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A comprehensive numerical model investigating the thermal-dynamic performance of scientific balloon

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Abstract

The increase of balloon applications makes it necessary for a comprehensive understanding of the thermal and dynamic performance of scientific balloons. This paper proposed a novel numerical model to investigate the thermal and dynamic characteristics of scientific balloon in both ascending and floating conditions. The novel model consists of a dynamic model and thermal model, the dynamic model was solved numerically by a computer program developed with Matlab/Simulink to calculate the velocity and trajectory, the thermal model was solved by the Fluent program to find out the balloon film temperature distribution and inner Helium gas velocity and temperature field. These models were verified by comparing the numerical results with experimental data. Then the thermal and dynamic behavior of a scientific balloon in a real environment were simulated and discussed in details.
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Keywords: Scientific balloon; Thermal performance; Dynamic performance; Numerical model

1. Introduction

Scientific balloon is the ideal platform to carry out communication and observation missions in near-space environment (Colozza, 2003). A comprehensive and precise understanding of the ascending velocity, ascending trajectory and the temperature distribution of the balloon film is of vital importance for the designer and operator. It can help the designer to shorten the design time and reduce cost, and assist the operator in determining the causes of failure and malfunctions during flight experiment and developing the remedial actions.

Many investigations have been carried out on the thermal and dynamic performance of the scientific balloons. Kreith and Kreider (1974) established a simple but excellent numerical model to calculate the average temperature of skin and lifting gas, predict the trajectory of balloon and validate this model with experiment data. This model was marked as the starting point for the subsequent research. Carlson and Horn (1983) developed a new trajectory and thermal model to analyze the average temperature of balloon skin and lifting gas during ascending, investigate the flight trajectory with the impact of ballasting, venting and valving. Stefan (1983) further studied the thermal behavior of a high-altitude airship by dividing it into a top half and a bottom half, and obtained the average temperature of these two parts. Farley (2005) constructed the motion model for a high altitude balloon and predicted its ascent trajectory in both vertical and horizontal directions. Dai et al. (2012) investigated the thermal performance of a high altitude balloon with higher accuracy by dividing the balloon film into small elements and building a thermal model for each of the elements.

As for the temperature distribution of the scientific balloon, Louchev (1992) developed a steady-state thermal model of hot air balloon to calculate the shell temperature field and the average temperature of the lifting gas in

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different conditions. Kenya et al. (2003) conducted a numerical and experimental investigation on the temperature distribution of different airships at different altitude. A thermal performance model on NASA's (National Aeronautics and Space Administration of American) scientific balloons was proposed by Franco and Cathey (2004) for investigating the temperature distribution of balloon film at floating conditions neglecting the convection effect. Xia et al. (2010) established a transient numerical model for calculating the temperature distribution on balloon films at floating conditions. The model employed a simplified radiation model and experiential convective heat transfer coefficients. Wang and Yang (2011) proposed a transient numerical method to study the temperature distribution along an airship envelop and evaluate natural convection inside the airship.

However, little work has been done to examine the thermal and dynamic characteristics of the scientific balloon in one model. The primary purpose of this study is to develop a comprehensive numerical model that can investigate the thermal-dynamic performance of scientific balloon in both ascending and floating conditions. The work including developing the dynamic and thermal models, creation of the simulation platform, simulation of ascent velocity, analysis of ascent trajectory, investigates the film temperature distribution and exploration of the Helium gas flow inside the balloon. The dynamic model was calculated numerically by a computer program developed with Matlab/Simulink, and the thermal model is solved by the Computational Fluid Dynamic (CFD) method. The accuracy of these models is verified by comparing the simulation data with the experimental data. Then the dynamic and thermal performance of a scientific balloon in a real environment were simulated and discussed in details.

2. Environment model

2.1. Atmosphere model

The scientific balloon will floats at height 30 km. Temperature, pressure and density of the atmosphere changes with altitude. Atmosphere model (The U.S. Standard Atmosphere, 1976) employed in this paper uses the following sea-level values that have been standard for many decades:

Temperature – 288.15 K, Pressure – 101325 Pa, Density – 1.225 kg/m^3

The temperature and pressure of the atmosphere from the sea-level up to 32 km were calculated by the following formulas, while the density of the air is determined by the ideal gas law.

Temperature:

$$T_{air} = \begin{cases} 288.15 - 0.0065 \cdot h & 0 < h \leqslant 11000m \\ 216.65 & 11000m < h \leqslant 20000m \\ 216.65 + 0.0010 \cdot (h - 20000) & 20000m < h \leqslant 32000m \end{cases} \quad (1)$$

Pressure:

$$P_{air} = \begin{cases} 101325 \cdot ((288.15 - 0.0065 \cdot h)/288.15)^{5.25577} & 0 < h \leqslant 11000m \\ 22632 \cdot \exp(-(h - 11000)/6341.62) & 11000m < h \leqslant 20000m \\ 5474.87 \cdot ((216.65 + 0.0010 \cdot (h - 20000))/216.65)^{-34.163} & 20000m < h \leqslant 32000m \end{cases} \quad (2)$$

2.2. Solar radiation model

The position of the sun in the sky is expressed in terms of the solar altitude angle β above the horizontal and the solar azimuth angle ϕ measured from the south. The coordinate system was shown in Fig. 1. The solar radiation direction unit vector $\mathbf{n_s}$ could be described as (ASHRAE Handbook, 2001):

$$\mathbf{n}_s = -\cos\beta\cos\phi \cdot \mathbf{i} - \cos\beta\sin\phi \cdot \mathbf{j} - \sin\beta \cdot \mathbf{k} \quad (3)$$

where **i**, **j**, and **k** are the positive unit vector along the directions of south, east and top, respectively. The solar altitude angle β and the solar azimuth angle ϕ could be calculated by:

$$\beta = \arcsin(\cos L \cos\delta \cos H + \sin L \sin\delta) \quad (4)$$

$$\phi = \arccos\frac{\sin\beta \sin L - \sin\delta}{\cos\beta \cos L} \quad (5)$$

Here L denotes the local latitude, δ and H represents the solar declination and hour angle.

The direct solar irradiation I_D at the earth's surface on a clear day is given by:

$$I_D = A/e^{B/\sin\beta} \quad (6)$$

where A indicates the apparent solar irradiation above the atmosphere, B is the atmospheric extinction coefficient (ASHRAE Handbook, 2001).

The atmosphere diffuse irradiance I_{Atm} is given by:

$$I_{Atm} = C \cdot I_D \cdot (1 + \cos\sigma)/2 \quad (7)$$

where C is a constant within a period of one month (ASHRAE Handbook, 2001), σ is the tilt angle of the surface from horizontal.

The earth's surface reflected irradiance I_{Ref} is given by:

$$I_{Ref} = I_D \cdot (C + \sin\beta) \cdot R_e \cdot (1 - \cos\sigma)/2 \quad (8)$$

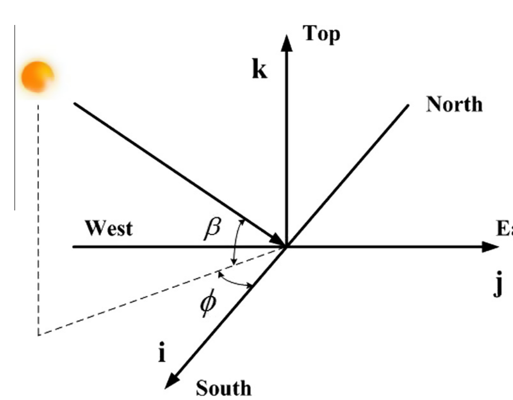

Fig. 1. Solar radiation direction.

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