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A heat transient model for the thermal behavior prediction of stratospheric airships

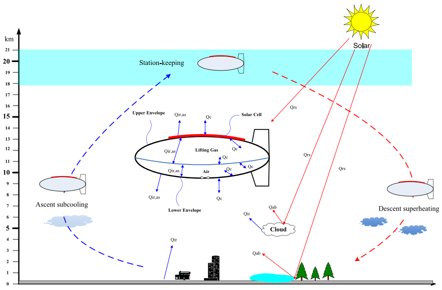
Wei Yao*, Xiaochen Lu [1], Chao Wang [2], Rong Ma [3]

Research Center of Aerospace Thermodynamics, Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology, P. O. Box: 5142-225, 100094 Beijing, China

HIGHLIGHTS

- A multi-nodes heat transient model for stratospheric airships is proposed.
- The thermal behaviors of the ascent and descent processes are predicted.
- The volume, vertical speed and solar radiation have significant influence.

GRAPHICAL ABSTRACT



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ABSTRACT

The gas temperature of a stratospheric airship plays an important role in its flight dynamics. A multi-nodes heat transient model is proposed and evaluated by the theoretical solutions of the adiabatic processes and the high altitude flight test data. A thermodynamic analysis code for stratospheric airships (TACSA) is developed to investigate the ascent subcooling induced by the thermodynamic expansion and the descent superheating induced by the thermodynamic compression. The simulation results show that the airship volume, vertical speed and the solar radiation have evident influence on the ascent subcooling descent superheating effects.

1. Introduction

Stratospheric airships (or high altitude airships) have been received much attention in recent years because they can perform persistent Earth observation and communication missions by keeping on station at an altitude about 20 km for several weeks or even several months [1,2]. Several important projects on stratospheric airships have achieved important progress, such as High-Altitude Airship of Lockheed Martin Company, Hisentinel Airship of Southwest Research Institute of the United States, Stratospheric Platform Airship of Japan and Stratospheric Airship Program of South Korea [1–3]. Some of these airships are on the flight test stage and are expected to realize practical applications in the near future [3]. Since a stratospheric airship should be the largest aerospace craft typically with a huge gas volume of several hundred thousand cubic meters, even a very small temperature difference between the inner gases (including helium and air in modern airships) and the outer atmosphere may result in a significant buoyancy variation [4]. Accordingly, the gas temperature of a stratospheric airship plays an important role in its flight

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* Corresponding author. Tel.: +86 10 6874 7483; fax: +86 10 6874 7505.
E-mail addresses: yaowei@cast.cn, yaowei_72@hotmail.com (W. Yao), lyuxiaochen@163.com (X. Lu), wangchao534@163.com (C. Wang), rong.jessica@hotmail.com (R. Ma).

[1] Tel.: +86 10 6811 3051; fax: +86 10 6874 7505.

[2] Tel.: +86 10 6811 3050; fax: +86 10 6874 7505.

[3] Tel.: +86 10 6811 3051; fax: +86 10 6874 7505.

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dynamics, which is an essential difference to airplanes and spacecrafts.

There are two main reasons which may result in the above mentioned temperature difference. The first one is the influence of the complex radiation-convection environment, which may lead to superheating (the temperature of the inner gas is higher than the ambient temperature) or subcooling (the temperature of the inner gas is lower than the ambient temperature) status. This kind of thermal problem has been investigated by several authors on the high altitude balloons [5–10] and the stratospheric airships [4,11–17].

The second reason is the thermodynamic effect during the ascent and descent process on which more research is needed. The ambient pressure decreases and the inner gases expand gradually when the airship ascends. It may result in the “ascent subcooling” of the gases. As a reverse process of ascent, the ambient pressure increases and the inner gases compress gradually when the airship descends. It may result in the “descent superheating” of the gases. The “ascent subcooling” was found in the Japanese stratospheric subscale flight tests [11] and also in the flight data and simulation results of the high altitude balloons [8,18]. Yao et al. [19] proposed a thermodynamic model of stratospheric airships to analyze the ascent subcooling numerically. Shi et al. [20] modified the thermodynamic model to study the ascent and descent process. It should be noted that in the above research work only one thermal equation is considered to calculate the average temperature of the airship surface. Due to the significant difference of the external heat fluxes between the lower and upper part of the airship surface (the upper part envelope and the solar cell panel are mainly influenced by the solar radiation while the lower part envelope is mainly influenced by the Earth albedo and infrared radiation), and the difference of thermal property between the solar cell panel and the envelope, the apparent temperature difference exists at the different part of the airship surface. For example, it was found the maximum temperature difference between the top and the bottom of a balloon surface could be larger than 30 K in the balloon flight data of Stefan [4].

In order to take into account the differences of external heat fluxes and radiative properties at the airship surface, a multi-nodes heat transient model is proposed in this paper, which contains two thermodynamic equations for inner gases and four thermal equations for different parts of the airship surface. Based on this proposed model, a thermodynamic analysis code for stratospheric airships (TACSA) is developed and evaluated. Then the “ascent subcooling” and “descent superheating” phenomena are investigated numerically. The effects of some key factors including the airship volume, the vertical speed, and the solar radiation on the “ascent subcooling” and the “descent superheating” are analyzed by the simulation results.

2. A multi-nodes heat transient model

2.1. Thermodynamic equations for the inner gases

Since helium is generally used as a lifting gas in modern airships, for the sake of simplicity, a stratospheric airship contains helium and air is discussed in this paper. In order to take into account the supplement and emergency discharge of the helium, and the suction and discharge of the air, the general equations for the energy conservation of the inner helium and air are derived from the first law of the thermodynamics as follows,

$$m_{he}C_{p,he}\frac{\mathrm{d}T_{he}}{\mathrm{d}t} = V_{he}\frac{\mathrm{d}p_{he}}{\mathrm{d}t} + \sum \dot{Q}_{k-he} - C_{p,he}(T_{he} - T_{he,in})\dot{m}_{he,in} \tag{1}$$

$$m_{\mathrm{air}}C_{p,\mathrm{air}}\frac{\mathrm{d}T_{\mathrm{air}}}{\mathrm{d}t} = V_{\mathrm{air}}\frac{\mathrm{d}p_{\mathrm{air}}}{\mathrm{d}t} + \sum \dot{Q}_{k-\mathrm{air}} - C_{p,\mathrm{air}}(T_{\mathrm{air}} - T_{\mathrm{air,in}})\dot{m}_{\mathrm{air,in}} + W_b \tag{2}$$

where m, ρ, T, p, V, C_p are the mass, density, temperature, pressure, volume, and constant pressure specific heat respectively. $\dot{Q}_{k-he}$ and $\dot{Q}_{k-\mathrm{air}}$ are the heat fluxes from the surrounding nodes to the inner helium and air respectively, which will be discussed in the following sections. W_b is the mechanical power of the air blowers, which should be taken into account when the blowers operate during the air suction process. The subscripts of he and air denote the inner helium and air respectively.

The mass change rate of the helium and air can be written as follows,

$$\frac{\mathrm{d}m_{he}}{\mathrm{d}t} = \dot{m}_{he,\mathrm{in}} - \dot{m}_{he,\mathrm{ex}} \tag{3}$$

$$\frac{\mathrm{d}m_{\mathrm{air}}}{\mathrm{d}t} = \dot{m}_{\mathrm{air,in}} - \dot{m}_{\mathrm{air,ex}} \tag{4}$$

where $\dot{m}_{he,\mathrm{in}}$ is the inlet mass flow rate of the helium which is determined by the helium supplementary system, and the inlet mass flow rate of the air can be written as,

$$\dot{m}_{\mathrm{air,in}} = \rho_{\mathrm{air}}G_{\mathrm{in}} \tag{5}$$

where G_{in} is the volumetric flow rate of the air blowers.

The exhaust mass flow rate of the helium and the air though the valves can be estimated by,

$$\dot{m}_{he,ex} = A_{v,he}\sqrt{\frac{2\Delta p_{he}\rho_{he}}{K_{v,he}}} \tag{6}$$

$$\dot{m}_{\mathrm{air},ex} = A_{v,\mathrm{air}}\sqrt{\frac{2\Delta p_{\mathrm{air}}\rho_{\mathrm{air}}}{K_{v,\mathrm{air}}}} \tag{7}$$

where A_v is the total exhaust area of the valves, Δp is the pressure difference between the inner gas and the ambient atmosphere, and K_v is the pressure loss coefficient of the valves.

The mechanical power of the air blowers can be estimated by

$$W_b = \Delta p_{\mathrm{air}} \cdot G_{\mathrm{in}} \cdot \eta_b \tag{8}$$

where η_b is the operational efficiency of the blowers.

The helium and the air are assumed to be ideal gases and the state equations can be written as follows,

$$p_{he} = m_{he}R_{he}T_{he}/V_{he} \tag{9}$$

$$p_{\mathrm{air}} = m_{\mathrm{air}}R_{\mathrm{air}}T_{\mathrm{air}}/V_{\mathrm{air}} \tag{10}$$

where R is the ideal gas constant.

In addition, it is assumed that the airship volume is constant during the flight process, and the membrane between the helium and the air is large enough to remain at a relaxed status. Thus we have,

$$V_t = V_{he} + V_{\mathrm{air}} = \mathrm{constant} \tag{11}$$

$$p_{he} = p_{\mathrm{air}} \tag{12}$$