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HEATER OF THE HOLLOW CATHODE WITH LaB_6 FOR OPERATION WITH HALL THRUSTERS

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Abstract. The article presents the results of design, development and laboratory tests at Space Electric Thruster Systems (Dnipro, Ukraine) of a hollow filament cathode based on lanthanum hexaboride (LaB6). The cathode is designed for joint operation with Hall thrusters of various input powers. The emitter material LaB_6 is very promising, because has a high emissivity and low ionization potential. However, to realize all the advantages of considerate material, it is necessary to provide a sufficiently high operating temperature (1400 ° C). Therefore, when developing the filament cathode, special attention was focused on the development and research of one of the key elements of the filament cathode - the heater. Thermal calculations of the hollow cathode were carried out when it was heated with a heater, as well as when the cathode was operating in auto mode. The results of thermal calculations made it possible to identify the shortcomings of the cathode structure and parameters and determine the ways to eliminate them. Laboratory tests of a cathode with a different number of heater thermal shields have been carried out. The results obtained made it possible to provide the required operating temperature of the cathode emitter with a minimum number of heat shields. Laboratory tests of the cathode were carried out both in diode mode (to the external anode) and in conjunction with the ST-25 Hall thruster developed by the company. In the course of laboratory tests of the cathode, the power supplies for the discharge, the keeper, and the heater, which are components of the power processing unit of the Hall thruster, were used. In the frame of experimental studies, a cyclogram of the cathode starting process was obtained, which is necessary to form the Hall thruster starting sequence. The tests carried out confirmed the correctness of the selected technical solutions for the choice of the cathode and its heater. The developed cathode can be used both in low-power (up to 200 W) Hall thrusters and in thrusters with increased input power (up to 5 kW).

Keywords: PREHEATED HOLLOW CATHODE, LANTHANUM HEXABORIDE, CATHODE HEATER, HEAT SHIELDS, HEAT CALCULATION, LABORATORY TESTING, HALL THRUSTER.

НАГРЕВАТЕЛЬ ПОЛОГО КАТОДА С LaB_6 ДЛЯ РАБОТЫ С ХОЛЛОВСКИМИ ДВИГАТЕЛЯМИ

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Аннотация. В статье представлены результаты разработки и лабораторных испытаний в компании Space Electric Thruster Systems (г. Днепр, Украина) накального полого катода на базе гексаборида лантана (LaB_6). Катод предназначен для работы совместно с Холловскими двигателями различной мощности. Материал эмиттера LaB_6 является весьма перспективным, т.к. обладает высокой эмиссионной способностью и низким потенциалом ионизации. Однако, для реализации всех достоинств рассматриваемого материала необходимо обеспечить достаточно высокую рабочую температуру (1400°C). Поэтому при разработке накального катода особое внимание было сконцентрировано на разработке и исследовании одного из ключевых элементов накального катода - нагревателя. Были проведены тепловые расчеты полого катода при его нагреве с помощью нагревателя, а также при работе катода в авторежиме. Результаты тепловых расчетов позволили выявить недостатки конструкции катода и определить пути их устранения. Проведены лабораторные испытания катода с различным числом тепловых экранов нагревателя. Полученные результаты позволили обеспечить требуемую рабочую температуру эмиттера катода при минимальном числе тепловых экранов. Лабораторные испытания катода были проведены как

в диодном режиме (на внешний анод), так и совместно с Холловским двигателем ST-25, разработанным в компании. В ходе лабораторных испытаний катода использовались источники электропитания разряда, кипера и нагревателя, входящие в состав системы электропитания Холловского двигателя. При проведения экспериментальных исследований была получена циклограмма процесса запуска катода, которая необходима для формирования циклограммы запуска двигателя. Проведенные испытания подтвердили правильность выбранных технических решений по выбору конструкции катода и его нагревателя. Разработанный катод может использоваться как в маломощных (до 200 Вт) Холловских двигателях, так и в двигателях повышенной мощности (до 5 кВт).
Ключевые слова: НАКАЛЬНЫЙ ПОЛЫЙ КАТОД, ГЕКСАБОРИД ЛАНТАНА, НАГРЕВАТЕЛЬ КАТОДА, ТЕПОВЫЕ ЭКРАНЫ, ТЕПЛОВЫЕ РАСЧЕТЫ, ЛАБОРАТОРНЫЕ ИСПЫТАНИЯ, ХОЛЛОВСКИЙ ДВИГАТЕЛЬ.

НАГРІВАЧ ПОЛОГО КАТОДУ З LaB_6 ДЛЯ РОБОТИ З ХОЛЛОВСКИМИ ДВИГУНАМИ

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Анотація. У статті представлені результати розробки та лабораторних випробувань в компанії Space Electric Thruster Systems (м. Дніпро, Україна) накального полого катоду на базі гексабориду лантану (LaB_6). Катод призначений для роботи спільно з холловскими двигунами різної питомої потужності. Матеріал емітеру LaB_6 є досить перспективним, оскільки має високу емісійну властивість і низький потенціал іонізації. Однак, для реалізації всіх його переваг необхідно забезпечити достатньо вимоку робочу температуру (1400°С). Ось чому під час розробки накального катоду особливу увагу було сконцентровано на розробці та дослідженнях одного з ключових елементів накального катоду – нагрівача. Були проведені теплові розрахунки полого катоду при його нагріві за допомогою нагрівача, а також при роботі катоду в авторежимі. Результати теплових розрахунків дозволили виявити недоліки конструкції катоду та визначити шляхи їх усунення. Проведено лабораторні дослідження катоду з різною кількістю теплових екранів нагрівача. Отримані результати дозволили забезпечити потрібну робочу температуру емітеру катоду при мінімальній кількості теплових екранів. Лабораторні випробування катоду були проведені як в діодному режимі (на зовнішній анод), так і спільно з Холловским двигуном ST-25, розробленим в компанії. Впродовж лабораторних досліджень катоду використовувались джерела електроживлення розряду, кіперу та нагрівача, які входять у склад системи електроживлення Холловського двигуна. Під час проведення експериментальних досліджень боло отримано циклограму процесу запуску катоду, яка необхідна для формування циклограми запуску двигуна. Проведені випробування підтвердили правильність вибраних технічних рішень щодо конструкції катоду та його нагрівача. Розроблений катод може бути використаний як в малопотужних (до 200 Вт) Холловських двигунах, так і в двигунах підвищеної потужності (до 5 кВт).
Ключові слова: ПОЛИЙ КАТОД, ГЕКСАБОРИД ЛАНТАНУ, НАГРІВАЧ КАТОДУ, ТЕПЛОВІ ЕКРАНИ, ТЕПЛОВІ РОЗРАХУНКИ, ЛАБОРАТОРНЫ ВИПРОБУВАННЯ, ХОЛЛОВСЬКИЙ ДВИГУН.

Introduction

The efficiency of the Hall thrusters operation is largely determined by the parameters of the hollow cathode, which provides the emission of electrons to maintain an electric discharge between the hollow cathode and the anode in the accelerating channel of the thruster, as well as neutralize the positively charged ions flowing out of the accelerating channel [1 – 3].

One of the most promising emitter materials in hollow cathodes is lanthanum hexaboride (LaB_6). Cathodes based on LaB_6 are stable under ion bombardment conditions, less sensitive to low vacuum and poisoning by oxygen, water vapor, air, CO_2, etc. compared to other emitter materials.

Hollow cathodes based on LaB_6 in Hall thrusters are capable of working in contact with various working substances.

LaB_6 has a high emissivity and low work function of electrons (φ = 2.66 eV) [4].

A feature of LaB_6 application in hollow cathodes is a rather high operating temperature (1400 - 1500°C) compared to other emitter materials, which causes certain problems in the development of a heater that provides initial heating of a hollow cathode.

Formulation of the problem

To develop a heater for a laboratory model of a filament cathode based on lanthanum hexaboride for its operation with Hall-effect thrusters, which are being developed by Space Electric Thruster Systems (SETS, Dnipro, Ukraine).

The developed hollow cathode should ensure the operation of Hall thrusters with low input power (up to 200 W), medium power (up to 600 W), and high power (up to 5 kW).

It needs to carry out the thermal calculations of the developed cathode, select the design and materials of the hollow cathode heater, and conduct laboratory testing of the laboratory cathode prototype.

Solution of the task

To solve the set tasks, a structure diagram of a laboratory model of the filament hollow cathode with lanthanum hexaboride was chosen, which is shown in fig. 1.

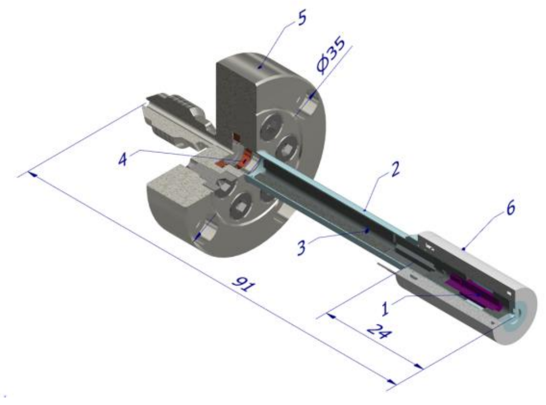

Figure 1 – Structure diagram of hollow cathode

The structure of the hollow cathode, as shown in fig. 1, includes the following main components:

1 - emitter (LaB_6);
2 - tube;
3 - pusher;
4 - copper seal;
5 - the base of the cathode;
6 - heater.

The emitter of electrons (1) has the shape of a cylinder with two holes - longitudinal along the cylinder and through, crossing the first hole, for feeding of the working gas. The tube (2) is made of refractory metal. The emitter (1) is held against a diaphragm with a small-diameter hole in a special sleeve made of material neutral for interaction with LaB_6 and is pressed by a pusher (3), which is acted upon by a spring. The materials used in the cathode were selected based on the analysis of the already existing cathode structures with lanthanum hexaboride.

The working substance for cathode operation (Xe) is feeding into the tube (2) at a predetermined mass flow rate, which is set by the laboratory system for storing and feeding of the working gas. By choosing the diameter of the diaphragm opening, it is possible to set the required working gas pressure inside the hollow cathode to ensure the discharge inside the cathode.

The heater (6) provides preheating of the cathode emitter to the operating temperature at which an internal discharge occurs. A separate power supply with stabilize the heater current is used to operate the cathode heater. When an internal discharge occurs in the cathode, the heater power supply turns off and the cathode continues to operate in auto mode.

The structure of the heater prototype was chosen from proposed by M.S. McDonald, A.D. Gallimore, D.M. Goebel (Naval Research Laboratory & California Institute of Technology) [5 - 6], a general view of which is shown in fig. 2.

Inside the hollow cathode, the heater is covered by heat shields (not shown in fig. 1), which reduce heat losses both during preheating process and in auto mode operation.

The developed hollow cathode also has outer cylindrical electrode - a keeper (not shown in fig. 1). The keeper is used to initiate a preliminary internal discharge, as well as to protect the cathode from ion bombardment during of the Hall thruster operation

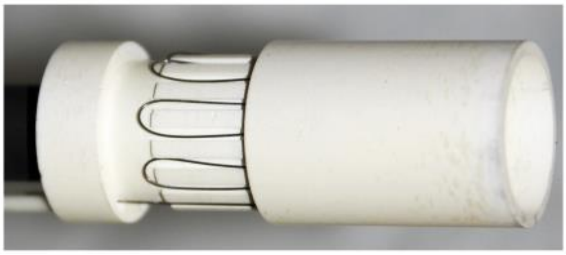

Figure 2 – Prototype of the hollow cathode heater general view

Test equipment

The developed hollow cathode was tested in the SETS vacuum chamber both in diode mode (when operating with a separate anode) and in conjunction with an ST-25 Hall thruster. The general view of the vacuum chamber in which laboratory tests of the hollow cathode were carried out is shown in fig. 3.

The vacuum chamber is equipped with a turbo-molecular pump, which provides the following conditions for the cathode testing behavior: residual pressure in the chamber $5.0 \cdot 10^{-6}$ Tor (in the absence of a working gas flow through the cathode); $1.0 \cdot 10^{-4}$ Tor (at the working gas mass flow rate through the cathode – 1.0 mg/sec).

Heater calculation

One of the most critical components of the hollow cathode is a heater, especially if this heater provides a high temperature above 1400°C.

The ANSYS software environment at a heater temperature of 1400°C carried out thermal calculations of the cathode, which is sufficient for generating electrons by the emitter.

The results of thermal calculations for simulating heating of the cathode at its start are shown in fig. 4. The calculations made it possible to determine the temperature distribution along the cathode structure, the magnitude of heat losses, and also to identify the most thermally stressed sections of the cathode

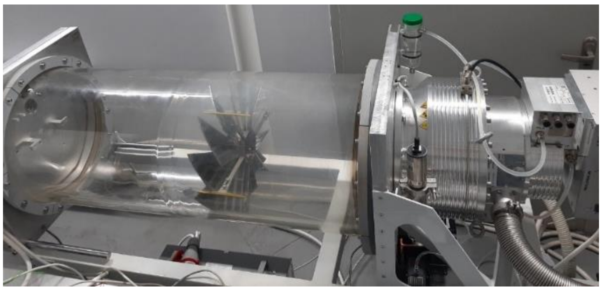

Figure 3 – General view of the vacuum chamber for the hollow cathode testing

Along with determining the temperature regimes of the cathode during start-up (when the heater is working), it was also calculated the temperature distribution along the cathode structure in auto mode (with the heater source turned off) after the initiation of an internal gas discharge in the hollow cathode.

The calculation results when the cathode is operating in the auto mode are shown in fig.5. The calculation results showed that the temperature of not the entire emitter is maintained at the same level sufficient to maintain the process of thermal emission of the cathode, but only two-thirds of the emitter will emit electrons, since the rear part of the emitter has a temperature of about 900°C.

Based on the calculation results, the following changes in the structure of the cathode and heater were carried out:

1. Modification of the pusher in order to reduce the contact area of the pusher with the emitter surface to reduce heat transfer losses.

2. Equipping the cathode heater with heat shields.

3. The sleeve of the cathode is designed and manufactured from a carbon composite material, in which the anisotropy of the thermal conductivity of the material was realized.

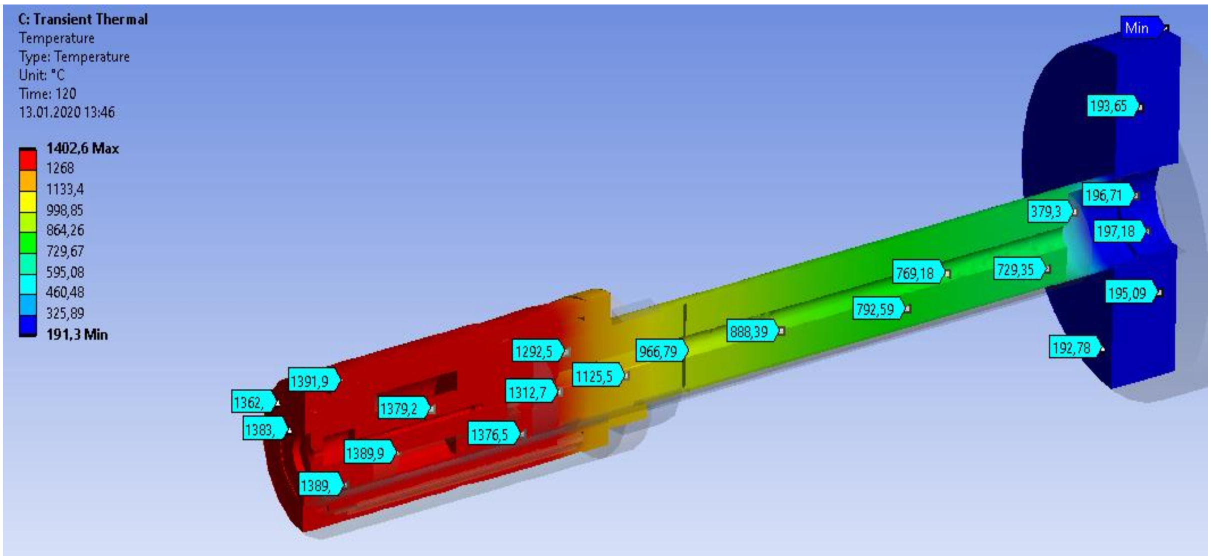

Figure 4 – Results of the cathode thermal calculation at cathode starting proces

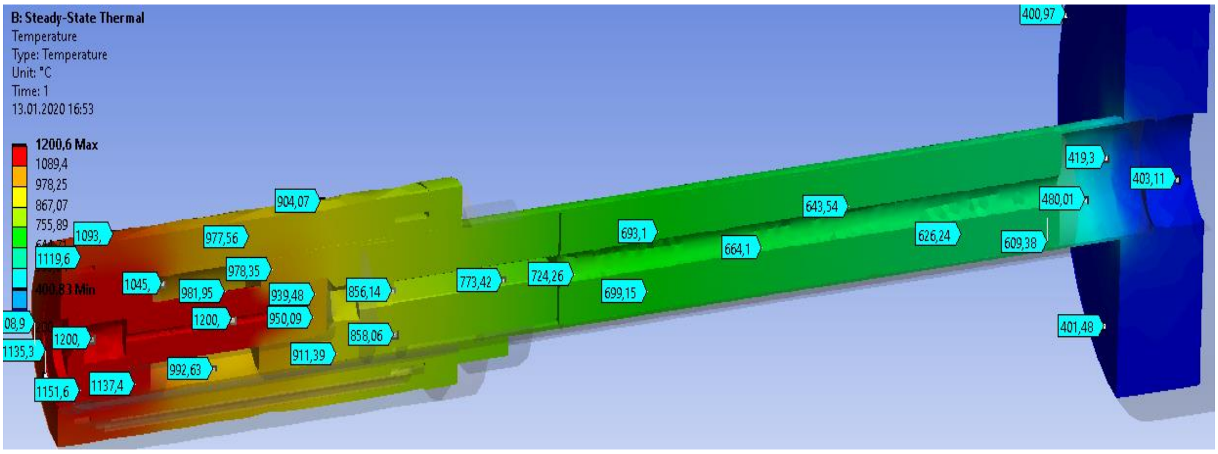

Figure 5 – Results of the cathode thermal calculation at auto regime cathode operation

During the development of the hollow cathode, laboratory tests of four modifications of the heater were proposed and carried out. The wire VR5 with a thickness of 0.35 mm was used as a filament element. The heater structure is shown in fig. 6.

To compare the results obtained in the frame of thermal calculations with the results of experimental studies of the cathode, the temperature was measured at two points of the cathode using thermocouples. One thermocouple was located at the outlet diaphragm of the cathode (T1.1), and the second was located on the heater mounting flange (T1.2), as shown in fig. 7.

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Figure 6 – Cathode heater structure

As the thermocouple T1.1. thermocouple Tungsten-Rhenium VR5 / VR20 was selected, such thermocouples are used for long-term operation and obtaining accurate results at extremely high temperatures (up to 2500 °C) in a number of both chemically inert and aggressive environment. These thermocouples work well in vacuum as well as in environments with high nitrogen, hydrogen, helium and argon contents.

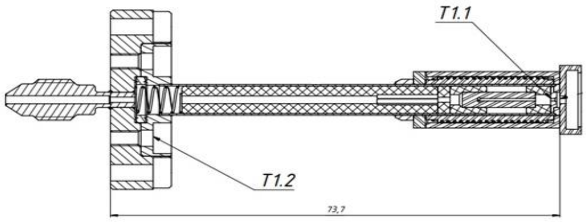


Figure 7 – The locations of the thermocouples on the cathode

As a thermocouple T1.2 a Chromel-Alumel thermocouple, type K, is selected. Temperature measurement with such a thermocouple can be carried out in the range from -200 to +1100 ° C. This range is sufficient for measuring the temperature at the base of the cathode

In the course of laboratory tests of the hollow cathode, the following heater structure design options were tested:

- heater without thermal shields;
- heater with 5 thermal shields;
- heater with 11 thermal shields and 3 end shields;
- heater with 19 thermal shields, 5 end shields and 9 shields in front of the diaphragm.

In fig. 8 the curves of the maximum temperature values measured after reaching thermodynamic equilibrium, depending on the heater power, are showed.

From the test results of the hollow cathode presented in fig. 8, it can be seen that an increase in the number of heat shields makes it possible to achieve the required temperature of 1400 - 1500°C in the emitter zone, as well as to significantly reduce the power consumption for heating the emitter.

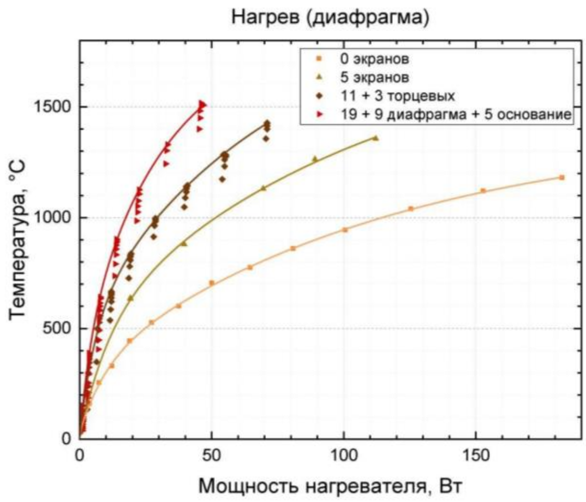


Figure 8 – Dependence the diaphragm temperature in point T1.1 from heater

In particular, an emitter temperature of 1200°C can be achieved in a maximally shielded heater with an expenditure of 25 W of electrical power, in contrast to a heater without heat shields, for which 195 W is required.

The process of testing a hollow cathode is shown in fig. 9 (9.a - cathode heater with 5 heat shields; 9.b - with 19 shields).

As a result of the laboratory tests carried out, the correctness of the thermal calculations was confirmed. The number of heat shields obtained as a result of experimental studies is optimal. This is due to the fact that a further increase in the number of screens does not lead to a significant decrease in heat losses, while the dimensions of the cathode increase significantly.

Further improvement of shields is associated with the optimization of the process of perforating shields and their polishing (to increase the radiation reflection coefficient), as well as the choice of the distance between the shields.

For the operation of the filament cathode, an important process is the process of cooling the cathode after the heater is turned off.

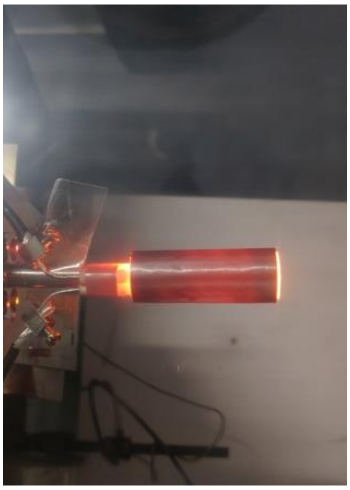
Experimental investigation of the hollow cathode have shown that the cooling rate of both the diaphragm and the base of the cathode is practically independent of the number of heater shields, as shown in fig. 10.

The performed experimental investigation of the cathode cooling process are of great importance. The results obtained are necessary:

1) for a correct assessment of the starting point and the time of subsequent heating;

2) to determine the time when the vacuum chamber can be opened during cathode and thruster tests;

3) to set the value of the starting current for heating the cathode - a low current up to 2.5 A if the cathode has cooled down below 300°C, and with a high current of 4 A and above if the cathode is hot



a) 5 shields, T=1400°C

b) 19 shields, T=1537°C

Figure 9 – Cathode testing with heater turned on

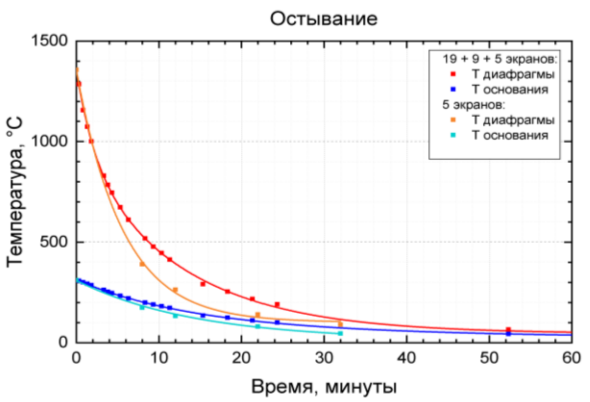


Figure 10 – Change of the diaphragm and base cathode at the heater turned off for 5 and 19 shields

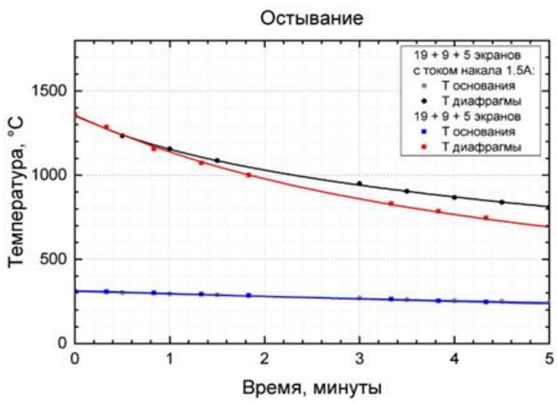


Figure 11 – Process of the diaphragm and base cathode cooling: a) full heater turned off; b) small heating (4.3 W) using 19 shields of heater

The purpose of the following experiments was to find out whether it is possible to use small additional heating to maintain the self-heating mode of the cathode.

The results presented in fig. 11 show that in the temperature range above 1200 ° C, small additional heating has no effect on the cathode cooling rate.

Scientific novelty

1. Experimental studies of a hollow cathode heater have shown that an increase in the number of thermal shields leads to an increase in the temperature of the diaphragm, a decrease in the temperature on the mounting flange, a decrease in energy consumption and an increase in the efficiency of the heater.

2. In the absence of cathode heater screens and 183 W of heater power, it is possible to reach a temperature of 1180 C ° at the cathode diaphragm.

3. Using 19 heater screens and 47 W of heater power, it was possible to reach a diaphragm temperature of 1517 C °, reduce the temperature on the cathode flange to 306 C °, and significantly increase the heater efficiency, spending 3.1 W for every 100 C °.

Conclusions

The laboratory investigation of a hollow cathode heater with lanthanum hexaboride have confirmed the correctness of the selected technical solutions for the choice of design and parameters of the heater providing the operating temperature of the emitter.

It is possible to recommend the proposed heater design for all filament cathodes developed by SETS.

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