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Altitude control performance of a natural energy driven stratospheric aerostat

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Abstract

The superheating induced overpressure is one of the key obstacles for long-endurance station-keeping of stratospheric aerostats. A novel stratospheric aerostat by utilizing the natural energy is presented and discussed in this paper. A thermo-mechanical dynamic model is established to analyze the altitude control performance of this novel aerostat. The simulation results show that the novel stratospheric aerostat can ascend to a high altitude about 25.8 km due to the combined heating effects of the solar radiation, the Earth albedo and the infrared radiation from the Earth's surface and keeps at an altitude about 22 km by the infrared radiation from the Earth's surface. In addition, the aerostat can be controlled within the desired altitude range by the simple open/close valve control strategy.

Keywords: Stratospheric aerostat; Thermo-mechanical model; Ascent process; Altitude control

1. Introduction

High altitude platform systems based on aerostats (balloons or airships) have been receiving 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 (Colozza and Dolce, 2005; Yao et al., 2014a). Several important projects on stratospheric aerostats have achieved great progress, such as the Ultra Duration Balloon (ULDB) of NASA (Cathey, 2008; Jones, 2014), the Project Loon of Google (Levy, 2013), the High-Altitude Airship of Lockheed Martin Corporation (Androulakakis and Judy, 2013), the Hisentinel of Southwest Research Institute of the United States (Smith et al., 2011). In addition, some novel aerostats have been proposed and investigated for the planetary exploration in other planet atmospheres (Dorrington, 2010, 2011; Yao et al., 2015).

Due to the complex radiation-convection environment, stratospheric aerostats may experience severe superheating and induced overpressure issues (Stefan, 1983; Franco and Cathey, 2004; Yao et al., 2007; Dai et al., 2012; Li et al., 2012, 2014; Liu et al., 2014). The overpressure may result in the damage of the envelope and the failure of the flight mission (Lee et al., 2009).

On the basis of the infrared hot-air balloon which has the longest flight record of 69 days (Letrenne et al., 1999), Yao et al. (2014b) proposed a novel stratospheric aerostat which can realize regional long-endurance station-keeping by utilizing the natural thermal (infrared radiation from the Earth's surface) and wind (quasi-zero wind layer) energy and avoid overpressure problem. Since the altitude control is the basis for utilizing the wind energy by flight in easterlies or westerlies, a thermo-mechanical dynamic model is established and the altitude control performance is analyzed in this paper.

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2. System description

Fig. 1 presents the basic structure of the novel stratospheric aerostat. It includes an infrared hot-air balloon, a helium ballonet, an air valve and a suspended gondola. The upper envelope of the balloon is coated with low infrared emissivity surface to avoid the thermal energy dissipating to the outer environment, and the lower envelope of the balloon is coated with high infrared emissivity surface to maximize the absorption of the radiated thermal energy from the Earth's surface and the lower atmosphere. The low solar absorptivity of the whole envelope is selected to reduce the day-night temperature variation. Accordingly, the air in the balloon and the helium in the ballonet could be always in a superheat status due to the absorption of the solar radiation, the Earth albedo and the infrared radiation from the Earth's surface. Since the temperatures of the inner gases (the air and the helium) are higher than that of the surrounding atmosphere, the densities of the inner gases are lower than that of the surrounding atmosphere and thus the buoyance of the aerostat generates.

The altitude control is realized by the air valve at the top of the infrared hot-air balloon. When the air valve is open, it cooperates with the vent at the bottom of the infrared hot-air balloon to form an air flow channel, through which the inner superheated air exhausts through the valve and the ambient cool air is sucked in through the vent. Accordingly, the temperatures of inner gases decease and it results in the decrement of the net buoyance. When the air valve is closed, the temperatures of inner gases gradually rise and the net buoyance increases.

3. Dynamic modeling

3.1. Transient thermal equations for the balloon envelope

Since the distinct differences of the radiative properties and the external heat fluxes between the upper and lower envelopes, two thermal nodes, that is, the upper part envelope (*eu*), and the lower part envelope (*el*) are employed for the thermal analysis of the balloon. Based on the thermal balance relations, the transient thermal equations of each node are derived.

The thermal equation of the upper part envelope is:

$$k_{en}A_{eu}c_{en}\frac{dT_{eu}}{dt} = \dot{Q}_{s,eu} + \dot{Q}_{ir,atm-eu} + \dot{Q}_{atm-eu} + \dot{Q}_{air-eu} \quad (1)$$

where k_{en} and C_{en} are the areal density and the specific heat of the envelope respectively, A_{eu} is the area of the upper part envelope, $\dot{Q}_{s,eu}$ is the absorbed heat flux from the solar radiation, $\dot{Q}_{ir,atm-eu}$ is the radiative heat flux from the ambient air, $\dot{Q}_{atm-eu}$ is the convective heat flux from the ambient air, and $\dot{Q}_{air-eu}$ is the convective heat flux from the inner air.

The thermal equation of the lower part envelope is:

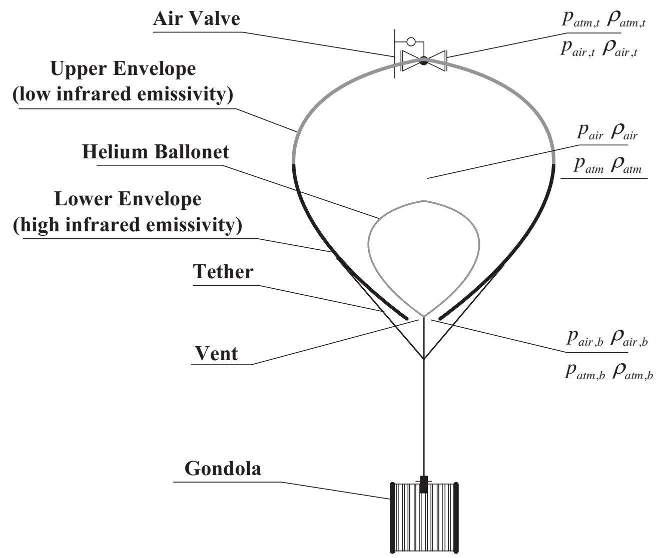

Fig. 1. Schematic of the novel natural energy driven stratospheric aerostat.

$$k_{en}A_{el}c_{en}\frac{dT_{el}}{dt} = \dot{Q}_{s,el} + \dot{Q}_{ab,el} + \dot{Q}_{eir,el} + \dot{Q}_{ir,atm-el} + \dot{Q}_{atm-el} + \dot{Q}_{air-el} \quad (2)$$

where A_{el} is the area of the lower part envelope, $\dot{Q}_{s,el}$ is the absorbed heat flux from the solar radiation, $\dot{Q}_{ab,el}$ is the absorbed heat flux from the Earth albedo, $\dot{Q}_{eir,el}$ is the absorbed heat flux from the infrared radiation of the Earth, $\dot{Q}_{ir,atm-el}$ is the radiative heat flux from the ambient air, $\dot{Q}_{atm-el}$ is the convective heat flux from the ambient air, and $\dot{Q}_{air-el}$ is the convective heat flux from the inner air.

The detailed calculation method of the above heat flux terms in Eqs. (1) and (2) can be found in Yao et al. (2014a).

3.2. Thermodynamic equations for the inner gases

The natural energy driven stratospheric aerostat consists of the infrared hot-air balloon and the helium ballonet. The infrared hot-air balloon is filled with the superheated air and could provide the main buoyance. The hot-air balloon with the air valve and the bottom vent is an open system which can exchange the air mass with the ambient. The ballonet is filled with the gas helium to provide the secondary buoyance. Normally, the helium mass in the ballonet keeps constant without emergency discharge. Accordingly, the energy balance equations of the inner air and helium are derived from the first law of thermodynamics as follows:

$$m_{air}C_{p,air}\frac{dT_{air}}{dt} = V_{air}\frac{dp_{air}}{dt} - C_{p,air}(T_{air} - T_{air,in})\dot{m}_{air,in} - \dot{Q}_{air-eu} - \dot{Q}_{air-el} + \dot{Q}_{he-air} \quad (3)$$

$$m_{he}C_{p,he}\frac{dT_{he}}{dt} = V_{he}\frac{dp_{he}}{dt} - \dot{Q}_{he-air} \quad (4)$$