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Research Paper

Output performance analyses of solar array on stratospheric airship with thermal effect

Jun Li [a], Mingyun Lv [a], Dongjie Tan [a], Weiyu Zhu [a], Kangwen Sun [a,*], Yuanyuan Zhang [b]

[a] School of Aeronautic Science and Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, PR China
[b] College of Geoscience and Surveying Engineering, China University of Mining and Technology, Ding No. 11 Xueyuan Road, Beijing 100083, PR China

HIGHLIGHTS

- A model investigating the output power of solar array is proposed.
- The output power in the cruise condition with thermal effect is researched.
- The effect of some factors on output performance is discussed in detail.
- A suitable transmissivity of external layer is crucial in preliminary design step.

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ABSTRACT

Output performance analyses of the solar array are very critical for solving the energy problem of a long endurance stratospheric airship, and the solar cell efficiency is very sensitive to temperature of the solar cell. But the research about output performance of solar array with thermal effect is rare. This paper outlines a numerical model including the thermal model of airship and solar cells, the incident solar radiation model on the solar array, and the power output model. Based on this numerical model, a MATLAB computer program is developed. In the course of the investigation, the comparisons of the simulation results with and without considering thermal effect are reported. Furthermore, effects of the transmissivity of external encapsulation layer of solar array and wind speed on the thermal performance and output power of solar array are discussed in detail. The results indicate that this method is helpful for planning energy management.

1. Introduction

The stratospheric airships, as a radio relay and monitoring station, has been attracting interests in the areas of telecommunications service, earth observation sciences and others [1–4]. Many researches and developments have been in progress in thermal analysis on stratospheric airships in the past decades. Wu et al. [5] presented a comprehensive literature review on thermal issues of stratospheric airships, and they developed a thermal modeling of stratospheric airships. Xiong and Bai [6] established a practical and valid analytical methodology for assessing accurately thermal behaviors, particularly steady equilibrium temperature in vehicle at float altitude. Li and Fang [7] developed the structural, thermodynamic and dynamic models of the semi-rigid airship to investigate the thermal characteristics and flight performances during the floating flight. Based on the thermodynamic models of photovoltaic arrays and airships, Li [8] conducted the numerical simulation to study the thermal performance of the photovoltaic array and the effect of the photovoltaic array on thermal characteristics of an airship.

Solar array is a critical appendage which provides primary power sources for long endurance stratospheric airship. Some scholars had made their contributions in recent years. Naito et al. [9] performed the design review on airship power subsystem including solar power subsystem of 200 kW class for supplying continuous electricity. Garg et al. [10] proposed a method to estimate and optimize the required area of solar panels to maximize the solar energy produced by per unit area of the solar panels. Li and Fang [8] analyzed the effects of the latitude, time of the year, wind speed, and insulation on the power output of the photovoltaic array. Wang et al. [11] presented their computation method

* Corresponding author.
E-mail addresses: geniuslee215@buaa.edu.cn (J. Li), lv503@buaa.edu.cn (M. Lv), 13261114560@163.com (D. Tan), zhuweiyu@buaa.edu.cn (W. Zhu), sunkw100@buaa.edu.cn, kangwensun513@163.com (K. Sun), yuanyuanzhang502@foxmail.com (Y. Zhang).

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for the curved surface solar cells on the high-altitude airship to study the effect of the high-altitude airship's attitude on the output performance of solar panel. Sun et al. [12] proposed a thermal heat transfer model of flexible thin-film solar cell and multilayer insulation material to research the thermal characteristics of flexible thin film solar cell array of stratospheric airship. An optimization design method for the power system of the stratosphere airship was proposed to present the sensitivity analysis of the weight and the reliability of the power system [13].

It is interesting to note in the above reviews that a large number of researches are grouped according to some important issues such as thermal behavior, airship power subsystem, feasibility analysis of photovoltaic array, and some influences on the output performance of solar panel without thermal effect. However, the investigation of output performance of solar array with thermal effect is rare. When the airship operates in the cruise condition, it is very important to know the output performance of large area flexible solar array. In this paper, a simplified numerical model is developed for investigating the output performance of solar panel with thermal effect. As we known, two typical factors, the transmissivity of external encapsulation layer and the wind speed, may influence the thermal performances of the airship and solar array by changing the heat quantity input, output of airship system respectively. In addition, there are a lot of primary factors that can affect the thermal performance of the airship and solar array. Further study should be carried out. For sake of simplification, this work researches representatively the effects of the typical factors on the thermal performances and the output power of solar array based on the numerical modeling of this paper.

2. Theory

As is well known, the output power of solar array on stratospheric airship is governed by the incident solar radiation on the array, the performance characteristics with thermal effect, and the geometry of the solar array etc. [9,14–16]. To analyze the output performance of solar array on stratospheric airship with thermal effect, the authors of this paper develop a simplified numerical model consisting of thermal model, incident solar radiation model on the solar array, and power output model. Before investigating these models, it is really necessary to make some fundamental assumptions.

(1) When the airship operates in the cruise condition, stratospheric airships cannot maintain its streamlined shape because of the load in the lower part of the vehicle. The geometric deformation of airships is neglected for the purpose of simplification. Therefore, the volume of airship is constant [6].
(2) Compared with diameter of the stratospheric airship, the envelope and solar panel are so thin. Therefore, the diameter of the streamlined airship is approximated as the overall diameter of the stratospheric airship.
(3) Actual thermal performance of envelope and solar cells are different which causes temperatures of envelope and solar cells at same position may be different. In order to simplify the model, authors make the assumption that temperatures of envelope and solar cells at same position are same.

2.1. Thermal model

The thermal environment for the airship includes the external and internal environments [17–20], as shown in Fig. 1. The external environment of stratospheric vehicle and solar array consists of the direct solar radiation, the scattered radiation, the reflected radiation, infrared radiation, and convection between film (or solar array) and external atmosphere [21]. The internal thermal environment mainly includes convection between envelope and internal gases, infrared radiation of envelope and diaphragm [22,23].

The direct solar irradiance, I_D, at the stratospheric altitude can be calculated with

$$I_D = \tau_h \cdot I_{top} \tag{1}$$

$$I_{top} = I_0 \cdot \left(1 + e_e \cdot \cos(\lambda_e)/1 - e_e^2\right)^2 \tag{2}$$

where I_0 is the solar constant that has a value of 1367 W/m^2, I_{top} is direct solar irradiance value at the top of the atmosphere, e_e is the orbital eccentricity, for earth e_e = 0.0016708, the true anomaly λ_e is given by

$$\lambda_e = \theta_{day} + 0.0334 \cdot \sin(\theta_{day}) + 3.49 \times 10^{-4} \cdot \sin(2 \cdot \theta_{day}) \tag{3}$$

where θ_{day} is the day angle of the sun, and can be calculated with

$$\theta_{day} = 2\pi \cdot (N - N_0)/365.2422 \tag{4}$$

where N is the day number in a year, such as, N = 1 when the date is the first day of January and N = 365 when the date is December 31 in an ordinary year, N_0 is the correction term of the day number [24].

And in the Eq. (1), τ_h is the transmissivity of a solar beam thru the atmosphere which is modified by influence factors of upper and low altitude atmosphere [25], p_h and p_0 are the atmospheric pressure at the stratospheric altitude and the sea level.

$$\tau_h = \frac{1}{2} \cdot \left(1 + c_{low}(p_h/p_0)^{c_{high}}\right)\left(e^{-0.65 \cdot \lambda_{am}} + e^{-0.95 \cdot \lambda_{am}}\right) \tag{5}$$

The scattered radiation I_S can be expressed as

$$I_S = 0.5 \cdot I_{top} \cdot \sin(\theta_{ele}) \cdot \lambda_{am} \cdot (1 - \tau_h)/(\lambda_{am} - 1.41 \cdot \tau_h) \tag{6}$$

where λ_{am} is the air mass ratio when sunlight passes through the atmosphere, which can be described by

$$\lambda_{am} = \begin{cases} FS_r \cdot (p_h/p_0) \cdot \left[\sqrt{1229 + (614 \cdot \sin(\theta_{ele}))^2} - 614 \cdot \sin(\theta_{ele})\right] & \theta_{ele} > 0 \\ p_h/p_0 \cdot (1 + \theta_{ele}/\theta_{DIP}) - 70 \cdot \theta_{ele}/\theta_{DIP} & -\theta_{DIP} \leqslant \theta_{ele} < 0 \end{cases} \tag{7}$$

where FS_r is a correction factor factored into the air mass ratio to account for fog and smoke, or for a different planet's atmosphere [26], θ_{DIP} is the angle of view at the altitude h, $\theta_{DIP} = \cos^{-1}(r_0/(r_0 + h))$. The radius of earth r_0 is generally selected to be 6400 km. And in Eq. (7), θ_{ele} is the solar elevation angle,