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Simplified analytical model for investigating the output power of solar array on stratospheric airship

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Abstract

Solar energy is the ideal power choice for long-endurance stratospheric airships. The output performance of solar array on stratospheric airship is affected by several major factors: flying latitude, flight date, airship's attitude and the temperature of solar cell, but the research on the effect of these factors on output performance is rare. This paper establishes a new simplified analytical model with thermal effects to analyze the output performance of the solar array. This model consisting of the geometric model of stratospheric airship, solar radiation model and incident solar radiation model is developed using MATLAB computer program. Based on this model, the effects of the major factors on the output performance of the solar array are investigated expediently and easily. In the course of the research, the output power of solar array is calculated for five airship's latitudes of 0°, 15°, 30°, 45° and 60°, four special dates and different attitudes of five pitch angles and four yaw angles. The effect of these factors on output performance is discussed in detail. The results are helpful for solving the energy problem of the long endurance airship and planning the airline.

Key words: Simplified model; Output power; Solar array; Stratospheric airship; Thermal effects

1. Introduction

With potential for scientific exploration as well as for observation and surveillance, there is growing interest in studying stratospheric airship as a long endurance vehicle in recent years [1-4].

For any type of long endurance vehicle, to maintain a fine balance of energy collection and energy consumption is the key element in the feasibility of achieving long duration high altitude flight [5, 6]. As the most important part of the energy collection, solar cell supplies energy for driving the vehicle and charges the battery during the day [7]. In order to analyze the balance influenced by a number of factors such as the operational environment, the capabilities and efficiencies of the power system components, it is necessary to predict the output power of solar panel on stratospheric airship before it launches [8]. For the sake of accomplishing the mission successfully, an accurate and reliable prediction method used to study output power of solar array is required in the period of preparation of the flight mission. Therefore, more and more attentions focus on dealing with the output power of solar panels on stratospheric airship.

In the past decades, several studies were carried out for investigating the feasibility of covering the solar array on the stratospheric airship. Naito and Eguchi [9] studied the power characteristics of the solar array to determine the technical possibility of a stratospheric platform airship. Colozza [10] made an initial look at the feasibility of operating a high altitude long endurance airship along the east coast by way of analyzing power and propulsion system.

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Based on the result that solar array can satisfy energy requirements of stratospheric airship, many investigations on solar array of stratospheric airship have been published. Wang and Song [11] partitioned the flexible solar cells of a curved surface on the back of the airship into n (along with heading) m (along with circumference) grids, and each grid can be seen as a tilted plane. In addition, the authors developed their computation method to study the effect of the high-altitude airship's attitude on the performance of its energy system when the airship is flying in 40 degree north latitude region in winter and summer solstice. Su Song [12] developed a higher precision model that was used for investigating the performance of the curved surface solar cell. The stratospheric airship was simplified as the cylindrical vehicle to analyze the power characteristic of the solar array and the effects of operation time, latitude, attitude, installation geometry of the array of the airship on the power[13]. In order to estimate the amount of solar energy incident on the airship, the available solar panel area was resolved into three perpendicular planes to propose a novel method [14]. Following the method, the authors estimated and optimized the area of solar panels so as to maximize the solar energy produced by per unit area of the solar panels. Li and Fang [15] developed a thermodynamic model of the photovoltaic array and airship to estimate the thermal performances of the array, what's more, they analyzed the effects of the latitude, wind speed, and insulation on the power output of the PV array.

These researches provide a base for investigating the output performance of solar array on stratospheric airship. However, the comprehensive investigation of output power of solar array on stratospheric airship is rarely studied. As we all know, many factors such as the latitude, working date and attitude have a huge impact on output power of solar array[16]. Like the airship surface, solar array will be shaped into a curved surface during the working hours. It is possible to induce worse error that simplifies the solar panel as a semi cylindrical surface. The curved surface solar array will be subjected to the different solar radiation flux when solar array is installed at different position and the attitude is different. In addition, the investigation of output performance of solar array with thermal effect is also rare. Therefore, it is very necessary to research the effect of the shape, and the attitude of airship on output power of solar array when the thermal effects are considered.

In this paper, for investigating the output performance of the solar array, a simplified analytical model of the stratospheric airship with solar array is developed. In this analytical mode, the effects of temperature of solar cell on the output performance are involved. Then a numerical simulation program is established to research the effects of airship's latitude, day number and airship's attitude on the output performance of the solar array.

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, the geometry of the solar array, the time of year (the day number) and stationary latitude[17]. To analyze the output power of solar array on stratospheric airship, fundamental assumptions made in this paper are as follows:

(1) Actual stratospheric airship cannot maintain its streamlined shape as a result of the load in the lower part of the vehicle. To simplify the model, the stratospheric airship subjected to a payload is idealized to be a streamlined airship.

(2) In addition, the airship surface wiggling will be neglected when the airship operates in the cruise condition. The effects of wiggling on the incidence angle of each cell were not considered.

(3) The stratospheric airship film and the solar panel are so thin that their thicknesses are less than 0.1% of diameter of stratospheric airship, therefore, the thicknesses can be neglected. The diameter of streamlined airship is approximated as the overall diameter of stratospheric airship.

From the above fundamental assumptions, the new analytical model is possible to induce a greater error than some more sophisticated but possibly more expensive approaches. But this model will still play an important role in analyzing the performance of solar array due to its expedient and easy application.

2.1 Geometric model of stratospheric airship

Generally, the stratospheric airship can be regarded as a smooth, streamlined body of revolution[18]. The axisymmetrical cross-section curve of airship is described with equivalent rotary radius r as the function of the coordinate y

$$r = f(\mathrm{y}) \qquad 0 \le y \le L \tag{1}$$

In the body coordinate system, based on the preceding assumptions, the curved envelop and solar panel can be described as a rotating surface. We can obtain

$$x^2 + z^2 = f^2(\mathrm{y}) \qquad 0 \le y \le L \tag{2}$$

The curved surface of the stratospheric airship is divided into finite grids which have different areas and these grids can be seen as the tilted planes, as shown in Fig. 1. If the area of each grid is small enough, the precision of calculation can satisfy engineering application. The streamlined airship is cut equally into sections along the axis of rotation. The length of each section is . Each section is partitioned into small circular arcs which central angles are described as along the circumferential direction. For the reason that each grid is small enough, the central point of tilted planes can be calculated through the four vertices of the grid, to study the area and normal vector of tilted grid.

The area of tilted grid is defined as , which can be described by

$$A_{ij} = r \cdot d\theta \cdot dy \cdot \sqrt{1 + \mathrm{r}'(\mathrm{y})^2} \tag{3}$$

where θ is the rotation angle of the generatrix along the circumferential direction, $\theta \in \left(-\pi, \pi\right)$.

The normal vector $\vec{n}_{ij}\left(n_{ijx}, n_{ijy}, n_{ijz}\right)$ of tilted grid ij is given by

$$\vec{n}_{ij} = \left(\frac{\partial F}{\partial x_{ij}}, \frac{\partial F}{\partial y_{ij}}, \frac{\partial F}{\partial z_{ij}}\right) / \sqrt{(\frac{\partial F}{\partial x_{ij}})^2 + (\frac{\partial F}{\partial y_{ij}})^2 + (\frac{\partial F}{\partial z_{ij}})^2} \tag{4}$$

where F=0 is the equation of the curved surface, x_{ij} and z_{ij} are the x and z coordinates of the central point of tilted grid ij, respectively. Which can be described by

$$\begin{aligned} &F = x^2 + z^2 - f^2(y) \\ &x_{ij} = r(y_{ij}) \cdot \sin\theta_{ij} \\ &z_{ij} = r(y_{ij}) \cdot \cos\theta_{ij} \end{aligned} \tag{5}$$

where y_{ij} is the y coordinate of the central point and θ_{ij} is the rotation angle of the grid ij. Which can be defined as

$$\begin{aligned} y_{ij} &= i \cdot dy + \frac{1}{2} dy \\ \theta_{ij} &= j \cdot d\theta + \frac{1}{2} d\theta \end{aligned} \tag{6}$$

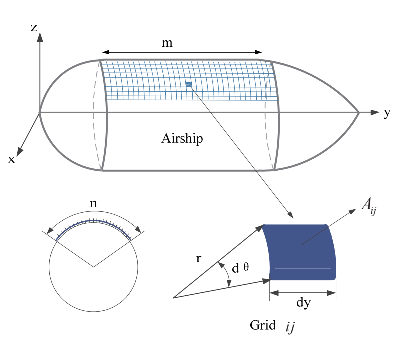

Fig. 1. Schematic of airship and finite grid *ij*.

2.2 Solar radiation model

Solar radiation that affects the output power of solar array on stratospheric airship consists of the solar direct radiation, the scattered radiation and the reflected radiation. The value of radiation can be obtained from the methods introduced by Farley [19], Ran and Thomas [20] , Shi and Song [21] and Dai and Fang [22].

The solar direct radiation intensity I_{top} irradiated on the top of the atmosphere at the normal direction can be expressed as

$$I_{top} = I_0 \cdot \left(\frac{1 + e_e \cdot \cos(\lambda_e)}{1 - e_e^2}\right)^2 \tag{7}$$

where I_0 is the solar constant that has a value of 1367 W/m^2, e_e is the orbital eccentricity, for earth e_e=0.0016708. The true anomaly λ_e can be calculated with

$$\lambda_e = \theta_{day} + 0.0334 \cdot \sin\left(\theta_{day}\right) + 3.49 \times 10^{-4} \cdot \sin\left(2 \cdot \theta_{day}\right) \tag{8}$$

where θ_{day} is the day angle of the sun, and is given by

$$\theta_{day} = 2\pi \cdot \left(\mathrm{N} - N_0\right) / 365.2422 \tag{9}$$

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.

At the stratospheric airship altitude h, the direct solar irradiance I_h is equal to the product of solar direct radiation intensity on the top of the atmosphere and the atmospheric transmittance, which can be expressed as

$$I_h = \tau_h \cdot I_{top} \tag{10}$$

where

$$\tau_h = \frac{1}{2} \cdot (1 + \mathrm{c}_{low}(\mathrm{p}_h / \mathrm{p}_0)^{c_{high}})(\mathrm{e}^{-0.65 \cdot \lambda_{am}} + \mathrm{e}^{-0.95 \cdot \lambda_{am}}) \tag{11}$$

where the transmissivity of a solar beam thru the atmosphere is correlated with modifying factor in the first bracket on the right side of the equation (11). For the modifying factor, c_{low} and $\mathrm{c}_{\mathrm{high}}$ are the calibration factors at low altitude and high altitude, respectively, p_h and p_0 are the atmospheric pressure at the altitude h and the sea level[23]. In the second bracket on the right side of the equation(11), λ_{am} is the air mass ratio when sunlight passes through the atmosphere as shown in Fig. 2, which can be described by

$$\lambda_{am} = \begin{cases} \left(\dfrac{p_h}{p_0}\right) \cdot \left[\begin{array}{l} \sqrt{1229 + (614 \cdot \sin(\theta_{ele}))^2} \\ -614 \cdot \sin(\theta_{ele}) \end{array}\right] & 0 < \theta_{ele} < \pi \\ \dfrac{p_h}{p_0} \cdot \left(1 + \dfrac{\theta_{ele}}{\theta_{DIP}}\right) - 70 \cdot \dfrac{\theta_{ele}}{\theta_{DIP}} & \begin{array}{l} -\theta_{DIP} \le \theta_{ele} < 0; \\ \pi \le \theta_{ele} < \pi + \theta_{DIP} \end{array} \end{cases} \tag{12}$$

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where θ_{DIP} is the angle of view at the altitude h, $\theta_{DIP}=\cos^{-1}(\frac{r}{r+h})$. The radius of earth r is generally selected to be 6400 km[24].

In equation(12), θ_{ele} is the solar elevation angle,

$$\theta_{ele}=\sin^{-1}(\sin(\theta_{dec})\sin(\Phi)+\cos(\theta_{dec})\cos(\Phi)\cos(\theta_{hour})) \tag{13}$$

where θ_{dec} is the declination of the sun, Φ is the local latitude, θ_{hour} is the hour angle of the sun (zero at noon, positive in the afternoon, negative in the morning) [11, 19].

The scattered radiation I_s can be calculated with

$$I_s=0.5\cdot I_{top}\cdot\sin(\theta_{ele})\cdot\frac{\lambda_{am}(1-\tau_h)}{\lambda_{am}-1.41\cdot\tau_h} \tag{14}$$

The reflected radiation I_R also has a great influence on the value of the radiation flux[25], which can be described by

$$I_R=r_e\cdot I_h \tag{15}$$

where r_e is the reflectivity that can be approximately adopted as 0.18 for clear sky and 0.57 for overcast sky.

2.3 Incident solar radiation model on the solar array

In the inertial frame of reference, the unit vector of solar direct radiation[25] $\vec{n}_s=\left(n_{sx},n_{sy},n_{sz}\right)$ is a function of elevation angle and azimuth angle:

$$\begin{aligned}\vec{n}_s&=(-\cos\theta_{ele}\cdot\cos(\pi-\theta_{azi}),-\cos\theta_{ele}\cdot\sin(\pi-\theta_{azi}),-\sin\theta_{ele})\\&=(\cos\theta_{ele}\cdot\cos\theta_{azi},-\cos\theta_{ele}\cdot\sin\theta_{azi},-\sin\theta_{ele})\end{aligned} \tag{16}$$

where

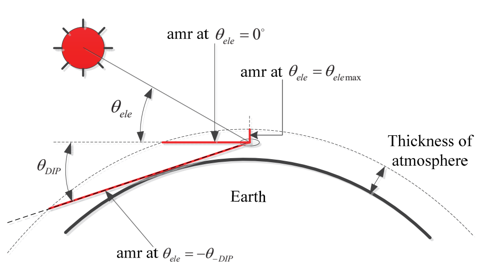

Fig. 2. Schematic of the air mass ratio.

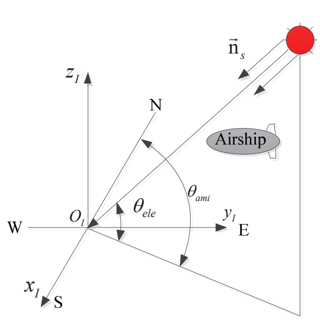

Fig. 3. Solar location under horizontal coordinate system[26].

$$\theta_{azi}=\cos^{-1}((\sin(\theta_{ele})\sin(\Phi)-\sin(\theta_{dec}))/\cos(\theta_{ele})\cos(\Phi)) \tag{17}$$

In the body coordinate system, the incident solar radiation is different with the change of position (characterized as the y coordinate and the rotation angle θ) on airship envelop when the time is certain. Therefore, it is conceivable to study incident solar radiation on the curved surface solar array during the day and night.

The solar direct radiation on the tilted grid ij can be expressed by

$$q_{dij}=\alpha_e\cdot\omega_{sign1}\cdot I_h\cdot A_{ij} \tag{18}$$

where α_e is the absorptivity of solar array to direct incident from the sun, $\omega_{sign}1$ is the projection coefficient of solar direct radiation on the tilted grid, and which is defined as

$$\omega_{sign1}=\begin{cases}\left|\vec{n}_s\cdot\vec{n}_{ijI}\right| & \vec{n}_s\cdot\vec{n}_{ijI}<0,-\theta_{DIP}<\theta_{ele}<\pi+\theta_{DIP}\\ 0 & others\end{cases} \tag{19}$$

In the equation (19), $\vec{n}_{ijI}=\left(n_{ijIx},n_{ijIy},n_{ijIz}\right)$ is the expression of the normal vector of tilted grid ij in the inertial frame of reference. It can be expressed by

$$\begin{bmatrix}n_{ijIx}\\n_{ijIy}\\n_{ijIz}\end{bmatrix}=R\cdot\begin{bmatrix}n_{ijx}\\n_{ijy}\\n_{ijz}\end{bmatrix} \tag{20}$$

where R is the transformation matrix from the hull coordinate system to the inertial frame of reference:

$$R=\begin{bmatrix}C_\varphi\cdot C_\psi & S_\phi\cdot S_\varphi\cdot C_\psi\text{-}C_\phi\cdot S_\psi & C_\phi\cdot S_\varphi\cdot C_\psi\\ C_\varphi\cdot S_\psi & C_\phi\cdot C_\psi+S_\phi\cdot S_\varphi\cdot S_\psi & S_\psi\cdot S_\varphi\cdot C_\phi\text{-}S_\phi\cdot C_\psi\\ \text{-}S_\varphi & C_\psi\cdot S_\phi & C_\phi\cdot C_\varphi\end{bmatrix} \tag{21}$$

In the equation (21), ψ, φ and ϕ are the Euler angles which represent yaw angle, pitch angle and roll angle, respectively[27].

The scattered radiation q_{sij} on the tilted grid ij can be given by

$$q_{sij}=\frac{1}{2}\cdot\left(1-\cos\left(\alpha_i\right)\right)\cdot I_s\cdot A_{ij} \tag{22}$$

where α_i is the included angle between the plane normal and the gravity direction[22], and which is defined as

$$\alpha_i=\cos^{-1}\left(\frac{\vec{n}_{ijI}\cdot\vec{n}_z}{\left|\vec{n}_{ijI}\right|\cdot\left|\vec{n}_z\right|}\right) \tag{23}$$

where $\vec{n}_z=(0,0,1)$.

The reflected radiation on the tilted grid is written as

$$q_{Rij}=\delta\cdot\alpha_R\cdot I_R\cdot A_{ij} \tag{24}$$

where α_R is the absorptivity of solar array to reflected radiation from the earth, δ is the index which takes into account the self-shadowing of the curved surface solar array from the reflected radiation, which is defined as

$$\delta = \begin{cases} 1 & \vec{n}_{ijI} \cdot \vec{n}_z \geq 0 \\ 0 & \vec{n}_{ijI} \cdot \vec{n}_z < 0 \end{cases} \tag{25}$$

According to the three types of solar radiation mentioned above, the solar radiation on the curved surface solar array Q can be calculated using the equation (26).

$$Q = \sum_{i=1} \sum_{j=1} \delta_{\mathrm{sc}} \cdot \left(q_{dij} + q_{sij} + q_{Rij} \right) \tag{26}$$

where δ_{sc} is a simple coefficient that can characterize the properties of the tilted grid ij. The value of this coefficient is 1 when the tilted grid ij is covered with solar panel. Otherwise, its value is 0.

The output power of solar array P can be given by

$$P = \eta_{SC} \cdot Q \tag{27}$$

where η_{SC} is the efficiency of the solar cell which changes with the changing temperature and can be expressed by[28]

$$\eta_1 = 0.56 - 3.556e(-3) \cdot T_{SC} + 1.22e(-5) \cdot T_{SC}^2 - 1.70e(-8) \cdot T_{SC}^3 \tag{28}$$

T_{SC} is the temperatures of solar cells which can be influenced by many factors, such as the radiation intensity, relative wind velocity, the transmissivity of external encapsulation layer of solar array and others. T_{SC} can be calculated according to the existing literature written by our team members[29, 30], which can be calculated with

$$\begin{aligned} & d_{ij} \cdot \rho_{ij} \cdot c_{ij} \cdot dT_{ij} = \left(q_{dij} + q_{sij} + q_{Rij} \right) + \left(\alpha_{IR-ex} \cdot I_{IRgh} + \alpha_{IR-in} \cdot I_{in-ab} \right) \cdot A_{ij} \\ & - \left[h_{out} \cdot \left(T_{SC} - T_{ina} \right) + h_{in} \cdot \left(T_{SC} - T_{Lgas} \right) \right] \cdot A_{ij} - \left(\varepsilon_{ex} + \varepsilon_{in} \right) \cdot \sigma \cdot T_{ij}^4 \cdot A_{ij} \text{-} P \end{aligned} \tag{29}$$

where α is the absorptivity, h is the convective heat transfer coefficient, ε is the emissivity.

I_{IRgh} is the infrared radiation power from the ground, $I_{in\text{-}ab}$ is the infrared radiation power from internal surface of envelop

$$\begin{aligned} I_{IRgh} &= \tau_{IRgh} \cdot \varepsilon_g \cdot \sigma \cdot T_g^4 \\ I_{rin-ab} &= \frac{\alpha_{IR-in}}{1 - r_{IR}} \cdot \varepsilon_{env} \cdot \sigma \cdot T_{env}^4 \end{aligned} \tag{30}$$

T_{ina} and T_{Lgas} are the temperatures of inner air and lifting gas, respectively. Supposing that the temperature in one balloon is the same, according to the Law of Thermodynamics, there are

$$\begin{aligned} C_{ina} \cdot m_{ina} \cdot dT_{ina} &= Q_{ina} + V_{ina} \cdot dp_{in} \\ C_{Lgas} \cdot m_{Lgas} \cdot dT_{Lgas} &= Q_{Lgas} + V_{Lgas} \cdot dp_{in} \\ V \cdot dp_{in} &= m_{ina} \cdot R_{ina} \cdot dT_{ina} + m_{Lgas} \cdot R_{Lgas} \cdot dT_{Lgas} \end{aligned} \tag{31}$$

where C_{ina} and T_{Lgas} are the isobaric specific heats of inner air and lifting gas, respectively. p_{in} is the internal pressure. Q_{ina} and Q_{Lgas} are the quantities of absorbed heat of inner air and lifting gas, respectively, which are given by

$$Q_{ina} = h_{ina} \cdot \left(T_{dia} - T_{ina} \right) \cdot A_{dia} + \alpha_{ina} \cdot \left(\sum_{i=1}^{M} \sum_{j=1}^{N} \frac{\tau_{IR}}{1 - r_{IR}} \cdot \varepsilon_{env} \cdot \sigma \cdot T_{ij}^4 \right) \tag{32}$$

$$Q_{Lgas} = \sum_{i=1}^{M} \sum_{j=1}^{N} h_{in} \cdot \left(T_{ij} - T_{Lgas} \right) \cdot A_{ij} + \alpha_{Lgas} \cdot \left(\sum_{i=1}^{M} \sum_{j=1}^{N} \frac{\tau_{IR}}{1 - r_{IR}} \cdot \varepsilon_{env} \cdot \sigma \cdot T_{ij}^4 \right) \tag{33}$$

where A_{dia} is the area of diaphragm and A_{ij} is the area of tilted grid ij which will be introduced in next section. α_{ina} and α_{Lgas} are the absorption coefficient of inner air and lifting gas, respectively.

3. Numerical results and analysis

To investigate the output power of solar array on stratospheric airship, the axisymmetrical cross-section curve of airship is considered in the equation (34). Some existing equations listed in the previous chapter are used to calculate the area and normal vector of tilted grid.

$$f(\bar{y}) = \begin{cases} 0.3077\sqrt{\bar{y}} & 0 < \bar{y} < 0.08 \\ 0.313 + 0.8671\bar{y} - 2.3583\bar{y}^2 + 2.9824\bar{y}^3 - 1.4912\bar{y}^4 & 0.08 < \bar{y} < 0.92 \\ 0.3077\sqrt{1 - \bar{y}} & 0.92 < \bar{y} < 1 \end{cases} \tag{34}$$

Table 1. Some parameters of this stratospheric airship.

Parameter	Value
Length, m	220
Diameter, m	54
Area, m^2	33000
Volume, m^3	380000
Flight altitude, m	20000

where $\bar{y}$=y / L, L is the total length of the airship[14].

According to some parameters of this stratospheric airship listed in Table 1, the influences of the airship's latitude, the day number and the airship's attitude on output power of solar array are analyzed.

3.1 Verification for the numerical model

The classical model described by Wang and Song [11] is used to validate the power output model in this paper. The area of the solar cells is 8200 m2 which is greater than that of this paper[29]. A comparison curve of the power output is obtained using proportional scaling(the method of proportional scaling is possible to derive comparative data with a greater error than some more sophisticated but possibly more expensive approaches, but it will still play an important role in engineering design due to its expediently and easily application[31]) in Fig. 4. It can be seen that the predictions agree well with the experimental results.

3.2 Results and analysis

The dependence of the solar cell efficiency on flight time is shown in Fig. 5 for the amorphous silicon thin film solar cells used in this paper. It can be found that the solar cell efficiency is gradually reduced before midday,then it will gradually increase, however. That is because the higher the temperature is, the lower the solar cell efficiency is.

Fig. 6 shows the comparative results of output power with and without considering thermal effect in summer solstice and winter solstice, respectively[29]. It can be seen that the output power of solar array with thermal effect is almost the same as that without thermal effect in the morning beacause that the temperature of solar cell is relatively low at around this time. However, this situation can not be maintained after 8:00 A.M., especially in the summer solstice. The reason is that the high temperature of solar cells reduces the solar cell efficiency. This result will be very helpful for planning cruise date of stratospheric airships before they launch.

Examples of how the solar array output performance is influenced by the airship's latitude are shown in Fig. 7. Latitudes of 0°, 15°, 30°, 45° and 60° are used, which represent a latitude range that encompasses the majority of stratospheric airship cruise area. During the simulation process, the attitude angle of airship is constant (the nose of

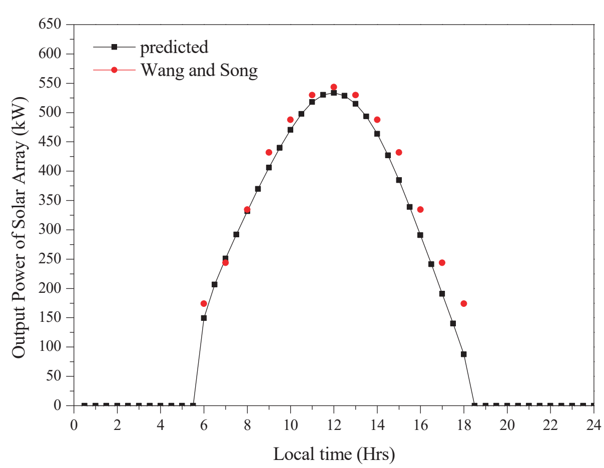

Fig. 4. Comparison of the power output.

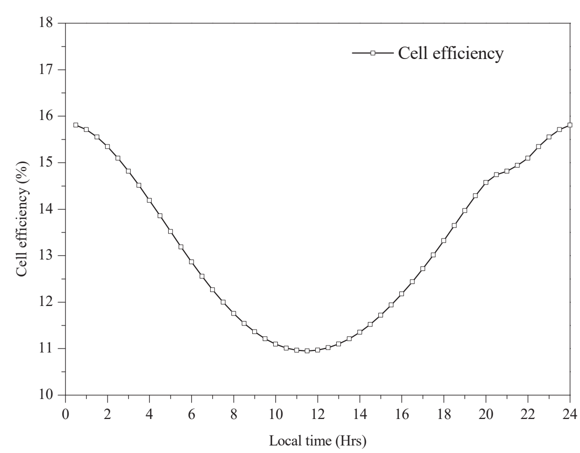

Fig. 5. The cell efficiency according to flight time.

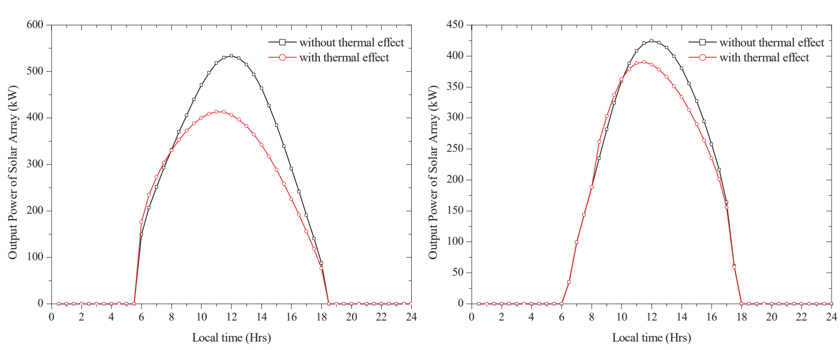

Fig. 6. The comparative results of output power with and without considering thermal effect. a) Summer solstice, b) Winter solstice.

the airship is pointed south and the pitch angle is zero).

In the summer solstice, the sun shines directly on the northern hemisphere which causes the variety of sunshine time with the change of latitude. Therefore, it can be found that the higher the airship's latitude is, the longer the duration of the power output will be in Fig. 7 a). At 60°N, the solar array outputs energy from 2:30 am to 21:30 pm. The duration of available power output decreases about 4 hours when the working latitude decreases from 60°N to 45°N. When the working latitude decreases from 45° N to 30°N, the variation of duration is approximately 2 hours. It also can be seen from Fig. 7 a) that the output power of solar cell changes rapidly at sunrise and sunset, and changing ratio of the output power is almost zero in the middle of the day. The peak of output power at 30° N is larger than that when stratospheric airship operates at other latitudes, this is because of the sun is shining the tropic of cancer (23.5° N) which causes the decrease of solar irradiance flux with slowly away from the tropic of cancer. The peak at 60° N is the smallest. In addition, the difference between maximum and minimum value of the peak of output power is about 196 kw.

Fig. 7 b) shows that the effect of the airship's latitude on output power is fairly clear in winter solstice. Contrary to the summer solstice, the duration of the power output decreases when the local latitude increases from 0° to 60°. It is clearly shown that the output power of the solar array during the day changes with the local latitude. The curve of output power at 0°N is larger than that when stratospheric airship operates at other latitudes, and the curve at 60°N is the smallest all the time. What's more, the difference between maximum and minimum value of the peak of output power is about 324 kW. There is no difficulty in drawing the result that output power is so small that the solar array cannot provide enough energy for stratospheric airship working at 60 degrees in winter solstice. However excess energy can be stored in the storage battery when the stratospheric airship floats in the low latitude regions. According to the results, it can be formulated that the stratospheric airship makes a round trip at different speeds in different latitudes.

Fig. 8 illustrates the output power curves for 20 and 45° N which represent low latitude and high latitude respectively. In these figures, four special dates (the spring equinox, summer solstice, autumnal equinox, winter solstice) are used for researching the effect of the day number on output

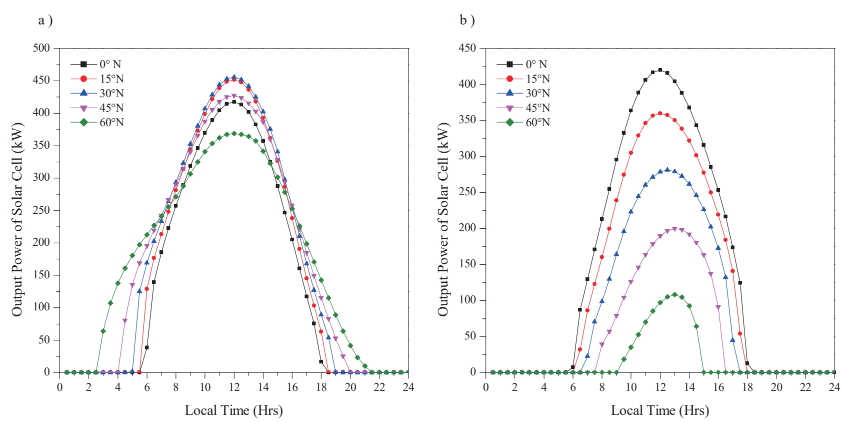

Fig. 7. Effects of latitude on output power, a) summer solstice; b) winter solstice.

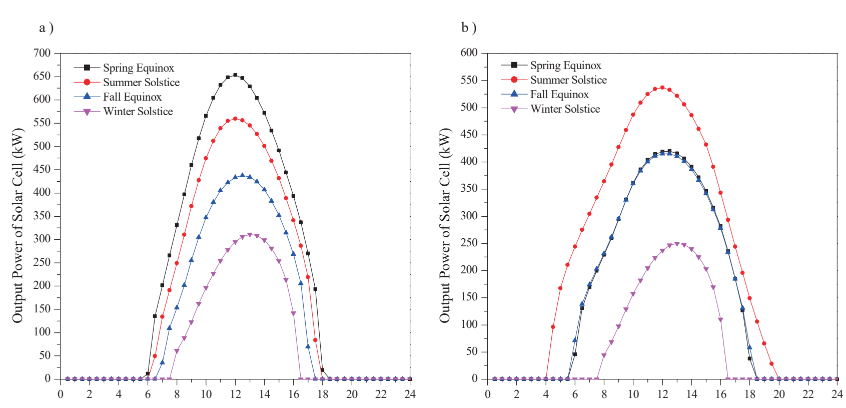

Fig. 8. Effects of the day number on output power, a) 20N; b) 45N.

power. All of the curves were produced for the fixed attitude that the nose of the airship points south and the pitch angle is zero.

Unlike the low latitude regions, the simulation curve of output power in the summer solstice is the highest, and the curve in the winter solstice is the smallest during the day at high latitude regions. The difference between the peak of output power in the summer and winter solstice at low latitude regions is about 232 kW which is far less than 314 kW (the difference at high latitudes region). At 20 degrees north latitude, the earliest sunrise time is at 5:20 am in the summer solstice, and the latest sunrise time is at 6:20 am in the winter solstice. At 45 degrees north latitude, the earliest sunrise time is at 4:00 am in the summer solstice, and the latest sunrise time is at 7:40 am in the winter solstice.

Fig. 9 expresses the effect of the airship's attitude, pitch and yaw, on output power. All of the curves are produced for single latitude, 30°N. It is known that when the airship's latitude and day number are invariant, the start and end time of solar array generating power remains unchanged during one day. Pitch angle of -30°, -15°, 0°, 15° and 30° are used, which can meet the airship attitude adjustment in working process. After that, the yaw angle is 180 degrees in Fig. 9 a) and Fig. 9 b). Additionally, yaw angle of 90°, 135°, 180° and 225° are used, which represent that the head pointing of airship faces towards east, southeast side, south and southwest side respectively in Fig. 9 c) and Fig. 9 d).

Fig. 9 a) illustrates that when the pitch angle is 0°, the peak of output power curve is the largest, and the peak in pitch angle of 30° at noon is the smallest. Variations in yaw angle effect the magnitude of these curves in winter solstice in Fig. 9 b). It can be seen that when pitch angle changes from -30° to 30°, the output power of solar array begins to largen gradually. The reason is that the included angle between horizontal plane and the sun light is so small that big pitch angle can make the solar array get more solar energy.

Fig. 9 c) gives the effects of yaw angle on output power in summer solstice. It can be obtained that most of the time all of the curves are so close that we cannot find differences. According to the result, it is found that when the sun shines on the tropic of cancer, the yaw angle plays a dispensable role in influencing output performance. Fig. 9 d) shows how the yaw angle affects output performance of solar array in winter solstice. When the head pointing of airship faces towards south, the output performance is superior to that heading for east. In addition, the output performance is different between heading for southeast side and southwest side. The reason is that the shape of the head and tail of the stratospheric airship is asymmetrical.

4. Conclusions

From the simulation results, the main conclusions are

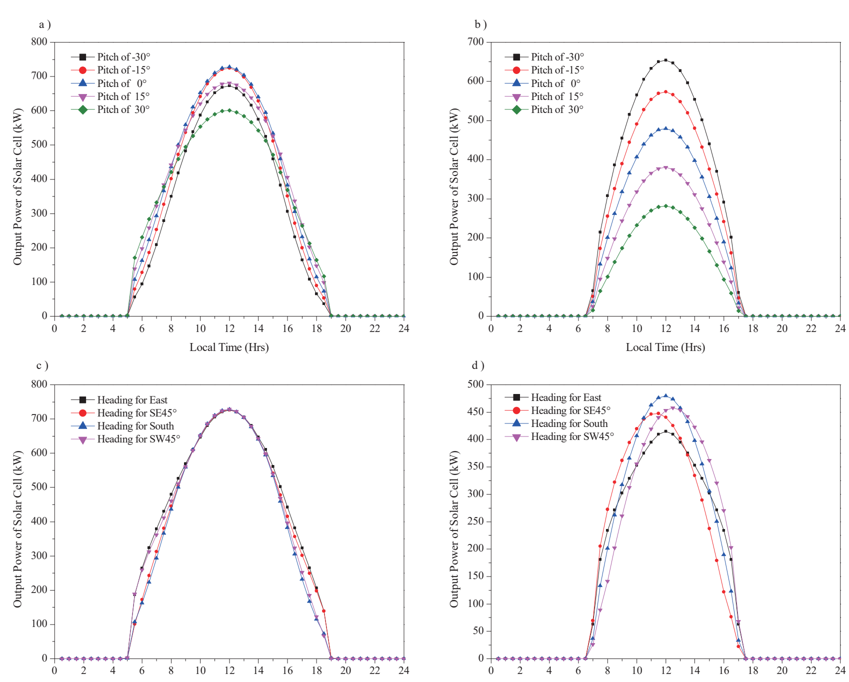

Fig. 9. Output power of solar array, a) the effects of pitch in the summer solstice; b) the effects of pitch in the winter solstice; c) the effects of yaw in the summer solstice; d) the effects of yaw in the winter solstice.

drawn.

1) The temperature of solar cell has a marginal influence on output performance, especially in the summer solstice. By comparing the two cases where the thermal effects on output power of solar array are being considered and not considered, the maximum value of output power of solar array decreases by 23.7%.
2) The airship's latitude has a significant influence on output performance, especially in winter solstice, and day number also is a main factor. Therefore, in the design phase, two factors should be considered: one is that the airline of the airship should be planned and another is that energy consumption for ultra-long endurance airship should be detailedly managed. In addition, it can be seen that this model can be uesd to optimize flight trajectory (time of the day, altitude, total solar energy).
3) In the specific operating environment, the yaw angle has a marginal influence on output power. By changing the pitch angle from 30° to -30°, 44.6% higher peak output power can be obtained in the winter solstice. Therefore, in the cruising process, it is an effective way to adjust the attitude angle to improve the output performance.

In addition, based on the investigation on effects of these factors, it can be found that the result of one factor has a strong dependence on the other factors. Hence, the works on the effects of these critical dependencies form the basis for some further investigation.

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