Investigation of SPT Performance and Particularities of it's Operation with Kr and Kr/Xe Mixtures*+

Vladimir Kim, Garry Popov, Vyacheslav Kozlov, Alexander Skrylnikov, Dmitry Grdlichko
Research Institute of Applied Mechanics and Electrodynamics of Moscow Aviation Institute (RIAME MAI)
Address: 5, Leningradskoye shosse, post box 43, Moscow, 125080, Russia
Phone:+7 (095) 1580020 Fax:+7 (095) 1580367 e-mail: riame@sokol.ru

IEPC-01-065

Experimental study results on the stationary plasma thruster (SPT) operation with Kr/Xe mixtures are represented in a paper. Such mixtures are cheaper than pure Xe mainly used in a modern propulsion system (PS). Therefore there is the possibility to reduce the PS propellant cost and expenses for propellant to be spent during thruster tests especially significant during life time tests. Obtained results show that thrust efficiency η_T is gradually reduced with reduction of Xe fraction in a mixture. Nevertheless there is the possibility to obtain the accelerator thrust efficiency (calculated not accounting for cathode mass flow rate) at level of ~50% and higher. It is shown also that acceptable performance level of SPT operating with Kr could be achieved under comparable with Xe case discharge voltages and mass flow rates what causes an increase of discharge current and power. Therefore it will be more difficult to ensure large thruster life time under its operation with Kr.

Specific impulse of thruster operating with Kr could be higher than in Xe case under the same discharge voltages but this increase typically is not so significant due to lower thrust efficiency. It is necessary also to take into account that Kr and Kr-Xe mixture storaging is more complicated than Xe storaging . So, there are some advantages and disadvantages of Kr and Kr/Xe mixtures as a prospective propellants of SPT-based PS

Introduction

As it is well known the stationary plasma thrusters (SPT) are successfully used in space and nowadays their application is extended significantly [1]. As a propellant of modem SPT's there is used only xenon due to its unic properties. But Xe is expensive enough. Therefore it is interesting to study the possibility to use other gases as the SPT propellants. Such studies were made earlier [2], but they was not systematic. Nowadays it is necessary to obtain more concrete and complete data on thruster performance and particularities of its operation. One of such studies were made at RIAME MAI and it was devoted to investigation of the SPT-100 scale thruster operating with Kr and Kr/Xe mixtures. Because Kr is cheaper at least by an order of magnitude than Xe implementation of Kr could reduce the propulsion subsystem cost and cost of propellant to be spent during thruster ground tests especially during its life time tests. Taking all the mentioned into account there was made characterization of SPT-100 scale laboratory model operating with Kr and Kr/Xe mixtures with fraction of Kr from 0 till 100%. Obtained results are represented below.

This study was fulfilled within the frames of INTAS 99-01225 project as well as under support of Russian Basic Research Fund (grant No 00-15-99025).

1. SPT laboratory model and test methodology description

To realize performance characterization of thruster operating with Kr and Kr/Xe mixtures there was used the SPT-100 scale thruster laboratory model

* Presented as Paper IEPC-01-065 at the 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October, 2001.

(Fig. 1) having magnetic system allowing variation of the magnetic field topology inside the accelerating channel, namely:

- there was the possibility to use magnetic poles with two interpolar gaps as well as magnetic screens of two sizes what gives several magnetic system configurations. One of them was similar to SPT-100 magnetic system configuration (Fig. 1, option a);
- there was the possibility to use the main (as in SPT-100) coils and one additional coil positioned inside magnetic screens (as in PPS-1350 model) and allowing significant change of magnetic field topology in a thruster by creation of additional magnetic field with the same or opposite direction relative to magnetic field induced by main coils (Fig. 2).

There was foreseen also the possibility to increase the accelerating channel length from 21 mm (characteristic for SPT-100) till 31 mm. Thruster performance characterization was made under its operation with fraction of Kr mass flow rate in a mixture from 0 till 100%. For characterization there was used the test facility with vacuum chamber of 2 m in diameter and 6m in length equipped by thrust-meter, mass flow meters and apparature for the accelerated ion current distribution measurements in a plume. The last measurements were made by RPA probe mounted on a boom rotating along circular curve within ±90° with radius $R_p \approx 0{,}7$m and center located at thruster exit plane (this curve and thruster axis were in a one plane). RPA collector had potential +50V relative to cathode as in [3].

Using data on accelerated ion current distribution there was determined the half-angle $\beta_{0,95}$ of cone coaxial to thruster and containing 95% of total measured ion current at distance $R_p \approx 0{,}7$m to estimate thruster plume divergence.

Characterization was made under comparable with pure Xe case ranges of operation mode parameters what is understandable if some one takes into account that free path of atoms before their ionization $\lambda_i \sim \frac{V_a}{<\sigma_i V_e> n_e}$, where V_a is the mean atoms velocity, $<\sigma_i V_e>$ is the ionization rate factor, $n_e \approx n_i$ is plasma density number. To obtain mass utilization efficiency comparable with Xe case it is natural to satisfy the following condition for Kr and Kr/Xe mixtures:

$$\left(\frac{\lambda_i}{L}\right)_{Kr} \approx \left(\frac{\lambda_i}{L}\right)_{Kr/Xe} \approx \left(\frac{\lambda_i}{L}\right)_{Xe}, \qquad (1)$$

where L is the accelerating channel length.

For operation modes with high enough mass utilization efficiency one can obtain [4] the following restriction for mass flow rate density

$$\frac{\dot{m}}{S_c} \geq \frac{V_i V_a}{<\sigma_i V_e> L} \approx C\frac{\sqrt{kT_a e U_d}}{<\sigma_i V_e> L}, \qquad (2)$$

where U_d is the discharge voltage, $\dot{m}_a$ and S_c are the mass flow rate through the accelerating channel and accelerating channel cross-section area, respectively, kT_a is the atoms temperature (in energetical units) could be assumed equal to the discharge chamber wall temperature, e is an electron charge, C≈const is the proportionality factor.

Considering nonequality (2) one can conclude that the mass flow rate density in the Kr and Kr/Xe mixtures are to be close to the Xe case, because it was expected that $<\sigma_i V_e>$ values are to be comparable for Kr and Kr/Xe mixtures and for Xe.

Then, because discharge current $I_d \sim \dot{m}_a$, where $\dot{m}_a$ is the mass flow rate through the accelerating channel, it becomes evident that power density under the same level of U_d is to be higher for Kr and Kr/Xe mixtures. The necessity to use comparable level of U_d follows from consideration of thrust efficiency dependence on U_d [5]

$$\eta_a = \frac{\dot{m} < V_z >^2}{2N_d} = \frac{I_i}{I_d}\eta_i \cdot \eta_\beta \cdot \eta_V \cdot \eta_\varepsilon \approx$$
$$\approx \frac{I_i}{I_d}\eta_i \cdot \eta_\beta \cdot \eta_V (1 - \frac{C_2 \Phi_i}{eU_d}) \approx C_1(1 - \frac{C_2 \Phi_i}{U_d}), \qquad (3)$$

where $<V_z>$ is the mean value of exhaust velocity longitudinal component, I_i is the ion current at thruster exit, I_d is the discharge current, η_i, η_β, η_V, η_ε reflect different kind of energetical losses, C_1 and C_2 characterizes the quality of thruster operation organization determining the mentioned losses, Φ_i is the propellant atoms potential of ionization.

From this expression one can derive that under the same level of C_1 and C_2 values to obtain high enough efficiency it is necessary to operate thruster with Kr or Kr/Xe mixture under comparable or higher discharge voltages relative to Xe case.

Taking all the mentioned into account characterization of thruster model with Kr and Kr/Xe mixtures was made under mass flow $\dot{m} = (3-6)\frac{mg}{s}$ and $U_d = (200\text{-}700)V$. The main magnetization currents (I_{m1} in internal coil and I_{m2} in external coils) were optimized using discharge current minimum criterion. If there is applied an additional magnetization coil the procedure of I_{m1} and I_{m2} values optimization was used for series of magnetization current I_{m3} values in this additional coil.

2. Results of characterization

At the beginning there was made the described SPT

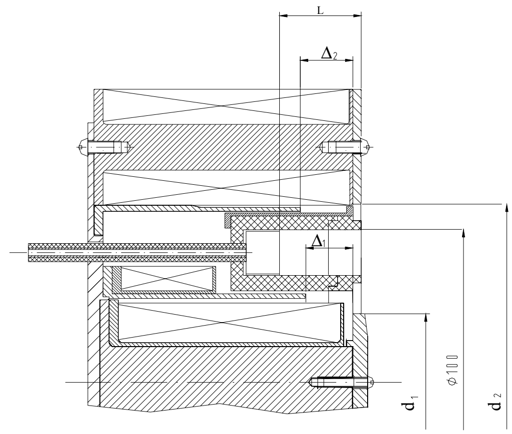

Figure 1 - SPT laboratory model design diagram.

Options	L, mm	d_1, mm	d_2, mm	Δ_1, mm	Δ_2, mm
a	21	45	117	2	6
b	21	45	117	20	20
c	21	62	106	20	20

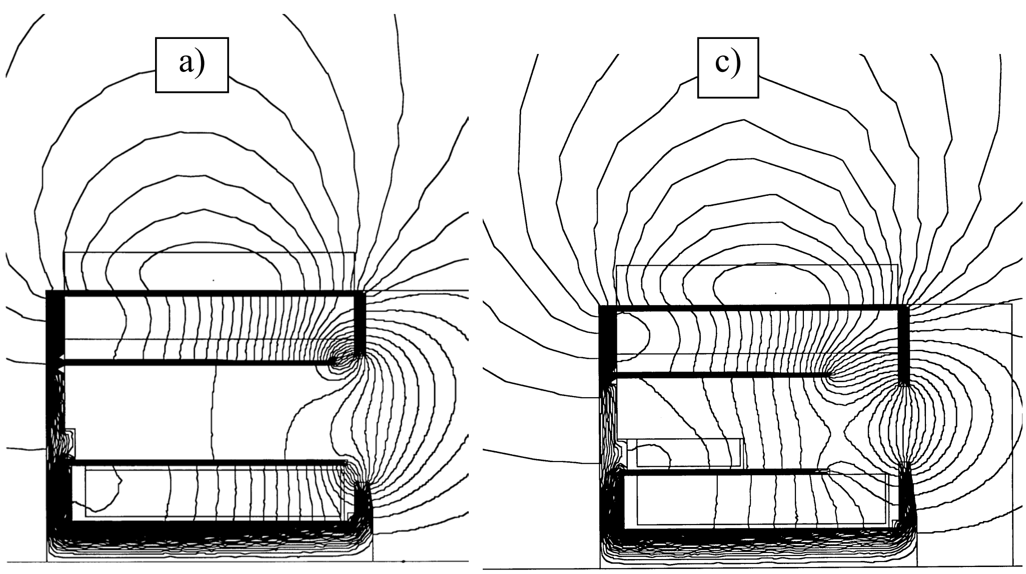

Figure 2 - Magnetic field topology.

a) I_{m1}=2.20 A, I_{m2}=1.47 A c) I_{m1}=1.36 A, I_{m2}=2.0 A, I_{m3}=-3.48 A model characterization under their operation mode optimization with usage only I_{m1} and I_{m2} values and I_{dmin} criterion for magnetic system configuration close to that one for SPT-100 (option a). Obtained results show (Fig. 3) that under the same $\dot{m}_a$ and U_d values the thrust efficiency values are lower for Kr and Kr/Xe mixtures than for Xe case and the higher Kr content in a mixture, the lower thruster performance level (for pure Kr case reduction is at level of 10-15%).

Then there was made an attempt to optimize magnetic field topology for Kr case with usage of additional magnetization coil. Obtained results show that such optimization gives the possibility to obtain accelerator thrust efficiency η_a (calculated not accounting for the cathode mass flow rate) ~54% (Fig. 4) under U_d~400V via ~0,59 for Xe case. Increase of specific impulse values for Kr does not exceed 150s what is not significant due to lower level of thrust efficiency. For Kr/Xe mixtures this increase is lower.

Similar optimization for Xe case gives magnetic field topology close to Kr case but η_a level in a Xe case is close to that one obtained for option a (SPT-100 type configuration). Thus, the magnetic field topology optimization gives more significant effect in a Kr case.

Thus it is possible to obtain SPT thrust efficiency over 50% under its operation with Kr. For SPT-100 scale thruster this level of thrust efficiency could be achieved under power level of (2,3-2,7)kW, which seems acceptable for long thruster operation. Nevertheless this power level is significantly higher than the nominal power of SPT-100. Therefore it is necessary to study the possibility to ensure large life time of SPT, operating with Kr or Kr/Xe mixture more carefully. In particular it is necessary to study the ceramics sputtering yield under their bombardment by Kr ions, the plasma potential and ion energy distributions along the accelerating channel, real discharge chamber erosion rate under thruster operation with Kr or chosen Kr/Xe mixture etc.

Considering the operation mode and characteristics particularities it is possible to make the following preliminary conclusions:

- It is more “difficult” to ignite discharge in a thruster operating with Kr, therefore it is necessary to study ignition process more detaily to find ways ensuring reliable discharge ignition;
- Besides lower thrust efficiency and not so significant specific impulse increase it is necessary to note that ratio of discharge current I_d to the current I_m corresponding to applied mass flow rate under voltages U_d=(300-500)V and mass flow rates $\dot{m}_a \approx (4-5)mg/s$ through the accelerating channel $\left(\frac{I_d}{I_m}\right)_{Kr} \approx (1,3-1,4)\left(\frac{I_d}{I_m}\right)_{Xe}$, what is lower than M_{Xe}/M_{Kr} ratio (~1,64).

Analysis of reasons for relatively small increase of specific impulse in a Kr case could be made using the represented above expression for the accelerator thrust efficiency. Indeed the longitudinal component of exhaust velocity could be represented as

$$< V_z >= \sqrt{\eta_a \frac{2N_d}{\dot{m}}} = \sqrt{\frac{2eU_d I_d}{I_m M}\eta_a} = \sqrt{\frac{2eU_d}{M}\cdot\frac{I_d}{I_i}\cdot\frac{I_i}{I_m}\eta_a} =$$
$$= \sqrt{\frac{I_i}{I_m}\eta_i\cdot\eta_\beta\cdot\eta_V\cdot\eta_\varepsilon\frac{2eU_d}{M}} = \eta_i\sqrt{\cdot\eta_\beta\cdot\eta_V\cdot\frac{2e}{M}(U_d - C_2\Phi_i)} \quad (5)$$

So,

$$\frac{< V_z >_{Kr}}{< V_z >_{Xe}} = \frac{\eta_{iKr}}{\eta_{iXe}}\sqrt{\frac{(\eta_\beta\eta_V)_{Kr}}{(\eta_\beta\eta_V)_{Xe}}\cdot\frac{(eU_d - C_2\Phi_i)_{Kr}}{(eU_d - C_2\Phi_i)_{Xe}}}\times \times\sqrt{\frac{M_{Xe}}{M_{Kr}}}, \quad (6)$$

where $\eta_i=I_i/I_m$ is the mass utilization efficiency, $\eta_\beta=<\cos\beta>^2$, where $<\cos\beta>$ is the mean value of $\cos\beta$, β is an off-axis angle of exhausting ion trajectory, η_V reflects the losses due to spread of ions in velocities. Mean energy level of Kr ions in a plume is close to that one for Xe case (see Fig. 4). So, it is possible to assume that C_2 values for Kr case are close to that ones for Xe case. $\beta_{0,95}$ values for optimized modes of operation are even lower for Kr (see Fig. 4) than for Xe case (see Fig. 3). Therefore one can assume that $\sqrt{\frac{(\eta_\beta\eta_V)_{Kr}}{(\eta_\beta\eta_V)_{Xe}}} \sim 1$.

Then under $U_d \approx$400V and the same C_2 values (C_2=5) for both cases one can obtain

$$\sqrt{\frac{(eU_d - C_2\Phi_i)_{Kr}}{(eU_d - C_2\Phi_i)_{Xe}}\frac{M_{Xe}}{M_{Kr}}} \cong 1,26 \quad (7)$$

Real $<V_z>$ difference (see Fig. 3 and Fig. 4) in the case of U_d=400V and $\dot{m}_a \approx 5mg/s$ was obtained as $\frac{(I_{sp})_{Kr}}{(I_{sp})_{Xe}} \approx \frac{< V_z >_{Kr}}{< V_z >_{Xe}} \approx 1,12$, what gives $\frac{\eta_{iKr}}{\eta_{iXe}} \approx 0,89$

Therefore one can conclude that significant part of specific impulse loss is caused by reduced propellant utilization efficiency. But reduction of η_i value in Kr case could be lower if there is less multiply charged ions in a Kr plume and this is to be checked.

Reduction of η_i magnitude surely causes the thrust efficiency reduction and at least partially explains reduction of I_d/I_m ratio.

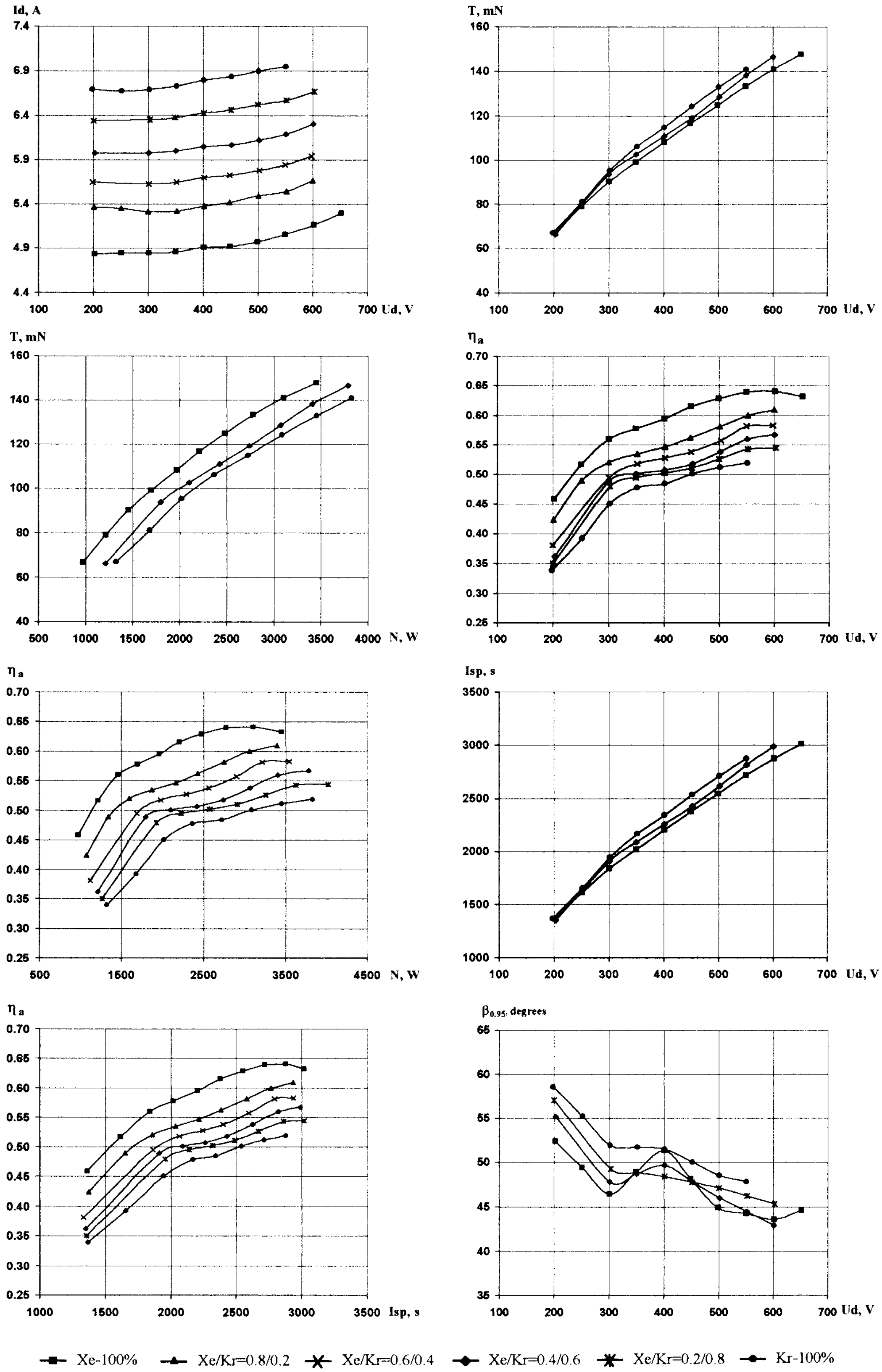

Figure 3 – Thruster characteristics ($\dot{m}_a$ = 5 mg/s)

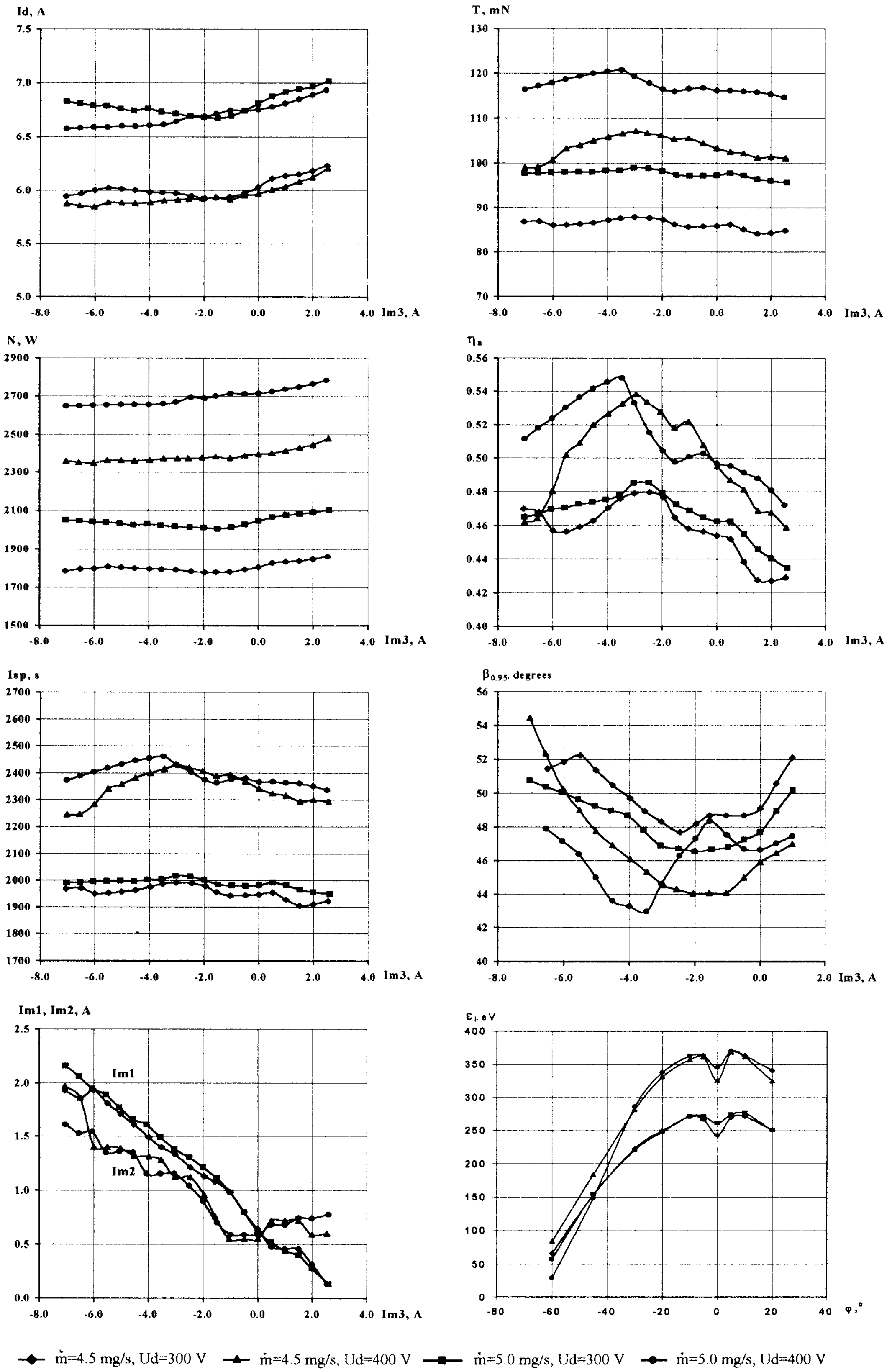

Figure 4 – Thruster characteristics under I_{m3} variation

As a whole obtained results confirm the conclusion of preliminary analysis on possibility to obtain high enough thrust efficiency under comparable with Xe case $\dot{m}$ and U_d values and consequently under increased powers. This is the main disadvantage of thruster operating with Kr or Kr/Xe mixture. Additionally it is necessary to note that Kr or Kr/Xe mixture storaging problem is more complicated than that one for Xe. Therefore it is possible to conclude that development of competitive SPT-based propulsion system operating with Kr or Kr/Xe mixtures is complicated enough task.

Conclusion

Obtained results show that it is possible to develop effective enough SPT operating with Kr or Kr/Xe mixtures, but it is necessary to operate such thruster under comparable with Xe case $\dot{m}$ and U_d values. Therefore the main problem of such thruster development will be connected with increase of ensurance of great enough its life time.

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