# OWN MAGNETIC FIELD IMPACT ON MPD THRUSTERS PERFORMANCE WITH EXTERNAL MAGNETIC FIELD

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## Abstract.

While discussing transport tasks of heavy vehicle space missions towards Moon and Mars, the problems of thruster choice for such missions arise inevitably. The discussion on thruster type and their performance is continued.

The conception of utilizing of MPD thruster with external magnetic field proposed by JPL and in the other papers involves thruster application with rated power 0,5-1,5 MW per one module. Characteristic parameters of such thrusters are: specific impulse 4000-6000 s, thrust efficiency 45-60% - under external magnetic field $B_{ext}$=0,3-0,4Tl.

The main restriction preventing from reaching such high parameters is the current crisis mode (onset phenomenon) related to charge transport conditions in the near-anode area.

Experimental studies of the lithium MPD thruster characteristics with external magnetic field, power from 100 to 200 kW, discharge current from 1700 to 2900 A have revealed some peculiarities in their operation.

In the paper presented there are discussed the reasons for the mentioned thruster characteristics changes under current increase and necessary changes of electrode system elements, magnitude and topology of the external magnetic field based on gained experimental data.

Conducted tests of the lithium thruster with power 200kW at external magnetic fields 0.07-0.09 showed the possibility to increase specific impulse up to 4000-4500 s and total thruster efficiency up to 47-50%.

## 1. Introduction.

The concept of nuclear power plant proposed by JPL[1] for manned Mars mission calls for utilizing lithium MPD thrusters with rated power 750 kW in one module. The same proposals were under consideration in Design Bureau named after S.P.Korolev (NPO "Energia") in the late 60-s - the beginning of 70-s. As EPT it was also considered a lithium MPD thruster with own (internal) magnetic field and power 500 kW in one module.

The experimental model of such thruster was developed in NPO "Energia" and underwent tests at specially built facilities in NPO "Energia", MAI and DB "Fakel". The thruster's characteristics were close at all three facilities.

The design diagram of 500 kW thruster, its peculiarities and main parameters are presented in [2].

The peculiarities of working processes in the high power thrusters with own(internal) and external magnetic fields, and experimental data on determination of parameters of plasma, electric and magnetic fields, and also stability boundary on current crisis were discussed in [3, 4].

The prospects of spacecraft payload increase due to use of EP and existent launchers attract more and more attention, especially during last decade. The following three problems are of the most interest: deliverance of heavy spacecraft onto geostationary orbit with the following returning on the base orbit; the similar mission Earth – Moon – Earth, and at last the problem of manned Mars mission.

Conducted estimations showed that to solve the first problem it is enough to use EP with power 100-250 kW, specific impulse 35-65 km/s at thrust

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efficiency 40-70%[5]. These parameters are also acceptable to solve the second problem. But the Mars expedition requires, according to the estimations, increase of the board power plant up to the 1-10MW level, with EP power in one module 500kW-1.5MW[6].

The most acceptable thruster for solving such problems is a lithium MPD thruster with own and external magnetic field. To test this thruster it is necessary to create a special facility and spend much time and efforts. Therefore experimental work on 150-200kW lithium MPD thruster enhancement is a necessary stage.

## 2.Design peculiarities of the 20kW thruster.

The principal design scheme of 100-130kW lithium MPD thruster was presented in our paper at 1997 Cleveland conference[7].

Experimental data on 135kW characteristics showed the possibility of increase the developed thruster model power up to 200kW with some alteration in design of the cathode and anode unit. Taking into account the fact that with current increase up to 3kA and earlier accepted ratio between anode and cathode diameter $D_a/D_c \approx 3.55$, besides the rise of the load on the cathode and anode surface, the range of thruster stable operation is limited and therefore specific impulse is limited too, it was decided to increase cathode diameter. The anode outlet diameter remained the same $D_a$ = 160mm. It was manufactured two cathode units with outlet diameters 52.5 and 55 mm, at these diameters the ratio $D_a/D_c$ was 3.05 and 2.91 correspondingly.

In the case of the 200 kW thruster, in some modes of the first test stage already we faced the appearance of current critical regions within the range of 1700-3000 A, which had not been observed earlier at the same mass flow rates and magnetic fields.

The following relation is a criterion defining the critical modes:

$$A_{0cr} = I\cdot B_c\,(R_a - R_c)\,10^{-7}/\mu_0\cdot a\cdot \dot{m} = \\ =3.6/(R_a/R_c - 0.5), \qquad (2.1)$$

where: I - discharge current, $R_a$ and $R_c$ - radius of cathode and anode, correspondingly, $\mu_0 = 4\pi\cdot 10^{-7}$ H/m, a - sound velocity in plasma, m - mass flow rate. $B_c$ - magnetic induction at the cathode cut. This criterion was validated earlier during the tests within the broad range of parameters using various propellants.

## 3. Distinctions of applied magnetic field on MPD thruster characteristics at high current.

Results of the tests and characteristic determination of the 150kW thruster agree well with calculation data at mass flow rate 80-100 mg/s, current 1500-2100 A and external magnetic field $B_{ext}$=0.045-0.09T[7]. Own magnetic field did not impact the stability of thruster operation under pointed modes. But with current increase the influence of pinch-effect and Hall-effect become stronger in the near-anode sheath. Since these effects are defined by impact of the total magnetic field existing in plasma it is necessary to take into account the impact of own magnetic field.

Equation (2.1) defines the relation between volumetric and gasdynamic forces. At low currents the contribution of self magnetic field into the volumetric force of plasma compression is not high and magnetic induction near the cathode may be determined on the basis of applied magnetic field produced by solenoid.

With the current growth the plasma is influenced by the total magnetic field, defined by applied field and self magnetic field of currents.

Thus, plasma compression (pinch-effect) is defined by two components of volumetric electromagnetic force: $j_\varphi B_z$ and $j_r B_\varphi$..

It is necessary to take this into account while defining critical currents using (2.1).

Cathode unit of 200 kW thruster is made in two variants with cathode diameters of 52 and 55 mm. Outlet diameter of anode is 160 mm.

Thus, the critical values ($A_{0cr}$) are 1.4 and 1.494, correspondingly.

Self magnetic field near the external cathode surface is defined by Ampere law:

$$B=\mu_0 J/2\pi r$$

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Self magnetic field near the external cathode surface is defined by Ampere

$$B_s = 2\bullet 10^{-7}\, I/R_c \qquad (2.2)$$

Total magnetic field $B_\Sigma = B_{appl} + B_s$ for the thruster with cathode of 52 in diameter is presented in Table 1.

Table 1.

| $B_{appl}$ / $I_d$, kA | 0.045 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|
| 2.0 | 0.0604 | 0.0654 | 0.0754 | 0.0854 | 0.0954 | 0.1054 |
| 2.25 | 0.0623 | 0.0673 | 0.0773 | 0.0873 | 0.0973 | 0.1073 |
| 2.5 | 0.0642 | 0.0692 | 0.0792 | 0.0892 | 0.0992 | 0.1092 |
| 2.75 | 0.0661 | 0.0711 | 0.0811 | 0.0911 | 0.1011 | 0.1111 |
| 3.0 | 0.0681 | 0.0731 | 0.0831 | 0.0931 | 0.1031 | 0.1131 |

The above Table shows that the total magnetic field grows in plasma with the current increase; this leads to the reduction of tolerable currents at a given mass flow rate.

It follows from (2.1) that:

$$I_{cr} = A_{cr}\cdot 12.56\cdot a\cdot m/(R_a - R_c)B_\Sigma$$

It was shown earlier that it is inadvisable to increase the applied magnetic field, because reduction of critical current limits both specific impulse of the thruster and its thrust efficiency.

Critical current limitation becomes even more substantial in view of the self magnetic field. But this has a positive side also. At high discharge currents, realized in the high power thrusters, it is not necessary to use solenoid generating high applied fields. It may be substantially smaller in dimensions and mass and consume less power for creating the magnetic field. This will lead to the growth of total thrust efficiency.

The main role of applied magnetic field will be to provide more uniform distribution of current density over the anode surface.

Self magnetic field influence upon the critical current for the thruster with $D_c$ = 52 mm at $B_{appl}$ = 0.09 and different mass flow rates is shown in Table 2. Upper digit corresponds to the critical current not accounting for the self field of the current, while the bottom one corresponds to the total magnetic field.

Table 2

$B_{appl}$ = 0.09

| $I_d$ | $\dot{m}$, mg/s / $B_\Sigma$ | 80 | 90 | 100 | 110 | 120 |
|---|---|---|---|---|---|---|
| 2.0 | 0.1054 | 2828<br>2370 | 3180<br>2670 | 3570<br>2970 | 3930<br>3260 | 4560<br>3560 |
| 2.25 | 0.1073 | 2828<br>2330 | 3180<br>2620 | 3570<br>2910 | 3930<br>3200 | 4560<br>3500 |
| 2.5 | 0.1092 | 2828<br>2290 | 3180<br>2580 | 3570<br>2860 | 3930<br>3150 | 4560<br>3440 |
| 2.75 | 0.1111 | 2828<br>2250 | 3180<br>2530 | 3570<br>2810 | 3930<br>3090 | 4560<br>3380 |
| 3.0 | 0.1131 | 2828<br>2210 | 3180<br>2490 | 3570<br>2760 | 3930<br>3040 | 4560<br>3320 |

It follows from Table 2 that for the thruster model with cathode diameter $D_c$ = 52 mm at the operation modes with currents of 2.5 - 3.0 kA the minimum mass flow rate is 110 mg/s in the case of applied field with $B_{appl}$ = 0.09 T. Deviations in current and mass flow rate are possible at discharge current variation. These deviations may cause the appearance of critical modes with all outflowing consequences.

The range of stable operation is slightly broader in the case of thruster model with cathode diameter $D_c$ = 55 mm.

It is necessary the decrease the applied magnetic field down to 0.06-0.07 T while investigating the 200-300 kW thruster performance in order to take into account the self magnetic field influence upon the critical current value.

### 3.1 Interrelation of thrust and current-voltage characteristics of the thruster.

Test results for defining the thrust and current-voltage characteristics of 150 kW thruster are in good correspondence with calculation data; the difference is within the measurement error. This good correspondence is stipulated by two reasons:

1. Calculation dependence for the thrust represents correctly the distinctions of physical processes, defining the variations in the propellant impulse during acceleration.
2. Rather substantiated determination of energy consumption for ionization, into the thruster electrodes and of the dependence for the anode potential drop variation as a function of current, mass flow rate and magnetic field.

These distinctions of calculation dependencies for the thrust and current-voltage characteristics allow to state that at good correspondence of theoretic and experimental current-voltage characteristics there will be rather accurate correspondence of calculation and test data for the thrust.

So, while conducting methodological tests on determining the plasma parameters, current and magnetic field distribution it is advisable to fix the current-voltage characteristic for the thrusters as an index of operation mode, and thrust may be measured from time to time at some modes.

It is important to provide stable mass flow rate to the thruster at the modes with maximum thruster efficiency (which are close to the critical modes in current or magnetic field).

At such modes even relatively low fluctuations of mass flow rate may cause deviations in potential difference at all other parameters being constant.

### 4. Test data for the 200kW thruster characteristics.

During the tests, our wish to obtain high specific parameters for the thruster at applied magnetic field $B_{appl}$ = 0.09 T faced sudden limitations in the current critical values. This phenomenon was analyzed after the test series described in Part 3. It was explained by the total effect of applied and self fields of currents upon the shift of stable operation boundary towards lower currents, as it is shown in Part 2.

A set of curves of Fig. 1 illustrates the total magnetic field influence on critical currents at different mass flow rates.

There is a clear tendency for the mass flow rate growth with discharge current and applied magnetic field within the power range of 150-200 kW at maximum discharge current of 3 kA (V~ 50-60 V) for providing the stable thruster operation.

Within the range of magnetic fields with $B_{appl}$ = 0.07 - 0.09 T, in which high specific impulses and thrust efficiency may be expected to obtain, the minimum mass flow rate is 90-110 mg/s at current of 3 kA.

Calculation assessments showed that in this case it is possible to reach the specific impulse $J_{sp}$ = 40 km/s and total thrust efficiency $\eta$ = 0.47-0.49.

Thruster characteristics at $B_{appl}$ = 0.045 T are presented in Fig. 2 a, b, c.

Current-voltage characteristics of the thruster at different mass flow rates are in satisfactory agreement with calculation data. But insufficient number of thrust measurements did not allow to get statistics for the specific impulse and thrust efficiency.

Thruster characteristics at magnetic field D = 0.068 T and 0.09 T are presented in Fig. 3.

One can see the disagreement in test and calculation data for the current-voltage characteristic and more satisfactory agreement for the thrust.

Specific impulse Jsp = 41 km/s and efficiency T| = 0.48 at power N = 190 kW were obtained in the maximum mode with I = 2.9 kA, Bappi = 0.09 T and m=107 mg/s.

Nevertheless, experience in de-bugging the thruster and test bench systems revealed all vulnerable elements and scopes for increasing the efficiency of such thrusters. Besides, all difficulties demonstrated the necessity in more detailed study for the 200 kW thruster characteristics for providing a more competent approach to designing and testing more powerful thrusters designed for the power of 500-1000 kW.

## Conclusion.

The developed 200 kW thruster model required to make substantial changes in the systems for cooling the test stand structural elements, thrust metering device, current leads to the thruster and to provide more intense heating for the cathode at start and operating modes.

Results of preliminary thruster tests revealed all weak elements in the stand systems causing unstandard situations during the thruster tests. Main breaks in the operation modes were mainly connected with disadvantages in the design of subsidiary units of the stand, with the underestimation of importance for providing the reliable insulation for the current leads and other elements at their severe heating due to thermal conductivity and radiation of thruster electrodes.

Test data analysis showed that the developed model provides stable and reliable start at the voltage of 40 V and preliminary cathode heating up to T~1200-1400°C.

At low applied magnetic field with $B_{appl} \leq$ 0.07-0.09 T an unexpected reduction of the critical current took place at simultaneous discharge current growth and thruster entered the ion-sound modes. Analysis of test results confirmed our assumption on the influence of self magnetic field on the critical current reduction.

In spite of the difficulties during the 200 kW thruster tests and insufficiency of test data the tendency to the specific impulse and thrust efficiency growth up to $J_{sp}$ = 40 km/s and $\eta$ =0.48 was confirmed.

Preliminary test results showed that the study of thruster characteristics and distinctions of its operation under stand conditions at power of 200 kW and over requires more detailed approach.

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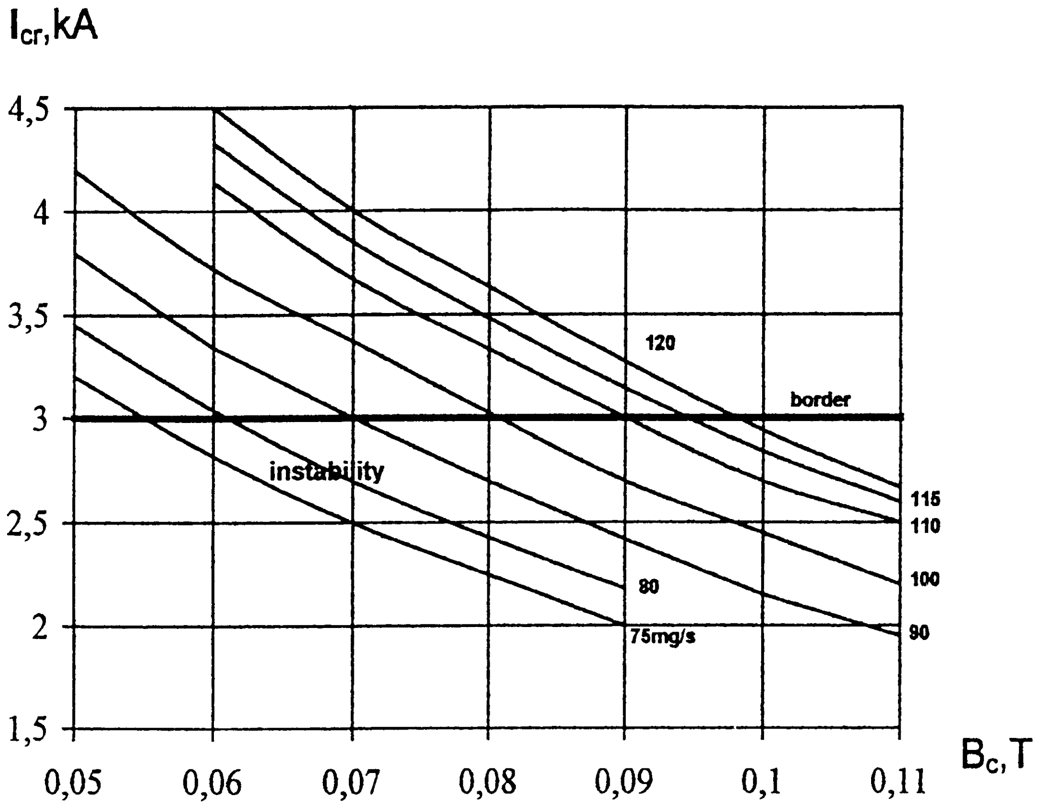
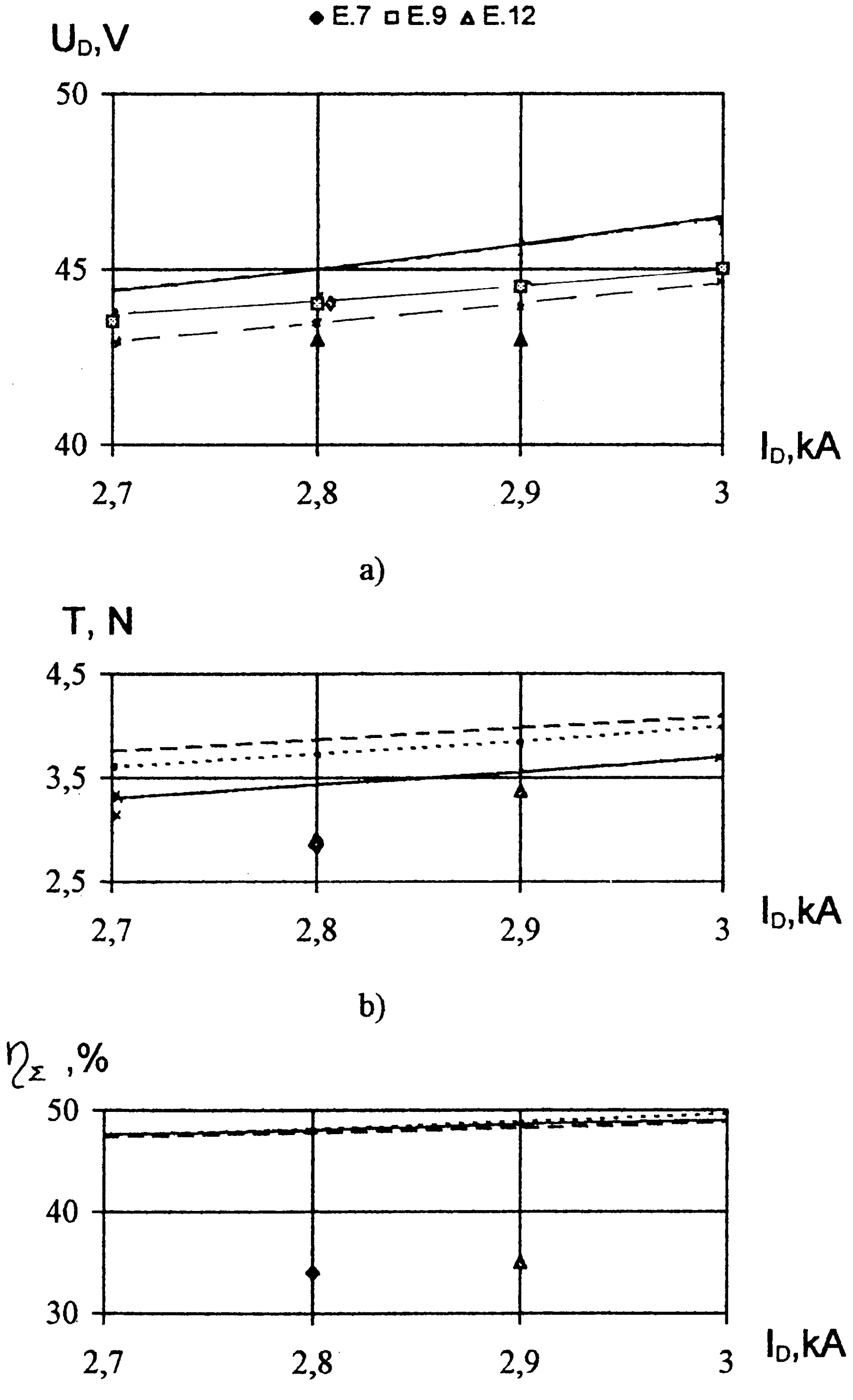


Fig.1 Critical currents at discharge current $J_d$ = 3kA and different mass flow rates.



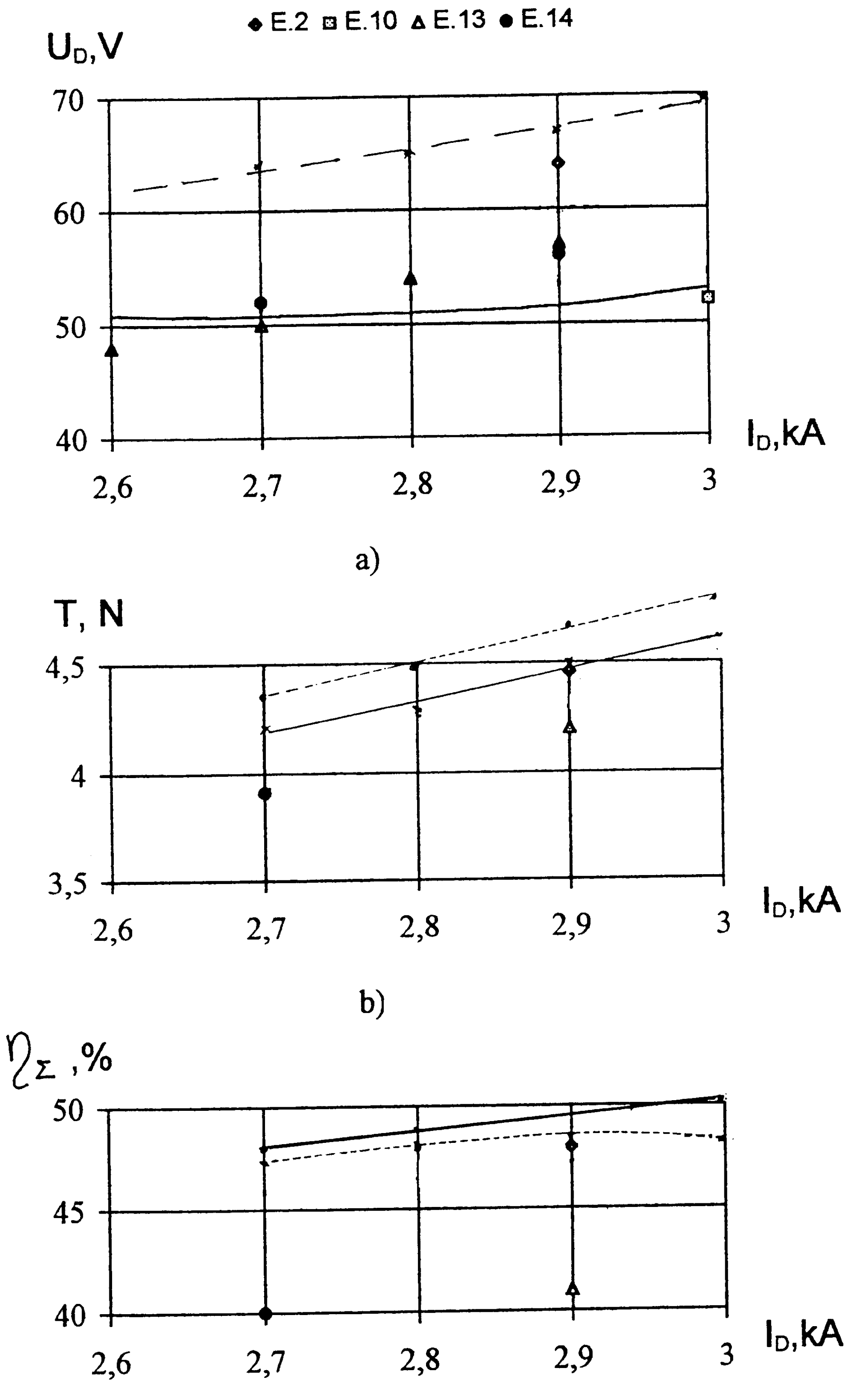
a)

b)

c)

Fig. 2 Thruster characteristics.

$B_c$ = 0.45T: ◆ m=92mg/s; —— m=90mg/s – theory.
◻ - m=110mg/s; ------- m=110 mg/s – theory.
Δ - m=126mg/s; —· — m=120mg/s - theory



a)

b)

c)

Fig. 3 Thruster characteristics.

$B_c$ = 0.0675T: Δ - m=124mg/s; □ - m=125mg/s; • - m=128mg/s; —— m=90mg/s – theory.

$B_c$ = 0.090T: ♦ m=107mg/s; ------ m=110 mg/s – theory.