

Prediction of thermal behavior and trajectory of stratospheric airships during ascent based on simulation

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Abstract

For designers, operators and users, the ability to accurately predict thermal behavior and trajectory of stratospheric airships is very important. Thermal models and dynamic models of stratospheric airships during ascent are developed, including solar radiation, infrared radiation, convection heat transfer and gas expulsion equation. Based on the model, performance parameters of a stratospheric airship during ascent are obtained, including film temperature, helium gas temperature, air temperature, pressure differential, altitude and ascent velocity, changing regulation for these parameters are discussed, and influence of initial helium gas volume and film radiation properties on thermal behavior is analyzed. Simulation results show that, (1) stratospheric airships experience supercooling during ascent, the maximum value is about 30 K, supercooling causes loss of net buoyancy, and affects ascent velocity and trajectory in the end, (2) stratospheric airships experience superheating at the floating altitude, and the maximum value is about 51 K, (3) initial volume ratio of helium gas and the solar radiation absorptivity of film have important effect on thermal behavior and trajectory during ascent, the larger the initial volume ratio is, the faster the ascent velocity will be, and the bigger the solar radiation absorptivity of film is, the smaller the temperature differential between helium gas and outside atmosphere will be.

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1. Introduction

Stratospheric airships are lighter-than-air (LTA) controllable flight vehicles flying in the altitude belt between 18 and 22 km, where wind velocities are comparatively low. Stratospheric airships can provide wide-area surveillance for months at a time, neither satellites nor aircrafts have this ability. In recent years, many countries all over the world have attempted to develop stratospheric airships or associated systems, including USA (Mueller et al., 2011; Androulakis and Judy, 2013; Smith et al., 2011), Japan (Harada et al., 2003; Harada, 2005), China (Zheng and Wu, 2011), Korea (Lee and Bang, 2007), and so on.

The ability to accurately predict thermal behavior and trajectories of stratospheric airships during ascent is very important for designers, operators, and users (Carlson and Horn, 1983). Meanwhile, if a failure occurs, performance prediction based on simulation can assist to determine the cause and take remedial actions. The vertical motion of stratospheric airships depends critically on thermal behaviors of the helium gas and air inside the film, because temperature and pressure of the gas determine the volume ratio of helium gas, and then determine the net buoyancy of the airship.

During ascent of stratospheric airships, temperature and pressure of the atmosphere outside experiences great variation, atmosphere temperature at 20 km is about 70 °C lower than that of sea level, and atmosphere pressure at 20 km is about 1/20 of that at sea level. Generally speaking,

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a stratospheric airship is consist of one helium gas envelope and two air envelope, during ascent, total volume of the airship remains unchanged, in order to provide necessary net buoyancy, air in the air envelope is exhausted, the helium gas envelope expend rapidly as a result, which will cause the temperature of helium gas rapidly drop and net buoyancy loss seriously, and affect flight trajectory in the end. Meanwhile, complex heat exchange process exists between stratospheric airships and the outside thermal environment, including solar radiation, infrared radiation, free convection, forced convection, and so on. As a result, accurate pre-flight prediction of thermal behavior and trajectories for stratospheric airships becomes difficult and complex (Stefan, 1983; Li et al., 2014).

In the past few years, many investigations have been carried out on this problem. Stefan (1983) studied temperature changes of the gas contained in a high altitude airship during floating condition, developed an analytical model and presented thermal effects for various surface possibilities. Japan conducted several flight experiments to research the thermal characteristics of stratospheric platform airship, and simulation program was developed and applied to predict ascent behavior successfully (Harada et al., 2003; Harada, 2005), the shortage is that the flight experiment is just in troposphere and the simulation mainly focus on flight dynamic. On the basis of some assumptions and simplifications, Shi et al. (2008, 2009) developed a thermal model to describe the heat transfer behavior of stratospheric airships during ascent and descent, in which the thermal environment considered is too simple. Li et al. (2011, 2012) investigated thermal characteristics and flight performances of the stratospheric semi-rigid airship during floating flight, and 3-D solar radiation and temperature distribution of airship film and temperature variation of inner gas were presented. Sun et al. (2015) proposed a numerical model to investigate output characteristics of photovoltaic array of stratospheric airships, and researched the thermal effect of the photovoltaic array on the airship using CFD/Fluent. Wang and Yang (2011) developed a novel computational model for analyzing transient thermal performance of stratospheric airships under different environmental conditions, in which radiative heat transfer and natural convection inside the airship were modeled using the control volume method. Xia et al. (2010) and Li et al. (2014) constructed an experiment apparatus to investigate the thermal response characteristics of stratospheric airships, and studied transient temperature distribution of both hull and inner gas under the irradiation of a solar simulator and various airflow conditions. Yao et al. (2014) established a heat transient model for the thermal behavior prediction of stratospheric airships, in which some convective heat transfer models need to be modified. Guo and Zhu (2013) researched the ascent trajectory optimization for a stratospheric airship with thermal effects, but they just assumed that the temperature of helium gas is equal to inner air. In addition, modeling and analysis of thermal performance of high altitude scien-

tific balloons, which have many similar features to stratospheric airships, also attracted many researchers' attention (Carlson and Horn, 1983; Dai et al., 2012).

In general, the shortage or disadvantage of above mentioned literatures is mainly in the following aspect, (1) most of them put emphasis on the thermal performance, and the coupling effect between thermal behavior and flight dynamics is ignored, which is the most typical feature of stratospheric airships compared with other flight vehicles, (2) most of them focus on the floating condition, few of which is about the ascent, in fact, the air envelope of stratospheric airships is empty, so the airship is just like a balloon and heat transient model are simplified as a result, (3) some important heat transfer behaviors and some influences of the atmosphere environment are not included, such as the infrared radiation from the sky, (4) just some simulation results are listed, and further analysis for results and factors affecting thermal behaviors is lacking. The aim of this paper is to make some improvements around above four aspects.

In this paper, thermal and vertical trajectory models for accurate performance prediction of a stratospheric airship during ascent are established, typical parameters for thermal behavior and trajectories are obtained, and influence of initial helium gas volume and film radiation properties on thermal behavior is analyzed. The rest of the paper is organized as follows, thermal models of the stratospheric airship is derived in Section 2, dynamic models are introduced in Section 3, performance predicting results and some further analysis for a stratospheric airship are presented in Section 4, and the last section is devoted to conclusions.

2. Thermal models for stratospheric airships

2.1. Governing equations for temperature

Thermal environment around stratospheric airships during ascent is shown in Fig. 1 (Li et al., 2012; Palumbo et al., 2007). According to the characteristic of stratospheric airships during ascent, some assumptions are as follows:

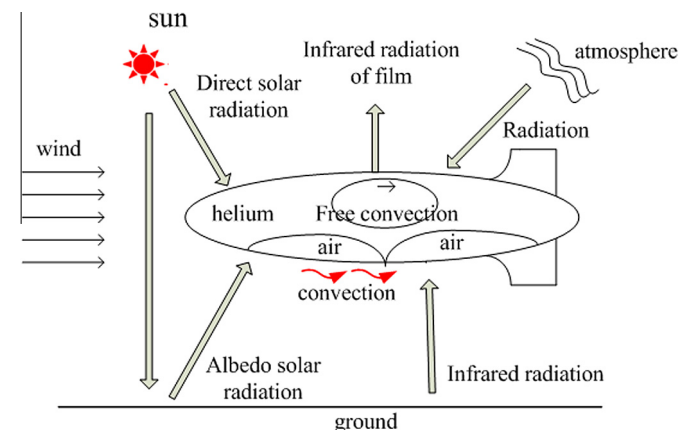


Fig. 1. Thermal environment of a stratospheric airship during ascent.

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