HIGH-VOLTAGE MODE OF THE TAL THRUSTER OPERATION

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ABSTRACT

High-voltage options of advanced propulsion systems are considered. To prove the possibility of single-stage TAL operation with high voltage the experiments with D-100-II laboratory thruster were made. TAL appears to be capable in operation within 300-1300 V with a thrust efficience exceeding 60%.

In the first approach possible limits of regulation of a specific impulse in one engine use analysed. The local electrical measurements in the thruster with segmented hollow anode were performed. The fraction of the electron current penetrating into the anode cavity of the single-stage TAL is increasing with discharge voltage and can achieve 25%.

INTRODUCTION

Nearly all current works dealing with the application of Hall thrusters as SPT and TAL are limited by consideration of a specific impulse range of about Isp=1600 s that with utilization of Xenon as propellant corresponds to a discharge voltage of Vd=300V at the thrust efficiency of 0.5 [1-4]. Whereas, there is a number of missions including orbit raising, GEO insertion, interplanetary flights and the like, requiring use of electric propulsion with a specific impulse Isp = 2500-4000 s.

If the advantage of low-Isp Hall thrusters resulting in significant mass savings for LEO missions is also achievable in a higher Isp range, this technology shall seriously compete with ion engines, thus stimulating certain interest to it's further evaluation in specified area of operating parameters.

ADVANCED HIGH-VOLTAGE OPTIONS

With a view to obtain a significant mass saving the direct-drive concept has been proposed for use in advanced electric propulsion systems[5]. With resolving of a sertain constraints a solar arrays supplying the thrusters can be configured on a voltage up to 750 V [6]. The new opportunities in application of relatively high-Isp Hall thrusters are opened with the recently proposed CDL capacitors technology for solar arrays energy storage[7-8]. The direct discharging of the stored energy into TAL with a maximum voltage of 400 V was demonstrated. This, so called, "long-pulse mode" of the thruster operation while sequently repeated in many test cycles is a sort of quasystationary regime with contolled range of applied voltage. Obviously, if to charge the CDL capacitor bank to a voltage of 750-1000V, it is possible to increase essentially a discharging time and average resulting Isp. It is fair to notice, that this system becomes very flexible when initial(upper level) and final voltage can be varied in a wide range, thus providing any desired average time-dependent Isp. The later may be utilized in the direct-drive CDL capacitor powering propulsion systems requiring the variable Isp, assuming thruster is capable to provide corresponding throattlability.

Thus the characterization of the thruster parameters (thrust, Isp and thrust efficiency) with a discharge voltage ranging between 1000 V and 300 V represents essential interest.

HALL THRUSTERS CHARACTERISATION AT HIGH VOLTAGE

For achievement with the help of steady-state operated Hall thrusters of specified Isp level in a first approach a simple increase of a discharge voltage Vd is required to the extent, determined by well-known dependence $Isp \sim Vd^{1/2}$, fair for electrostatic character of ion acceleration.

The recently published results of the tests[10] of US-qualified SPT-100 at high voltage have shown growth of a specific impulse up to 2800 s at increase of a discharge voltage up to 700 V, though experiments failured to show with increase of voltage any increase in SPT thrust efficiency, which remained constant near to 0,52.

In the tests[11] of a single-stage TAL D-100 the specific impulse up to 2750 s was demonstrated and measured thrust efficiency appreciably grew from 0.54 at discharge voltage of 300 V till 0.64 at 600 V.

It is well to recollect that the thruster with anode layer, developed in TSNIIMASH, has two basic designs - single-stage and two-stage [12]. Two-stage TAL was primary created for operation at high specific impulse. By use of condensed substances as bismuth or cesium as a propellant it is possible to obtain thrust efficiency of the TAL close to 0.7 at Isp=3000-8000c [13,14]. The effective operation of the modified two-stage engine on xenon and other inert gases in a range of a specific impulse of 2500-4250 s with efficiency of 0.65-0.7 was also successfully demonstrated. The appropriate data can be found in [16]. So, a two-stage TAL operated in a steady-state mode at high Isp has superior to all other Hall thhrusters performance characteristics.

However, two-stage TAL requires more complex power supply system, consisting, as a rule, from two sources. The applicability of the direct-drive option for two-stage TAL is questionable at least for today. Therefore, a capability of a single-stage TAL thruster usually employing only one discharge power supply,that may be simply replaced by CDL capacitor, to provide effective operation with initial high voltage is of great interest.

PRELIMINARY ANALYSIS

With a view to estimate a single-stage TAL capability to work efficiently at high voltage "long pulse" mode it is good enough to analize the potential constraints inherent to steady-state mode.

Typical TAL design does not preclude a formation of a strong E-field in accelerating gap usually located in the area with relatively strong magnetic field. In a two-stage TALs operating with high voltages the achievable magnitude of electric field is as much as several thousands volt per millimeter. The strength of vacuum gap between the TAL electrodes is high enough to prevent gas discharge breakdown. High voltage can be applied by short pulse or can be increased and decreased step by step. So, generally, there are no visible limitations at this point to apply high voltage in the single-stage TAL design.

The natural limit on increase of a discharge voltage in the thruster with the ion beam current and mass flow rate both kept constant can be expected due to the threshold magnitude of general power, consumed by the thruster, or more exactly by allowable thermal stress of its elements. The concrete mechanism of thermal losses in the TAL thruster is connected with a heating of electrodes (anode) by backstreaming electrons. The electron temperature in the discharge channel of a TAL is much higher than in SPT, where the losses of energy of electrons on dielectric walls are inherent. Therefore in steady-state operated TAL the average energy of electrons interacting with the anode and allocated waste energy in general case grow at increase of Vd.

However, trivial dependence of wasted energy of the thruster input power like Pw ~ IdVd does not describe adequately a limit of voltage increase. As it was observed in experiments at a very low mass flow rates a high-voltage operation of TAL causes thermal regime which is comparable with the thruster thermal loading at rather larger power consumption with the increased mass flow rates.

Fig.1, shows usual dependence of single-stage TAL thrust efficiency versus specific impulse assuming that thruster power consumption is constant (IdVd=4.5 kW). At a lower mass flow rates a thrust efficiency drops significantly with the increase of discharge voltage. Similar dependence for two-stage TAL of the same size and at the same power level is given on Fig.1 for comparison. The nature of efficiensy decrease at Isp more than 2600 s at this power level is directly connected with rapid reduction of mass flow rate. Constant power mode does not represent the interest for direct-drive application, though it demonstrates certain constraints on choice of a thruster parameters.

The efforts were made with a view to investigate potential peculiarities of the single-stage TAL operation in extended range of discharge voltages. Due to the evident influence of a mass flow rate on the thruster performances and thermal regime it was of interest to obtain more detailed understanding of processes of the electron transfer in the discharge chamber.

Direct probe measurements of plasma parameters in the hollow anode of single-stage thruster involves a number of difficulties. Some portion of the information regarding electron current distribution inside anode cavity can be obtained in a design of the TAL thruster with the segmented anode as it is described in next section.

EXPERIMENTAL MODEL AND PROCEDURES

The TAL tests were performed with a range of applied discharge voltage from 300 V to 1300 V (in a number of cases up to 1700 V). A laboratory model of the D-100-II TAL thruster which discharge chamber is schematically shown on Fig. 2 was used for experiments. The hollow segmented anode consists of two separate electrodes that have equal electric potential during experiments. Voltage-current characteristics of the D 100-II with various mass flow rates are shown on Fig. 3 for the range of applied discharge voltage at 300-1300 V.

The magnetic field strenth in the channel of the accelerator was controlled and was established in each operating point at achievement of a minimal discharge current. Dependence of a resulted magnetic field versus discharge voltage with increase of the mass flow rate is presented onFig.4.

For an estimation of a electron current portion, penetrating directly into a hollow anode cavity the electrical circuit shown on Fig. 2 was applied. Besides a common discharge current Id, the Is - an electron current on a surface of the anode, exposed to an accelerating layer, was separately measured. The difference in currents Id and Is related to a general discharge current determined a percentage share of an electron current going inside anode cavity on depth at least more than one Larmor radius. On Fig.5 change of this share depending on an applied voltage is shown. The measurements were performed for a range of the mass flow rates at m= 5.3 - 17.5 mg/s. Fig. 6 illustrates the influence of the mass flow rate to an normalised electron current into a cavity.

THE DISCUSSION OF EXPERIMENTAL RESULTS

As it was expected, the increase of voltage does not result in significant change of discharge current. Volt-ampere characte-ristics obtained with different mass flow rates show the possibility to save linear dependence of Id at the voltages ranging from 300 V to 1300 V. As a rule, at mass flow rate close to 10 mg/s the thruster effisiency exceeded 60%.

Magnetic field strenth increases with Vd and remains almost constant when the voltage achieving 600 V. A drop of magnetic field with a larger mass flow rates is not clear enough, and requares more experiments.

Experimental data obtained with the segmented anode allow to understand better some features relating to plasma formation in a single-stage TAL.

As it shown on Fig.5 the fraction of high-energy backstreaming electrons penetrating into the anode cavity achieves a value of about 10% at low voltage (300 V) and grows up to more than 20% at higher voltages (Vd>800 V). The dependence of this fraction versus mass flow rate (Fig.6) has a more complicated character. At a very low mass flow rates electron current to the anode is rather high and achieves the maximum value. Then it decreases rapidly and again begin to grow slowly with the mass flow rate increase.

Based on experimental results consideration certain assumptions can be made.

Hall current does not exist in anode cavity. Ionization inside the hollow anode is provided by high energetic backstreaming electrons going from E×B discharge. The density of quasineutral plasma filling the anode depends of mass flow rate and has a maximum value near the anode exit plane.

Accelerating layer is closely linked with anode surface. Applied voltage determines the escape of ions from plasma boundary, which shape in optimal conditions repeats the shape of anode exit. At a very low mass flow rates the direct losses of high energy electrons on the internal walls of anode are significant. These losses grow sharply with the discharge voltage increase, thus causing anode heating.

Magnetic field strength establishes a conditions for electron transport to anode cavity at each value of applied voltage. Note, that in described experiments the magnetic field was controlled.

A value of electron current fraction penetrating into hollow anode is critical for support of effective ionization inside anode. Any significant violation (decrease) of this electron flux magnitude, for instance due to the increase of magnetic field near the anode, cause a reduction of plasma density in anode cavity and shift of ionization zone beyond anode toward discharge channel exit, thus resulting in E-field and potential re-distribution. In this case discharge current is increasing, electron current is going mostly to external surface of the anode, the value of parameter (Id-Is)/Id drops down.

With the larger mass flow rate the utilization of electron current inside anode is more efficient, ionization efficiency grows while the average electron temperature and related heat flux to anode decrease. The increase of voltage leads to slow general increase of electron flux required to compensate direct losses of fast electrons coming to the anode without ionization collisions. Wasted energy grows slowly with the increase of a general power consumption.

Whereas, real limit of the thruster thermal regime may occur with different discharge parameters. The main overheating problem is caused by high voltage operation at very low mass flow rate.

Let's note that as the discharge chamber of TAL has conducting walls, it is reasonable to apply the graphite as material of the electrodes. A graphite has highest among other materials energy of ablation at the influence of high-energy fluxes on its surface. It is known [16], for example, what even at influence of laser radiation with power density up to 100 êW/sm^2 the effective energy of destruction of carbon materials exceeds 30 kJ/g. Thus, taking into account also perfect radiative ability of the graphite, it is possible not to be worry about large thermal flux in the anode, if it does not cause problems with a thermal mode of other thruster elements.

CONCLUSION

A single-stage TAL thruster can be used in advanced propulsion systems employing high voltage (up to 800 V) direct drive cofigurations at steady state mode as well as at "long pulse" mode.

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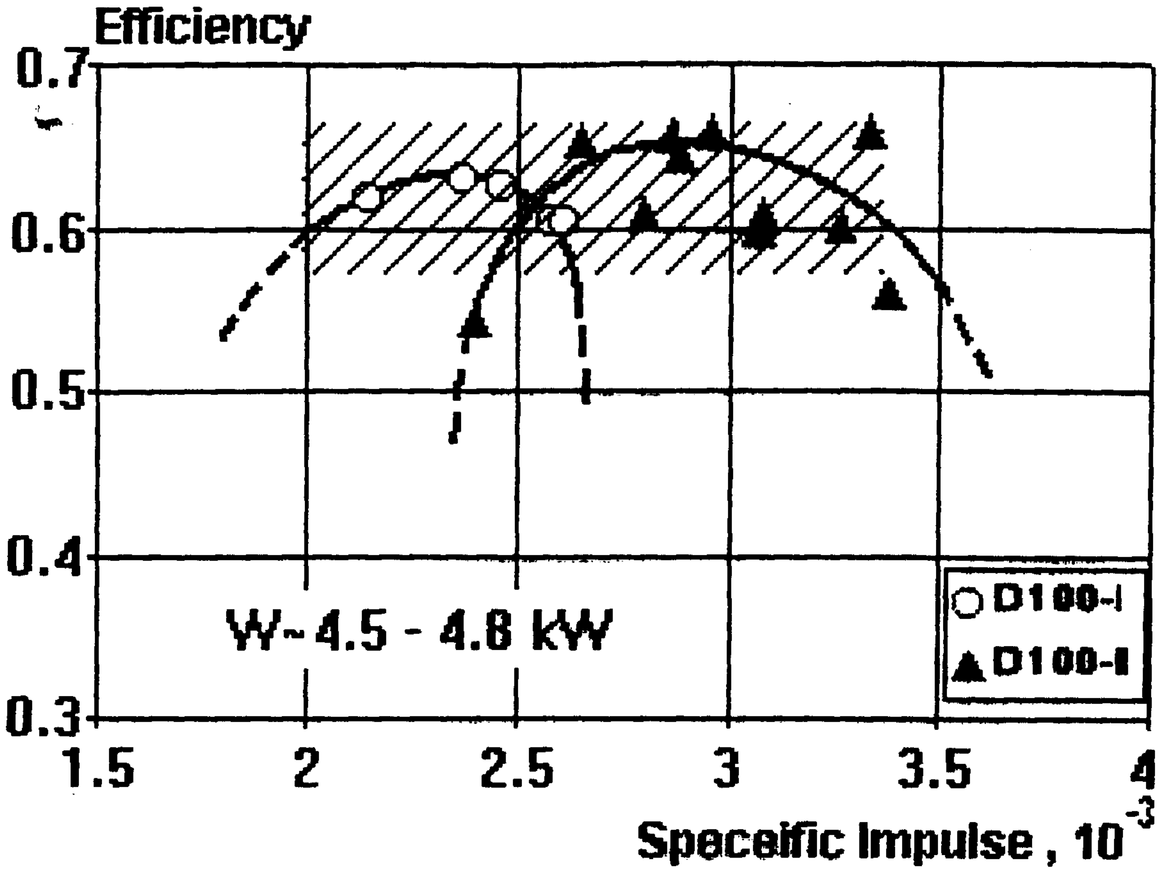

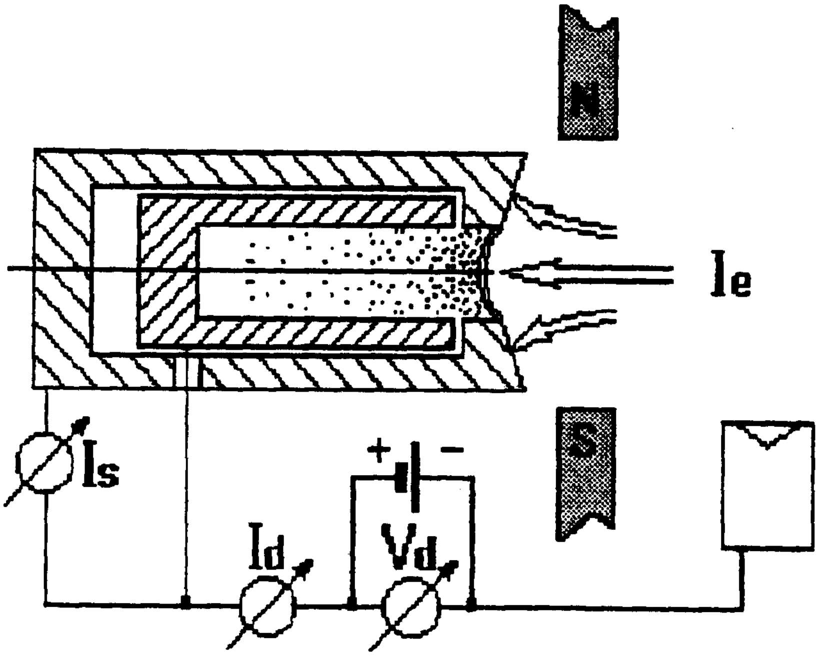

Fig.2.Discharge Chamber with Scheme of Measurements

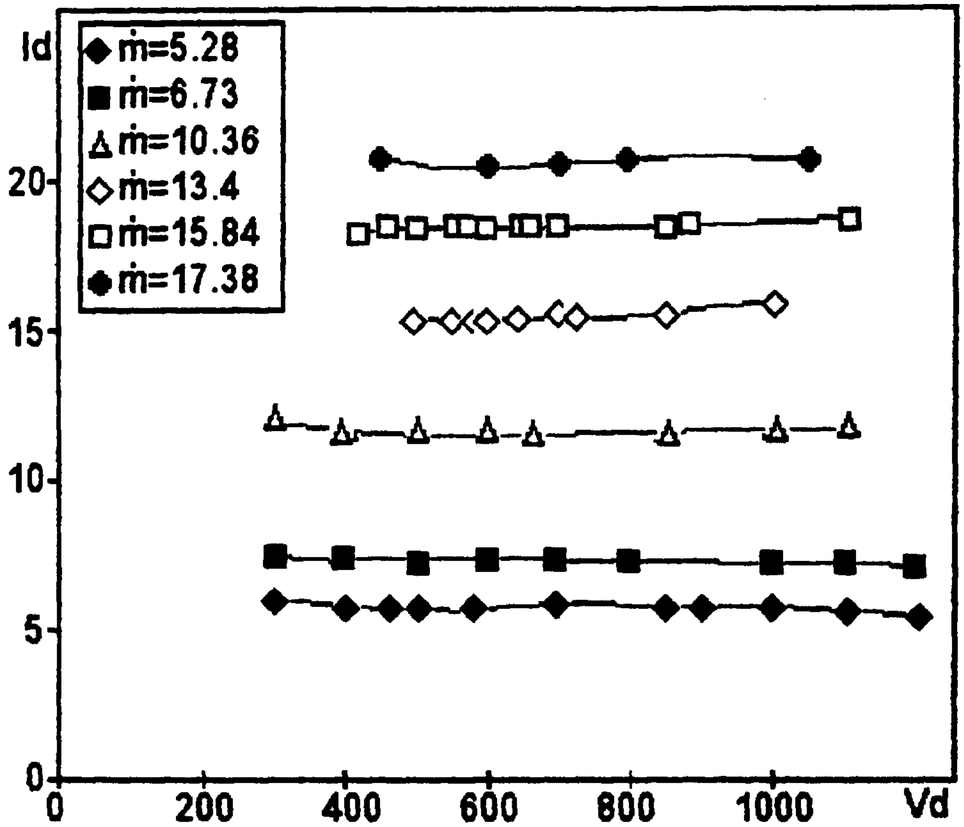

Fig.3. CV curves of D-100-II

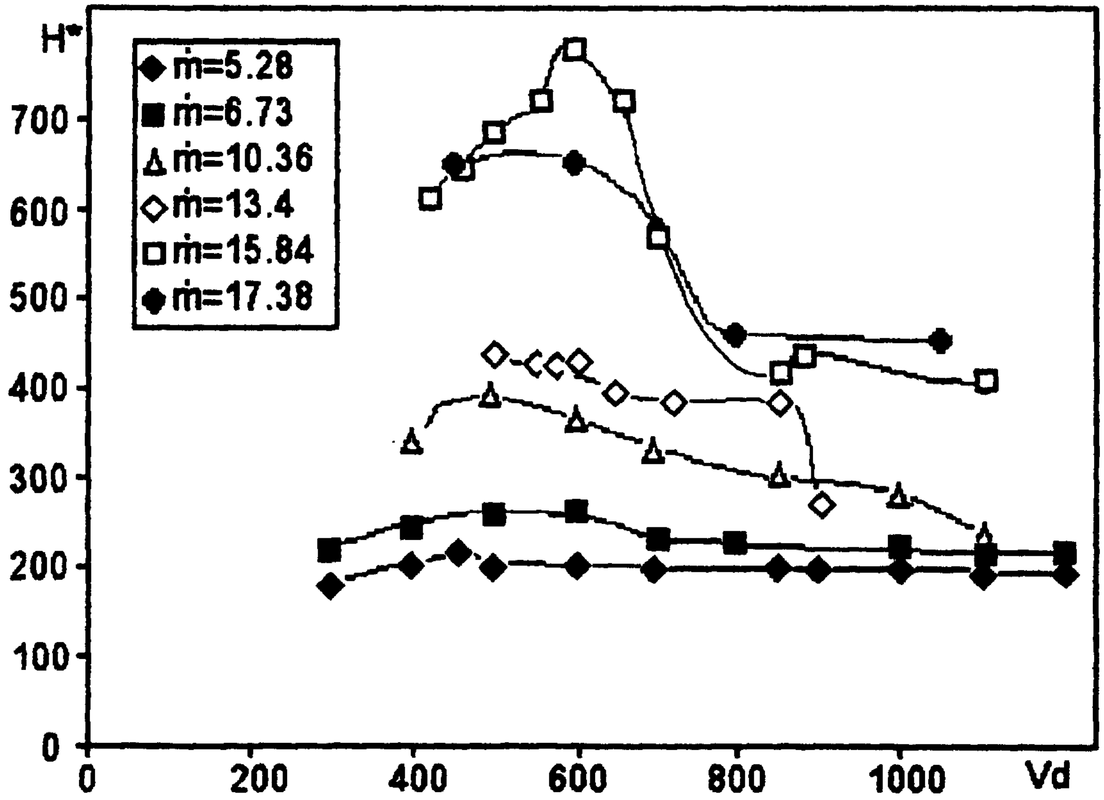

Fig.4. Optimized Magnetic Field vs Discharge Voltage

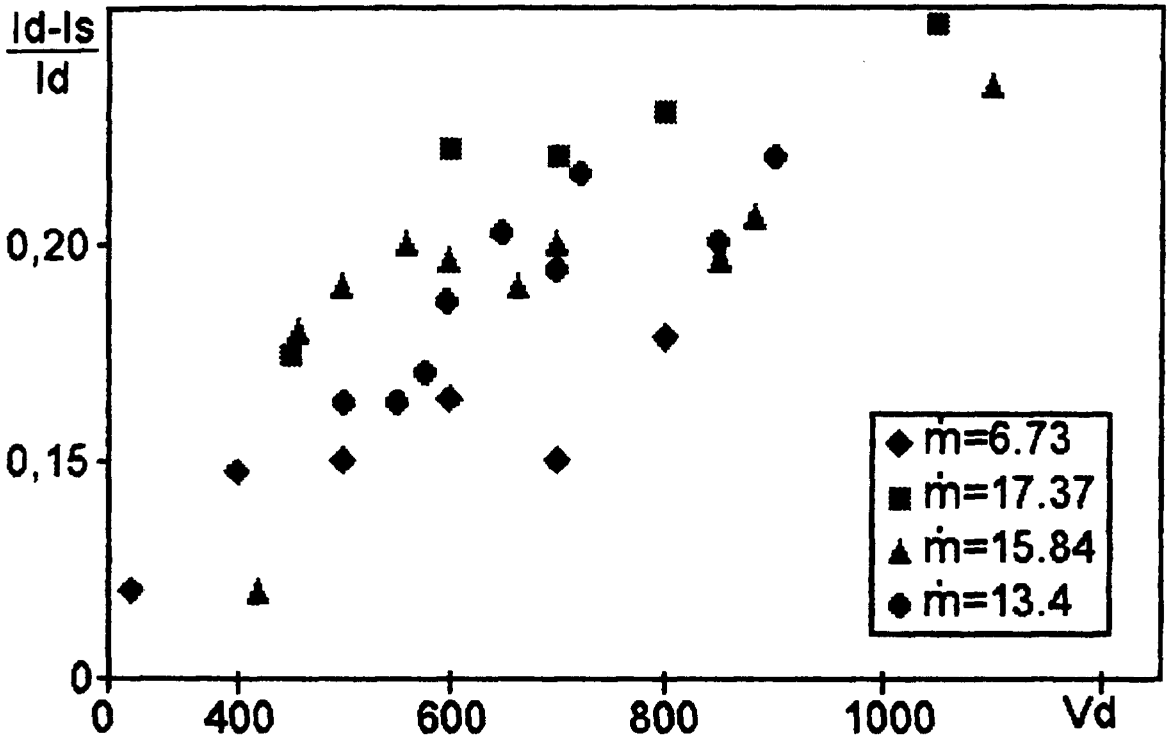

Fig.5. Normalized Electron Current to Anode vs Discharge Voltage

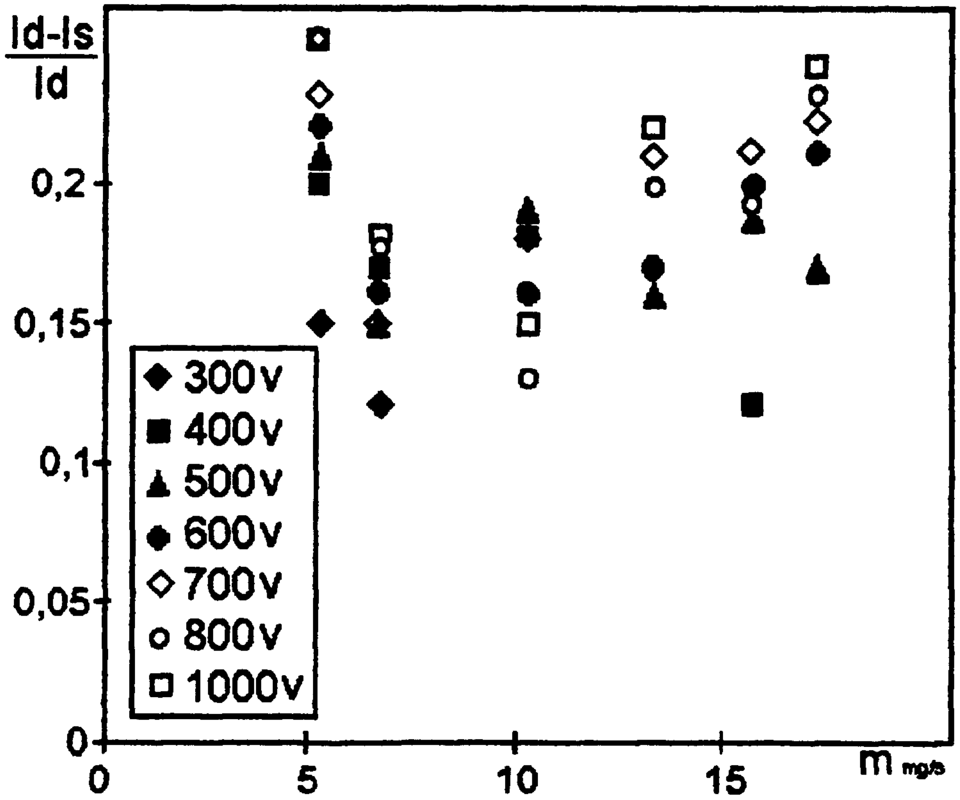

Fig.6. Normalized Electron Current to Anode vs Anode Mass Flow Rate