Development of electric heaters with increased efficiency of unpressurized designed space vehicles

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Abstract. Ensuring the temperature mode of operation of the equipment and spacecraft units in a given temperature range and maintaining a balance between the received thermal energy and its impact with the redistribution of thermal energy between the structures of the apparatus is an important technical task. The authors have presented the main results and stages of development of electric heaters for unpressurized designed space vehicles based on the photolithography method and etching of the resistive layer, allowing to produce flexible film heaters of various shapes and sizes using materials produced by domestic industry in the framework of the import substitution program, with reduced mass-dimensional characteristics and high efficiency. The proposed method can be used to manufacture electric heaters of various designs, forms and properties: flexible, flat, flexible-flat, three-dimensional forms, with a given level of manufacturability and quality when creating modern and promising spacecraft. The presented results can be used in other areas of technology, where electric heating elements are made and used with given geometric properties, strength characteristics and normalized thermal output.

1. Introduction

The construction of modern unpressurized designed spacecraft with imposes special requirements on the thermal control system, which should ensure the maintenance of its other systems in working condition during the active lifetime under the influence of space conditions with a significant temperature difference. Ensuring the operation temperature mode of the spacecraft equipment and assemblies in a given temperature range and maintaining a balance between the received thermal energy and its impact with the redistribution of thermal energy between the spacecraft structures is an important technical task [1].

The increased requirements for the thermal control system impose special requirements on the active actuators of the system – electric heaters and their technical characteristics.

We list technical requirements for the perspective electric heaters’ characteristics:

- work resource in the spacecraft for more than 20 years;
- temperature range of use is from −125°C to + 125°C;
- permissible heating temperature of more than + 125°C;
- set geometrical dimensions: length, width, thickness;
- strength characteristics: flexibility, resistance to mechanical and radiation effects;
- reservation of the heating function is not less than double;
- specific heat load is more than 2 W/cm²;
- insulation resistance of at least 500 MΩ;
- the variation of electrical and thermal parameters is not more than 10%;
- mechanical strength of the electric heaters current leads – pullout load not less than 1 kg;
- resistance reduced to the heating area is not less than 100 Ohm / cm²;
- manufacturability [2].

2. Development stages of design and technological solutions

In order to obtain an electric heater with the necessary technical characteristics, authors, on an initiative basis, have carried out the work on the materials selection and on the new design and technological solutions development, which can be applied in the production of electric heaters in the conditions of existing production. The work consisted of five stages.

2.1. Manufacturing method of electric heaters

At the first stage, an unparalleled manufacturing method of electric heaters [3] was developed which is based on using the photolithography method and etching the heating resistive layer to obtain the required pattern of conductors by pressing the layers, soldering the current leads and testing them. The use of a photoprocess to create a pattern of a resistive layer and a chemical reaction of metal removal allows the production of various geometric shapes and sizes layers without using mechanical devices [4]. The first experimental model of an electric heater is shown in figure 1.

![Figure 1. Photo of the experimental flexible film heater.](image)

The samples for shear strength determining were cut from the experimental electric heater in order to determine the mechanical strength according to the industry-specific methodology. Figure 2 shows the layout of the sample.

![Figure 2. Scheme of samples for determining shear strength: 1 - flexible glass fiber with a binder; 2 - constantan foil; 3 - flexible glass fiber without binder.](image)

2.2. Tests to confirm performance

At the second stage, to confirm the compliance of the design, technological, technical and operational characteristics of electric heaters with the requirements imposed on the resource; reliability and efficiency of the new generation electric heaters for use in unpressurized designed spacecraft, electric heaters were installed with adhesive on the honeycomb panel and tested under normal conditions to
confirm performance. Figure 3 shows one of the electric heaters of the dimension range products, installed with adhesive on the spacecraft honeycomb panel for testing with the following characteristics:

- heating surface area – 21.7 cm²;
- track width – 3.5 mm;
- distance between tracks – 2.0 mm;
- loading density – 0.64;
- material of the resistive layer – constantan;
- weight without wires – 1.46 g.

Figure 4 shows the temperature field of the electric heater while testing, taken with a thermal imager.

This electric heater provided the release of heat load density $P = 2.2 \text{ W/cm}^2$ with the temperature difference between the electric heater and the heated surface $\Delta T = 50^\circ\text{C}$.

2.3. Development of etching and soldering technology

At the third stage, in order to increase the efficiency and expand the possibilities of using electric heater as a resistive layer, we worked at using thin foil made of an alloy with high electrical resistance of the X20H80 grade (nichrome) [5], which made it possible to obtain an increased specific electrical resistance of the electric heater. In addition, nichrome has a high heat resistance, resistance to cracking and plasticity, keeps its shape well. Nichrome is a promising material for manufacturing high-resistance flexible film heaters.

The resistance of the electric heaters with the same width of the track is twice as large (compared to constantan), which ensures the transition of the electric heater’s power supply to the 100V bus [6]. The use of nichrome imposes increased requirements on the technologies of etching the resistive layer and soldering the current leads. It is necessary to reduce the amount of lateral subtrain of the nichrome resistive layer and reduce the soldering temperature of the wires to the contact pads.

To etch nichrome the etching mode of a constantan resistive layer was originally applied. Upon completion of the etching operation we made measuring the width of conductive tracks at ten random points of each electric heater.

The results of measuring the width of the conducting tracks are presented in table 1.

The graph of values distribution of conducting tracks widths is shown in figure 5a, there is a significant scatter of values.

To obtain stable results, the etching mode of the nichrome resistive layer was changed and improved: the temperature of the solution in the etching bath is $+26^\circ\text{C}$; billet movement speed of the electric heater is 0.55 m/min. After the etching operation was completed, there was made measuring the width of the conductive tracks at ten random points of each electric heater. The results of measurements are presented in table 2.

The graph of the distribution of the conductive track width values made of nichrome is shown in figure 5b, the scatter of values is minimal.
Table 1. The measurement results of conductive track width.

| No. of measuring point | No. of electric heater |
|------------------------|------------------------|
|                        |                        |
| 1                      | 0.421 0.4315 0.4275 0.4285 0.4365 0.435 |
| 2                      | 0.42 0.4365 0.42 0.433 0.4365 0.4305 |
| 3                      | 0.4165 0.429 0.424 0.4275 0.4245 0.4275 |
| 4                      | 0.4225 0.433 0.42 0.43 0.423 0.435 |
| 5                      | 0.4195 0.4245 0.425 0.432 0.4275 0.428 |
| 6                      | 0.4225 0.424 0.4215 0.4335 0.4365 0.431 |
| 7                      | 0.4215 0.4305 0.4255 0.421 0.4285 0.429 |
| 8                      | 0.424 0.427 0.421 0.4305 0.4315 0.425 |
| 9                      | 0.4245 0.4285 0.426 0.432 0.4205 0.424 |
| 10                     | 0.4225 0.4205 0.4235 0.4365 0.4205 0.425 |
| Max                    | 0.4245 0.4365 0.4275 0.4365 0.4205 0.4350 |
| Min                    | 0.4165 0.4205 0.42 0.421 0.4205 0.4240 |
| Average                | 0.42145 0.4285 0.4234 0.43045 0.42855 0.429 |

Table 2. The measurement results of conductive track width after improving etching mode.

| No. of measuring point | No. of electric heater |
|------------------------|------------------------|
|                        |                        |
| 1                      | 0.434 0.434 0.435 0.44 0.442 0.439 |
| 2                      | 0.441 0.435 0.44 0.438 0.439 0.44 |
| 3                      | 0.441 0.435 0.441 0.439 0.445 0.44 |
| 4                      | 0.44 0.435 0.439 0.44 0.443 0.437 |
| 5                      | 0.439 0.44 0.432 0.439 0.437 0.44 |
| 6                      | 0.44 0.441 0.435 0.439 0.439 0.439 |
| 7                      | 0.439 0.44 0.435 0.441 0.442 0.441 |
| 8                      | 0.438 0.438 0.439 0.44 0.439 0.439 |
| 9                      | 0.433 0.44 0.439 0.442 0.441 0.44 |
| 10                     | 0.444 0.438 0.44 0.441 0.439 0.445 |
| Max                    | 0.448 0.44 0.438 0.439 0.443 0.445 |
| Min                    | 0.448 0.441 0.441 0.442 0.445 0.445 |
| Average                | 0.433 0.434 0.432 0.438 0.437 0.437 |

Figure 5. The graphs of values distribution of conducting tracks widths before (a) and after (b) improving etching mode.
The smallest undercut value and a stable result were obtained using an improved etching mode. In order to reduce the deviations in the electric heater’s resistance, it is necessary to change the photomask, reducing the width of the specified conducting track to 0.44 mm instead of 0.48 mm. Then, in the process of etching, the technological allowance of 0.04 mm will be etched and the track width will be 0.4 mm (this value is a calculated one and is indicated in the engineering documentation).

In order to improve the quality of electric heaters’ production and increase the design technological effectiveness, a new constructive-technological solution was developed: soldering the current leads to the gearbox with low-temperature silver-containing solder using active flux and preliminary maintenance of the gearbox, followed by washing the active flux in a soda ash and running water solution, which allowed to reduce the soldering time to 3 seconds, lower the soldering temperature to +210 °C and reduce the thermal effect on the fiberglass base.

To assess the quality of etching and soldered joints, the installation batch of the electric heater in the amount of three pieces, manufactured with new technology, was subjected to destructive testing by the method of metallographic thin sections in four sections and results evaluation for compliance with the standard technical documentation.

As a result, the worked-out technological regimes allow producing an electric heater using a nichrome resistive layer with a high repeatability of parameters and solder the current leads to the gearbox without detaching the gearbox from the glass fabric with the required quality of solder joints according to the standard technical documentation.

2.4. Structural and technological solutions of flexible film heaters

At the fourth stage, in order to confirm the compliance of the design, technological, technical and operational characteristics of the electric heater with the requirements imposed on the life, reliability and efficiency of the new generation electric heaters for using them in the unpressurized designed spacecraft, the tests were carried out to confirm electric heaters’ performance capacity installed with adhesive on the spacecraft honeycomb panel. Figure 6 shows one of the electric heaters in a dimension range spacecraft for testing following characteristics: heating surface area – 17.5 cm²; track width – 0.4 mm; distance between tracks – 0.4 mm; loading density – 0.5; material of the resistive layer – nichrome; weight without wires – 1.3 g.

![Figure 6. Outer appearance of the electric heater.](image)

This electric heater provided the release of the specific heat load $P_{\text{level}} = 2.2$ W/cm² at $\Delta T = 25$°C. In the overload mode with $P_{\text{level}} = 2.85$ W/cm², $\Delta T$ ranged from 29°C to 31°C. With the maximum allowable temperature difference between the electric heater and the heated surface $\Delta T = 55$°C Ore ranged from 5.1 W/cm² to 5.4 W/cm², which is more than twice the value of the electric heater with the constantan resistive layer. The largest Ore that could be transferred using this electric heater was 6.8 W/cm² at $\Delta T$ = from 70°C to 75°C, while the electric heater’s surface temperature reached +144 °C.

Figure 7 shows the electric heater’s thermogram in the mode +125 ± 5°C (P = 112W; $P_{\text{level}} = 6.2$ W/cm2). It shows that due to the adhesive layer’s unevenness the temperature at two points located in close proximity to each other can vary with high Ore: thus, at the Sp1 point T = 121°C, at the Sp3 point T = 137.2°C. To confirm the efficiency of the electric heater at elevated temperatures, additional
tests were carried out with a step increase in temperature to +175°C. The situation with the thermal field remained unchanged.

![Figure 7. Electric heater’s thermogram.]

As a result, technical characteristics of two variants of the new generation electric heaters both based on the constantan and based on the nichrome resistive layers substantially exceed the technical characteristics of the previously used electric heaters. In order to eliminate the unevenness of the adhesive layer and increase the reliability of the electric heaters in a state installed with adhesive on the spacecraft honeycomb panel, the particle size of the glue filler is reduced from 0.2 mm to 0.1 mm.

Waste constructive-technological solutions of flexible film heaters involve the use of materials with a reduced pressing temperature and ensure the efficiency of the electric heaters in open space for a specified period. In the electric heaters manufacturing a method of successive technological operations is used, in which blanks are made from selected materials, a base is assembled consisting of flexible non-impregnated glass fabric, impregnated flexible glass fabric and foil and the first pressing is performed. On the foil by photolithography using a photomask and a photoresist we create a pattern of resistive (heating) layer, and then etch the pattern by etching in an etching solution. Remove residual pickling solution by washing. Conduct preliminary electrical testing, solder flexible current leads. After that we perform a second pressing of the work piece with current leads with the preform made of fiberglass fabric impregnated with a binder; and carry out final mechanical and electrical tests. The use of a photoprocess to create a resistive layer pattern and a chemical metal removal reaction makes it possible to produce various geometric shapes and sizes layers without using mechanical devices, including those with a conductor width of less than 0.5 mm and with a spacing between conductors of less than 0.5 mm, which allows designing various electric heaters with required technical characteristics with the possibility of “hot” and “cold” backup of the heating function.

Domestic materials were chosen as the main structural materials: flexible fiberglass (polyimide can be used), constantan or nichrome, wires with fluoroplastic insulation (others are possible), tin-lead solder or low-temperature silver containing solder.

2.5. Confirmation of the electric heaters performance characteristics in open space

At the fifth stage, in order to confirm the operational characteristics of waste electric heaters in open space, tests were carried out of the entire dimension range products with simulated space by cryogenic screens of a thermal vacuum unit with a volume of 120 m3, cooled during the tests to -180 ± 10°C. To ensure a given operating pressure of the electric heaters to values of 1×10−5 mm Hg, a vacuum pumping system was used. During the tests, the thermal vacuum units’ measuring system ensured the recording of all temperatures of the tested equipment using an automated system for measuring the temperature parameters of the installation. The error in measuring temperature parameters was no more than ±0.5% of their measurement ranges. In the course of carrying out all modes of thermal vacuum tests, the electric heaters control was carried out through the separate regulated channels from stabilized DC sources according to the test program. The measuring error of power consumption was no more than ±2%.
Thermal infrared emitters (IR emitters) were installed in case of electric heaters’ power failure and they were not used during this work. The required boundary temperatures were provided by adjusting the values of power supplied to the electric heater.

Twenty thermal cycles were carried out in the range from −70°C to +70°C of the simulator of radio electronic equipment (REA) (figure 8) with the established electric heaters. The maximum temperatures $T_{\text{max}}$ and maximum specific heat powers of the $P_{\text{level}\ max}$ on the electric heater are shown in Table 3. The exposure in the mode was 1 hour. The transition to the lower level up to −70°C was made with the electric heater switched off. When switching to the upper level, the power $P$ increased in steps (figure 9).

![Figure 8. Outer appearance of the REA simulator located in thermal vacuum unit.](image)

![Figure 9. The graphs of thermal cycle electric heaters’ mode as part of the REA simulator.](image)

| No. of electric heater | Exit to the top level | Lower level |
|------------------------|-----------------------|-------------|
|                        | $T_{\text{max}}$, °C  | $P_{\text{level}\ max}$ W/cm² | $T_{\text{max}}$, °C  | $P_{\text{level}\ max}$ W/cm² |
| 1                      | 134                   | 5,1         | 126                   | 4,8               |
| 2                      | 133                   | 5,1         | 123                   | 4,8               |
| 3                      | 87                    | 2,3         | 76                    | 1,9               |
| 4                      | 99                    | 2,3         | 86                    | 1,9               |
| 5                      | 105                   | 2,3         | 91                    | 1,9               |
| 6                      | 123                   | 4,3         | 112                   | 4,2               |
| 7                      | 118                   | 4,3         | 111                   | 4,2               |
| 8                      | 117                   | 4,3         | 110                   | 4,2               |
| 9                      | 107                   | 2,6         | 92                    | 2,1               |
| 10                     | 106                   | 2,6         | 91                    | 2,1               |
| 11                     | 86                    | 1,1         | 77                    | 0,7               |
| 12                     | 85                    | 1,1         | 75                    | 0,7               |
| 13                     | 139                   | 0,25        | 112                   | 0,21              |
| 14                     | 133                   | 0,25        | 108                   | 0,21              |
| 15                     | 136                   | 0,25        | 111                   | 0,21              |
| 16                     | 130                   | 2,9         | 124                   | 2,8               |
| 17                     | 126                   | 2,9         | 119                   | 2,8               |
| 18                     | 137                   | 2,9         | 130                   | 2,8               |
| 19                     | 164                   | 2,3         | 142                   | 2                 |
| 20                     | 125                   | 2,3         | 112                   | 2                 |
| 21                     | 148                   | 3,1         | 129                   | 2,7               |
The electric heaters have been tested at $P$ level from 2.2 W/cm$^2$ to 2.85 W/cm$^2$. At $P$ level = 2.2 W/cm$^2$, $\Delta T$ did not exceed the specified limit of 55°C. When conducting thermal cycling, the seats reached temperatures above +70°C, and the $P$ level for the electric heaters’ series significantly exceeded to 2.2 W/cm$^2$, reaching for individual electric heater (with a nichrome resistive layer) to 5.1 W/cm$^2$. At that, the temperature of the electric heater with these thermal fields reached +135...+155°C. The thermal cycle passed with a developmental reserve of 10 to 30°C relative to the set operating temperature of the EN. After the completion of the shopping center and the opening of the TSS, there were no comments on the electric heater’s appearance; no changes in the thermal field of the electric heaters were noted during the thermal imaging.

3. Conclusion
Conducted works and tests showed, that the new generation electric heaters developed based on photolithography method and etching of a resistive layer using materials produced by domestic industry as structural and technological materials allow to implement various electric heaters designs, significantly increase the electric heaters’ efficiency and provide the specified technical characteristics during operation in conditions of ambient vacuum and temperatures, corresponding to the standard application in the composition of the unpressurized designed spacecraft, as well as ensuring technological independence from foreign materials manufacturers and create a leading research and technological groundwork.

The new method can be used to manufacture electric heaters of various designs, forms and properties: flexible, flat, flexible-flat, three-dimensional forms, with a given level of manufacturability and quality in the creation of modern and promising spacecraft [6].

The considered method can be used in other technological areas, where electric heating elements are made and applied with given geometric properties (dimensions), strength characteristics (flexibility, resistance to mechanical and radiation effects), normalized by heat output and minimal costs during production.

References
[1] Lukonin N V and Shestakov I Ya 2015 A method of manufacturing a flexible flat electric heaters of spacecraft Proc. of XIX Int. Science and Research Conf. Reshetnev Readings (Krasnoyarsk)
[2] Lukonin N V, Shestakov I Ya, Sheverdov V F 2015 Spacecraft Electric Heaters Proc. of Int. Science and Research Conf. Modern state of science and technology (Sochi)
[3] Lukonin N V, Polyakova G V, Shusherina G P and Sny’tko D V 2016 A method of manufacturing a flexible flat heater (Moscow: Rospatent)
[4] Fedotov A Ya and Pol’ G 1974 Photolithography and optics (Moscow: Sov. radio)
[5] Al’tgauzen A P, Gutman M B, Malyshev S A et al 1978 Low-temperature electric heating (Moscow: E’nergiya)
[6] Lukonin N V, Dmitriev G V, Morozov P S and Shestakov I Ya 2017 A method of manufacturing electric heaters increased efficiency of spacecraft unpressurized design Proc. of XIX Int. Science and Research Conf. Reshetnev Readings (Krasnoyarsk)