Study of Low Power TAL Characteristics

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Abstract

The general physical factors associated with the low power Anode Layer Thruster (TAL) development are considered. Experimental data, obtained at existing TsNIIMash thrusters – D-55, D-38, T-27 (with average diameter of the discharge chamber 55, 38 and 27 mm correspondingly) at power range 100…1000 W are analyzed to identify general tendencies in thruster parameters with thruster size variation. Results of T-27 and D-38 tests in a range 100…500 W, performed under EOARD funded program, are described. For discharge power 155 W demonstrated thruster efficiency was 0,35 with Isp 1050…1100 sec and thrust 1,05 G. At input power about 200 W the efficiency was not less than 0,4 with specific impulse 1300…1400 s. For analyzed data base no essential negative influence on thruster operation was identified despite on significant variation of the thruster size. Obtained data show a possibility to develop effective TAL thruster for power range 50…200 W .

Introduction

Electric thrusters are currently in successful use for station keeping and orbit correction thus providing increased life time of spacecrafts of such kind [1]. Recently the demonstration of interest in low power electric propulsion systems (a few hundreds watts) is the world tendency [2]. The systems of such kind require electric thrusters of reduced down to 50…200 watts input power, which must be as effective as the available devices normally consuming 0,5…50 kW [1,3].

Development of thrusters of reduced input power is a new task for the electric propulsion technology requiring detail review of all aspects concerning the thruster efficiency. Demonstration of available TAL performance level together with analysis of possibilities and ways to develop thrusters of reduced input power down to 100 ... 200 Watts is an objective of the work presented below.

The propulsion systems of low energy consumption are expected to perform a wide range of orbital maneuver including orbit rising and correction, drag compensation, station keeping in the Sun-synchronous orbit and satellite orientation. In addition the new market of space communication and the Earth sounding systems poses requirements of cancellation keeping and deorbit of exhausted spacecrafts.

The present paper contains the consideration of problems associated with development of thrusters of reduced input power using the concept of Hall plasma accelerator with anode layer (TAL).

TALs with power consumption significantly less then 500 W had not been systematically studied up to present moment. The existing TALs at 500 W and higher level are capable to provide the efficiency of 0,55 and specific impulse up to 1800 s . In accordance with situation mentioned above 500 W level not satisfies to the newest low weight SC requirements and needs its reducing. Thus, saying about low power TAL today we must assume under "low power" much lesser power level such as 50…200 W. In this paper attempt to give an answer about possibility and advisability of extremely low energy consumption TAL development is made.

Necessity of TAL consideration as a potential candidate to low power unit is determined by several attractive features. Unlike another Hall accelerators with closed drift of electrons such as SPT, TAL has conductive walls of the discharge chamber that improves working processes and also simplifies the thruster structure and technology in total. In addition, the conductive walls of TAL discharge chamber may be made of pyrolitic graphite, the most resistant material against erosion in consequence of bombardment by energetic particles of the discharge plasma.

Due to specific of discharge in TAL, near-wall processes in discharge chamber are not so significant for anode layer thrusters as compared with SPT. Together with relatively low erosion of the thruster parts it leads to several enough important features:

stability of the thruster parameters, insensitivity to outer contamination and in turn low contamination of the spacecraft surface, such as solar arrays, optic devices and so on, by sputtered material.

For given operating mode and input power TALs are more compact, less heavy and less noisy in the sense of electromagnetic interference as compared to other electric thrusters [4,5].

Extremely low energy consumption never looked as an special goal for Hall propulsion technology, so that there is no distinct approach to solve this problem. The following initial data were used to determine newest low power TAL face:

- A designated purpose of the propulsion system is station keeping and orbit correction.
- Thruster input power – 100…200 W.
- Propellant– Xenon.
- Specific impulse is not strictly limited and may be chosen in the range up to 2000 s under the condition of maximal thrust providing at given input power.
- The characteristic thruster life time is about 1000 hours.
- The thruster operating mode – periodical runs with duration from a few seconds to tens minutes (within the given life time).

Normal energy consumption of a cathode-neutralizer is not greater than a few percent of the total thruster input power. Therefore an effective operating TAL at input powers in the range from 100 to 200 W should be provided with a cathode-neutralizer consuming only a few watts. Traditionally used hollow cathodes are not serviceable at such low powers so that currently there is neither design nor firing experience on cathodes acceptable for micro TAL. The problem of creating of economical cathode is a separate one and is out of the consideration.

Consideration of factors arising with TAL power decreasing

The main existing bulk of data on TAL design and performances is collected for the range of input powers from 0,5 to 50 kW, and the available experience shows that no essential changes in thruster behavior occur over this wide range of operating conditions.

In contrary to this trend, with decreasing of input power and thruster structure dimensions some scale factors should impact TAL working process and performance.

Important to note, that during development of exiting TAL the reaching effective operation in 100…200 W power range was not a task. Therefore, work were advanced in three main directions:

- experimental demonstration of characteristics of the existing TAL devices at lower than designed input powers,
- analysis of physical and technical factors limiting possibility to develop highly effective anode layer thruster for operation at low input powers,
- evaluation of possibility to create a special TAL version for operation at input powers in the range from 100 to 200 W.

The available understanding in physical mechanisms of TAL operation and the experience in TAL operation suggest that there are two ways to decrease input power of TAL:

- Decreasing of the discharge voltage,
- Decreasing of the anode mass flow rate and the discharge current.

Both possibilities have inherent natural limitations. The following general limitation factors are first of important:

- Danger of transition to Anomalous thruster operation;
- Thruster down scaling required to keep high propellant ionization;
- Defocusing shape of magnetic force line;
- Rising radial inhomogeneity of the magnetic field;
- Increasing of boundary effects;
- Possible erosion increasing of thruster parts.

Anomalous thruster operation. Fig. 1 shows a typical Volt-Ampere characteristics of a single stage thruster with anode layer. On this curve there are two distinct ranges where discharge current depends on discharge voltage quite differently. Operating mode, named as "accelerating" one, relates to the region of nearly constant discharge current. This operating mode is the most effective and the ion beam is properly focused. With decreasing of the discharge voltage below the threshold, *V**, the current begins to rise and the thruster transits to "anomalous" operating mode characterizing with enhanced oscillations and lower efficiency whereas the ion beam is non-focused.

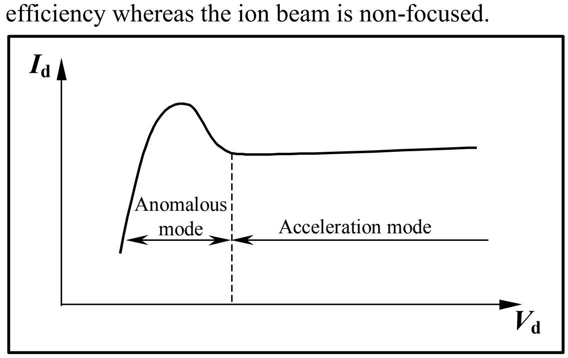


Fig. 1. TAL Volt-Ampere characteristic.

The nature of this transition to "anomalous" operating mode is not still quite clear. Under the current consideration the threshold V^* is the substantial value. It puts the lower bound of tolerable decreasing of the thruster input power using regulation of discharge voltage. For the thrusters with anode layer the characteristic values of V^* relates to the range from 100 to 200 V depending on the thruster design and operating mode established. For considered task to obtain maximum thrust at given input power level (to provide accelerating mode with minimal power to thrust ratio) is essential possibility.

Thruster down scaling necessity. The second way to decrease input power of TAL with lowering of the anode mass flow rate and the discharge current correspondingly is also characterized with its inherent limitation. This limitation is determined by reduction of propellant ionization efficiency. The mass flow density, j, in the discharge region must meet requirement $j > j_a$, the minimal value providing propellant ionization effective enough, where

$$j_a = \frac{e^2 \cdot B \cdot \sqrt{4 \cdot k \cdot T}}{M \cdot \sqrt{(m \cdot \langle Q_{ea} \cdot \upsilon_e \rangle \cdot \langle Q_i \cdot \upsilon_e \rangle)}}, [3]$$

where

E is electron charge,
B is average value of magnetic field,
M is ion mass,
Q_{ea} is cross sectional area of electron-atom collisions,
Q_i is effective cross sectional area of ionizing collisions,
υ_e is electron velocity.

According to this expression the mass flow density of Xenon in the discharge region must be kept greater than approximately 0,1 A/cm^2 [3]. So that input power of TAL can not be arbitrary decreased with no penalty in thruster efficiency and that also there is necessity to minimize thruster structure dimensions to keep high ionization efficiency.

Defocusing shape of magnetic force line. The average anode diameter is parameter generally characterizing operating range of a thruster, will be further used as the main parameter for thruster type classification. From one hand to provide high propellant lionization level the thruster structure and average diameter correspondingly must be down scaled, how it was mentioned above. From another hand, however, the discharge chamber geometry and size thruster parts ratio have optimum providing the best working process organization. Thus, while average diameter is decreasing the characteristic dimensions of the pole pieces gap (dimension h in Fig. 2) and the anode dimension in radial direction can not be proportional changed to each other. Fig. 2 illustrates how may change spatial picture of magnetic force lines distribution from traditional lens geometry to that of defocusing shape, as expected trend with decreasing of the average anode diameter d_a. It is obvious, that the picture of magnetic force lines in the second variant (b) is significant differ from lens geometry (a) providing optimal thruster work process. Thus, it is may be expected that beam focusing and efficiency will be deteriorated. In other words, in extreme case (b) the development innovate magnetic system is required to overcome the problems mentioned above.

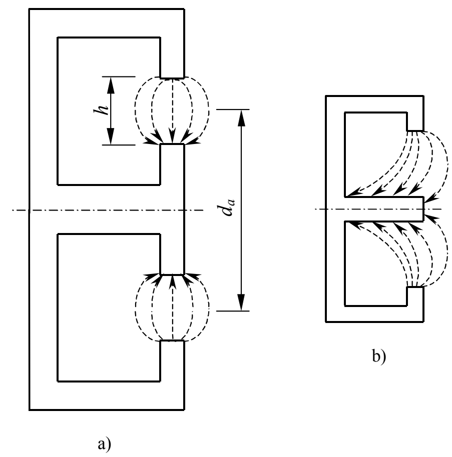


Fig. 2. Schemes of traditional (a) and microTAL (b) magnetic system.

Radial inhomogeneity of the magnetic field. Along with magnetic force line change in the low power TAL there is natural radial inhomogeneity of the magnetic field, which additionally influences on the TAL operating process. Fig. 3 shows a distribution of the value of the radial magnetic induction over the gap between the pole pieces, i. e. in the discharge region. The radial difference in magnetic field value leads to arising of additional electric fields between magnetic poles. The electric field of such kind may lead to beam defocusing. In this case the angle divergence value is proportional to $2L/d_a$, where L – anode layer length.

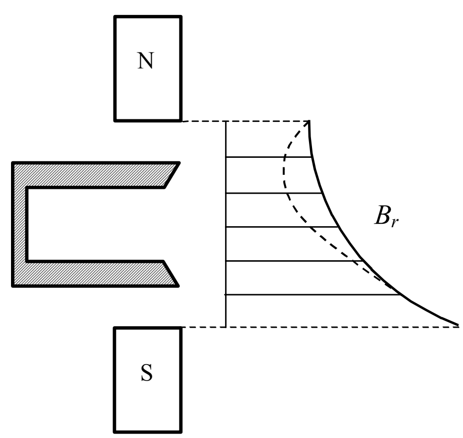


Fig. 3. Radial distribution of magnetic field.

It is quite clear that with decreasing of the average anode diameter whereas the gap between the magnetic pole pieces are reserved almost constant, the radial inhomogeneity of the magnetic field tends to grow causing additional beam defocusing with corresponding penalty in the thruster performance.

Boundary effects. For low power thrusters one can expect increasing of boundary effects causing reducing of efficiency as compared with existing TAL. For example, decreasing of discharge voltage results in ion beam defocusing with corresponding increase of portion of ion flow bombarding the discharge chamber walls [7, 8, 9].

Erosion of thruster parts. Speaking about low power thruster life time and taking into account application specificity of such thrusters it is may be limited by 1000…2000 hours range. It is clear, that TAL lifetime is defined by erosion of discharge chamber walls. Generally there are two ways to provide lifetime of Hall thrusters. The first one is using of special screen protecting the magnetic system from sputtering by accelerated ion beam. Time of erosion of such screens limits thruster life time, and it have to be thick enough to provide required life value. The second one and of most effective way to minimize erosion of discharge walls and provide life time of Hall thrusters is proper choice of magnetic field distribution over the discharge zone. This way is ultimately realized in the concept of "external anode layer" eliminating straight accelerated ion beam incidence on any structural parts of the thruster. This concept provides possibility to regulate axial position of anode layer with proper choice of the magnetic field distribution profile and allows to shift the discharge zone outdoor the structure exit plane with corresponding reduction of structure wearing and increase of thruster life time [8, 10]. However, the perspectives to realize magnetic structures of such kind are significant reduced with decreasing thruster dimension-type and strictly limited for thruster with small size.

Concerning the problem of thruster life time increasing and basing on the experience available one can characterize the expected relation between the life time and thruster dimensions with the scheme of Fig. 4 displaying three regions of design parameters.

In region III the thruster size allows to realize the concept of "external anode layer" increasing thruster life time since expected erosion of the pole pieces guard rings (the screen protecting the pole pieces from ion bombardment) is minimal. Increase of thruster dimensions may be accompanied with some grow of life time since allows to make the guard rings thicker and increases the time of their wearing. In region II the concept of "external anode layer" may be realized only partly. The smaller thruster, the lower opportunity to realize this concept. Thruster design variations in this region may result in dramatic change of expected erosion rate and life time. In region I the concept of "external anode layer" can not be realized at once so that the thruster life time depends predominantly on thickness of the guard rings being strictly limited in smaller thrusters.

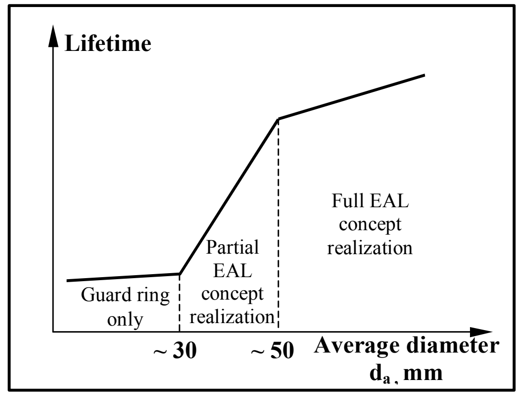


Fig. 4. Lifetime of thruster.

Fig.3 (see region II) suggests that specially shaped magnetic systems are non-usable for thrusters with average anode diameter lesser than 30…50 mm with input power range of 1....0,5 kW. Nevertheless it is reasonable to expect that the specified life time value of 1000 hours for thrusters of low input power may be provided with no special shaping of the magnetic field. It is worth noting that evaluated life time of the thruster with average anode diameter of 55 mm at input power of 700 W is greater than 3000 hours with no special shaping of the magnetic field [8]. Erosion rate for graphite guard ring at that thruster was about 1 mkm/hour. For the same density of xenon mass flow expected erosion rate decreases approximately proportional to applied discharge voltage. So that to get life time 1000 hours at 125 V it is enough to have thickness of the graphite guard ring about 0,5 mm. Obviously that such small value requires small space in the thruster discharge chamber and does not provide any problems for the thruster design. At the same time such thruster parts can be easily manufactured with using existing technologies, and ts operation in the thruster is not accompanied with any specific effects - like local overheating, thermal shock cracking and so on. For example, graphite guard rings with thickness 1 mm many times were successfully used in various thruster with anode layer.

Summary. At the bottom line of the discussion presented above let us resume the main factors to be taken into account while decreasing input power of thruster with anode layer:

- decreasing of the thruster size leads to non optimal magnetic system geometry and field profile, which cause defocusing of accelerated ion flow and reducing of thruster efficiency,
- an existed radial inhomogeneity of the magnetic field enhances and additionally impacts the thruster operating process especially for small size thrusters,
- the smaller discharge chamber the greater role of

edge effects at boundary between plasma and the chamber walls enhancing energy losses to the structure,

- design solutions providing minimal erosion of the structure and maximal thruster life time at high input powers are not applicable for small thrusters.

Being not critical for the traditional operating range of TALs, most of these scale factors never were specifically evaluated in past. For example, many of problems connected with low power TAL elaboration are determined by ionization processes. This problem has been successfully resolved for existing thrusters designed to operate at high input power and propellant density. Potentially the thruster may be modified to get effective ionization at low power and mass flow, but it requires specially dedicated research program, which is out of current efforts.

Big portion of considered scaling factors can not be quantitatively estimated based on available mathematical methods and computer codes, and dedicated experimental study is necessary to get information of boundary limits. So that, in the reported work significance of considered scaling factors for low power TAL was estimated based on existing experimental data obtained on D-55, D-38, and T-27.

Facility and test procedure

Two TsNIIMash vacuum chambers of 5 and 11 cubic meters equipped with 5 oil diffusion pumps each and with forvacuum mechanical pumps were used to run the thrusters. Both vacuum tanks are equipped with identical power supply, xenon management systems and measurement equipment.

The power supply and control system consist of:

- control panel of the power supply and Vacuum systems;
- a set of *DC* supplies to energize thruster anode, cathode-neutralizer and magnetic coils circuits
- a set of *AC* supplies to energize measuring and accessory equipment

The used *DC* discharge power supply is controllable three-phase rectifier with *LC* dumping oscillations of the output voltages to the levels less than 6%. The thruster discharge circuit includes a ballast resistor, limiting circuit current pulses during occasional arcing and shorting. The discharge gap was shunted by accessory condenser. The thrusters was tested with TsNIIMash Xenon multi-purpose laboratory hollow cathode providing electron current from 3 to 10 A. The cathode-neutralizer power supply provided ignition of start up cathode discharge at voltage up to 1000 V and maintenance of the auxiliary discharge with current of 3…4 A inside cathode cavity at voltage 15…20 V. While operating the thrusters at low input powers, the auxiliary discharge inside cathode cavity was being kept permanently so that the cathode steady state operation mode did not depend on the thruster discharge presence. Inner and outer magnetic coils were supplied each with independent current stabilized power supply providing controllable output current within a regulation range from 0 to 10 A. Voltage and current measurements in all circuits namely of the thruster main and the cathode-neutralizer auxiliary discharges as well as of the magnetic coils one were taken using digital instruments. All meters and measuring circuits had been beforehand calibrated using special calibration instruments of 0,5 accuracy class according to the Russian standard. The propellant management system included two independent feed line for the thruster anode and the cathode-neutralizer correspondingly. Xenon mass flow rate was regulated manually using a fine leak valve. Flow rate values were determined using a constant volume technique based on measuring of climb speed of a liquid driving a known volume (here 10 ccm) of a supplied gas out a glass tube with a scale here marked in 0,1 ccm. The time of the tube filling with the liquid was measured using a stopwatch with the scale factor of 0,1 s. The indicated value is an average of 2 – 3 readings. The mass flow rate value was calculated as:

$$m_a = 1{,}36 \cdot 4{,}3 \cdot \frac{10 \cdot T_0 \cdot P}{T \cdot P_0 \cdot \tau},$$

where

P_0 is the normal atmospheric pressure (760 Torr)

P is the current atmospheric pressure inside the measuring tube at the time of reading

T_0 = 273 K

T is the gas temperature

τ is the time of the measuring tube filling with a liquid

The thruster equipped with a cathode-neutralizer was mounted to a pendulum style thrust measuring device using automatic compensation of the measured force with direct feedback. The thrust value was calculated according to the relationship:

$$F = (A/A_0)\cdot F_0$$

where A is a difference of output thrust stand signals for switched on and off thruster, A_0 is the output signal value of the thrust stand being loaded with the calibrated weight and F_0 is the calibrated weight value. Before a test run thruster's circuitry insulation was examined and the thruster was remained at vacuum level of 10^{-1} - 10^{-2} Torr for at least 8 h allowing the structure to outgas. At every operating point before any reading to perform a 5-10 min lag was made allowing the thruster to achieve steady heat state. Also at every operating point magnetic coil currents were optimized on criterion of minimal discharge current I_d. Every measurement was repeated at least 2 times for better statistics.

Tests were performed using TsNIIMash D-38 and T-27 thrusters. Both thrusters are based on one and the same design scheme. The thrusters general view is shown in Fig. 5. D-55 thruster, used for comparison of the thrusters performances, is shown also (left one on Fig. 5).

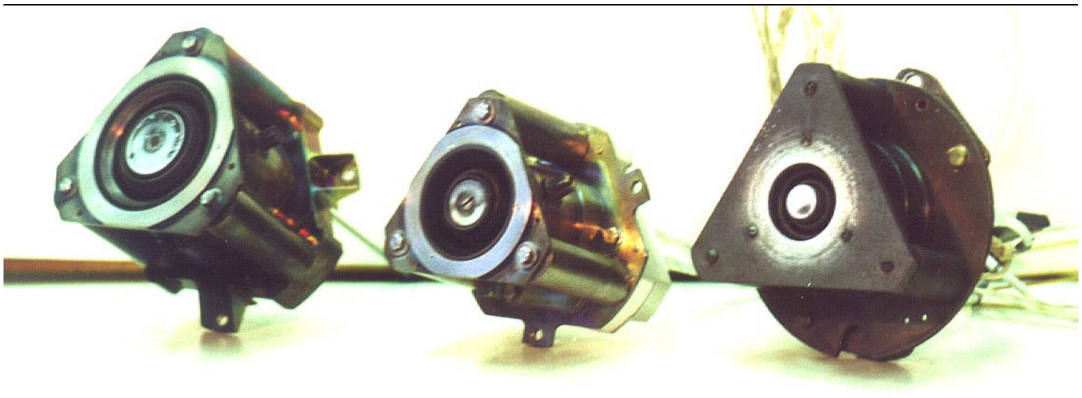


Fig. 5. General view of D-55, D-38, T-27 thrusters (from left to right).

The D-38 thruster is a flight prototype version for Module-M flight experiment [10], whereas the T-27 thruster is a ground laboratory version designed for technological use. The thrusters both were designated to operate at higher input powers than 100…200 W range of interest. Partially the D-38 thruster was designed to consume 750 W at specific impulse 2200 s with ability to be reinforced up to 1500 W. The T-27 thruster was designed to operate in 300…1000 W input power range. During the tests a performance characterization of the thrusters was accomplished over 50…500 W range with an emphasize to that of 100…200 W. Discharge voltage was varied over 100…300 V range where thrust to input power ratio is expected to be maximal. The lower border of the discharge voltages tested was put by thruster transition to the "anomalous" operating mode characterized with enhanced plasma oscillations and ion beam defocusing. Energy expenses in the magnetic coils and cathode-neutralizer as well as gas flow rate through the latter were not taken into account while calculating the thruster efficiency and other characteristics. The D–38 and T–27 performances flexibility is presented in Table 1.

Table 1. D-38 and T-27 performances.

Operating Point	D-38								T–27							
	ma	**Vd**	**Id**	**F**	**N**	**Isp**	**N/F**	**Eff.**	**ma**	**Vd**	**Id**	**F**	**N**	**Isp**	**N/F**	**Eff.**
	mg/s	**V**	**A**	**mN**	**W**	**s**	**W/G**		**mg/s**	**V**	**A**	**mN**	**W**	**s**	**W/G**	
Min. Power Level	0.62	148	0.50	4.12	74	692	178	0.18	0.53	120	0.54	3.72	65	719	173	0.20
Power Level 100 W																
High Isp	0.62	200	0.55	5.1	110	862	210	0.19	0.53	190	0.6	5.29	114	1033	211	0.23
High Thrust	1.11	102	1.07	7.3	109	680	148	0.22	0.87	120	0.9	7.06	109	848	152	0.26
Power Level 150 W																
High Isp	0.88	170	0.90	8.7	153	1027	172	0.28	0.7	200	0.72	8.04	144	1203	175	0.32
High Thrust	1.03	150	1.07	9.8	161	993	160	0.29	0.99	150	1.03	10.3	155	1084	147	0.35
Power Level 200 W																
High Isp	0.88	250	0.88	11.4	220	1336	190	0.33	0.7	251	0.8	9.60	201	1430	206	0.33
High Thrust	1.93	95	2.23	12.9	212	699	160	0.21	1.35	152	1.46	14.6	222	1129	149	0.36
Power Level 300 W																
High Isp	1.01	300	1.00	15.1	300	1546	195	0.37	0.87	300	1.0	13.7	300	1656	214	0.37
High Thrust	1.38	202	1.51	18.0	304	1357	167	0.39	1.36	203	1.42	18.6	288	1427	152	0.44

Being shown in Fig. 6 and Fig. 7, typical dependencies of thrust, specific impulse, efficiency and power to thrust ratio on Xenon flow rate for D-38 and T-27 thrusters illustrate general performance features of the thrusters with anode layer namely efficiency grow with increasing of propellant flow rate. It is necessary to note, that the optimal discharge voltage range, where power to thrust ratio is minimal was 100…150 V that corresponds to general tendency of the most powerful thrusters. The power to thrust ratio value was about 145 W/Gram for both thrusters. As it was mentioned above, effective thruster operation at minimal discharge voltages depends on boundary between “acceleration” and “anomalous” modes. Such boundary for tested D-38 and T-27 was at 100 V and 125 V correspondingly. Should be noted that no special efforts were made to adjust the hardware for operation at minimal voltages and the thrusters were taken as it is.

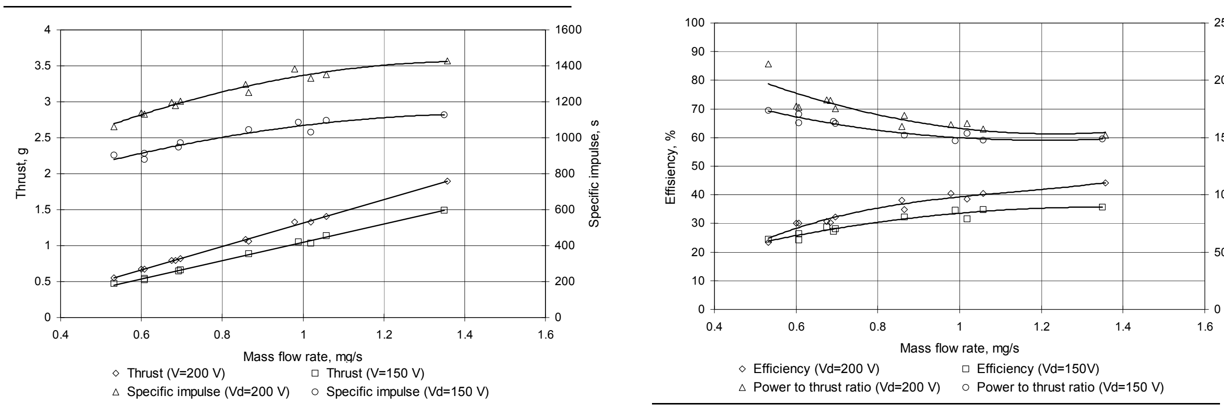


Fig. 6. Performances of T-27 thruster versus mass flow rate.

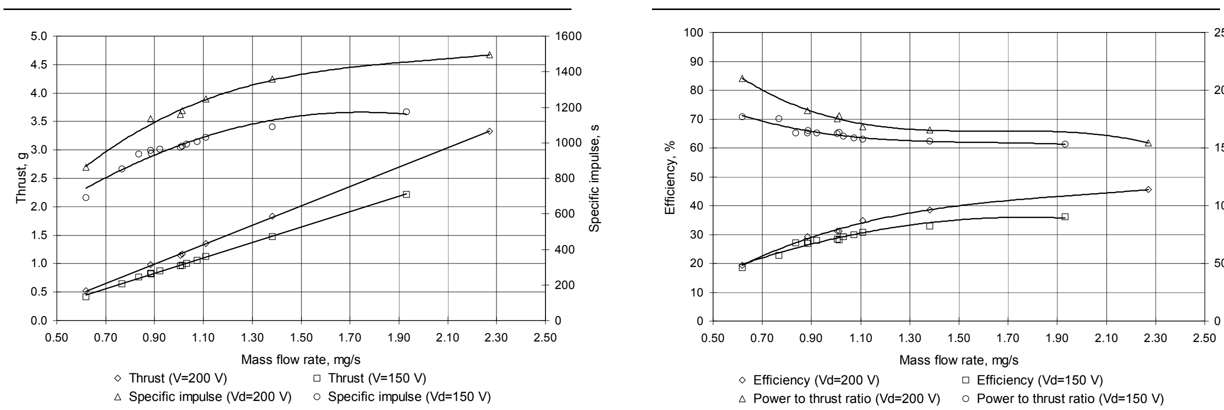


Fig. 7. Performances of D-38 thruster versus mass flow rate.

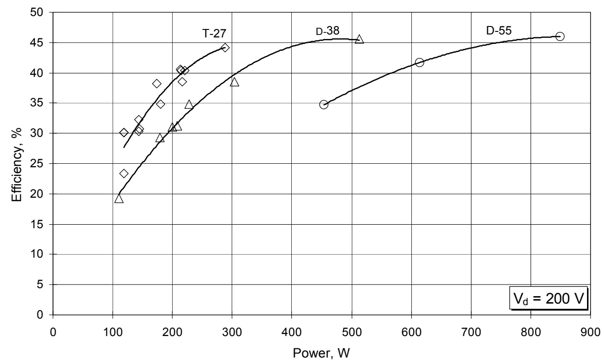
Two typical zones may be specified on the dependencies of efficiency versus mass flow. At low mass flows – near the boundary of effective ionization thrust efficiency grows up significantly with increasing of Xenon flow. With further increasing of mass flow efficiency value reaches the upper limit and is approximately constant. At the latter regimes the thruster reaches maximum of propellant ionization and thrust value is proportions to mass flow with good accuracy. So that such regimes should be considered as optimal one for particular thruster. Speaking about efficiency of the smallest tested thruster, it is may be concluded that for fixed 155 W operating mode the T-27 thruster exposed the best efficiency of 0,35 with thrust 1,05 g at specific impulse 1085 s. At input power 214 W the efficiency was risen to 0,41 with increase in thrust up to 1,37 g and in specific impulse to 1347 s.

Discussion

To analyze influence of scaling factors, discussed above in Chapter "Consideration of factors arising with TAL power decreasing", on characteristics of tested thrusters let us to compare their performances with D-55 thruster, which may be considered as good basis for such comparison. This thruster is convenient for comparative analysis because, on one hand, it is closest one to tested small thrusters. On another hand, it definitely has no scaling problems as compared with a bigger TALs of input power

up to 50 kW, and working processes are one and the same for these thrusters at corresponding operation modes [10].

In Fig. 8 thrust and efficiency for D-38 and T-27 thrusters are plotted versus input discharge power together with the same data on the basic D-55 thruster had been thoroughly tested earlier in NASA LeRC and JPL during the joint work between NASA and TsNIIMASH [4]. Fig. 8 suggests that region of effective thruster operation tends to shift to lesser levels of propellant mass flow rate in accordance with characteristic thruster size. Smaller size provides higher xenon flow density and , correspondingly, allows to get effective ionization at smaller mass flows.



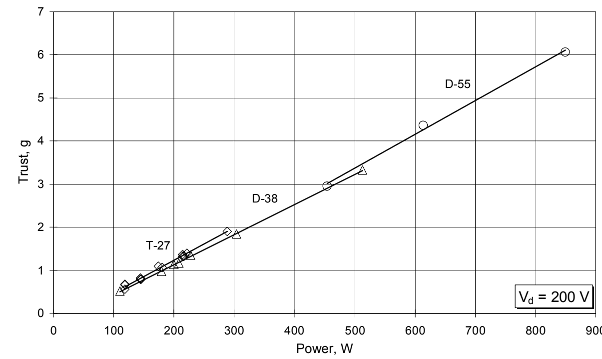


Fig. 8. Comparable characteristics of T-27, D-38 and D-55 thrusters.

Ratio of mass flow to average anode diameter is a reasonable criteria for selection of comparable operating modes of thrusters with different size. But it is correct for the thrusters with identical geometry of discharge chamber. For our case it is not fully applicable, because of some differences in discharge chamber geometry of T-27, D-38, D-55. As a criteria for comparison of the thrusters their efficiency and specific impulses at optimal operation regimes for each thruster - where efficiency value reaches the upper limit and is approximately constant with variation of mass flow - may be considered. For such regimes one can expect linear dependence of thrust versus discharge power also.

As it follows from Fig. 8, for given discharge voltage (200V) efficiency of all three thrusters tend to one and the same level with increasing of discharge power, i. e. increasing of mass flow and discharge current correspondingly. For used regimes value of efficiency goes up to 0,45 and specific impulse – up to 1500 sec.

It is also important that the observed dependencies of thrust on input power (Fig. 8) reserved their linearity being more inherent for higher input powers in accordance with Fig. 9. Fig. 9 suggests that dependence of thrust on input power is linear at a preferable discharge voltage 300 V for several devices tested despite of a change in sizes. Thus, it is may be pronounced that throttling capability behavior is the same for all TAL Family despite variation of thruster size and thruster can be scaled in accordance with particular requirements.

Linearity of Thrust vs. Power dependencies (Fig. 8) and one and the same level of efficiency for comparable regimes for all considering thrusters allow to say, that working processes are the same in all of them, and no essential negative influence on thruster operation was identified despite on significant variation of the thruster size. This suggests that a physical limit at which the discussed above in the Chapter "Consideration of factors arising with TAL power decreasing" negative factors should noticeably disturb TAL working process, was not still reached even while operating the T-27 thruster, the smallest one of the tested thrusters. Therefore there is a reason to develop a new TAL version with further decreased average anode diameter and expected improvement of performance in low input power range. Such development may be done with using available design methodologies and technical solutions, collected for thrusters with relatively high input power. And our consideration shows that these data base is applicable for the thruster with smaller size, than existing TALs.

Error! Not a valid link.Fig. 9. Linear thrust characteristic.

The leading factor for reducing of size of low power thruster is efficiency of ionization processes. At the same time, as it was mentioned above, specially dedicated efforts never were made to get effective thruster operation at low propellant flow density and discharge voltage. So that, it is enough reasonable to perform such study in support of development of smaller thruster. Miniaturization of the thruster may involve specific technological aspects also and simplification of the design is desirable. A preliminary consideration suggests that a perspective way to get it in regard of thruster magnetic system is use of permanent magnets instead of electrically driven ones. It is allow to simplify thruster cabling also and reduce total energy losses. It is important, that technologies and materials using for main TAL part – anode-gas distributor (typically- stainless steel), insulators (very wide spectrum of materials), metallic or graphite guard rings – do not have any difficulties in manufacturing and operation with small size and thickness, which are necessary for small low power thrusters with anode layer.

Conclusion

1. Feasibility study of problems associated with development of thrusters with anode layer of 100…200 W range is performed. It is shown that decrease of dimensions and input power should be followed by enhancement of a number of scale factors reducing thruster's efficiency compared to

that achieved on existing TALs at input powers greater than 500 W.

2. At TsNIIMASH facilities test program was performed using existing TAL devices D-38 and T-27 in input power range from 100 to 500 W. The tested thrusters reserved effective operating mode in 100…200 W range of interest. For fixed 155 W operating mode the T-27 thruster exposed the best efficiency of 0,35 with thrust 1,05 G at specific impulse 1085 s. At input power 214 W the efficiency was risen to 0,41 with increase in thrust up to 1,37 G and in specific impulse to 1347 s.

3. An analysis of experimental data collected on available devices D-55, D-38 and T-27 in input power range from 100 to 1000 W suggests that a physical limit at which existing negative factors were expected to disturb TAL working process noticeably, was not reached even while operating the T-27 thruster, the smallest one of the thrusters tested. Therefore there is a reason to develop a new TAL version with further decreased average anode diameter and expected improvement of performance in low input power range.

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