APPLICATION OF HOLLOW CATHODE IN ARCJET PROPULSION AT
LOW AND AVERAGE POWER.

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ABSTRACT

The paper is devoted to the design and test of hollow cathodes for arcjet thrusters at
low (0.5...2 kW) and average (10...50 kW) power operating on nitrogen and nitrogen-inert
gas mixtures. Two models of arcjet devices have been tested for two working parameter
ranges: 1. power 0.5...1.5 kW, pressure 100-200 kPa, discharge current 10...25 A, working gas
- nitrogen. 2. power 10...50 kW, pressure up to 50 kPa, discharge current 200...1200 A,
working gases: Ar, (Ar+He) mixture, (Ar+N) mixture.

Performances and main properties of hollow cathode erosion have been studied in the
course of long-duration tests from 4 to 250 hours for different arcjet devices. Upon testing
method of electronic microscopy have been used for diagnostics of cathode surfaces. Several
significant advantages of hollow cathode arcjet devices were revealed.

INTRODUCTION

The potential benefits of arcjet (AJ) technology for satellite stationary keeping in
geosynchronous orbits are set forth in [1]. Hydrazine 1.8 kW AJ is installed aboard Telstar-4
geosynchronous communications [2]. The tests will enable to govern the AJ compatibility
with communications. Widening the scope of missions which can be solved with AJ brings to
life the development of average 10...50 kW AJ. Such work is conducted in many countries.
There is information on planned flying tests of AJ at average power [3]. It has been suggested
that AJ be used not only for space but for ground technology as well. In spite of throughout
history and wide "geography" related to AJ R&D all over the world there exist a number of
problems in physics and engineering without resolving of which one can not count on the AJ
wide range application. One of such fundamental problems is that one, pertaining to cathode
lifetime.

The feasibility of hollow cathodes' application in AJ and arc plasma generators being
the same by parameters and embodied ideas has been under research at Moscow Aviation
Institute over many years. The results of these researches are outlined partially. The idea to
apply hollow cathodes instead of rod ones lies in the fact to decrease specific heat loadings at
the expense of widening the emission zone on the cathode and on the anode in the constrictor
area. There exist some rather complete reviews of the work on arc discharges when a hollow
cathode is used [4,5]. However, there are practically no publications on the usage of hollow cathodes in discharge devices with the parameters, mentioned above.

This paper summerizes the results of experimental research on AJ with a hollow cathode of two operating parameter ranges.

1. Power 0.5...2 kW, pressure in a discharge chamber 100...200 kPa, working gases: nitrogen, nitrogen-hydrogen containing mixtures, discharge current 10...25 A.
2. Power 10...50 kW; pressure - up to 50 kPa: working gas: nitrogen, argon; mixtures of nitrogen with helium; discharge current 200...1200 A.

There have been:
- investigated the main integral discharge characteristics;
- considered the patterns of hollow cathode AJ start procedure, by performing the tests which from 4 up to 50 hrs;
- obtained the data on specific erosion rate of the cathodes, the latter being of various configuration and made of different materials.

The work has been partially performed in the frame work of Contract with European Office of Aerospace Research and Development (EOARD) (Contract F6170894W0744).

1. RESEARCH ON HOLLOW CATHODES IN ARC DISCHARGES.

Experimental apparatus.

The models of arcjet plasma generators simulating physical and thermodynamical processes in arcjet propulsion were designed for investigation of hollow cathode arc discharges.

AJG-1 model.

AJG-1 model is used for investigation of the discharges at current range of 600...1200 A (power level is 50...60 kW). A schematic design of AJG-1 is shown in Fig.1. A discharge chamber 1 has cooled walls. Cathode unit 3 and anode-nozzle 4 and accelerating nozzle 5 are mounted in the vacuum chamber. The critical cross-section of the anode-nozzle is 15 mm and the critical cross-section of the accelerating nozzle is 12 mm. The discharge chamber 1 is equipped by thermal-screens 6. The propellant is fed to the discharge chamber through the system of holes in the screens as it is shown in Fig. 1 by the arrows. For the examination of the stability and interaction of the longitudinal magnetic field with the arc the solenoid 7 was used, creating the field with the induction 0.055 T. The anode unit consisting of the anode-nozzle and accelerating nozzle was designed to reach M=2.7. AJG-1 was mounted in the bottom of the vacuum chamber, the schematic diagram of which is shown in Fig. 1. The windows 9 were used for optical diagnostics of plasma properties.
AJG-2 model.

The investigation of the discharges in the current range of 200...300 A (power 10...25 kW) with a hollow cathode was performed at AJG-2 model, shown in Fig. 2. The main difference of this model from the AJG-1 is in utilising of the electrode system designed for the given power range. Anode-nozzle includes a system of rechangable elements 7,8,9. In different tests the part 8 being a constrictor had a critical cross section diameter from 3.5 to 20 mm.

Cathode unit design.

The schematic of the cathode unit design as a part of AJG-2 model is seen in Fig. 2 and is shown separately in Fig. 3.

The cathode unit consists of a hollow cathode itself (point 2 in Fig. 2 and point 1 in Fig. 3), a system of electrical conductors (point 3 in Fig. 2 or 2,3,4 in Fig. 3). Electrical conductors 2 (Fig. 3) adjoining the cathode have a smaller cross section than the conductors 3 (Fig. 3) and are used as emitting elements at the stage of preliminary discharge firing. The electrical conductors 3 (Fig. 3) also serve as thermal conductors for the cooling of the emitting elements by conducting of heat to the cold parts of the conductors 4 (Fig. 3). The cathode of the following design is determined as Y-like cathode unit. Taking into account the function of the conducting parts they are manufactured from different materials: emitting elements are from W+La alloys, thermal conducting parts are from W, cooling part are from W or Mo.

The design of the high current cathodes is shown in Fig. 3. The cathode consists of a number of welded sticks the amount and diameter of which are chosen due to fixed channel diameter. Only single-channel cathodes were tested in the current range of 200...1200 A.

Experimental research on hollow cathode discharges.

Experimental apparatus.

The following systems were installed in the test facility:
- vacuum system including vacuum chamber 1.2 m in diameter and 2.2 m long;
- pumping system on the base of vacuum mechanical and diffusion pumps of the pumping rate up to 1500 l/s providing the residual vacuum about 10⁻³Pa;
- system of the electric supplying including the d.c. generator 36, 200, 400 kW of electric power for the current value 300, 1000, 5000 A;
- system of working gas feeding;
- system of the discharge start up;
- system of gas or water cooling;
- diagnostic systems.
Discharge ignition system and start up procedure.

High-current discharge firing problem (often when there is a decrease of volt-ampere characteristics) and further smooth transition of the preliminary discharge to the nominal operational mode always causes some technical problems. During the investigation of hollow cathode parameters which includes the determination of the average erosion rate at the nominal modes the problem of smooth start up to provide minimal erosion at the transitional regimes is of great importance.

The system of the discharge start up used in the tests is shown in Fig. 4. The same d.c. generator E is used both at the start up and at the nominal operational modes. So voltage ripples at the firing mode are minimized. Switch K₁ in "a"-position switches on the start cathode heating circuit. The parameters of the different parts of the electrical conductors and the resistors R₃ and R₂ are determined to proceed the achievement of equality of the values of the anode voltages and the discharge firing voltages. The firing voltage depending upon the working gas is within 40...60 V when the emitting parts of the conductors are at the temperature corresponding to the effective emission. For example at discharge in nitrogen at pressure (1...2) 10² Pa and discharge current of 200...300 A the required heating current was 300...350 A and ignition voltage was 40 V. The resistance of the resistors were R₁=0.50 Ohm, R₂=0.05 Ohm, R₃=0.055 Ohm.

For argon the following parameters were observed: discharge current 1000...1200 A, pressure (2...3) 10² Pa, and discharge firing voltage 40 V. It was provided at R₁=0.013 Ohm, R₂=0.015 Ohm, R₃=0.025 Ohm.

After discharge firing the K₁-switch was turned in "b"-position and the nominal value of the discharge parameters was being achieved by the varying of the working gas expenditure. The parameters of the Y-cathode unit and values of R₁,R₂,R₃ resistors could be chosen experimentally for every discharge current and gas expenditure values. The half-empirical method of calculation allows us also to choose the parameters of the cathode itself.

Thus, for the discharge current of 600...1200 A the cathode may consist of 5 sticks of 6 mm in diameter, made from W+La alloy. The emitting parts of the electrical conductors were made from the same alloy. The hollow cathode for 200...300 A discharge current consisted from 6 sticks of 3 mm in diameter. The emitting elements were of the same diameter.

Diagnostic systems.

To measure the velocity of the directed atoms and ion in the plasma flow the temperature of the particles (atoms,electrons,ions), as well as electron density the well-known spectral methods were used. Plasma properties in the discharge chamber were also measured. Interferometer Fabri-Perot for plasma diagnostics equipped by spectrograph was used.
Investigation of the integral parameters of average power follow cathode AJ devices.

VAC of the discharges in different gases under different pressures and flow rates are given in Fig.5. The investigation of the discharges at the current range of 550...1200 A was made at AJG-1, and in the range of 150...350 the AJG-2 was used.

The full working parameter range:
- flow rate m - 0.1...2.4;
- input discharge chamber pressure p=1.6...73 kPa;
- working gases: Ar (curves a and e); Ar+He (curves b,c,g); N\textsubscript{2} (d,h,j); Ar+N\textsubscript{2} (f) (Fig. 6).

The integral performances given in Fig.5 show the general conformities of the hollow cathode arc discharge inspite of the fact that different curves were obtained under different conditions and for not similar geometries of the electrode system. Thus, curves a,b,c - were obtained at the anode assembly shown in Fig. 1, curves f,g,h,j - with the electrode configuration shown in Fig. 2. In the most cases a weak magnetic field (up to 0.05 T) was used to stabilize the discharge. Dependences d and e were determined in the absence of the magnetic field. We should mention that the applying of a weak magnetic field didn't almost influence either at the hollow cathode discharge performances or at discharge stability and its azimuthal homogeneity. That is why the magnetic field in hollow cathode arc devices cannot be used.

The discharge chamber gas pressure was varied by the flow rate changing and by the usage of the constrictors with different channel cross section. Thus, we could choose the discharge conditions so that at each flow rate value different pressure values could be (see for instance the curves a and e).

Average longitudinal current density was (3...5) 10\textsuperscript{6} A/m\textsuperscript{2} for various regimes. Taking into account the real electrode configuration and estimating current distribution over the cathode surface we can assume that the average emission current density changes in very narrow limits.

One can see a very low dependence of the discharge voltage on the Ar pressure and current values according to the data of curves a and e that are shown in Fig. 5. In discharge current range of 150...1200 A the discharge voltage changes within 13.5 - 15 V. The influence of the gas kind or a percentage of gas addmixtures in Ar such as He or N\textsubscript{2} is very strong. In such gas mixtures the discharge voltage and power trend to be increased. The V-A performances corresponding to the curves a,b,c, were determined at the "dynamic regime" when at the fixed gas flow "rate the electric moving force of the generator was upped meanwhile the discharge current increased from 550A to 1200 A. Then the voltage was down to lower: the current in the same interval (scanning time was 7 sec). The lower current limit corresponds to the discharge extinguishing voltage. Different V-A characteristics sections are marked by the arrows at the a,b,c curves in Fig. 5. The visible small relaxation effect was caused apparently by the heat relaxations in the electrode systems.

The discharge voltage in the pure nitrogen (point j) is much higher than in Ar under the same conditions. The discharge in Ar and N\textsubscript{2} mixture (point f) is higher than the voltage
in (Ar+He) mixture (point e). Increasing N₂ percentage in (Ar+N₂) mixture one can receive the anode temperature higher. It means that the power losses in the anode increase. Another factor, causing the growth of the discharge voltage in N₂ is evidently the energy expenditures in N₂ molecules dissociation.

Besides the above mentioned regularities that are typical for are discharges, we should emphasize the special properties of the hollow cathode discharge, determining the advantages of the hollow cathodes in comparison with the stick cathodes. It mainly concerns the high azimuthal homogeneity of the positive plasma column and of the current distribution over the anode surface consequently. This property was observed over the whole range of the tested discharge conditions and for all electrode system geometries.

This conclusion is confirmed by the photos of the anode parts that are shown in Fig. 6. They are taken from the side of the discharge chamber. Anode "a" with the constrictor diameter of 10 mm was used in Ar-discharge with the stick cathode influenced by an axial magnetic field at the discharge current value of 700 A and pressure 10 kPa. The azimuthal heterogeneity of the current distribution over the anode surface is clearly displayed in the photo.

Anode "b" with the constrictor diameter of 20 mm was used with the hollow cathode (work time 10 hours) at the current value of 1200 A. The working gas was (Ar+He) mixture, pressure - 1.6 kPa.

Anode "c" corresponds with the following condition: working gas - (Ar+He), current power is 1500 A, constrictor diameter is 30 mm. The inner surface of the anode "b" after 0.5-hour tests at current value 1000 A in the (Ar+N₂) blend much the pressure of 40 kPa is pictured in Fig. 6. As we can realize from the deterioration type a great azimuthal homogeneity and axial symmetry of the current distribution over the anode surface takes place (Fig. 7, b,c,d).

The longitudinal section of the cathode after the 17-hour endurance test is shown in Fig. 7 to analyze the whole picture.

From the cathode form changing one can conclude that discharge current closes both on the inner and on the outer surfaces of the cathode. A good axial symmetry of the cathode erosion is also visible. Average specific cathode erosion was 5x10⁻¹² kg/c.

**Basic thermodynamic and thruster performances.**

The dependences of main thermodynamic and thruster parameter of arcjet devices with hollow cathode are given in Fig. 8. We should emphasize, that the main goal of this research was to examine the properties of hollow cathode high current arc discharges. The questions of the accelerating channel optimization (system: anode - nozzle) were out of this research field. Inspite of that the gained results consist a lot of useful information about the thermodynamic and plasmodynamic processes in the hollow cathode arc generators.
Hollow cathode unit design.

The cathode configuration designed for the current value of 10...25 A is given in Fig. 11. The hollow cathode is a rod of 3 mm in diameter with a cavity of 12 mm deep drilled at the working tip.

The cavity diameter was varied from 1 to 3 mm. W+2\%La₂O₃ cathodes A,B (polycrystal structure) manufactured from the whole rod. The W+3\%ThO₂ cathodes C,D (polycrystal structure) 35 mm long has a working part welded to the W rod. The working cathode tip is milled to achieve round edges as it is shown in Fig. 11.

Two variants of the cathode placing in the discharge chamber were tested as it is shown in Fig. 12,13. The difference of the insulator's form and dimensions is seen. In all tests the same anode was used, the schematic of which is given in Fig. 13. In the first version of the design the insulator was similar to the insulator that has been used in [6]. As the tests have shown the insulator erosion was intolerably high in this design. To decrease the erosion rate another modification of the device was designed (Fig. 13), which behaviour in the tests was acceptable. The optimization of the discharge chamber configuration is the main goal of further investigation.

Results of experimental research.

Experimental apparatus.

The tests were made at the test facility described in part 1.3.1. The AJT was placed in a vacuum chamber as it is schematically shown in Fig. 14. Discharge initiations were made with the help of the plasma source D mounted at the thruster exit (Fig. 14). The electric feeding diagram is given in Fig. 14. The resistance of the water-cooled resistors \(R₁=0.225\ \text{Ohm};\ \ R₂=0.825\ \text{Ohm}\) were chosen experimentally and used for measuring of the discharge current ripples. The resistor \(R₃=0...6.5\ \text{Ohm}\) is a load.

Starting up procedure.

The discharge initiation is made due to creating of the plasmoid at the output thruster cross-section. The high-voltage (1500 V) and low-current (0.5 A) arc generator not electrically connected with the thruster electrode system was used for this purpose.

The firing voltage of the main discharge was set at the thruster electrodes from the main generator so that the current value in the main discharge does not exceed 25 A after the discharge firing.

At the operation in \(\text{N}_2\) the firing voltage was 140...150 V, resistance of \(R₃=6.5\ \text{Ohm}\), discharge chamber pressure 5 kPa and vacuum chamber pressure 25 Pa. After the discharge firing the operational mode of the discharge was achieved by the increase of the gas flow rate. Operational mode parameters were following: - pressure 100...200 kPa; - voltage 55...65 V; - current 10...20 A.
The device shown in Fig. 1 was used in the most of tests. The mixture of Ar+He with different percentage of He was used as a working gas. The discharge current was kept constant (~1200 A) for the whole range of parameters given in Fig. 8.

In flow rate range 0.17...0.8 g/s the device parameters were being changed in the following limits:
- the discharge power \( P = 15...60 \) kW;
- working gas molar mass: \( M = 4.0...5.2 \) Kmol;
- specific impulse: \( I_{sp} = (1.5...6) \times 10^3 \) m/s;
- total specific enthalpy: \( H_0 = 10...30 \) MJ/kg;
- static flow temperature: \( T_{st} = 1900...2200 \) K;
- discharge chamber pressure: \( P = 1.6...21 \) kPa;
- total efficiency: \( \eta_t = 6.5...29 \% \).

We can conclude from the data given above that the power, specific impulse and enthalpy grow with the increasing of the He percentage in the mixture. We should observe the same tendency using hydrogen-containing gases.

2. RESEARCH AND DEVELOPMENT OF THE LOW-POWER HOLLOW CATHODE ARCJET DEVICES.

Low power AJT experimental model.

Low-power AJT model was designed taking into account the following requirements:
- to provide the start up procedure, including discharge firing and transition to the nominal operational mode;
- to reach operational parameters in the given range: discharge current \( 10...25 \) A; gas pressure \( 100...200 \) kPa;
- to provide the discharge stability and homogeneity.

The anode channel configuration of the 1 kW AGT was accepted as a prototype designed by CENTROSPASIO (Pisa, Italy) and described in [9,10]. The schematic of the hollow cathode AJT is given in Fig. 9.

The main design units are: 1 - injector (material W); 2 - anode (W); 3,10 - insolator (Bornitrid); 4,5,6,7,8,30,31,32 - parts of connecting unit; 9 - housing; 11,23,24,25,26,27,28,29 - parts of cooled unit of anode electric supply; 12 - output insulator; 13 - compacting blanket; 14,15,16,17,18,19 - cathode unit parts; 20 - hollow cathode (W; W+La; W+Th); 21,22 - AJT assembly parts.

The parts of the anode unit are described in [10]. The hole diameter of the constrictor is - 0.6 mm. The photo of the experimental model is shown in Fig. 10.
1 kW arcjet integral parameters.

The investigation of the hollow cathode in the discharge at the pressure range 100...200 kPa was made for the first time. The main goal of the research was to show the hollow cathode efficiency under the given conditions and to determine the integral thruster performances, to reveal the conditions of stable homogenous discharge, to get the preliminary estimations of erosion rate of the cathode. The comparison of the W+2°La2O3 and W+3°ThO2 cathodes were also revealed. Depending upon the test objectives the cathode operational time was from 4 to 50 hours.

Experimental dependences of voltage Ud (Fig. 15) and power N (Fig. 16) on discharge current Id for the cathodes of different materials at operating in N2 are shown in Fig. 15, 16.

Steady thruster operation was observed in current range of 7...25 A, power 0.5...1.4 kW under the pressures of 202...224 kPa and nitrogen flow rate 110 mg/s.

In hollow cathode arcjet similar to low power thrusters with rod cathode in approximately the same parameter range [6] the falling volt-amper characteristic is observed. The thoriated tungsten hollow cathode with the same cavity diameter (1.3 mm) demonstrated higher discharge voltages at the same current values (Fig. 15) than the W+2°La2O3 cathode. The current value of the discharge going out in the case of the thoriated cathode (10 A) is also higher than in the case of lanthanated cathode (7.5 A). The influence of the cavity diameter in the limits 1...1.3 mm practically do not influenced on the VAC character.

50-hour tests at the given nitrogen flow rate 110 mg/s and discharge chamber pressure 203...224 kPa were made with the A-cathode. Test procedure included start up mode transition to the preliminary discharge mode by changing flow rate and heating for 30...40 min before the stationary heat regime. Then the nominal operational mode was being achieved with the following parametres: - pressure 205± 5 kPa; - consumption 110± 10 mg/s; - discharge current 15± 0.5 A.

Under 50-hour tests of the W+2°La2O3 cathode the discharge current was kept up at 10 ± 0.5 A.

Discharge current changing was followed by both: discharge voltage and gas pressure changing. The average value of the magnitude ΔU/ΔP at the current 15 A was approximately 0.4 V/kPa and of the magnitude ΔU/ΔI was about 0.7 V/A. Thus set accuracy of the operational mode by voltage ± 2 V and by current ± 0.35 A at the digital-device registration accuracy 0.01 V and 0.5 A.

After transition to the given operational mode its stability was provided by the gas feeding and vacuum pumping systems during the whole experimental time. Usually each test took 4...7 hours. 50-hour test were made without model resetting. In cases when the erosion analysis was necessary the resettings were inevitable. Nominal mode setting procedure was repeated after each resetting for example after the next working gas balloon replacement and after turning off the discharge.

Figures 17 shows the typical discharge voltage and current time histories at the steady mode for different cathode work duration. In the references to the figures the average values
and their mean-square deviations are given. We see a great discharge stability at the nominal modes. We should increase the pressure setting accuracy for a discharge pressure in the order of its value to keep the nominal mode parameters in the given limits 0.1...0.25 V.

**Features of 1 kW arcjet hollow cathode erosion.**

The hollow cathode erosion investigations in arcjet discharge under the pressure 100...200 kPa were made for the first time. Nitrogen under the pressure of 200 kPa and at the current value 10 A and 15 A was used in these tests.

Cathode erosion of the (W+2°La2O3) cathode was studied for 50-hours at the discharge current value 10 A and discharge voltage 57 V (power is nearly 600 W). The thruster was not resetted during the whole 50 hours. Total number of starting up was 26. Average specific erosion was 5.8 10^{-11} kg/C. The longitudinal section of the cathode after the test is shown on the photo in Fig. 18.

The initial form of the working tip was of truncated-cone-shape. Taking into account the test results the working tip form was similar to the one shown in the photo in Fig. 18a. The erosion of two other cathodes estimated at duration time tests of about 4 hours. The photos of the cathodes before and after the tests are shown in Fig. 18b,c. We should notice that the cathode tip form was near to regular during the whole period of the tests. In the W+2°La2O3 cathode test at the current value 15 A and power 825 W the forming of a "plug" at the cavity origin was observed as it is seen in Fig. 18b.

The plug growing was noticed after the first 4 hours of the test. Such formation was not observed at the thoriated cathode even with more powerfull discharge: current 15 A, power 960 W. The average specific erosion of both cathodes was rather similar:

- for (W+2°La2O3) cathode - 1.7x10^{-11} kg/C,
- for (W+3°ThO2) cathode - 2.0x10^{-11} kg/C.

**Research on hollow cathode working surfaces.**

Research on different parts of the cathode active zone was made using light and scanning electron microscopy. The cathode surface photos made by the light electron microscopy method are shown in Fig. 19,20.

The laminated material structure of the cathodes is clearly seen in the photos, it is typical for the technology of the thin sticks (3 mm) manufacturing. Probably this kind of structure influence on the properties of the cathode such as diffusion rate of light ionized additions (La,Th) to the cathode working surface and emission characteristics. Thus, as it is seen in Fig. 21, this structure cathode leads to the (W+3°ThO2) cathode tip deformation. The microphotos of the (W+2%La2O3) cathode surface after 30-hour test in nitrogen are shown in Fig. 21. The uniform distribution of the erosion tracks along side and on inner surfaces are evident. Spectral analysis shows the presence of lanthan inclusions on the side surface. We can make an assumption that the erosion predominates over the condensation on
the tip and side cathode surfaces, though near the plug the condensation can dominate. The photo of the inner surface and the plug (Fig. 21) indicates the complicated physical and chemical processes in the cavity. All the photos show a good discharge uniformity of the cavity surface erosion. A boundary of the active surface zone inside the cavity is observed distinctly in Fig. 21. It is located approximately a cavity diameter from the cathode tip. The comparison of Fig. 21 and 22 for thorialed and lanthanated cathodes shows that the thorialed cathode structure is grained finer. Thorium inclusions were revealed on the cavity surfaces (Fig. 22).

One of the most important goals of the further research is a more detailed analysis of the surface processes at high nitrogen pressures in hollow cathodes in the comparison with the processes in hydrogen containing gases.

CONCLUSION

1. High current arc discharges in nitrogen, argon and (Ar+He) mixture in current range 200...1200 A and pressure range 10...50 kPa has been investigated. It is shown that hollow cathodes of designed type be assembled with arcjet thrusters of power level 10...50 kW.

2. Different hollow cathode units has been designed and tested. The hollow cathode discharge start up procedure has been developed.

3. Single-channel hollow cathodes formed by a system of sticks has been designed and tested for high-current arcjet middle power plasma generators and thrusters.

4. Cathode erosion peculiarities for middle power thrusters has been studied. Total operational time of some cathodes is more than 250 hours and they keep their work capability. Specific \((W+2\%La_2O_3)\) cathode erosion is \(5\times10^{-12}\) kg/s for (Ar+He) mixture.

5. For the first time low-power hollow cathode arcjet has been tested in nitrogen at pressure 100...200 kPa in current range 10...25 A (discharge power 0.5...1 kW).

6. Four hollow cathodes were designed for 1 kW power thruster and the hollow cathode effect was demonstrated under the given conditions.

7. \((W+2\%La_2O_3)\) and \((W+3\%ThO_2)\) hollow cathodes with 3 mm outer diameter and 1...1.3 mm cavity diameter has been tested in 1 kW thruster operating in nitrogen. All cathodes demonstrated thruster operation with uniform distributed discharge. Current and discharge voltage stability corresponds to root - mean - square deviation value 0.15...0.2%.

8. Endurance 50-hour tests were made for a \(W+2\%La_2O_3\) cathode at 26 startings.

9. The special features of 1 kW arcjet hollow cathode erosion has been researched with the help of electron microscopy for 1 kW thruster. The average specific erosion was within \(1.7\times10^{-11}\) kg/C... \(20\times10^{-11}\) kg/C at nominal operational modes.
REFERENCES

AFTER 15-HOUR TESTS IN ARGON

7. VIEW OF HOLLOW CATHODE CHANNEL

Fig. 8. THERMODYNAMICAL PROPERTIES OF AJG-1 MODEL

Fig. 9. 1 KW ARCJET HOLLOW CATHODE DESIGN

Fig. 10. 1 KW ARCJET WITH CATHODE SHIFTER

Fig. 11. 1 KW ARCJET - EAS (MBK)

Fig. 12. 1 KW HOLLOW CATHODE ARCJET CONFIGURATION (1st modification)

Fig. 13. 1 KW HOLLOW CATHODE ARCJET CONFIGURATION (2nd modification)

Fig. 14. 1 KW ARCJET EXPERIMENTAL SCHEMATIC

Fig. 15. 1 KW SIMULATED HYDRAZINE ARCJET V-I AND N-I CURVES

Fig. 16. 1 KW SIMULATED HYDRAZINE ARCJET V-I AND N-I CURVES

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