Aerospace Science and Technology 79 (2018) 118–130

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

# An approach for estimating perpetual endurance of the stratospheric solar-powered platform

Jun Li [a], Jun Liao [a], Yuxin Liao [a], Huafei Du [b,*], Shibin Luo [a,**], Weiyu Zhu [b], Mingyun Lv [b]

[a] School of Aeronautics and Astronautics, Central South University, Changsha 410083, PR China
[b] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China

ARTICLE INFO

*Article history:*
Received 2 January 2018
Received in revised form 16 April 2018
Accepted 21 May 2018
Available online 24 May 2018

*Keywords:*
Perpetual endurance
Stratospheric solar-powered platform
Energy ratio
Solar array area
Perpetuity threshold

ABSTRACT

The high altitude solar-powered airships have been proposed for use as long endurance platforms, for a variety of military and civilian applications. The challenges of perpetual endurance flight require the airship to generate sufficient power over a wide range of operational latitudes so that the aerial vehicle can keep station through high wind events and maintain persistence. This paper provides a theoretical approach to analyzing the perpetual endurance performance of a high altitude solar-powered airship. According to the features of stratospheric airship and the theoretical model, a custom tool is developed using MATLAB computer program when the airship operates in the cruise condition. The effects of the operational latitudes, wind velocities and solar array areas on the energy ratio are numerically investigated in detail, and the required areas of solar array under the conditions of different minimum energy ratio were discussed. The results showed that the solar-powered airships faced severe operational limitations at high latitudes in the winter, especially in the high wind. In addition, a case study was analyzed to demonstrate the effectiveness of this approach to predicting the perpetual endurance region. The results demonstrated that the theoretical approach suggested a pathway towards planning the flight date and location for an airship.



## 1. Introduction

The high altitude solar-powered airships are lighter-than-air aerial vehicles, which can fly in the stratosphere with long endurance, high payload-to-weight ratio as well as low energy consumption [1,2]. It is ideally suited to provide potential applications especially for border patrol, homeland security, maritime and airborne surveillance, data and communications relay, and environmental research that require reliable and persistent station keeping capability [3]. Meanwhile, the high altitude airships are required to provide scientific and technological investigations, including fundamental scientific discoveries that contribute to the understanding of the Earth [4,5]. Various countries have paid great attention to the development of high altitude airships in the past two decades. In particular, with the rapid development of related subjects, the flight tests of these scientific platforms have been more frequent recently [6–8].

For a high altitude airship, the station-keeping flight is one of the key technologies because the vehicle is required to have the ability to fly for an extended duration of time at the high altitude [9]. In order to survey the long-endurance station-keeping performance of the solar-powered airships, many studies have been carried out previously. Colozza [10] expatiated that technologies were the key elements in the feasibility of achieving long duration high altitude flight, such as thin film solar arrays, fuel cells, electrolyzers and power management. A number of factors such as the operational environment and efficiencies of the power system components which can influence the energy balance of a stratospheric solar-powered airship were listed. In addition, the author analyzed the feasibility of operating a high altitude long endurance airship and pointed out any limitations or restrictions [11]. Eguchi and Yokomaku [12,13] found that the stratospheric airship system might be realized with advanced component technologies. The key technologies of feasibility study program included design and manufacturing of a huge lightweight envelope, a clean solar power generation system with photovoltaics and fuel cells and so on. In the project developed by Knaupp and Schafer [14], several technical challenges had to be passed to demonstrate the feasibility of a small ultra-lightweight solar powered airship and to show one possible ecological alternative in some fields of the air traffic.

* Corresponding author at: School of Aeronautic Science and Engineering, Beihang University.
** Corresponding author.
*E-mail addresses:* lv312@buaa.edu.cn (H. Du), aircraftdesign_scu@163.com (S. Luo).

https://doi.org/10.1016/j.ast.2018.05.035
1270-9638/

**Nomenclature**

| | |
|---|---|
| $A_{SA}$ | the area of solar array |
| $e_e$ | orbital eccentricity, for earth $e_e$ 0.0016708 |
| $c_{low}$ | the calibration factor at low altitude |
| $c_{\mathrm{high}}$ | the calibration factor at high altitude |
| $C_{drag}$ | the total drag coefficient of the airship |
| $C_{envelope}$ | the volumetric coefficient of the airship envelope |
| $D$ | the largest diameter of an airship |
| $F_{drag}$ | the total drag of the airship |
| $F_{propulsion}$ | the propulsion force |
| $fr$ | the fineness ratio of an airship |
| $I$ | solar radiation |
| $I_0$ | solar constant, $I_0 = 1367\ \mathrm{W/m^2}$ |
| $L$ | the length of an airship |
| $N_0$ | the correction term of the day number |
| $N_{day}$ | the day angle of the sun |
| $p$ | the power for an airship and its payloads |
| $p_0$ | the atmospheric pressure at the sea level |
| $p_h$ | the atmospheric pressure at the altitude $h$ |
| $P_{SA}$ | the output power of the solar array |
| $q_{ij}$ | solar radiation on the grid $ij$ |
| $Q_{\mathrm{in}}$ | the output energy of solar array in a period |
| $Q_{\mathrm{out}}$ | the total required energy in the period |
| $r_e$ | the reflectivity, 0.18 for clear sky, and 0.57 for overcast sky |
| $T_{SA}$ | the temperature of solar cell |
| $v_{wind}$ | the wind velocity |
| $V_{airship}$ | the volume of the airship |
| $\alpha_i$ | included angle between the plane normal and the gravity direction |
| $\alpha_R$ | the absorptivity of solar array to reflected radiation from the earth |
| $\gamma_0$ | the minimum energy ratio for the special flight condition |
| $\gamma_{\mathrm{energy}}$ | the energy ratio |
| $\eta_{\mathrm{a}}$ | the solar cell packing area efficiency |
| $\eta_{\mathrm{con}}$ | the solar cell conversion efficiency |
| $\eta_{\mathrm{eff}}$ | the electrical components efficiency |
| $\eta_{\mathrm{E}}$ | the electrolyzer efficiency |
| $\eta_{\mathrm{FC}}$ | the fuel cell efficiency |
| $\eta_{PV}$ | the conversion efficiency of solar cells |
| $\theta_{day}$ | the day angle of the sun |
| $\theta_{dec}$ | the declination of the sun |
| $\theta_{DIP}$ | the angle of view at the altitude $h$ |
| $\theta_{hour}$ | the hour angle of the sun |
| $\lambda_{am}$ | the air mass ratio when sunlight passes through the atmosphere |
| $\lambda_e$ | the true anomaly |
| $\rho_a$ | the density of the ambient air at the design altitude |
| $\tau$ | transmissivity of external encapsulation layer of solar array |
| $\tau_h$ | the transmissivity of a solar beam through the atmosphere |

Subscripts

| | |
|---|---|
| *control* | the control system |
| *D* | the direct solar irradiance |
| *payload* | the payload system |
| *propulsion* | the propulsion system |
| *R* | the reflected radiation |
| *req* | the total power required |
| *S* | the scattered radiation |
| total | the total solar radiation received on the solar array |

As mentioned in the foregoing description, it can be seen that the solar-powered airships with ability of station-keeping at the high altitude are feasible. And the following conclusions can be drawn that solar energy is one of the most ideal of renewable energy and the renewable energy technologies such as thin film solar arrays, fuel cells, electrolyzers and power management become the key technologies to achieve the ability to fly for an extended duration of time. Therefore, many researches and developments have been in progress in renewable energy system for a solar-powered airship. Garg and Burnwal [15] proposed a method of estimating and optimizing the required area of solar panels to maximize the solar energy produced by per unit area of the solar panels. Wang and Song [16] presented their computation method of 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. Li [17] put forward a kind of regenerative fuel cell with low pressure gasbags to store hydrogen and oxygen with the huge volume of airships. Compared with the common regenerative fuel cell, the regenerative fuel cell with gasbags made the total weight of airship decrease by 19%. The results confirmed that the regenerative fuel cell with gasbags had great advantages and feasibility on the high altitude airship. Based on the traditional renewable energy system for an airship, Lv [18] designed a rotatable renewable energy system (mainly including solar array) playing a role in improving the current status of the energy system, which had shown that the rotatable renewable energy system made the total weight of energy system decrease by 25% at the maximum design speed of the airship of greater than 22 m/s.

For pursuing long endurance, the energy is obtained mostly through solar powered regenerative fuel cells. Only a part of the collected solar irradiance is available for the direct propulsion while the rest has to be used to charge the energy storage for the night time [19]. The sketch of energy system is showed in Fig. 1. The above research results can serve as a basis for the further research about the perpetual endurance of a high altitude airship, in addition, the energy demand model of an airship remains to be studied. In the recent years, a large body of literatures related to the energy demand methods of a high altitude airship were emerging [20]. The power required to run an airship and its payloads consists mostly of control system, payload system and propulsion system [21,22]. Li [23] made a numerical prediction on the power required of the high-altitude airship and emphasized that the wind velocity, the airship's latitude and the working date had a great effect on the power required. In addition, it was of essential interest to minimize the aerodynamic drag and maximize the propulsion efficiency because the propulsive power required depended mainly on the aerodynamic drag of the airship hull, accounting for about 2/3 of the total drag [24].

These scholars and specialists paid the attention to the feasibility of an airship, the output performance of solar array and the power required. It could be obtained that a high-altitude airship with an adequate energy system would fly for an extended duration of time (months to years) within the suitable flight area. However, it was rare to discuss the perpetual endurance of a solar-powered airship for different flight tasks in these studies. Furthermore, the airship's latitude and the flight date had a great impact on the energy generation and the required area of solar array for different flight missions. The horizontal wind varied with altitude in the lower stratosphere (see in Fig. 2). And the effects of variable wind speed on the power required and the mass of the renew-