Thermal control technology for the space station adjoint modular satellite based on new thermal control materials

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Abstract. A modular satellite could perform various functions with various modules and the function of the satellite could be expanded easily. Therefore, the modularization design is an important development direction of space station adjoint satellites and others. However, every module of a modular satellite is structurally independent and the heat dissipation is unevenly distributed, while the interface between modules should support repeatable connection-separating. The traditional thermal control design could not satisfy the thermal control demand. In this paper, the thermal control technology for the space station adjoint modular satellite based on the thermal interface of carbon nanotube array on copper substrate, graphene coating and smart thermal control coating is proposed. By using the new technology, the thermal connection of the assembly and reconstruction system is built and the synergistic heat dissipation of the whole satellite is achieved. As to validate the proposed technology, the finite element model of the space station adjoint modular satellite is established and the whole flight process is simulated. The result indicates that the thermal control technology proposed in this paper can satisfy the thermal control demand of the modular satellite.

1. Introduction
The space station adjoint satellite is a kind of multi-purpose spacecraft that flies around and services the space station. It has the unique advantage of monitoring, defending and technically supporting the station. The space station adjoint satellite has been studied and developed since the 1980s. The typical projects include Nanosat-D[1], Inspector, and the Shenzhou-7 spaceship adjoint satellite[2]. However, the existing adjoint satellites are micro-nano satellites whose volumes are small and functions are rather simplex. Considering the increase demand of the space exploration, the space station adjoint satellite needs to undertake more complicated and flexibly configurable mission. A modular satellite could perform various functions with various modules and the function of the satellite could be expanded easily. Therefore, the modularization design is an important development direction of space station adjoint satellites and others.

The concept of modular spacecraft[3] has been proposed by NASA in 1970s. A modular satellite consists of several structurally independent modules which are connected by uniform mechanical, electrical and thermal interface. The modular satellite could be reassembled to satisfy the need of various missions. The Orbital Express[4] and Phoenix projects[5] which are the in-orbit verification projects, have been launched in 2007 and started up in 2011 separately. But the modular satellite with complex functions and large heat dissipation hasn’t been reported.

Different from traditional satellites, a modular satellite consists of several modules whose structure is independent and heat dissipation is unevenly distributed, while the interface between modules should
support repeatable connection-separating. Considering the particular conditions, the cross-module heat transfer based on the traditional thermal control technologies is inefficient. Meanwhile, the surface area of the module that is integrated and miniaturized is limited so that the heat flow of the large power payload equipment cannot be dissipated by the module itself. Therefore, the thermal control technology based on which the effective synergistic cross-module heat dissipation can be realized is the key technology for modular satellites.

In this paper, the thermal control technology for the space station adjoint modular satellite based on new thermal control materials is proposed. The cross-module thermal interface is designed by using the carbon nanotube array on copper substrate[6-7]. The inner faces of modules are coated by graphene film[8] while the outer faces are painted by smart thermal control coating[9-10]. So that the thermal connection of the assembly and reconstruction system can be built and the satellite can be adapted to the variety of the orbital heat fluxes.

2. Space station adjoint modular satellite

Configuration
Considering the basic demand of the space station adjoint satellite, the modular satellite is configured with four standard modules, including guidance and control module (GNCM), chemical propulsion module (CPM), electric power module (EPM) and satellite management module (SMM), as shown in Figure 1. The standard module adopts miniaturized design with side length of 0.5m and is equipped with standard docking interfaces integrating thermal, mechanical, electrical functions, as shown in Figure 2. The modules connected by standard docking interfaces could be assembled by space robot and support repeated installation and removal on orbit.

The heat dissipation of modular satellite is unevenly distributed in four modules. Specifically, the heat dissipation of GNCM, CPM, EPM and SMM is 80, 50, 120 and 60, respectively. The range of temperature control requirements is from -15°C to +55°C.

Orbital heat fluxes
The orbital heat fluxes, which are the main heat source accepted by the satellite in space, are one of the main factors affecting the temperature of the satellite equipment and the basis for the thermal design and thermal analysis of the satellite. The orbital heat fluxes of the space station adjoint modular satellite are determined by the space station orbit parameters that takes the international space station[11] ones, the adjoint orbit parameters which is an elliptical orbit relative to the space station with a perigee height of 0.5km and a apogee height of 1km, the position of the sun that takes the winter solstice as an example and the attitude of the satellite. In the whole flight process, the missions of the space station adjoint
modular satellite are mainly divided into three stages including release, orbit and capture. The attitude of satellite is various in different stages.

Based on the given settings, the dependence of the incident heat flux on time is simulated, as shown in Figure 3. It can be seen that all six surfaces are exposed to sunlight and there is no surface with stable heat flow that can be set as the heat rejection surface with traditional thermal coating.

![Figure 3. Dependence of the incident heat flux of every surface on time.](image)

3. Thermal control technology and simulation verification

Considering the configuration characteristics, mission requirements and orbital heat fluxes variations, the thermal control design needs to meet the uneven heat dissipation demand, adapt to the unstable orbital heat fluxes, and support the on-orbit assembly and replacement of modules. The traditional thermal control technology, which supports the independent heat dissipation of a single satellite system, cannot meet the thermal control requirements of the modular satellite. Therefore, it is necessary to develop new thermal control technology.

The module of the satellite is equipped with standard docking interfaces that support repeatable connection-separating. The cross-module heat transfer is realized by compressing the thermal interfaces. The separable contact heat transfer between the two interfaces becomes the key of the whole heat transfer path. The traditional methods of solid-solid contact heat transfer enhancement have the problems of non-separation, destructive separation or low thermal conductivity, which are not suitable for the modular satellite. The separable thermal disk based on the carbon nanotube array on copper substrate[6-7] is proposed in recent years. Under the contact pressure, the carbon nanotubes which are higher than the copper matrix are inserted into the copper matrix on the other side during the contact process, so that the contact heat transfer is enhanced and the separable and efficient heat transfer between modules is realized. Thus, the thermal disk can be used as the thermal interface of the modular satellite. The influence of the contact heat transfer coefficient at the thermal interfaces on the temperature response is calculated by numerical analysis, which indicates that as long as the coefficient reaches 1500W/(m²·K) by controlling the properties of carbon nanotubes, optimizing the disk configuration and pressing pressure, it can meet the engineering requirements.

Besides, the module adopts miniaturized integrated design with limited internal space. The traditional method of internal heat transfer enhancement is to arrange the heat pipe network, which needs to occupy large space and then is not suitable for the modular satellite. Graphene is a new type of thermal conducting material with the theoretical thermal conductivity of 5000W/(m·K)[8]. Coating graphene film on the internal surface of the module can significantly increase the thermal conductivity of the deck, and realize the efficient internal thermal conduction. The thermal conductivity of graphene film coating prepared via modified Hummers method with the thickness of 25μm is about 800W/(m·K), which is 5.6 times higher than that of the conventional aluminum skin of the deck.

The ±y surfaces of all the modules are set as heat rejection surfaces, since their orbital heat flux variations are relatively small and the ±y surfaces of a single module cannot meet its own heat dissipation demand, especially for EPM. In addition, as to adapt to the unstable orbital heat fluxes, the smart thermal control coating is used at all the heat rejection surfaces. In this paper, Ag/VO₂/SiO₂/VO₂ multi-layer smart thermal control coating is used. The emissivity varies from 0.38 to 0.74 in the temperature range...
of 40–60°C, and the solar absorptance is only 0.32\textsuperscript{[10]}. By using the smart thermal control coating, the heat rejection surface has the ability to adapt to the orbital heat flux variations.

In order to verify the thermal control technology, the temperature responses of the satellite in the whole flight process by using both the new and traditional technology are modeled, as shown in Figure 4. The results show that by using the new technology the temperature of equipment in every module is within the temperature control range, which proves that the thermal control technology for modular satellites based on new thermal control materials proposed in this paper is available.

**Figure 4.** Dependence of the equipment temperature on time

4. Conclusion

The thermal control technology for modular satellites has been studied by taking the space station adjoint modular satellite as an object in this paper. Considering the characteristic of structural independence of every module and requirement of cross-module synergistic heat dissipation for the modular satellite, the thermal control design of repeatable connection-separating interface, internal heat transfer enhancement and adaptive heat rejection surface based on the carbon nanotube array on copper substrate, graphene film and smart thermal control coating is proposed. With this design, the thermal connection of the assembly and reconstruction system is built and the heat flow distributed dispersely in every module can be synergistically dissipated through the whole satellite. As to verify the thermal control technology, the temperature response of the space station adjoint modular satellite in the whole flight process is modeled. The result shows that the temperature of equipment in every module is within the temperature control range and the thermal control technology for modular satellites based on new thermal control materials proposed in this paper is available.

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