AN EXPERIMENTAL INVESTIGATION OF THE HOLLOW CATHODES FOR LOW-POWER ION THRUSTER

O. A. Gorshkov and V. A. Muravlev
Keldysh Research Center,
8/10, Onnazhskaya, Moscow, 125438, RUSSIA

Abstract

One of the modern tendencies in the space technology evolution is a mass reduction of medium and low-orbit spacecraft. Moreover, its lifetime should be increased up to 5 - 10 years. At the same time, the electrical power of these spacecraft accounts for tens - hundreds Watts. To solve the number of tasks the propulsion systems of such spacecraft should provide both high level of electrical efficiency and high specific impulse, that considerably decrease the required propellant mass. One of the systems that are able to meet such requirements is a propulsion system on the base of ion thruster. The effective performance of ion thruster largely depends on operating characteristics of the cathode in discharge chamber and the neutraliser. Nowadays, hollow cathodes are used in ion thrusters. Effective operation of hollow cathode can be achieved only if both power, released on the cathode, and propellant flow rate via cathode exceed some limiting values. These values depend on the design of the cathode unit. With total power of the ion thruster and propellant flow rate decrease the requirements to cathodes become more stringent.

This paper describes the results of experimental investigation of the hollow cathodes for the ion thruster with power less than 200 W. An operation of capillary-type hollow cathodes with LaB6 activator was studied. Operating characteristics of cathodes, fabricated from different materials, were compared. The cathodes were tested as a part of 5-cm laboratory model of Kaufman-type ion thruster. It is shown, that the cathodes demonstrate stable operation without external heating, when discharge power exceeds 15 W and cathode propellant flow rate exceeds 10 - 30 eq.mA.

Introduction

The increase of satellite on orbit operation period makes high demands to such propulsion system parameter as propellant consumption. The use of electric propulsion system for orbit correction instead of conventional chemical engines allows the considerable reduce of required propellant mass on board the spacecraft. For some tasks facing small spacecraft the use of low power ion thrusters can be advantageous. For example, ion thrusters with power range between 50 and 130 W can be used for atmospheric drag compensation of spacecraft with mass equal to 250...750 kg at orbit altitudes above 400 km¹.

The ion thruster effectiveness depends greatly on the operation of cathode in discharge chamber and neutraliser. This is especially important for low power thrusters. In ion thrusters the hollow cathodes are usually used because of its long lifetime and high efficiency. To keep the hollow cathode in operation state the part of discharge power should be consumed. Besides, for cathode operation it is necessary to pass some propellant flow rate through its cavity. In the case of discharge chamber cathode for low power ion thruster the situation is possible when the value of existing discharge power will be not enough to provide the cathode working temperature. Even more strict requirements face the neutraliser. The mass flow rate through it and the discharge power in keeper circuit are the direct losses. For ion thruster with power less than 100 W these losses can lead to thruster efficiency decrease on tens of percents.

In Keldysh Research Center two ion thrusters, designed to operate within the power ranges of 50...150 W and 150...500 W, are being investigated. In this paper the results of experimental research of cathode unit laboratory model, based on hollow cathode, which is used in both thrusters, are presented. The main attention is paid to the operation parameters in the range of low powers and flow rates, i.e. conformably to 5-cm ion thruster application. One was investigated the perspective of this cathode unit use both as discharge chamber cathode and neutraliser. It was obtained that this cathode might be utilised in ion
thrusters with power above 80...120 W. The results of comparison of cathodes made from different materials are also presented in the paper.

Requirements to hollow cathodes

The effectiveness of ion thruster operation depends greatly on cathode unit work. Just the electrons, emitted by cathode, input energy to the gas discharge, where propellant atoms ionisation occurs. Presently in ion thrusters the hollow cathodes are used, which provide the best parameters on efficiency and lifetime comparing with other cathode designs.

To heat the cathode to working temperature and to keep it on the mode the certain energy consumption is required. The most energy efficient operation modes of the cathode are realised in that case when its working temperature keeping is provided by the power, taken from the discharge, without using special heater. Besides, usually during cathode operation in the cathode-keeper gap the certain voltage is maintained to provide the discharge with power not higher than 10...20 W. This discharge is the additional source of energy to maintain the hollow cathode of discharge chamber on operation mode and the main power source at neutraliser operation. For ion thrusters of kilowatt power level these energy losses are not important. But with decrease of thruster consumed power and especially in the case of power consumption less than 100 W these mentioned energy expenditures can become appreciable in total power budget of the thruster.

The following requirements can be formulated for the hollow cathodes of ion thrusters:
- low energy expenditures to maintain the cathode working temperature, i.e. operation without additional heating at low discharge powers in discharge chamber and in keeper circuit;
- minimal propellant consumption;
- long lifetime.

The second requirement is critical for neutralisers of ion thrusters. When using hollow cathode as neutraliser the propellant, passing through it, does not produce a thrust, i.e. it is the loss. The appreciable gas flow rate through the cathode leads to decrease of propellant utilisation efficiency and thruster total efficiency.

For ion thrusters with power above 400 W the problem of effective hollow cathodes design is considered to be solved. From literature the cathodes, operating at power consumption less than 10 W\textsuperscript{24} and at xenon flow rates of 30...40 eq.mA\textsuperscript{35}, are known. For example, the expenditures of power and propellant on the operation of UK-10 neutraliser\textsuperscript{4} at power consumption above 400 W leads to decrease of thruster total efficiency on approximately 8% that is quite acceptable. Conformably to this class of thrusters, it has sense to discuss only the problem of providing the stable parameters of the cathodes at long time operation.

At thruster power decrease the requirement to provide the cathodes effective operation becomes more important and at power of about 100 W and less the cathode energy and propellant losses get major concerning realisation of thruster satisfied output parameters. Therefore for 5-cm ion thruster with design range of power consumption between 30 and 150 W the development of hollow cathodes, capable to operate at low energy expenditures and propellant flow rate, is the separate and complex problem, which has not been solved yet.

To estimate the acceptable power (\(N_e\)) and propellant (\(\dot{m}_p\)) losses in cathode-neutraliser it is reasonable to use the following simple relationships:

\[ N_e = N_{\Sigma} - \frac{\eta_c - \eta_e}{\eta_c} ; \quad \dot{m}_p = \dot{m}_e \frac{\eta_m^* - \eta_m}{\eta_m^*} , \]

where \(N_{\Sigma}\) - total energy consumption, \(\eta_c\) - electric efficiency, \(\eta_m^*\) - electric efficiency without taking into account the losses in neutraliser, \(\dot{m}_e\) - total mass flow rate through the thruster, \(\eta_m\) - propellant utilisation efficiency, \(\eta_m^*\) - propellant utilisation efficiency without taking into account the losses in neutraliser.

<table>
<thead>
<tr>
<th>(N_{\Sigma}, W)</th>
<th>50</th>
<th>80</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge chamber cathode</td>
<td>(\dot{m}_c, \text{eq.mA})</td>
<td>36</td>
<td>58</td>
<td>73</td>
<td>108</td>
</tr>
<tr>
<td>(N_d + N_{\text{keep}}, W)</td>
<td>9</td>
<td>14</td>
<td>18</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>Neutraliser</td>
<td>(\dot{m}_n, \text{eq.mA})</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>(N_n, W)</td>
<td>6</td>
<td>10</td>
<td>13</td>
<td>19</td>
<td>25</td>
</tr>
</tbody>
</table>

The acceptable propellant and power losses on neutraliser operation, the discharge power and the maximal flow rate through the cathode of discharge chamber for various operation modes of ion thruster at low power range and \(\eta_e = \eta_m = 0.7, \eta_c = 0.8, I_{FP} = 3000\ s\) are presented in Table 1. It is seen that to provide xenon ion thruster operation with total efficiency of about 50% at power equal to 50 W the requirements to the cathodes should be very strict. The neutraliser
should utilise not more than 5 eq.mA of xenon and not more than 6 W of power and power to discharge chamber should not exceed 9 W.

**Equipment**

In this paper the study of operating parameters of the cathode unit based on hollow cathode of capillary type in the range of low powers and flow rates. The general view of the cathode unit is shown in Figure 1. This cathode unit was used in 5-cm and 10-cm laboratory models of ion thruster.

![Figure 1. The laboratory model of cathode unit (a), niobium cathode (b) and combined cathode (c).](image)

The cathode itself consists of tube from high melting metal, closed by orifice from downstream edge. Inside the tube the ampoule with LaB₆ powder is placed. LaB₆ is used as activating substance to decrease the work function of capillary walls. From the outside of the cathode the spiral of starting heater is reeled up. For cathode ignition it is necessary to heat it within 1.5...2 minutes by starting heater with power of 100...150 W and to pass xenon flow rate of 30 eq.mA through it. From downstream edge of the cathode the keeper is placed. To break down the distance between cathode and keeper the potential of 150...300 V is applied to keeper. After ignition the maintenance of temperature of cathode operation zone (near 1900 K), required for thermal electron emission is occurred by the power, evolved on cathode due to its bombardment by the ions. If this power is insufficient then the additional heating of cathode is required. However, it leads to considerable reduce of thruster electric efficiency.

The estimations indicated that the main channel of energy removal from active zone of cathode is the heat conduction along the cathode tube. The decrease of these losses is possible either by reducing the thickness of the tube wall or by using material with low heat conductivity. However, the reduction of tube walls thickness is limited by the construction strength. To study the influence of heat conduction of the cathode material on its heat losses the cathode unit with three cathodes made from different materials were investigated in this work. Cathodes from molybdenum (λ=110 W/(m·K)), niobium (λ=70 W/(m·K)) (Figure 1b) and combined one (Figure 1c), were tested.

The upstream part of combined cathode was made from niobium and downstream - from molybdenum. These two parts were welded together.

The cathode unit was tested together with 5-cm laboratory model of Kaufman-type ion thruster. Tests were conducted in the vacuum chamber of 1.2 m³ volume. Pumping of the chamber was carried out by turbomolecular pumps with 2.5 m³/s productivity. The pressure inside the chamber was within the range of 2...8·10⁻³ Pa (by xenon) at gas flow rates of 30...140 eq.mA. The propellant could be supplied to the discharge chamber by two channels: through the hollow cathode and through the ring-shaped collector situated on the backplate of the chamber.

The absolute error in measuring the discharge power was ±1 W. The error in measuring power, consuming in the keeper circuit, was about ±3%, that did not exceed ± 0.1 W at powers of 2...3 W. The xenon flow rate was set and measured with the flow regulators of PPT-9 type with maximal xenon flow rate of about 600 eq.mA. The error of flow rate measuring was ± 5% at flow rates above 30 eq.mA. With flow rate reduce the error grew. Therefore, for additional control the indications of vacuumometer were used, assuming that the relation between the gas flow rate and the change of pressure in the vacuum chamber is linear.

**Results**

The comparison of parameters of different cathodes was carried out in two stages. First the minimal discharge power in discharge chamber necessary for stable cathode operation without additional heating was determined.

For the cathode of discharge chamber in small ion thrusters the main limiting factor is the consumed power, not the propellant flow rate through it. As it is seen from Table 1 for ion thrusters with power between 50 and 100 W the total flow rate of xenon through the discharge chamber is 36 - 73 eq.mA. If it is required this entire flow rate can be directed through the cathode without considerable deterioration of thruster parameters. It is more difficult to provide cathode operation without additional heating at such low discharge power values (9 - 18 W).

To investigate the cathodes the following procedure was adopted. After discharge ignition and cathode heater switch off or after xenon flow rate change the mode with power not more than 30...40 W was maintained for 20...30 minutes. Then each 3...5 minutes the power was reduced on 2...5 W until the discharge became unstable. After that the power was increased on 1...2 W. If at this mode the stable operation was observed within 15...20 minutes, then this power was taken as minimal possible. In this experimental series the ion beam was not extracted from the thruster.
The results, obtained when using the cathodes made from various materials are presented in Table 2.

Table 2. Minimal discharge power for cathodes from different materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mo</th>
<th>Nb</th>
<th>Mo+Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{min}, W</td>
<td>36.0</td>
<td>39.0</td>
<td>36.3</td>
</tr>
<tr>
<td>U_{d}, V</td>
<td>580</td>
<td>270</td>
<td>310</td>
</tr>
<tr>
<td>I_{keep}, mA</td>
<td>2.8</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>U_{keep}, V</td>
<td>18.4</td>
<td>22.8</td>
<td>21.2</td>
</tr>
<tr>
<td>I_{keep}, mA</td>
<td>150</td>
<td>81</td>
<td>114</td>
</tr>
</tbody>
</table>

Use of niobium as the cathode material allowed reducing the minimal discharge power on 10 W comparing with the cathode from molybdenum. However, together with it the discharge voltage increased that could negatively influence the cathode lifetime. Besides, lower melting temperature of niobium comparing with molybdenum one (2742 and 2893 K) probably was the reason of closing by melting the cathode orifice, which was occurred in some experiments. Just to avoid the mentioned disadvantages the combined cathode was tested. Niobium cathode tube allowed maintaining of low heat losses and molybdenum orifice provided more reliable cathode operation at less discharge voltages.

In Table 2 the results, obtained at xenon cathode flow rates of 50,...60 eq.mA and total flow rates through the discharge chamber of 90...95 eq.mA, are presented. For all three materials the influence of propellant flow rate on cathodes operation was investigated. As an example in Table 3 the results for niobium cathode are shown. From this Table it is seen that there are no noticeable influence of flow rates on minimal discharge power. The similar results were obtained during the tests of two other cathodes.

Table 3. Discharge parameters with niobium hollow cathode for its operation at minimal discharge power

<table>
<thead>
<tr>
<th>m_2, eq.mA</th>
<th>30</th>
<th>30</th>
<th>30</th>
<th>40</th>
<th>40</th>
<th>60</th>
<th>60</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_3, eq.mA</td>
<td>30</td>
<td>60</td>
<td>90</td>
<td>40</td>
<td>70</td>
<td>60</td>
<td>90</td>
<td>140</td>
</tr>
<tr>
<td>U_{keep}, V</td>
<td>23.8</td>
<td>24.0</td>
<td>24.2</td>
<td>23.6</td>
<td>24.6</td>
<td>22.7</td>
<td>22.8</td>
<td>23.0</td>
</tr>
<tr>
<td>I_{keep}, mA</td>
<td>70</td>
<td>68</td>
<td>68</td>
<td>71</td>
<td>64</td>
<td>79</td>
<td>81</td>
<td>80</td>
</tr>
<tr>
<td>N_{keep}, W</td>
<td>1.7</td>
<td>1.6</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
<td>1.8</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>U_{d}, V</td>
<td>49.5</td>
<td>45.5</td>
<td>44.0</td>
<td>44.5</td>
<td>43.5</td>
<td>42.0</td>
<td>39.0</td>
<td>38.5</td>
</tr>
<tr>
<td>I_{d}, mA</td>
<td>250</td>
<td>290</td>
<td>300</td>
<td>250</td>
<td>250</td>
<td>290</td>
<td>270</td>
<td>280</td>
</tr>
<tr>
<td>N_{min}, W</td>
<td>12</td>
<td>13</td>
<td>13</td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

Therefore, assuming the total expenditures in discharge chamber (N_{min} + N_{keep}) for the work with the combined cathode equal to 14 W, it can be obtained that working without additional heating this cathode unit is able to provide ion thruster operation at the modes with total power of 80 W and above.

The second part of cathodes testing was devoted to determination of minimal power, required for cathode stable operation for the case when keeper plays the main role in discharge maintenance. Such situation is realised when using cathode as neutraliser.

For measurements the cathode unit was installed in discharge chamber of 5-cm laboratory model of ion thruster. All elements of model excluding keeper were at ground potential. The propellant was supplied only through the hollow cathode. Initially, to ignite the discharge the flow rate of 50 eq.mA was supplied. After that it was reduced. During this reducing the dependence of minimal power in discharge, necessary for cathode stable operation without additional heating, from xenon flow rate was measured. The procedure of minimal power determination did not differ from that described earlier. The obtained dependencies for three cathode modifications are presented in Figure 2. Its comparison indicates that in the case of niobium cathode the minimal power is two times less than for molybdenum one. This reduce is especially noticeable at low flow rates. On other side, as it was during discharge chamber cathodes tests, such material substitution led to voltage increase on 3...4 V. The use of combined cathode made it possible slightly to decrease this voltage.

Figure 2. The minimal power in the keeper circuit as a function of xenon flow rate for different cathode materials.
Thus, in conducted experiments the best results were shown by combined cathode. It was selected for further research. To investigate the electron emission capability of this cathode in the range of low flow rates and powers the dependence of current on secondary anode from voltage between cathode unit keeper and this anode was measured. This dependence is shown in Figure 3. It was obtained at cathode flow rate of 10 eq.mA and power of subsidiary discharge between the cathode and the keeper equal to 19 W (31.5 V, 600 mA). From the shown voltage-current characteristic it is seen that even at small values of bias (less than 2 V) the cathode can provide the electron current of about 50 mA. That is enough for neutralisation of beam from ion thruster with power up to 85 W (at $\eta_e = \eta_m = 0.7$, $I_{eq} = 3000$ s). With bias increase up to 10 V the electron current grows up to 90 mA that is sufficient for neutralisation of beam from ion thruster with power up to 135 W.

![Figure 3. The emission characteristic of neutraliser when using the additional anode. $m_n = 10$ eq.mA, $N_e = 19$ W.](image)

Finally the experiment on ion beam neutralisation was conducted. The laboratory model of 5-cm ion thruster generated the ion beam with the current of about 60 mA. The beam was collected by the isolated target, which potential was controlled during the experiment. To neutralise the beam the cathode unit on the base of combined hollow cathode was installed beyond thruster edge. Initially the neutraliser flow rate was set equal to 30 eq.mA. During the experiment it was reduced down to 10 eq.mA. The obtained dependence of minimal power in neutraliser keeper circuit, necessary for its stable operation, from flow rate is presented in Figure 4. The neutraliser keeper was grounded through the ammeter. Throughout the experiment the electron current, emitted by neutraliser, exceeded ion beam current and ranged between 60 and 85 mA. The target potential at operating neutraliser was 3...5 V.

In Figure 4 the calculated relationship between the acceptable expenditures of propellant and power in neutraliser is also shown. The straight line, going from the origin of coordinates, corresponds to increase of these expenditures with thruster total power growth. This function was plotted for ion thruster operation modes, shown in Table 1 ($I_{eq} = 3000$ s, at $\eta_m = \eta_e = 0.7$; $\eta_m^* = \eta_e^* = 0.8$). The crossing point of this line with experimental curve corresponds to thruster power, starting from which it is possible to use this cathode unit as neutraliser without considerable losses of thruster efficiency. For combined cathode this power is 120 W.

![Figure 4. The minimal power in neutraliser keeper circuit as a function of xenon flow rate and the calculated relationship between the acceptable expenditures of propellant and power in neutraliser for the case of $I_{eq} = 3000$ s, at $\eta_m = \eta_e = 0.7$; $\eta_m^* = \eta_e^* = 0.8$. The numbers on the straight line correspond to the total power of ion thruster.](image)

**Conclusion**

In paper the results of experimental investigation of laboratory model of cathode unit based on hollow cathode with activator from $LaB_6$ are presented. The main attention was paid to operation in the range of low powers and flow rates. This unit operation both as the main cathode in discharge chamber of ion thruster and neutraliser was studied. The parameters of three cathodes made from different materials were compared.

During the tests of cathode unit as discharge chamber cathode of 5-cm laboratory model of ion thruster it was obtained that this cathode is able to operate without additional heating starting from discharge chamber power equal to 14 W. This corresponds to total power of ion thruster of about 80 W.

The tests of this cathode as neutraliser indicated that it could operate at the modes with power consumption in keeper circuit of about 15 W at gas flow rate between 10 and 30 eq.mA. Such losses in neutraliser are considered to be acceptable for ion thruster with power above 120 W.

The comparison of cathodes, made from different materials, indicated that the main part of heat losses in cathode was conditioned by heat conduction along the cathode tube. The choice of
niobium as cathode material made it possible to decrease the level of minimal discharge power, necessary for cathode stable operation, in two times comparing with molybdenum. The use of combined cathode, the upstream part of which was made from niobium and downstream – from molybdenum, allowed increasing the operation reliability comparing with niobium cathode at low heat losses.

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References


