HIGH EMISSION SELFHEATED ARC DISCHARGE
HOLLOW CATHODES

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Abstract

The given message presents the experience of high emission selfheated arc discharge cathodes for space and ground engineering, conducted by author and his employees from 1970 for present time in Electric Propulsion Rocket Engines (ERE) Laboratory of Kharkov Aviation Institute (transformed in 1994 in Scientifical and Technological Centre of Space Power and Engines of Kharkov Aviation Institute (STC SPE KhAI).

The series of high emission selfheated arc discharge hollow cathodes (HC) containing the film thermoemetters, working with xenon and argon, possessing high power and gas efficiency, long life-time, small pre-start preparation and intended for various technical applications is developed during this period.

The analysis of HC of given type theoretical researches results is carried out: physical and mathematical models, techniques and results of account. The stand base of SCT SPE KhAI intended for experimental researches and experimantal design improvement of HC eighther independently or in structure of ERE of various types and technological installations is described.

Some results of experimental researches, choosing of emitter material, erosion characteristics, start processes are represented.

The areas of possible applications and examples of practical use of 5 main typesize of developed HC and their main parameters present.

All listed cathodes are developed by industry and can be made by enterprises of the Ukraine.

Introduction

One of main problems, arising at development and manufacturing of majority of ERE (arc engines(EAE), stationary plasma thrusters (SPT), anode layer thrusters (ALT), ion engines (IE), magnetoplasmadynamic thrusters (MPDT) etc.) is the creation of arc discharge HC entering in structures of these engines, as far as the cathode unit determines in any respects the reliability, durability and dynamic ERE characteristic as a whole and influences appreciably on its gas and power efficiency.

The arc discharge devices are applied in space engineering in systems of flying vehicles differential electrical charge active control as well as in various

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geophysical scientific experiments. HC are applied in all listed modern devises because of series of their advantages. HC arc discharge has also received the wide distribution in ground plasmaion vacuum technological installations for drawing of films, smelting-on, ion-beam processing, etc.

Despite wide spectrum of applications the following common requirements submit to the arc discharge HC:

- high life-time (from hundreds to tens of thousands of hours);
- low energy consumption - about 10 W/A;
- small gas consumption - to 100 electron/atom;
- high reliability of work as during the start, as in steady regime in appropriate working environment in structure of engine or technological installation (probability of nofailure to 0.9999 for objects of space engineering).

Series of cases of practical application puts forward the additional specific requirements. For example: short start time (from several milliseconds to units of seconds) and large number of ignitions (1000-10000000) is submitted to HC of spacecraft orientation systems ERE and of technological installations.

The high emission selfheated arc discharge hollow catodes which are developed in STC SPE correspond to majority of bore requirements.

The series of theoretical and test of researches of working processes are conducted, the experimental base is created and the improvement and tests of HC as independently as in structure of ERE of various types and technological installations are executed during these cathodes development.

The brief description of these work is caused below.

The brief characteristics of researched and developed object

The developed and investigated cathodes are film cathodes. Their high stationary parameters are reached by application of insertions from high emission film thermionic emitters in active zone of cathode, or by introducing of emission activizing additives in plasmagenerate gas to formate the film on working surface of cathode. The cathodes are gas-fed. Operational gas - xenon or argon is supplied directly through the working cavity of cathode. The cathodes are mainly orificed. Their high gas efficiency is reached by applying of narrows on tips of cathodes (orifices). The cathodes are completely selfheated, i.e. as their heating to temperatures necessery for switching on, as their keeping in required temperature regime is provided by own discharge without application of special heaters. Therefore, it is provided not only small power consumption, but also short time of switching on of cathodes (less 1 sec.), increasing of reliability, lifetime; etc.

The physical and mathematical models and account results brief description

The functioning of activated film hollow cathodes is a result of difficult and interconnected processes. The discharge current value sets the scale of plasma components concentration and, in turn, depends on them. The activator state on the surface is determined by its temperature. At given current depends on the
the latter, etc. So the processes of various and difficult physical natures take place in the volume and on the surface of HC.

Making the models of processes the various authors allocated as object of simulation any group of processes taking into account the rest of them using of experimental data or valuations. The processes of plasma components flow in HC were stimulated in works [1 - 4]. Here some components of impulse density total time derivative in two-component plasma dynamics equations were neglected. Our valuations show that in the case of intensive ion-making such simplification results into considerable distortions.

The processes of activator dynamics on the HC surface and its influence on emission ability were investigated in reasonable details in works [5, 6].

The assumption about maxwellian electron energy distribution is allowable at calculation of average total spectrum characteristics. However, the determination by maxwellian distribution of electron return current and inelastic collisions cross-section values connected with high-energy (the most nonequilibrium) spectrum part features can result in appreciable errors. The theoretical analysis of electron energy distribution was made in different works with different degree of completeness. The electron kinetics is rather in detail considered in [7] with account of ionization and excitation but without account of e-e collisions which are main kinetic factor in the high current case. The latters were taken into account in work [8-10] but with record of collision integral only in estimated small distortion form.

The surface temperature distribution in HC was calculated in [11-14]. Complete enough selfagreed models of HC processes were received for high-pressure, about atmospheric, discharges [15], or for tubular cathodes [16, 17], or for HC without activator [18]. The local discharge parameters were calculated for tubular HC in [19, 20] but temperature here was considered the same for ions and electrons.

So the necessity of creation of as possible utmost self-agreed model of HC processes has arisen.

The model is developed includes the following submodels.

The submodel of the processes in main hollow volume describes the electrons and ions dynamics in the discharge volume by the method of local thermodynamics balance with account of ionization, diffusion and agility, electron emission, plasma components flow to the surface.

The submodel of the processes beside the exhaust orifice describes the plasma components behaviour near the cathod orifice, where the subsonic effects are not neglected.

The submodel of the electrons energy spectrum is devoted to calculation of the electrons energy distribution function with account of electron emission, e-e collisions, energy losses on ionization and excitation, electron flow through the orifice and to the surface.

The energy distribution function is using for the calculation of the average for spectrum electron characteristics.

The submodel of activator dynamics describes the activator film state on the surface accounting its evaporations, migrations and influence on the surface emission ability.
The submodel of Langmuir layer is devoted to the determination of the influence of discharge electric field and electrons quant reflection on the emission current value.

The submodel of the surface temperature distribution uses the quasi-one-dimensional heat conduction equation for the calculation of the temperature distribution forming by emission cooling, heat radiation from the external surface, surface heating by excited atoms radiation and ion bombardment.

The technique of account and Pascal-program created on the basis of model permit to calculate integrated and the local discharge parameters. The comparison with experimental data in range of currents 2 - 70 A and of gas consumption 0.4 - 0.8 mg/s has shown the maximal discrepancy about 1 % in voltage and about 5 % in surface temperatures.

The model structure and analysis of calculation results are shown in more details in [21].

The detaility of accounts using developed technique permits to apply their results also for analysis of cathode erosion as it was made in the work that is submitted in the report IEPC-95-210 of present conference.

The integral balances model [8] also was developed. The last does not permit to calculate the discharge local parameters. But its use in the calculations required only the discharge common values - gas consumption, voltage, power, - permits considerably reduce the time of accounts.

The stand base, methods and hardware of mesurements.

The experimental base STC SPE KhAl consists of three stands, enabling to conduct the complex improvement practically of all modern types ERE (EAE, SPT, ALT. IF, MPDT). The researches and improvement of developed cathodes in structure of these engines were conducted on these stands. The independent researches and tests of HC were conducted on two specialized installations pumping-off by turbo-molecular pumps and ensuring vacuum of order 0.001 - 0.0001 Pa. The stands are equipped by automated system basing on personal computer of type IBM PC/AT and microprocessor controllers. Hardware and software of system provide the start and steady work of testing device (ERE or HC) in automatic regime, tax, primary processing, representation and archiving of measuring information. The measurements were conducted with use of standard devices and methods (currents, voltage, pressure, temperature), as well as of specially developed techniques and instruments. The latter are the methods and hardware of measurement of gas microcharges, plasma parameters, spectra of fluctuations of power supply circuits and plasma electromagnetic radiation, transients while ignition, etc. The methods developed by us for cathode erosion rate determination on the basis of quantitative spectral analysis take the specific location on complexity and gravity for HC research and development among them. They are the out-of-contact methods of diagnostics, permit to receive the gas-fed HC characteristics directly during experiments execution in steady regime (report IEPC-95-208 of given conference), as well as at start (IEPC-95-209).

The cathodes were tested also in structure of four technological installations being present in STC SPE KhAl: in CDM, in installation for ion arcing, in
device for ion-beam etching (cuttering) and in installation for smelting-on in vacuum.

The choosing of emitter material

It is known, relation of work function \( \varphi \) to activation heat (connection energy) \( q \), i.e. \( \varphi/q \) [22], is widely used for valuation of cathode material fitness for manufacturing of emission engineering vacuum electron devices cathodes. Our experimental researches have shown that criterion \( \varphi/q \) does not work for valuation of emitter qualities arc discharge HC conditions. It is found, that more the suitable criterion, which evaluated simultaneously the issuing ability of emitter and its erosion resistance in HC, is the adduced rate of emitter destruction in discharge cavity:

\[
K_{er} = \frac{\Delta m}{\tau \cdot I} \cdot \frac{kg}{C}
\]

where \( \Delta m, kg \) - cathode mass decrease;
\( \tau, s \) - test time;
\( I, A \) - discharge current.

We were conduct the complex researches of film thermoemitters of three types:
1) from refractory materials (tungsten, tungsten-renium alloys), including barium in various combination (with aluminium, scandium, tungsten), impregnated, as well as pressed;
2) from zirconium carbid with tungsten (ZrC-W) of various percentage structures;
3) from yttrium-containing materials on bases of tungsten and tungsten-renium alloy with adding of yttrium and its alloys;
4) lantanum hexaborid (LaB\(_6\)) - pressed, hot-pressed, received by zoned smeltinc method, including the granulated.

The work of these emitters in identical conditions of arc discharge in structure of HC with spherical work cavity diameter of 2.5 mm, currents 1-10 A, xenon consumption 0.2-0.3 mg/s, with identical heat transimion. The results of researches are shown in Table 1.

Table 1

<table>
<thead>
<tr>
<th>N</th>
<th>Emitter material</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \varphi, eV )</td>
<td>( q, eV )</td>
</tr>
<tr>
<td>----</td>
<td>------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>1</td>
<td>W+Re-B(_2)</td>
<td>2.0 - 2.2</td>
</tr>
<tr>
<td>2</td>
<td>LaB(_6)</td>
<td>2.6 - 2.8</td>
</tr>
<tr>
<td>3</td>
<td>W+Re-Y</td>
<td>3.0 - 3.2</td>
</tr>
<tr>
<td>4</td>
<td>ZrC-W</td>
<td>3.5 - 3.7</td>
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</table>
One can see from Table 1 that tungsten-barium emitters, developed by industries for vacuum electron devices, have appeared the most effective in conditions of arc HC work. They are characterized by high criteria of quality, low working temperature, ability to support discharge channel geometry and HC parameters practically by constant during whole life-time, large stock of active substance (life-time), satisfactory operational properties and adaptability to manufacture.

The developed cathodes main type-sizes and the examples of their applications

The Table 2 submits the main type-sizes and characteristics of developed cathodes.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>discharge current, A</td>
<td>2-3</td>
<td>4-5</td>
<td>10</td>
<td>50</td>
<td>500-800</td>
</tr>
<tr>
<td>discharge voltage, V</td>
<td>17-18</td>
<td>16-17</td>
<td>14-15</td>
<td>9-11</td>
<td>15-20</td>
</tr>
<tr>
<td>life-time, hrs</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>5000-6000</td>
<td>1000</td>
</tr>
<tr>
<td>gas consumption, mg/s</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td>0.8</td>
<td>3-4</td>
</tr>
<tr>
<td>start-time, s</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

The cathodes of 1-4 types may be applied in electric propulsion rocket engines of orbit correction and orientation systems of spacecrafts, as well as in structure of spacecraft differential electric charge control systems. The cathodes of these types are successfully used in ground plasma technological installations which produce protective and decorative covers on details of various purposes. The cathodes of 5 type are applied in EAE and SPT, as well as in vacuum smelting-on installations.

Hollow cathodes for ERE

The work processes, calculation methods and accounts results for various design of ERE HC are in detail described in [8, 23-25].

The non-incandescent HC (БК-1, БК-2, БК-3, БК-4, БК-5, БК-6, БК-7, БК-8 and KM-290) developed by us in 1988-1994 were used in Fakel Experimental and Design Bureau (Russia) while the creation of experimental engines SPT-70, SPT-100, SPT-140, SPT-200 and SPT-290.

The complex test improvement of power plant based on SPT-100 engine and БК-4 (the 2-nd type-size) cathode, including 5-days non-stop tests (about 120 hrs) and 2000 of engine ignitions was provided in STC SPE KhAI in 1993. The power-and xenon-supply and control system developed by us ensured reliability of all 2000 ignitions of SPT-100 with БК-4 HC with the achieving of 6-65 mN thrust.
(about 80% of nominal value of 80 mN for this thruster) while each of ignition during 3 - 5 ms. These long tests have shown that the ignition system and BK-4 cathode developed by us will ensure the SPT-100 engine life-time not less than 4000.0 hrs with number of ignitions not less than 3000.

The experience obtained and recommendation developed by us were used while the creation of non-incandescent cathode (the 2-nd type-size) CT-160 for 4 kW Hall-Type (SPT) Electric Thruster T-160 in the Scientific-Research Institute of Thermal Processes (Russia) [26].

The voltage and xenon charge dependence on current are done for the comparison in Fig. 1-a and 2-a, while the activator mass remove rate dependence on the current and xenon charge - in Fig. 1-b and 2-b. These dependencies are obtained by the spectra method (report IEPC-95-208 of present conference) for BK-4 and CT-160 cathodes. The tungsten orificed plates of these cathodes had very small rate of changing (about 10^{-14} \text{ kg/s}) and practically not limit the cathode life-time.

![Fig. 1-a.](image1)

![Fig. 1-b.](image2)

![Fig. 2-a.](image3)

![Fig. 2-b.](image4)

The measurements of mass remove rates have demonstrated that KM-290 cathode (the 4-th type-size) intended for SPT-290 thruster has the activator storage counted for more than 10000 hrs life-time. It is limited by orifice firmness. The KM-290 cathode tungsten orifice size changing obtained by long (2500 hrs) test for 50 A current and 0.8 mg/s xenon charge and by accounts (IEPC-95-210) are represented on Fig. 3. The valuation made on the base of these data show the forecast lif-time of KM-290 cathode of not less than 5000-6000 hrs.
Hollow cathodes for plasma technological installations

The prototype of protective and decorative covers vacuum drawing module (CDM) is created basing on 3-4 type-size of SH HC developed in STC SPE KhAI (see Table 1) for currents 10 - 50 A. CDM represents the complex which consists of selfheating HC, ignition system, power- and gas supply system, control system, placed into vacuum system for maintenance of some or another processes.

In comparison with existing covers vacuum drawing devices in which refractory tubular HC are used, the CDM developed by us basing on high emission SH HC has following advantages:
- simplified sequence (routine) and reduced duration of ignition;
- reduced power consumption in steady regimes;
- increased resource as for continious work time, as for number of ignitions;
- smaller cost of development, manufacturing and operation.

The experience we have and valuations we've conduct show on economic expediency of developed CDM use in following vacuum technological processes of covers drawing:
- heat isolating films which are obstacle for infra-red radiation (for glasses in windows of buildings of houses, etc.);
- covers on optical devices;
- photo-electric converters films;
- corrosion proofs sheetings on details of machines and building materials (equipment for chemical industry);
- strengthening and antifriction covers;
- decorative covers for goods of mass consumption (crockary, bijouterie, glass package, packing materials, etc.).

It was already marked that the film emitters work inside the arc discharge HC has the series of features in comparison with work in vacuum. But the experience of their operation inside the arc discharge HC of the 4-th and 5-th type-size in structure of technological installation [27] shows also how much the top allowable work border of the impregnated tungsten emitters can be removed due to the producing current in comparison with pure vacuum conditions.

It is known that hot HC arc discharge is widely used as technological tool for execution of processes of resmelting, smelting-on, soldering, evaporation and heat treatment of metals in vacuum. The rigid requirements are submitted to such cathodes material: the resistance to poisoning by processable metals steams, allocating gases at high work temperature (more than 2000 K) and low...
working vacuum (1 - 0.1 Pa), resistance on air while frequent revacuuming, adaptability to manufacture, etc.

The conventional HC material in these installations is tungsten (less often tantalum).

The purpose of work executed by us together with employees of Rostov-na-Donu Agriculture Engineering Institute is the research of possibility and efficiency of impregnated W-Ba HC in arc installations for welding and smelting-on in vacuum.

The researches were conducted in discharge currents range of 50 - 500 A, cathode discharge current density 50-300 A/cm², voltage 10-30 V, argon supply 0.05-0.3 l/min.

The following materials were chosen for comparative analysis: tungsten, tantalum, lantanum hexaborid, tungsten-barium (impregnated). The HC made from listed materials were manufactured as cylindrical tubes for the comparative researches with identical sizes: internal diameter -6 mm, thickness of wall - 1 mm, length of cathode - 30 mm. Orificed plates were not used. The system of self-heating ignition was applied.

The decrease of discharge voltage has appeared the most significant in discharge with impregnated W-Ba cathodes (Fig.4) that can be explained by reduction of impregnated cathode electron work function down to 2.1 eV in comparison with 4.54 eV for pure W. The decrease of work function causes also to reduction of capacity necessary for maintenance of cathode processes that is accompanied by cathode temperature decrease from 2300-2500 K down to 1500 - 1800 K for impregnated HC.

Fig. 4. The voltage-current dependance for different materials HC arc discharge: 1 - W; 2 - Ta; 3 - LaB₆; 4 - W-Ba.

Fig. 5. The efficiency-current dependance for different materials HC arc discharge: 1 - W; 2 - Ta; 3 - LaB₆; 4 - W-Ba.

Except the reduction (2-3 times) of energy allocated on cathode, its relative redistribution in discharge other parts takes place such as its anode allocation is increased. It results in discharge efficiency increase from 0.75 for W to 0.90 for W-Ba cathode (Fig.5). The other materials investigated take the intermediate places.
The electrical and power parameters of lantanum hexaborid cathode are the most close to impregnated W-Ba cathode parameters. However, the resistance tests have shown that lantanum hexaborid cathode is more inclined to destruction with current more than 300-500 A. It's because it was removed from tests after some hours.

The impregnated W-Ba HC long tests in technological installations directly for metals smelting-on and welding have shown their total fitness for work in such conditions. For example, one of the cathodes have operated in installation for smelting-on of fast cutting steel P-18 over 300 hours without changes of the properties and it is not yet the limit of its life-time.

The specific speeds of losses of active substances by investigated W-Ba cathodes in ranges of investigated parameters are (0.7-1.8)*10^-12 kg/Cl.

The cathode resistance to poisoning by steams of processable materials was not specially investigated, but it is obviously that it is high enough taking into consideration that fact, that the discharge burned on liquid bath of such materials as stellite ВЗК ВХН-1, steel Р-18, 30 ХГСА and X18H9T, titanium, copper, bronze BРХ0.8 while the long tests during 100-300 hour.

It is possible insignificant inclusion of barium into the processible material while the smelting it by impregnated cathode discharge that in the most of cases is not only allowable but also positive fact.

Taking into account the high efficiency and voltage decrease for impregnated W-Ba catode, the high enough such cathode resistance to poisoning by metals steams, small speed of active substance removing, life-time value of hundreds of hours, as well as possibility of repeated regeneration of cathode issuing properties by the reimpregnating, it is possible to recommend it for application instead of cathodes from refractory materials in installations for smelting, welding, smelting-on, heat treatment and evaporation of materials in vacuum.

References


