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Magnetoplasmadynamic thruster with an applied field based on the second generation high-temperature superconductors

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Abstract. The present work reports the results of the magnetoplasmadynamic (MPD) thruster with an applied field (AF) based on the second-generation high-temperature superconductor (2G HTS) tape functioning research. Achieved thrust, specific impulse, and efficiency were investigated. Experiments were performed on the 25-kW magnetoplasmadynamic thruster model with two types of 10-mm and 17-mm cathodes. The investigation tests were performed with the goal of studying the efficiency of using 2G HTS tape as electromagnetic coils creating applied field for MPD thruster. The used as the applied magnetic field for thruster 2G HTS coil creates magnetic field up to 1 Tesla. The results showed that the thrust and specific impulse with HTSC applied field increases up to 300% and efficiency increases up to 700%. The best achieved results are following: thrust up to 850 mN, specific impulse up to 3840 s, and efficiency up to 54%. Created MPD thruster with HTSC applied field has a resource of 5400 s work total with all the cathodes, more than 150 launches, and single continuous launch up to 140 seconds. The experiments performed show the high efficiency of using the 2G HTS tape as the material for the electromagnetic coils creating applied field for magnetoplasmadynamic thrusters. Strong applied field up to 1 T electromagnetic coils were maid of the 2G HTS tape by SuperOx own production facilities.

1. Introduction

As it well known MPD thruster is a form of electrically powered spacecraft propulsion which uses the Lorentz force (the force on a charged particle by an electromagnetic field) to generate thrust [1].

MPD thrusters are the most perspective type of thrusters because, in theory, it could produce extremely high specific impulses with an exhaust velocity of up to and beyond 110000 m/s, triple the value of current xenon-based ion thrusters, and about 25 times better than conventional thrusters that utilize chemical fuel by burn. MPD technology also has the potential for thrust levels of up to 200 newtons, by far the highest for any form of electric propulsion, and nearly as high as many interplanetary chemical rocket engines that uses stored rocket propellants as reaction mass for forming a high-speed propulsive jet of fluid, usually high-temperature gas [2-3]. This would allow use of electric propulsion on missions which require quick delta-v maneuvers (such as capturing into orbit around another planet), but with many times greater fuel efficiency [4-5].

One of possible application of the MPD thrusters we consider is the main propulsion thruster for spacecraft heavy cargo transport. The propulsion unit can be functioning as an upper stage for cargo, drag compensation for space stations, lunar cargo delivery, satellite repositioning, satellite refueling, maintenance and repair, in space resource recovery, and deep space robotic missions [6]. As with all ion thrusters, higher efficiency is balanced against longer transit times.

Other proposed applications for applied field magnetoplasmadynamic (AF-MPD) thruster such as the rapid transportation to Mars would require a very high power, low mass energy source, such as a nuclear reactor [4] or, what can be realized nowadays, a large area flexible solar panels to provide the necessary power for a propulsion system.

Cargo with the power of 100-200 kW would be sufficient for effective lifting satellites from LEO to GEO and backwards.

As it known applied-field thrusters have magnetic coils surrounding the exhaust chamber to produce the magnetic field. Applied fields are necessary at lower power levels, where self-field configurations are too weak.

In the developing the thruster for the tasks stated above, limitations occur caused by applied magnetic field. For effective thruster operation, strong magnetic fields are required. The use of electromagnets on classical copper coils leads to problems of insufficient magnetic fields, and to obtain powerful fields up to 1 T, these electromagnets are bulky, have a large weight, and have huge power consumption. That loses practically all their attractiveness for space applications.

This problem is solved by using 2G HTS tape as the material for magnetic coils generating the strong applied magnetic field up to 1 Tesla. Besides, in this case the coils significantly advantages are light weight, small volume, and have much lower energy consumption in contrast to copper analogs. This becomes possible thanks to an affordable 2G HTS tape made by the own SuperOx production base facilities. The following article describes the results obtained due to the operation of the created MPD thruster with an applied field based on the 2G HTS specially designed for studied thruster. All the experiments were carried out in own laboratory test facility specially designed for testing the researchable 20-25 kW scale AF-MPD thruster.

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2. Experimental Procedure

2.1. AF-MPDT Testing Facility

All the experiments were carried out in own testing facility constructed specially for researchable magnetoplasmadynamic thruster created.

Testing facility represents oblong vacuum chamber with total effectively used volume of 2 m^3. In the vacuum chamber installed portholes for observing the experiment and also pump compartment for placing any types of pumps. In one of the end walls a porthole is also installed for the possibility of observing the work of the thruster in front, while on the opposite end wall installed fastenings for placing the thruster itself directly with supplying electric energy, propellant, and also the HTSC to create applied magnetic field of the AF-MPD thruster. AF-MPDT testing facility vacuum chamber is shown in the Figure 1.

Figure 1. *AF-MPDT Testing Facility Vacuum Chamber*

On the testing facility mounted one forvacuum pump and two turbomolecular pumps to create thruster dynamic operating conditions. Turbomolecular pumps produce suction rate of about 20 772 m^3 per hour at about 1 Pascal. Vacuum created in chamber is about 10^{-4} mbar dynamic and about 10^{-7} mbar static.

Propellants used are Argon, Krypton and Xenon. Accurate delivery of the propellant is regulated by Coriolis mass flow meter. Supply accuracy of the propellant does not exceed 0.5% of the values.

Thruster facility has two power supplies: for thruster pulse mode and for thruster continuous steady state. Thruster pulse mode power supply direct current circuit is up to 2200 A, working voltages are 140, 280 and 560 V. Maximum power output is limited at 240 kW. Thruster steady continuous state power supply direct current circuit is up to 600 A, working voltages are 50, 100, 150 and 300 V. Maximum power output limited is at 30 kW. Discharge initiation voltage is 5 kV. Thruster power supplies facility is shown in the Figure 2.

Figure 2. *Thruster Power Supplies Facility*

2.2. 2G HTSC generating Applied Field for MPDT

For testing the engine, its own specially constructed electromagnet based on the 2G HTS SuperOx tape is used. This electromagnet is a design of four sections of magnetic coils to control the current of the coils in order to achieve uniformity of the magnetic field.

Each section consists of 200 turns of a 12 mm tape. All four sections can be connected in series or coils can be individually connected to the current sources, if necessary to stabilize the uniformity of the magnetic field. The HTSC is 120 mm in diameter.

The current density of 12-mm 2G HTS SuperOx tape used for the electromagnetic coil is up to 300 A per mm^2 and can be reached to 500 A per mm^2 current density.

The total weight of the HTSC used is about 9 kg.

The four sections of the HTSC are shown in the Figure 3.

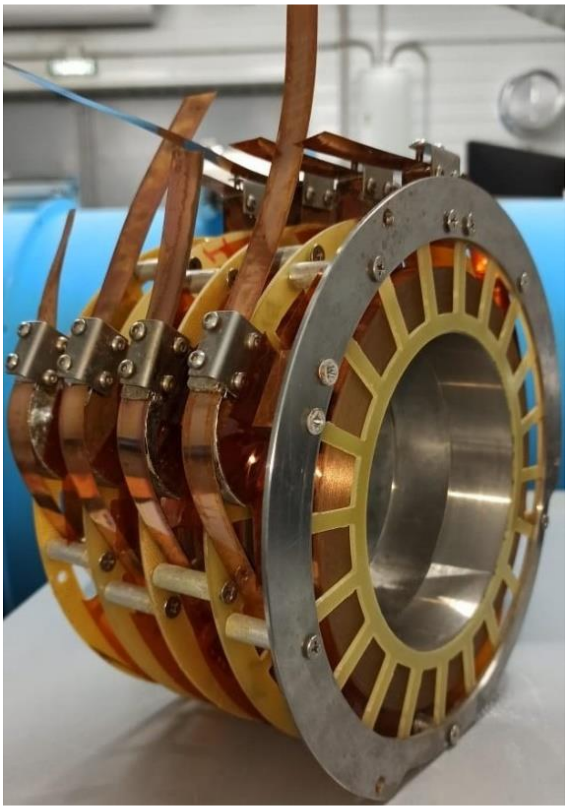

Figure 3. *The four sections of the HTSC*

The HTSC is stationary mounted on the side wall of the vacuum chamber, the test engine is installed inside it. The HTSC is cooled by the circulation of the supercooled liquid nitrogen (LN_2).

The HTSC operating with the currents up to 90 A. The magnetic field of 950 mT in the reference point (anode outlet) is reached at 90 A. Receiving at average 50 mT of magnetic field per 4,7 A. Thus, the HTSC itself has power of 90 W and working currents up to 90 A, and can be included in thrust efficiency. Totally, this model of the HTSC can produce up to 1 Tesla magnetic field.

The HTSC stationary mounted on the side wall of the testing vacuum chamber, as well as the researchable MPD thruster installed inside the HTSC, is shown in the Figure 4. More detailed description of the obtained magnetic field measurements and measurement methods will be given below.

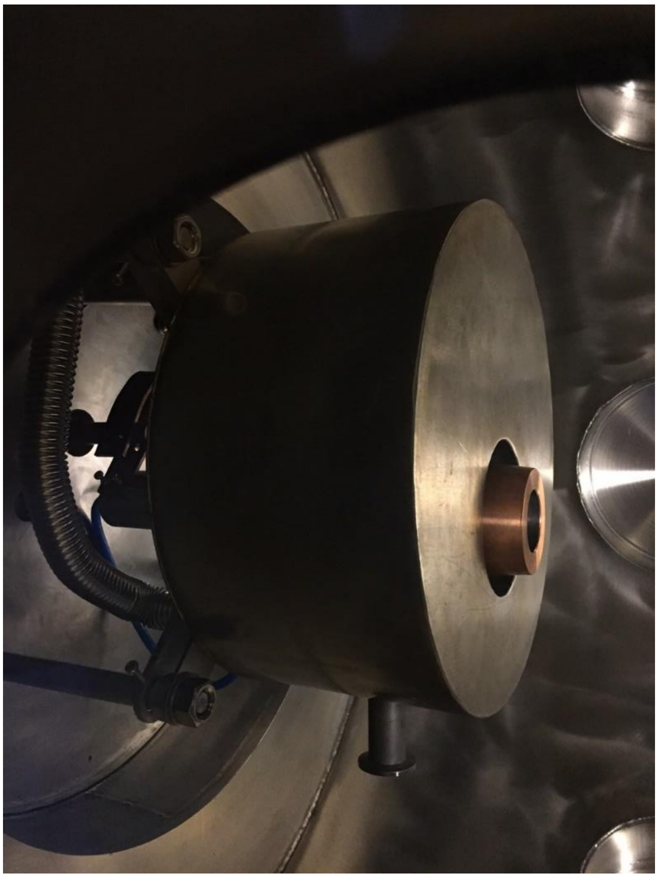

Figure 4. *The HTSC with installed AF-MPD Thruster inside Testing Vacuum Chamber*

2.3. Thrust Measurement System

For the investigations of the magnetoplasmadynamic thruster, own production thrust measuring system [7-12] is used.

The system presents itself a plasma receiving plate (target) [8, 10, 13-14] made of mark DE21 graphite, which placed through the lever of mark SN21 graphite to the supporting element (beam) mounted inside the testing vacuum chamber. The graphite target itself receives the flow of plasma [15-18] and strain gauge [19-20] detects micro-displacements [21]. That way the thrust created by the magnetoplasmadynamic thruster, specific impulse, efficiency – all-important characteristics of the thruster – are measured [22-23]. The method measurement error is less than 2 %. The thrust measurement system mounted inside testing vacuum chamber is shown in the Figure 5.

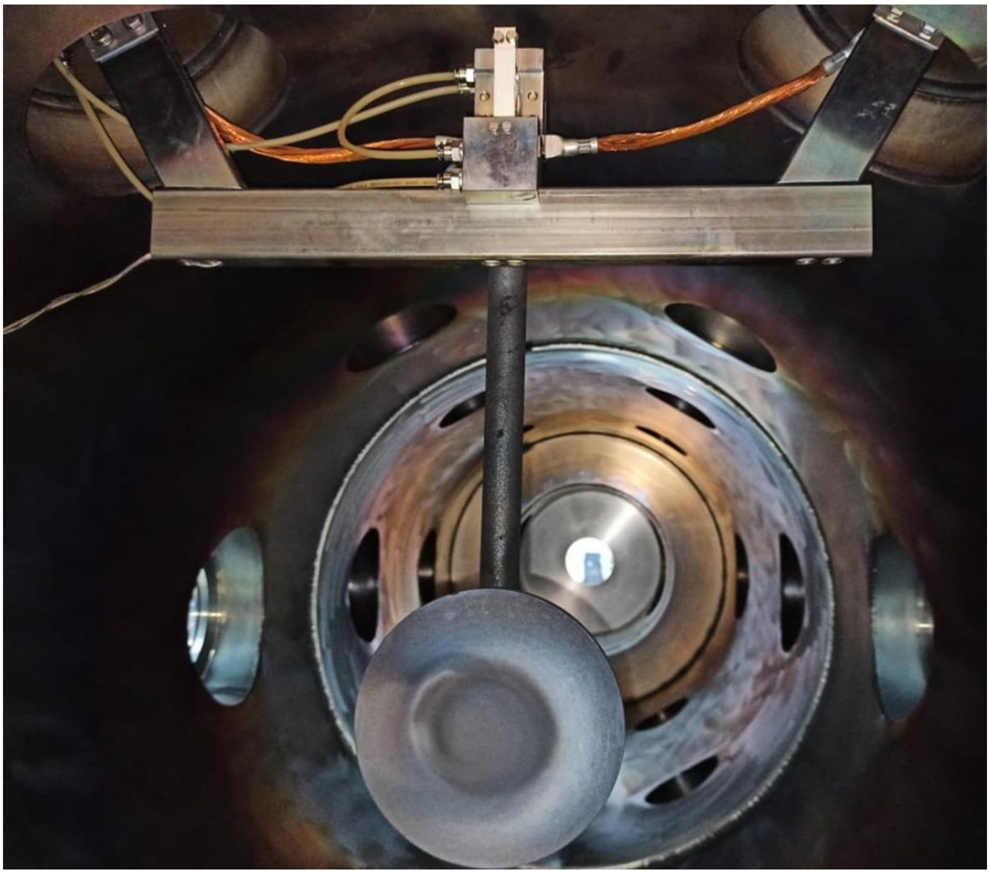

Figure 5. *The Thrust Measurement System mounted inside Testing Vacuum Chamber*

The thrust measurement system capable of continuously receiving plasma flow [13, 21, 24] due to get the thrust measurements for not more than 300 seconds. That becomes possible thanks to its own fully autonomous 40 liters per hour water-cooling of thrust measuring system strain gauge circuit.

To ensure the accuracy of the experiment, the strain gauge is calibrated at high temperatures by using a ceramic heating element to ensure the stability of the maintained high temperatures (50°C) throughout the process of calibration. The plot of the calibration process at 50°C heating with ceramic elements represented in the Figure 6.

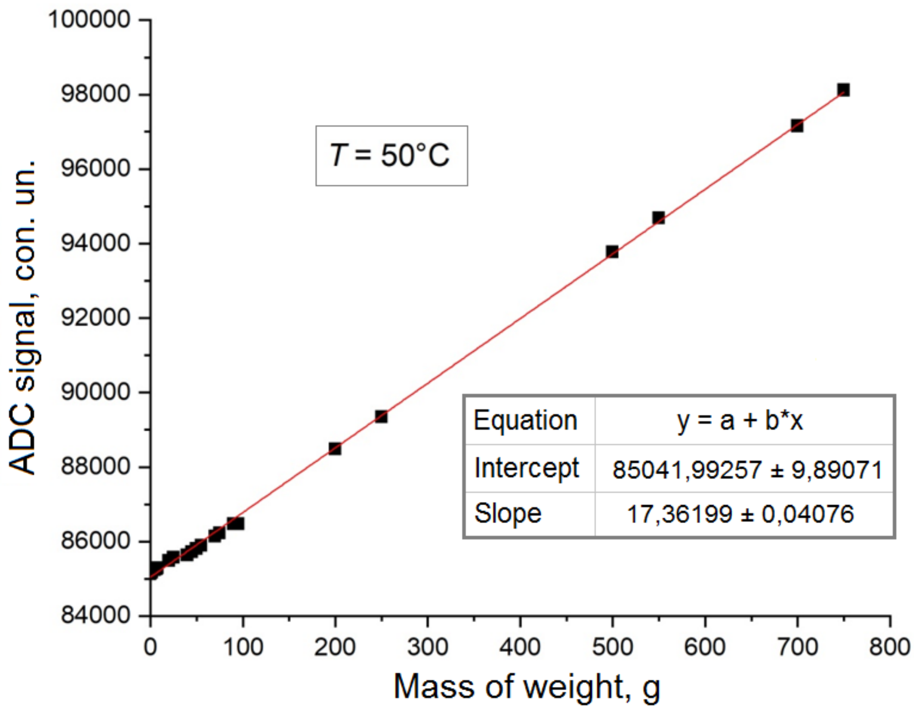

Figure 6. *The plot of the thrust measurement system calibration process at 50°C heating with ceramic elements*

3. Results Obtained

3.1. 2G HTSC generated Applied Magnetic Field

For the measuring of the MPD thruster applied field, the HTSC based on the 2G HTS SuperOx tape is used [25-26]. The HTS coil itself

consists of four sections connected in series together between themselves. The use of the 2G HTS tape favorably distinguishes the obtained electromagnet coil from its copper counterparts - the tangible advantages are received both in weight and in the dimensions of the magnet coil, while the measured magnetic field reached is up to 1 T.

Magnetic field measurements were carried out by installing a Hall sensor moved along the axis of the magnetic field inside the cryostat. The Hall sensor itself mounted inside the cryostat with the HTSC, as well as the method for its installation, are shown in the Figure 7.

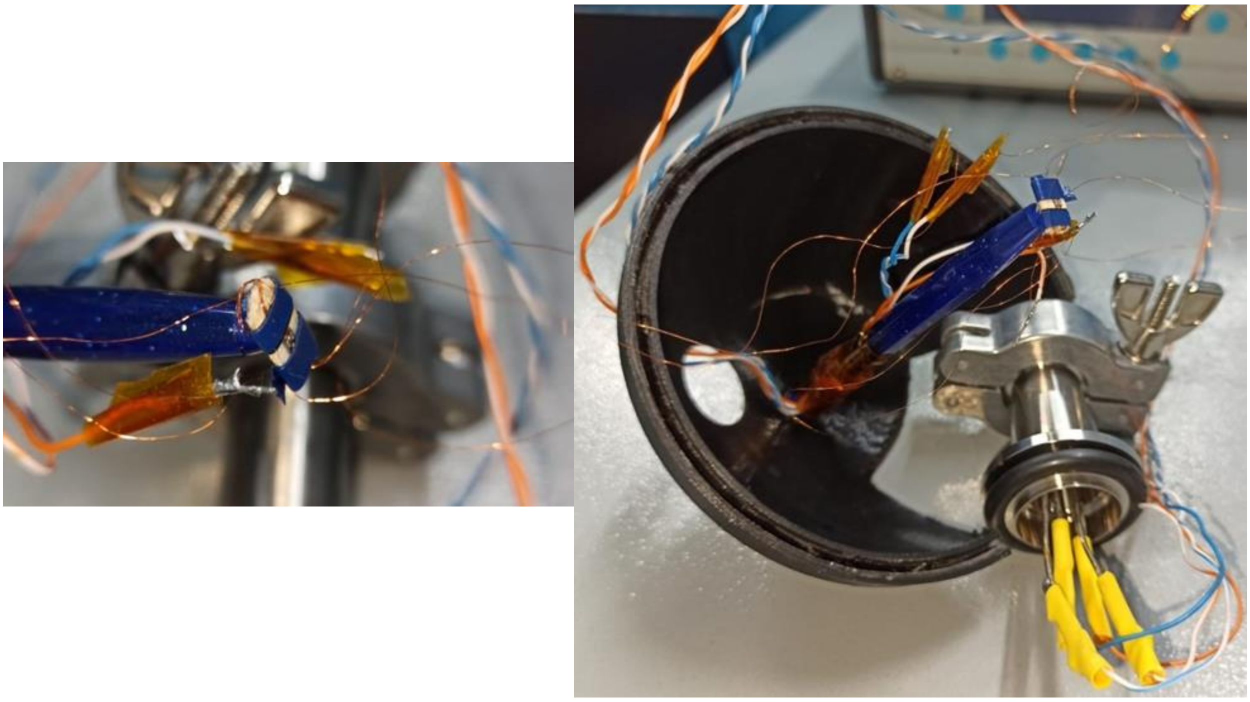

Figure 7. *The Hall sensor itself and the method of mounting it inside the cryostat with the HTSC*

The magnetic sensitivity of the Hall sensor with a magnetic field of 100 mT is 96.5 μV/T, and, in turn, the divergence coefficient with a magnetic field of 100 mT is about 0.1%.

The point of the maximum HTSC magnetic field obtained was established experimentally. With the dimension of the HTS coil of 115 mm, the point is inside at a depth of 70 mm that is approximately in the middle of the magnet coil located inside the cryostat. The graph of

experimentally obtained points of measurement of the magnetic field in order to determine the profile of the magnetic field is in the Figure 8.

The graph of the measurements of the magnetic field from the current supplied to the HTS magnet coil is shown in the Figure 9. As it can be seen from the graph the dependence is linear and the achieved magnetic field has the value of up to 1 T at applied currents up to 90 A.

In that way the use of a 2G HTS tape made it possible to create a powerful, compact and lightweight electromagnet coil cooled with liquid nitrogen that can be used in space with the cryocooling as the applied magnetic field of up to 1 T for the MPD thruster.

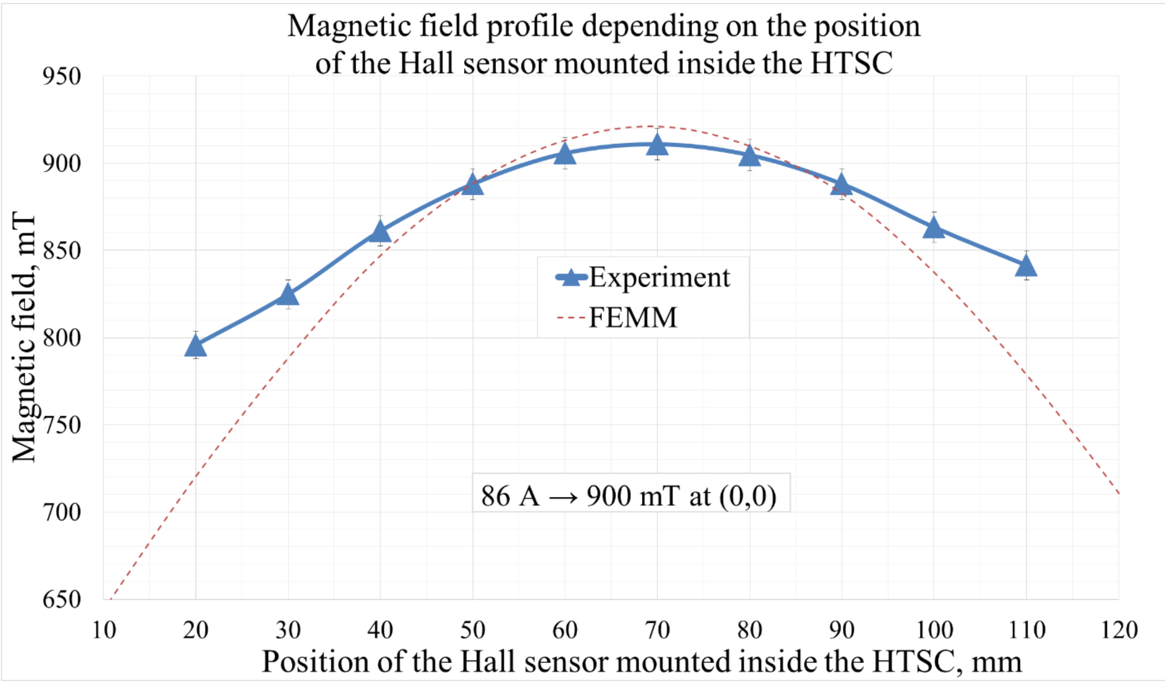

Figure 8. *The plot of the experimentally obtained measurement points in order to determine the profile of the HTSC magnetic field*

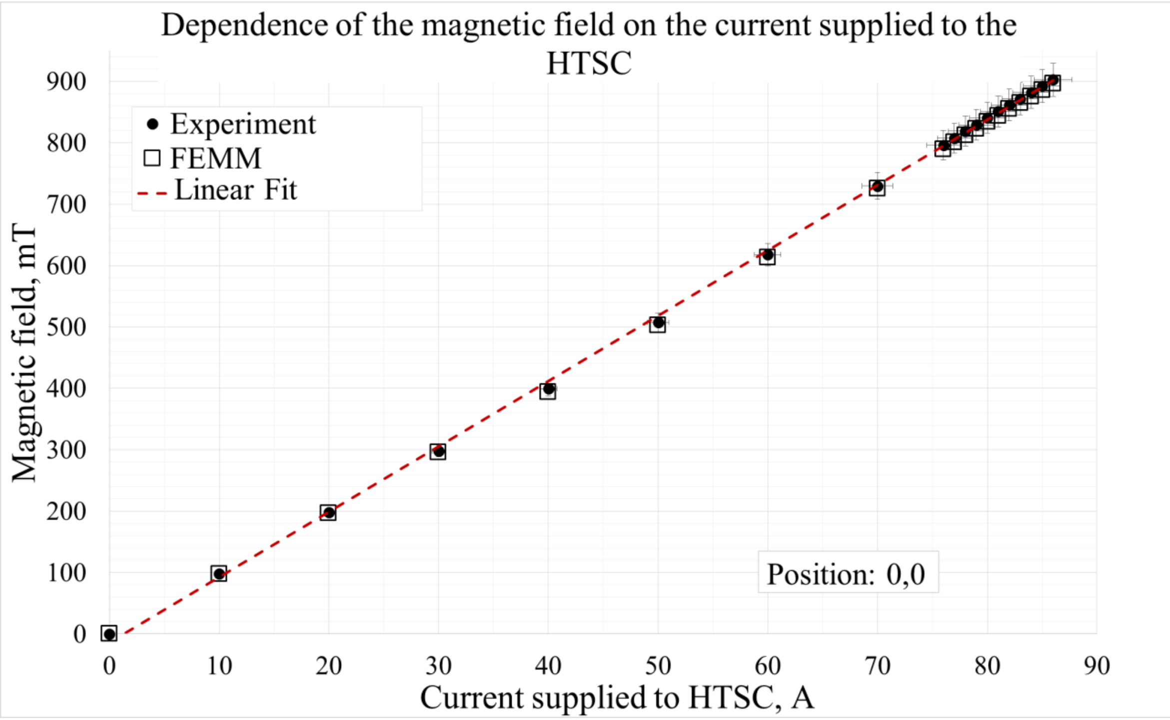

Figure 9. *The linear plot of the magnetic field measurements from the current applied to the HTSC*

The use of the strong magnetic fields up to 1 T based on 2G HTS tape coil allows, by increasing the voltage up to 30-40 V, to significantly reduce the operating currents to values of 600 A, which has a very beneficial effect on the cathode resource of the MPD, while the thruster itself operates in the most efficient mode with an efficiency of up to 60% and the thrust of not lower than 550 mN.

Thus, the research data results show that the use of strong magnetic fields based on the second-generation high-temperature superconductor tape allows increasing thrust and specific impulse with an applied HTSC magnetic field up to 300%, while the efficiency of the AF-MPDT itself increases to 700%.

For the clarity, the indicative comparison of the thruster operation in the absence of the applied magnetic field, as well as the operation of the AF-MPDT in a systematic incremented applied magnetic field up to 0.75 T, are shown in the Figure 10.

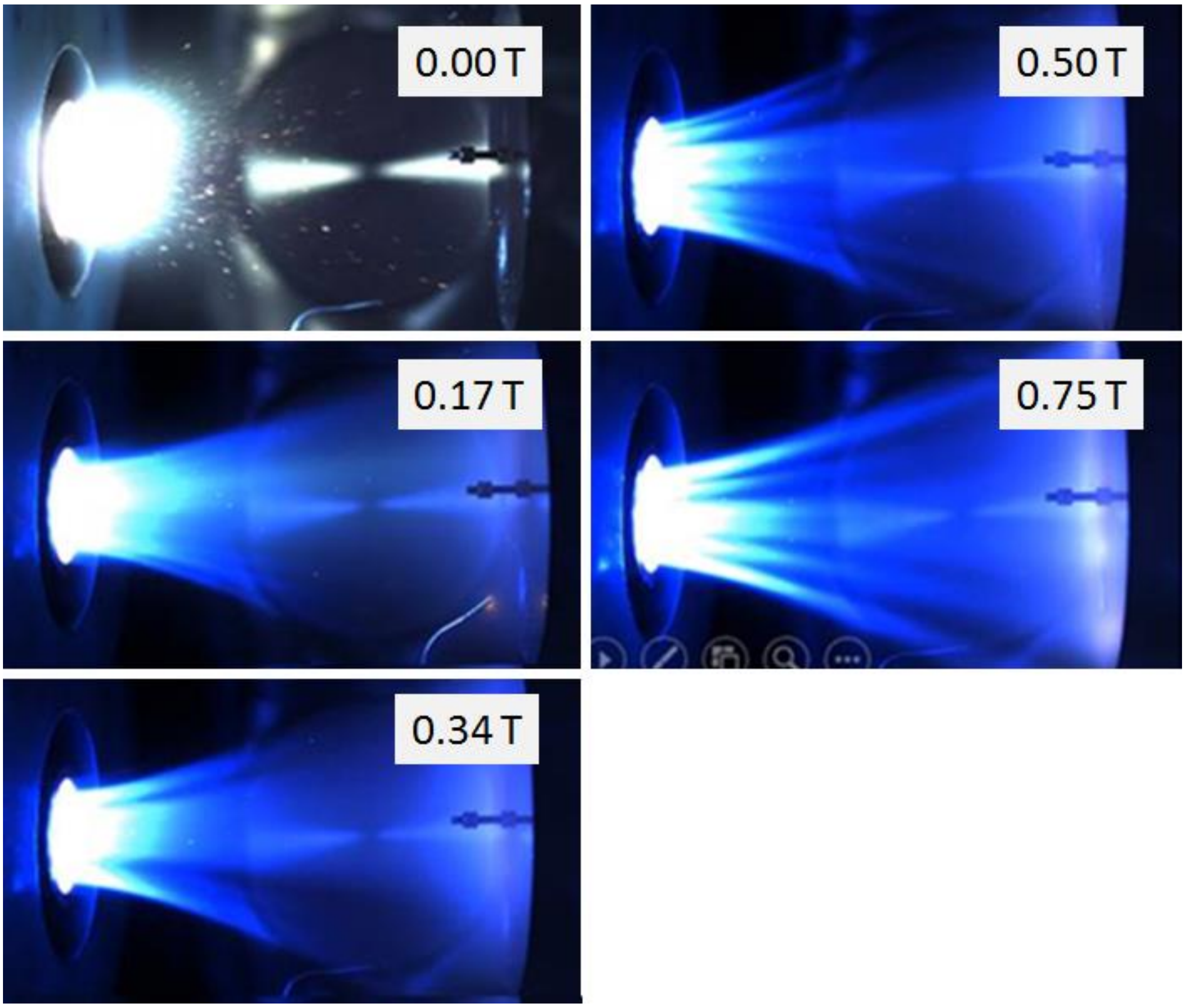

Figure 10. *The indicative comparison of the thruster operation in the absence of the applied magnetic field, as well as the operation of the AF-MPDT in a systematic incremented applied magnetic field up to 0.75 T*

In addition, the plasma acceleration in the MPD thruster directly depends not only on the value of the magnetic field, but also on the magnetic field gradient. The electromagnet based on the 2G HTS tape coil has the great excellence in the obtained gradient in comparison with classical copper magnets. That gives HTSC another strong advantage.

The applied magnetic field value and the magnetic gradient distribution chart of the theoretical and measured values for 120 and 325 mm coils are shown in the Figure 11.

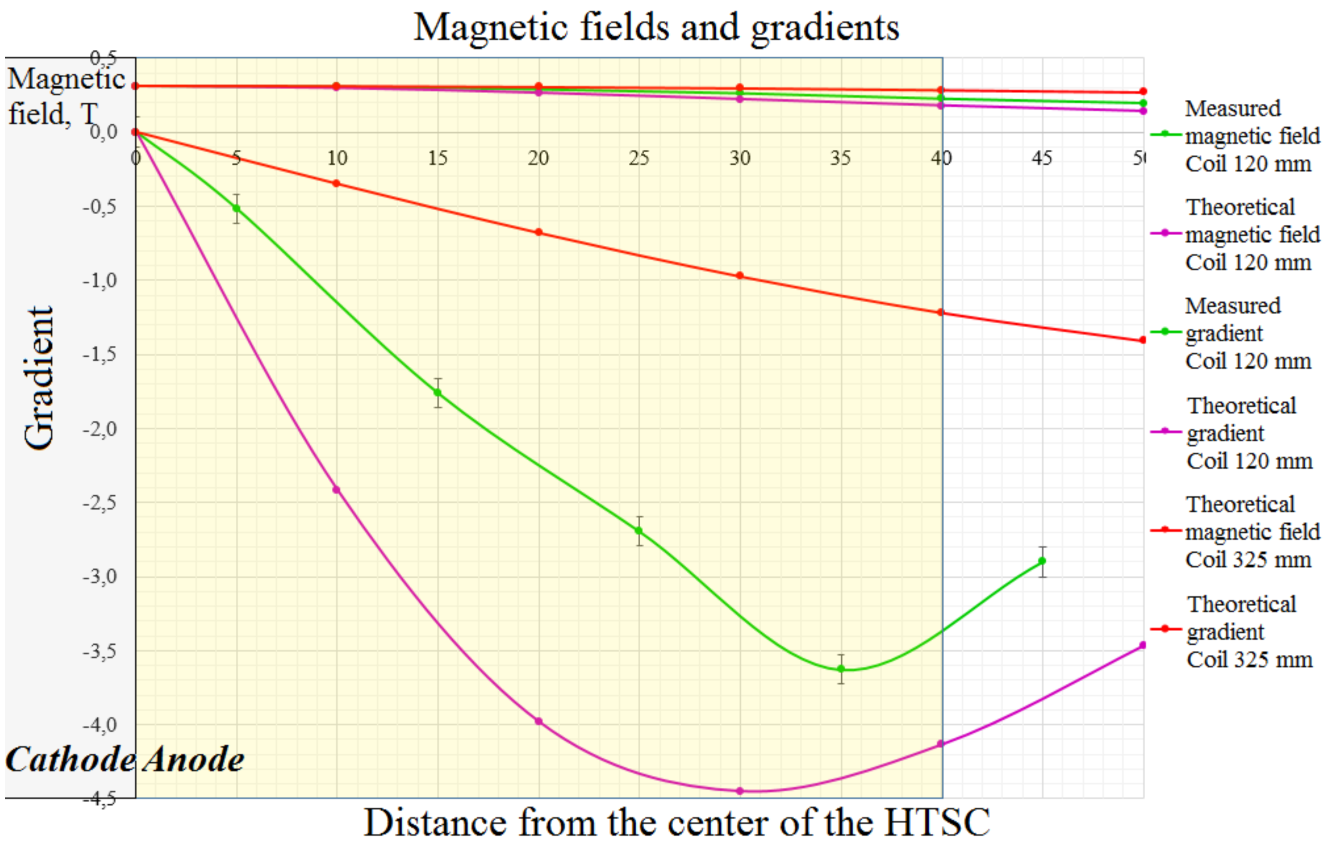

Figure 11. *The applied magnetic field value and the magnetic gradient distribution chart of the theoretical and measured values for 120 and 325 mm coils.*

3.2. The Application of the Multi-Cavity Cathode

For researching the thruster with an applied magnetic field based on the 2G HTS SuperOx tape, the following model of the magnetoplasmadynamic thruster was selected, shown in the Figure 12.

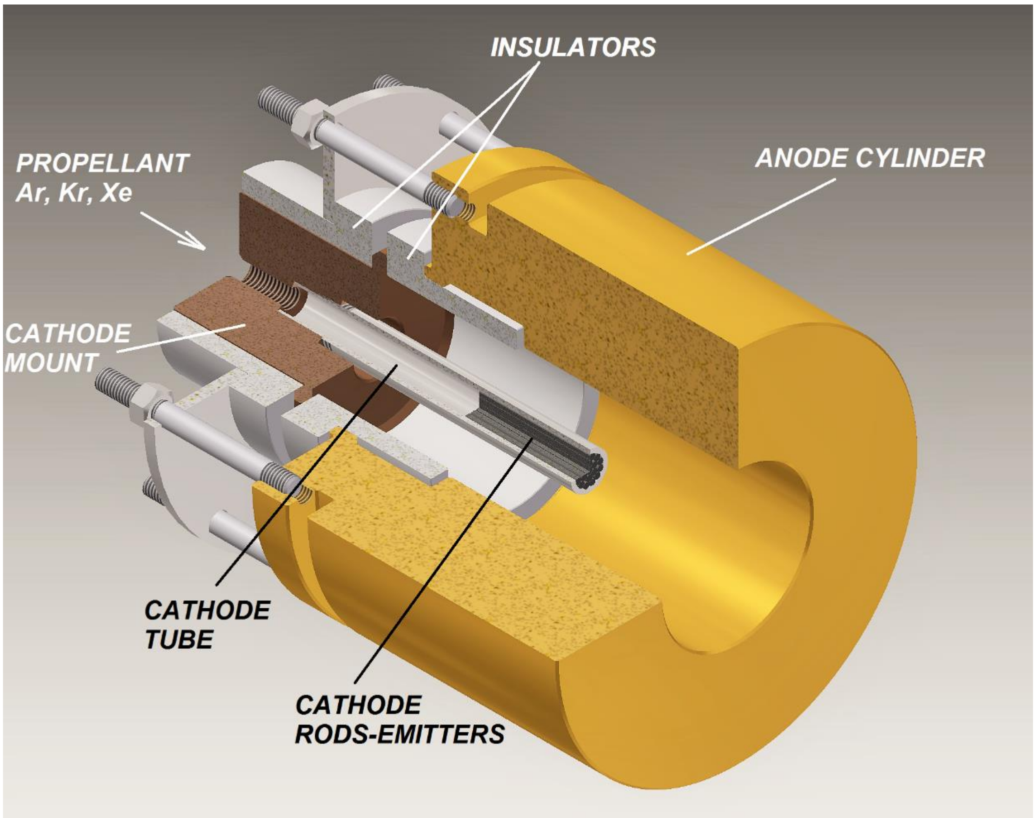

Figure 12. *The structure of the MPDT with Applied Field based on the 2G HTSC magnetic field*

As it can be seen from the Figure 12 the cathode with many cavities was chosen for the implementation of the researchable applied field magnetoplasmadynamic thruster. The choice of the multi-cavity cathode [27] is due to several reasons listed below.

Advantages of choosing the multi-cavity cathode:

1) Ensuring effective ionization of the propellant due to:

- Acceleration of electrons in the near-cathode electric field and their subsequent oscillation inside the cavities caused by their reflection from the near-cathode potential barrier;

- Increased concentration of the propellant created inside the cavities of the cathode, resulting from the use of the cathode for supplying the propellant.

2) Ensuring increased cathode resource of the thruster due to:

- Created the required electron emission at a lower operating temperature, which is possible due to the large surface area of the multi-cavity cathode;

- Reducing the erosion rate of the cathode due to the re-deposition of a significant part of the cathode material sprayed or vaporized from the surface inside the cavities during thruster operation.

3) Improving the reliability of discharge ignitions in the cavities of the cathode tube:

- To increase the stability of the multi-cavity mode, the cathode rods emitters of electrons are made of materials having a lower electron work function than the tube materials.

4) Reducing the flow rate of the working substance through the cathode:

- By ensuring effective ionization of the propellant, the thruster operates with high efficiency and at low flow rates of the propellant (10-15-20 mg/s).

The working thruster multi-cavity cathode front view can be seen in the Figure 13.

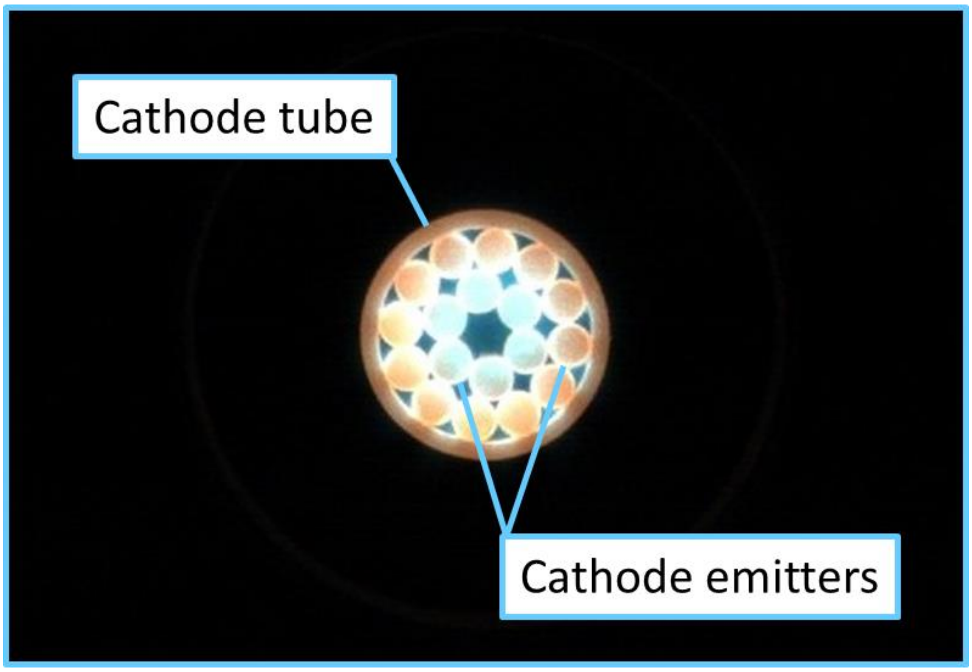

Figure 13. *The working thruster multi-cavity cathode front view*

Observation of the plasma combustion inside the cathode cavities showed the validity of the ignition uniformity, the combustion was stable, the ignition was carried out with high repeatability, and the cathode cavities made it possible to indeed have the maximum effective flow rate of the propellant and the minimum wear out of the cathode surface [28].

The analysis of the researches carried out with laboratory 2G HTSC applied field magnetoplasmadynamic thruster model studied with different types of the cathodes are given below.

3.3. The Application of the 17-mm Cathode

For the AF-MPD thruster functioning with high currents (up to 600 A) the 17-mm multi-cavity cathode for thruster laboratory model was developed.

It takes to 17-mm cathode up to two seconds to warm up. The charge ignited uniformly on the whole multi-cavity cathode surface, the reproducibility of the thruster launches is high and the thruster operation is productively stable.

Best results achieved are as follows below. AF-MPD 17-mm cathode average data with propellant (Argon) flow 25, 20 and 15 mg/s are 0.87, 1.07 and 1.24 kJ/mg. The maximum estimated thrust achieved is 809.3 mN at 50 mg/s. The best specific impulse received is 3364 s at 15 mg/s. Maximum received thrust value at specified thrust propellant flow is 43.5 mN/kW at 50 mg/s. Best 17-mm cathode efficiency achieved is 49% at 15 mg/s with 493.2 mN thrust and 3352 s specific impulse at 16.5 kW (520 A, 31.8 V) with 29.9 mN/kW and 1.1 kJ/mg. The Table 1 given below shows the best AF-MPD 17-mm cathode thruster performance results. The thruster operation propellant mass flow rate - thrust characteristics and the propellant mass flow rate - specific impulse characteristics graphs are shown in the Figure 14 and Figure 15.

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Table 1. *The best AF-MPD 17-mm cathode thruster performance results.*

AF-MPD 17-mm cathode characteristics	Best achieved results	Mass flow rate
Best performance with propellant (Argon) flow	0.87-1.07-1.24 kJ/mg	25-20-15 mg/s
The maximum estimated thrust achieved	809.3 mN	50 mg/s
The best specific impulse received	3364 s	15 mg/s
Maximum received thrust value at specified thrust propellant flow	43.5 mN/kW	50 mg/s
Best 17-mm cathode efficiency achieved	49%	15 mg/s
Best 17-mm cathode efficiency achieved with 493.2 mN thrust and 3352 s specific impulse at 16.5 kW (520 A, 31.8 V) with 29.9 mN/kW and 1.1 kJ/mg.		

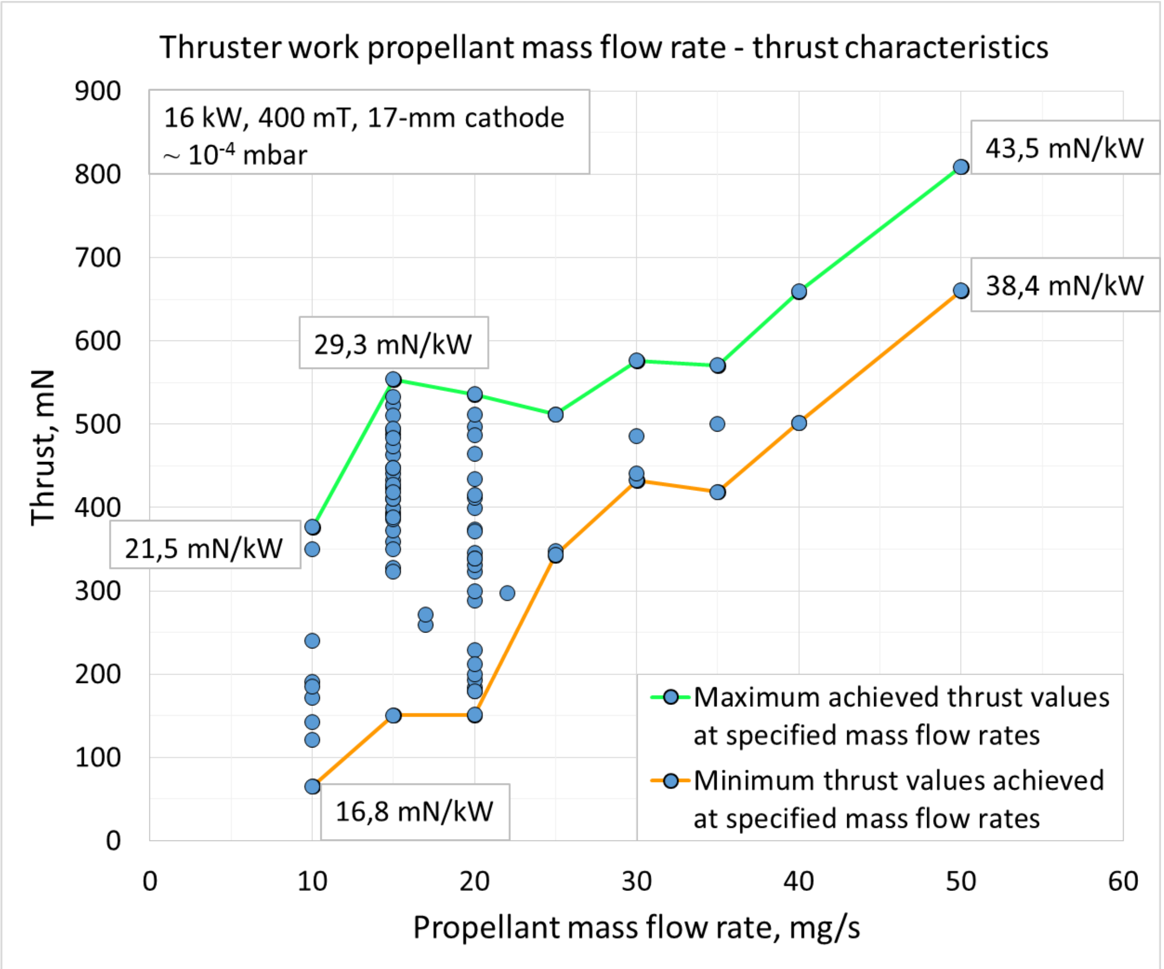

Figure 14. *The thruster operation propellant mass flow rate - thrust characteristics graph*

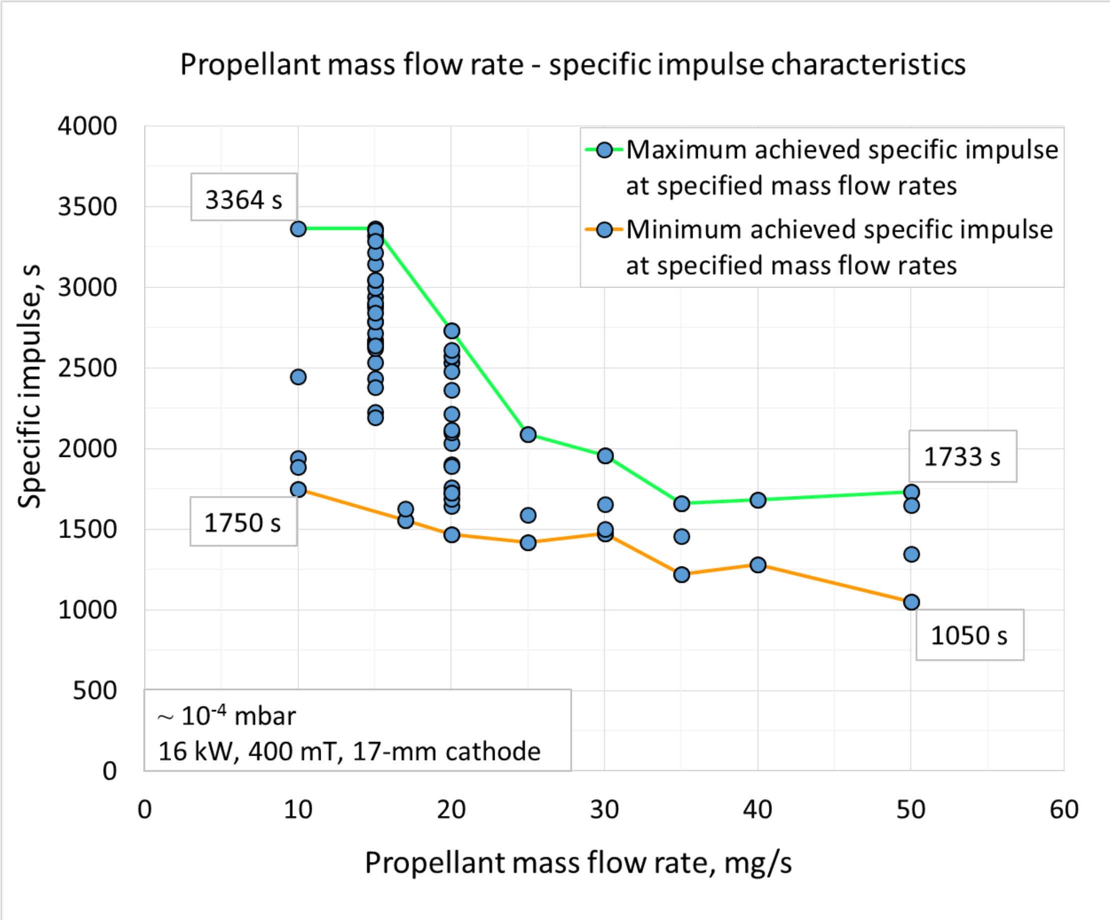

Figure 15. *The propellant mass flow rate - specific impulse characteristics graph*

The 17-mm model of the multi-cavity cathode proved to be extremely positive both from the point of view of operation and from the resource of the thruster for every all launches from the beginning. The total life of launches for all tests for this cathode was 2500 s. Single continuous launch not more than 140 seconds. After all the researches have been carried out the erosion observed at the cathode is minimal. The 17-mm multi-cavity cathode after 50 launches and 2500 s total experiments heavy campaign is shown in the Figure 16.

Figure 16. *The 17-mm multi-cavity cathode after 50 launches and 2500 s total experiments heavy campaign*

3.4. The Application of the 10-mm Cathode

For the applied field magnetoplasmadynamic thruster functioning with lower currents (up to 450 A) the smaller diameter 10-mm multi-cavity cathode for thruster laboratory model was developed.

The 10-mm cathode getting warmed up for about one second. The charge also ignited uniformly on the whole multi-cavity cathode surface, the reproducibility of the thruster launches is even higher than with 17-mm cathode. The thruster operation is absolutely stable.

Best 10-mm multi-cavity cathode applied field magnetoplasmadynamic thruster laboratory model results achieved are given below. The average data with propellant (Argon) flow 20, 15 and 10 mg/s are 1.22, 1.34 and 1.75 kJ/mg. The maximum estimated thrust achieved is 850 mN at 50 mg/s. The best specific impulse received is 3840 s at 10 mg/s. Maximum received thrust values at specified thrust propellant flow is 48 mN/kW at 50 mg/s. The highest power arc obtained is 27.5 kW at 20 mg/s. Best 10-mm cathode efficiency achieved is 54% at 15 mg/s with 554 mN thrust and 3763 s specific impulse at 18.9 kW (450 A, 42.1 V) with 29.3 mN/kW and 1.3 kJ/mg. The Table 2 given below shows the best AF-MPD 10-mm cathode thruster performance results. The thruster operation specific impulse - efficiency characteristics and the thruster operation thrust per arc power [mN/kW] characteristics graphs are shown in the Figure 17 and Figure 18.

Table 2. *The best AF-MPD 10-mm cathode thruster performance results.*

AF-MPD 10-mm cathode characteristics	Best achieved results	Mass flow rate
Best performance with propellant (Argon) flow	1.22-1.34-1.75 kJ/mg	20-15-10 mg/s
The maximum estimated thrust achieved	850 mN	50 mg/s
The best specific impulse received	3840 s	10 mg/s
Maximum received thrust value at specified thrust propellant flow	48 mN/kW	50 mg/s
The highest power arc obtained	27.5 kW	20 mg/s
Best 10-mm cathode efficiency achieved	54%	15 mg/s
Best 10-mm cathode efficiency achieved with 554 mN thrust and 3763 s specific impulse at 18.9 kW (450 A, 42.1 V) with 29.3 mN/kW and 1.3 kJ/mg.		

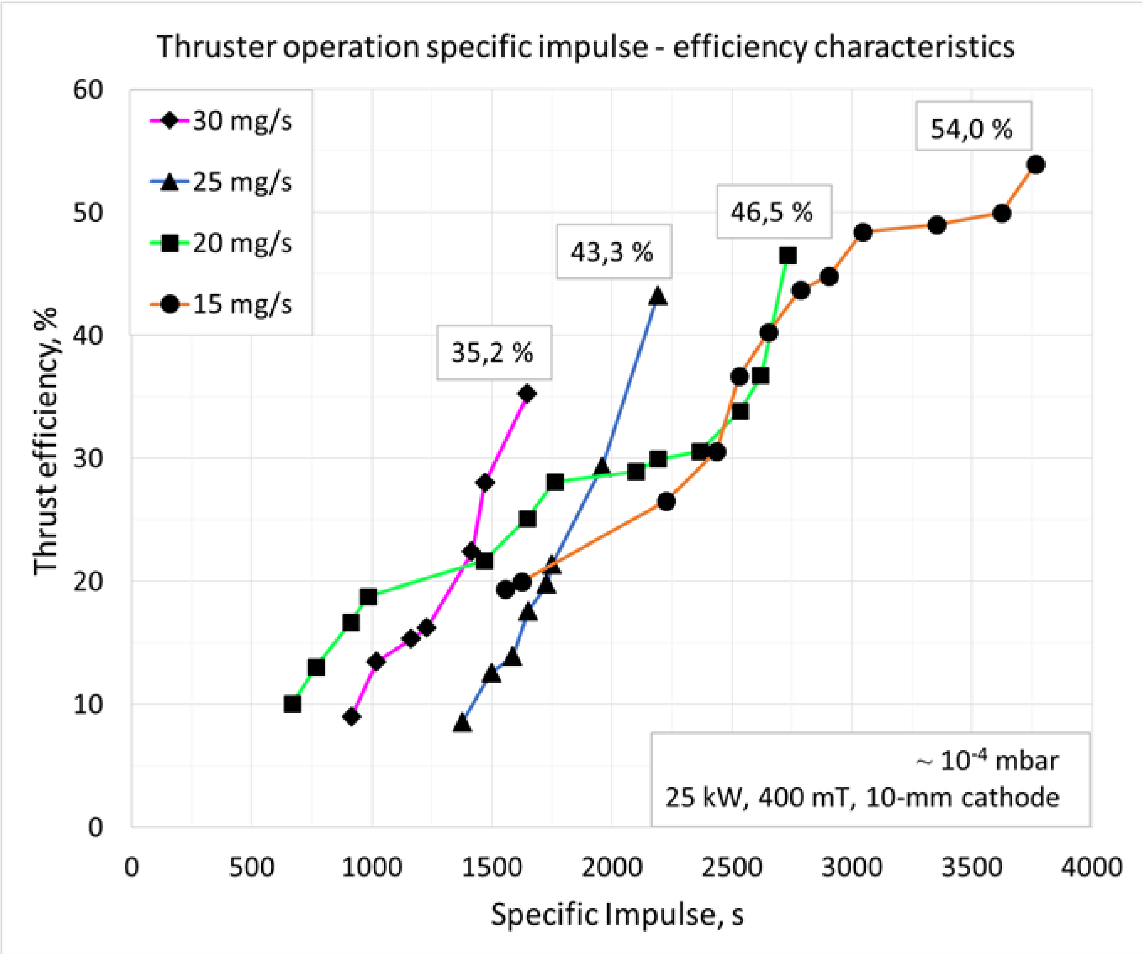

Figure 17. *The thruster operation specific impulse - efficiency characteristics graph*

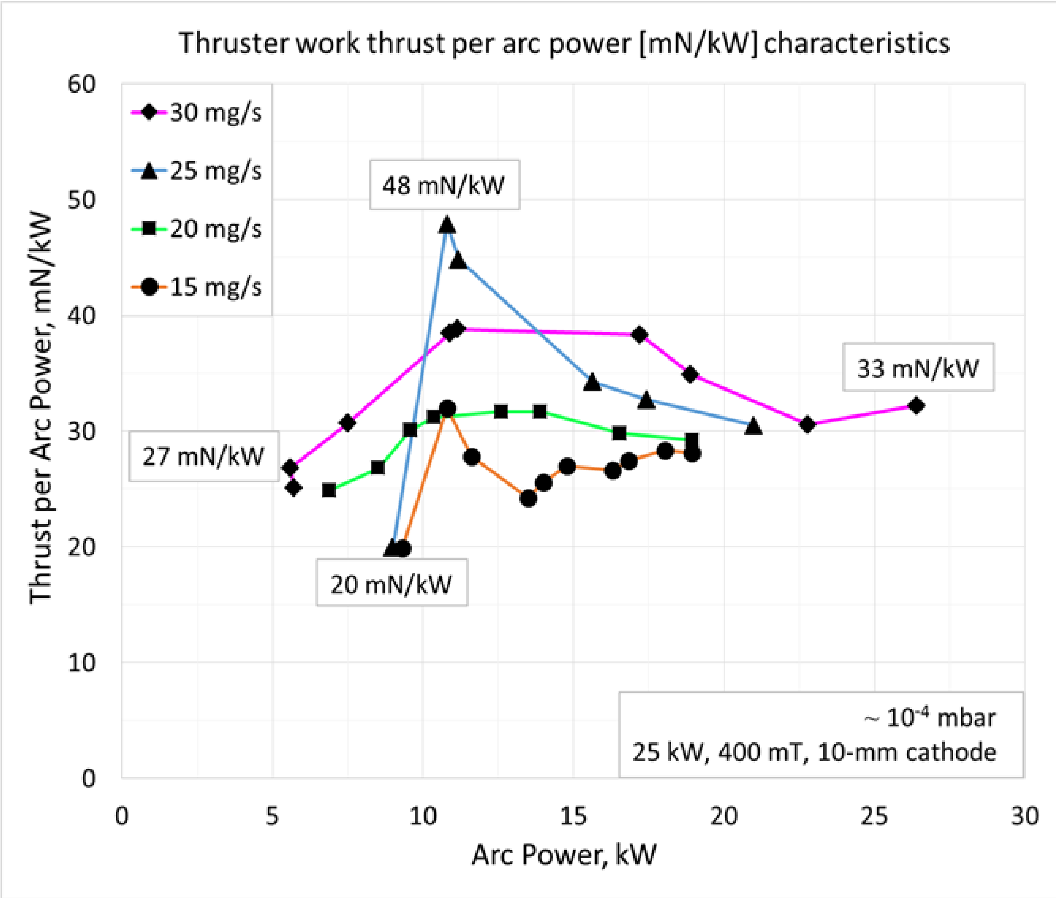

Figure 18. *The thruster operation thrust per arc power [mN/kW] characteristics graph*

The 10-mm model of the multi-cavity cathode proved to be the best cathode solution for currents under 450 A. The cathode warmed up and launched the plasm flow almost instantly, had a very high repeatability of ignitions, and also showed itself excellently from the point of the resource and resistance to erosion. The total life of launches for all tests for this cathode was about 2900 s. Single continuous launch not more than 140 seconds. After all the researches have been carried out the erosion observed at the cathode was absolutely minimal. The graphs of the experiments with the best achieved reactive thrust and specific impulse are shown in the Figure 19 and Figure 20.

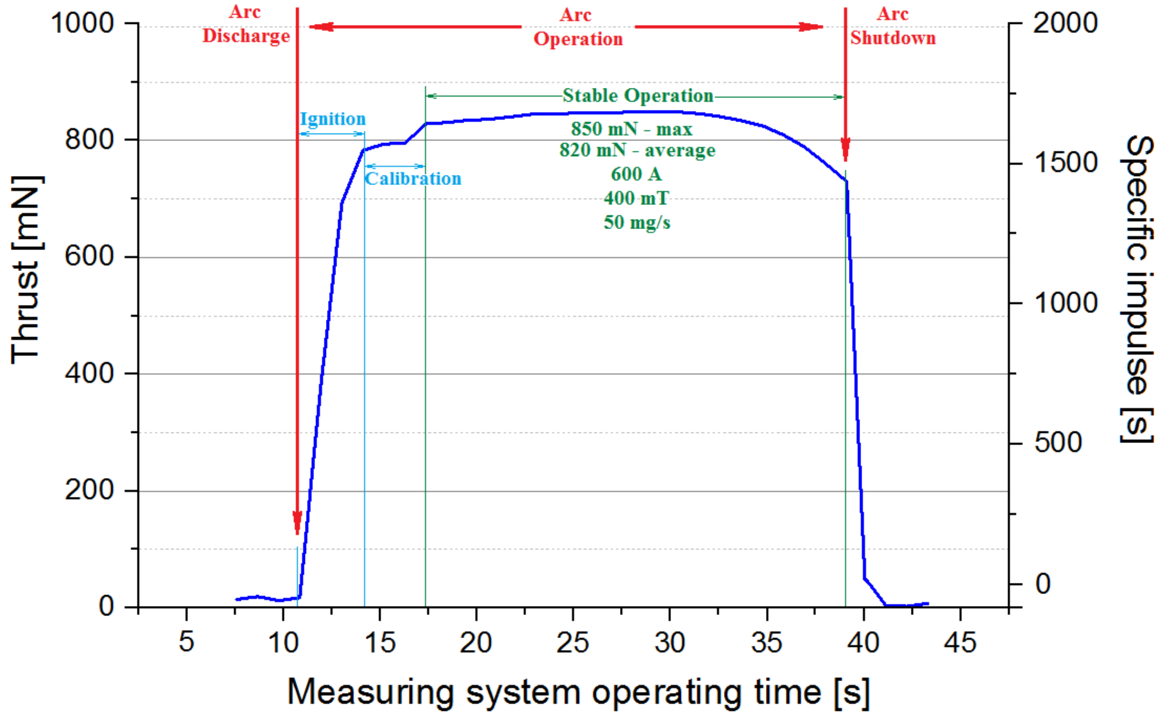

Figure 19. *The graph of the experiment with the best achieved reactive thrust of 850 mN with the 10-mm multi-cavity cathode*

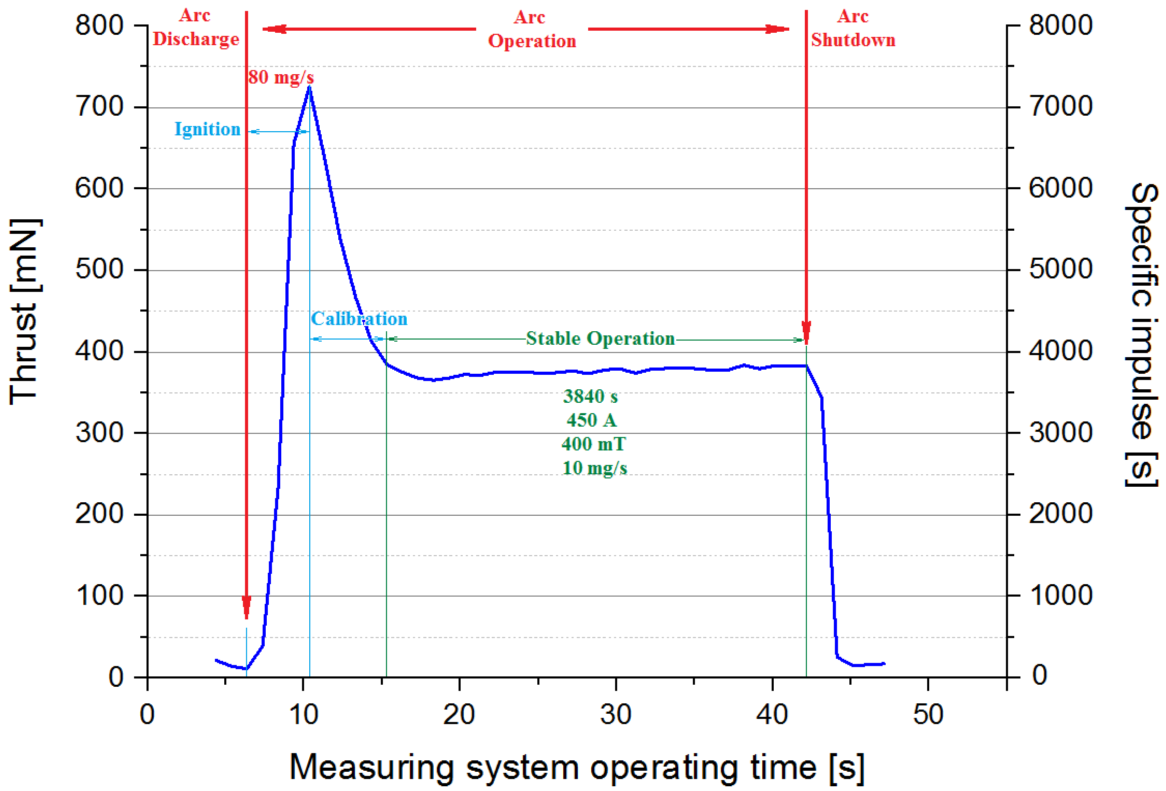

Figure 20. *The graph of the experiment with the best achieved specific impulse of 3840 s with the 10-mm multi-cavity cathode*

The snapshot of the experiment with the 10-mm multi-cavity cathode type laboratory model of the 2G HTSC applied field magnetoplasmadynamic researched thruster at which highest efficiency of 54% was reached at 15 mg/s with 554 mN thrust and 3763 s specific impulse at 18.9 kW (450 A, 42.1 V) with 29.3 mN/kW and 1.3 kJ/mg is shown in the Figure 21.

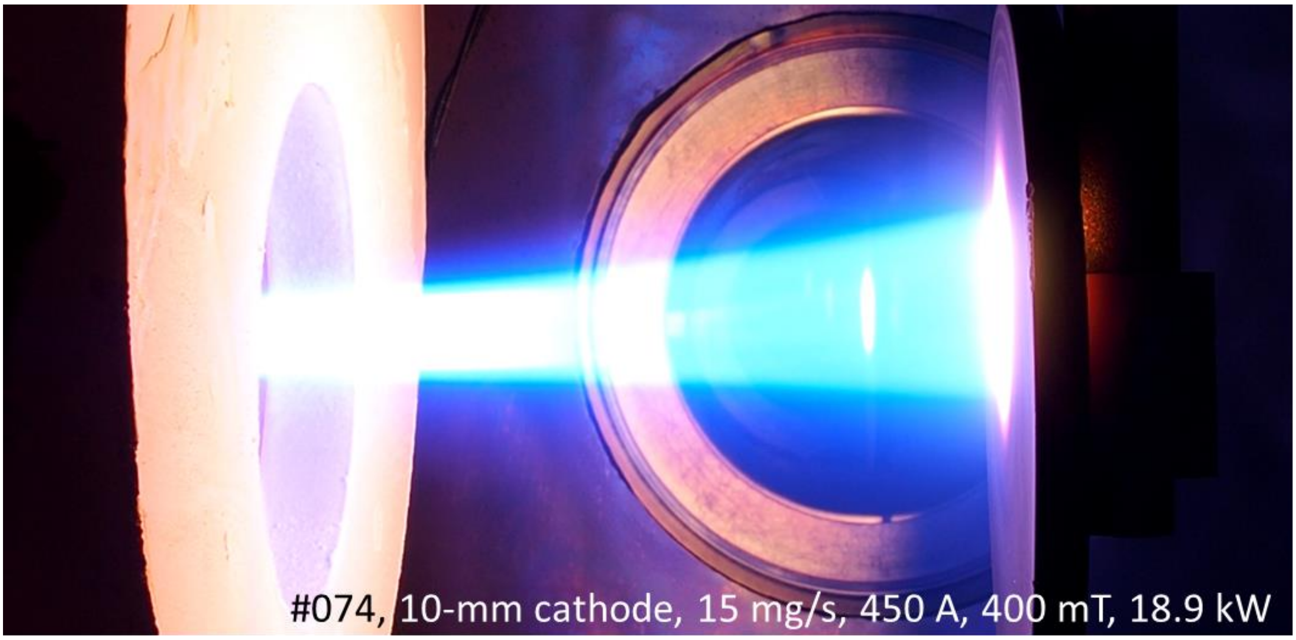

Figure 21. *The snapshot of the experiment with the best efficiency of 54% reached with the 10-mm multi-cavity cathode 2G HTSC AF-MPDT*

4. Conclusions

The use of the 12-mm 2G HTS SuperOx tape allowed the creation of the high-tech electromagnet. This electromagnet, in addition to creating strong magnetic fields up to 1 T, also has a very high gradient of the magnetic field, which makes it possible to efficiently accelerate the plasma of the AF-MPD thruster. The electromagnet we created surpasses its copper counterparts both in power consumption, in weight, in volume and in the efficiency of the created field. For space applications also has been developed electromagnet model based on a 2G HTS 4-mm tape with cryocooling, this HTSC model has even better characteristics.

This electromagnet based on a superconductor tape has been tested as the application for magnetoplasmadynamic thruster applied magnetic field. Effective application of the magnetic field to accelerate the plasma allowed us to obtain the results of the MPD thrust of 850 mN, a specific impulse 3840 s, and the efficiency 54%. The total thruster resource is 5400 seconds, 150 launches, erosion is minimal due to the correct selection of the cathode type and the use of a strong applied magnetic field, which also reduce cathode erosion.

For the 20-25 kW class AF-MPD thruster the 10-mm multi-cavity cathode shows the best achieved characteristics, but it is limited by currents of not more than 450 A. For high currents the cathode of a larger cathode tube diameter and, accordingly, the larger cathode rods diameter was created. However, work with 17-mm cathode showed redundancy due to the maximum acceptable working current of 600 A for testing facility power supply. Thus, the optimum diameter for the entire working range of our operating currents is experimentally set to a diameter of 12-mm multi-cavity cathode.

In this way, the effective application of the 2G HTS tape manufactured by SuperOx was shown.

The current AF-MPDT model can be mounted for flight tests.

5. Acknowledgments

All the researches were carried out on our own testing facility vacuum chamber, which was created for tasks from scratch completely on our own, by SuperOx means and initiative. The authors of the article are grateful to MEPhI Institute Department of Plasma Physics for their help in the manufacture of the reactive thrust measurement system for MPD thrusters.

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