue.

3. The description of the SPT design (M-70)

The SPT M-70 anode block design (without the cathode-neutralizer) is shown on the assembly drawing. The plasma-making gas moves to the discharge chamber of the thruster through the anode-gas-distributor 1 which is fastened to the discharge chamber 2 by means of three pins, welded to the anode, threaded spigots 10 screwed onto these pins; nuts 9; lock washers 12 and washers 11. The input of an electric voltage to the anode is carried out through anode current lead 5, which is connected (after dielectric isolation) to the pipe of plasma-making gas feeding. Uniformity of plasma-making gas distribution in DC on azimuth is provided with a special design of the anode–gas-distributor which creates hydraulic resistance to the flow of plasma-making gas. The plasma-making gas from the pipe move to the first of two consecutive chambers of the anode–gas-distributor divided by a diaphragm, further it flows through 8 apertures of 0,5 mm in diameter into the second chamber from which it goes into the DC through 24 pairs of anti-directed radial apertures of 0,3 mm in diameter. The discharge chamber 2 representing a modular unit, consisting of dielectric chamber itself and a metal cylinder, is fastened to the external pole 15 by means of four screws 44. Magnetic conductor 13 is a basic load-bearing element of the thruster design to which all other elements are fastened. The surfaces of the internal and external polar tips are protected from sputtering by reverse ion streams by means of a dielectric blanket with low sputtering coefficient. In order to create a magnetic field in model M-70 the following magnetization coils are used: internal coil 3, located on the central core, and four external coils 4 located on the periphery of magnetic conductor. After installation of coils on magnetic conductor, the ends of the windings are connected with soldering and isolated. In the places of soldering the wires fastening is provided by means of special arms 21, 22 and screws 43. To prevent breakdown between winding and coil case, winding is connected to the cathode lead of the discharge circuit. The internal polar tip 14 is fastened to the central magnetic conductor core 13 by screw 45. The external polar tip 15 is fastened with four screws 38 and washers 44 to the cores of external magnetization coils 4, which, in turn, are fastened to the magnetic conductor 13 by means of bolts. The thruster is fastened to the load-bearing frame of a space vehicle by means of bolts, for which purpose four threaded orifices are made from the back side of the magnetic conductor.

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