Analysis and test for thermal performance of High Altitude Super Pressure Balloons during ascending process

Da Zhao, Dong-xu Liu*, Kai Feng, and Ming Zhu

School of Aeronautic Science and Engineering, Beihang University, Beijing, 100191, China

Abstract. A two-node model for thermal characteristics and a dynamic model of High Altitude Super Pressure Balloon (HASPB) during ascending process are established. The thermal performance of HASPB during ascending process is analyzed. Several simulations are conducted under the same conditions with the real flight test. Results show that supercool phenomenon occurs during ascending caused by free expansion of gas, and the value is about 10-15 K. Once the balloon reaches the design height and becomes over-pressured, the temperature of balloon rises rapidly, and this adjustment process lasts for about 10 minutes. The real flight test to 20000 m validates the reliability of the two-node model.

1 Introduction

High Altitude Super Pressure Balloons (HASPB) has altitude-keeping and long duration abilities, which is a perfect observation platform and has been researched by many countries. The thermal characteristics and thermal control of balloon during its ascending process are the key technologies in HASPB design. Thermal performance of HASPB has been researched by many organizations around the world. NASA[1] has developed several Pumpkin Balloons and studied their thermal performances deeply. Cathey[2] developed a simulation software to calculate ascending trajectories of balloons. Stefan[3] established a HASPB thermal model and analyzed average temperature of the air and helium. Wang and Yang[4] studied the temperature distribution of airship hull based the testing data in the Japan 35m airship low altitude experiment[5]. Lee[6] established a 3D airship model and studied the temperature distribution.

However, due to the high cost and complexity of flight tests, only few scholars and organizations around the world could obtain the real thermal data[7]. There are few papers that can use the real flight data to validate their models. In this paper, a two-node model for the thermal characteristic of HASPB during ascending process is proposed. Some real thermal data, which was obtained by a balloon test in Ximeng City (China), are used to validate the accuracy of the two-node model. In addition, the simulation predicts that supercool phenomenon occurs during ascending process, which is also confirmed by the real thermal data.

* Corresponding author: liubuaa@163.com

2 Two-node model of HASPB

2.1 Thermal characteristics modeling

Thermal characteristics of HASPB are comprehensively influenced by the following factors: direct solar radiation, clouds and earth reflection, atmospheric diffuse radiation, infrared radiation of envelope surface, earth and sky radiation, external and internal heat convection, as shown in Figure 1.

Fig. 1. Thermal Environment of HASPB.

According to the first law of thermodynamics, energy equation for envelope surface is expressed as follow:

$$\frac{dT_{nt}}{dt} = \frac{Q_{sun} + Q_{abd} + Q_{IREth} + Q_{conv} - Q_{IRout}}{c_{nt}m_{nt}} \quad (1)$$

where m_{nt} , c_{nt} and T_{nt} are mass, specific heat capacity and average temperature of envelope, respectively. Q_{sun} is the energy received from solar radiation and diffuse radiation per unit time, Q_{abd} is the energy from clouds and ground reflected radiation per unit time. Q_{IREth} is the energy received from infrared radiation of atmosphere and ground per unit time. Q_{conv} means the energy received from convection per unit time, including the external heat convection $Q_{convext}$ and the internal natural heat convection $Q_{convint}$. Q_{IRout} is the energy from the infrared radiation of envelope surface per unit time.

This paper assumes that the internal gas follows the ideal gas law, and the temperature and pressure distributions of ballonets are uniform respectively. The energy equation for internal gas is expressed as follow:

$$\frac{dT_{he}}{dt} = (\gamma - 1) \frac{T_{he}}{\rho_{he}} \frac{d\rho_{he}}{dt} - \frac{Q_{convint}}{c_v m_{he}} \tag{2}$$

where m_{he} , ρ_{he} , c_v and T_{he} are mass, density, specific heat at constant pressure and average temperature of internal helium, γ is heat capacity ratio.

2.2 Dynamic modeling

During the ascending process, the balloon is affected by the forces, such as, helium buoyancy, platform gravity, aerodynamic drag and additional inertia force. So the dynamic equation can be expressed as follow:

$$(m + m_{add})\ddot{h} = F_{buo} - mg - x(\dot{h}) \tag{3}$$

where m is the whole mass of HASPB, F_{buo} is the buoyancy, h is the current height and $X(\dot{h})$ is the aerodynamic drag. m_{add} is the additional inertia mass, which reflects the movement of large size objects in the air to drive the surrounding air, and it can be calculated as follow:

$$m_{add} = 0.5\rho_a V_{he} \tag{4}$$

where ρ_a is the density of external air and V_{he} is the current volume of internal helium. The values of the buoyancy and the equivalent diameter (can be used to obtain aerodynamic drag) must be calculated by the volume of helium. The volume can be expressed as follow:

$$V_{he} = \frac{m_{he}}{\rho_{he}} = m_{he} \frac{8314 * T_{he}}{p_{he} M_{he}} \tag{5}$$

3 Simulation and analysis

In this paper, a two-node model for thermal characteristic and a dynamic model during ascending process are established. According to the test conditions real flight in Ximeng City (China), the main parameters of simulation are set up as shown in Table 1.

Table 1. main parameters of two-node model for thermal characteristics of HASPB.

Parameter	value
Balloon diameter	17 [m]
Envelope mass	164 [kg]
Design height	20 [km]
Material absorptivity	0.2
Material emissivity	0.7
Material transmissivity	0.01
Infrared absorptivity	0.7
Infrared transmissivity	0.2
Takeoff time	11:18:20 Oct 9th

During ascending process of super pressure balloon, the change of solar radiation intensity at different time should be taken into consideration. As shown in Figure 2(a), the solar radiation intensity varies with altitude, the higher the height, the stronger the radiation.

The solar radiation intensity begin to rise at 6 a.m. and reaches its peak at 12 noon, then decreases after 18 p.m., as shown in Figure 2(b).

Fig. 2. Solar radiation intensity curve of Ximeng City at Oct 9th .

The super pressure balloon takes off at 11 a.m. and then the ascending velocity increases to 6 m/s rapidly. The balloon reaches 20 km after about 52 minutes, then it flies at a fixed altitude, and the pressure difference of the envelope reaches 1200 Pa. As shown in Figure 3, the calculated results are very consistent with the experimental results.

Fig. 3. Comparison of simulation and flight test.

Although the intensity of the solar radiation, the earth albedo and infrared radiation is changing with time and flight height, the amplitude of variation is not large. However, with the volume of the balloon increasing more than 10 times in the process of ascending, the total energy of radiation on the envelope changes greatly during ascending. As shown in Figure 4(a), the total energy of solar radiation increases from 10 kW on the ground to 62 kW at 20 km altitude. When the ascending speed is larger than 6 m/s, air convection becomes stronger than the initial state. Totally, when the balloon reaches the equilibrium altitude, the energy that is transferred away by the atmospheric convection from the envelope surface is about 50 kW. In addition, the material has strong absorptive capacity to infrared light with 8 micron wavelength, so the warming effect by earth infrared radiation on envelope material is extremely obvious, the infrared radiation energy absorbed by material close to 80 kW.

(a) Variation of radiation components.

(b) Comparison of temperatures.

Fig. 4. Simulation and comparison results.

Atmospheric density decreases with altitude increasing, so there is a large expansion of internal helium, which results in a reduction in internal energy and a decrease in temperature. The temperature of helium during ascending process is lower than the 10~15 K of the atmospheric temperature, that is, supercool phenomenon occurs. The supercool phenomenon affects the buoyancy of the balloon, and the net buoyancy produced by the cold gas is much lower than that produced by the gas with ordinary temperature. In addition, supercool makes it difficult to predict the ascending velocity. There is no enough velocity to ascend to the design altitude especially when supercool is extremely serious.

As shown in Figure 4(b), when it is after 11:45 a.m., the balloon raise to altitude of 11 km and the temperature of atmosphere is stable. Meanwhile the temperature of internal gas trends to be stable, too. Finally, the value of supercool is about 13 K. When the balloon ascends to the design altitude, the gas expands to the maximum volume. At the same time, the rising velocity decreased significantly and the forced convection decreases in the convection parts, and the natural convection become the main part of the convective heat transfer. Under the comprehensive effect of radiation, the temperature of gas rises rapidly. It takes less than about 10 minutes to achieve a new equilibrium state from the supercool state. Comparisons of test data and simulation results shows that the accuracy of model agree with the real test well and the model is reliable.

4 Summary

Through the comparisons of simulations and test data, following conclusions can be drawn:

- During the ascending process of balloon, the value of supercool caused by free expansion of internal gas is about 10-15 K.
- Once the balloon reaches the design height and becomes over-pressured, the temperature of balloon rises rapidly, and this adjustment process lasts for about 10 minutes.
- Simulation results by the model agree well with the real data of flight test. The two-node model accurately reflects the thermal equilibrium state and thermal characteristics of HASPB during ascending process. So the model proposed in this paper is reliable, can be used as an auxiliary tool for the thermal analysis of HASPB and other near space vehicles.

Acknowledgement

This work was supported in part by the National Key R&D Program of China under grant No.2016YFB1200100.

References

1. Henry M. Cathey, David L. Pierce, Duration Flight of the NASA Super Pressure Balloon, *R. AIAA* 2009-6808, (2009)
2. Karl Stefan. Thermal Effects on a High Altitude Airship, *R. AIAA* pp 1983-84(1983)
3. Henry M. Cathey, Advances in the Thermal Analysis of Scientific Balloons, *R. AIAA* 1996-0695, (1996)
4. Y. W. Wang and C. X. Yang. *Thermal analysis of stratospheric airship in working process*, *R. AIAA* 2009-2805, (2009)
5. Yoshitaka Sasaki, Development of Stratospheric Platform Airship, *J. K.H.I. Technical Review*, **158** (2005) pp 24-29
6. Lee Y G, Kim D M, Yeom C H, Decelopment of Koeran high altitude platform systems, *J. Int Wireless Information Networks*. **13**(2006) pp 31-42
7. Zhao D, Liu DX, Sun KW, Tao GQ, Zhu M, Wu Z, Research status, technical difficulties and development trend of stratospheric airship, *J. Acta Aeronautica Et Astronautica Sinica*. **37**(2016) pp 45-56