A small spacecraft microengine with SHF impact on working medium: cooling and dilatometric evaporator valve

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Abstract. The results of experiments and a theoretical research of a cooling method for SHF-transistor crystal of a correcting small spacecraft (SS) microengine are presented. A distinctive feature of a proposed approach is an efficient use of the heat removed from SHF-transistor in the dilatometric evaporator-valve. Generally, this paper continues to create methodological foundations for a design of a correcting SS microthrust engine with SHF-heating of a working medium. This paper is about cooling of SHF-transistor in vacuum with the application of removed energy in a dilatometric valve and for preliminary heating of a working medium before its input to the SHF-chamber. A mathematical model of SHF transistor crystal cooling by the working medium was verified as a result of studies. In case of certain geometrical and initial thermodynamic conditions are met, the intensity of cooling increases and heating of working medium also increases (micro consumption of air cools the experimental surface by 1 W). The heating of working gas, according to theoretical processing, is suffice to create a jet thrust of 1.2 mN. The application field of studied physical processes is the engine-building for small spacecrafts, for example CubeSat 3U, in particular, building of a microengine with SHF-acceleration of a working medium and a dilatometric throttle valve.

1. Introduction

The authors of this article repeatedly emphasized in previous papers [1, 13] that a low thruster design of very small spacecrafts (VSS) involves a number of restrictions which are:
– low VSS power;
– small VSS weight and dimensions;
– possibilities of an orientation control system.

In this regard the implementation of a «Swiss knife» concept in the development of VSS microengines, when one structural element performs more than one function in the operation of a propulsion system (PS) is relevant for those microengines. The application of this concept reduces the nomenclature of PS elements that will directly lead to reduction of weight, dimensions and power consumption. This poses a question on efficient use of dissipative energy, which, generally, irreversibly passes in the space. The utilization of dissipative energy allows us to increase the PS overall efficiency.

The dissipative energy in an electrothermal microengine (ETME) with SHF-heating of a working medium is a heat flow emerging in a solid-state SHF-generator under its normal operation. In solid-state SHF-generators basic elements are SHF-transistors which normal operation requires convective cooling. Such devices are usually mounted on massive metal plates providing heat removal onto an external case or in the ambient space by means of convection and emission. For example, the operation of high-power LDMOS-transistors can heat surrounding equipment to 60°C [2].

An operating temperature of a transistor's crystal affects greatly the output power, as well as, the device efficiency. Promising carbide-silicon SHF-transistors can provide preset specifications if a crystal temperature is up to 255°C [3].

Data on temperatures are given for the research performed "in open air" when a convective heat exchange provides a considerable heat removal from a transistor case. In vacuum the temperature of a case as experimental studies showed, can be 100–120°C higher.
The efficiency of SFH-transistors is in the range of 40 to 70% now. For example, high-power generator SFH-transistor KT9197B with the output power of 5 W has the efficiency of 55% [4], dissipative power losses are 4 W. Regarding to high-power PS (with power consumption of 60-100 W) especially as for large SS, these values can be neglected. However, the propulsion system in case of VSS can be provided only with 5-7 W to work without any negative effects on the main systems. In this case it is necessary to utilize all possible power opportunities of a spacecraft and to minimize losses.

2. Problem statement
The “Swiss knife” concept was embodied in an electrothermal microengine of VSS as a power element of a throttle evaporator-valve representing a rod radiator with an internal gas conduit (fig. 1).

Graphite heating elements (GHE) mounted in channels of base-plates created a heat flow of a certain value and a thermocouple installed in a plate registered the value of equilibrium temperature of 250 °C “in open air” tests without installation of a rod radiator. Thus the electric power required for imitation of heat effects arising during the work of a carbide - silicon SHF-transistor was defined. The basis of a rod and a radiator-rod represent a non-assembled element, in the basis of which there is a gas conduit entering the gas conduit of the rod. Gas in its motion made a double path: from an inlet through a capillary pipe to a dead-end area and back via an annular gap to the rod basis and an outlet in the ambient space. The rod basis was fixed on the heated plate by means of the dovetail lock (joint).

Components and materials’ characteristics of the experimental sample, necessary for a theoretical analysis, are given in table 1.

An experimental study was divided into several interrelated stages:
stage 1: a research of heat transfer of a heated plate in vacuum;
stage 2: a research of heat transfer of a heated plate with a rod radiator installed in vacuum;
stage 3: a research of heat exchange of a heated plate with the installed rod radiator and a gas flow in a gas conduit in vacuum.
### Table 1. Elements of the experimental sample and the properties of materials

| Name / Image | Typical dimensions, mm | Emissivity factor, ε | Thermal conductivity coefficient, λ, W/(m · K) |
|--------------|------------------------|----------------------|-----------------------------------------------|
| **A heated plate** | | | |
| Aluminium | 64×33.5×6 | 0.33 | 220 |
| **A rod-radiator** | | | |
| Aluminium | Ø10×100 | 0.045 | 155 |
| Duralium | Ø2.5×95 | 0.03 | |
| **A rod basis** | | | |
| Aluminium | 13×33.5×5 | 0.33 | 220 |
| **GHE** | | | |
| Corundum, graphite | Ø3×35 | 0.7 | 3.34 |

3. **Theory**
At stage 1 the heated plate was placed in a vacuum chamber, 19.4 W heat flow was fed to the plate from GHE, the plate temperature was measured by three thermocouples, one of them (thermocouple 3 in fig. 1 and 2) was arranged inside the plate, the others were placed on the plate surface. In fig. 2 the temperature
dependence of the plate versus heating time according to the results of experiment is shown. We can see that equilibrium temperature of a plate takes value 288 °C.

The purpose of a theoretical study in stage 1 was the verification of power balance equation which for the “GHE-plate” system looks like:

\[ P_{el} = P_{emi,GHE1} + P_{emi,GHE2} + P_{emi,PL}, \]  

(1)

where \( P_{el} = 19.4 \text{ W} \) is instrument electric power brought to the plate from GHE; \( P_{emi,GHE1} \) and \( P_{emi,GHE2} \) are respectively, the power emitted by extending areas of GHE and power losses in GHE areas in channels of the heated plate;

\( P_{emi,PL} \) is the power emitted by the plate surface in the ambient space.

\[ P_{emi,GHE1} = \sigma \cdot T_{GHE}^4 \cdot \varepsilon_{Al,O_3} \cdot F_{Ext}. \]  

(2)

where \( \sigma \) is a Stefan-Boltzmann constant; \( \varepsilon_{Al,O_3} \) is the emissivity factor of the GHE case (the value is determined by [6] and provided in Tab. 1). \( T_{GHE} \) is a GHE ceramic surface temperature which is defined by the power balance equation for steady thermal conditions when the entire electric power is used for the radiation from GHE ceramic surface with the total square \( F_{GHE} \):

\[ P_{el} = \sigma \cdot T_{GHE}^4 \cdot \varepsilon_{Al,O_3} \cdot F_{GHE}. \]  

(3)

The value of losses in the transfer by the emission from the GHE ceramic surface to the internal cylindrical surface of plate’s channels is defined as the difference between the brought heat flow and the heat flow absorbed by the plate [7]:

\[ P_{emi,GHE2} = \sigma \left( T_{GHE}^4 - T_{PL}^4 \right) \cdot \varepsilon_{RE} \cdot F_{GHE,PL}. \]  

(4)

where \( T_{PL} \) is a temperature of the heated plate;

\[ \varepsilon_{RE} = \frac{1}{\varepsilon_{Al,O_3}} + \frac{F_{GHE,PL}}{F_{CHA,PL}} \left( \frac{1}{\varepsilon_{Al,O_3}} - 1 \right) \]

is a reduced emissivity factor of the bodies system [7];

\( F_{GHE,PL} \) is the area of the GHE emitting surface covered by the internal cylindrical surface of the plate channel \( F_{CHA,PL} \); \( \varepsilon_{Al} \) is an emissivity factor of a plate material (its value is determined by [8] and provided in table 1).

The heat emission from the whole surface of the heated plate \( F_{PL} \) to (ambient) space is defined in accordance with the Stefan-Boltzmann law:

\[ P_{emi,PL} = \sigma \cdot T_{PL}^4 \cdot \varepsilon_{Al} \cdot F_{PL}. \]  

(5)
Solving equations (1–5), we obtained the required theoretical heating plate temperature $T_{PL}$.  The experimental and obtained calculated values are given in table 2.

At stage 2 the heated plate with the rod radiator were placed in a vacuum chamber. The heat flow with the power of $19.4\ W$ was brought to the plate from the GHE, the plate temperature was measured by a thermocouple, the rod temperature was measured in the middle point (thermocouple 2, fig. 1) and in the upper point (thermocouple 1, fig. 1).

In fig. 3 the dependence of plate temperature versus heating time according to the experiment results is shown. We can see that the equilibrium temperature of the plate is $195\ ^\circ\mathrm{C}$.

![Figure 3. Results of the experiment on the heat transfer of a plate with a rod in vacuum](image)

The purpose of a theoretical research at stage 2 was to define the quantity of heat emitted by a rod to the ambient space in a form of emission.

The quantity of heat transferred by the entire surface of the rod $F_{RO}$ for a finite length $L_{RO}$ and a diameter $D_{RO}$ in heating of one side up to the temperature of $T_{H,RO}$ can be defined, using the formula [9]:

$$
\begin{align*}
  P_{em,RO} &= \frac{\alpha_L}{m \cdot \lambda_{DAL}} + \frac{thm \cdot L_{RO}}{1 + \frac{\alpha_L}{m \cdot \lambda_{DAL}}} \\
  \end{align*}
$$

where $\lambda_{DAL}$ is a duralumin thermal conductivity coefficient (it is defined by [10] and provided in table 1); $\alpha_L$ and $\alpha_{EF}$ are respectively heat-transfer coefficients of a rod lateral surface and of its end face (these values are different since there is an electroplating on a rod surface, but an end face is processed by a lathe). Heat-transfer coefficients in case of radiation heat transfer depend on a body temperature and a surface emissivity factor (values of emissivity factors are defined by [11] and given in table 1).

On the other hand, the heat flow emitted by the rod is a part of heat transferred from the heated plate to the rod basis in a direct contact of surfaces in the dovetail lock. Thus, the same value $P_{em,RO}$ can be expressed by the heat transfer between two flat walls taking into accounting heat emission of power in vacuum [9]:

$$
\begin{align*}
  P_{em,RO} &= \frac{\theta}{\lambda_{Al}} \cdot \frac{T_{PL,exp} - T_{H,RO}}{T_{H,RO} - T_{bas,RO}} \cdot F_{CON} \\
  \end{align*}
$$

where $\lambda_{Al}$ is an aluminium thermal conductivity (the value is defined by [10] and given in table 1); $\theta$ is a basis thickness of a rod; $T_{PL,exp}$ is a temperature of heated plate according to the experiment results ($195\ ^\circ\mathrm{C}$); $F_{bas,RO}$ is an area of a rod in a site of contact with the basis; $F_{bas}$ is an emission surface area of a rod basis which is not shaded by its end face surface; $F_{CON}$ is a contact area of a rod basis with a heated plate.

A simultaneous solution of the equations (6) and (7) gives the value of temperature $T_{H,RO}$ (table 2). From the equation (6) we obtain the rod emission power $P_{em,RO}$ (table 2).
The Pem.RO value can also be defined in a different way, if to consider the emission power of a rod radiator as the difference between the heat flow brought from GHE and the emission power of a free plate surface (the area of a heated plate minus the area covered with a rod basis):

\[ P_{em,R0} = P_{em} - P_{em,PL2}. \]

Here \( P_{em,PL2} \) is defined according to the formulas (1–5) taking into account a new experimental temperature \( T_{PL,exp} \), which is reduced by the value of a plate square covered with its basis. The calculated value is given in table 2.

For verification of calculation results we have to construct a diagram of temperature distribution along the rod length and compare it with experimental values. To construct the temperature diagram we can use the formula [9]:

\[
T(x) = T_{H,R0} \left\{ 1 - \frac{\alpha_f}{m \cdot \lambda_{DL}} \right\} e^{\alpha_f \cdot x \cdot \lambda_{DL}} + \left\{ 1 + \frac{\alpha_f}{m \cdot \lambda_{DL}} \right\} e^{-\alpha_f \cdot x \cdot \lambda_{DL}}. \]

Parameters in the formula (9) are the same, as in the formula (6).

The diagram constructed by the formula (9) is shown in fig. 4. The comparison of calculated values and experimental data is given in table 2.

Figure 4. Temperature distribution along the length of the rod

At stage 3 a heated plate and a rod radiator were placed in a vacuum chamber. Gas (air) with the volume flow rate \( Q_{air} = 6.007 \times 10^{-6} \text{ m}^3/\text{s} \) (it was defined by PM-A-0.063 GUZ rotameter) and inlet pressure \( p_{air} = 14665 \text{ Pa} \) in a gas conduit (according to a manometer installed in the vacuum chamber) was fed via the internal gas conduit. The heat flow with the power of 19.4 W was brought to the plate from GHE, the plate temperature was measured by thermocouple 3, the rod temperature was measured in a middle point (thermocouple 2, fig. 1). Fig. 5 shows the dependence of the plate temperature versus heating time, which is constructed on the results of experiments. We can see that the equilibrium temperature of the plate is 173 °C.
Figure 5. The results of the experiment on the heat transfer of a plate with a rod in vacuum with the of supply gas (the area of attainment of the equilibrium temperature is shown).

The purpose of theoretical research at stage 3 is to determine the value of gas heating when it flows through the internal gas conduit.

Heat exchange between gas and a heated body is described by Newton-Richmann formula [9]:

$$ P_{\text{GAS}} = \alpha \left( T_{\text{AIR}} - T_{\text{RO}} \right) \frac{\pi}{L_{\text{EQU}}} \cdot \frac{D_{\text{EQU}}}{4} $$

(10)

where $\alpha$ is a heat-transfer coefficient from a gas conduit surface to the air; $L_{\text{con}}$ is a gas conduit length in a rod; $T_{\text{AIR}}$ is a temperature to which air will heat up in its flow in the gas conduit. $D_{\text{equ}}$ is an equivalent gas conduit diameter equaled a quadruple square of a gas conduit cross section divided into its entire perimeter [9].

The coefficient $\alpha$ is defined by Nusselt number:

$$ \alpha = \frac{N_{\text{U}} \cdot \lambda_{\text{AIR}}}{L_{\text{con}}} $$

(11)

where $\lambda_{\text{AIR}}$ is an air thermal conductivity coefficient under pressure in a gas conduit.

The Nusselt number is determined by an empirical dependence for particular flow conditions in a gas conduit. The Reynolds number is defined to establish flow conditions:

$$ \text{Re} = \frac{4 \cdot Q_{\text{AIR}}}{\pi \cdot D_{\text{EQU}} \cdot \eta_{\text{AIR}}} $$

(12)

where $\eta_{\text{AIR}}$ is a dynamic air viscosity under pressure in a gas conduit.

Dynamic viscosity of rarefied polyatomic gas at the gas conduit input $\eta_{i}$ and with a wall temperature $\eta_{\text{wa}}$ can be calculated as a function of empirical parameters [12]:

$$ \eta_{i}(\eta_{\text{wa}}) = 2.6693 \cdot 10^{-6} \cdot \frac{M_{\text{AIR}}}{\sigma_{A}^{2}} \cdot \frac{T_{i}}{\eta_{\text{WA}}} $$

(13)

where $M_{\text{AIR}}$ is an air molecular weight; $T_{i}$ is an air temperature at a gas conduit input and $T_{\text{WA}}$ is a wall temperature, $\sigma_{A}$ is a diameter of molecules, angstrom; $\Omega_{\eta}$ is a slowly changing function of a dimensionless temperature [12].

The calculation of $\text{Re}$ number showed that it is in a range of $10<\text{Re}<1 \cdot 10^{4}$. According to [9] an average heat-transfer coefficient can be determined by the formula:

$$ N_{\text{U}} = 4.1 \cdot \left( \text{Re} \cdot \frac{D_{\text{EQU}}}{L_{\text{EQU}}} \right)^{0.4} \cdot \left( \frac{\text{Pr}_{i}}{\text{Pr}_{\text{WA}}} \right)^{0.33} \cdot \left( \frac{\text{Pr}_{i}}{\text{Pr}_{\text{wa}}} \right)^{0.25} $$

(14)

where $\text{Pr}_{i}(\eta_{i}) = \frac{\eta_{i}(\eta_{\text{wa}}) \cdot c_{\text{P}}(T_{\text{WA}})}{\lambda_{i}(\lambda_{\text{WA}})}$ are Prandtl numbers for a gas temperature at the inlet in a gas conduit ($\text{Pr}_{i}$) and for a temperature of a gas conduit internal wall ($\text{Pr}_{\text{wa}}$).
Isobaric heat capacities of air under thermodynamic parameters in a gas conduit (at the inlet in a gas conduit $c_{p,\text{air}}$ and with a temperature of a gas conduit wall $c_{p,\text{wa}}$), can be expressed by Van der Waals heat capacity of gas:

$$c_{p,i}(c_{p,\text{wa}}) = \frac{R}{1 - \frac{2a_{\text{air}} \cdot \rho_{\text{air}}}{T_i(T_{\text{wa}}) \cdot R \cdot M_{\text{air}}} \left(1 - \frac{b_{\text{air}} \cdot \rho_{\text{air}}}{M_{\text{air}}}ight)^2 + \frac{5 \cdot R}{2}} - \frac{1}{M_{\text{air}}},$$  \hspace{1cm} (15)

where $R$ is a universal gas constant; $a_{\text{air}}$ and $b_{\text{air}}$ are Van der Waals constants for air; $\rho_{\text{air}}$ is an air density with pressure $p_{\text{air}}$ (which is determined by the Van der Waals equation); $T_i$ is an air temperature at the inlet of a gas conduit and $T_{\text{wa}}$ is respectively, a temperature of a gas conduit wall.

Heat conductivities of rarefied air (at the inlet in the gas conduit $\lambda_i$ and with the temperature of gas conduit wall $\lambda_{wa}$) can be estimated by the dependence [12]:

$$\lambda_i(\lambda_{wa}) = 8.322 \cdot 10^{-2} \cdot \frac{\sqrt{M_{\text{air}}}}{\sigma_i^2 \cdot \Omega_i},$$  \hspace{1cm} (16)

where $\Omega_i$ is an integral which numerical value is calculated within the model of potential of Lennard-Jones intermolecular interaction [12].

To determine a heat flow value selected from a rod by the air when it flows in a gas conduit it is necessary to define a heat flow value given by the rod to the ambient space. The technique of its definition is described at stage 2. The equations (6) and (7) are solved simultaneously taking into account that at stage 3 it is necessary to define a heat flow value given by the rod to the ambient space. The technique of its definition is described at stage 2. The equations (6) and (7) are solved simultaneously taking into account that at stage 3 it is necessary to define a heat flow value given by the rod to the ambient space.

Heat flow selected by gas can be obtained as the difference of a heat flow of a rod without gas and a heat flow of a rod when the air flows in a gas conduit:

$$P_{\text{GAS}} = P_{\text{emi.RO}}(P_{\text{emi.RO}}^\prime) - P_{\text{emi.RO}}.$$

Here $P_{\text{emi.RO}}^\prime$ is defined by the formula (8).

Calculated values of the power for gas heating are given in table 2.

Solving the equations (10–17) we obtain the required air temperature $T_{\text{air}}$ of a rod at the outlet of a gas conduit (table 2).

Knowing the gas temperature we can estimate the velocity of particles motion at the outlet of a gas conduit. For this purpose we shall use the equation of average kinetic energy of molecules motion for monoatomic gas which, according to the experimental data, can be used for polyatomic gas (calculation is provided for nitrogen as a predominant component in a mixture):

$$v = \sqrt{\frac{3 \cdot k \cdot T_{\text{air}}}{m_{\text{N}_2}}}$$

where $k$ is a Boltzmann constant; $m_{\text{N}_2}$ is a nitrogen molecular mass.

Calculated values of the velocity are given in table 2.

If to consider ETME as a test sample which work results in a creation of a jet thrust then it can be determined by the formula:

$$R_{\text{ETME}} = Q_{\text{air}} \cdot \rho_{\text{air}} \cdot v.$$  \hspace{1cm} (19)

The results of calculation are given in table 2.

It should be noted that the obtained thrust value satisfies the requirements of the orientation control system of VSS. The gas was heated from a radiator-rod which temperature did not exceed 110 °C.

### Table 2. Results of experimental studies and theoretical analysis

| Indicator                                      | Experimental value | Calculated value |
|-----------------------------------------------|--------------------|------------------|
| An equilibrium temperature of a heated plate  | 561/288            | 572.507/299.507  |
| at stage 1, TPL, K / 0C                       |                     |                  |
| An equilibrium temperature of a hot end of a  | 380.05/107.052     |                  |
| rod at stage 2, TH.ST.RO, K /0C              |                     |                  |
| A heat flow removed by a radiator-rod at      | -                  | 7.007/6.481      |
| stage 2, $P_{\text{emi.RO}} / P_{\text{emi.RO}}^\prime$, W |         |                  |


A temperature of a rod middle at stage 2, °C 
A temperature of a rod end at stage 2, °C 
An equilibrium temperature of a hot end of a rod at stage 3, T_{HRD}, K / °C 
A heat flow removed by a radiator-rod at stage 3, P_{em,ROD}, W 
A heat flow removed by the air at stage 3, P_{GAS}, W 
An air temperature at a gas rod outlet at stage 3, K 
A velocity of nitrogen molecules in air, v, m/s 
A thrust of ETME as an experimental sample, P_{ETME}, mN

4. Results of experiments

Three experimental stages of studies with theoretical processing of each stage were conducted in a course of problem solving of SHF-transistor cooling with a micro consumption of working gas. The results of experimental study and theoretical analysis are provided in table 2. The data on heating dynamics of sample elements obtained in the course of experimental studies are given in fig. 2, 3 and 5.

A mathematical model of cooling for SHF-transistor crystal by a gas working medium have been verified as a result of researches. It is shown that if particular geometrical and initial thermodynamic conditions are met, the intensity of cooling increases, and a heating value of the working medium grows (micro consumption of the air cools the experimental surface by 1 W). The heating of working gas, according to theoretical processing, is suffice to create a jet thrust of 1.2 mN with the gas exit velocity of 1000-1200 m/s.

5. Discussion of results

In the course of experimental and theoretical work the main results essential to further studies have been obtained:

1. The mathematical model describing thermal processes for a gas flow of small volume in a gas conduit of a heating element is verified;
2. The value of a heat quantity selected by gas when it moves in a gas conduit of the sample is obtained experimentally. This value allows us to make a conclusion about a large value of kinetic temperature of gas at the gas conduit outlet and a high value of a specific thrust impulse.

6. Conclusion

Thus we can draw the following conclusions:

1. As for a cooling capacity of a rod radiator and a gas conduit we should note that in case of large rods with a big emitting surface (as in the experiment described) the role of air capillary cooling is not substantial since the gas removes no more than 1.5 W of heat power with 19.4 W fed. Due to the air-cooling, a symbolic crystal of SHF-transistor was “22 °C colder”, than without it. However the rod radiator cooled the symbolic crystal of SHF-transistor by 104 °C. In case of small emitting surfaces and low power inputs (up to 7–10 W) the cooling effect of gas increases;
2. The first paragraph entails the conclusion that a rod radiator and an internal gas conduit can be efficiently utilized as a working body preheater of a microengine since with small gas consumptions it is possible to obtain a high extent of gas heating and a high specific impulse of the thrust;
3. Concerning a dilatometric effect and a possible use of a rod as a throttle valve plunger we may say that there is no sense to use directly the material of a rod in a dilatometric drive at temperatures up to 110 °C. This is due to a small coefficient of thermal extension in metals. We propose to introduce an intermediate element in a form of a polymeric (epoxy resin, ebonite, polyethylene, fluoroplastic) tube in a structure. A thermal expansion coefficient of the tube is 10-15 times higher, than for metals.

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