Energy Conversion and Management 140 (2017) 51–61

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A theoretical study of rotatable renewable energy system for stratospheric airship

Mingyun Lv, Jun Li, Weiyu Zhu, Huafei Du *, Junhui Meng, Kangwen Sun

School of Aeronautic Science and Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, PR China

ARTICLE INFO

Article history:
Received 18 December 2016
Received in revised form 15 February 2017
Accepted 23 February 2017

Keywords:
Renewable energy system
Rotatable solar array
Stratospheric airship
Theoretical study
Rotation angle
Required area

ABSTRACT

Renewable energy system is very critical for solving the energy problem of a long endurance stratospheric airship. Output performance of the traditional solar array fixed on the upper surface of the airship remains to be improved to reduce the area and weight of renewable energy system. Inspired by the solar tracking system and kirigami, a rotatable renewable energy system (mainly including solar array) is designed to improve the current status of the energy system. The advantages of the rotatable solar array are studied using a MATLAB computer program based on the theoretical model established in this paper. The improvements in output energy and required area of the solar array were compared between the traditional airship and improved one. Studies had shown that the rotatable renewable energy system made the total weight of energy system decreased by 1000 kg when the maximum design speed of the airship was greater than 22 m/s. The results demonstrate that the rotatable renewable energy system for the airship can be a good way to improve the output performance of solar array, and the conceptual design and theoretical model suggest a pathway towards solving the energy problem of a stratospheric airship.

1. Introduction

A stratospheric airship is a lighter-than-air aircraft which can fly in the stratosphere to provide potential applications especially for the border patrol, homeland security, maritime and airborne surveillance, data and communications relay, and environmental research. The last 20 years have witnessed the projects establishment and researches of stratospheric airship in various countries, especially the developed countries in Europe and America, which greatly promote the development of the stratospheric airship [1,2].

Compared with the traditional aircrafts, the stratospheric airship can stay in the stratosphere with the advantages of long endurance and low energy consumption. In order to accomplish an extended duration of time (months to years) at high altitudes (18–20 km), the renewable energy technologies such as the thin film solar arrays, the fuel cells, electrolyzers and the power management become the key. Hence, many researches and developments have been in progress in the renewable energy system on stratospheric airships in the past decades [3]. Colozza [4] made an initial look at the feasibility of operating a high altitude long endurance airship along the east coast by the way of analyzing the payload capacity and power requirements, size (drag), component efficiencies and power management. The result showed that the solar array, as a renewable energy system, could provide enough energy for a stratospheric platform airship. Wang [5] presented a computation method for solar radiation on solar cells of the curved surface of the high-altitude airship, and studied the effect of the HAA's attitude on the performance of its energy system when the airship was flying in 40 deg north latitude region. Zhang [6] established a new simplified analytical model with thermal effects to analyze the output performance of the solar array and studied the effects of latitude, date, attitude and attitude angle on the output performance of the solar array.

These researches provided a base for investigating the output performance of solar array on stratospheric airship. In these research works, based on the fact that the efficiency of lightweight flexible thin film photovoltaic cells was generally low [7], there was a simplified problem that the airships needed to sacrifice some useful functional loads to carry a heavier energy system when the lightweight flexible thin film photovoltaic cells was used as a renewable energy device. This problem should be considered carefully in the design phase due to the adverse effects on the practical performance and utilization efficiency of the entire airship. Therefore, the renewable energy system of airship is required for further research to solve the above-mentioned problems. The similar studies have been carried out by some scholars and research institutions [8]. In these traditional designs, the solar array is fixed on

* Corresponding author.
E-mail address: lv312@buaa.edu.cn (H. Du).

http://dx.doi.org/10.1016/j.enconman.2017.02.069
0196-8904/

Nomenclature

c_{high}	the calibration factor at high altitude
c_{low}	the calibration factor at low altitude
C_{total}	the total drag coefficient of the airship
$C_{envelope}$	the volumetric coefficient of the airship envelope
D	the maximum diameter of airship, m
e_e	orbital eccentricity
$F_{propulsion}$	the propulsion force, N
F_{drag}	the total drag of the airship, N
$\vec{n}$	normal vector of tilted grid
I_0	solar constant, $I_0 = 1367$ W/m^2
I_h	the direct solar irradiance, W/m^2
I_s	scattered radiation, W/m^2
k_{energy}	the factor of energy
l_{SA}	the length of the solar array, m
L	total length of the airship, m
m	the masses, kg
$\vec{n}_s$	unit vector of solar direct radiation
$\vec{n}_{ij}$	the normal vector of grid ij
$\vec{n}_{ijI}$	the expression of the normal vector of tilted grid ij in the inertial frame of reference
N_{day}	the day number
N_0	the correction term of the day number
p_h, p_0	the atmospheric pressure at the altitude h and the sea level, reflectivity
p_{SC}	the output power of solar array, kW
p_{req}	the total power required, kW
q	radiation on the tilted grid, W
Q	total radiation on solar array, W
Q_1	the energy available for storage, GJ
Q_3	the energy supplied for the power consuming function on the airship, GJ
Q_{req}	the total energy required to run an airship and its payloads, GJ
Q_{SA}	the output energy of the renewable energy system, GJ
Q_{SA_min}	the minimum output energy of solar array in daytime, GJ
r	the equivalent rotary radius of airship, m
r_e	the radius of earth, m
v_{wind}	the relative velocity between the airship and the flowing air, m/s
x	chordwise coordinate
x_{ij}, z_{ij}	the x and z coordinates of the central point of tilted grid ij
y	chordwise coordinate
z	vertical coordinate
y_1	the y coordinate of leading edge of solar array
y_2	the y coordinate of trailing edge of solar array
α_e	absorptivity of solar array to direct incident
α_R	absorptivity of solar array to reflected radiation
θ	central angles of solar array, degrees
θ_{day}	day angle of the sun, degrees
θ_{dec}	the declination of the sun, degrees
θ_{DIP}	the angle of view at the altitude h, degrees
θ_{ele}	solar elevation angle, degrees
θ_{hour}	the hour angle of the sun, degrees
Φ	the local latitude, degrees
Φ_{error}	the allowable misalignment of flight latitude, degrees
φ	the rotation angle of solar array, degrees
φ_{up}	the upper bound of rotation angle, degrees
η_{SC}	the efficiency of the solar cell
η_{FC}	the fuel cell efficiency
η_E	the electrolyzer efficiency
$\eta_{propulsion}$	the propulsive efficiency
λ_{am}	air mass ratio, degrees
λ_e	the true anomaly
δ	the index which takes into account the self-shadowing of the curved surface solar array from the reflected radiation
τ_h	the transmissivity of a solar beam thru the atmosphere
ρ_a	the density of the ambient air at the design altitude, kg/m^3
ξ	the included angle between the plane normal and the gravity direction
ω_{sign1}	projection coefficient of solar direct radiation on the tilted grid

Subscripts

Belt	the drive belt
BP	the butter paper
FI	the fixed infrastructure used for installing and fixing the solar array
h	the altitude h
ij	tilted grid ij
Improved	the improved airship
Insulation	the lightweight insulation substrate for solar array
Motor	the electric motor
SA	solar array
SC	solar cell
Storage	the storage system
Traditional	the traditional airship

the upper surface of the airship, as shown in Fig. 1(a). In order to maximize the output energy of the solar array, different solar array layouts should be designed when the dates and locations of the flight task are different. However, based on the result shown in Fig. 1(b), the output power is the maximum only at noon. The main reason is that, most of the time, the normal vectors of the solar cells do not point to the sun and the solar cells suffer optical coupling losses due to a decrease in projected area that scales with the cosine of the misalignment angle between the cell and the sun, as shown in Fig. 2(a).

On the other hand, one conclusion can be obtained that the solar array has a great influence on the thermal performance of the envelope and lifting gas. The high solar irradiation flux, low convective heat transfer, and low ambient temperature make superheat and supercool phenomena easily happen in stratosphere [9]. The simulation results reported by Harada [10] indicated that the highest temperature on PV-panel would reach about 370 K at noon due to the high solar absorptivity of solar cells. However the highest temperature on envelope without PV-panel was only 320 K in the summer solstice. This phenomenon made the superheat problem even worse. Excessive high temperature of inner lifting gas induces the rise of pressure which can break the envelope and even destroy the airship. Therefore a thermal insulation layer between solar cells and envelope has become an essential structure [11,12]. However, large areas of thermal insulation layer make the energy system heavier. It is clear that the area of the solar array is necessary to be reduced to save the weight of solar array and thermal insulation substrate.

Inspired by the solar tracking system and kirigami (the art of paper cutting shown in Fig. 2) [13–15], to cut these losses and maximize the power output, curved solar array on stratospheric airship can be rotated to track the positions of the sun over the course of the day. Depending on the geographic location of the system, and whether there are one or two tracking axes, traditional