Parametric studies of 1.5 and 2.5 kW Hall Thrusters with external layer

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Abstract: The paper provides description and analysis of test results for two Hall thrusters with external layer. Both thrusters have geometrical similar designs of the magnetic circuit and discharge chamber. The tests were carried out in wide ranges of power and discharge voltage. Based on the test results, maps of output parameters were build and the boundaries of sustainable operation were determined. It was shown that for thruster with an external layer there is both a top discharge power and a top discharge voltage at which efficient operation is achievable.

I. Introduction

Hall thrusters (HET) with an external (plasma) layer (EL) are being recently a direction under active development in the field of state of the art HET technology (as to "plasma layer" authors refer to a discharge region, which encloses the bulk of the main electric field). In this case, magnetic field geometry and construction parts of the thruster are organized so that the, typical for HET with classical schematics, erosion of discharge channel exit section is almost absent[1]. This effect is achieved by shifting the peak point of the magnetic field on the discharge channel mean diameter forward in the downstream direction, so that it locates outside discharge chamber, behind the thruster exit plane. Another thing contributing to the effect is selection of exit insulator profiles suitable to the magnetic field configuration, so that the surface of the exit region of the discharge chamber is practically parallel to magnetic field lines. The extreme case of this approach is the «magnetic shielding»[2, 3], for which it is achieved an effect of "shielding" of the discharge chamber exit region by the anode plasma. Such method allows decreasing erosion level of exit insulators significantly, and respectively, increasing the thruster operational lifetime, including the case of high voltage.

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Even though the progress in this direction of studies is active, there is a lack of a complete theory, as well as of a commonly accepted design methods for the thrusters with EL. In Russia, for instance, development of EL HET is carried out by means of semi-empirical methods based on the experience gained in the course of development of the preceding models[4, 5]. However, the EL HET have several design features that alter it from thrusters of the classical configuration. They cause difference in the discharge chamber physics. One of the principal dissimilarities is the design of magnetic system and of chamber exit region. The magnetic field lines are practically parallel to the walls in the ionization and acceleration zone of thrusters with EL, while in thrusters with classical schematics, the field lines are practically perpendicular to the discharge chamber surface. It changes electron conductivity in the discharge channel, thermal fluxes on the surfaces of the discharge chamber and ion production processes. Consequently, the scaling factors alter in the design and scaling procedure. Here, the scaling procedure refers to the choice of geometric parameters of an experimental model on basis of an existing HET model parameters. This practice includes using of phenomenological model describing HET processes and their dependency on the input parameters, such as design of the magnetic system and the discharge chamber, discharge voltage, propellant flow rate.

In the connection with the facts described above, this work relates to experimental studies of the performance parameter dependencies of EL HET from their design and input parameters. Two models of EL HET with geometrically similar designs with different diameters were subject of the study. The tests were carried out in wide range of discharge voltage and power.

II. Overview of the test procedure

The tests were performed at KeRC, in CVF-90 vacuum chamber with diameter of 3.8 m and length of 8 m. Pressure in the chamber was sustained using cryopumps at the level not exceeding $5 \cdot 10^{-3}$ Pa. The vacuum chamber is fitted with a probe diagnostics system including several three-grid RPA, capable measuring angular divergence and energy spectrum of ion flow in a thruster plume. Thruster operation parameters are monitored by an automatic control and data acquisition system. The data includes currents, potentials, gas flow rate, temperatures of thruster parts and thrust measurement device (TMD) signal reading.

A. Test object description

The tests were held out with two experimental models of EL HET. The design of the thrusters is made in such a way that the surface of the output part of the discharge chamber is practically parallel to the magnetic field lines (Figure 1). Both thrusters were fitted with sets of thermocouples attached to the main structural elements, including the external and the internal exit insulators (ceramic rings) which are in direct contact with the plasma layer.

The prototype of the first thruster, KM-1T5-BC, is flight thruster model KM-60[6]. It has discharge channel with middle diameter of 60 mm. The second thruster, KM-2T5-BC, which prototype is a flight thruster model KM-75[7]. Its middle diameter of discharge channel is 77 mm. Both thrusters have geometrically similar design of magnetic circuits and discharge chambers. Heat removal was almost completely caused by radiation from external surfaces of the thruster elements.

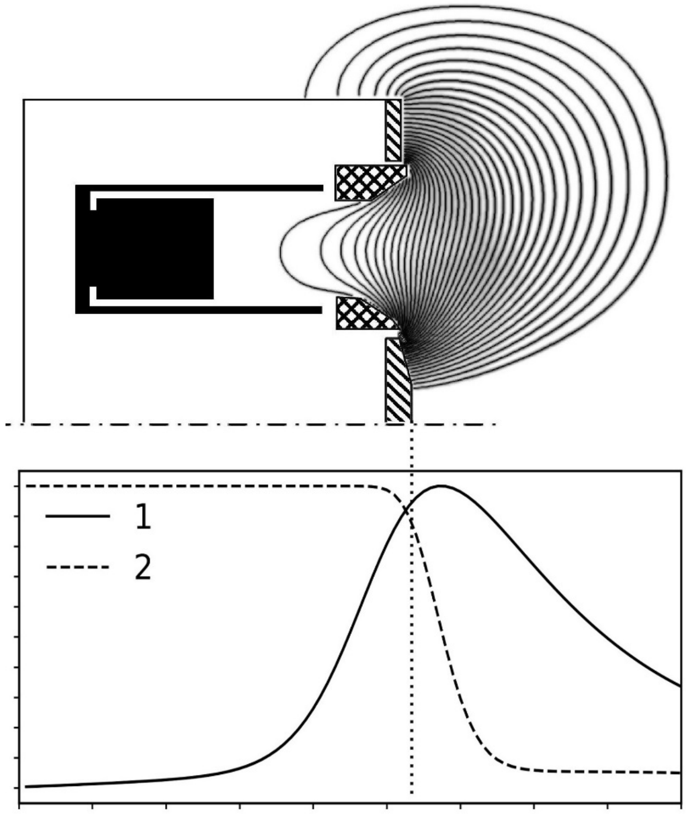

Figure 1. Thruster schematics with magnetic field lines. Marks: slanted hatch – thruster magnetic poles, crossing hatch – inner and outer ceramic exit rings, black fill – anode unit, 1 – typical potential distribution on the middle channel diameter, 2 – typical magnetic field distribution on the middle diameter of the channel.

B. Test sequence and methodology

KM-1T5-BC was tested according to Table 1.

Table 1. KM-1T5-BC test table.

m_a, mg/s \U, V	200	300	400	450	500	550	600	700	800	900
1,0	+	+	+	-	-	-	-	-	-	-
1,5	+	+	+	+	+	+	+	+	+	-
2,0	+	+	+	+	+	+	+	+	+	-
2,5	+	+	-	-	+	+	+	+	+	+
3,0	+	+	+	+	+	+	+	+	-	-
3,5	-	-	-	-	+	-	+	-	-	-
4,0	+	+	+	+	+	-	-	-	-	-
4,5	-	-	+	-	-	-	-	-	-	-
5,0	+	+	-	-	-	-	-	-	-	-
6,0	-	+	-	-	-	-	-	-	-	-

The optimal magnetic field and magnetic field range of stable operation (operating range) were determined for each operating mode. The magnitude of the magnetic field at which a sharp increase of discharge current and temperature was observed was taken as the lower boundary of the operating range. Either the magnitude of the magnetic field at which discharge operation mode changes[8], or the value of coil current exceeds the design constraint, was taken as the upper boundary. The point between the boundaries of the operating range corresponding to the optimal temperature state and anode efficiency was chosen as the optimal magnetic field. Measurements of all output parameters of the thruster were carried out after achieving quasi-stationary thermal condition. Plume parameters were measured for each discharge voltage at the gas flow rate of 3 mg/s to evaluate the anode efficiency structure according to the technique described in Ref. 9.

A similar test table for KM-2T5-BC thruster is shown below (Table 2).

Table 2. KM-2T5-BC test table.

m_a, mg/s \U, V	300	400	500	600	700	800	900	1000
2,0	+	+	+	+	+	+	+	+
2,5	-	-	-	-	-	-	+	+
3,0	-	+	+	+	+	+	+	+
3,5	-	-	-	-	+	+	+	+
4,0	+	+	+	+	+	+	+	+
4,5	-	-	-	-	-	+	-	-
5,0	-	+	+	+	+	-	-	-
6,0	+	+	+	+	-	-	-	-
7,0	+	+	+	+	-	-	-	-

Registering of operating parameters and optimal point selection were performed in the same manner as for KM-1T5-BC.

III. Test results

A. KM-1T5-BC test results

The diagram of the thrust dependency on the specific impulse at different values of discharge voltage and power for KM-1T5-BC is shown in Fig. 2.

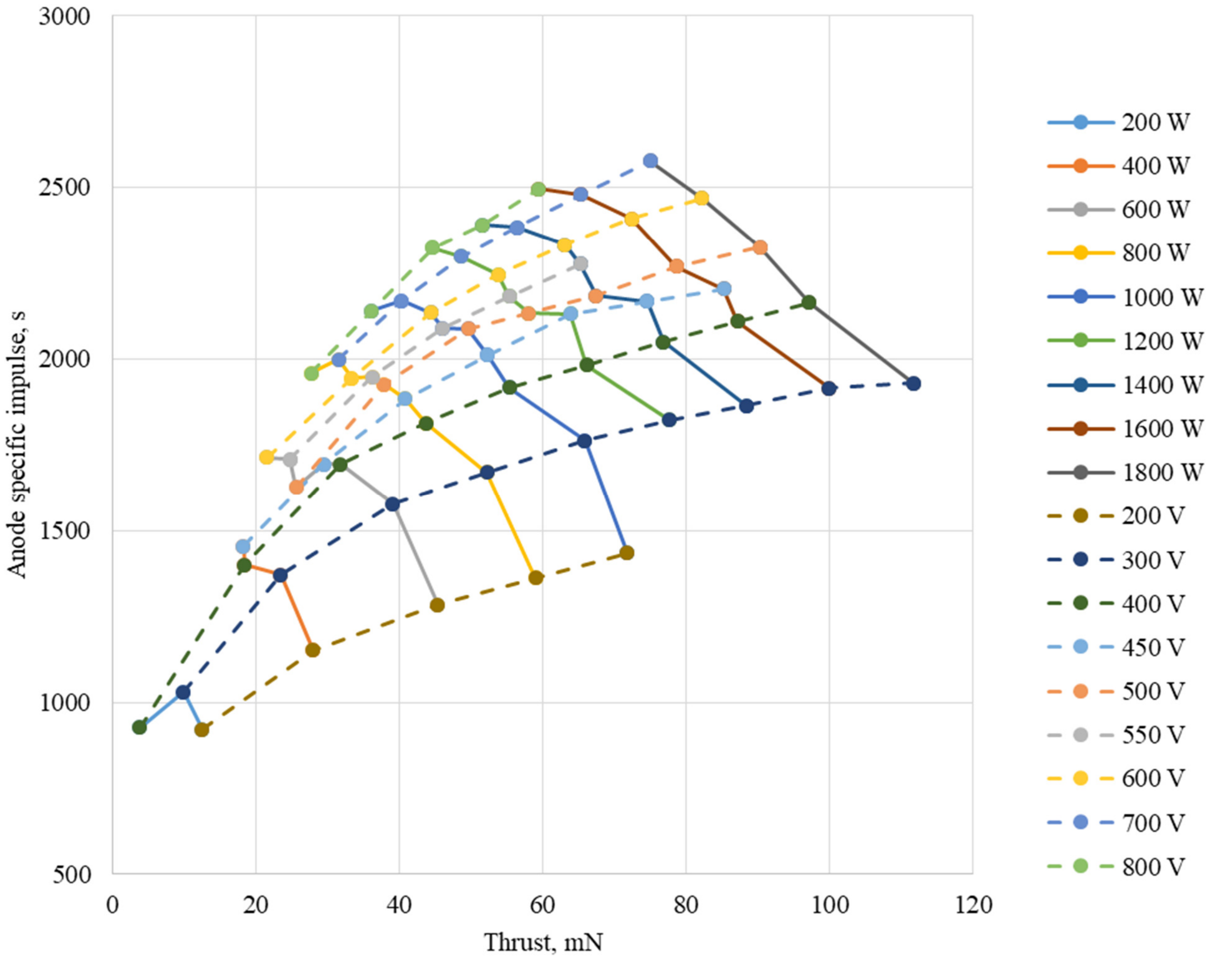

Figure 2. КМ-1Т5-ВС output parameter dependency on discharge parameters.

Temperatures of inner and outer discharge chamber ceramic rings of the discharge chamber are shown in Fig. 3.

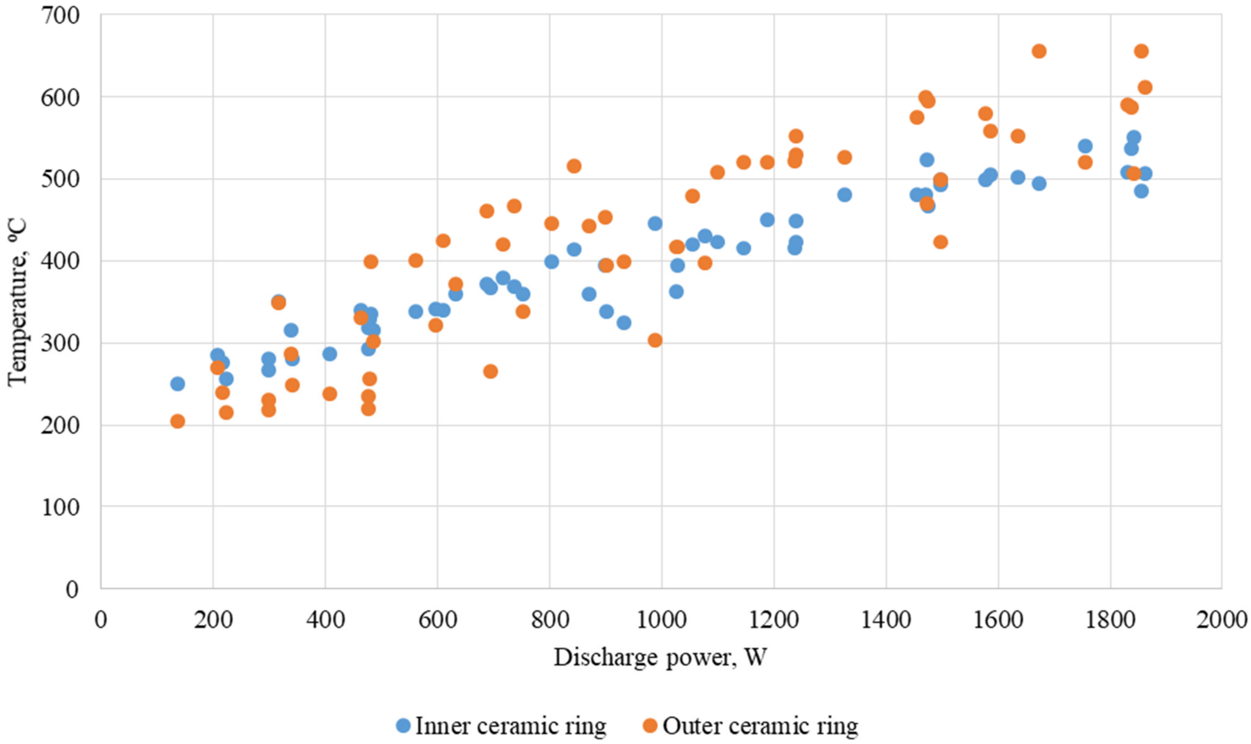

Figure 3. Discharge chamber exit temperatures of KM-1T5-BC.

It can be seen that, especially for the inner ceramic ring, the temperature is a function of the discharge power. The spread is somehow wider for the outer ring, and a dependency on the voltage manifests as well. However, it should be noted that there was observed an azimuthally non-uniform heating of the outer ring, that indicates a noncoaxiality of the thruster parts, and for instance, of the discharge chamber. So, the dependency of the outer ring temperature on the operation mode may be considered as a feature of the particular thruster. Thus dependency of the iner and outer ring temperatures is generally a function of discharge power. This is confirmed by KM-2T5-BC test results (Figure 10).

On the basis of the expirience of exploitation of KM-60 and KM-75 flight thrusters, that passed through complete sets of ground testing, it can be stated that the temperature of exit rings that allows the prolonged HET operation lifetime should not exceed 600 °C. As a consequence, it can be made a conclusion that the top operation power for KM-1T5-BC is 1.4 – 1.6 kW.

The behavior of the operation magnetic field range, depending on operation mode, is shown in Fig. 4. It is measured as the difference between the upper and the lower boundary of operation magnetic field range, divided by the optimal magnetic field for the given operation mode. The magnetic field margins, required for this, were obtained for each mode in a following way: the lower margin was being detected while decreasing the magnetic field until the moment of rapid current growth, and change in the observed discharge plume shape. It should be noted that this margin was detected for all the operation modes of the thruster. The upper margin was detected either by the initiation of the so-called "bell" mode (a mode of HET operation, which is not optimal)[8], or was taken just to be fit to the maximal possible coil current (design restricrion). The latter is corresponding to both the magnetic saturation in the inner magnetic core, and, as well, to the top allowed current of magnetic coil wires.

Discharge conversions to the "bell" mode were observed at discharge voltage over 400 V, at relatively low gas flow rates, in the other cases the upper margin for the magnetic field was caused "by the design".

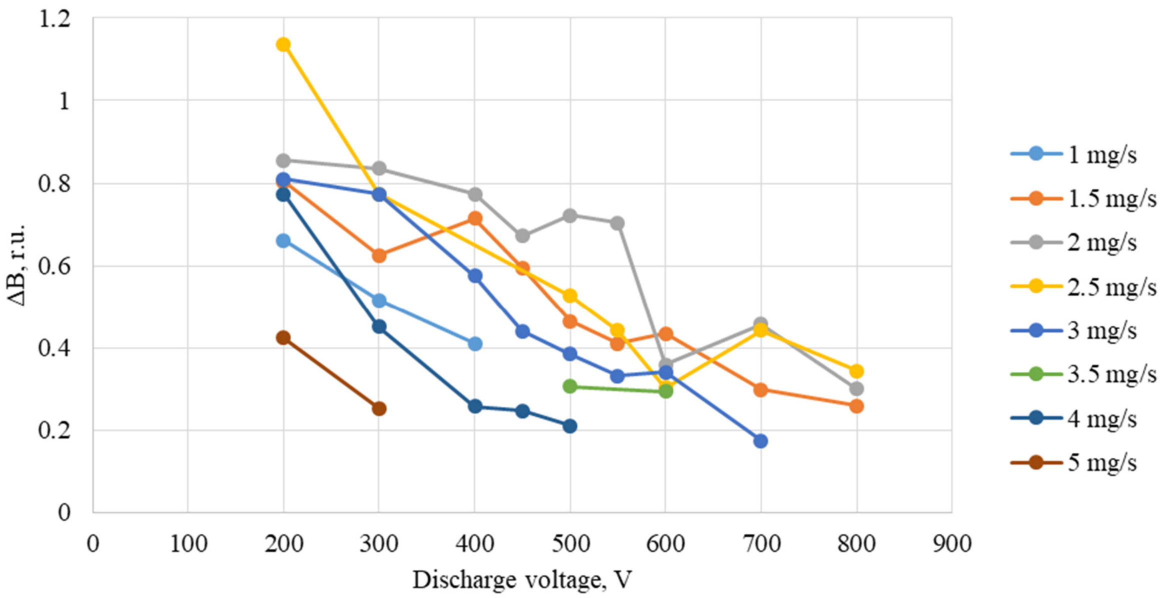

Figure 4. KM-1T5-BC operation magnetic field range as function of discharge voltage at different propellant flow rates.

It can be clearly seen in Fig. 4 that the magnetic field operation range suffers nearly linear reduction with the growth of the discharge voltage. Extrapolation to the intersection with the abscissa gives a critical voltage of about 1000 V. Indeed, there were not observed any stable and efficient operation modes at 900 V for any values of the magnetic fields and the gas flow rate. The widest range of magnetic field operation modes is achieved at propellant mass flow rate from 1.5 to 3.0 mg/s.

Further, we provide the information on the behavior of the performance of the KM-1T5-BC thruster, depending on operation mode parameters. The dependencies for the efficiency, specific impulse and thrust are given in Fig. 5, 6, 7. Several important elements should be pointed out. While analyzing Fig. 5 we may conclude that the thruster efficiency does not change significantly starting with the power of 1.2 kW in the all voltage range, so at power of ~1.5 kW the thruster would operate with nearly maximal efficiency at all voltage range. Another interesting fact is that KM-1T5-BC thruster efficiency is almost a certain function of the discharge current (see Fig. 8). Analysis of the Fig. 6 reveals that at any power, the specific impulse does not increase with growth of discharge voltage over 700 V at constant power. Considering the top operation power of 1.5 kW, it can be concluded that the maximal value of specific impulse is reached at the top allowable parameters of 2.15 A, 700 V and is equal to 2430 s at ~30 % width of magnetic operation range and thrust of 60 mN.

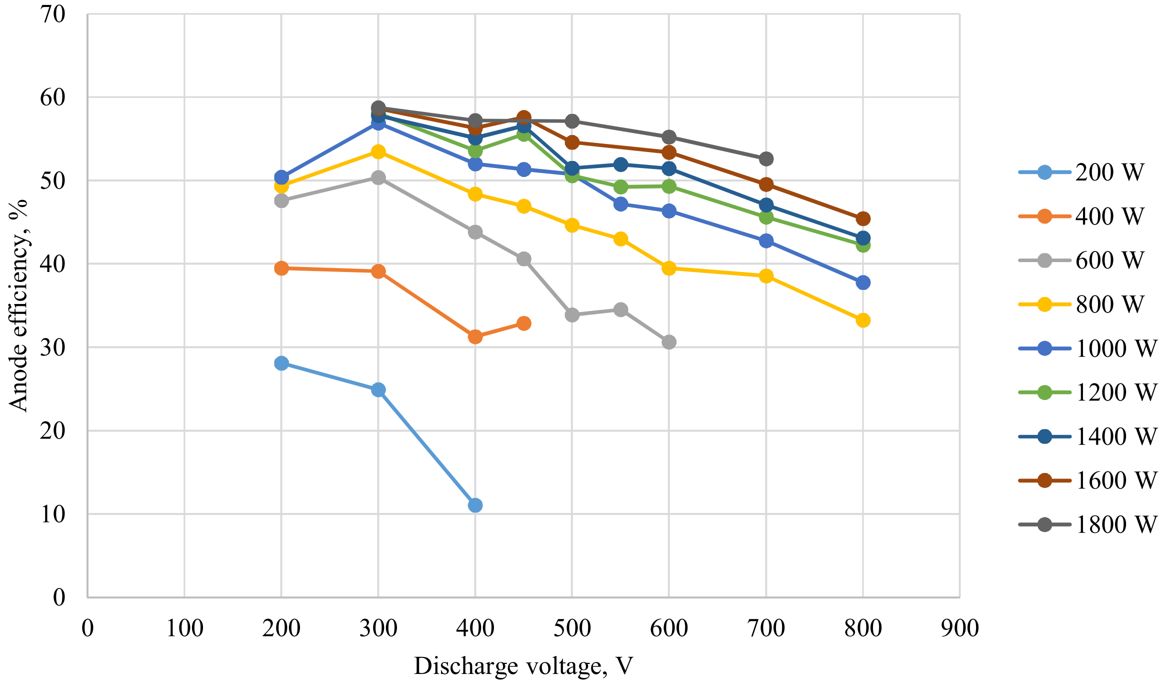

Figure 5. KM-1T5-BC thruster efficiency dependence on discharge voltage at varying discharge power.

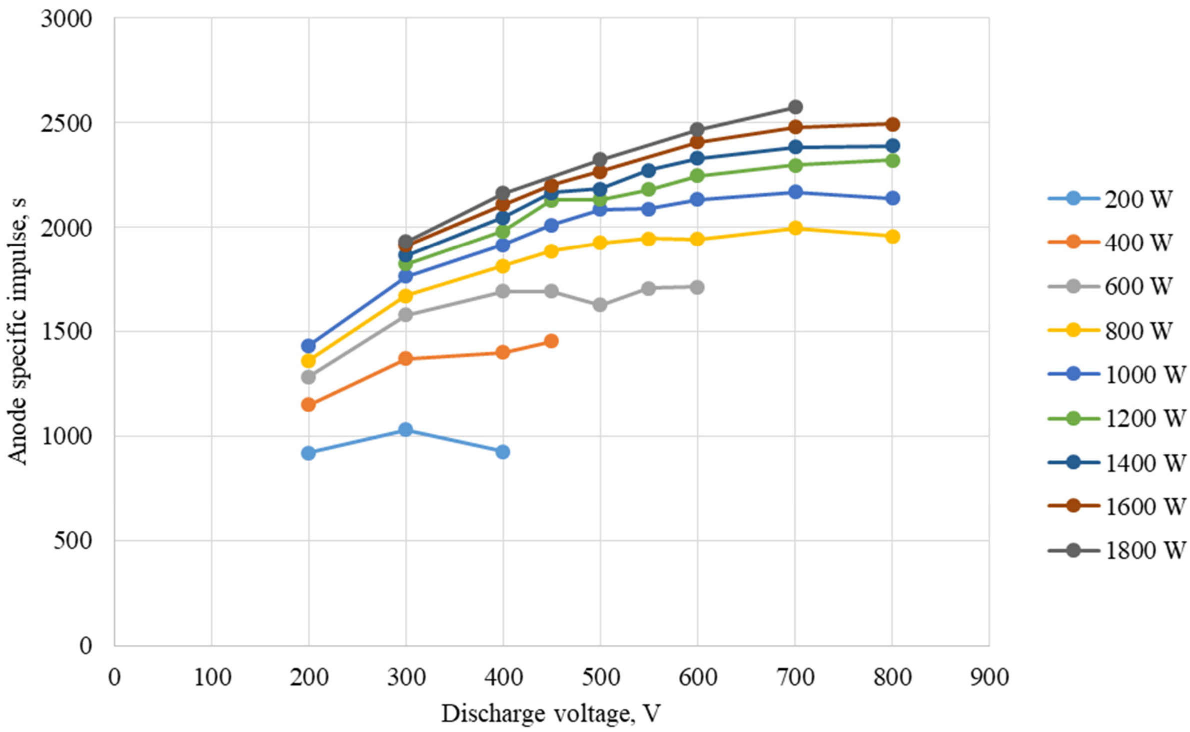

Figure 6. KM-1T5-BC thruster specific impulse dependence on discharge voltage at varying discharge power.

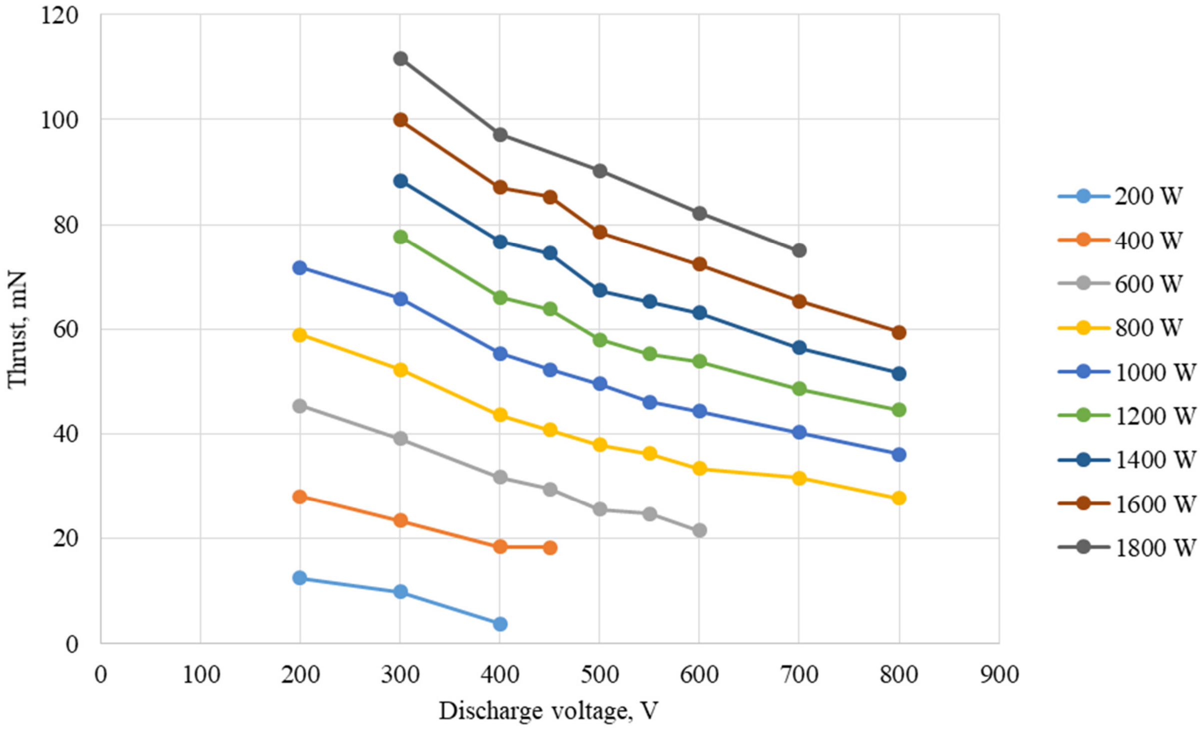

Figure 7. KM-1T5-BC thruster thrust dependence on discharge voltage at varying discharge power.

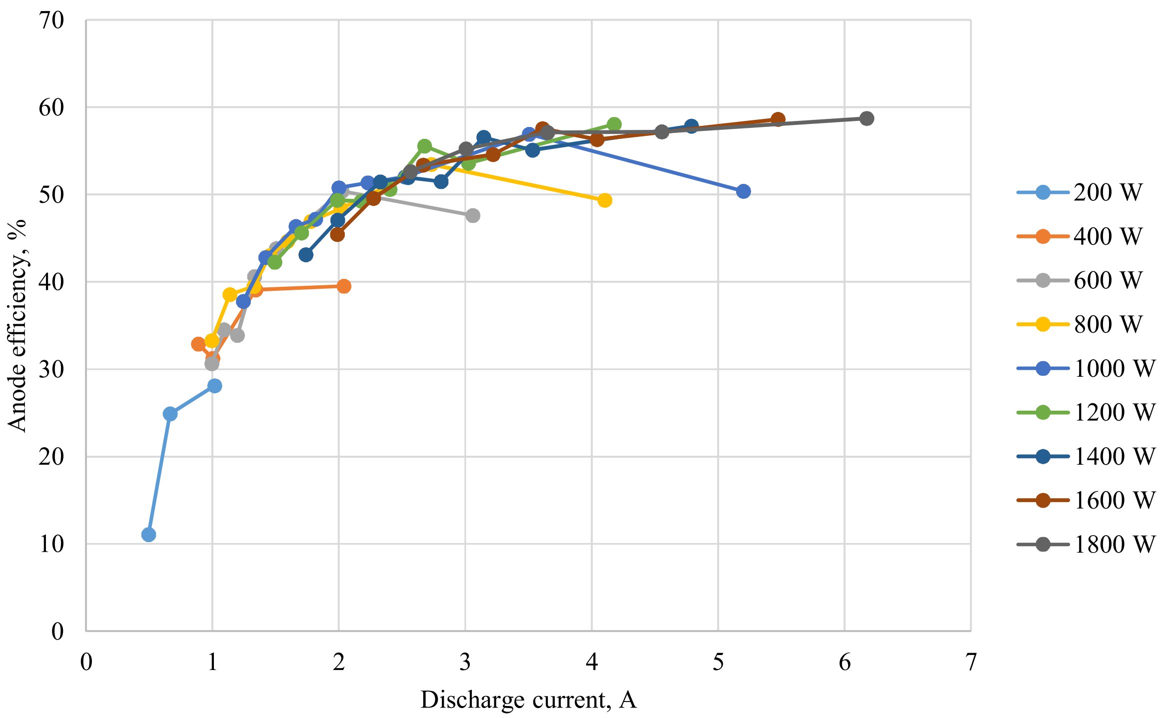

Figure 8. KM-1T5-BC thruster efficiency dependence on discharge current at varying discharge power.

Analyzing the Fig. 7 allows clearly define that thrust is a linear function of power at constant discharge voltage. The maximum of thrust is achieved at discharge current of 5.1 A and voltage of 300 V, however the magnetic field range suitable for stable operation was very narrow in this operation mode. If taking the allowed width of working range equal to ~30 %, the maximum thrust would be reached at the top allowable parameters of 4.5 A, 300 V, and would be equal to 83 mN at anode specific impulse of 1840 s.

B. KM-2T5-BC test results

The diagram of thrust dependency on specific impulse at various voltage and discharge power values for KM-2T5-BC is shown in Fig. 9.

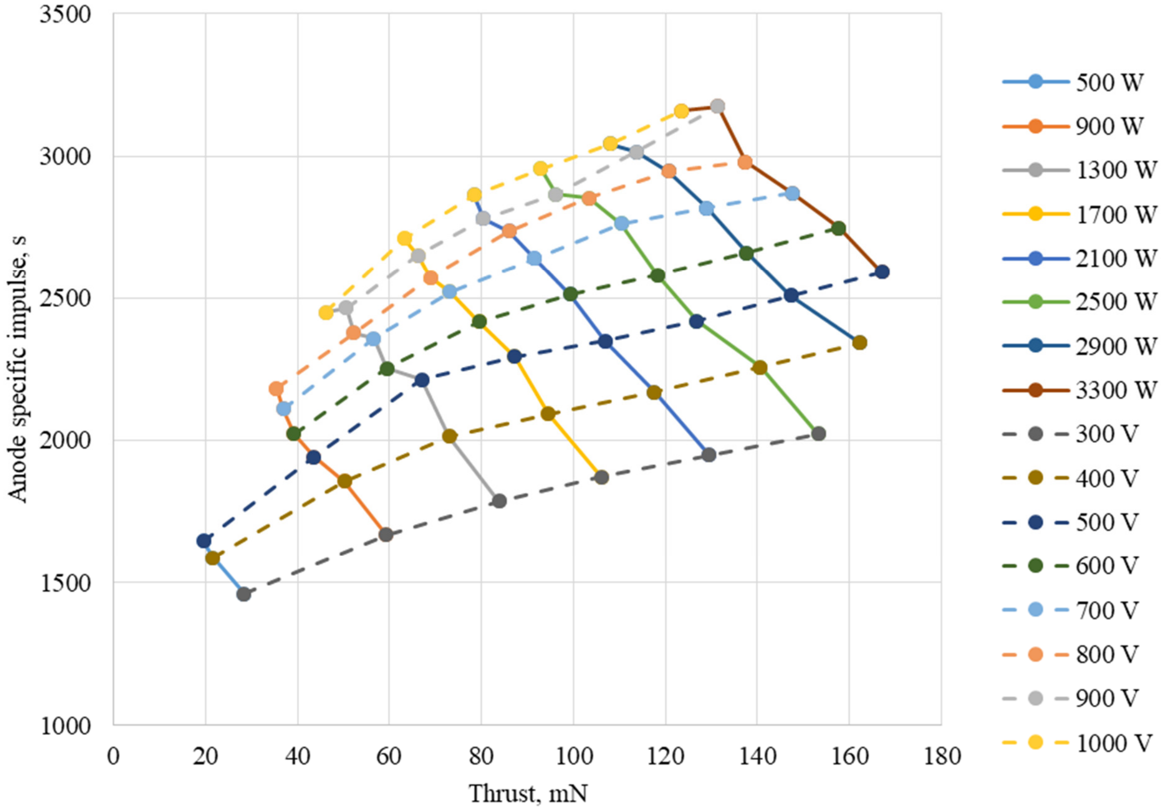

Figure 9. Diagram of principal output parameters for KM-2T5-BC thruster dependencies on discharge parameters.

Temperatures of inner and outer discharge chamber ceramic inserts of the discharge chamber are shown in Fig. 10.

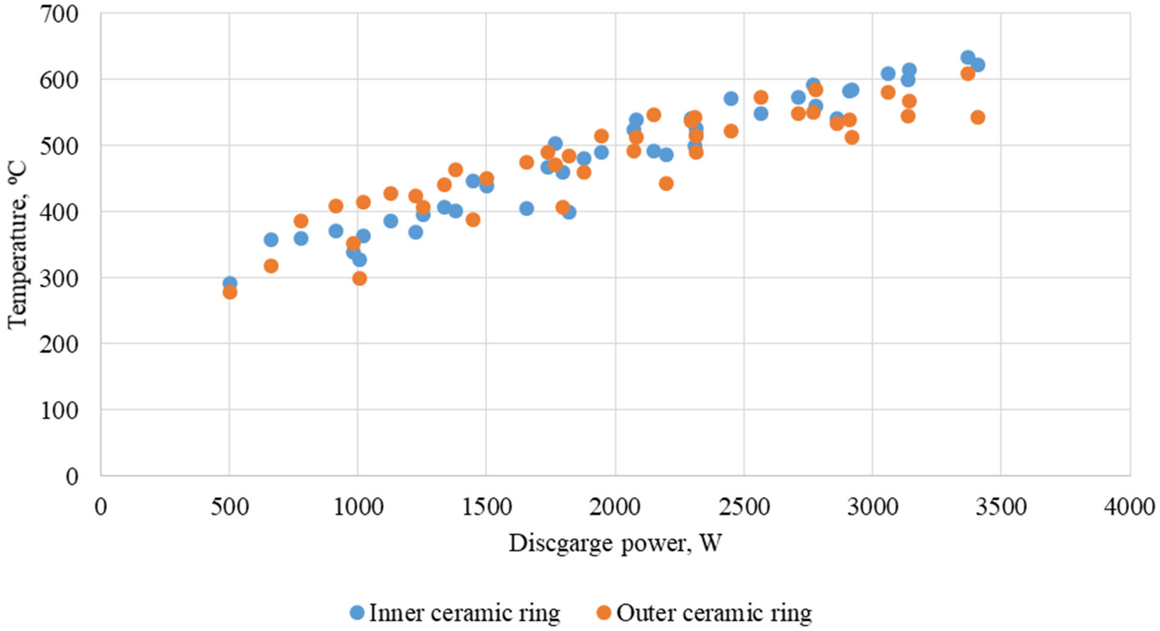

Figure 10. Discharge cmaber exit temperaures in KM-2T5-BC.

We may conclude, according to considerations, regarding the top operation power, analogous to that of the previous section, that for KM-2T5-BC thruster this power is ~ 2.5 kW.

Behavior of the width of the magnetic field range suitable for stable operation, defined by a technique similar to the described in the previous section for KM-1T5-BC thruster, is shown in Fig. 11.

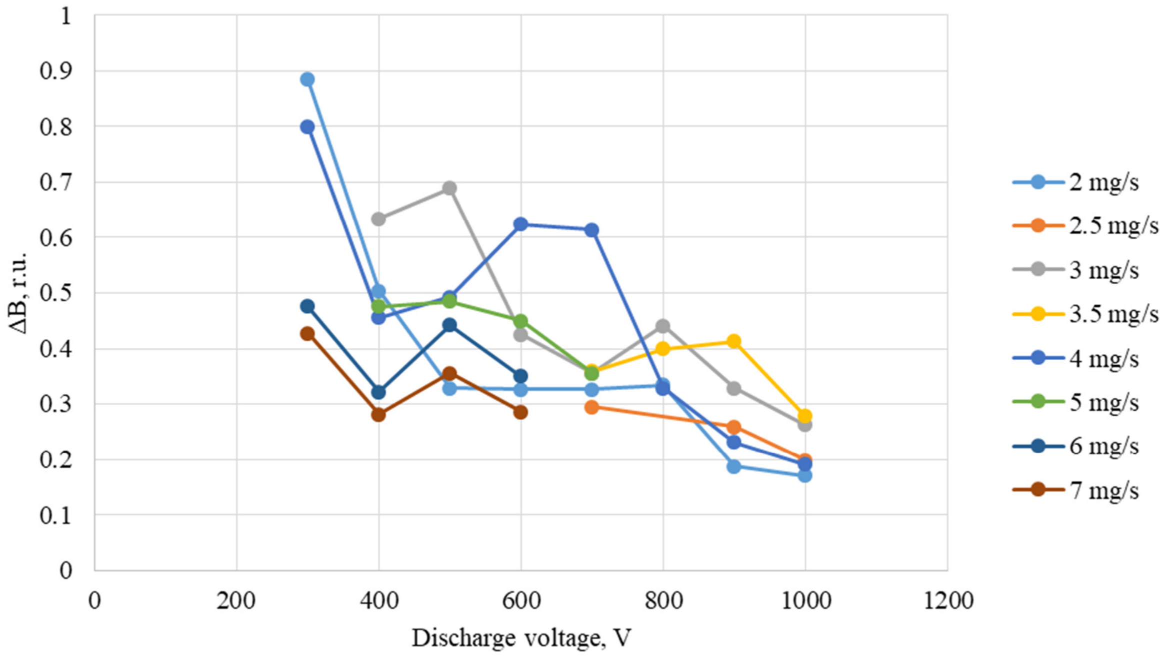

Figure 11 KM-1T5-BC operation magnetic field range as function of discharge voltage at different propellant flow rates.

One can see approximately linear decrease of the width of the operation magnetic range with voltage increasing in Fig. 11, as for the KM-1T5-BC; and extrapolation of the curves in Fig. 11 towards an intersection with *abscissa* gives the critical voltage of ~1200 V. The widest magnetic field operation range is reached at flow rates of 3-5 mg/s.

Further, the information on the behavior of the main integral characteristics of the KM-2T5-BC thruster is presented, depending on operation mode parameters.

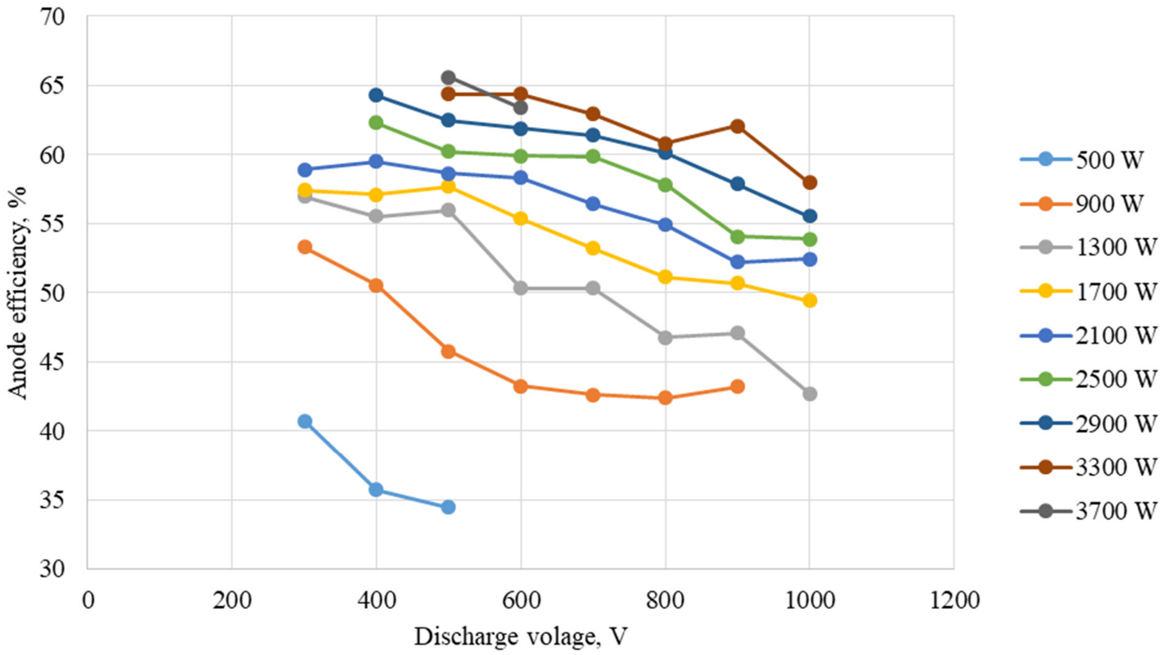

Figure 12. KM-2T5-BC thruster efficiency dependence on discharge voltage at varying discharge power.

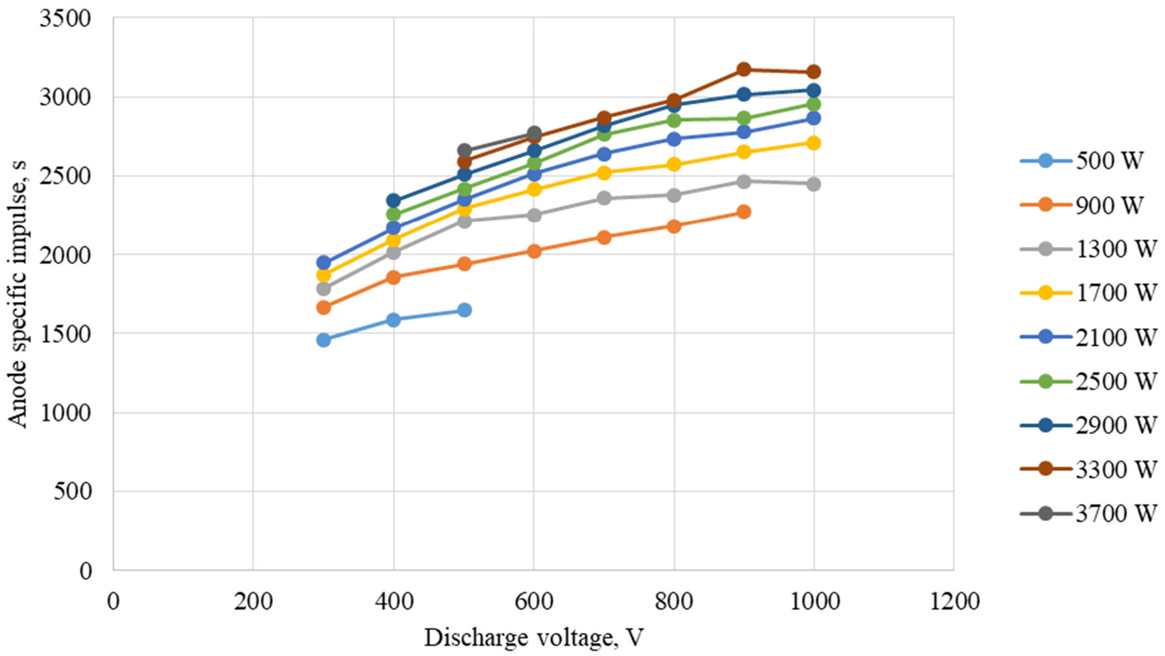

Figure 13. KM-2T5-BC thruster specific impulse dependence on discharge voltage at varying discharge power.

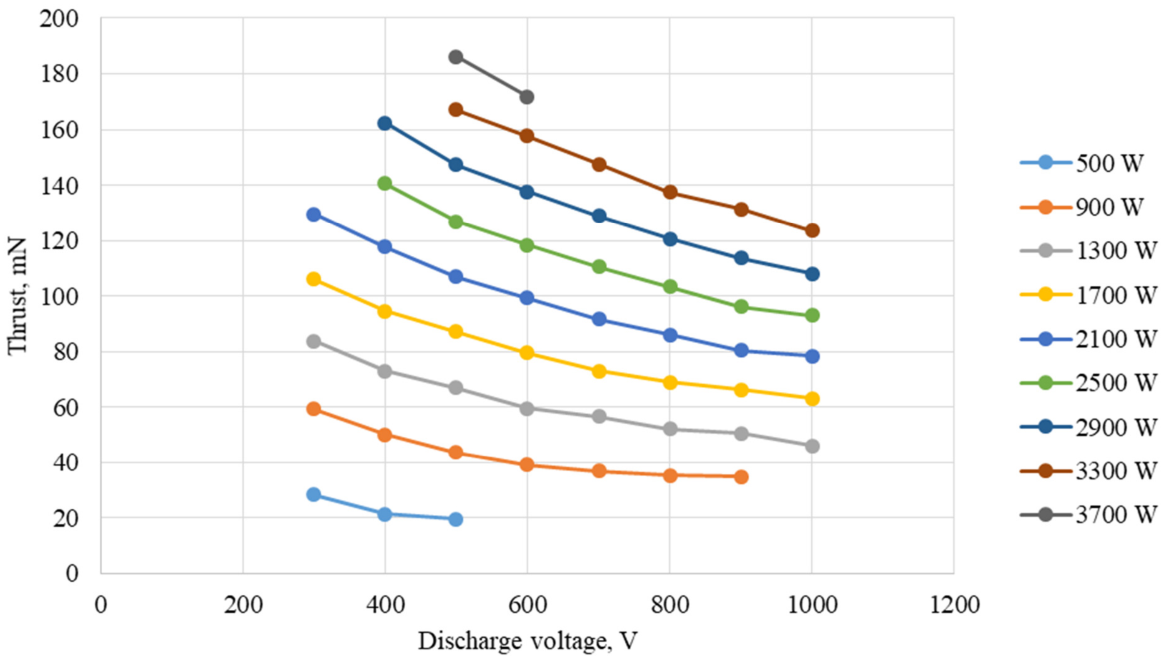

Figure 14. KM-1T5-BC thruster thrust dependence on discharge voltage at varying discharge power.

Let us discuss below the top characteristics of KM-2T5-BC thruster similar to that in the previous section. It can be made a conclusion by analyzing Fig. 12 that no obvious “saturation” in efficiency magnitude can be noticed, unlike that for KM-1T5-BC, so the value of power of 2.5 kW may be selected as the top power, defined by the top allowed temperature of the exit ceramic rings. Figure 13 analysis allows concluding that the increase in specific impulse stops after discharge voltage riches the range of 900-1000 V. Therefore the top voltage is defined as 900 V, so the specific impulse would be equal to 2900 s at thrust of 96 mN, anode flow rate of 3.5 mg/s and the magnetic field range for stable operation of 40%.

It can be seen in Fig. 9 that the maximum thrust is reached at discharge voltage of 300 V, current of 8.3 A, gas flow rate of 7.8 mg/s and is equal to 153 mN at specific impulse of 2000 s, at that the range of magnetic fields for stable operation of ~30 %.

IV. Test result analysis

Selecting geometry for a classical HT is started by selection of the mean diameter, which is based on the discharge power. The condition of direct proportion of the mean diameter to a root of power is satisfied for a great number of classical HET models[4, 5] (Fig. 15). The physical explanation of this trend is as follows: the heat generated in thruster structural elements is proportional to discharge power, and the flux density is inversely proportional to the surface of the elements that collect it, which is proportional to the diameter to the power of 2 in such geometries.

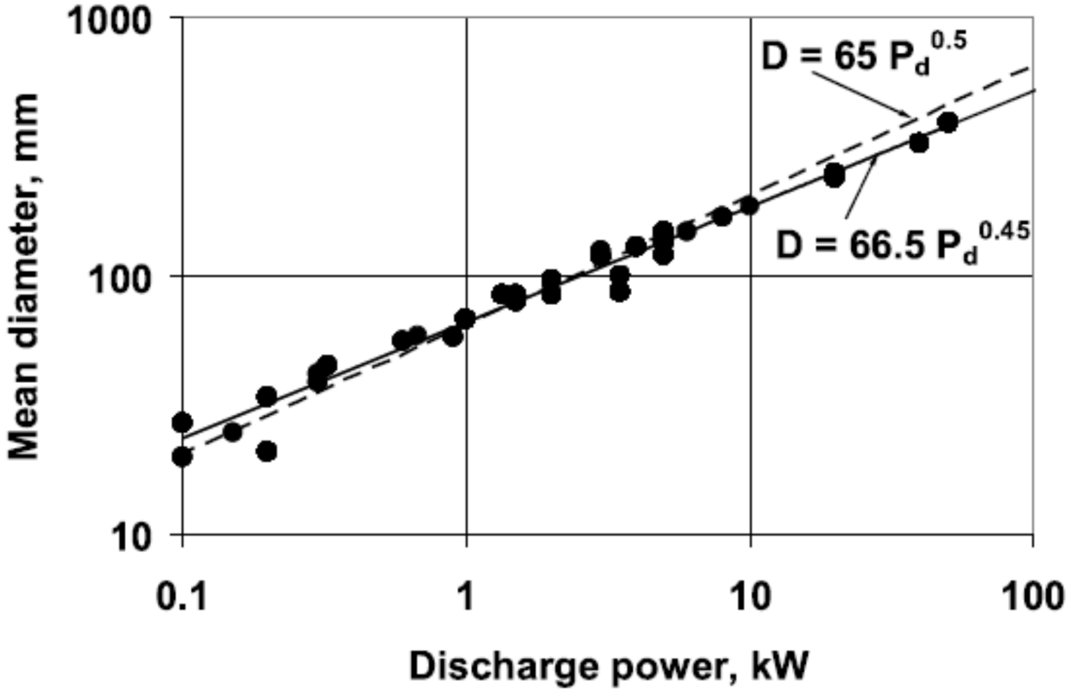

Figure 15. Relationship between diameter and discharge power in HT of classical design[5].

We can suppose that the same trend should be correct for thrusters with an EL. Indeed, the top allowed power for KM-1T5-BC is 1.5 kW at the mean diameter of 60 mm, and 2.5 kW at diameter of 77 mm for KM-2T5-BC. It is noticeable that the ratio of diameters is about to be equal to square root of ratio of the powers, however the proportionality coefficient is ~25 % less than for classical HET (see Fig. 15). Therefore, EL thrusters provide higher power density (ratio of discharge power to channel cross section area) as compared to HET with classical design.

The height of discharge chamber is defined after the diameter, which is usually proportional to the discharge ionization region length and plasma layer length. It should be noted that the classical scaling implies photographic scaling, so that the diameter selection defines height of the discharge channel and ionization region length. However, as it was demonstrated above, there is another limiting factor for each of the studied models, in addition to the top power. It was the top voltage, which appeared to be about 700 V for KM-1T5-BC and about 900 V for KM-2T5-BC thruster. Therefore, we can assume that the top and critical voltage is about to be proportional to mean diameter. If taking into account the geometric (photographic) similarity of these two thrusters, then the top voltages are not only proportional to their diameters, but also to height of discharge channel and plasma layer length. The ratio of discharge voltage to plasma layer length is responsible for maintaining the electric field and is seems to be an important factor to efficient and stable operation of the thruster. This must be taken into account when designing thrusters with an external layer.

Thus, selecting discharge channel geometric parameters should depend on power and discharge voltage as well. Output parameter estimations for the model being designed are to be carried out after defining the geometry. It may be done using methodology and general algorithms given in Ref. 4, but the scaling factors used in Ref. 4 should be corrected with consideration of EL HET features. Such a correction is to become a subject of consequent studies in this field.

V. Conclusion

The main results of the work are as follows:

1) Two Hall thrusters with an external layer were manufactured and tested in wide ranges of discharge power and voltage. The thrusters have geometrically similar designs and differ by mean diameters: KM-1T5-BC has discharge channel mean diameter of 60 mm, KM-2T5-BC - 77 mm.
2) Output parameter maps were obtained and top operation modes were defined for both thrusters.

3) It was demonstrated that thermal condition depends only on discharge power and defines its top value: about 1.5 kW top power for KM-1T5-BC and about 2.5 kW for KM-2T5-BC. The ratio of diameters is about to be equal to square root of ratio of the powers, the proportionality coefficient is ~25 % less than for classical HET.
4) It was demonstrated that the range of magnetic fields providing stable operation linearly reduces with growth of discharge voltage, and limits its top value: the top voltage was 700 V for KM-1T5-BC and 900 V for KM-2T5-BC. The top voltage is proportional to the length of plasma layer and, therefore, the height of discharge channel.

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