Research of thermal control system for nanosatellite with carbon fiber reinforced plastic body

Wang Yu, Zarni Soe-Moe, O V Denisov*, L V Denisova

Bauman Moscow State Technical University, 2-nd Baumanskaya, 5, b.1, 105005, Moscow, Russia

E-mail: denisov.sm13@mail.ru

Abstract. One of the key problems in the design of nanosatellites is to provide a specified temperature range for the operation of electronic equipment. In structures of modern nanosatellites mainly used the elemental base of smartphones. To process a large amount of information, more advanced processors with high thermal power are required. The specified thermal mode of the on-board computer can be achieved using a remote heat removal system or by direct contact of the processor cover with the carbon fiber reinforced plastics (CFRP) body of the nanosatellite. Using a model of nanosatellite as an example, a thermal control system with miniature loop heat pipes and highly heat-conducting refrigerators-emitters is designed. The influence of the thermal conductivity coefficient in the reinforcement plane of the nanosatellite CFRP body on its temperature state in low Earth orbit is studied.

Key words: carbon fiber reinforced plastic, nanosatellites, thermal conductivity coefficient, loop heat pipes, thermal control system.

1. Introduction

Currently, the space technology, associated with small spacecraft – micro-nanosatellites, is actively developing around the world. The great demand for the application of micro-nanosatellites is due to the relatively low cost of operation and great potential in the global space goods market. Over the past 5 years, the number of launches of micro-nanosatellites has increased more than twice. According to forecasts, by 2023, more than four hundred devices would be launched [1, 2]. The cost of launching spacecrafts largely depends on their mass. Therefore, composite materials with high specific characteristics – CFRP are promising for the manufacture of nanosatellites. High heat-conducting CFRP are perspective [3].

One of the key problems in the design of nanosatellites is the guarantee of a specified temperature range for the operation of electronic equipment (Figure 1) [4]. For the normal functioning of most processors, the allowable temperature should not exceed 90 °C [5]. The constantly increasing information load leads to the need to use more advanced processors with high thermal design power (TDP) in the on-board computers of nanosatellites. The thermal regime of nanosatellites is determined by external thermal loads and heat generated by airborne equipment [6-8]. In the conditions of orbital flight, the use of the usual thermal control system for processor is impossible due to the lack of convective heat transfer. The small overall dimensions and dense layout make it difficult to discharge heat by radiation into the internal volume of nanosatellites. This can lead to overheating of the processor and failure of the on-board computer.

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To solve this problem, it is necessary to ensure the removal of excess heat from the on-board computer processor to the CFRP body of the nanosatellite and its discharge into the surrounding space. This can be implemented in two ways. The first – using remote heat removal systems – miniature loop heat pipes (LHP), which have high effective thermal conductivity and are easily adapted to operating conditions [9-11]. They are distinguished by relative simplicity of design, complete autonomy and transmission a large amount of heat to the required distance. The second way to remove excess heat is through direct contact of the processor cover with the nanosatellite body. At the same time, to increase the cooling area of the surface, it is advisable to use heat-conducting refrigerators-emitters.

Purpose of the work – theoretical justification of the possibility of using LHP and heat-conducting refrigerators-emitters to ensure the operability of the on-board computer processor of nanosatellites with CFRP body.

2. Objects and materials
The nanosatellite has a frameless structure in the form of a thin-walled parallelepiped, in the center of which is installed a motherboard 6 with a processor 3 and six RAM elements 1 (figure 2). Between the processor 3 and the processor cover 4, a thin layer of thermal grease such as Evercool Nano Diamond is applied, which ensures perfect thermal contact between them. The processor and RAM elements are the only heat sources with the TDP of 15 W and 1 W, respectively. The processor Intelcorei7-8650U for light laptops can serve as an analogue.

The material of nanosatellite is orthotropic CFRP with thickness 2 mm (table 1). Assumed that $\lambda_y$ and $\lambda_z$ are the thermal conductivity coefficients, respectively, in the Y and Z directions of the reinforcement plane of each face of the nanosatellite body, and $\lambda_x$ is thermal conductivity coefficient in the normal direction X of each face of the nanosatellite body.
Table 1. Geometrical dimensions and materials of nanosatellite construction

| Name                  | Material       | Coefficient of thermal conductivity $\lambda$, W/(m·K) | Size, mm |
|-----------------------|----------------|------------------------------------------------------|----------|
| Motherboard           | fiberglass     | 0.244                                                 | 100x100x1|
| Processor board       | fiberglass     | 0.244                                                 | 60x60x0.8|
| Processor             | silicon        | 148.0                                                 | 24x42x1.3|
| RAM (6 pieces)        | silicon        | 148.0                                                 | 10x10x1.5|
| Thermal grease        | diamond micro particles | 8.0                                                  | 24x42x0.1|
| Processor cover       | Aluminium alloy| 144.0                                                 | 53x53x0.5|
| Satellite body        | CFRP           | $\lambda_x = 0.5; \lambda_y = \text{var}; \lambda_z = \text{var}$ | 100x100x200|

3. Thermal control systems

3.1 Loop heat pipes.

When the processor is cooled with LHP, the excess heat is transferred through the aluminum cover 4 to the copper interface 2, inside of which locates an evaporator 1 with a capillary-porous structure (figure 3). The evaporator 1 and the condenser 7 are connected by pipelines 11 to separate the circulation movement of the vapor (steam line) and liquid (condensate line) phases of the coolant. To increase the intensity of heat discharge into the surrounding space and to increase the contact area between the heat pipe capacitor 7 and the inner surface of the wall of the nanosatellite body 9, thermal grease 8 is used.

One of the main characteristics of LHP is its effective thermal conductivity coefficient $\lambda_{ef}$. According to published data [12–16], the value of $\lambda_{ef}$ can vary over a wide range and is higher the thermal conductivity of aluminum more than 100 times.

The temperature state of the processor is analysed in the module – Steady-State Thermal of ANSYS, which showed that for the given geometric dimensions of the LHP (table 2) with $\lambda_{ef}$ values from 5000...
W/(m·K) to 20000 W/(m·K), the processor temperature changes less than 10%. In further calculations, it was assumed that the LHP is a monolithic body with effective thermal conductivity coefficient $\lambda_{ef} = 20000$ W/(m·K).

**Table 2. The geometric dimensions of the loop heat pipe**

| Component               | Characteristics     | Value, mm |
|-------------------------|---------------------|-----------|
| Evaporator              | diameter / length   | 8.0/50.0  |
| Pipelines               | diameter / length   | 3.0/68.5  |
| Capacitor               | diameter / length   | 3.0/400.0 |
| Vaporizer interface     | length / width / thickness | 50.0/50.0/10.0 |

3.2 **Refrigerators-emitters.**

When the processor is cooled with the help of refrigerators-emitters, the aluminum cover of processor is in contact with the nanosatellite body (figure 4). To ensure perfect thermal contact between them, a thin layer of thermal grease is applied. The processor board is connected to the motherboard with the information cable 4. The refrigerators-emitters are screens made of high-conductivity CFRP, that will unfold after the nanosatellite is put into orbit of the Earth.

![Figure 4](image)

**Figure 4.** Thermal control system with the help of refrigerators-emitters:

a) – general view; b) – contact diagram of the processor with the surface of the nanosatellite body

1 – processor board; 2 – processor cover; 3 – processor; 4 – information cable; 5 – nanosatellite body; 6 – refrigerators-emitters; 7 – RAM; 8 – motherboard

4. **Mathematical simulation**

The simulation was carried out in the Siemens NX program in elliptical orbit conditions with an angle of inclination 95° and an operating period 5980 s. The following values served as initial data: thermal conductivity coefficients in Y and Z directions of the reinforcement plane nanosatellite body $\lambda y = 6.0$
W/(m·K) and $\lambda_z = 4.0$ W/(m·K); the emissivity coefficient of the nanosatellite surface was assumed to be $\varepsilon = 0.9$; the solar absorption coefficient $A_s = 0.3$. The geometric dimensions of the nanosatellite elements and the thermophysical characteristics of the materials were taken from tables 1, 2.

When the processor is cooled with LHP, the temperature of the processor on the illuminated side of the orbit exceeds its permissible value and amounts to 132°С (figure 5). The maximum processor temperature on the shadow side of the orbit is only 4 °C lower. In this case, the temperature of the nanosatellite body varies from minus 30°C to plus 50°C (figure 6). RAM elements are heated unevenly. The RAM element located between the interface and the LHP capacitor near the illuminated face of the nanosatellite body has the maximum temperature of 174°С. Therefore, at further stages of nanosatellite design, it is necessary to determine a more rational location of RAM elements on the circuit board or to change the structure of the LHP interface in order to remove the additional heat.

![Figure 5. Temperature state of the nanosatellite on the illuminated side of the orbit when cooling with LHP (t = 2990 s): a) general view; b) interior fittings; c) processor](image)

![Figure 6. The temperature in the center of each face of the nanosatellite body during orbital flight when the processor is cooled with LHP](image)

Similar calculations were carried out for scheme 2, when the processor is cooled with refrigerators-emitters. The maximum processor temperature on the illuminated side of the orbit also exceeds its permissible value and amounts to 147 °С. At the same time, all RAM elements remain relatively cold and their temperature does not exceed 67°C (figure 7).
Figure 7. Temperature state of the nanosatellite on the illuminated side of the orbit (t = 2990 s) when the processor is cooled with the refrigerators-emitters: 
a) general view; b) motherboard and memory; c) processor

The anisotropy of the thermal conductivity coefficient in the reinforcement plane [17, 18] of each face of the CFRP nanosatellite body has a different degree of influence on the temperature state of the processor depending on the selected thermal control system. For example, when cooling the processor with LHP, increasing the thermal conductivity in the Y and Z directions of each face of the CFRP body from 4.0 W/(m·K) to 100.0 W/(m·K) reduces the temperature of the processor by 10 ... 16°C, and when cooling the processor with the help of refrigerators-emitters – by 55 ... 60°C (figures 8, 9). Thermal control system based on LHP is preferable for composite materials with low values of $\lambda_y$ and $\lambda_z$. When using highly heat-conducting CFRP, it is more efficient to remove heat from the processor using refrigerators-emitters.

Figure 8. The influence of the thermal conductivity coefficient $\lambda_z$ on the processor temperature on the illuminated side of the orbit for different thermal control systems ($\lambda_y = 4.0$ W/(m·K)):
1 – refrigerators-emitters; 2 – LHP
Figure 9. The influence of the thermal conductivity coefficient \( \lambda_y \) on the processor temperature on the illuminated side of the orbit for different thermal control systems (\( \lambda_z = 4.0 \text{ W/(m·K)} \)):

1 – refrigerators-emitters; 2 – LHP

With the values of the thermal conductivity coefficients of the CFRP \( \lambda_y = \lambda_z = 100.0 \text{ W/(m·K)} \), the processor temperature will be respectively 90°C and 73°C for cooling systems with loop heat pipes and highly heat-conducting refrigerators-emitters.

5. Conclusions

The possibility of using loop heat pipes and highly conductive refrigerator-emitters to cool a processor with the thermal power of 15 W (class of light notebooks) in nanosatellites with a CFRP body has been studied. It has been established that at values of thermal conductivity coefficients in the reinforcement plane of the CFRP body up to 20...40 W/(m·K), the heat is more effectively removed by LHP, and at higher values of \( \lambda_y \) and \( \lambda_z \) – by refrigerators-emitters. For normal processor operation, the nanosatellite body under consideration must be made of CFRP with a thermal conductivity coefficient of 100 W/(m·K) and higher.

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