INVESTIGATION OF THE SPT OPERATION UNDER HIGH DISCHARGE VOLTAGES

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Abstract

This paper presents studies of stationary plasma thrusters (SPT) operated at high discharge voltages. These investigations are related to investigation of the possibility to obtain high specific impulse thrusters based on the SPT concept and concern the ability of such thrusters to be operated efficiently with high thrust at moderate specific impulse as well as with high specific impulse at moderate thrust. This concept of dual mode SPT (DMSPT) has been investigated at various power levels involving RIAME laboratory models SPT-80, SPT-115 and, by end of 2002, SPT-140 thruster operated in a voltage range 200-1000 Volts. These new results on SPT-140 were acquired in the frame of the Dual Mode High Power SPT project (DMHPSPT) supported by ESTEC ESA and involving a collaboration between GREMI and RIAME. All these studies were performed on thrusters which were designed for optimized performance under discharge voltages of 300-400 Volts, ensuring specific impulses ~ (1500-2200)s. Nevertheless high voltage studies on these thrusters, especially for the high power device, show that efficient operation can be achieved at discharge voltages ~1000V, ensuring specific impulse over 3000s. Interesting trends have been evidenced:

- increasing the thruster size (and power) increases both its efficiency and its ability to lead to efficient DMSPT's ;
- oscillation level of discharge voltage (or current) is not enhanced, and even reduced, in the high voltage range.

Detailed data concerning the characteristics of the SPT-140 plume, obtained for a broad range of discharge voltage are also reported.

Introduction

SPT's have been successfully used in Russian Space Technology many years ago. Their implementation on Western satellites or space missions /1/ is under way. An example is given in western Europe by the SMART-1 mission to be launched in 2003 and satellites equipped by SPT's will be launched during nearest few years by Alcatel and Astrium /2/. A similar trend is characteristic for USA also /3/. This interest for SPT's in Space Technology is related to several features of these thrusters :

- high enough performance level under moderate specific impulses I_{sp}=(1000-2000)s what ensures high enough thrust under moderate power consumption;
- great flight heritage confirmed by reliable operation of the SPT-based propulsion systems (PS) on board many Russian satellites;
- relatively simple conceptual design diagram, efficient operation on gaseous propellant under moderate discharge voltages and possibility to reach high life-times compatible with requirements.

In the last years significant industrial and scientific programs was launched. Industrial developments (SNECMA and Matra Marconi Space (nowadays Astrium) in Europe/2/, Busek, Primex (nowadays General Dynamics) and SPI (nowadays Pratt Whitney) in USA /3/) and research programs in Europe underlined the world wide interest for SPT's concept and technology.

In the above developments SPT's were considered for ISP values around 2000 s. In connection with new requirements in terms of power and/or ISP and with the extension of their applications, it is attractive to look at the possibility of SPT's to operate efficiently with high specific impulses (> 3000 s) and, even more, to evaluate the ability of higher power thrusters (4-6 kW) to operate effectively at least under two operation modes:

- mode 1 with high enough thrust at moderate specific impulse;
- mode 2 with high specific impulse allowing mass saving for long term missions.

Such dual mode high power SPT's (DMHPSPT's) would be clearly of interest for geostationary satellite (geosat) by using the mode 1 for contribution to orbit transfer, and the mode 2 for station keeping on orbit.

In spite of some previous studies made earlier (for example in /1,4,5/) there are still some open issues concerning SPT operation under high voltages. In particular high voltage and reduced mass flow operation lead to some problems mainly related to the decrease of the plasma density and the corresponding difficulty to ensure high probability of full propellant flow ionization. As shown in part I, this problem for the development of high specific impulse SPT's is thought as being less constraining when the SPT's size and power is increased. New inputs on such an investigation of high voltage high power SPT's operation are presented in part II. Previous results obtained for SPT-80 and SPT-115 /1,4/ are of interest for the trend mentioned above and are included in this paper, the new results obtained on the SPT-140 laboratory model for high voltage operation being presented with some details.

I. SPT-80 and SPT-115 laboratory models performance and impact of SPT size and power on possible performance under high voltage conditions

As mentioned above, the SPT-80 and SPT-115 laboratory models have already been tested under high discharge voltages /1,4/. These models had design close to traditional ones but different scales. Therefore it is possible to analyze general up-scaling trends for similar SPT's operation and performance under increased discharge voltages.

These models were tested at the test facility with vacuum chamber of 2m in diameter and 6m in length. The working pressure inside this chamber under Xenon mass flow rate $\dot{m} \cong 5$ mg/s was not higher than $(5\text{-}6)\cdot 10^{-5}$ Torr, i.e. acceptable for test of SPT's. Under this mass flow rate it was possible to test thrusters till discharge voltages U_d~1000V and discharge powers till N_d~5kW.

Test facility has a thrustmeter allowing measurement of thrust within the expected range of its values and accuracy of measurement ± 2%, the gas feeding system controls mass flow rates through the channel and cathode with an accuracy of ±2% and ±4% respectively. Other diagnostics include :

- acquisition of discharge voltage and discharge current intensities and waveforms;
- measurement of the accelerated ion flow density distribution in off-axis angle with usage of RPA probe /6/. That is the test facility has measuring and controlling devices allowing full enough SPT laboratory models performance characterization under their operation with discharge voltages till U_d~1000V.

Results of the SPT-80 performance characterization were published previously in /4/ for a broad voltage range. Similar data was presented but not published in details for SPT-115 performance tests /1/ and are presented below. These results have been obtained for an anodic mass flow rates (Xe) in the range 2-4 mgs^{-1}, this range being defined by thermal issues at high voltage (1000V) operation. They are presented on Fig. 1-4, showing that:

- under increase of the discharge voltage, the discharge current is increased more or less regularly (Fig.1). This result appears as typical for SPT operation at such power levels and low mass flow rates through the accelerating channel. It could be induced both by an increase of the multiply charged ions fraction in ion flow and by an increase of mass utilization efficiency;
- thrust and specific impulse (calculated not accounting for the cathode mass flow rate) are increased also more or less monotonically with increase of the discharge voltage (Fig.2,4);
- the most distinguishing data refer to the dependence of the thrust efficiency on the discharge voltage (Fig.3). The maximum of the thrust efficiency decreases and is obtained at higher discharge voltage when the mass flow rate is lowered.

Similar results were obtained for the SPT-80 /4/ and for other models (see, for example /5/). So, it seems that the above trends are common for thrusters of different scales. This point will be considered below in more details. From a practical point of view it is worth to recall that :

- to get high thrust and high enough thrust efficiency it is necessary to operate thruster with maximum mass flow rate allowed by thruster thermal design and moderate discharge voltage;
- to get maximum of specific impulse it is necessary to operate thruster under minimum of mass flow rate but such a reduction of the mass flow rate is limited by the mentioned above reduction of thrust efficiency level under reduction of mass flow rate;
- a reduction of the thrust efficiency induces a limitation of the maximum operating power due to the internal losses and a related thruster thermal overloading.

The above data underlined that an important effect observed for these thrusters is the reduction of thrust efficiency for low mass flow rates through the accelerating channel. This observation is to be related to the fact that decreasing the mass flow under critical level leads to a decrease of ionization efficiency, with an excessive decrease of both the plasma density in the channel and neutrals ionization probability.

Up-scaling trends on this effect, in terms of thruster size or power, are considered below.

The free path of atoms before their ionization inside the accelerating channel can be expressed as

$$l \cong \frac{V_a}{\langle s_i V_e \rangle n_e} \tag{1}$$

where V_a is the atoms velocity, $\langle s_i V_e \rangle$ is the ionization rate factor, n_e is the mean plasma (electron) density /7/.

The $\langle s_i V_e \rangle$ factor could be assumed as ~ constant under high enough electron temperatures, taking into account the Xe ionization cross section for electron energies close to or higher than the ionization energy of Xe. Because under discharge voltage U_d ~ (200-300) V the electron temperature is already high enough /8/ and because the electron temperature is increased when increasing discharge voltage, the above estimation is retained for discharge voltages higher than 300V. Under approximately the same thruster thermal state, the atoms velocity could be also assumed as constant one.

These considerations mean that l value depends mainly on the plasma density. For receiving high thrust efficiency, a high ionization probability through the ionization layer of a characteristic size L_a must be achieved. A broad set of data obtained previously on various magnetically optimized thrusters shows that L_a is almost proportional to the accelerating channel width b_c /7/. Taking into account this experimental input and the plasma quasi-neutrality one can estimate the plasma density as

$$n_e \approx n_i \approx \frac{\dot{m}_a}{M V_i S_c} \approx \frac{\dot{m}_a}{M V_i p d b_c} \tag{2}$$

where $\dot{m}_a$ is the mass flow rate through the accelerating channel, *M and* V_i are respectively the ion mass and velocity, and finally $S_c \approx p d b_c$ is the accelerating channel cross-section area (d is the accelerating channel mean diameter).

There are two possible approaches for estimation of the mean ion velocity in formula (2). According to the first one the potential drop inside the accelerating channel is proportional to discharge voltage /7/. Moreover, part of ions is created outside the accelerating channel. Therefore the mean ion velocity within the accelerating layer could be estimated as

$$V_i \approx \sqrt{\frac{2 k_e e U_d}{M}} \tag{3}$$

where $k_e \approx \frac{e_i}{e U_d}$, e_i is the mean ion energy within the accelerating layer.

Another approach /11/ considers that the mean potential drop within the so-called ionization zone $\Delta U_i \approx const$. Therefore

$$V_i \approx \sqrt{\frac{2 e \Delta U_i}{M}} \tag{4}$$

It is evident that free path of atoms before their ionization has to be less than L_a. If some one supposes that $l \approx k_l L_a \approx k'_l b_c$, where k_l <1, then with usage of (3) one can obtain /7/ an expression of the minimal mass flow rate keeping left an efficient ionization:

$$\dot{m}_{a\min} \approx k'_l \frac{p d V_a}{\langle s_i V_e \rangle} \sqrt{2 k_e e U_d M} \tag{5}$$

This expression shows that the minimum mass flow rate ensuring effective enough propellant flow ionization should increase when increasing the discharge voltage. Or under fixed mass flow rate an increase of discharge voltage should decrease ionization and thrust efficiencies, if the discharge voltage reaches a level such as $\dot{m}_{a\min}$, according to (5), exceeds chosen $\dot{m}_a$ value.

An important consideration refers to up-scaling effects for such limitations. It can be seen also that with increase of thruster characteristic size (its mean diameter) the minimum of the mass flow rate required for efficient ionization should increase linearly with the channel width. The maximum values of mass flow rates, at nominal power, increase as channel cross section. It means that a larger size thruster is able to accommodate properly increasing values of the ratio between standard and minimal mass flow rates. This qualitative derivation will be considered in more details later.

Another result, derived from (4), is the following one :

$$\dot{m}_{a\min} \approx k'_l \frac{pdV_a}{\langle s_i V_e \rangle} \sqrt{2k_e Me\Delta U_i} \qquad (6)$$

It means that the minimum mass flow rate practically does not depend on U_d. But it is interesting to notice that experimental data suggest that expression (5) is more adequate to describe the observed up-scaling trends.

Another possible source for the mentioned reduction of the thrust efficiency under low mass flow rates and moderate discharge voltages could be an increase of the oscillation intensity. This intensity was not measured in the broad voltage scans for SPT-80 and SPT-115 /1,4/. When investigating the performance of the SPT-140 up to 1000 V discharge voltage such measurements were made (see below). The results show that the oscillation level at high (1000) voltage is not increased but somewhat reduced when compared to the level recorder at low voltage (300-400 V). The conclusion is that oscillations are not the main source of efficiency reduction.

When considering the thruster scaling factor impact in more details, it is interesting to introduce the mass flow density calculated for the thruster cross-section area $S_c \approx pdb_c$. From the equations (5) and (6) one can obtain that respectively

$$\frac{\dot{m}_{a\min}}{S_c} \approx k'_l \frac{V_a}{\langle s_i V_e \rangle b_c} \sqrt{2k_e eU_d M} \qquad (7a)$$

$$\frac{\dot{m}_{a\min}}{S_c} \approx k'_l \frac{V_a}{\langle s_i V_e \rangle b_c} \sqrt{2k_e Me\Delta U_i} \qquad (7b)$$

As one can see in both cases the power density corresponding to minimum of the mass flow rate is inversely proportional to b_c. Because discharge current in the first approximation is proportional to the mass flow rate through the accelerating channel the mentioned conclusion means that acceptable minimum of the discharge current density is reduced with increase of the accelerating channel width. Under fixed power density, limited by thermal issues, such a decrease of discharge current density allows an increase of the discharge voltage keeping left ionization and thrust efficiencies.

To conclude this part, all the above considerations emphasize the fact that thrusters of increased sizes (and power) are able to be operated efficiently in a wider relative mass flow range. It means that they could be operated with high thrust efficiencies and high specific impulse. This conclusion as well as the possibility to develop effective DMHPSPT was checked during the SPT-140 high voltage performance characterization. These tests, achieved in cooperation GREMI-RIAME, are presented in the part II below .

II. SPT-140 laboratory model: high voltage performance characterization

II. 1. High power SPT's and SPT-140 mode 1 performance

As mentioned above, it is interesting to look at DMHPSPT's: in the nearest future for the geostationary satellites, final orbit transfer and station keeping will require rather high thruster powers (> 3-4 kW) and high specific impulse devices (> 3000 s) are also welcome . High power SPT's, at moderate ISP, are under developments in several companies such as Design Bureau Fakel (within the International Space Technology, Inc. (ISTI) R&D program /8/), Busek and Primex – now General Dynamics /3/, Astrium and SNECMA /2/. Academic research programs on such thrusters are also developed, for example in France within a coordinated research program (GDR 2232). Studies of SPT performances for thrusters of increased sizes were made earlier in Russia by several organizations including RIAME MAI /9/ where performance investigations have been achieved for laboratory models having external diameters of the accelerating channel d=100-200mm. The DMHPSPT concept and the above considerations on up-scaling trends have been tested through a characterization for modes 1 and 2 of the RIAME MAI SPT-140 laboratory model. This SPT-140 has a traditional design diagram for Russian SPT's, with external accelerating channel diameter 140 mm and internal one equal to 100mm. Data on mode 1 was already available and high voltage (mode 2) tests were made jointly by RIAME and GREMI within the frame of the ESTEC ESA DMHPSPT project.

The results on mode 1 presented on figure 5 show that this model has high enough efficiency under powers till 7kW. Under discharge voltage $U_d \approx 300$V, power ~3-6kW it provides a thrust F≈270mN and demonstrates a thrust efficiency $\eta_a \approx 0.6$ and a specific impulse $I_{sp} \approx 1800$s (not accounting for cathode mass flow rate).

Power to thrust ratio at U_d=300V and mass flow rate through the accelerating channel $\dot{m} \approx 14.1$ mg/s is at level of 14.1 kW/N and close to minimum. This means that under N_d=5kW the thrust value is to be at level of F≈342mN that is great enough.

Taking into account the cathode mass flow rate $\dot{m}_c = 0.1\dot{m}_a$, specific impulse value I_{sp}=1636s could be achieved, typical for the best versions of modern SPTs at the beginning of life (BOL). If $\dot{m}_c = 0.1\dot{m}_a$ then $I_{sp} \geq 1700$s what is good enough. Even better performance was demonstrated on a SPT-140 developed and manufactured by Fakel Design Bureau or on the SPTX1000 thruster developed by SNECMA.

To summarize: the SPT-140 laboratory model exhibit significantly good performances in mode 1 operation. The study of its performances in mode 2 is presented in the following sections.

II.2. Methodology of high voltage experiments and test facility description

The high voltage performances was measured in the test facility used for investigation of SPT-80 and SPT-115 laboratory models. Performance characterization was made using the following procedure. After setting up the mass flow rates into cathode and into the accelerating channel and heating of the cathode, the preliminary values of the magnetization currents were set up (typically lower than nominal ones). The discharge was ignited at discharge voltage of 300-400V. Discharge voltage scans have been performed, starting from 300V till 1000V, by steps of 100V. For each voltage the magnetization currents were adjusted in order to maximize the thrust efficiency. In fact as will be pointed out below, this optimization encounters limitations due to coils current supplies, especially at high thruster temperature.

After the voltage scan where performance was recorded at each voltage step, the discharge voltage was reduced till 300-500V for thermal relaxation: under thruster operation at Ud~1000V and discharge powers higher than 3kW overheating can be observed (see later). Such procedure allows analysis of the SPT performances in a wide range of parameters and gives in a short way an information on the achievable performance levels.

After thruster cooling the performance data registration was repeated 2-3 times under the same mass flow rate. Then another mass flow rate was set up and performance characterization was repeated using the same procedure. Due to different rate of thruster heating from case to case some difference of characteristics obtained during different attempts or different day was observed and performance data have been assigned to "cold", "heated" and "overheated" thrusters.

The "cold" and outgassed state of the thruster was obtained by its operation during previous day for several hours under powers (1-4) kW and cooling during night without opening of chamber. So, thruster was cooled in a vacuum conditions. Then in the morning of the next day there was made the performance characterization according to described above procedure starting from thruster cold state. By applying such procedure repetitive data was obtained.

"Heated" thruster state corresponds to a situation where performance characterizations was made without interruption but the cooling step at 300-400V discharge voltage and 1-1.5 kW power.

The "overheated" thruster state corresponds to situation where the magnetic system is far from optimization of coil currents, due to its limited capabilities.

Before high voltage performance characterization, a performance determination was achieved under moderate voltages and increased mass flow rates, in order to test thruster quality deviations. The performance results, obtained several times for various thermal conditions, are summarized in § II.3 below.

A plume characterization was performed by using RPA probe with a retarding potential ~50V, allowing estimation of the accelerated ion flow angular divergence. Langmuir probe was used to get data on plasma parameters in the plume. RPA and probe were mounted on the boom, rotating diagnostics along a semicircle with radius R=0,7m.

Discharge oscillation characteristics were recorded with a bandwidth 1kHz-1MHz, wide enough for voltage and current analysis, as far as ionization type oscillations was concerned. The main frequency of these oscillations can be expressed as $f \sim V_a / L_a$, where V_a is the atoms velocity and L_a is the ionization and acceleration layer thickness. It means that experimental variations of the main frequency give some input on the modifications of La versus U_d and represent an useful input for test of simulations.

II.3 Results of the SPT-140 laboratory model performance and plume characterization

The performance characterizations was made for the mass flow rates through the accelerating channel 3mg/s, 3,5mg/s, 4mg/s, selected after preliminary runs defining this range in terms of power at 1000V. Nevertheless it appears that overheating at 1000 V is highly significant for the highest mass flow i.e. that the magnetic optimization was far from optimum in high voltage conditions. Therefore data obtained for 3mg/s and 3,5mg/s are more consistent ones. For comparison it is worth to recall the nominal mass flows of this thruster in mode 1, i.e. 12-14 mg/s.

The recorded performance data are presented on figures 6-11. They show that:

- for the "cold" thruster thrust efficiency and specific impulse values under discharge voltage Ud~1000V are high enough (see Fig. 6-7);
- performance data for increased mass flow rates are not better than for 3mg/s ; this could be explained by the overheating of thruster under high discharge voltages. Indeed, the dashed line on figure 8 gives the indication of a limitation of the coil currents due to temperature effects and this limitation appears at respectively 800 V-700V-600V for 3-3.5 and 4 mg/s. It is clear that the current increase observed in the I(V) characteristics is coherent with such interpretation. It means that recorded performance represents not the optimal possible one which could be obtained with another thruster design. This is especially true for the 4 mg/s runs.
- the thrust data shown on figure 9 suggest clearly that the ionization remains high. It means that the efficiency decrease is induced by an excessive electron current related to a poor magnetic optimization.

The first conclusion which can be derived from these tests is that it is possible to achieve, under mass flow rates 3-3,5 mg/s and U_d~1000V, thrust efficiency and specific impulse values calculated not accounting for cathode mass flow rate at level of 0,57-0,60 and 3400-3600s respectively. When including the cathode mass flow rate (not exceeding 10% of the anode one) one can obtain a total thruster specific impulse over 3000s.

The second conclusion is that a thrust efficiency (not accounting for magnetization power losses) can reach 0,51-0,54. Due to its design the magnetization losses were great enough for the tested model but all experience on SPT developments shows that for optimized design these losses do not exceed 3%. So, taking this into account one can conclude that a total thrust efficiency level ≥ 50% could be achieved also.

The possibility of a stable thruster operation under discharge voltage U_d~1000V was tested through a 6-hour test of thruster at a mass flow rate of 3mg/s, consisting of two cycles with duration of ~3 hours. This test demonstrated the ability of thruster design to operate in a steady state thermal state (the transient time to reach the steady state thermal state is ~1,5 hours for power density realized in the SPT-140 under power ~3kW) under discharge voltage U_d~1000V.

To conclude, it should be emphasized that an improved magnetic design is clearly expected to lead to better performance than that obtained during this test on high voltage performance of the SPT-140 laboratory model.

Results on the angular ion flow distribution are shown on figure 10. A minimum value of plume divergence variation was observed at discharge voltages U_d~600V. Similar plume divergence was observed earlier for smaller thrusters but at lower discharge voltages. As shown on figure 10, the 95% half angle of plume distribution is significantly decreased to 30° under $m_a = 4mg/s$. Even if this value is derived from the RPA measurements at distance ~0,7m which could be too small for thrusters of the SPT-140 scale, this significant reduction of the plume divergence seems interesting.

Data on the oscillatory behavior are shown on figure 11 for the 3.5 mg/s flow rate. The oscillations have the following features:

1. The discharge voltage oscillation intensity has definite maximum at U_d~600V for all studied mass flow rates. This is in the same range as the observed one for a lowest divergence of the plume and extended studies in this voltage range are clearly required
2. For the $\dot{m}_a = 3mg/s$ the oscillation intensity shows a jump-like increase for U_d = 1000V, not observed for other mass flows. This could be induced by transient artifacts on thruster or recording system.
3. The character of oscillations seems similar for all cases and there was not found the so-called oscillating regime as can occur under nominal mass flow rates. It means that under low mass flow rates the oscillating behavior is significantly different.
4. The frequency of the main mode is generally reduced with increase of U_d from ~400V in all cases. Even if this evolutions is different for different mass flows, this trend suggests that the accelerating layer thickness increases with an increase of the discharge voltage. This interpretation was confirmed by the observed increase of the erosion traces length on the channel walls.

Oscillation intensities of discharge voltage and current were obtained as the mean root square amplitudes averaged for 50 harmonics of their Fourier representation. Under increased voltages the frequency spectrum of oscillations is expanding, with enhancement of several harmonics. All these features on oscillating behavior are to be studied and discussed more carefully in the future but the most important result, in terms of DMHPSPT's concept, is that the oscillation level is really not a significant problem for operation in a discharge voltage range of 1000 Volts.

Plasma parameters have been measured in the plume by using Langmuir probes. Some results are summarized below :

1. The plasma (and probe) floating potential appears to be increased (by at most 10 Volts) when the discharge voltage is increased from 300 V to 1000 Volts.
2. The electron temperature values are changed not significantly with increase of U_d.
3. Plasma and floating potentials are reduced with increase of the mass flow rate through the accelerating channel.

The plasma potential variations are of interest and should be investigated more carefully, taking for example into account the impact of fluctuations in the probes characteristics.

Conclusion

These preliminary results on high voltage SPT obtained in the 4 kW power range underestimate the possible performance with an improved magnetic design. Nevertheless they confirm the possibility to obtain high enough thrust efficiency and specific impulse over 3000s under thruster operation with discharge voltage U_d~1000V, although this thruster being designed for optimal operation at reduced ISP and high thrust. It means that a DMHPSPT design has to be defined in terms of high voltage, mode 2, operation. It is expected that thruster optimized for high voltage operation will operate with good efficiency in the mode 1, as conditions for thruster operation under standard voltages are significantly better.

The main trends derived in the paper on up-scaling effects of interest for dual mode SPT's are illustrated on figure 12 where are given dual mode performances of laboratory models SPT-80, SPT-115 and SPT-140. These data are coherent with a crude up-scaling analysis and emphasize the potential interest of high power thrusters (> 4 kW) for DMHPSPT's.

Directions of the thruster design optimization for high voltage operation are qualitatively clear. The first one is an increase of the magnetic system capabilities by increase of magnetization coil turns. From the previous experience it is known that such increase besides increase of magnetic field control ability ensures reduction of the power losses for magnetization. Surely these changes will increase thruster sizes and mass but for high specific impulse thruster they are seemed acceptable because increase of thruster mass will be small in comparison with the mass gain obtained due to significant specific impulse increase. For operation under increased voltage it seems prospective also to optimize the cathode position to reduce plume plasma potential because for these operation modes the level of this potential is notably higher. Increase of the plume plasma potential under increased discharge voltages could be caused by increase of magnetic induction level in a near cathode zone where electrons are extracted into plume and into discharge. Such conclusion is confirmed indirectly by an observed reduction of the plume plasma potential when the mass flow increases, leading to an increase of the plasma density and of its conductivity in near cathode zone and plume. Finally improving of thruster thermal design and high voltage insulation are required.

These preliminary data, in spite of the limitations evidenced on this SPT, clearly open the way for designing efficient SPT thrusters able to operate properly in a high ISP mode and are encouraging for the dual mode high power SPT (DMHPSPT) concept.

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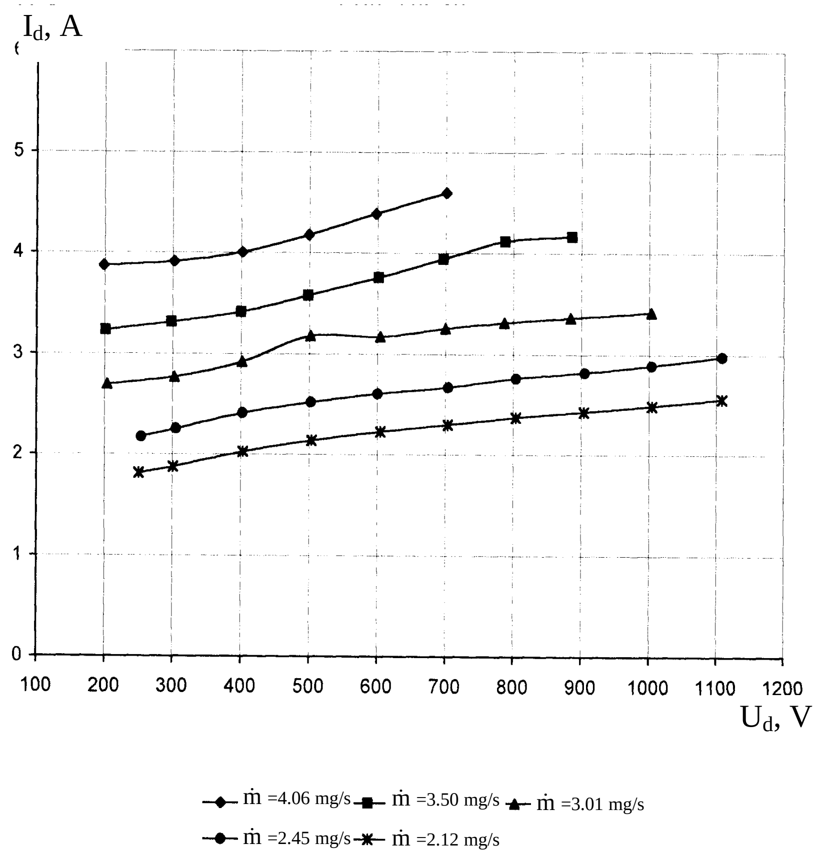


Fig. 1. SPT-115 laboratory model voltage-current characteristics

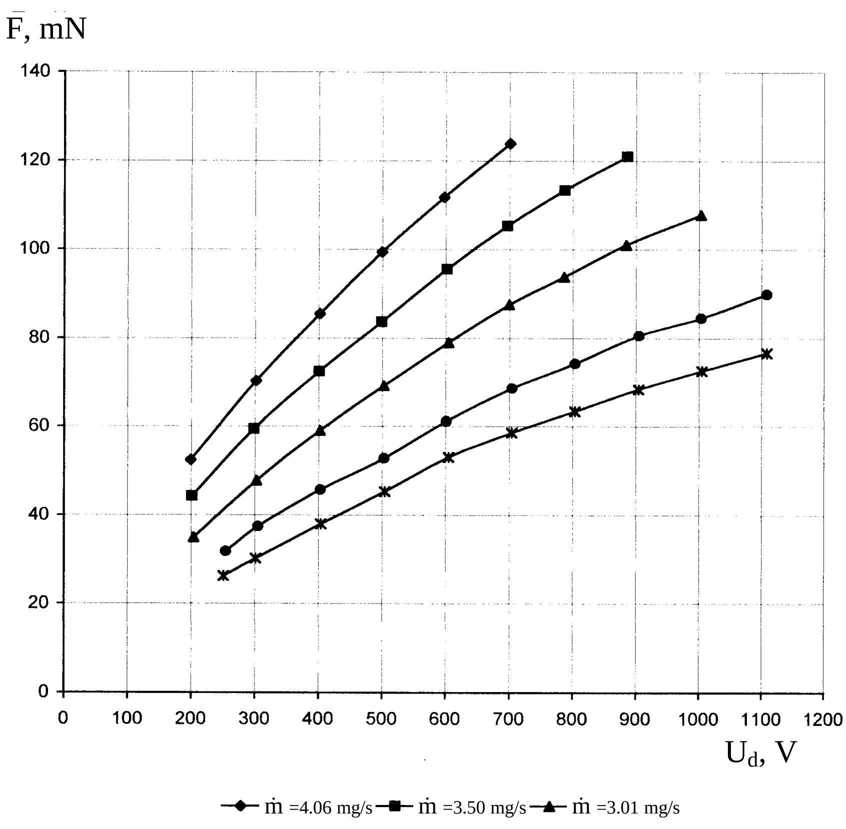


Fig. 2. Thrust versus the discharge voltage for SPT-115 laboratory model

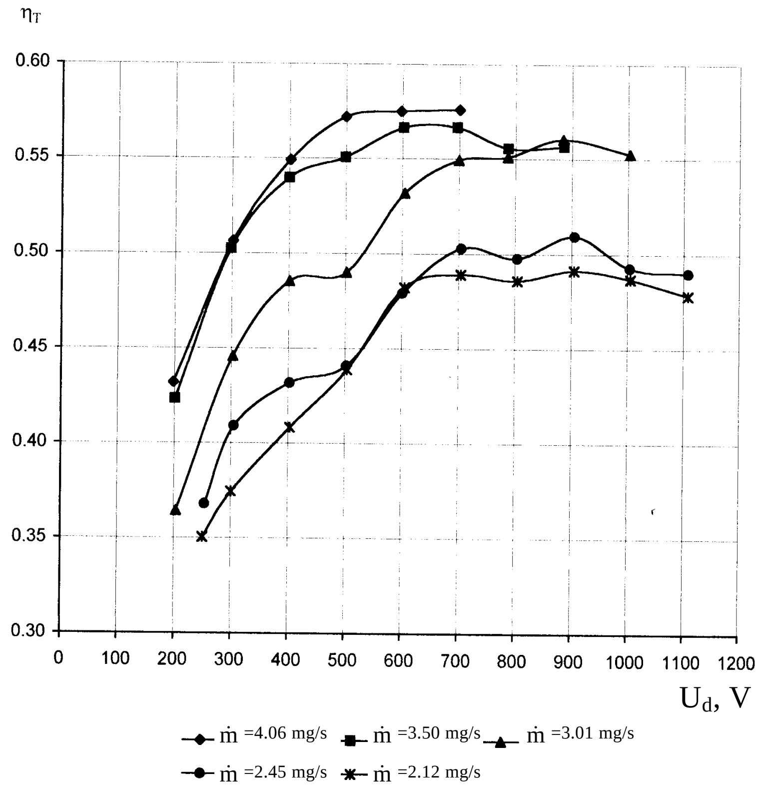


Fig. 3. SPT-115 laboratory model thrust efficiency calculated not accounting for the cathode mass flow rate versus the discharge voltage

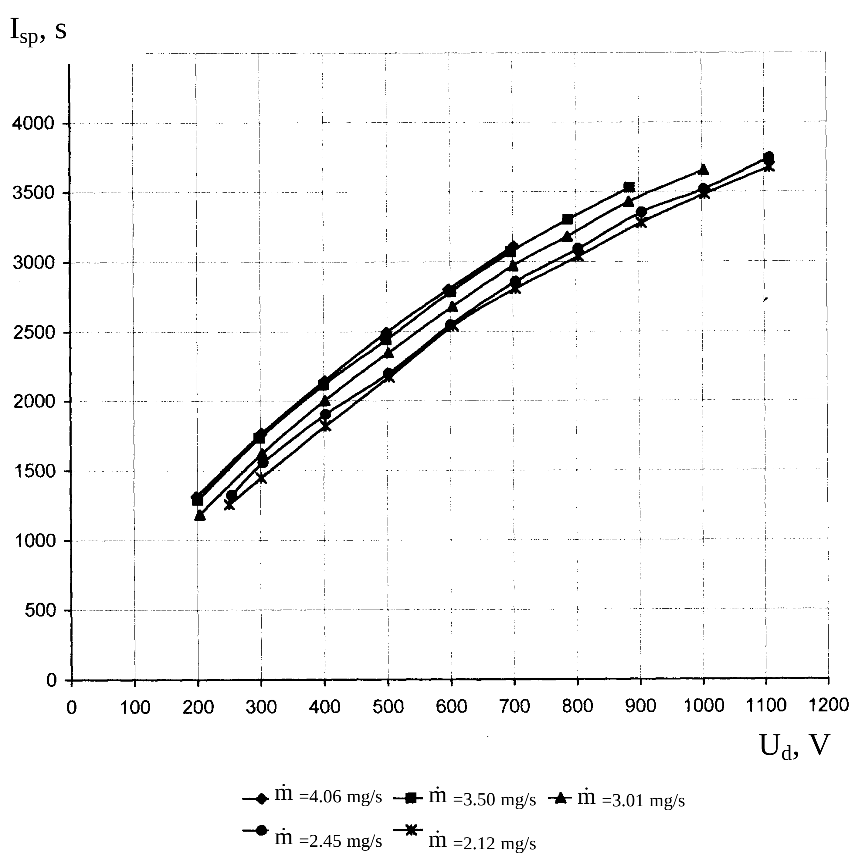


Fig. 4. SPT-115 laboratory model specific impulse calculated not accounting for the cathode mass flow rate versus the discharge voltage

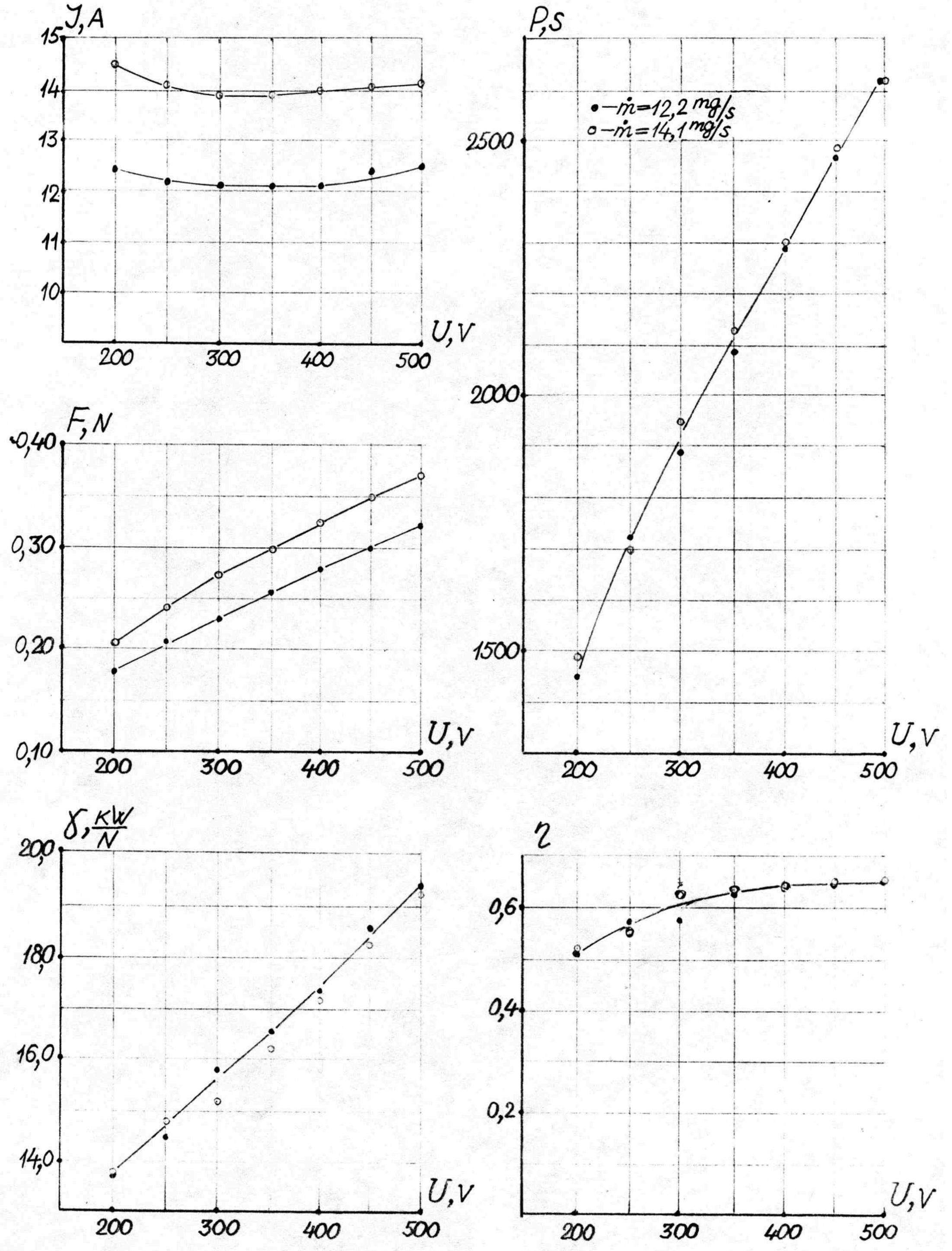


Fig. 5. SPT-140 laboratory model characteristics under moderate discharge voltages (thrust efficiency h and specific impulse P calculated not accounting for the cathode mass flow rate)

Figure 6
Thrust efficiencies for two mass flows (SPT 140)

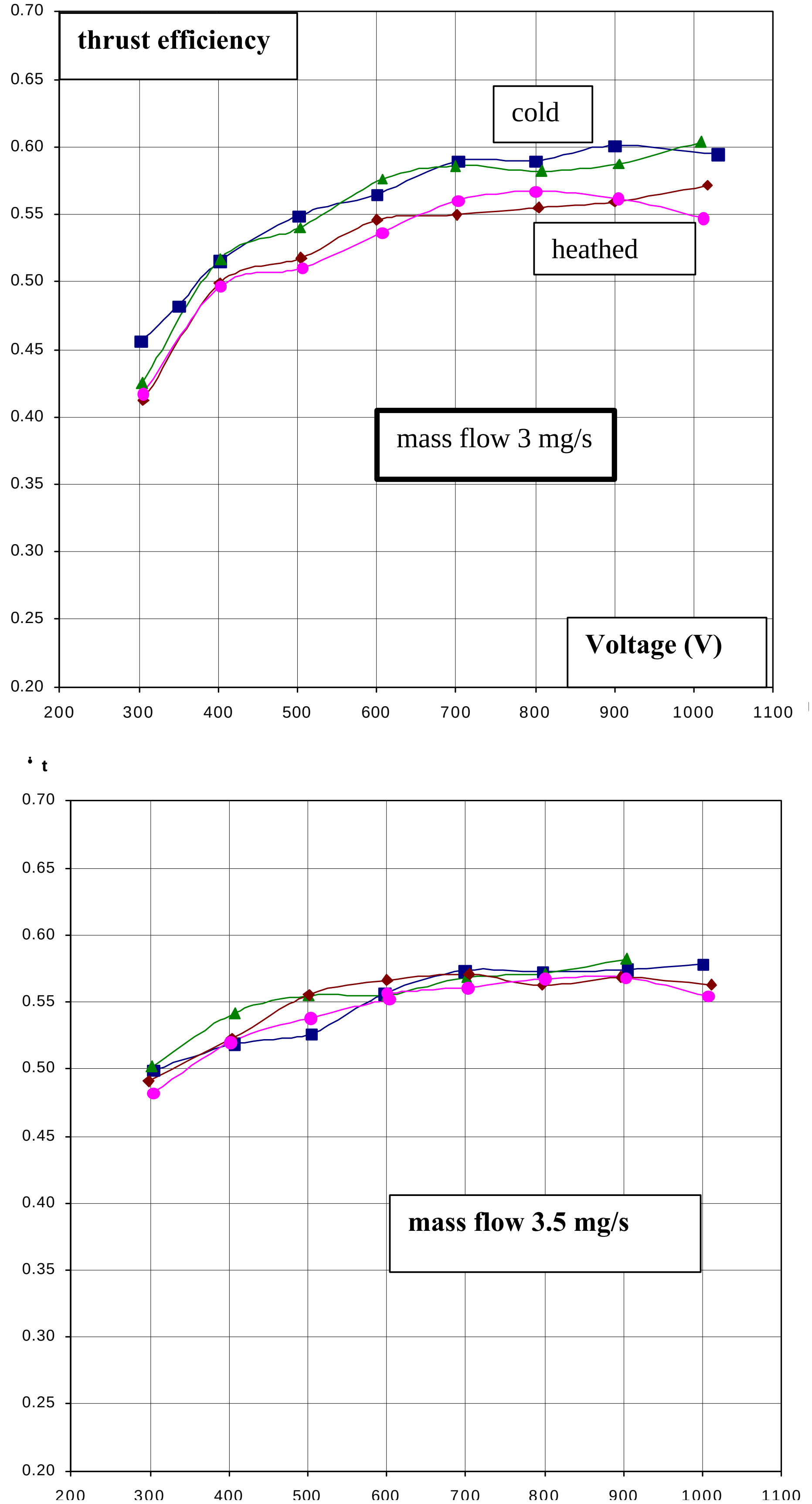
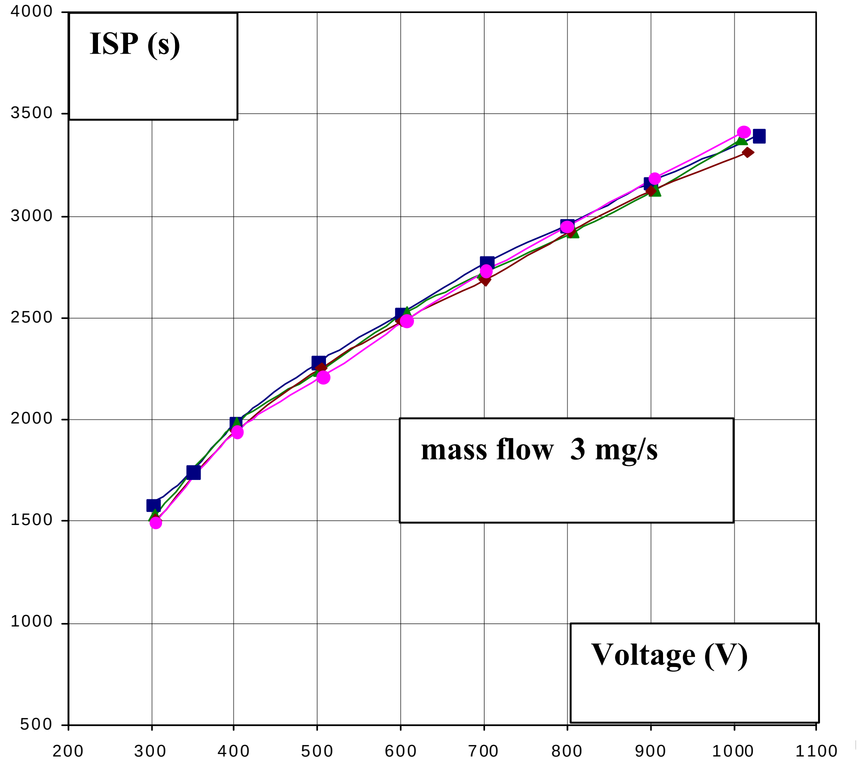


Figure 7

ISP data (cathode flow not accounted for) at two mass flows (SPT 140)



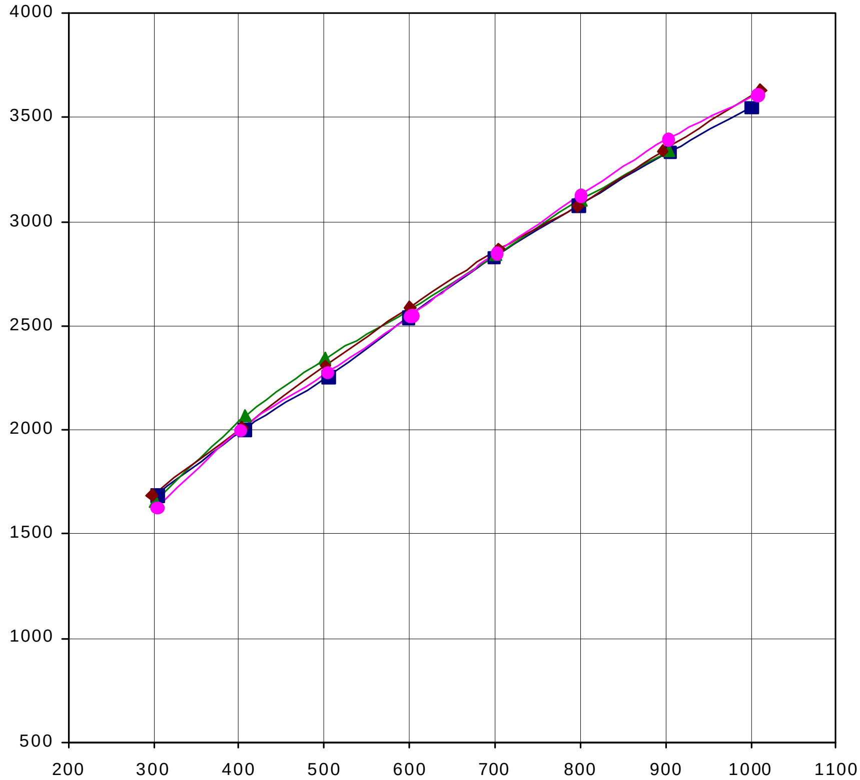


Figure 8

Discharge characteristics for three mass flows (SPT 140)

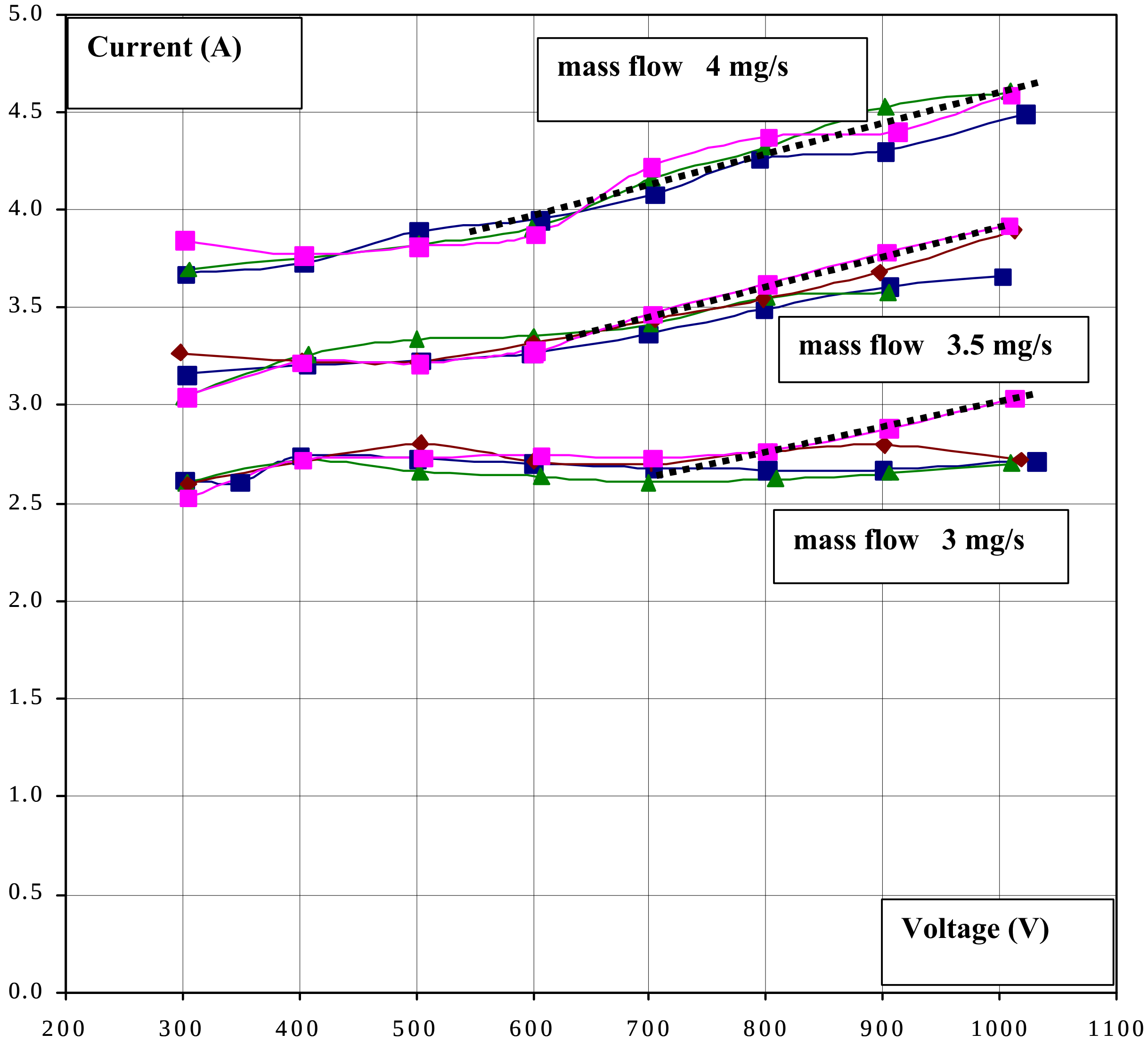
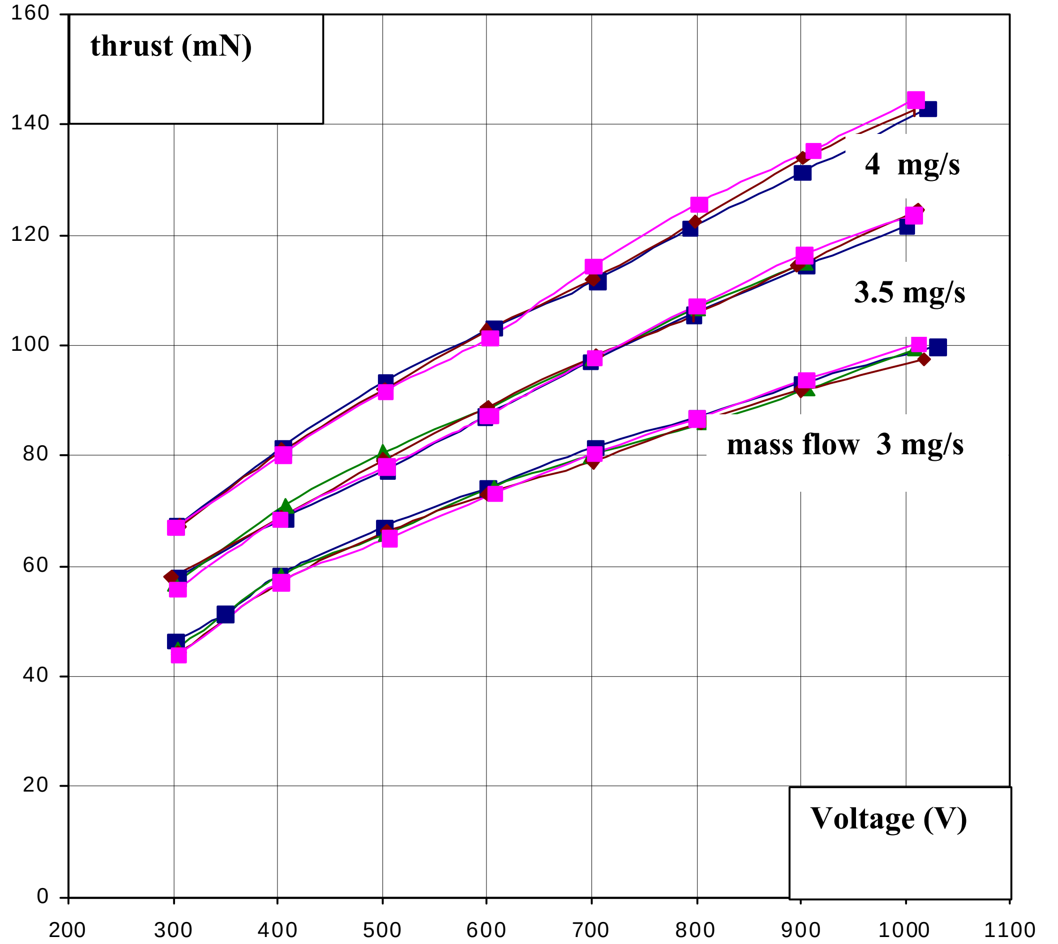


Figure 9

Thrust as function of discharge voltage for three mass flows (SPT 140)



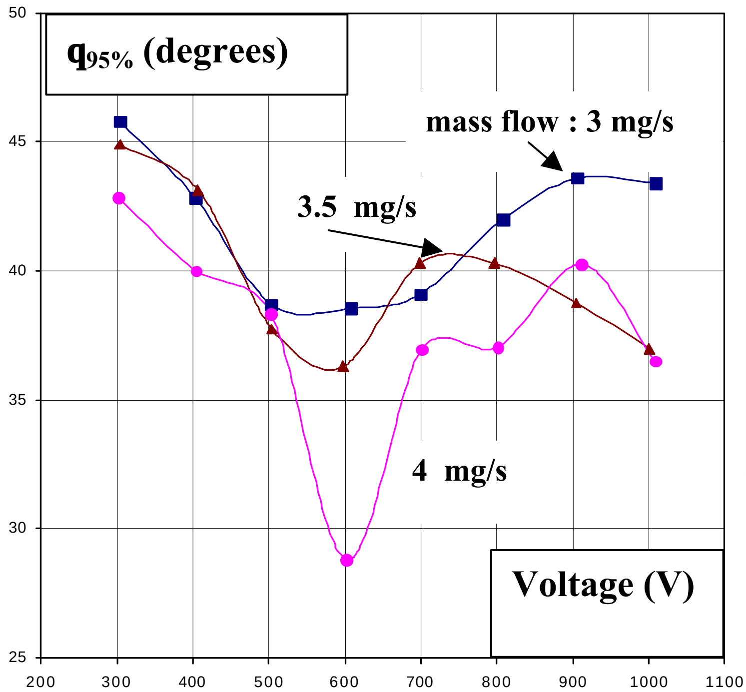


Figure 10

angular distribution

as function
of discharge voltage
for three mass flows

(SPT 140)

Figure 11

Example of evolution of oscillations as function of discharge voltage

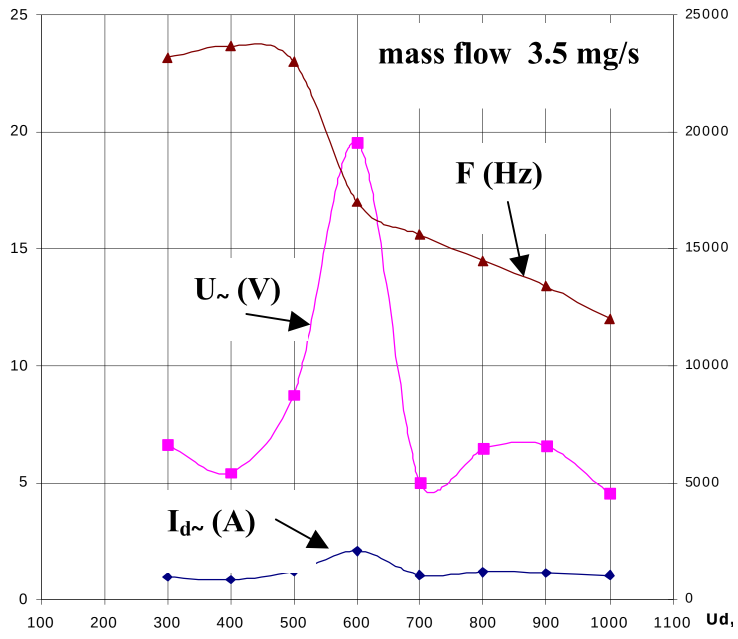


Figure 12

Comparative data for dual mode operation of RIAME MAI laboratory models SPT's with various sizes and power

mode	Voltage (V)	Current (A)	Power (kW)	Thrust (mN)	ISP (s)	efficiency
SPT 80 (LM)						
1	300	4.65	1.39	84.5	1550	0.46
2	600	2.33	1.40	55.7	2180	0.43
SPT 115 (LM)						
1	300	8.67	2.6	162	1630	0.51
2	800	3.3	2.64	94	2730	0.48
SPT 140 (LM)						
1	300	13.9	4.17	273	1730	0.55
2	1000	4.5	4.5	142	> 3100	0.50