THERMAL ANALYSIS OF THE ANODE LAYER THRUSTER OPERATION

V. Garkusha, S. Semenkin, S. Tverdokhlebov.

Central Researche Institute of Machine Building, Moscow reg., Russia©

Abstract

Based on a concept of a regular heat regime a methodology of processing of a thruster temperature measurement is considered. As a result a radiated power and effective radiating surface are obtained for a number of TAL engines.

Introduction

Electric thruster, consuming a considerable part of the onboard power, is of a most power tense spacecraft part . The power which is absorbed by the thruster and after that radiated in a space may be of hundreds watts to several kilowatts. The emitting surfaces dimensions being limited, the thruster bulk is warmed up to temperatures about hundreds degrees. A certain part of the radiated power effects on the another spacecraft parts, heating them. That is why the assess of the heat fluxes coming out of thruster is an important constituent of a process of a thruster integration in spacecraft . This problem must has drown attention any team working in electric propulsion implementation in space programs [1,2].

The analog of the TAL heat regime based on mentioned specific features allows to get temperatures and heat fluxes estimations since a lack of data about heat transfer processes at the discharge area and shift of the emission ratios value along the thruster operation make the results been rather rough. That is why it is important for the heat problem to get experimental data of temperatures and heat fluxes and make modeling the heat release processes to obtain more precise initial data for modeling process

A useful information about a thruster heat parameters may be derived from the analysis of the temperature variation in time to be measured at a number of points of its surface at both the thruster heating after switch on or cooling after switch off. Such data processing is of considerable use at various heat apparatus evaluation. A base for so analysis is the concept of a regular heat regime [3].

Analysis

The regular heat regime considers a heat transfer process at its stage where the specimen initial state in a negligible part cause the process. At that stage the temperature field is governed by the law (T_w -is the environment temperature):

$$T(x, y, z, t) - T_w = T_0(x, y, z)\, e^{-at} \qquad (1)$$

Another words, the temperature field remains the self-similar to be varied only in magnitude with time. That means that as time passes the specific regime follows which distinctive feature is the linear variation with time of the logarithm of difference between the specimen and environment temperatures. And in this case the speed of so variation is identical for any specimen point.

The theoretical base for the regular heat regime is the Newton cooling law which was declared by Newton for heat transfer between a specimen and gaseous medium. It states the linear dependence the specimen temperature on the value of heat to be transferred. An electric thruster specific feature lies in its operation in vacuum, so that heat transfer goes by radiation and the dependence mentioned above is made nonlinear. Nevertheless under a certain conditions the electric thruster heat transfer may be reduced to the regular heat regime.

Any electric thruster consists of a set of parts to be exchanged by a heat. Supposing the part heat parameters to be constant, a heat problem for it may be described with a heat transfer equation:

$$c\rho(\partial T/\partial t) = \lambda \Delta T + p \qquad (2)$$

where - c, ρ, λ - are specific heat capacity, density and thermal conductivity for the piece we deal with;

T - piece temperature field;

p - heat release rate.

Heat transfer between pieces may be depicted by the following equation

$$-\lambda(\partial T/\partial \mathbf{n}) = q_1 - q_2 \qquad (3)$$

Where - **n** - unit normal vector at any point of the specimen surface and q_1, q_2 - heat to be radiated and accepted at the point of surface

Upon integrating (2) over the piece bulk we obtain

$$cm(\partial T_a /\partial t) = \lambda \int(\partial T/\partial n)ds + P$$

where m-piece mass; T_a - its average temperature; P - heat to be released in piece. Integration in the equation has to be performed over the piece surface, in appears as a result of application Gauss theorem to integration of ΔT over the piece bulk. After substitution (3) we obtain:

$$cm(\partial T_a/\partial t) = Q_2 - Q_1 + P \qquad (4)$$

where Q_1 and Q_2 - in their nature are result of integration of values q_1 and q_2 over the piece surface that describe outgoing and incoming heat.

Combining all equations like (3) for all pieces of electric thruster and taking into account that all terms which describe heat interchange between pieces to be mutually neglected so that only terms responsible for heat radiation into space and heat coming from surrounding walls we can write:

$$C(\partial T_a /\partial t) = -R (T_s^4 - T_w^4) + P_s \qquad (5)$$

here: $C = \Sigma_I c_I m_I$ - total body heat capacity;
T_a - average body temperature;
T_s - surface average temperature;
T_w - chamber walls temperature;
P_s - total released heat ;
$R = \sigma\Sigma_I \varepsilon_I S_I$ - summary radiant heat transfer ratio;
σ - Stephen - Boltzmann constant
$\varepsilon_i = 1/ (1/\varepsilon + (S/S_w)(1/\varepsilon_w - 1/\varepsilon))$ - reductant emissivity for i - piece component of body, which to be derived via the piece emissivity ε , the wall emissivity ε_w , wall surface area S_w and piece surface area S. As far as $S_w >> S$, we derive
$\varepsilon_i = \varepsilon$. If pieces emissivity differs slightly, we can derive

$$R = \sigma S_{eff} = \sigma \varepsilon_a S_a \qquad (6)$$

S_{eff} , S_a and ε_a are an efficient thruster surface of radiation, average thruster surface and efficient thruster emissivity correspondingly.

Note that in actual truth we have to summarize combinations like $c_I m_I T_I$ and $\varepsilon_I S_I T_I$ which include corresponding piece volume and surface temperatures. It is correct to factor out the temperature from the summarization symbol if the piece temperatures differ in minor value. Below is given the assessment for temperature dispersion.

Taking the left side of equation (5) to be zero that means that the body to be in the state of heat equilibrium, we gain the magnitude of surface equilibrium temperature for that state.

$$T_e^4 = T_w^4 + P_s / R$$

An important for practice case corresponds to regime of heating, at which a part of discharge power goes into the thruster body. Since almost always the discharge power P_s is much more than power to be radiated by walls, the last one may be neglected and the equilibrium temperature for operated thruster may be derived as

$$T_e = (P_s / R)^{1/4}$$

The another case corresponds to cooling regime where P_s is zero. For that case the thruster equilibrium temperature corresponds to wall temperature $T_s = T_w$.

Resolution for equation (5) is:

$$\ln(T_s - T) - \ln(T_s + T) - 2\operatorname{atan}(T/T_s) = -at \qquad (7)$$

(on the left side the substitution also made $kT_a = T_s$ where k, a scale factor, is constant because of self similarity of the regular heat regime, and describes a value of temperature distribution inuniformity inside the specimen bulk) and

$$a = 4kRT_e^3 / C$$

shows the rate of thruster heat transfer.

The temperature pace in time to be measured for a number of the thruster surface points at both its heating for operation mode and cooling for off mode allow to define the equilibrium temperature at warm-up state, and the rate of thruster heat transfer of which the thruster heat parameters so as a radiation ratio

$$R = aC/ 4kT_e^3$$

and power to be released in thruster

$$P_s = CaT_e / 4k \qquad (8)$$

may be determined.
Taking into account (6), we get appraisal for a efficient surface of radiation

$$S_{eff} = aC / 4 \sigma kT_e^3 \qquad (9)$$

To estimate a temperature dispersion let us make integration a boundary condition for every thruster piece $\lambda_I(\partial T /\partial n) = - \sigma\varepsilon T^4$ over that part of its surface which radiates in space and combine these equations. As a result we obtain

$$(\partial T_s /\partial n) = -RT_e^4 / \lambda_e = - P / \lambda_e$$

where $\lambda_e = \Sigma_I \lambda_I S_I$ -is efficient conductivity. Than we can estimate an average temperature (L_o -is average thruster length)

$$T_s \sim T_e - L_o (\partial T_s / \partial n) \sim T_e + L_o P / \lambda_e$$

and the temperature uniformity factor k may be derived as

$$k = T_e / T_s \sim 1 - L_o P / \lambda_e T_e$$

Experiment

Described procedure was used for processing data obtained at heat test thruster TAL-WSF. Fig.1 shows a general thruster scheme and points of temperature measurement to be used at following analysis. Fig.2 shows temperature variation in time for points chosen. The temperature dispersion over a thruster surface may be derived from the data. It does not exceed $dT < 15$ C°, or $dT / T_s < 0.03$, justifying advent of the average surface temperature at equation (5).

Plots of Fig.3 show result of employment of the procedure (7) to the temperature curves of Fig.2. As a T_e the temperature of last measurement was taken. It was corrected yet by addition $dT \sim 5$C°. The addition is necessary since the last measured temperature is slightly less than a real equilibrium temperature that may be reached by thruster operation for a long additional time. At the time range from 2000 up to 8000 seconds the said plots to a good accuracy may be approximated by a straight lines with almost equal declination. The magnitude of dT, mentioned above has been chosen so that the plots become mostly like straight lines.

The thruster dimensions and heat parameters to be needed for further analysis are shown below

Thruster mass	$M_t = 2200$g
Average thruster surface	$S_a = 530$ sm^2
Average specific heat capacity	$\lambda = 0.440$ W/ gK°
Typical length	$L_o = 10$sm

Table 1 represents values for equilibrium temperature T_e for each point of measurement and speed of heat transfer which is nothing but tangent of declination angle for lines of Fig 3. Further columns of the Table 1 contain values for released power P_s , efficient radiant surface S_{eff} and efficient thruster emissivity to be found by using (6), (8) and (9).

Table 1.

	T_e (K)	$a \cdot 10^4$ (1/s)	P_s (W)	S_{ef} (cm^2)	ε_a
T1	497	6.2	75	218	0.42
T2	513	5.8	72	187	0.36
T3	497	5.9	71	207	0.40
T4	503	6.3	76	213	0.41

For the cooling mode The temperature variation only for point T1 has been measured. Values of the thruster effective surface and emissivity to be defined are pointed out below

$a = 8.92 \cdot 10^{-5}$ (1/s) $S_{ef} = 189.6$ (cm^2) $\varepsilon = 0.36$

Comparison with data of the Tab. 1 shows a satisfactory coincidence.

Tab. 2. contains results of processing data for thruster operation power level 1350W . The temperatures had been measured at two points that correspond to points T1 and T[illegible] Of Fig1.

Table2

	T_e (K)	$a \cdot 10^4$ (1/s)	P_s (W)	S_{ef} (cm^2)	ε_a
T1	585	8.4	119	180	0.34
T2	593	8.9	128	183	0.35

And Table 3 contains data for D-100 TAL at cooling regime. The points of the temperatures measuring correspond to T1 and T6 of Fig1.
The thruster mass and thermal data are presented below:

Thruster mass	$M_t = 7900$g
Average thruster surface	$S_a = 1100$ sm^2
Average specific heat capacity	$\lambda = 0.440$ W/ gK°

Table 3

	$a \cdot 10^4$ (1/s)	S_{ef} (cm^2)	ε_a
T1	0.47	275	0.25
T6	0.58	337	0.30

Conclusions.

The proposed method of processing an experimental data of temperature variation in time allows to determine important parameters of the thruster as a heat engine so as an average emissivity and power released. Despite their importance both of them are as a rule unknown for a real thruster engine. A reliable emissivity determination for bodies of a complicated shape and composed of parts with different emissive capabilities usually uses just similar procedure for a body cooling mode. We offer to use both the cooling and heating modes to get more data for analysis and comparison.

The heating mode makes it real to define a very important but a most up to now vague parameter as a the value of heat coming into thruster elements from the discharge area. The upper limit of it may be estimated easily, it is W(1-h) where W is thruster power and h is its efficiency. It is clear nevertheless that a certain part of that power is utilized for ionization, the another one is utilized for cathode operation and unknown part may be emitted by the anode in space. That is why it is not easy task to estimate the power going to a thruster body. The procedure proposed allows to do that.

It is necessary to make a number of remarks relating the procedure implementation. First, the data obtained by procedure the more accurate the less difference between the body and surface temperatures so that the factor k in (7) might be taken as unit, that means that power exchange between a thruster parts is more intense than power emission in space. The same might be said about the surface temperature deviation over the surface points. That means that the procedure is applicable if power flows along the surface are less intense than the emission. If so part exists that its temperature is dramatically differs from temperatures of another parts, that means that it is thermally insulated from another ones and must be considered separately.

References

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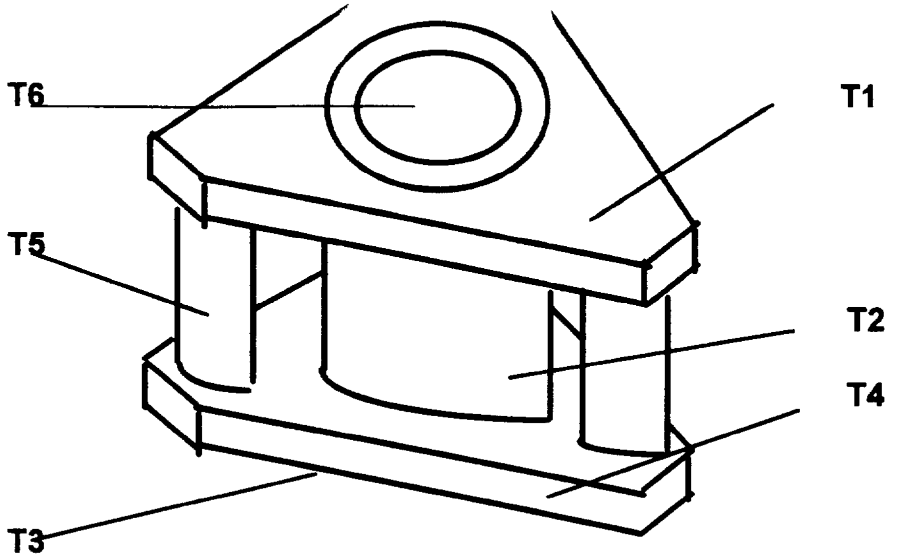

Fig.1 TAL-WSE schematic and points of temperature measurement.

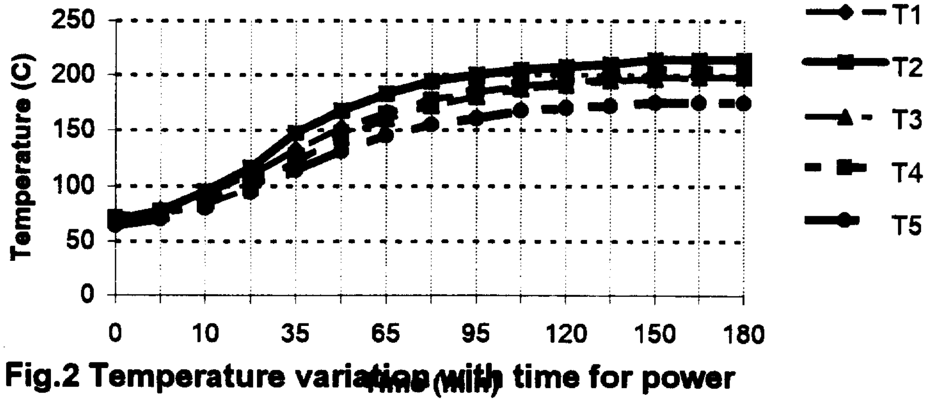

Fig.2 Temperature variation with time for power 0.6kW

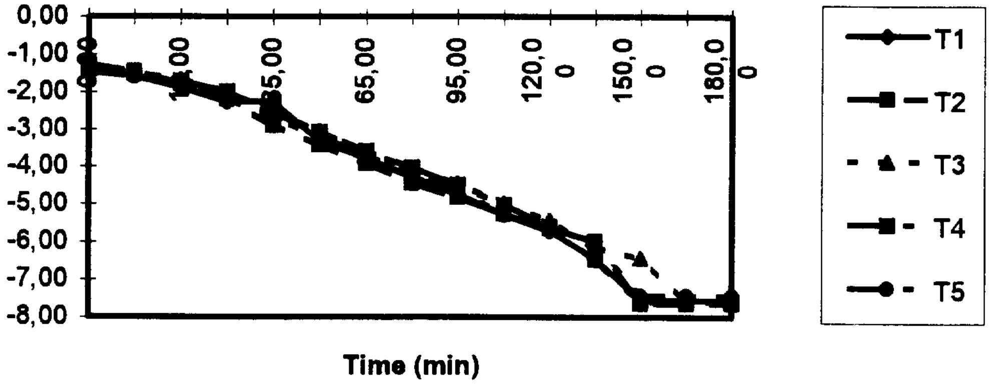

Fig.3. Temperature data to be processed by eq(..)