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Effect of angular losses on the output performance of solar array on long-endurance stratospheric airship

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ABSTRACT

The solar array is one of the major components of long-endurance stratospheric airship which converts the solar energy to electric energy. Exact calculation of the output performance of solar array is significant to the operation of the airship. The move of the sun and the curve surface of the airship lead to the dramatic change of the incidence angle of solar radiation. Therefore, the angular losses, caused by the change of incidence angle, decreasing the efficiency of solar cell and then reducing the output energy of solar array, should be taken into account. But the relevant investigations are rare. In this paper, a simplified numerical model including solar radiation model, thermal model and angular losses model was established. A MATLAB computer program was developed based on the model to research the deviation of output energy of solar array with/without angular losses. The effects of date, airship's attitude and latitude on the deviation were also discussed in detail. The result indicates that the output energy of solar array on stratospheric airship was overestimated without considering the angular losses and the angular losses should be taken into account for an accurate calculation. It is believed that the present models and program will lead to a better design for the energy management system of stratospheric airship.

1. Introduction

The stratosphere, with the characteristic of stable atmosphere and weakly vertical convection, is the ideal location to deploy aerial platforms for the purpose of surveillance, early alarming, communications relay, navigation and environmental monitoring [1,2]. Conventional airplanes and satellites can't fly for a long period at this location. With the advantage of long-endurance (months to years) and station-keeping, stratosphere airships have received much attention in recent years [3]. Since the US Navy first proposed the high-altitude airship in 1978 with the HASPA program [4], many other countries, such as China, Japan, South Korea and European countries, have developed many investigations and experiments of stratospheric airships [5–7]. Fig. 1 shows the airship designed by our team.

For the purpose of long-endurance, the thin film solar array which can utilize solar energy, regenerative fuel cell and lithium rechargeable battery are the common collocation to supply energy for many stratospheric airships [8]. Since the solar energy is the main energy source of the airship, it is significant to calculate the output power of solar array and design the energy management system based on it. Many researches were carried out for it in the past decades. Wu [9] presented a comprehensive literature review focusing on the thermal issues, including direct solar radiation model, diffuse solar radiation model and reflected model for clear skies, which provides guides for solar radiation model selections and suggests topics be worth for further research. Naito [10] studied the concept design and analyzed the generated energy of the solar array. The result shows that sufficient energy is available at solar array over a year to distribute to the propulsive motors, control unit and payload mission. Considering that the solar radiation on the solar cells of a curved surface is different from that on the horizontal projection plane, Wang [11] proposed a computation method for solar radiation on solar cells taking into account the effect of surface curvature and studied the effect of the airship's attitude on the performance of solar array. Li [12] developed a numerical model for investigating the effects of solar array layouts on the output performance and optimized the solar array layouts under four common airship operating conditions. They found that the solar array layout optimization for stratospheric airships can comprehensively improve the output power of the solar panel, which is helpful in guiding to install suitable solar array for long-endurance airship. Ma [13] proposed a new management technology of the multi-power system based on the variation of airship flight modes and system related energy demands.

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Nomenclature

A	area, m^2
$AL(\theta)$	angular losses factor
$c_{env/SC}$	specific heat capacity of envelope or solar cell, J/(kg K)
c_{high}	calibration factor at high altitude
c_{low}	calibration factor at low altitude
d	thickness, m
g	gravitational acceleration, m/s^2
h	altitude, m
h_{in}	internal natural convective heat transfer coefficient, $W/(m^2\ K)$
h_{out}	external convective heat transfer coefficient, $W/(m^2\ K)$
I_0	solar constant, 1367 W/m^2
I_{DN}	normal direct solar intensity, W/m^2
I_{IR_ex}	envelope/solar cell internal surface infrared radiation, W/m^2
I_{IR_g}	ground infrared radiation, W/m^2
$I_{IR\_grid\_i0}$	internal surface infrared radiation of envelope/solar array grid *i0* from other grids, W/m^2
I_{IR_in}	envelope/solar cell internal surface infrared radiation, W/m^2
I_{SUN}	extraterrestrial normal solar intensity, W/m^2
k	thermal conductivity, W/(m K)
L	length of airship, m
L_0	characteristic length of airship, m
N	day number
N_0	correction term of the day number
Nu	Nusselt number of free convection
n_0	refractive index of air
n_1	refractive index of encapsulation material
$\vec{n}_{ij}$	normal vector of titled grid *ij* in the body fixed coordinate system
$\vec{n}_{ijI}$	normal vector of titled grid *ij* in the inertial reference system
$\vec{n}_s$	unite vector of direct solar radiation
P	output power of solar array, W
Pr	Prandtl number
p_0	atmospheric pressure at sea level, Pa
p_h	atmospheric pressure at altitude *h*, Pa
q_{DN}	absorbed direct solar radiation energy, W
R	transformation matrix
Re	Reynolds number of airship
$r(\theta)$	reflectivity of solar cell surface
r_0	radius of earth, m
r_{IR}	albedo of internal surface of envelope
$r_{airship}$	rotary radius of airship, m
r_p	reflection coefficient of transverse-magnetic
r_s	reflection coefficient of transverse-electric
T_0	standard test temperature of solar cell efficiency, 298.15 K
T	temperature, K
T_g	temperature of ground, K
TC	temperature coefficient of solar cell efficiency, %/K
TL	temperature loss of solar cell efficiency
α_{DN}	absorptivity of solar cell to direct solar radiation
α_{IR_ex}	absorptivity of external surface of envelope or solar array
α_{IR_in}	absorptivity of internal surface of envelope or solar array
γ	angle of refractive, rad
γ_0	central angle of solar array, rad
ε_{ex}	emissivity of external surface of envelope or solar cell
ε_{in}	emissivity of internal surface of envelope or solar cell
ε_g	emissivity of ground
$\varepsilon_{env/SC}$	emissivity of envelop or solar cell
ζ	true anomaly, rad
η	efficiency of solar cell
θ	incident angle of solar radiation, rad
θ_{DIP}	angle of view at altitude *h*, rad
θ_{azi}	sun azimuth angle, rad
θ_{day}	day angle, rad
θ_{dec}	declination of sun, rad
θ_{ele}	elevation angle of sun, rad
θ_{hour}	hour angle of sun, rad
λ_{AM}	air mass ratio
μ	dynamic viscosity
ρ	density, kg/m^3
σ	Stefan-Boltzmann constant
τ_{IR_g}	transmittance of atmosphere at altitude *h*
τ_{atm}	infrared radiation transmissivity of solar beam through the atmosphere
$\tau(\theta)$	transmittance of encapsulation material
Φ	local latitude, rad
φ	pitch angle, rad
ϕ	roll angle, rad
ψ	yaw angle, rad

subscripts

atm	atmosphere
env	envelope
env/SC	envelope or solar cell
ij	tilted grid *ij*
Lgas	lifting gas
SC	solar cell

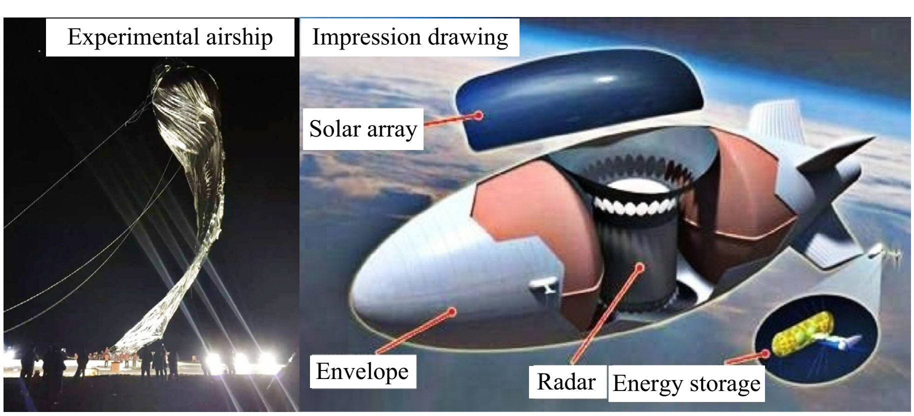

Fig. 1. The experimental stratospheric airship designed by our team and its impression drawing.