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Thermal performance analysis and comparison of stratospheric airships with rotatable and fixed photovoltaic array

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ABSTRACT

The thermal performance of stratospheric airship is closely related to the superheat/overpressure of airship, the thermal stress of the hull, the mechanics property of the envelope, as well as the airship reliability and lifetime. A comprehensive understanding of the thermal performance of the airship is important for the increase of airship applications. For the improved airship with rotatable photovoltaic array, the location of the photovoltaic array changes with time to utilize the solar radiation maximally, which decrease the mass of photovoltaic array greatly. The thermal performance may be different with the traditional airship with fixed photovoltaic array. In this paper, a thermal model of stratospheric airship with rotatable photovoltaic array was proposed to investigate the thermal performance and compare with traditional stratospheric airship with fixed photovoltaic array. A user define function program in computational fluid dynamic software was developed based on the model. The temperature distribution of surface and flow field of inner lifting gas of the airship with rotatable/fixed photovoltaic array were simulated and compared. The result shows that the temperatures of photovoltaic array and envelope of the improved airship are slight higher than that of traditional airship. The temperature fields of the Helium are also various and the uneven temperature distribution leads to the formation of eddies and chaotic state of the flow field. It is helpful in guiding the design of novel stratospheric airship with low-weight power system, especially the design of thermal control system and inner pressure regulation system of the airship.

1. Introduction

Different with the conventional airplane, the stratospheric airship with long-endurance, station-keeping at an altitude of approximately 20 km and low cost of manufacturing and maintenance, is of great importance for surveillance, early alarming, communication relay, navigation and environment monitoring [1]. Since the US Navy first proposed the high-altitude airship in 1978 with the HASPA program, many other countries, such as Japan, South Korea and European countries, have developed many investigations and experiments of stratospheric airships [2].

In order to accomplish the long-duration fly mission (months to years), sufficient energy is essential for stratospheric airships to supply the propulsion motors, buoyant control unit, fight control unit and the payload mission. It is unadvisable to carry a great amount of fuel or accumulator for adding weight. Therefore, the renewable energy system including thin film photovoltaic array which can utilize solar energy constantly, proton-exchange membrane fuel cells and electrolyzer cells, was proposed to achieve minimum power system mass while satisfy the energy demand. Yang [3] introduced the composition of renewable power system and proposed the high accurate calculation method of the output power of photovoltaic array. The whole operation process of the system was simulated and the endurance of the airship was evaluated. Some important factors, including wind resistance strategy, efficiency of photovoltaic array and the specific energy of lithium buttery, were analyzed to evaluate the influence on endurance. However, the power system is still heavy for the large area of photovoltaic array. Eguchi [4] studied the feasibility of stratospheric platform airship technology in Japan. According to the design, the area of the photovoltaic array with a maximum power of 700 kW occupies 45% of total envelope area. The total mass of the renewable energy system amounts to 34.6% of the gross weight of the airship, which severely compresses the payload because the buoyancy of the airship is limited.

There are two approaches to reduce the area of the photovoltaic array, improving the efficiency of photovoltaic cell or optimizing the layout of photovoltaic array. Naito [5] investigated the relationship between array area and solar cell efficiency. The result shows that the area of photovoltaic array drastically decreases when solar cell

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Nomenclature

A	area, m^2
c	specific heat capacity, J/(kg·K)
c_{high}	calibration factor at high altitude
c_{low}	calibration factor at low altitude
e_e	orbital eccentricity, 0.016708
h	altitude, m
h_{ex}	external convective heat transfer coefficient, W/(m^2·K)
$h_{natural\,ex}$	natural convective heat transfer coefficient, W/(m^2·K)
$h_{forced\,ex}$	forced convective heat transfer coefficient, W/(m^2·K)
h_{in}	internal natural convective heat transfer coefficient, W/(m^2·K)
I_0	solar constant, 1367 W/m^2
I_D	direct solar irradiance intensity at altitude h, W/m^2
$I_{IR\,atm}$	atmosphere infrared radiation, W/m^2
$I_{IR\,ear}$	earth infrared radiation, W/m^2
$I_{IR\,grid\,i0}$	internal surface infrared radiation of envelope/ photovoltaic array grid $i0$ from other grids, W/m^2
$I_{IR\,in}$	internal surface infrared radiation of envelope/ photovoltaic array, W/m^2
I_R	earth reflected radiation intensity, W/m^2
I_S	atmosphere scattered radiation intensity, W/m^2
k	thermal conductivity, W/(m·K)
L_0	characteristic length of airship, m
m	mass of surface unit ij
N	day number
N_0	correction term of the day number
Nu	Nusselt number of natural convection
$\mathbf{n}_D$	unite vector of direct solar radiation
$\mathbf{n}_{ij}$	normal vector of tilted grid ij in the body fixed coordinate system
$\mathbf{n}_{ij\,I}$	normal vector of tilted grid ij in the inertial reference system
$\mathbf{n}_{ij\,R}$	normal vector of tilted grid ij in the body fixed coordinate system after the rotation operation
Pr	Prandtl number
p_0	atmospheric pressure at sea level, Pa
p_h	atmospheric pressure at altitude h, Pa
Q	power of photovoltaic array, J
q_D	absorbed direct solar radiation energy, J
$q_{IR\,atm}$	absorbed infrared radiation energy from atmosphere, J
$q_{IR\,ear}$	absorbed infrared radiation energy from earth, J
$q_{IR\,grid}$	absorbed infrared radiation energy from other grids, J
$q_{IR\,in}$	absorbed infrared radiation energy from inner lifting gas, J
$q_{conv\,ex}$	convection energy between airship and external atmosphere, J
$q_{conv\,in}$	convection energy between airship and internal lifting gas, J
q_{power}	electrical power of photovoltaic cell, J
q_R	absorbed earth reflected radiation energy, J
q_S	absorbed atmosphere scattered radiation energy, J
Re	Reynolds number of airship
r	rotary radius of airship, m
r_0	radius of earth, m
r_e	reflectivity of the earth surface to atmosphere
r_{IR}	albedo of internal surface of envelope or photovoltaic array
T	temperature, K
y_1	y coordinate of the nose of the airship, m
y_2	y coordinate of leading edge of photovoltaic array, m
y_3	y coordinate of trailing edge of photovoltaic array, m
y_4	y coordinate of the stern of the airship, m
α_D	absorptivity of photovoltaic cell to direct solar radiation
$\alpha_{IR\,in}$	absorptivity of internal surface of envelope or photovoltaic array
α_R	absorptivity of envelope/solar cell to reflected radiation
γ	rotation angle of photovoltaic array, rad
γ_{up}	upper bound of rotation, rad
ε_{ex}	emissivity of external surface of envelope or photovoltaic array
ε_{in}	emissivity of internal surface of envelope or photovoltaic array
η	efficiency of photovoltaic cell
θ_0	central angle of photovoltaic array, rad
θ_{azi}	sun azimuth angle, rad
θ_{DIP}	angle of view at altitude h, rad
θ_{day}	day angle, rad
θ_{dec}	declination of the sun, rad
θ_{ele}	sun elevation angle, rad
θ_{hour}	hour angle of the sun, rad
λ_{AM}	air mass ratio
λ_e	true anomaly, rad
μ	dynamic viscosity
ρ	density
σ	Stefan-Boltzmann constant
τ_h	transmissivity of a solar beam thru the atmosphere
$\tau_{IR\,ear}$	transmittance of atmosphere at altitude h
Φ	local latitude, rad
Φ_0	flight latitude of airship, rad
φ	pitch angle, rad
ϕ	roll angle, rad
ψ	yaw angle, rad
ω	projection coefficient of solar direct radiation on the tilted grid

Subscripts

atm	atmosphere
env	envelope
env/PV	envelope or photovoltaic cell
$Lgas$	lifting gas
PV	photovoltaic array

efficiency is improved from 10% to 11% and then decreases slowly when the efficiency exceeds 11%. Li [6] developed a numerical model to investigate the effects of photovoltaic array layouts on the output performance and found that the photovoltaic array layout optimization can comprehensively improve the output power of the solar panel.

The solar radiation vector can be resolved into two parts: one perpendicular to the photovoltaic array surface and one parallel to it. Of these two parts, only the perpendicular one is effective in producing electrical energy [7]. Therefore, enlarging the perpendicular part of the solar radiation vector is a key point to maximize the collecting of solar energy and decrease the area (or mass) of photovoltaic array.

Different with the traditional solar-power stratospheric airship with the photovoltaic array fixed on the upper of the airship, an improved airship with a rotatable photovoltaic array was proposed [8]. The position of the photovoltaic array can be adjusted to maximize the perpendicular part of the solar radiation vector. As shown in Fig. 1, the photovoltaic array is connected with the electric motor and control device installed in equipment cabin by drive belt. Therefore, the photovoltaic array can be rotated around the airship axis driven by the electric motor. Based on the local time, date and location, the rotation angle is optimized to maximum the output energy of photovoltaic array. Compared with the traditional airship, the theoretical study