THE EXPERIMENTAL PERFORMANCES OF THE 100 KW LI MPD THRUSTER WITH EXTERNAL MAGNETIC FIELD.

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Abstract.

According to the plan of mutual work of NASA and MAI for 1994-95 dealing with MPD thrusters of high power research in RIAME MAI in collaboration with the chair of Electric Propulsion of MAI a test model of MPD thruster with applied magnetic field with power up to 100 kW was designed, assembled and tested lithium propellant was used.

The main project parameters of the thruster are the following: discharge current 1000-2000 A voltage 50-70 V, lithium mass flow rates 60-100 mg/s, magnetic field of a water cooled solenoid B = 0,07 - -0,15 T. Flow velocities v = 35-40 km/c and thrust efficiency 40 % were expected.

Intoduction.

Preliminary investigations of thrusters of the same type, performed in MAI from 1975 to 1993 at power levels 20 to 50 kW of various designs, allowed to pinpoint the major peculiarties of their operation and the influence of electrode system geometry, external magnetic field, mass flow and discharge current on thrusters characteristics. Local diagnostics of plasma parameters with electric probes and electromagnetic probing of distribution performed in 80-s allowed to make the physical model of processes of plasma acceleration more preside. Partly the results of experiments aimed at the thrusters characteristics determination are given in [1-7].The results of investigation of local and integral plasma parameters and thrusters characteristics allowed to define the basic requirements to the thrusters design, leading to the increase of its efficiency.

To ensure the reliability of the thrusters ignition and to decrease cathode erosion at the ignition models, multyhollow cathodes with autonomous heater and lithium evaporation inside the cathode were used. Experiments showed that with cylindric anodes a significant uniformity of current distribution and temperature distribution along the anode is present,because the major part of current (~80%) is flowing to the exit edge of the anode.

Magnetic sound measurement analysis showed the necessary of anode profilation along magnetic force lines of the applied magnetic

field. Tests of the thruster of profilated anode showed that such design significantly changed electrons current density distribution which lead to more uniform distribution of temperature along the anode as well as to the decrease of the temperature to 2000 K. All the previously performed investigations of such trusters at low power levels were used as a basis for the design of a 100 kW thruster.

Experimental model design.

MPD thruster with applied magnetic field the design scheme of which is shown on Fig. 1, has four main units: the cathode unit, the anode, insulator and solenoid.

The cathode unit with a graphite heater placed inside ensures lithium heating and evaporation in the channels between the outer housing of the cathode and inner eglinder. The exit part of the cathode is formed by tungsten wires density packed, which forms multiple hollow cathodes. Lithium vapour comes through the opecings between the edges of wires as well as from the side surfaces of the openings between them. Therefore, the developed surface of emittion allows to increase significantly the average current density near the cathode avoiding intensive erosion of its surface. Independent heater of the cathode ensured the temperature of tungsten wires edges up to 1000-1200 K, consuming 3,5 kW power.

The insulator separating the cathode unit from the anode is made of aluminum boron nitride (BNA) and is placed in the area of relatively low cathode and anode temperatures ($T \leq 1700$-1800 K), which ensures its long duration operation.

The anode unit consists of a cylindric part and a profilated exit part, which accepts the main heat flow from plasma, carried by electrons. Lithium plasma radiation is insignificant.

All the main parts of cathode and the anode units, operating in extreme conditions, are made of tungsten by method of condensation from vapor with further heating in hydrogen atmosphere.

The solenoid, applying external magnetic field, is made of a copper tube of outer diameter 12 mm and inner diameter 10 mm and is water cooled. To decrease hydrolic resistance it is made of three sections.

The thruster design ensures reliable ignition while feeding

lithium in the previously heated cathode, with voltage ~40 V without applied magnetic field. The following mode of cathode and anode heating by the increase of current is necessary to increase the emittion ability of the multyhollow cathode. The increase of magnetic field with the same discharge current leads to the increase of voltage with fixed lithium mass flow rate.

Thrusters characteristics and peculiarities volt-ampere characteristic and thrust efficiency dependencies on the main parameters. All of them are complicated relationships of mass flow, discharge current and electrode system geometry.

The thruster under consideration has the thrust, consisting of three parts: electromagnetic part, due to interaction of applied magnetic field and Hall-currents; electromagnetic thrust due to the self magnetic field and gasdymamic thrust.

The first one may be expressed as:

$$T_{ed.} = K_{TH}\, J\, B_a\, D_a \qquad (1)$$

where K_{TH} - coefficient of Hall component of thrust, depending on geometry and magnitude of applied magnetic field, electrode system geometry and the may the current flows.

The magnitude of K_{TH} is within range 0,1-0,2.

J - discharge current;

B_a - applied field at the edge of the anode;

D_a - anode diameter.

Electromagnetic component due to self field.

$$T_{es} = K_{TS} \cdot 10^{-7}\, J^2 \qquad (2)$$

As soon as magnetic pressure in such thrusters is less than gasdynamic pressure K_{TS} may be determined by the relation of anode average radius to that of the cathode: $K_{TS} \approx \ln \frac{R_a}{R_c}$. The existing design gives $K_{TS} \approx 1{,}6$.

Gasdynamic component of thrust is defined by the change of lithium propellant impulse while passing the cathode and by pressure to the butt of the cathode.

If is well known that at the exit of a hollow cathode with moderate currents plasma velocity is equal to ion sound velocity.

Therefore, gasdynamic component of thrust may be determined as

$$T_{g.d.} = m\dot{a} + p_c S_c \qquad (3)$$

where a - ion sound velocity;

p_c - pressure near the cathode,

S_c - square of cathode.

This relation can be easily rewritten in

$$T_{g.d.} \approx 1{,}6\ \dot{m} \qquad (4)$$

Electron temperature at the exit of the cathode is 1-1,5 eV, which is approved by probing. Thrust characteristics are shown on Fig.2. There is a satisfactory correspondence between calculated and experimental data.

Volt-ampere characteristics calculation is much more complicated. This is connected with variation of temperature near the anode with the increase of current and magnetic field, as well as with variation of anode voltage drop. Lots of experiments, made earlier, aimed at determination of plasma parameters inside the thruster, showed that the stated effects are present. That is why the balances methods of voltage determination by power expenditures gives satisfactory result a only relatively low magnetic fields.

Volt-ampere characteristics (Fig.2a) show the increase of voltage in comparison to calculated results with the increase of magnetic field.

Thrust efficiency of the engine not taking into account energy losses on magnetic field and cathode heating, is determined by a known relationship:

$$\eta_T = \frac{T^2}{\dot{m}\, V\, J} \qquad (5)$$

This value is always greater than total thrust efficiency, including all the losses

$$\eta_{T\Sigma} = \frac{T^2}{\dot{m}\,(VJ+N_S+N_H)}$$

Preliminary experiments on moderate modes showed the total thrust efficiency up to 34% with specific impulse 32 km/sand power in discharge ~ 90 kW.

Conclusion.

Testing of the designed thruster model showed its workability, reliability of ignition in range of current 1000-1500 A, magnetic field B=0,045-0,09 T, mass flow 50-60 mg/s.

At maximal modes thrust efficiency of 35% with specific impulse 35 km/s was obtained.

Cathode and anode temperature measurements showed $T_e \approx 3000$ K, $T_a \approx 1900$ K.

The increase of current from 1500 to 2000 A with corresponding increase of mass flow and magnetic field will ensure the increase of thrust efficiency to 40% with not significant increase of specific impulse.

The developed thruster model can operate at power levels greater than 100 kW which opens the way for thrusters creation with power levels 200-250 kW in one module. The main problem is the increase of cathode life time.

As soon as electrode erosion investigations on thrusters of such a power level are extremely difficult and expensive, this tasks should be solved on the models of lower power, with electrode loading simulation.

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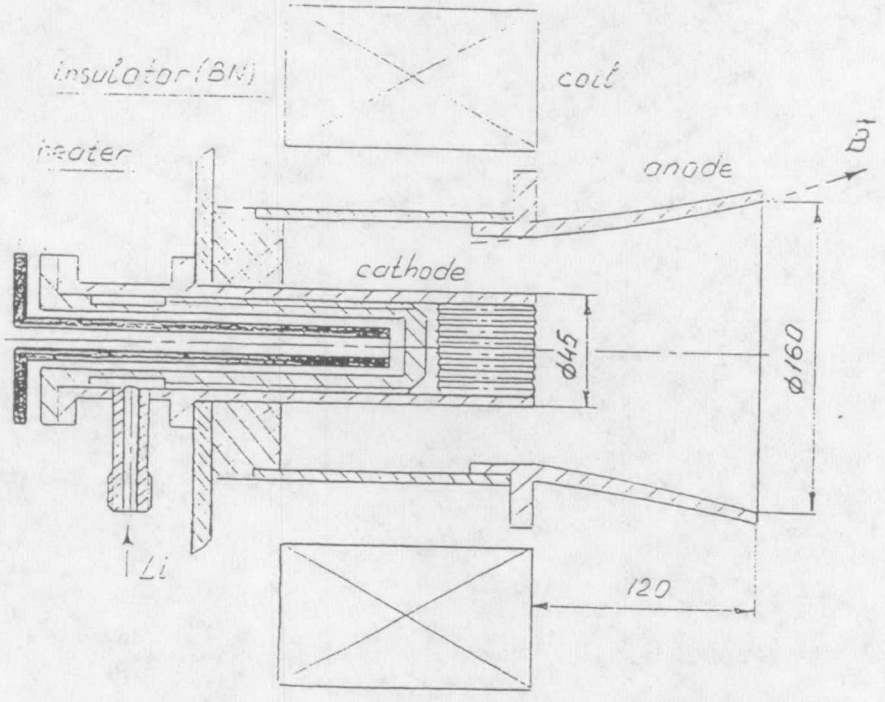

Fig 1 MPD-thruster design diagram.

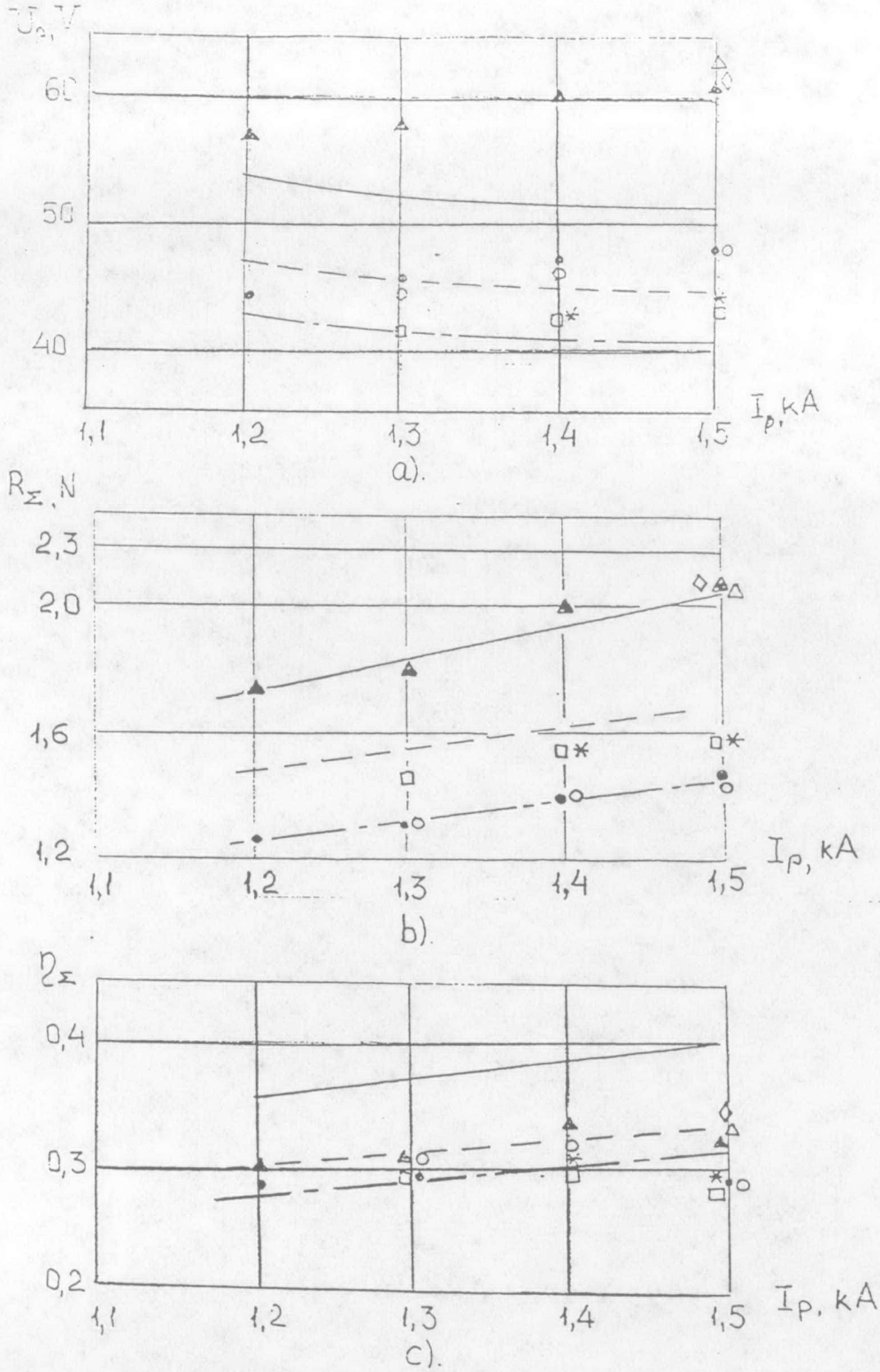

Fig. 2 Thruster characteristics.

$B_K = 0.045\,T$: $\dot{m}$ = ○ - 45 , ∘ - 47, * - 61, □ - $62 \cdot 10^{-6}$ kg/s

$B_K = 0.09\,T$: $\dot{m}$ = ◇ - 61, △ - 62, ▲ - $65 \cdot 10^{-6}$ kg/s

Theory : —— $B_K = 0,09\,T$, $\dot{m} = 60 \cdot 10^{-6}$ kg/s

– – – $B_K = 0,045\,T$, $\dot{m} = 60 \cdot 10^{-6}$ kg/s

—·— $B_K = 0,045\,T$, $\dot{m} = 50 \cdot 10^{-6}$ kg/s