Thermal State Investigations of Two-stage Thruster with Anode Layer

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Abstract: **Thermal analysis is critically important for development of EP thruster and modern anode layer thrusters (TAL) in particular. Absence and/or uncertainty of thermal boundary conditions is the one of the main principle difficulty appearing during heat calculations of the thruster construction. The purpose of the work was accurate definition of thruster heat emissive characteristics and verification of existing heat calculation methods. Necessary heat boundary conditions were obtained and verified by using of semiempirical method. Two approaches of temperature fields calculations were used: analytical and variation one (Finite Elements Method FEM). Comparison of these methods was carried out. Based on simulation experiment performed with the help of ohmic heating emissive characteristics of outer TAL surfaces were obtained. Temperature fields modeling by iterative method for different thruster modes was carried out. Experimental data were compared with calculated ones. It resulted in obtaining of heat generation distribution in the thruster. Emissive data table was composed for considered type of thrusters. Thruster thermal balance was analyzed.**

Nomenclature

ε = emissivity factor
σ = Stefan-Boltzmann constant
T = temperature
k = thermal-conductivity coefficient
Q = heat generation
A = element area
F = view factor
I = current strength
U = voltage
W = power

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I. Introduction

Thermal analysis is critically important for development of EP thruster and modern anode layer thrusters (TAL) in particular[1,2]. TAL construction thermal intensity defines and limits applied constructional materials as well as their treatment.

It is incorrect to determine thruster operating modes characteristics without taking into account thermal distribution, since the thruster efficiency directly depends on thermal intensity. Thruster heat balance analysis allows to increase input power range and to optimize thruster operation in different modes, including transient modes.

There are several thruster temperature field simulating approaches for now. All of them can be divided to two main types: analytic and numerical. Analytic approaches are based on system heat balance equations and classical heat transfer equations. The principle of numerical methods (for example, finite element method) lies in the approximation of a sought temperature value varying continuously by volume of a body, by its discrete model.

Advantage of numerical approach is precise description of investigated model and operating mode conditions. Since modern computer equipment allows calculating large equations set-up (more than 1 million of equations).

To realize these two calculation approaches heat transfer boundary conditions definition is needed.

Mainly radiant heat transfer takes place in TAL, so for thruster parts besides standard material properties surface emissivity factor value (ε) is also needed to know. For the first test run ε can be taken as nominal value for part material, but in case of continuous operating surface properties will change and it will lead to heat fluxes redistribution. The second needed boundary conditions are the thruster parts heat generation values (Q), which is determined with help of total thruster heat balance equation.

Hence boundary conditions data tabulation is important task needed for new thruster construction thermal intensity quick estimation under development stage. Task of boundary conditions definition can be solved by semiempirical approach, combining experimental data and numerical simulation.

II. Motivation

Two-stage TAL D-80-type with average diameter of discharge channel about 60 mm (see Fig.1) was chosen for thermal analysis. Thruster uses xenon as a propellant and it can be operated in modes with input power up to 2 kW. Thermal analysis data obtained for this sample can be applied for all two-stage xenon TAL.

A. Brief TAL Design Description

The thruster consists of two main parts (see Fig.2):

- Magnet system.
- Anode unit.

Magnet system, in turns, consists of following main components:

- mounting flange (#6);
- inner coil with magnetic pole (#3);
- outer coils (#4);
- outer pole piece (#5).

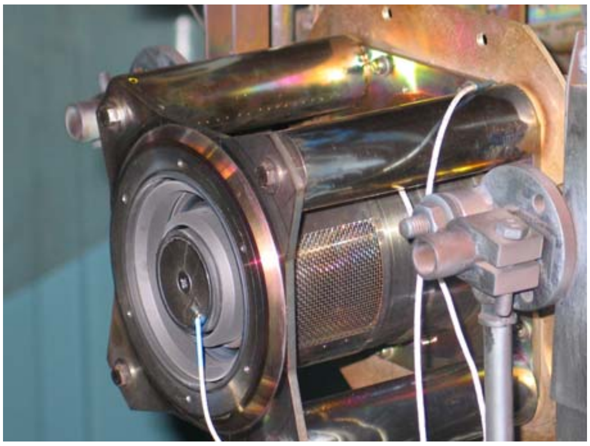

Figure 1. Photo of TAL with thermocouples.

The anode unit is mounted on magnet mounting flange. It includes gas distributing anode (#1), first stage cathode (#2), guard rings (#7), insulators (#8), screen (#9). Anode unit components which are under different potential are isolated from each other with the help of insulators (#8). Magnet system poles are protected from ion sputtering by guard rings (#7).

Heat in the thruster construction is generated by the first and the second stages discharge plasma and by magnet system coils.

B. Research stages

The work was aimed on creation of boundary conditions data base of existing thrusters. These data is needed for new thruster construction thermal intensity quick estimation under development stage and thermal analysis.

Main steps were the following:

- Thruster construction parts thermal intensity preliminary calculation, with help of reference and boundary condition empirical data;
- For two thruster operating modes temperature field measurement;
- Obtained results analysis and boundary conditions correction;
- More accurate calculation;
- Thruster heat balance analysis.

Calculation algorithm is given in Fig. 3.

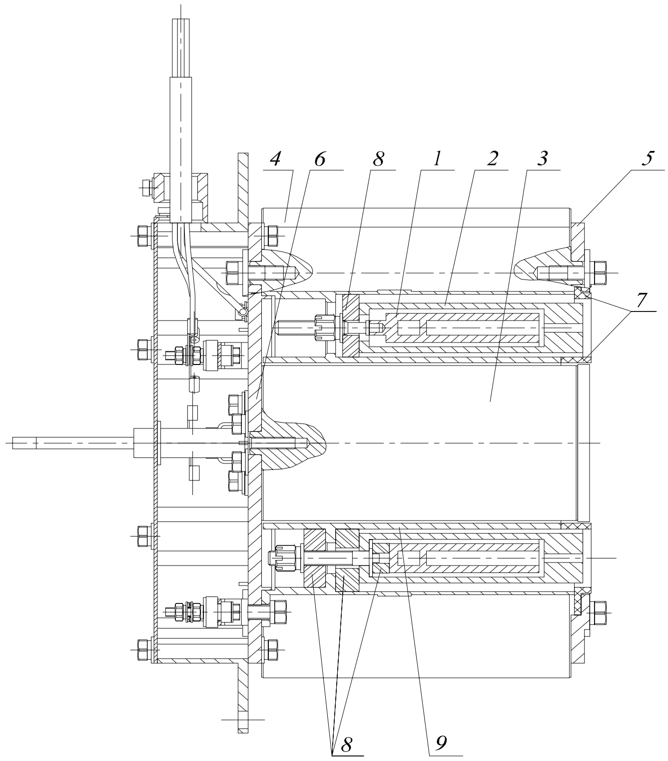

Figure 2. Two-stage TAL principle design scheme.

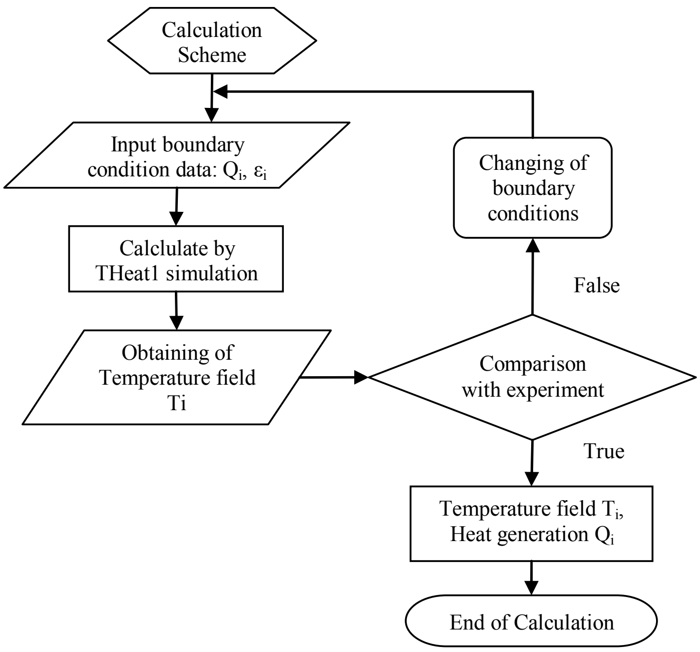

Figure 3. Calculation algorithm.

III. Thruster Thermal State Simulation

Thruster temperature field was calculated by both analytical methods and finite element method (FEM). THeat1 bundled software (developed in TsNIIMASH) was used for analytical investigations. The software was specially developed and optimized for TAL temperature field simulation.

A. Prerequisites

Program algorithm contains classical heat transmission equations, particularly radiant heat exchange one. Heat transfer between surfaces was described by equation 1 (see Fig.4).

$$Q_{rad} = \sigma \cdot \varepsilon_i \cdot A_i \cdot F_{ij} \cdot (T_i^4 - T_j^4) \qquad (1)$$

where F_{ij} – view factor between surfaces i and j

ε_i - emissivity factor of surface i

A_i - area of radiation surface i

T_i , T_j - surfaces i and j temperatures accordingly

View factor *F* has a main influence for two surface heat interaction description. It defines heat quantity transferred from *i* surface to *j* surface taking into account their positional relationship.

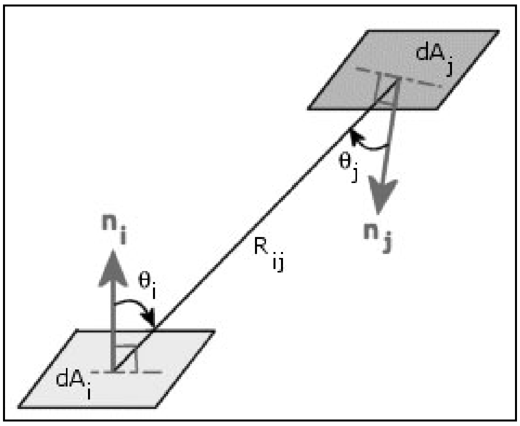

Figure 4. Calculation algorithm

For two elementary surfaces dA_i and dA_j view factor F_{ij} looks as follows:

$$dF_{ij} = \frac{\cos(\theta_i) \cdot \cos(\theta_j)}{\pi \cdot R_{ij}^2} \cdot dA_j \qquad (2)$$

Where θ_i, θ_j - direction angles between perpendicular to surface and line R_{ij} , which connected two surfaces.

In integral form view factor looks as follows:

$$F_{ij} = \frac{1}{A_1} \cdot \int_{A_1} \int_{A_2} \frac{\cos(\theta_i) \cdot \cos(\theta_j)}{\pi \cdot R_{ij}^2} dA_i dA_j$$

(3)

B. THeat1 simulation

THeat1 bundled software permits quick heat field calculation of both: thruster stationary state and no stationary one. Calculating speed was the main advantage of this program. It allows organizing iteration algorithm of boundary conditions selection. Also it is necessary to mark that THeat1 is adapted just for TAL radiation simulation. This program models all necessary conditions of radiation heat transfer, which are typical for thruster operation.

Calculating model is presented as axisymmetric one. It can be explained, that the most of TAL construction parts have solid of revolution shape, excluding outer magnet coils. However, these four coils have been equally distributed around a circle, that allows integrally

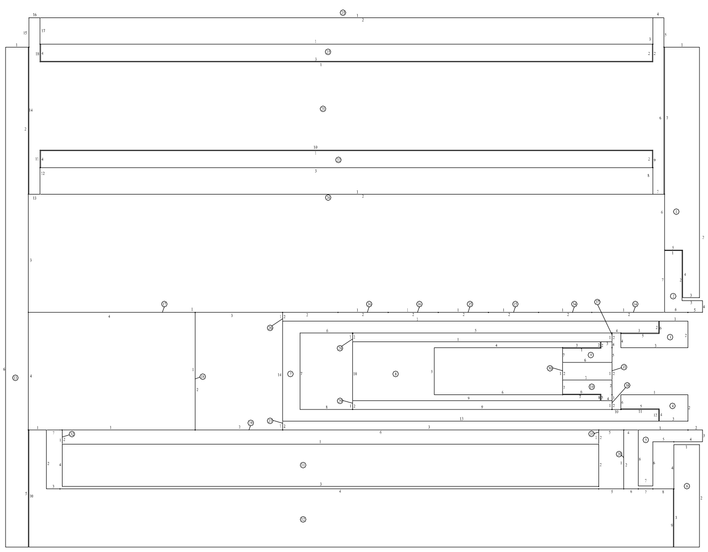

Figure 5. THeat1 simulation model

considering ones contribution in heat transfer by flat axisymmetric examination.

Nominal value of Emissivity ε was given for all thruster surfaces. Heat generation Q was given for thruster surfaces also. View factor was defined between all radiant interaction surfaces. THeat1 simulation scheme was presented in Fig. 5.

As a first approach the calculation was carried out once without iterations. The result of this simulation was taken as a reference point for further calculations and comparison with experimental data.

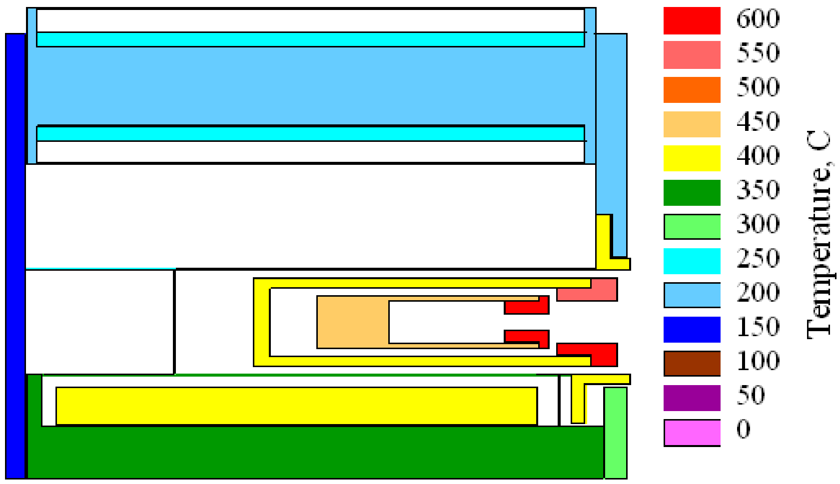

Figure 6. THeat1 simulation results (presented temperature has averaged by thruster parts)

C. Verification

For verification of the THeat1 code similar task has been performed with help of well known Finite Elements Method. The used boundary conditions (ε and Q)and thruster model were the same as the one in the THeat1. Considered finite element model is shown in Figure 7. The calculations have been done by ANSYS software.

The temperature distribution obtained by both methods - THeat1 and ANSYS – are shown correspondingly on Figures 6 and 7. As one can see from the Table 1 below, the difference of the temperature values calculated by both methods do not exceed 5%. This result confirms that THeat1 is good enough for quick calculations of the thruster part temperature mode.

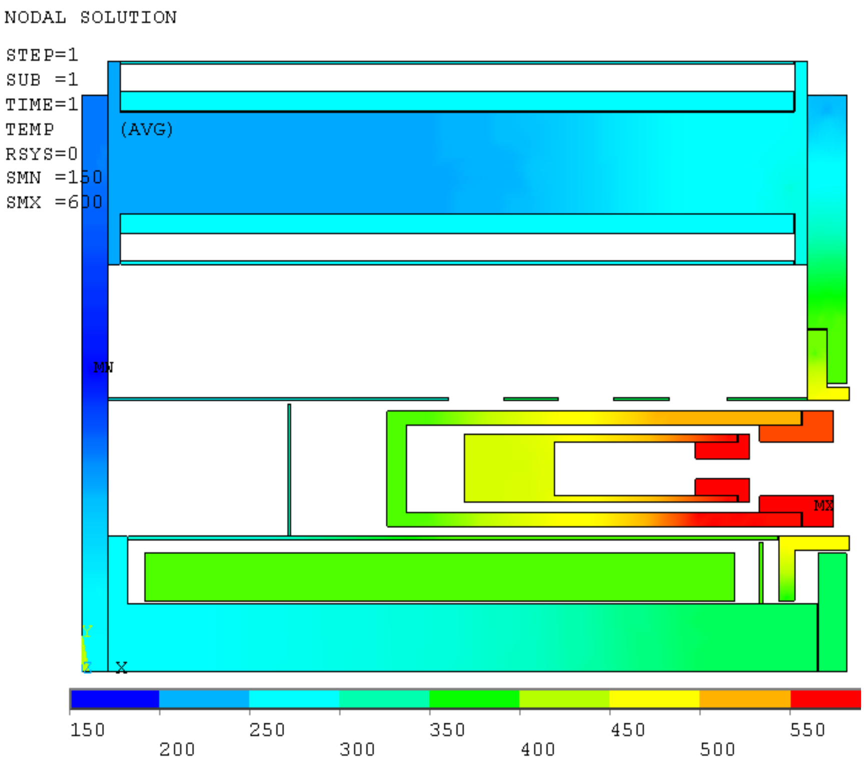

Figure 7. ANSYS verification simulation results

Table 1. Two simulation methods results

Simulation type	THeat1	Ansys
First stage cathode	403 C	421 C
Anode	462 C	479 C
Out guard ring	413 C	425 C
Inner guard ring	430 C	449 C
Outer pole	180 C	171 C
Inner pole	301 C	312 C
Thermal screen	298 C	304 C

IV. Experimental thruster temperature measurements

TAL temperature distribution study was carried out in TsNIIMASH laboratory by thermocouples specially imbedded in the structure. Scheme of thermocouple location is presented in Fig. 8.

Thermocouples status:

- T1 – inner pole;
- T2 – thermal screen;
- T3 – mounting flange ;
- T4 – mounting frame;
- T5 – cover;
- T6 – out pole;
- T7 – out guard ring.

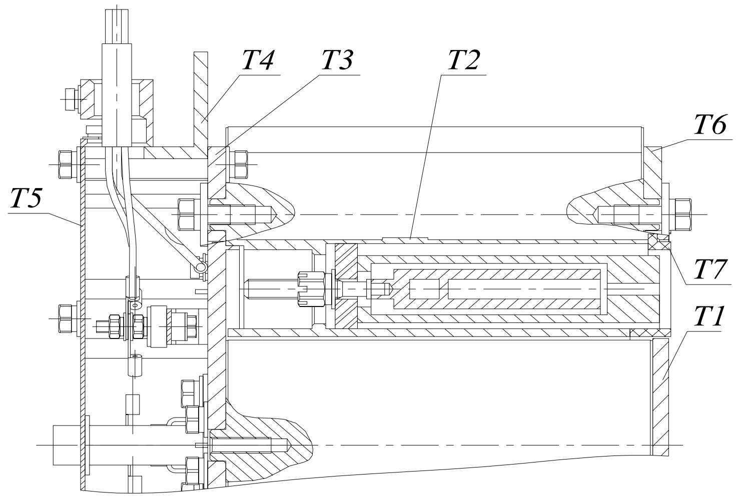

Figure 8. Scheme of thermocouple location

Average temperature of magnetic coils was obtained by measurements of coil resistance during thruster heating/test and standard ohmic thermal dependence for coil material.

Two phase TAL thermal field measuring experiment was carried out, when in use investigations:

- First phase (preparatory) – thermal field measuring with operation (means ohmic heating) of magnetic system only;
- Second phase (main) – thermal field measuring with thruster firing at nominal mode;

Mode parameters presented in Table 2.

Table 2. Thruster mode parameters

Mode parameters	Magnetic system operate	Nominal mode
Inner coil current , Iinn, A	5	1.75
Inner coil voltage, Uinn, V	10.4	4.5
Out coils current, Iout, A	5	1.2
Out coils voltage, Uout, V	7	2
First stage current, Id, A	–	2.75
First stage voltage, Ud, V	–	150.8
Second stage current, Ia, A	–	2.5
Second stage voltage, Ua, V	–	553
Summary thruster power, W, W	87	1800

In view of failing discharge by only magnetic system operation maximum convenient imbedding thermocouple in thruster parts was possible. Magnetic system heat generation Q was determined via measurements of magnet coil currents and voltages.

Main thermal field measuring experiment phase was carried out at nominal thruster operation mode (W=1800w). Experimental data was processed and used for surfaces emissivity and heat generation accurate definition. It took about 4 hour to reach thermal equilibrium. The temperature data versus time is shown on Figures 9,10.

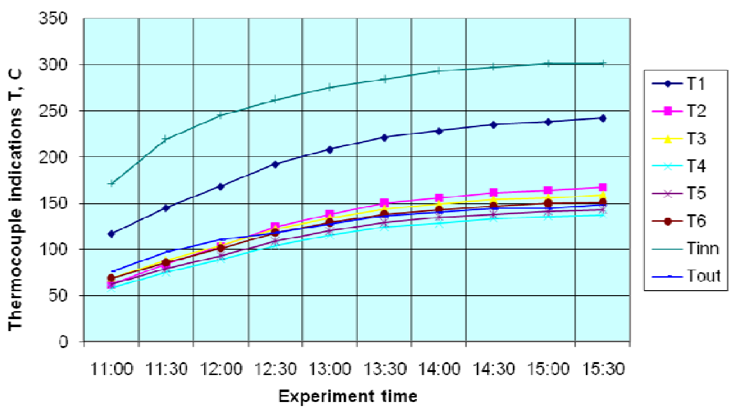

Figure 9. Thermocouple data for the thruster with magnetic system operation/heating mode

As a result of the two experimental phases temperature distribution has been obtained for two cases (see Table 3):

- Ohmic heating by magnetic coil currents
- Total thruster heating at nominal operation regime

It is important to note, that for the first case heat flux into the thruster elements is known, thus obtained preparatory results was used for simulation scheme verification.

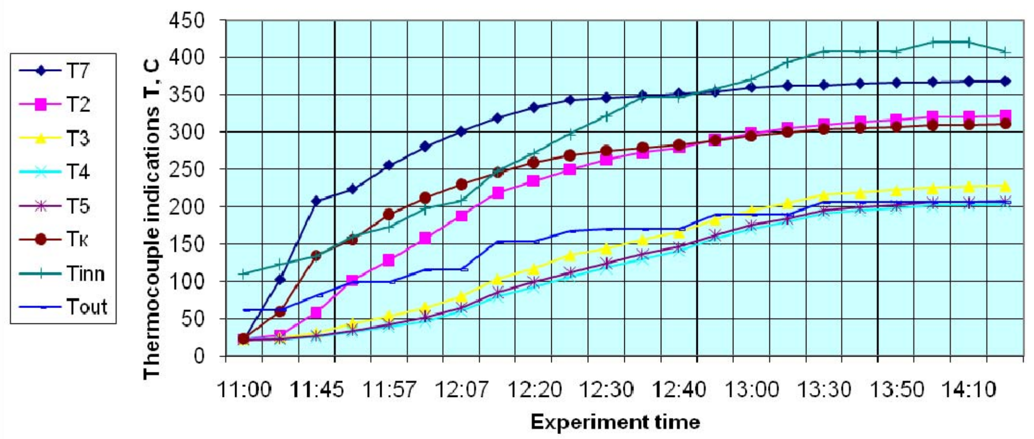

Figure 10. Thermocouple data for nominal operate mode

Table 3. Thruster mode parameters

	Thruster parts temperature T, C	
Mode	Magnetic system operate	Nominal mode
T1 – inner pole	242	–
T2 – thermal screen	167	322
T3 – mounting flange	159	228
T4 – mounting frame	137	203
T5 – cover	143	207
T6 – out pole	151	311
T7 – out guard ring	–	368
Tinn – Inner coil	301	407
Tout – Out coils	148	206

V. Getting thermal boundary conditions database

Obtained experimental temperature distribution and heat flux known for preparatory case allowed to determine and clarify boundary conditions. The boundary conditions were determined via following iterations:

- Preliminary calculations with pre-selected boundary conditions;
- Comparison of the calculated and experimental data;
- Correction of the boundary conditions in accordance with result of comparison (see Figure 12).

The iterations were made until the agreement between the calculations and experiment. The allowable difference between the data were not than 5% (see Figure 11).

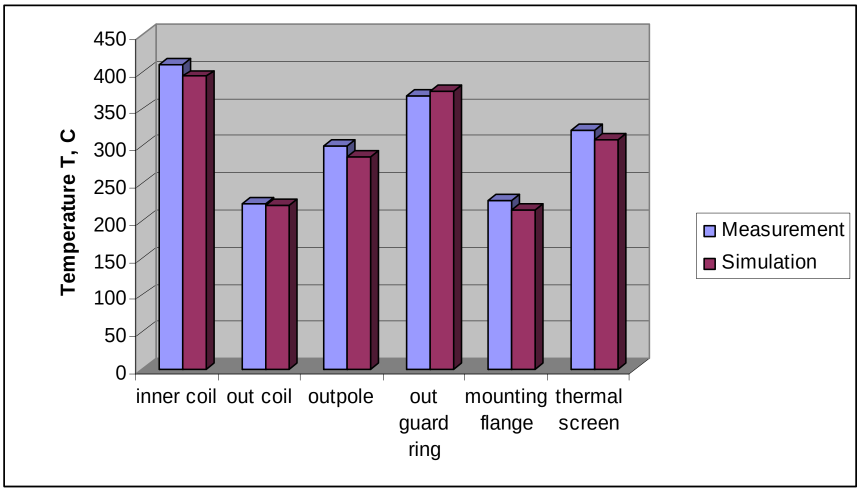

Figure 11. Final difference between the data

Finally the calculated temperature distribution was fully equivalent to the measured one. So that, one can conclude, that the boundary conditions selected for the final calculations are correct and represents real parameters of the used hardware and can be for further analysis of similar thrusters.

The performed study allowed to get correct data about heat dissipation in the thruster during operation. Heat flux from the discharge and magnet coil ohmic heating did not exceed 17% of total electric power consumption value of 1800 W.

Values of emissivity factor for thruster surfaces (shown in the Table) has been determined as a result of performed analysis.

Table 4. Boundary conditions Data base structure

Element	Value ε	Value Q, W
Out guard ring (inner side)	0.95	–
Out guard ring (out side)	0.88	
Inner guard ring (inner side)	0.91	–
Inner guard ring (out side)	0.97	
Anode (inner side)	0.25	90
Anode (out side)	0.21	
First stage cathode (inner side)	0.20	40
First stage cathode (out side)	0.24	
ect		

VI. Conclusion

Dedicated study of two stage anode layer thruster thermal mode has been performed. By the comparison of experimental data and results of calculations thermal boundary conditions and emissivity of the thruster surfaces have been determined and proven.

Obtained data base is the one necessary as well as for further thruster operation mode and design improvement as for development of a new thrusters implementing two stage scheme.

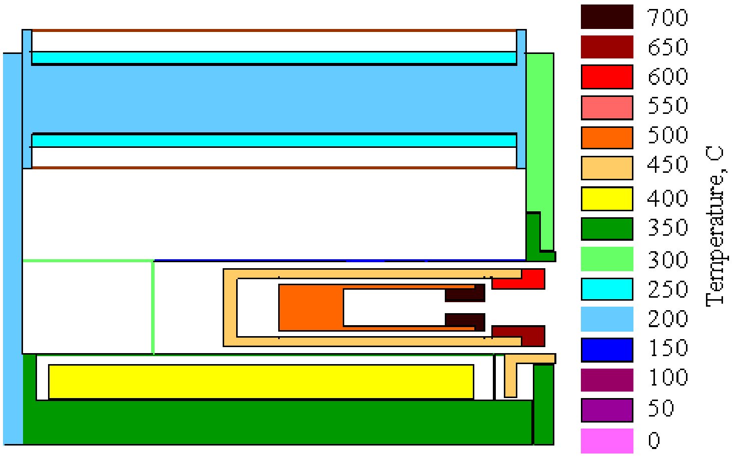

Figure 12. THeat1 final simulation results (presented temperature has averaged by thruster parts) operate mode

References

1 Solodukhin A.E., Semenkin A.V. "Study of discharge channel erosion in multi mode anode layer thruster", IEPC 2003-0204, 28th International Electric Propulsion Conference, March 17-21, Toulouse, France.

2 Solodukhin A.E., Semenkin A.V. "Operation of Two-stage Thruster with Anode Layer in "Floating Electrode" scheme", IEPC 2005-0145, 29th International Electric Propulsion Conference.