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Research Paper

A thermal model to investigate the power output of solar array for stratospheric balloons in real environment

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A R T I C L E I N F O

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A B S T R A C T

It is very important to solve the energy problem of stratospheric balloon to operate at high altitude for extended durations. Solar energy is the ideal power choice for long endurance stratospheric balloon. This study outlines a simplified numerical model validated using field data covers the thermal model of solar array that is not affected by balloon inside environment as airship does, the solar radiation model, the power output model. The predicted and measured solar array temperature and output power values yield correspondence with deviations below 2.16%, 6.6%, respectively. Based on this numerical model, computer program has been developed and simulated. The simulation was applied to a stratospheric balloon flight in one of the cities of Turkey's atmospheric conditions including real wind data. The output performance of solar array with and without thermal effect is reported. Furthermore, transmissivity of external encapsulation, wind speed on thermal performance and power output of solar array is discussed in detail. The results would be helpful for the design, operation of stratospheric balloon solar power system.

1. Introduction

It has been long realized that stratospheric balloons as high altitude long endurance platforms provide a unique vantage point for scientific experiments, observation, surveillance and telecommunication purposes located in the stratosphere layer of the atmosphere. For civilian applications they are low cost alternative to satellite. For the military, they provide continuous wide area coverage for extended durations. Long endurance balloons are unmanned and field with lift gases especially helium. They are capable of carrying payloads of several tons to desired altitude of the stratosphere. Therefore, the ability to fly balloons for long durations of years at high altitude has been attractive goal for many years.

For any type of long endurance vehicle, to maintain a fine balance of energy collection and energy consumption is the key element in addition to geometry, transport phenomena of lift gas, flight trajectory and velocity control of the balloon in the feasibility of achieving long duration high altitude flight [1,2]. To operate at high altitudes for extended durations requires a renewable based power system. Solar energy is the ideal power choice for stratospheric airships and this type of power system is a photovoltaic (PV) array coupled to an energy storage system. During daytime, the PV array converts solar energy into electrical energy by photoelectric and photochemical effects. During night, the energy storage system provides power to the airship [3,4].

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 output power of solar panel on stratospheric airship before it launches [5]. The efficiency of PV panel depends on certain physical parameters, such as solar radiation intensity falling on PV surface, PV panel operating temperature, heat loss from PV panel surface, and its material technology. For a typical PV panel, 5–25% radiated solar energy on PV panel front surface is transformed into electricity [6] and remaining is transformed into heat that leads to enhance the module temperature [7].

The PV panel operating temperature is dependent upon any factors; solar radiation, ambient temperature, wind speed and direction, panel material composition and mounting structure. Increased PV operating temperature leads to reduce the power available [8].

Solar array is a critical appendage which provides primary power sources for long endurance stratospheric airship [9] and the other type of long endurance vehicles as balloon. In the past decades, some research has been published on the energy of the high altitude platform. Naito et al. [10] proposed the design and analysis of solar power system stratospheric platform airship operations. Harada et al. [11] reported experimental study on thermal characteristics of SPF airship with PV array. Wang et al. [12] studied the power output of the solar cells on the condition that the conversion efficiency of the solar cells is constant. Li et al. [4] developed the thermodynamic models of PV arrays and airships to investigate the thermal performance of the PV array. Sun et al.

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Nomenclature

A	area of solar array (m^2)
c	specific heat capacity (J/kg K)
c_m	solar array heat capacity (J/kg K)
d	thickness (m)
dt_{cell}	temperature difference of solar cell (K)
F_{bs},F_{bg}	view factor of back-side of the solar array to sky and ground
F_{fs},F_{fg}	view factor of front-side of the solar array to sky and ground
H	floating altitude of the balloon (m)
h_{fb}	convective heat transfer coefficient of front and back side of the solar array ($W/m^2 K$)
h_{forced}	forced convective heat transfer coefficient ($W/m^2 K$)
h_{free}	free convective heat transfer coefficient ($W/m^2 K$)
I, I_{max}	global solar radiation flux density and its maximum (W/m^2)
k_{atm}	thermal conductivity of atmosphere (W/m K)
L	characteristic length
N	day length
η	efficiency of solar array
η_{ref}	panel's electrical efficiency
Nu_{atm}	free convection Nusselt number
P_{out}	power output of the solar array (W/m^2)
q_{conv}	convective heat loss to environment (W/m^2)
q_r	radiative heat loss to environment (W/m^2)
q_{rad}	solar radiation flux density (W/m^2)
Re_{atm}	Reynolds number of atmosphere
ST	solar time
t, dt,	time and its step, s, min or h
T_a, T_{cell}	atmospheric and solar cell temperature (K)
T_{cloud}	temperature of cloud (K)
T_{ref}	temperature at STC
t_{rs}	time of sunrise
T_s, T_{grd}, T_e	temperatures of the sky, ground and earth (K)
v_{wind}, v	wind speed (m/s)
v_z	velocity of the balloon in z direction (m/s)
α	absorptivity of solar cell surface
β, β_{ref}	volumetric thermal expansion and solar array temperature coefficient
ε_f, ε_b	solar array emittance of the front and back-side
ρ	density (kg/m^3)
τ	transmissivity of external encapsulation of solar array
σ	Stefan-Boltzmann constant ($5.67E-8\ W/m^2 K^4$)
CC	cloud cover
PID	proportional, integral, derivative controller
PV	photovoltaic panel

[13] proposed a mathematical model and numerical model to investigate the output characteristics of photovoltaic array of stratospheric airship. Li et al. [14] studied a numerical model including the thermal model of airship and solar cells, incident solar radiation model on the solar array, and the power output model. Yang and Liu [15] researched renewable power system simulation and endurance analysis for stratospheric airships. Liu et al. [16] proposed a numerical model to simulate the thermal performance of a stratospheric airship with photovoltaic array and developed analysis code based on thermal model.

It is important to note that above researches are base for investigating the output performance of solar array on stratospheric airship. However, the comprehensive investigation of output power of solar array for stratospheric balloon has not been studied up until now.

Many factors such as incident solar radiation, the stationary latitude, working date, physical characteristics of the solar array have a huge impact on output power of solar array [17]. The atmosphere of our planet is very dynamic environment with great fluctuations in temperature, pressure, density, wind speeds and solar intensity [3]. Atmospheric conditions around the balloon are significantly important for the design of the stratospheric balloons [18] and power system of the balloon. The point to be noted that the solar panel system of the balloon is independent of the balloon internal heat and mass transfer system and solar panel temperature does not affect lifting gas and envelope temperature compared to airship.

As known two typical factors, the transmissivity of solar array external encapsulation layer and the wind speed may influence the thermal performances of the solar array by changing the heat quantity input [9], output power of the solar array of the balloon. The magnitude and direction of the wind varies with altitude [18]. In above researches, some simulations of wind effect are not run into real wind environment and wind speed is constant as assumption. In this paper, output performance of solar array is investigated into real environment including real wind data of the balloon flight region and wind velocity variations with latitude, longitude coordinate and altitude has been taken into account.

In this study, for investigating the output performance of the solar array for stratospheric balloon simplified thermal model of the solar array is developed for the first time. Thermal model is simulated to research the effects of some parameters such as latitude, time of the year, environment of the atmosphere, solar array physical characteristics solar cell temperature on the output performance of the solar array in real environment independent with balloon's internal lifting gas effect unlike airship studies above.

2. Theory

The power output of the solar array for stratospheric balloon is governed by the incident solar radiation on the array, the performance characteristic with thermal effect, and physical characteristics of the solar array. The author of this paper developed a simplified numerical model including thermal model, solar radiation model and power output model.

For the stratospheric balloon, previous author's studies include a balloon model based on balloon dynamics, heat and mass transfer aspects combined with gas-compress control system for velocity control to track the balloon and keep it at target altitude for longer period [19], and simulation and control of the serviceable wind driven stratospheric balloon via transport phenomena and PID traversing a region and safe landing [18].

The balloon system that combined with solar power in this study is shown in Fig. 1. Balloon system consists of many subroutines such as heat transfer, mass transfer, balloon dynamics, control etc. And in this study, solar array system subroutine has been added to the balloon system that developed before to investigate the output power of the solar panel. It is important to note that solar power system does not affect internal flight gas aspects but it effects balloon dynamic movement.

2.1. Thermal environment

The thermal environment of the PV array is shown in Fig. 2. Heat transfer between the solar array and its environment comprises radiation, convection between the solar array surfaces and external environment. The external thermal factors include the instantaneous global solar radiation, which is composed of direct solar radiation, diffuse solar radiation, reflected solar radiation, infrared radiation and