THE DEVELOPMENT INVESTIGATION OF THE CATHODE-COMPENSATOR OF STATIONARY PLASMA THRUSTERS FOR DISCHARGE CURRENTS OF TO 50 A
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ABSTRACT

Current status and future of space technology place more strict requirements on propulsion systems to provide for transportation, orbit control and attitude maintenance.

Currently the most promising technology among electric thrusters are Hall thrusters SPT and TAL and plasma-ion thrusters PIT, which have long life and high thrust/energy and dynamic parameters.

Any thrusters development effort significantly depends upon a cathode-neutraliser development; cathode operates under the most hard conditions and this is the component, which is currently determining the thruster life.

For powerful thrusters — 5—30 kW, “Fakel” completed several scientific research works targeted on development of cathode-neutraliser (hereinafter cathode) for 50 A discharge current.

Cathode is protected by Russian Federation patent 2012948, Europatent 0464383B1 and US patent 5359254.

INTRODUCTION

Cathode is used to neutralize the ion flow and to close the electric circuit in SPT and TAL thrusters and to generate discharge in volumetric ionization chamber (PIT).

“Fakel” had developed and qualified cathodes for many years and had accumulated large experience in this area. Cathodes for up to 5 A current have been developed and operated with modules M76 and M100 (KN-3 and KE-5 cathodes), which are currently flown with SPT70 and SPT100.[1]

CATHODE OPERATION

Cathodes developed at “Fakel”, are gas discharge electron sources on hollow cathode principle. Similar to 5 A cathodes, 50 A cathodes are heated units and operate as follows:

Propellant (inert gas) is supplied through hollow cathode (thermal emitter), thus providing required pressure inside cathode.

To start cathode, emitter is heated to efficient thermal emission temperature by special heater. Ignitor switches on and discharge appears between cathode and ignitor.

This discharge initiates main discharge cathode–anode. Heater and ignitor are turned off and cathode continues operation automatically.

CATHODE DESIGN

Basic design of 50 A cathode (K50–1) employs technical solutions, which already prove positive during KN–3 and KE–5 cathodes development.

Another two models of 50 A cathode — K50–2 and K50–3 have been developed on K50–1 basis.

K50 design is shown in Fig. 1.

Fig.1 Design of K50–1 cathode
All three models (K50-1, K50-2, K50-3) have the following components: 1 - emitter, 2 - heater, 3 - getter, 4 - ignitor, 5 - gas and electric connects, 6 - gas line.

Principal element of every model is thermal emitter (1).

Thermal emitter of K50-1 cathode (Fig. 1) is a tablet with cylindrical passage for propellant flow. Thermal emitter of this cathode is made of highly emissive material - lanthanum hexaboride (LaB$_6$).

Thermal emitter of K50-2 cathode (Fig. 2) is a cylindrical tablet with internal cavity. Different from K50-1 and K50-3 cathodes, K50-2 is made of porous tungsten saturated with activator. Thermal emitter of K50-3 cathode (Fig. 3) is a hollow cylinder with n-shaped grooves for propellant supply. At the outlet of thermal emitter housing a 1.0 mm orifice is mounted. Thermal emitter of this cathode is made of highly emissive material - lanthanum hexaboride with alloying additions. Due to additions such thermal emitter has better emission and strength parameters and lower sputtering and evaporation.

**EXPERIMENTAL CONDITIONS**

Cathode K50-1, K50-2 and K50-3 have been tested in vacuum facility, providing pressure inside vacuum tank of $2 \times 10^{-4} \text{ mm Hg (by air)}$ at flow rate in cathode up to 1 mg/s.

Xenon was used as a propellant. Flow rate in cathode was measured by thermal flow meters. Power was provided by facility power supply at ripple factor no greater than 6%. During testing electrical parameters were acquired by standard methods and instruments.

While testing cathodes independently, a target anode was used as an ion flow simulator, placed at ~15 mm from cathode edge.

**EXPERIMENTAL INVESTIGATION OF CATHODES**

The following major directions were set for investigation:

- investigation of performance and optimizing of cathode design (parametrical test);
- life test;
- thermal design development

**PARAMETRICAL TEST**

The completed cycle of parametrical test demonstrated operation of all three models (K50-1, K50-2 and K50-3).

Start-up preparation period of cold thruster was 130-180 s at heater power 180-220 W.

To optimize cathode performance, cathode parameters have been investigated at different propellant flow rate (mk) and discharge current (id).

Fig. 4, 5, 6, 7, 8, 9 show volt-ampere curves (VAC) at xenon flow rate 0.9, 0.7, 0.5 and 0.3 mg/s and volt-flow rate curves (VFC) at different discharge current from 5 to 60 A.

![Fig. 2 Volt-ampere chart for K50-1 cathode (mk=0.7 mg/s)](image)

![Fig. 3 Volt-ampere chart for K50-2 cathode](image)
Above charts show that cathode VAC at flow rate 0.5–0.9 mg/s demonstrate less steep curvature and significantly lower discharge voltage (Ud). VAC at 0.3 mg/s demonstrates higher Ud and discharge tends to go out at this flow rate. VFC are steeply dropping till 0.6–0.7 mg/s flow rate level.

This work allowed to optimize and select the flow rate of xenon for all three models — 0.7 mg/s, which provides stable automatic mode within discharge current range from 10 to 60 A. VAC of each model at 0.7 mg/s are pictured in Fig. 8.

Minimal discharge current, providing stable cathode operation in automatic mode, was 10 A.
LIFE

Life test completed same as parametrical by diode schematic (target operation) at Id = 50 A and mk = 0.7 mg/s.

High cathode performance stability had been demonstrated. Fig. 11, 12 and 13 show cathode VAC during life test.

![Graph](image1)

Fig. 9 Volt-ampere curve of K50-1 cathode during life test

![Graph](image2)

Fig. 10 Volt-ampere curve of K50-2 cathode during life test

![Graph](image3)

Fig. 11 Volt-ampere curve of K50-3 cathode during life test

Test indicated that thermal emitter is a life critical components of cathode. Life testing also revealed that stable automatic mode boundary moved to greater flow rate zone due to thermal emitter erosion and evaporation which changed geometry of hollow cathode and due to gas pressure drop within discharge zone. Total accumulated operation time on K50-1 cathode was 2500 hours. K50-2 and K50-3 life test duration was 2700 hours on K50-2 and 1972 hours on K50-3.

Thermal emitter wear extent was below 40% within life test duration. It is supposed that life of K50-2 cathode would amount 5-6 thousand hours.

During investigation of structure condition of K50-3 cathode after life testing no change of geometry of inner cavity of thermal emitter and no erosion have been observed.

Presumably, K50-3 life at 50 A would be 10000 hours.

K50-2 and K50-3 tests demonstrated that at discharge current Id = 45 A cathode life would amount 10000 hours.

LIFE IMPROVEMENT METHODS

Modular cathode development attempt was made to provide for over 10000 hour life, which is to improve life at least by four times.

4K cathode is an assembly of four capsules with emitters of K50-1 type on single plate. All four capsules have common heater and housing.
4K cathode completed parametrical and life test under conditions, identical to K50 test conditions. Power of heater required for reliable start-up within 4 - 5 min was determined in test.

Minimal discharge current of 4K cathode, providing stable automatic mode operation, was 10 A.

VAC and VFC of one of four cathode channels are demonstrated in Fig. 12 and 13.

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Also thermal condition of cathode during operation with thruster was calculated. Calculation and experiments indicated:
1. In every operation mode of cathode with thruster, thermal interface of cathode housing with thruster mounting plate does not affect thermal condition of cathode;
2. During independent operation of cathode (at target) in vacuum chamber maximal temperature was observed at front portion of thermal emitter from the side of diaphragm - 1300 - 1500°C, temperature of side portion of start-up electrode varied gradually from 900°C up to 300°C.
3. Temperature of soldered joint was about 500°C, that provides for operational state of principal cathode assembly.

CONCLUSION

In process of study of cathode for 50 A discharge current, high stability of K50 - 1, K50 - 2, K50 - 3 and 4K performance had been demonstrated. The obtained performance parameters of cathodes in comparison with KN - 3 cathode performance are summarized in Table 1.
Comparison of performance data of studied cathodes indicates that cathode with tungsten impregnated thermal emitter provides slightly less electron cost. Diaphragmed cathodes can operate at lower flow rate.

Obtained life data are summarized in Table 2.

Results of life test allow to conclude that developed cathodes K50-1, K50-2, K50-3 and 4K provide for required discharge parameters at flow rate below 0.7 mg/s and bearing in mind higher unification of specific components and their qualification in cathode KN-3 can be recommended as a SPT and PIT component and as a material for experimental works and qualification.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KN-3</th>
<th>K50</th>
<th>4K</th>
<th>4K</th>
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</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>xenon</td>
<td>xenon</td>
<td>xenon</td>
<td></td>
</tr>
<tr>
<td>Propellant flow rate, mg/s</td>
<td>0.3-0.5</td>
<td>0.4-0.7</td>
<td>0.4-0.7*</td>
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<tr>
<td>Discharge current, A</td>
<td>1.2-5.0</td>
<td>10-60</td>
<td>10-60</td>
<td></td>
</tr>
<tr>
<td>Start-up period, s</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Start-up power consumption, W</td>
<td>80</td>
<td>80</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Cost of electron, W/A</td>
<td>32</td>
<td>250</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Overall dimensions, mm</td>
<td>70x55x34</td>
<td>75x29x34</td>
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<td></td>
</tr>
</tbody>
</table>

* flow rate in each channel

### Table 2

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Life, hour</th>
<th>Calculated life, hour</th>
<th>Cycle number</th>
<th>Calculated cycle number</th>
</tr>
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<tbody>
<tr>
<td>K50-1</td>
<td>2600</td>
<td>4000</td>
<td>1020</td>
<td>10^3</td>
</tr>
<tr>
<td>K50-2</td>
<td>2550</td>
<td>4000</td>
<td>40</td>
<td>10^3</td>
</tr>
<tr>
<td>K50-3</td>
<td>1972</td>
<td>4000</td>
<td>63</td>
<td>10^4</td>
</tr>
<tr>
<td>4K</td>
<td>4000</td>
<td>18000</td>
<td>250</td>
<td>10^5</td>
</tr>
</tbody>
</table>

Results of life test allow to conclude that developed cathodes K50-1, K50-2, K50-3 and 4K provide for required discharge parameters at flow rate below 0.7 mg/s and bearing in mind higher unification of specific components and their qualification in cathode KN-3 can be recommended as a SPT and PIT component and as a material for experimental works and qualification.

### Literature