Laboratory tests of 10.5 kW Hall thruster with external layer

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Abstract: The results of laboratory tests of an engineering model of KM-10 Hall thruster with external layer are presented in this paper. The thruster is designed with a high specific power equal to 0.9 kW/kg, near-zero ceramics erosion and a low cathode flow rate equal to 3.7% of the anode flow rate. The laboratory tests included parametric operation tests, anode flow rate uniformity measurements, plume divergence measurements and a comparison of the total efficiency of KM-10 thruster with internal and external cathode. In addition, laboratory tests included mechanical test, climatic test, and a 500 hour wear test with discharge voltage of 500 V and input power of 10.5 kW. The wear test has shown that the ceramics erosion rate of the KM-10 thruster is near-zero and pole covers erosion rate corresponds to the service life of at least 10 kh. Finally, operating parameters of a 42 kW cluster of 4 KM-10 thrusters are presented in the paper.

I. Introduction

AN increase in solar battery power generation and development of self-sufficient high power space energy sources enable the use of high power electric propulsion devices for satellites orbit-rising, human flights to the other planets, and asteroid danger prevention. Implementation of electric propulsion for these missions provides significant propellant reduction, which leads to either payload increase or launch cost saving.

The attempts to elaborate high power electric propulsion for manned missions were made ever since 1960s. One of the possible electric propulsion schemes is a magnetoplasmadynamic (MPD) thruster[1]. MPDs have specific thrust 10000 times higher than Hall thrusters[2] and can produce specific impulse 10 times higher than chemical thrusters, which are commonly used for manned missions. However, MPDs are not widely used at the present moment due to the complexity of their service life extension. The maximum operation time was achieved in a wear test conducted in RSC "Energia"[3] for a Li-powered MPD thruster with the power of 500 kW. The wear test lasted 500 h and was stopped because of the problems with vacuum facility.

Hall thrusters can serve as an alternative source of electric propulsion for high power satellites with a long service life. The example of a high power Hall thruster is 50 kW NASA-457M[4] with a classical design. The highest operating parameters achieved for NASA-457M are 2.9 N thrust and 3250 s of specific impulse at 600 V discharge voltage. A vital problem of high power Hall thruster elaboration is supporting a long duration wear test, since the utilization of high power and corresponding Xe flow rates is very expensive and technologically difficult.

Another variant of high power Hall thruster design is the multichannel scheme. The representative of such approach is a X3 thruster[5]. X3 is a 100 kW multichannel Hall thruster with maximum thrust of 5.4 N and specific

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impulse of 2300 s, which requires discharge voltage of 400 V. Multichannel scheme gives a wider throttling ratio and more compact geometry but brings instead a number of disadvantages. The main disadvantage is associated with magnetic coils. Firstly, the process of magnetic field regulation is quite complicated because a change of the magnetic field in one channel leads to a change in the rest channels[6]. Secondly, the stationary temperature of the magnetic coils between inner and outer channels is higher than in a single channel Hall thruster because there are two sources of heat flux from both sides of the middle coils and not enough surface for effective heat loss by radiation. In addition, it was shown in Ref. 5 and independently at Keldysh Research Centre that the summed efficiency of separately working channels is higher than the efficiency of simultaneously working channels.

An alternative approach to creating a high power electric propulsion system is elaboration of a cluster of middle power thrusters. For example, elaboration of a cluster with both ion and Hall thrusters for Space Nuclear Reactor with Electric Propulsion System was carried out within the "Prometheus" project[7]. Another electric propulsion system based on a high power ion thruster IT-500 is being independently designed at Keldysh Research Centre, reaching the final stages of qualification. The thrust of IT-500 could be ranged from 375 to 750 mN within the throttle ratio, its specific impulse is about 7000 s and the maximum power is 35 kW[8]. The diameter of IT-500 is comparable with NASA-457M Hall thruster (460 mm) and corresponds to 500 mm.

In this paper, we present the results of the laboratory tests of the KM-10 Hall thruster, which lies at the core of 42 kW cluster that can be used as an alternative to the IT-500 cluster. KM-10 cluster consists of 4 KM-10 thrusters and produces 2 N thrust and 2600 s total specific impulse. The diagonal of KM-10 cluster is comparable with IT-500 and NASA-475M diameter. Specific power of KM-10 cluster is about 0.9 kW/kg against 1 kW/kg of IT-500 thruster. Alternatively to IT-500, KM-10 cluster has 3 times higher thrust and 3 times lower total specific impulse.

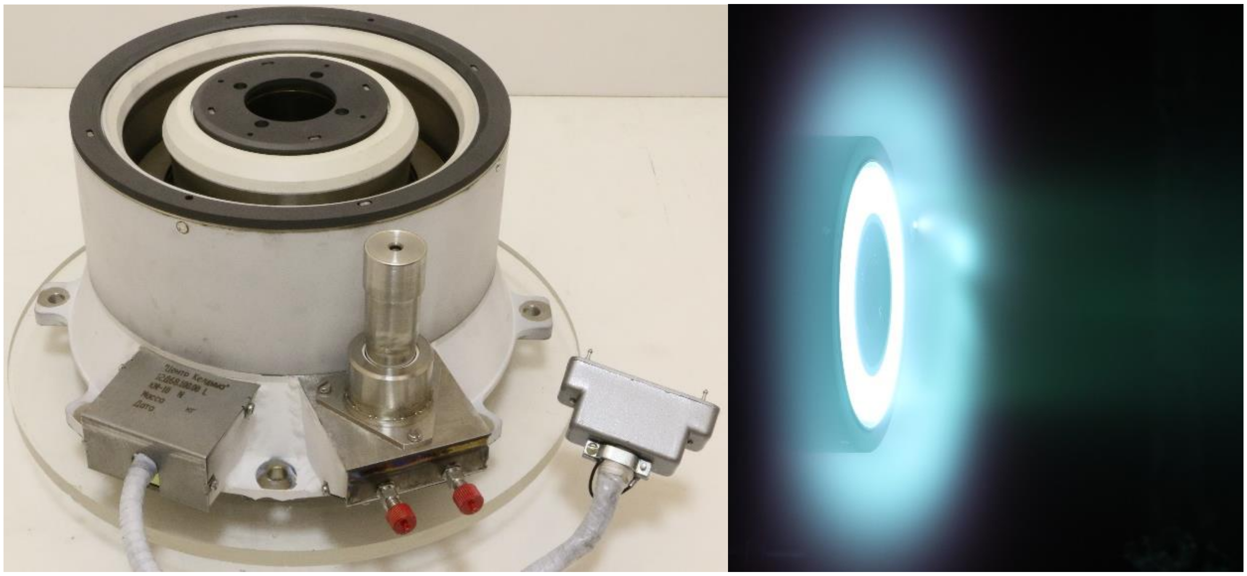
The nearest analogues for KM-10 are a magnetically shielded 12.5 kW HERMeS thruster[9], which had operated for about 1500 h with the same pole covers within the wear test[10], and a magnetically shielded 9 kW H9 thruster[11].

The paper presents the results of KM-10 laboratory tests and a 500 h wear test. The next Section shows the design and the results of operating tests of KM-10. Section III describes the results of the gas uniformity measurement, mechanical test, climatic test, and plume divergence measurements. Section IV illustrates the results of the comparison of KM-10 total efficiency with internal and external cathode. Section V is devoted to the wear test and the Section VI is focused on the results of the KM-10 cluster operating test. The last Section concludes the results of the study.

II. KM-10 Design and Individualities

Target service live of KM-10 is minimum 10 kh with minimum total specific impulse of 2500 s and minimum thrust of 500 mN. Along with that, the target discharge voltage is 500 V, target specific power is 0.9 kW/kg and KM-10 should be able to stand the load comparable with the load on the launch vehicle. Consequently, the engineering model of KM-10, which is presented on the Fig. 1, has a variety of individualities, distinguishing the thruster from the analogues. According to the Hall thruster scaling theory[12,13], 500 V discharge voltage and 10.5 kW of discharge power correspond to 520 mN thrust and 2450 s total specific impulse. Service life of 10 kh on 500 V of discharge voltage demands using some methods of the erosion rate decrease. One of the possible variant for the erosion decrease is a shift of the ionization and acceleration region (IAR) location toward the exit plane using the middle-line magnetic field gradient maximum shift. A magnetic shielding technology[14] which is widely used for the extension of the service life is a boarder-line case of the IAR location shift, when plasma with the anode potential totally covers the ceramics. Commonly, magnetic shielding leads to an increase in thrust and decrease in specific impulse in comparison with classical Hall thrusters' design (SPT-100 like design[15]), which is not appropriate for target parameters. Therefore, service life of 10 kh was achieved by using shift of the IAR location towards the exit plane below the magnetic shielding threshold but much further than in classical design. The KM-10 magnetic field configuration made it possible to retain the classical proportion between the thrust and the specific impulse with the increase of the service life. Also, graphite magnetic pole covers are used in KM-10 to protect the magnetic poles from the erosion, caused by the back flux of ions[16]. Finally, a special low consuming cathode was developed to minimize the cathode losses. The cathode discharge voltage throttle ratio is from 3 to 30 A with the flow rate of 3.7% from the anode flow rate. The cathode has poriferous tungsten emitter impregnated with barium oxide. KM-10 design implicated both internal and external placement of the cathode.

The research was carried out in KVU-90 vacuum chamber in Keldysh Research Centre[17]. The pumping speed of KVU-90 is not sufficient to provide a convenient facility pressure, however the facility pressure was lower than $1 \cdot 10^{-2}$ Pa during the wear test and lower than $1.5 \cdot 10^{-2}$ Pa during the operating tests. The influence of the facility pressure on the thruster's parameters was taken into account using the methodology suggested in Ref. 18. All the results presented in this paper are recalculated in accordance with mentioned methodology to zero facility pressure.



(a) (b)

Figure 1. KM-10 thruster before (a) and during (b) the operation.

The operating tests have shown that the operating envelope spans 5-30 A discharge current (6:1), 300-900 V discharge voltage (3:1) and 1.5 – 12.5 kW discharge power. The stable operating envelope is shown on the Fig. 2a. The limit in discharge power for each discharge voltage was defined as the power, which makes magnetic coils temperature high enough to influence the service life. The discharge power of 12.5 kW corresponds to the inner magnetic coil temperature of about 450°C. This temperature corresponds to the service life of the magnetic coil of 10 kh, therefore, 12.5 kW is the upper power limit. The lower power limit is determined as the rapid efficiency decrease operating point for each discharge voltage. The higher is the discharge voltage the higher is the lower power limit. For example, the lower power limit at 300 V is 1.5 kW, when the lower power limit at 900 V is 10.5 kW. The upper discharge voltage limit is derived from the magnetic field range and discharge power range. The lower power limit at 1000 V is the same as the upper power limit. Along with that, there is a too narrow magnetic field range with a stable operating. Therefore, the upper discharge voltage limit for KM-10 is 900 V.

The operating parameters of KM-10 during the operating tests in comparison with the operating parameters of the analogues[9,11] are presented on the Fig. 2b-2d. Fig. 2d shows that the total efficiency of KM-10 at 300 V is the same as the HERMeS total efficiency and is about 4% lower than H9 total efficiency at the same voltage. At the discharge voltage higher than 300 V KM-10 total efficiency is comparable with the H9 total efficiency and is 2-3% higher than HERMeS total efficiency. Along with that, Fig. 2b and 2c present that the thrust of KM-10 is lower than the thrust of the analogues and the total specific impulse is higher in the whole range of discharge voltages. It was possible to achieve the derived from the technical specification values of total specific impulse due to using IAR location shift instead of magnetic shielding.

III. Laboratory tests of KM-10

The azimuthal anode flow uniformity measurements were carried out within the laboratory tests program. The flow uniformity facility is conventional and does not differ from the analogues[11,19]. The appearance of the facility is shown on the Fig. 3a. The whole thruster was placed at the center of a rotary stage and an ion gauge inlet was placed at the middle line of the thruster. The ion gauge sensibility in target pressure range is about 0.2%. The facility pressure during the measurements was about $3{\cdot}10^{-2}$ Pa when the pressure inside the thruster's channel was within the range from $3{\cdot}10^{-1}$ Pa to $8{\cdot}10^{-1}$ Pa. The measurements were conducted at the thruster's exit plane, at 5 mm under and 5 mm above the exit plane. The adequacy of the measurements was additionally checked by measuring flow uniformity clock wise and counter clock wise. Fig. 3b illustrates the azimuthal anode flow uniformity at the exit plane. The anode flow uniformity at 5 mm under and above the exit plane is the same as at the exit plane. According to the agreement of the clock wise and counter clock wise measurements, the adequacy is good enough. The divergence of the pressure inside the channel is about 1.5%, which is within the limit of 3%. The limit is attributable to the fact that the anode

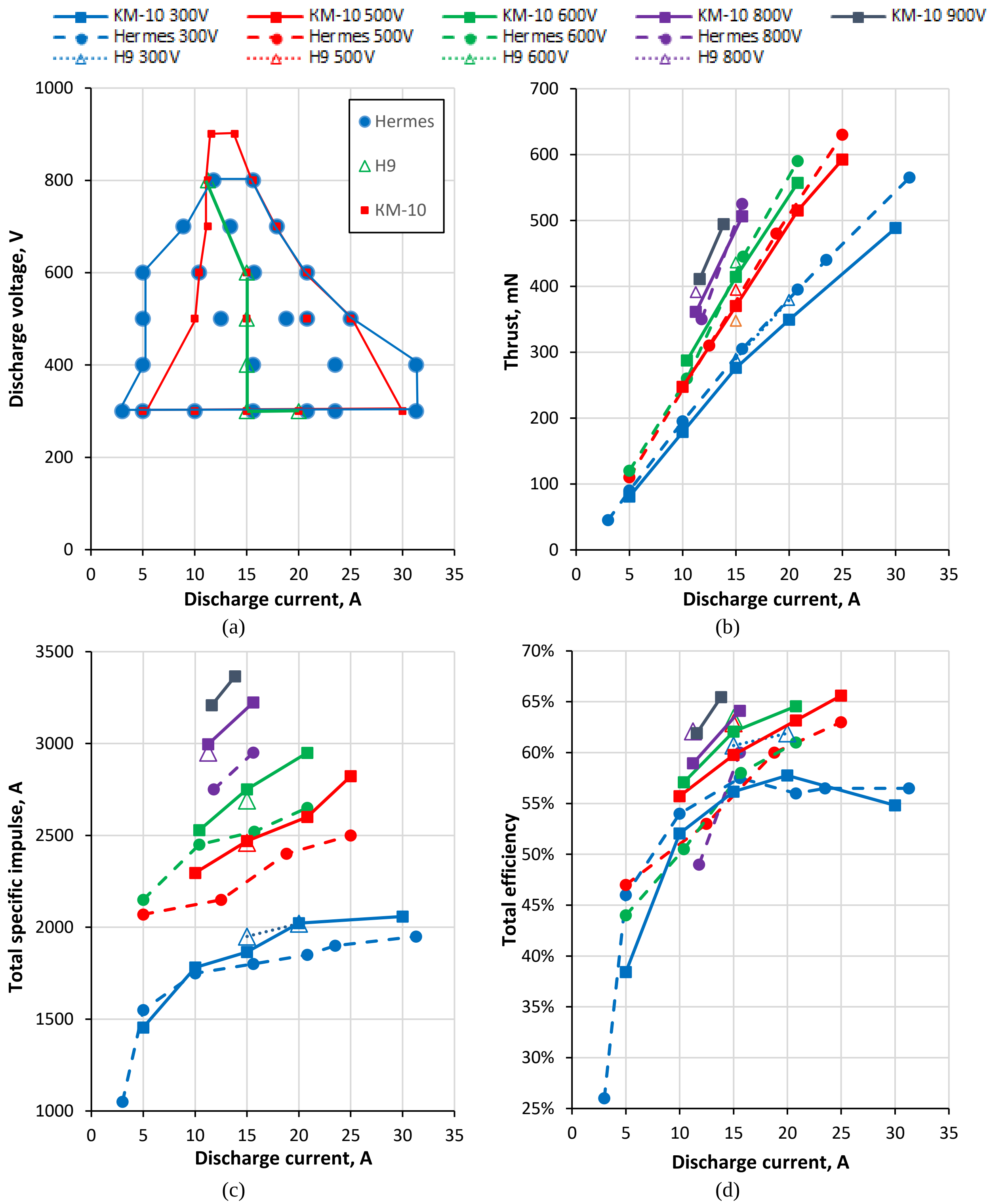
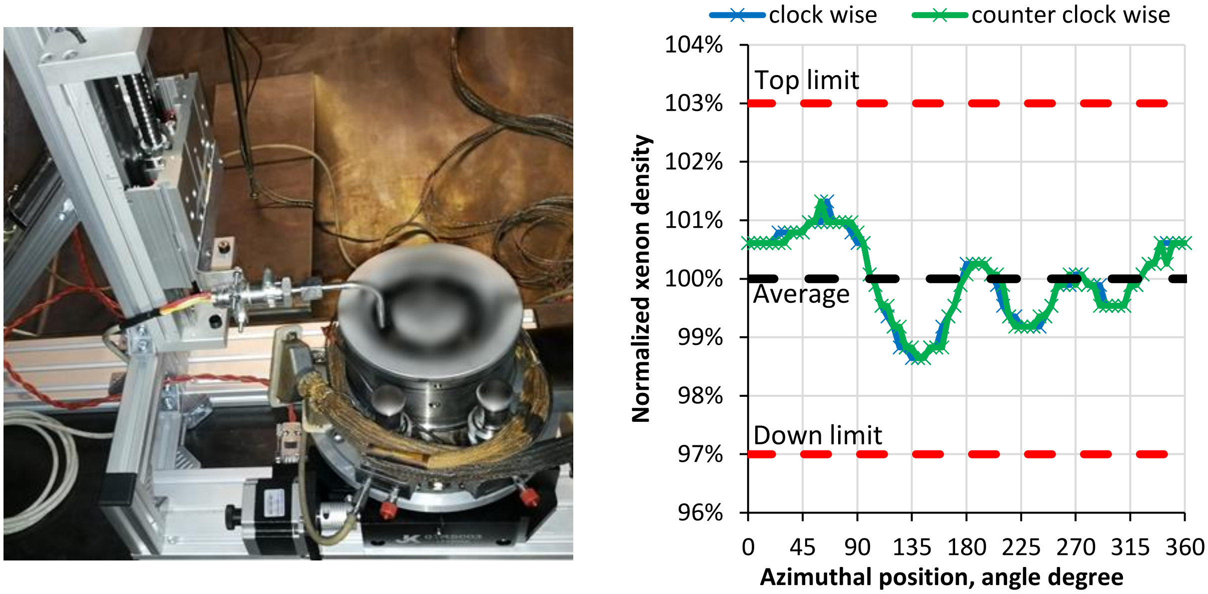


Figure 2. Operating parameters of KM-10 in comparison with the closest analogues: HERMeS (dashed dots)[9] and H9 (dashed triangles)[11]: (a) operating envelope of KM-10, (b) thrust, (c) total specific impulse and (d) total efficiency of KM-10 within the throttle ratio.



(a) (b)

Figure 3. The gas flow rate uniformity measurements: (a) the facility for the gas flow rate uniformity measurements and (b) results of the KM-10 gas flow rate uniformity measurements.

flow inhomogeneity higher than 3% leads to the operating parameters decrease and azimuthal inhomogeneity of the ceramics particle contamination, which is the result of the azimuthally non-uniform discharge burning.

KM-10 has successfully passed the climatic test as well. Within the laboratory tests, the thruster was placed into the climatic chamber ARS-110 with temperature of 50°C and humidity of 60% for 24 hours. After that, the thruster passed the operation test. There were no changes in launch time or the operating parameters.

The mechanical test included harmonic and accidental vibrations, a 1000 g shock test, and a transport stresses test. Maximum, minimum, and acting stress load are presented on the Fig. 4. After the mechanical tests the thruster passed a visual examination and another operating test. There were no destructions or operating parameters deviations after the mechanical tests. The mechanical tests were the most important because the mass of the thruster was extremely decreased to achieve the specific power of 0.9 kW/kg.

In addition, within the laboratory tests, the plume divergence was measured using RPA probe. The design and the detailed operation of RPA is similar to given in Ref. 20 ones. A schematic view of the RPA position system is illustrated on the Fig. 5a. During the plume divergence measurements, RPA moved along the arc of the circle with the radius of 1.5 m at the height of thruster's centerline. The facility pressure was not higher than 10^{-2} Pa. The results of the measurements are presented on the Fig. 5b. The divergence angle was calculated as the limit of the integral from the ion density curve corresponding to the 95% of the square under the measured curve. According to the obtained data, the divergence half angle is about 15°. It means that 95% of ions accelerate within the 15° half angle, when the common value for Hall thrusters is about 20°. Probably, the obtained value is a bit artificially low due to the high facility pressure. According to the research carried out earlier at Keldysh Research Centre for Hall thrusters with 1-3 kW discharge power, the facility pressure of 10^{-2} Pa reduces the plume divergence angle by 15-20%. Consequently, the real plume divergence half angle of KM-10 is about 18°, which is still better than the average value for Hall thrusters with similar power.

IV. Influence of the cathode placement on the Hall thruster operating parameters

The influence of the cathode placement on the thruster operating parameters was studied within the laboratory tests. For this purpose, an additional laboratory cathode was used besides the regular one. The additional cathode mainly differs from the regular cathode by the aperture of the emitter diaphragm, it has roughly twice as narrow aperture of the emitter diaphragm as the regular one. The research was carried out in two stages. The first stage was focused on the external placement, the second one was concentrated on the central placement. The measured operating parameters are presented on the Fig. 6. According to the results of the study, there is no significant difference among

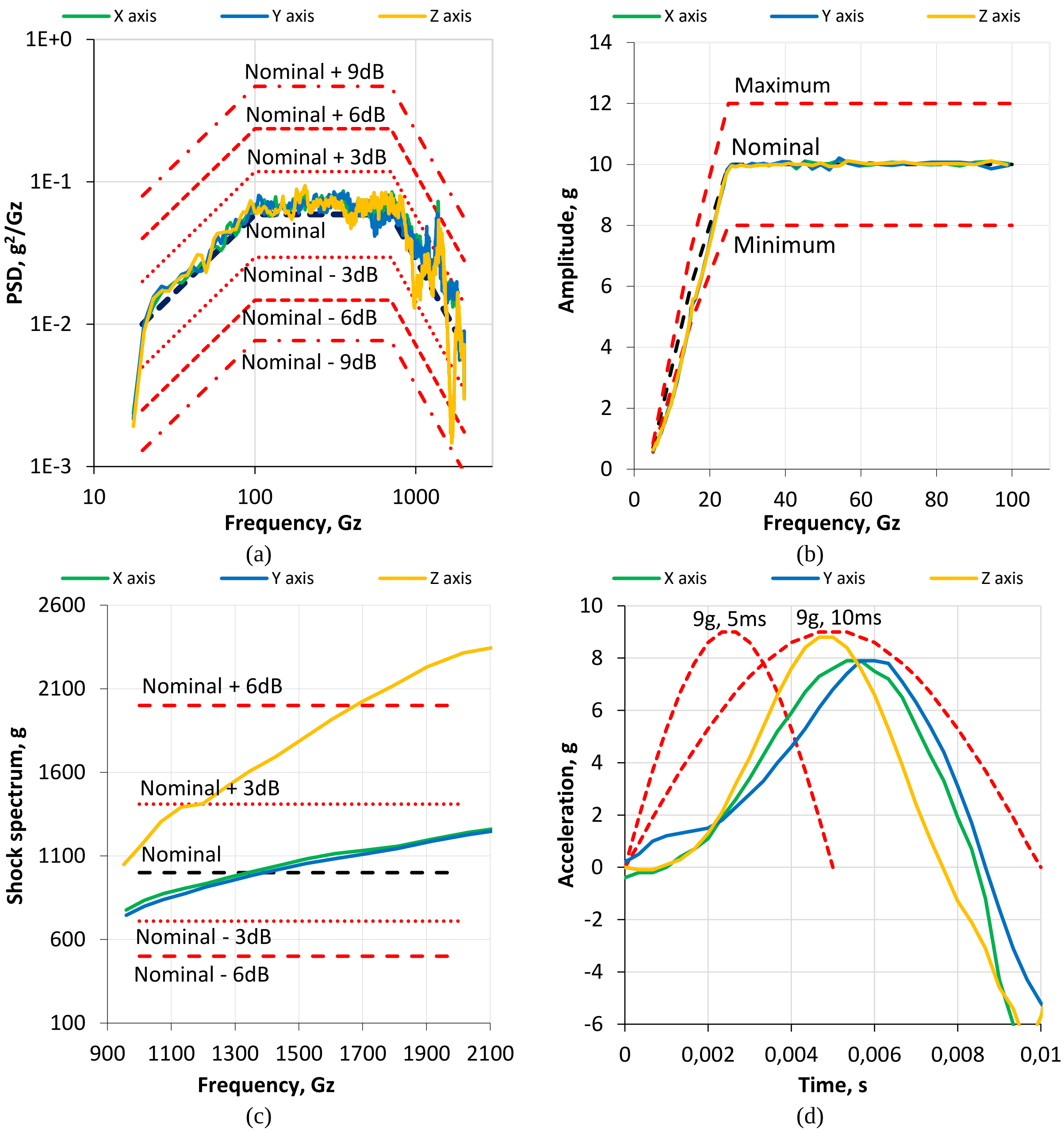
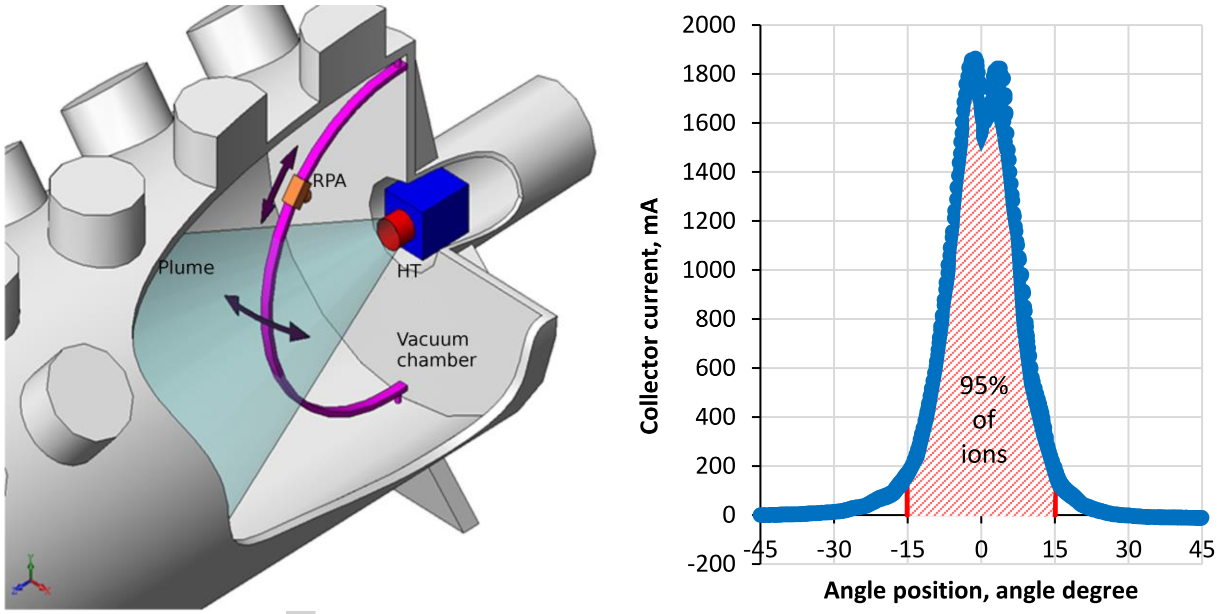


Figure 4. Stresses acting on the KM-10 during the mechanical tests: (a) harmonical vibrations, (b) accidental vibrations, (c) shock test, (d) transport stresses test.

the diameters of the emitter aperture when the cathode is externally placed, and the narrow aperture is preferable when the cathode is placed at the center. However, the central position for both cathodes does not lead to a significant operating parameters growth. The cathode-ground potential for both cathodes is lower for central position when the cathode flow rate is not above the target value of 3.7%, and the cathode-ground potential becomes approximately the same for both cathodes and both placements when the cathode flow rate is twice higher than the target flow rate. Fig. 6b illustrates that the total efficiency is higher for both cathodes when they are placed externally with the target flow rate. Notably, the cathode with a narrow emitter aperture is more efficient in case of central placement when the cathode flow rate is twice higher than the target value. When the cathode flow rate is higher than 5% of the anode flow rate, the total efficiency becomes roughly the same. The type of the dependence of the operating parameters on the cathode flow rate is more sensitive to the cathode placement rather than to the emitter aperture. The cathode



(a) (b)

Figure 5. Scheme of the plume divergence measurement system (a) and results of KM-10 plume divergence measurements (b).

placement does not affect the total specific impulse significantly but it does affect the thrust. Consequently, the cathode placement does not affect the mass utilization efficiency[21] but has an influence on the current utilization efficiency.

The placement is important for low flow rate cathodes and becomes insufficient when the cathode flow rate is high enough to compensate for the lack of electrons in the discharge. The Fig. 6c shows that there is no influence of the cathode flow rate on the thrust when the cathodes are externally mounted, and there is a significant influence when they are centrally mounted. When the cathode flow rate is high enough, there is no difference among the cathode placements in the context of thruster's efficiency. However, when we say "high enough" we mean that the cathode flow rate amounts to about 8% of the anode flow rate. It is a quite adequate cathode flow rate comparable with the flow rate of the cathodes from Refs. 22 and 23. In these articles, the authors conclude that the central cathode placement leads to an increase of the total thruster's efficiency. Fig. 6b illustrates that the described increase in efficiency, indeed, occurs for a specific cathode construction and a high enough flow rate. However, there are cases, most likely for the cathodes with a lower flow rate and a different design, when the central cathode placement will not have the desired effect on the total thruster's efficiency.

To sum up, the cathode operating test shows that the external placement is preferable for KM-10 thruster. Therefore, the wear test was carried out with externally mounted cathode.

V. Wear test

The wear test was conducted in two cycles of 250 h and 500 launches. Each of the cycles consists of short launches of 3 minutes (increasing the number of launches) and long launches of 3 h (working on thermal equilibrium). The thruster was withdrawn from the vacuum chamber after 70 h and 250 h of operation to measure the ceramics erosion. The ceramics geometry was also measured at the beginning and at the end of the wear test. Expectative erosion rate of the graphite magnetic pole covers is too low to be measured after 500 h of KM-10 operation. Therefore, the magnetic pole covers were dismounted from the magnetic poles to increase the erosion rate. Since we know the Xe-Fe to Xe-C atomic erosion rate ratio, we can recalculate the graphite erosion rate using the magnetic poles erosion data. This approach has a poor accuracy because the erosion is a threshold process. The Fe atom would be sputtered by Xe ion with the energy of minimum 40 eV when the C atom would be sputtered by Xe ion with energy of minimum 200 eV[24]. Thus, this approach gives us only an estimation of the maximum erosion rate. The real erosion rate of the graphite pole covers would be even lower than the one calculated in this paper. Otherwise, the wear test should be much longer to measure the erosion rate with the profilometry method.

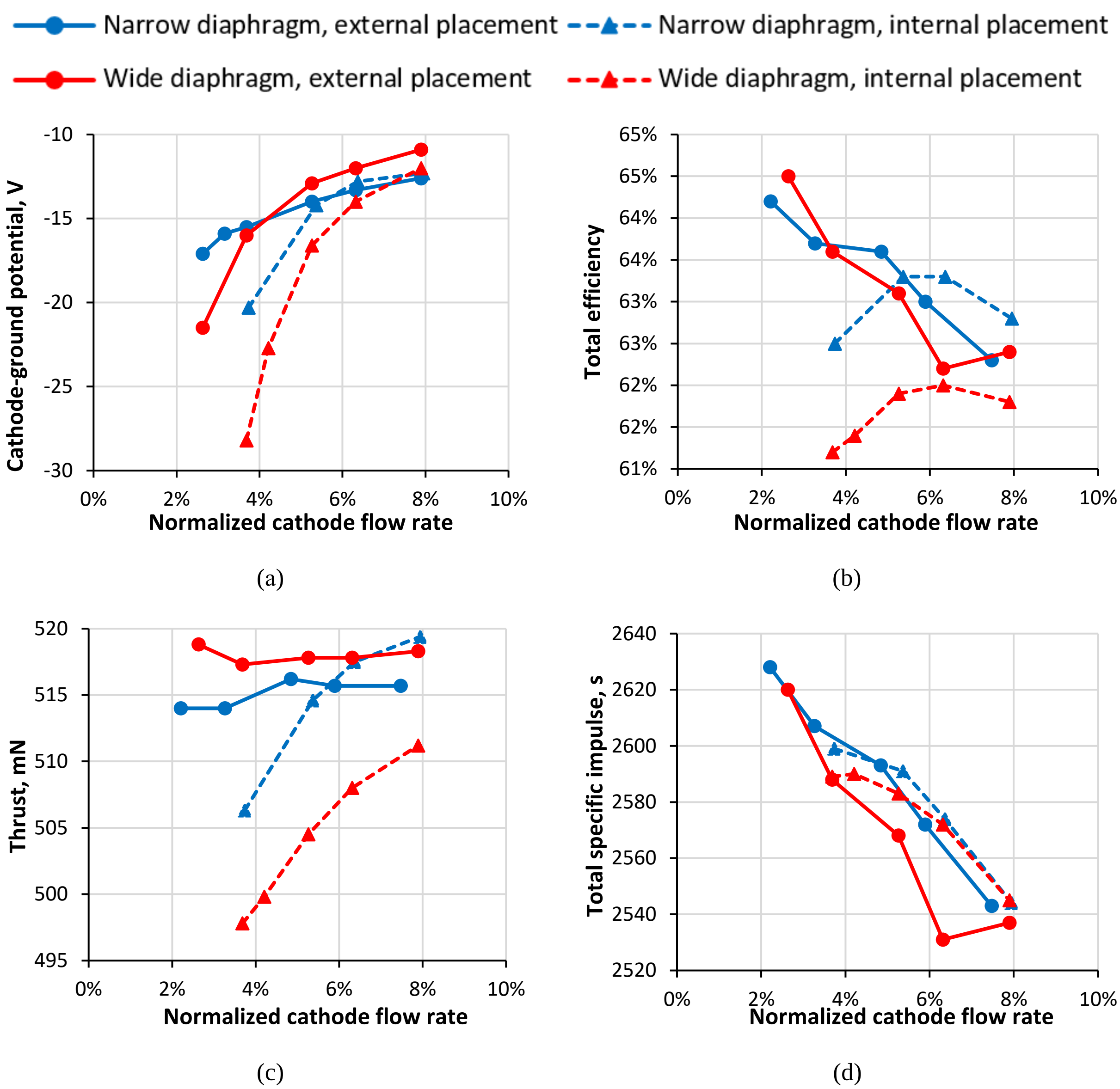
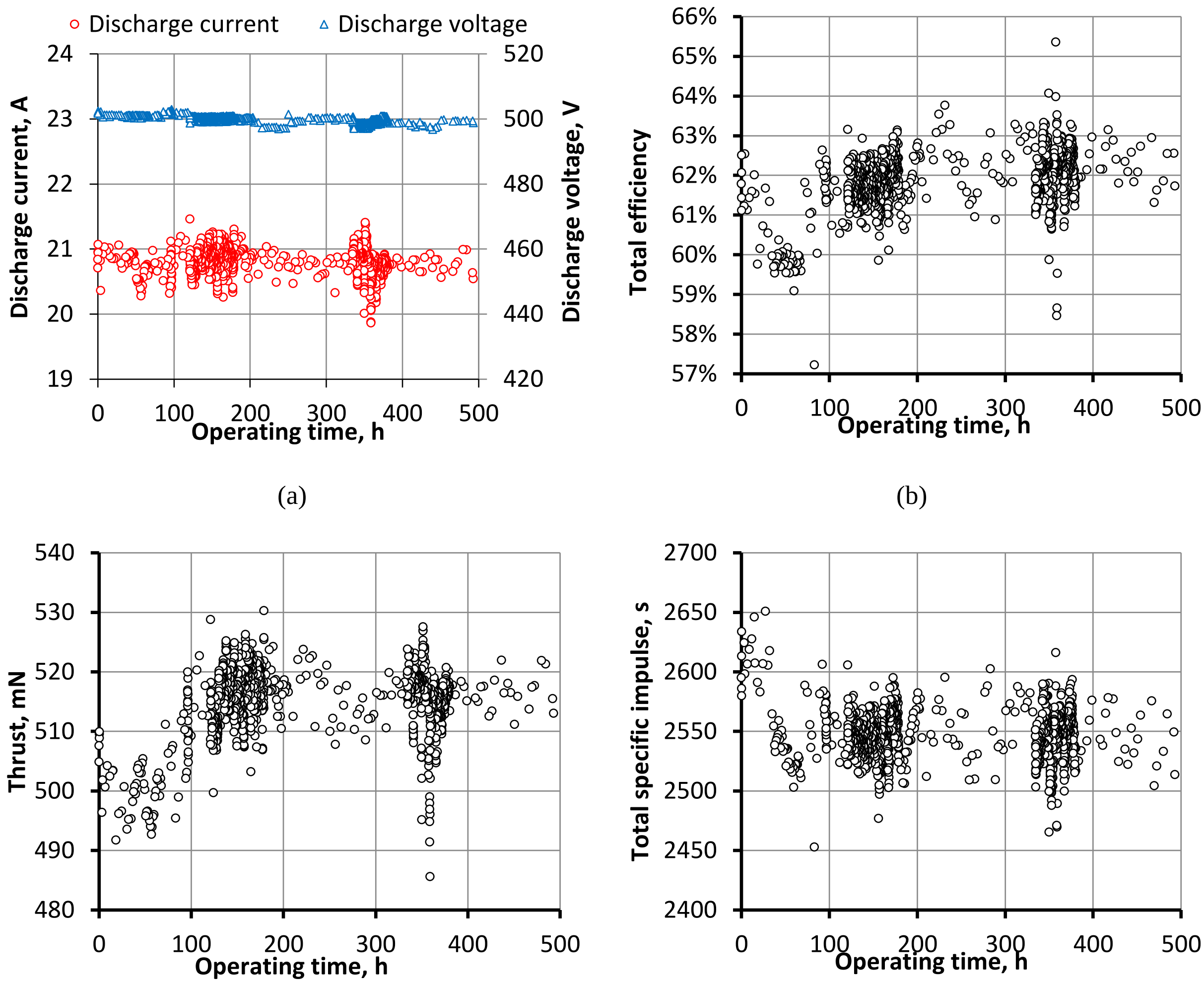


Figure 6. KM-10 operating parameters with external and internal cathodes placement: (a) cathode-ground potential, (b) total efficiency, (c) thrust and (d) total specific impulse.

Thrust measurements were carried out in the end of each launch. The dynamics of the operating parameters change is presented on the Fig. 7. The values of the total specific impulse and total efficiency are recalculated in accordance with the zero facility pressure. The operating parameters of KM-10 had been changing for first 100 h, and then achieved a constant value and stopped changing. Figs. 7c and 7d show that the thrust was rising and the total specific impulse was insufficiently dropping during the first 100 h, which resulted in slight total efficiency growth. The most likely reason for this is the insufficient ceramics expansion causing the interaction between the ceramics and plasmas.

Fig. 8 illustrates the results of the KM-10 ceramics and magnetic pole covers erosion rate measurements. Fig. 8d shows the ceramics of KM-10 after 500 h of operation at 500 V and 20.8 A. According to the Fig. 8d, the outer ceramics is covered by a dense black coat of vacuum chamber sputtering materials. Only one tiny white strip is observed at the edge of the outer ceramics. However, according to the measured erosion rate, which is presented on the Fig. 8a, the erosion depth of the outer ceramics after 500 h of operation is lower than the surface analyzer



(a) (b) (c) (d)

Figure 7. Evolution of the KM-10 operating parameters during the 500 h wear test: (a) discharge current and discharge voltage, (b) total efficiency recalculated to the absolute vacuum, (c) thrust, (d) total specific impulse recalculated to the absolute vacuum.

sensitivity, which is about 0.05 mm. The inner ceramics is covered by a less dense coat than the outer ceramics and the edge of the ceramics has a sign of the primary erosion (see Fig. 8d). The Fig. 8c shows that the erosion depth after 500 h of operation is approximately 0.17 mm and the speed of the erosion was decreasing during the wear test. The geometry of the inner ceramics was initially chosen in such a way to leave the interaction between plasma and inner ceramics surface and, at the same time, add some thickness to the inner ceramics. That gives an increase in specific impulse. The magnetic field of the thruster was chosen to stop the erosion of the inner ceramics and to allow self-correction of the ceramics profile to near-zero erosion. Fig. 8d shows that the lateral size of erosion belt is one order of magnitude less than the width of the inner ceramics. Thus, the inner ceramics takes the form of the plasma flux self-sustainably, contrary to a commonly used method when the form of the ceramics is predetermined at the stage of the design development. The erosion depth of the inner magnetic pole after the 500 h of operation was lower than the surface analyzer sensitivity. The erosion depth of the outer magnetic pole is presented at the Fig. 8b. The erosion rate of the magnetic pole is slightly heterogeneous. That fact could become a big problem during the long service life. The most intensive erosion rate was observed near the cathode (0° azimuthal position). The maximum erosion rate of the outer magnetic pole is 0.46 mm/kh. Xe - C sputtering rate is about 10 - 15 times lower than X - Fe sputtering rate[24]. In addition, the threshold value of the ion energy for Xe – C sputtering is 5 times higher than the Xe – Fe one. In case

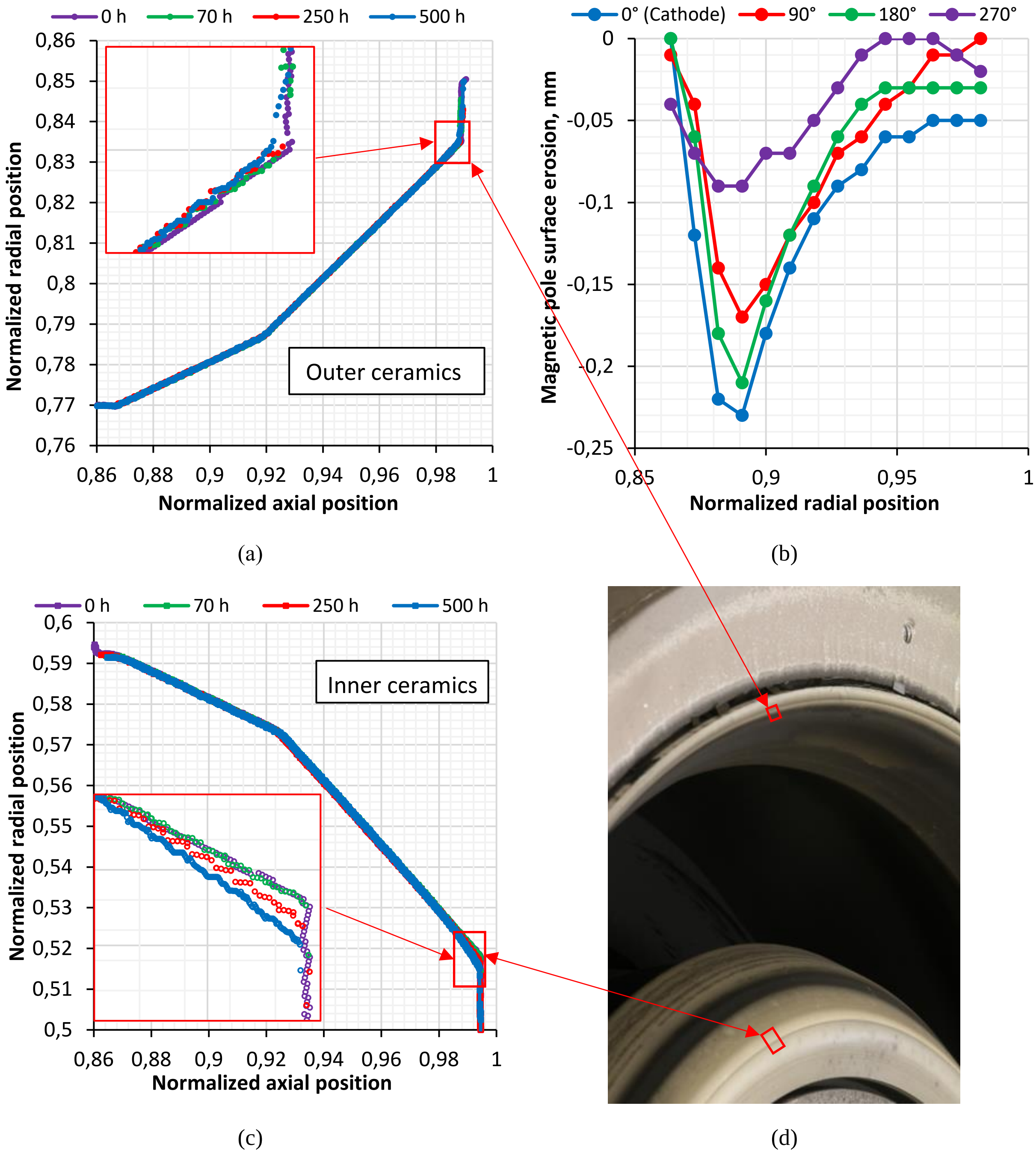


Figure 8. Erosion of KM-10 ceramics and magnetic poles after 500 h of operating: (a) outer and (c) inner ceramics erosion rate after 0, 70, 250 and 500 h, (b) erosion depth of the outer magnetic pole at different azimuthal positions, (d) view of KM-10 discharge channel exit plane after 500 h of operation.

the ion energy threshold value is not taken in consideration, it is possible to obtain the upper-bound estimate for graphite pole covers erosion rate, which would be about 0.03 mm/kh. Even in case of upper-bound estimation, that value is comparable with the erosion rate of the pole covers of HERMeS[10], which is expected to has the service life of 50 kh.

VI. KM-10 cluster operating results

After the end of the KM-10 laboratory tests, the operating test of the KM-10 cluster, which consists of 4 KM-10 thrusters, was carried out. The appearance of the KM-10 cluster is presented on the Fig. 9. The total specific impulse of the KM-10 cluster after the correction on the facility vacuum was 2540 s when the discharge voltage was 500 V and discharge current was 83 A. The thrust was about 2040 mN. These values of the operating parameters correspond to the total efficiency drop on about 3 % in comparison with the sum of separately operating thrusters. This drop could be connected both with the vacuum chamber walls influence and with the thrusters mutual influence. Anyway, the thrust of about 2 N was shown for electric propulsion device, which had finished the 500 h wear test and had shown a near-zero erosion rate.

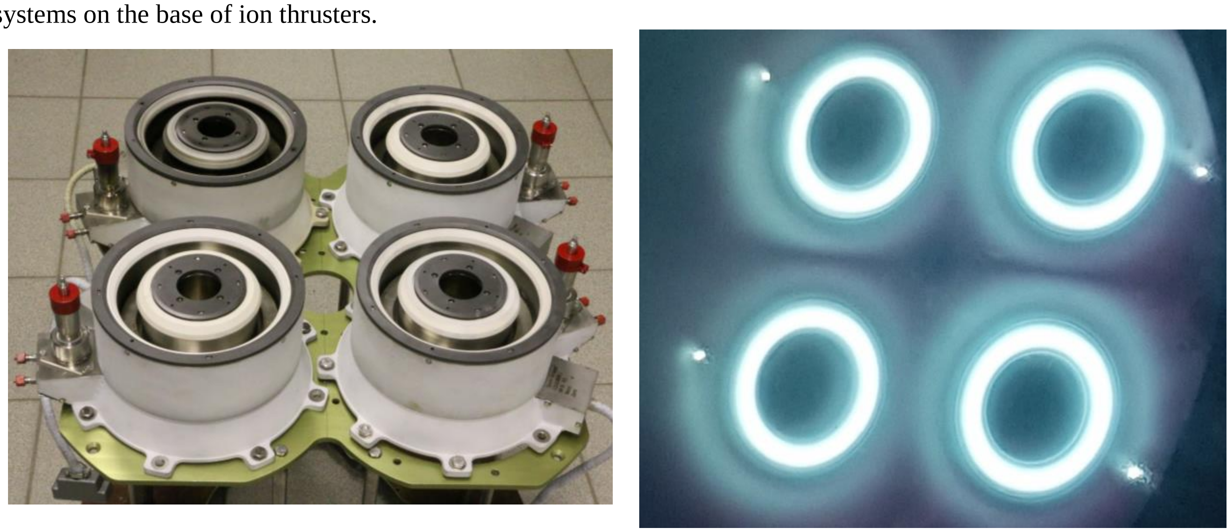
VII. Conclusion

The results of the laboratory tests of 10.5 kW KM-10 Hall thruster with external layer were described in this paper. KM-10 differs from the other thrusters by the cathode with the flow rate about 3.7% from the anode flow rate, a high specific power of about 0.9 kW/kg, and external layer design. The thruster has successfully passed all the mechanical tests. The operating parameters of the thruster correspond to the parameters of the magnetically shielded analogues. However, KM-10 is intentionally not magnetically shielded. The ionization and acceleration region was shifted outside of the discharge channel to increase the specific impulse of KM-10 at the price of thrust. Along with that, the wear test has shown that the erosion rate of the ceramics is near-zero and the magnetic pole covers erosion rate is comparable with the erosion rate of magnetically shielded HERMeS.

The parametric operation tests have shown that the discharge voltage throttle ratio ranges from 300 to 900 V and the discharge current throttle ratio ranges from 5 to 30 A. The thrust varies from 80 to 590 mN within the throttle ratio and the total specific impulse reaches 3360 s at the discharge voltage of 900 V and discharge power of 12.5 kW.

The study of the influence of the cathode placement on the Hall thruster operating parameters has shown that the external placement is preferable for KM-10 thruster. According to this study, centrally mounted cathodes could increase the total efficiency of the thruster in case the flow rate of the cathode higher than 5% from the anode flow rate. In case the cathode flow rate is lower than 5% from the anode flow rate, the external placement is more efficient.

A 42 kW cluster was developed on the basis of KM-10. The operating tests of the cluster have demonstrated the thrust of 2040 mN and specific impulse of 2540 s. KM-10 cluster illustrates the approach of creating high power electric propulsion systems with only one middle power thruster passing the wear test and defining the service life of the whole cluster. That approach does not demand a huge vacuum facility with outer water cooling and high pumping speed. In addition, it allows to save propellant for wear test. KM-10 cluster is an alternative to the electric propulsion systems on the base of ion thrusters.



(a) (b)

Figure 9. View of the KM-10 cluster: (a) after the manufacturing and (b) during the operating.

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