

Autonomous Tests of the Cathode for Use in the Discharge Chamber of the High Power Ion Thruster

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Abstract: A novel design scheme of a hollow cathode emitter assembly is discussed in this paper. The scheme was tested while working on high-current 100 and 50 A - class cathodes development. A description is given for the test procedure used for autonomous tests of those cathodes developed at KeRC, which completely satisfy the required specifications for thermoemission cathodes of high-power ion thrusters. Results of the autonomous tests are provided. Dependencies of voltage as functions of the discharge current were acquired in ranges of 20 – 120 A for a laboratory model and 10 – 65 A for an engineering model. Stationary temperatures of the cathode parts were also measured for both.

I. Introduction

New generation transportation systems with significantly increased propellant efficiency are required for future exploration of Solar system and development of useful in-space applications. A power and propulsion system with high operational lifetime and low propellant consumption is necessary for a space travel. Recently a megawatt class transport-power module (TPM) with nuclear primary energy source is under development in Russia. Electric propulsion based system is planned for use as its main propulsion system. Today ion thruster looks like the most suitable option to become a basis of a high performance power and propulsion system as providing the best composition of characteristics. Ion thrusters have high specific impulse (experimentally demonstrated values are up to $80\,000\text{ m/s}^{-1}$), as well as high operation lifetime (exceeding 30 000 hours^{2,3}).

Power of a single thruster of TPM is estimated to be tenth of kilowatts. Discharge chamber, that is a high-efficient plasma source, is to be developed to create such an ion thruster. One of the most well-elaborated state-of-art technologies, used to produce plasma in a discharge chamber, is initiation of a direct current discharge with a help of a hollow cathode. According to numerical estimates, for use in an ion thruster with power of about and over 50 kW, such a cathode should operate at discharge currents of an order of 100 A.

Design scheme and tests of a new type of hollow cathodes, developed at KeRC, are discussed in this article. The cathodes are capable providing emission current ranging from 20 to 120 A and match to the main requirements applied to the thermal emission cathodes of high-power ion thruster. The results of autonomous tests are presented.

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II. Polyemitter hollow cathode

A. Description of a polyemitter hollow cathode scheme

Cathodes operating in Xenon at currents of about 100 A have been developed to date^{4,6}. At the same time, some multiple-cavity design scheme cathodes exist⁷. The latter design scheme features many active cavities for electron emission, that have their axis in parallel with each other. At that the emitter part of the cathode is, as a rule, still being made in a shape of a single active emitter bush (see fig. 1). Although the activities for development of cathodes with currents of 100 A and above exist, state-of-art cathodes intended to be used in discharge chambers are capable operating at discharge currents up to 60 A, and the continued operation tests (with duration of about 30 000 h) have been held only at currents of 10 – 15 A.

In the course of the high-power ion thruster discharge chamber cathode development, the main attention was paid to providing the required operational lifetime. In accordance with this condition, as well as considering the needs for sustaining thermal state of the cathode and simplicity of its manufacturing, it was decided to perform design and development of a W-Ba cathode using polyemitter scheme. The cathode is to be operating in a 50 – 100 A range. The above mentioned polyemitter scheme of a cathode utilizes several emitters, which simultaneously participate in emission, at that sharing a common mechanical assembly and provided with a single startup heater and igniter electrode. At that the emitter part of the cathode would be a set of cylindrical hollow emitters placed inside a common casing, with the cylindrical emitter axis being parallel.

A scheme for realization of an emitter assembly of a polyemitter cathode is shown in fig. 1 c. Use of the polyemitter scheme is the main feature of high-current cathode models described in this article.

The following properties may be considered as the main advantages of the polyemitter W-Ba cathodes:

1. The overall area of the electron emission surface would be significant (an order of 10 square centimeters) at 50 – 100 A discharge current. This surface would also contact the discharge plasma. Ion bombardment from the plasma would be intensely heating the emitters. A valuable heat power (hundreds of Watts) would be produced in the emitter assembly. It is necessary to provide a sufficient overall contact area between the emitter and its casing in order to withdraw such an amount of heat to the cathode parts. In the polyemitter scheme it is possible making this surface area substantially larger than in case of a single cylindrical emitter.

2. Simplicity of emitting element manufacturing.

3. At uniform distribution of the discharge current and gas flow rate between the emitters, the polyemitter scheme ensures same operation mode for each emitter, and uniform Ba depletion in the emitter volume.

As an essence, it may be said that the only drawback of the polyemitter cathode scheme, if compared to the cathode scheme with a single cylindrical emitter, is the complexity of providing the uniform gas flow rate distribution between all the emitters, that results in complexity of achieving uniform discharge current distribution.

In a multi-cavity emitter, besides its technological complexity, a radial nonuniformity of Ba depletion may occur. This takes place in connection with the fact that in the emitter hole cavity active surface fractions directed towards the external enveloping surface of the emitter (see fig. 1, c), may suffer from Barium loss, while in the fractions, facing emitter axis such a loss may be still absent.

An engineering model of polyemitter cathode (HCEM-50) was developed after manufacturing and testing of a laboratory model of cathode (HCLM-100). The engineering model is designed to operate at 20 to 55 A discharge

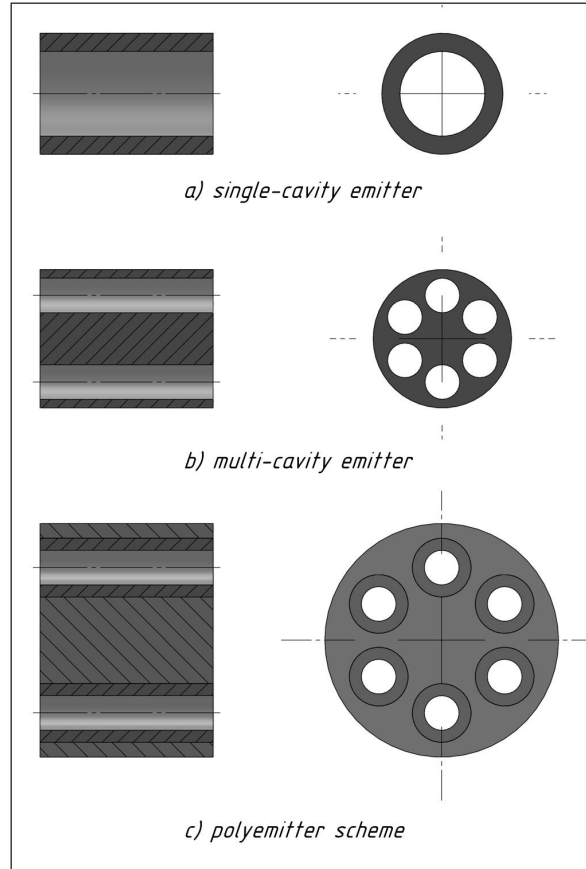


Figure 1. Principal schemes of emitters.



a) laboratory model



b) engineering model

Figure 2. Appearance of laboratory and engineering model of cathodes.

current range. Design of emitter assembly is the principal difference between HCEM-50 and HCLM-100. Namely, as HCEM-50 is to be operated at lower discharge currents of about 50 A, it is fitted with a fewer number of emitters. It was also a getter added to the emitter unit of HCEM-50 for gas decontamination of substances capable causing cathode failure by emitter poisoning.

The emitter casing of HCLM-100 has four, and emitter casing of HCLM-50 has three channels. Size and thermal distribution of the massive base assemblies of high current cathodes allows placing getter there, what was done for the engineering model of the cathode.

The appearance of laboratory and engineering model of cathodes is shown in fig. 2.

B. Procedure for parametric test of cathode

Tests were held in a vacuum chamber of 10 m³ volume, fitted with eight diffusion pumps. During firing tests with Xe mass flow rate in the required range of 1 – 5 mg/s the experimental facility is capable providing pressure of about 10⁻² Pa inside the vacuum chamber. The vacuum chamber has internal diameter of 1.6 m. That is enough to avoid any noticeable heating of its walls or other elements when the arc discharge is fired in a gap between the cathode and an anode.

A schematic image of the facility for autonomous firing tests of the laboratory model of cathode is shown in fig. 3.

An appliance for cathode and anode placement was manufactured and mounted inside the vacuum chamber. The appliance provided electric insulation from the

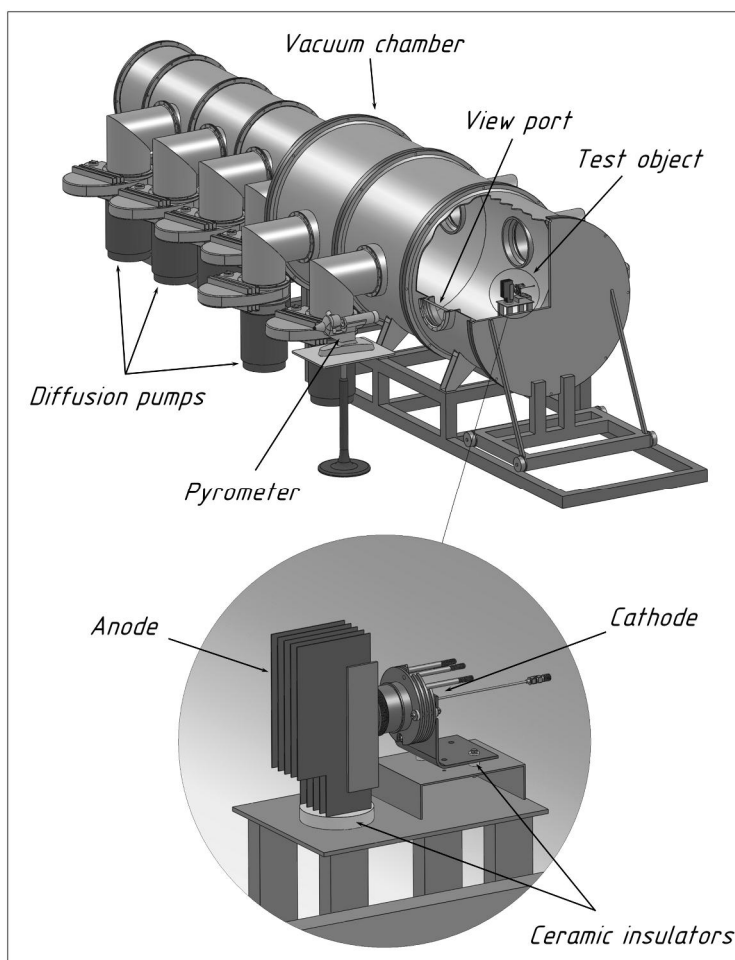


Figure 3. Scheme of experimental facility.

vacuum chamber elements for all conductive parts of the cathode, mounted on it. Moreover, the appliance was suitable for installation of diagnostic instruments. It was located inside the vacuum chamber in front of a viewport, so that the exit end of the keeper electrode of the installed cathode could be subject to visual inspection and pyrometry. Cathode autonomous firing tests are held using an simulator of a ion thruster discharge chamber, which is usually an anode made of material with a high melting temperature.

Carrying out cathode firing tests with high discharge currents ($20 \div 120$ A) required development of a new anode. A flat plate, placed at a distance of $5 \div 10$ cm from a cathode exit end perpendicularly to the cathode main axis is typically used as an anode for autonomous firing tests of different cathodes⁸. A new design of high-current anode was developed. It was mounted on the appliance.

The anode was shaped as a set of electrically connected plates, made of metal with high melting point and positioned in a vertical plane with gaps left between them. The gap width between plates was 10 cm, plate thickness 2 mm. The cathodes were installed at distance of 10 mm from the anode.

This anode configuration offers free passage of a plasma plume, that is created by the discharge and emerges from the cathode, at the same time collecting electron current from the plume through lateral surfaces of the plates. At that the plasma plume remains virtually unaffected, as it could appear in the case of using an anode in a shape of a flat plate placed in front of the cathode perpendicularly to its axis. Moreover, presence of the gaps allowed using pyrometric measurements to define temperatures of the cathode parts during operation.

Figure 4 shows the cathode with the anode in the course of their installation into the vacuum chamber.

The tests were held in order to check possibilities of operating in ranges of discharge currents of $50 - 100$ A for the laboratory model of cathode and $25 - 50$ A for the engineering model. Another purpose of the tests was to study the operation characteristics of the cathodes in those ranges of discharge current.

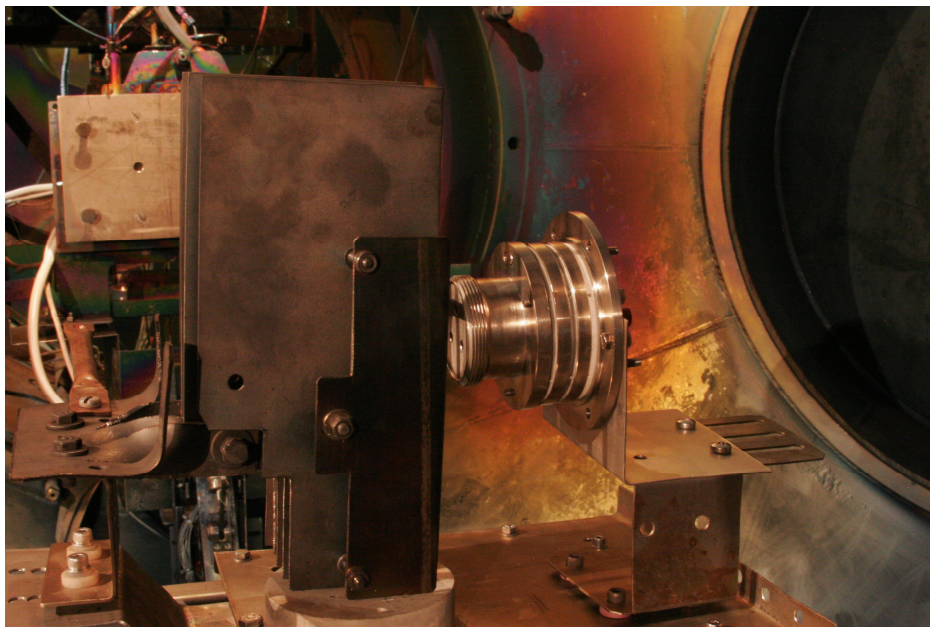


Figure 4. The cathode and anode in the process of installation inside the vacuum chamber.

III. Results of parametric tests

C. Laboratory model of the cathode

Volt-ampere characteristics (VAC) of the laboratory model of cathode, acquired at flow rates of 1.5 mg/s, 2.0 mg/s, 3.5 mg/s, 4.5 mg/s are shown in fig. 5. The currents range was chosen depending on the flow rate. A larger flow rate allows “pushing through” larger currents. Increase in discharge current at smaller flow rates may lead to negative effects, such as harsh growth of discharge voltage and discharge incursion deeper into the emitter with increase of its temperature.

One can see that a descending dependency of the voltage from the current in range of 50 – 100 A exists at Xe mass flow rate of 4.5 mg/s. At flow rates in 2 – 3.5 mg/s range a slowly ascending VAC is observed. While at flow rate of 1.5 mg/s, VAC is growing with increasing discharge current in range of 40 – 60 A.

Ascending dependency of the discharge voltage from the discharge current signals of negative effects (in terms of cathode operation), such as grows of cathode potential drop, significant increase of discharge incursion depth, unwanted growth of plasma temperature in the emitter zone, emitter overheating.

It may be concluded according to the VAC data that at a discharge current about 100 A the flow rate equal to 3.5 mg/s is to be considered as the acceptable minimum. In contrast it is possible to operate at flow rates of about 2 mg/s at discharge currents of 40 – 50 A. In general, basing on relatively low discharge voltage values of this laboratory model of cathode, observed in a wide range of discharge currents 30 – 120 A, one can make a conclusion, that the laboratory model appeared to be an efficient instrument for generating high electron flows.

Visual and pyrometric studies made during the tests have demonstrated that light intensity in all the igniter electrode holes, as well as temperatures of all emitter groups are same in the cathode operation modes with high enough discharge currents (50 – 100 A). These results provide evidence that all emitters equally participate in the arc discharge. For instance, same current is provided by each emitter. The cathode laboratory model operation is very stable in these modes.

At discharge currents of about 20 A some non-uniformity in emitter operation was observed, namely the discharge was switching periodically from one emitter to another, that was visible as decrease of light intensity of individual emitter orifice holes. This operation mode is caused by the fact that at a current of about 5 A running through each of the four emitters (at that the cumulative current is 20 A) the heat flux from the arc discharge to the emitter is insufficient to sustain W-Ba emitter temperature in range from 1100 to 1200 °C.

The graphs of measured stationary operation temperatures of the laboratory cathode parts at discharge currents of 35 A, 50 A, 70 A, 80 A are shown in figure 6. The emitter orifice is connected directly to the emitter and operates under conditions of intense bombardment by charged particles from the plasma that presents inside the emitters. As a result, temperature of the orifice is close to emitter temperatures. Therefore the emitter temperature value may be estimated as the orifice temperature.

At discharge current range of 30 – 100 A, the emitter unit orifice temperature was in 1100 – 1200°C range. It corresponds to normal operation conditions of W-Ba cathodes. Visual inspection of cathode parts held after the

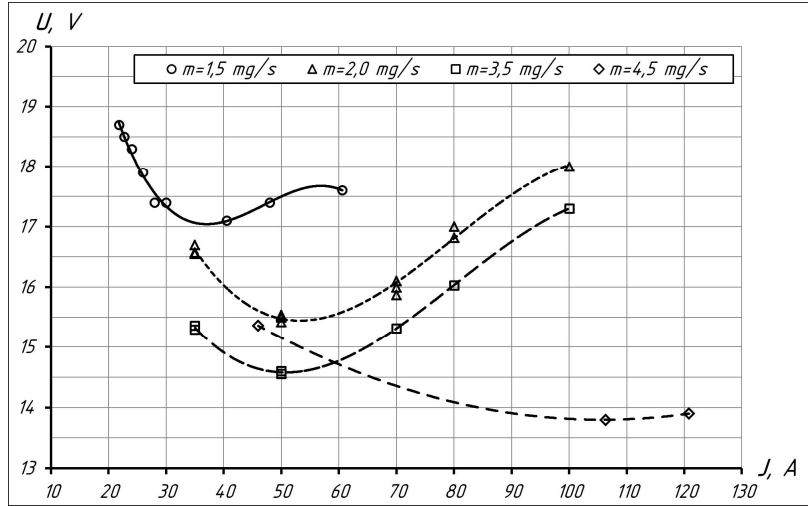


Figure 5. Volt-ampere characteristics of the laboratory model of cathode.

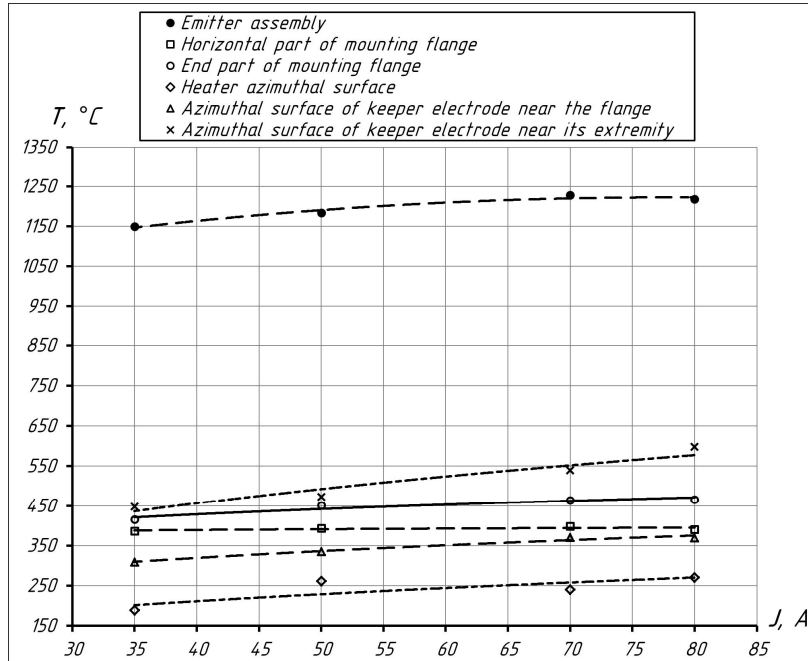


Figure 6. Temperatures of cathode parts (laboratory model).

autonomous firing test showed no signs of melting or coloration change due to heating. This verifies reliable functioning of the laboratory model of cathode at high discharge currents.

D. Engineering model of the cathode

Engineering model of cathode test results qualitatively coincide with the results of laboratory model tests (certainly, with a correction due to different operation modes of those models).

Figure 7 shows VAC of the engineering model of cathode, acquired at propellant flow rates of 1 mg/s, 2 mg/s and 3 mg/s.

It can be seen that in the discharge current range of 30 – 50 A, monotonously descending dependency takes place at Xe flow rates over 2 mg/s. At flow rate of 1 mg/s and discharge currents in range of 30 – 50 A the volt-ampere characteristics quickly ascend with increasing discharge current.

According to the VAC data, flow rate of 2 mg/s is to be considered the most acceptable minimal flow rate for this engineering model of cathode at currents of 30 – 55 A, while if current range is 10 – 25 A it is possible functioning at a mass flow rate of about 1 mg/s.

The cathode operation at discharge currents in 25 – 60 A range and mass flow rate over 2 mg/s is stable. All emitters participate in the discharge, running at the same current.

Emitter operation non-uniformity was observed for the engineering model of cathode at discharge currents below 10 A, at 1 mg/s mass flow rate.

The graphs of measured stationary operation temperatures of the engineering cathode parts at discharge currents of 20 A, 35 A, 50 A are shown in figure 8

At discharge current range of 35 – 50 A the emitter orifice temperature is in range of 1100 – 1250 °C, that corresponds to normal conditions of W-Ba emitter operation. Visual inspection of cathode parts held after the autonomous firing test showed no signs of melting or coloration change due to heating. This verifies reliable functioning of the laboratory model of cathode at high discharge currents.

The engineering model of cathode was subject to autonomous mechanical tests. A random vibration load analogous to the load applied to the cathode when being in composition of an ion thruster was simulated while holding out the test. Random vibration load was 17.5 g with duration 120 s per axis. Firing tests

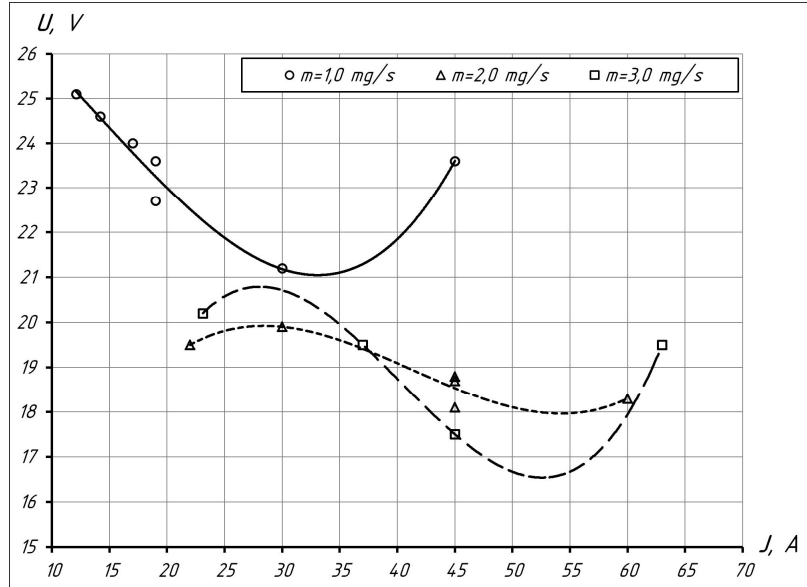


Figure 7. Volt-ampere characteristics of the engineering model of cathode.

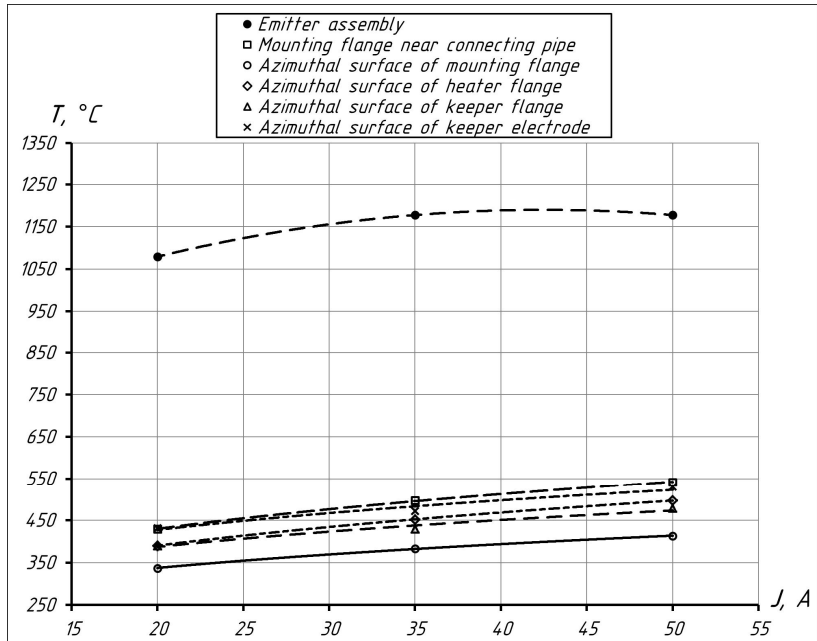


Figure 8. Temperatures of cathode parts (engineering model).

were repeatedly performed after the mechanical tests. They proved ability for functioning of the engineering model of cathode.

IV. Conclusion

A hollow cathode design of polyemitter scheme was developed at KeRC.

A laboratory and engineering model of cathodes based on the polyemitter scheme were developed.

The laboratory model of the cathode showed stable operation in the discharge current range of 30 – 120 A, at xenon flow rates of 1.5 – 4.5 mg/s and low discharge voltage.

The engineering model of the cathode showed stable operation in the discharge current range of 10 – 60 A, at xenon flow rates 1 – 3 mg/s and low discharge voltage.

The polyemitter scheme is a promising scheme of an emitter unit, which can become basic for cathodes with currents significantly exceeding the acquired values.

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