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Research Paper

Thermal protection method of the solar array for stratospheric airships

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HIGHLIGHTS

- Theoretical calculation, experimental test and CFD simulation are carried out for the investigation.
- The thermal protection effects of coating film, heat insulation layer and heat dissipation layer are compared.
- The output power, thermal protection effect and structure weight are comprehensively considered.

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ABSTRACT

Part of the sunlight energy received by the solar array on the stratospheric airship surface is converted to electric energy, and considerable energy is transformed into heat, which is bad for the envelope material and the internal pressure of the airship. It is necessary to develop different methods for the solar array to reduce its thermal effects on the stratospheric airship. Coating film, heat dissipation structure and heat insulation structure are developed to reduce the thermal effects. A series of theoretical studies are carried out to analyze the effects of three layers, especially the heat dissipation structure made up by arrayed fins, which are verified by the experimental test and CFD simulation. As for the solar array system, the mutual coordination among output power, thermal protection effect and the structure weight ought to be considered at the same time in the design of solar array system of the stratospheric airship.

1. Introduction

The stratospheric airship (SSA) is a class of Lighter-Than-Air (LTA) vehicle with application potential in communication, investigation, science exploration and other fields [1–3]. Therefore, study in the SSA has become the focus in many counties in recent years [4,5]. However, there is no mature and practical SSA in the engineering at the present stage. The energy system is one of the bottlenecks for the development of the SSA, which directly determines the long endurance flight performance of the airship [6–9]. The solar cells array, which is actually a photovoltaic (PV) array, coupling with an energy storage system is an ideal choice for the energy providing of the SSA [9].

Unfortunately, the conversion efficiency of thin film flexible solar array is around 10%, which is very low in nowadays [10]. It means that only a portion of sunlight energy received by the solar array is converted to electric energy, and considerable energy is transformed into heat, which puts the SSA a great disadvantage. The temperature difference between solar cell surface and envelop surface, where no solar array overcasts, could go up to 60 K in the daytime [11]. The heat generated by the solar array will increase the pressure of the helium inside the hull and age the envelope material underlaid the cells. In addition, the thermal performance of a stratospheric airship can have a big effect on the output performance of the solar array. Therefore, it is necessary to develop different methods for the solar array to reduce its thermal effects on the SSA.

The methods of reducing thermal effects can be divided into two types: active method and passive method. The active method is to reduce the heat generated by the thin film solar cells actively on the premise of guarantee the output electric power. And the passive one is to reduce the amount of heat transferred to the airship. As for the reducing of the heat generation, surface modification of the solar cell can be developed to restrain the penetration of the near-infrared spectrum (900–1200 nm) and increasing the transmittance of the visible light (400–800 nm) at the same time [12,13]. The methods of antireflection film and infrared cut coating preparation on the solar cells can be divided into chemical vapor deposition (CVD), physical vapor deposition (PVD), sol–gel method and so on. The transmittance of visible light for the solar cells is increased to more than 90% using different methods by a number of researchers for the past few years [14–16]. The main methods to reduce heat transferred from the solar array to the airship

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envelope are heat insulation and heat dissipation, which have been carried out by many scholars [17–20]. The multilayer insulation (MLI) structure was carried out as early as 1950s and has been quite mature application in spacecraft [21]. Different kinds of thermal insulation coatings and materials are used on the surface of the protected objects, such as polymer sheets, reflective metal and so on [22–24]. As for the dissipation structure, plate fin heat sinks (PFHSs) are the most widely used due to their simple structure and easy manufacturing. Zhou et al. [17] investigated the thermal and hydraulic performance of 20 different plate-pin fin heat sinks with various shapes of pin cross-sections. Hung et al. [20] optimized the thermal performance of a micro-duct heat sink with a sandwich distribution porous medium using the geometric variables as search parameters. Li et al. [25] developed a thermal analysis model of composite solar array with complex structure to characterize the thermal response of the whole solar array system subjected to space heat flux. The above designs of insulation structures for other aircraft or space vehicle are referenced in this paper.

Nevertheless, the envelope of the SSA and the solar array on the surface are both flexible, which requires the thermal protection structure is also flexible. Sun et al. [10] developed a MLI material and proposed a thermal heat transfer model of flexible thin-film solar cell and MLI to study the heat insulation effects. Li et al. [26] investigated thermal insulation performance of three types of lightweight insulation substrate (LIS) subject to low ambient temperature and high solar irradiation flux conditions representative of stratospheric thermal environment for solar arrays on an airship. Li et al. [27] explored the effects of an insulation material installed between the photovoltaic array and the airship hull. They found that the insulation material may reduce the superheat of the airship hull and diurnal temperature variation of buoyancy gas, but the output of the array will decrease. The design of thermal protection structure of the solar array is not only to achieve the purpose of insulation, but also to minimize the mass of the structure. What's more, the most important premise is to guarantee the output electric power of the solar array for the SSA.

In this paper, a multilayer thermal protection (MLTP) structure including active method and passive method for solar array on the SSA is developed firstly. Theoretical models are carried out to investigate the thermal protection effects of the MLTP structure. The comparison tests and simulations using the FLUENT software of the thermal protection effects for the MLTP structure are conducted to verify the theory in the next. The thermal protection effects of coating film, heat dissipation layer and heat insulation layer are discussed respectively for contrastive analysis. A comprehensive analysis of the thermal protection structure is introduced to evaluate the overall performances of output power of the solar array, the weight of MLTP structure and its thermal protection effects.

2. The thermal protection structure of the solar array for the SSA

The MLTP structure of the solar array for the SSA studied in this paper is shown in Fig. 1, which including antireflection film, infrared cut coating, thermal insulation and dissipation layers. The antireflection film on the surface of solar array is used to increase photoelectric conversion efficiency by increasing transmittance of the visible light. The infrared cut coating is applied to reduce the transmittance of near-infrared light. In the design of the integrated film system for the solar array, SiO_2 and Ta_2O_5 are used for antireflection and cut-off, and the areal density is 5 g/m^2. The spectral response curve of the film system tested in this paper is shown in Fig. 2. It can be seen from the figure that the average transmissivity of the visible wavelengths (400–800 nm) is almost 95% and the reflectivity of near-infrared wavelengths (900–1200 nm) is close to 69%.

The heat dissipation layer of the MLTP is composed of air ducts, which are made of a series of arranged fins. The direction of the air duct is consistent with the flight direction of the SSA, so that the heat can be taken away by the airstream through the interspace between fins in the process of relative motion. As shown in Fig. 3, three kinds of fins are selected for comparison in this paper, which are long strip fin, zigzag fin and cylindrical fin. On account of the flexibility and lightweight demand for the MLTP structure, NOMEX paper honeycomb is manufactured to the fins. The heat insulation layer has the same requirement which is made of a certain thickness of paper honeycomb.

3. Thermal protection performance analysis

3.1. Theoretical analysis

The exploded view of the solar array with the MLTP structure is shown in Fig. 4, which can be divided two parts. The first part is the solar array with the optical film system. A majority of solar flux is absorbed by the solar cells, especially after coating the antireflection film. A part of the solar flux absorbed by solar cell is converted into heat energy to radiate to the external environment and transmit to the second part [26]. The second part of the structure is

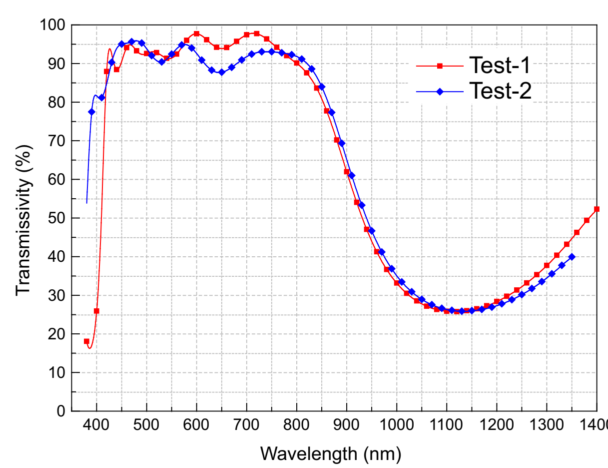

Fig. 2. Transmittance curve along with the change of wavelength.

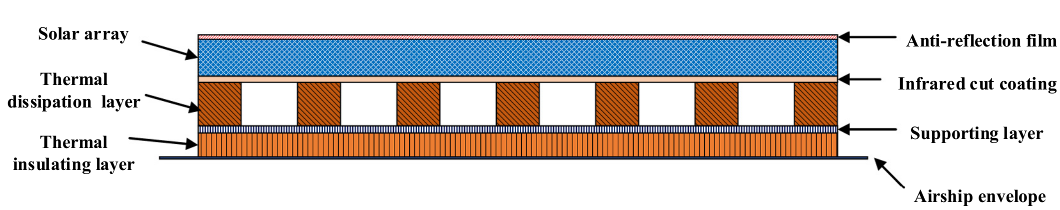

Fig. 1. The MLTP structure of the solar array for the SSA.