International Journal of Thermal Sciences 76 (2014) 82–89

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Simplified analytical model for predicting the temperature of balloon on high-altitude

Junjiang Xiong*, J.B. Bai, L. Chen

School of Transportation Science and Engineering, Beeihang University, Beijing 100083, People's Republic of China

ARTICLE INFO

Article history:
Received 16 April 2013
Received in revised form
5 August 2013
Accepted 5 August 2013
Available online 3 October 2013

Keywords:
Balloon film
Lifting gas
Radiative heat
Convective heat
Absorption
Emission
Thermal equilibrium

ABSTRACT

This paper outlines an analytical model to predict the temperature of fully-inflated balloon on float at high altitude in stratosphere. Simplified radiative and convective heat transfer models are developed to estimate absorption and emission heat of balloon film and lifting gas within balloon. Thermal equilibrium equations for the balloon system in the day time and night time are derived by incorporating radiative and convective heat transfer models. The new model is applied to calculate the day and night temperatures of the balloon system on float at a high-altitude in stratosphere and reasonable correlation is achieved between the predictions obtained from new models and from prior flight testing data, demonstrating the effective use of the proposed models.

1. Introduction

With potential for the wider applications of high-altitude balloons as the cost-effective means in the Earth's atmosphere, there is growing interest in assessing thermal behavior of high-altitude balloon. Various experimental and analytical techniques and numerical analysis have been developed to predict thermal behavior and to simulate the heat transfer mechanism of high-altitude balloon during ascent, descent and float phases of flight. Lucas and Hall [1,2] conducted flight tests to measure transient and equilibrium radiation temperatures of lifting gas, ambient air and balloon film. Cathey et al. [3] developed an experimental method to determine the absorptivity and emissivity of the balloon with any size and construction, demonstrating a small quantifiable error in actually measured results of absorptivity and emissivity in balloon film and tapes. Since resource constraints limit the numbers of actual experiments, a significant amount of research has been performed by incorporating the principles of thermodynamics and finite element analysis (FEA) or computational fluid dynamics (CFD) methodology, etc. to evaluate thermal properties of high altitude balloon system. Spencer et al. [4] presented a simple hand-generated method to assess radiant heat transfer on high-altitude balloon and compared the calculations with the predicted values of radiant heat load and steady state temperature generated by SINDA and TRASYS models. Li et al. [5] established thermodynamic model to simulate transient thermal response of stratospheric spherical balloon during ascending, demonstrating that the temperature distribution of the balloon is non-uniform and variable during ascent phase. Xu et al. [6] proposed a CFD model for predicting temperature change of the balloon during one day and found that natural convective heat transfer in balloon was so faint as to be ignored in modeling simplification. Palumbo et al. [7] and Liu et al. [8] reported a modified thermodynamic model to predict thermal behavior of high-altitude balloons with zero pressure during ascending. The flight altitude, trajectory and climb rate of balloon were predicted and compared with the data from flight tests, demonstrating that the predicted results correlate very well with the experimental results. Dai et al. [9] developed a thermodynamic model to evaluate the influences of radiative property of film and clouds on thermal behaviors of super pressure balloon. Clark et al. [10] simulated the heat transfer mechanism of orbiting space vehicles under the mid-altitude and antarctic flight conditions by TRASYS code. Anderson et al. [11] numerically computed the convective heat field in the heated balloon resulted from solar heating by CFD code and obtained an axisymmetric solution of temperature field within the 22 million cubic foot balloon. In

* Corresponding author.
E-mail address: jjxiong@buaa.edu.cn (J. Xiong).

1290-0729/$ – see front matter © 2013 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.ijthermalsci.2013.08.002

Nomenclature

A	balloon surface area, m^2
g	acceleration due to gravity, N/kg
Gr	Grashof number
H	altitude above sea level of the Earth, m
h_1	convective heat-transfer coefficient between balloon film and ambient air, W/(m^2 K)
h_2	convective heat-transfer coefficient between balloon film and lifting gas, W/(m^2 K)
I_0	solar constant, W/m^2
I_1	irradiance level of solar scattered radiation, W/m^2
L	characteristic dimension of balloon, m
Nu	Nusselt number
Pr	Prandtl number
$Q_1(t)$	solar direct incident from the Sun to top half surface of balloon, W
$Q_2(t)$	solar scattered radiation from ambient air to balloon film, W
$Q_3(t)$	solar reflected radiation from the Earth to bottom half surface of balloon, W
$Q_4(t)$	infrared radiation (IR) from the Earth to bottom half surface of balloon, W
$Q_5(t)$	IR emitted from balloon film, W
$Q_6(t)$	IR absorbed from internal reflection of balloon film, W
$Q_7(t)$	convective heat transfer rate between the ambient air and balloon film, W
$Q_8(t)$	convective heat transfer rate between the lifting gas and balloon film, W
r	reflectivity of balloon film
R	spherical radius of balloon, m
Ra	Rayleigh number
R_e	radius of the Earth, km
Re	Reynolds number
φ	included angle of the sunlight with the line linking the Earth and balloon, rad
t	time corresponding to balloon location with the Earth rotation
T_1	absolute temperatures of balloon film, K
T_2	absolute temperatures of ambient air, K
T_3	absolute temperature of lifting gas, K
V	flow velocity of atmosphere, m/s
α_1	absorptivity of balloon film to direct incident from the Sun
α_2	absorptivity of balloon film to infrared radiation emitted from the Earth
ε	infrared emissivity of balloon film
θ	latitude in spherical coordinates, or solar radiation angle, or included angle of the sunlight with normal direction of balloon surface, rad
λ	thermal conductivity, or thermal conduction coefficient, W/(m^2 K)
ν	kinematic viscosity, N S/m
ρ_1	density of atmosphere, kg/m^3
ρ_2	density of lifting gas, kg/m^3
ρ_g	mean of reflectivity
σ	Steffan–Boltzman constant, W/(m^2 K^4)
τ	transparence coefficient of atmosphere
ϕ	longitude in spherical coordinates, or included angle of the element's normal direction of balloon with the x axis, rad

general, in order to produce thermodynamic model based on the FEA or CFD code, straight inclined segments or continuous mathematical functions were used to depict details of the idealized gore and other structures. However, the drawbacks of the above models are the intensity and complexity to depict the balloon geometry and constrains and to solve the solution of temperature field [11].

It is interesting to note in the above reviews that a large number of researches are grouped according to some important issues such as thermal behavior, heat transfer mechanism and steady state temperature by experimental approach and numerical simulation. However, there is lack of practical and valid analytical methodology to assess accurately thermal behaviors, particularly steady equilibrium temperature in balloon at float altitude, which is the focus of this paper. In fact, the steady equilibrium temperature in balloon at ceiling float altitude plays an important role in the design and application of balloon and there is a need for a more practical and expedient analytical model for balloon applications, particularly in the aerospace field. The paper, therefore, aims to develop more expedient and exact analytical models to assess the temperature of balloon on high-altitude by considering the effects of thermal environment and radiative properties of balloon film as well as the nature of heat convection mechanism.

2. Fundamental assumptions

As is well known, the temperature of balloon on high-altitude is governed by thermal environment, radiative properties of balloon film and the nature of heat convection mechanism. In order to analyze the temperature of balloon on high-altitude, fundamental assumptions made in this paper are as follows:

(1) Actual natural-shape balloon has a water drop-like shape and the upper portion of balloon approximates an ellipsoid, while the lower portion is close to a cone. Fig. 1a shows the axisymmetrical cross-sectional configuration of fully-inflated natural-shape balloon subjected to a payload. In order to simplify the model, the water drop-like shape of the balloon is idealized to be a round sphere (shown in Fig. 1b). The diameter

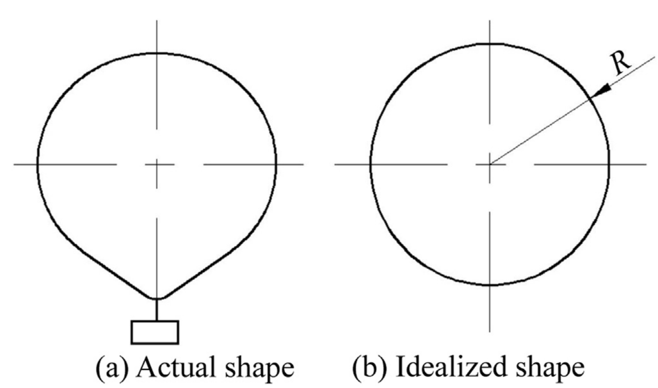

Fig. 1. Axisymmetrical cross-sectional configurations of a balloon subjected to a payload.