

Proceeding Paper

A Thermal Analysis of Atmospheric Balloons Using Different Coating Materials [†]

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[†] Presented at the Third International Conference on Advances in Mechanical Engineering 2023 (ICAME-23), Islamabad, Pakistan, 24 August 2023.

Abstract: Atmospheric balloons are the cheapest source utilized by scientists to investigate various research areas. Thermal analyses of atmospheric balloons is usually performed to attain the required thermal equilibrium in the shortest timeframe. In this paper, a mathematical model was developed that numerically solved material properties (i.e., ϵ (emissivity of balloon surface), α_V (balloon absorptivity averaged over the visible and near infrared band), ϵ_{IR} (absorptivity averaged over infrared band), α_{IR} (balloon absorptivity averaged over infrared band), etc.) as well as geometric properties (i.e., A_C (cross-sectional area), A_S (surface area), M (balloon mass), etc.) by incorporating these values in the heat balance equation. An optimized code was engendered in MATLAB, which simultaneously solved input parameters and delivered the required thermal equilibrium in the shortest timeframes. This may serve as a guide to new material generation.

Keywords: atmospheric balloon; transient thermal behavior; optimization process



Citation: Aslam, N.; Haroon, M.; Rasheed, S.; Rai, F.U.; Iftikhar, M. A Thermal Analysis of Atmospheric Balloons Using Different Coating Materials. *Eng. Proc.* **2023**, *45*, 42. <https://doi.org/10.3390/engproc2023045042>

Academic Editors: Mohammad Javed Hyder, Muhammad Mahabat Khan, Muhammad Irfan and Manzar Masud

Published: 14 September 2023



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1. Introduction

Balloon technology is considered one of the low-cost options for carrying different types of scientific payloads. The studies on balloon and airship systems have carried vital importance for many years in the fields of control system, flight testing, structural analysis and others. Payloads with long durations and massive area/mass have the capacity to fly over nearby space conditions that provide charming opportunities for the development of actual science, e.g., for many of NASA's top-priority zones for future and current missions. Missions involving balloon-borne technology carry less cost than concerned satellite missions with minimum timescales. Atmospheric balloons designed to analyze the "in situ" data and air mass tracking intelligence information at high altitudes have been studied around the globe for many years.

In the thermal analysis of a balloon, solar and ground radiation are the source of temperature elevation, while the thermal emissivity, surface reflection and convection heat of the balloon results in temperature deterioration [1]. Infrared (IR) radiation is an important candidate for affecting the thermal performance of balloons at high altitudes [2]. The rate of the temperature change on the surface of a balloon is much faster compared with other infrared targets.

This study is focused on the thermal analysis of atmospheric balloons by varying mass, size, initial deployed temperature and coating materials. The main goal of this study is to produce an optimized transient thermal model to numerically investigate the transient thermal behavior of spherical atmospheric balloons at various geometric and material properties and their acquiring of peak thermal equilibriums. It can be noticed that the heating effect produced by the external heating element is not only linked with

the thermo-physical properties and surface structure of the thermal balloon but also linked with the shape and initial deployed temperature of the balloon.

2. Methodology

To study the thermal equilibrium effect of atmospheric balloons placed in space, a numerical code was developed in MATLAB (9.7 R2019b version), which describes the complete optimization behavior of thermal atmospheric objects. To obtain maximum and minimum thermal equilibrium ranges, a thermo-physical model could be generated and solved numerically for objects in daylight and at night. But, in this paper, only objects in daylight are discussed. The thermo-physical model for daylight is described below:

For a balloon illuminated by different fluxes and at a temperature T ,

$$P_E = P_A + P_I \tag{1}$$

where P_E is the power emitted by the object, P_A is the power absorbed by the object and P_I is the internal power generated by the object, which is neglected (gives $P_E = P_A$).

$$P_E = A_S \times \epsilon_{IR} \times \sigma \times T_{eq}^4 \tag{2}$$

$$P_A = A_C \cdot [(S + S_R) \cdot \alpha_V + \alpha_{IR} \cdot E] \tag{3}$$

where σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-12} \text{ W/cm}^2\text{-K}^4$), T_{eq} is the equilibrium temperature, S is the solar flux (1360 W/m^2), S_R is the albedo flux ($0.3 S$), E is the earth infrared flux (240 W/m^2) and C_P represents the specific heat capacity of the balloon.

Using the fact that $\alpha_{IR} = \epsilon_{IR}$, for an object in thermal equilibrium,

$$P_A = A_C \cdot [(S + S_R) \cdot \alpha_V + \epsilon_{IR} \cdot E] \tag{4}$$

$$T_{eq} = \left[\frac{(A_C/A_S) \cdot [(S + S_R) \cdot \frac{\alpha_V}{\epsilon_{IR}} + E]}{\sigma} \right]^{\frac{1}{4}} \tag{5}$$

where T_{eq} is independent of the balloon radius and for a spherical balloon, $A_C/A_S = \frac{1}{4}$.

Various parameters like mass, initial temperature, size and coating materials depend on thermal equilibrium, and the effect of these parameters is incorporated in the heat balance Equation (6) below:

$$M \times C_P \times \frac{dT}{dt} = -A_S \cdot \sigma \cdot \epsilon \cdot T^4 + A_C \cdot [(S + S_R) \cdot \alpha_V + \epsilon_{IR} \cdot E] \tag{6}$$

The equation is solved numerically by incorporating material and geometric properties, as shown in Table 1 below. All parameters and equations are collected from [3].

Table 1. Material properties of various coatings and geometric properties of an atmospheric balloon [3].

Material Properties of Various Coatings					Geometric Properties of the Atmospheric Balloon	
Surface Coating	α_V	ϵ_{IR}	$\frac{\alpha_V}{\epsilon_{IR}}$	T_{eq}	Mass (kg)	0.3, 0.4, 0.5
White TiO ₂ Paint	0.19	0.94	0.20	227	Size (m)	2.0, 3.0, 4.0
Aluminum Foil Shiny Side	0.192	0.036	5.33	454	Initial temperature (K)	300, 350, 400, 600
Black Paint	0.975	0.874	1.12	314	C_p (J/kg.K)	1090
Aluminum paint	0.54	0.45	1.20	320	A_c (m ²)	$\pi \times r^2$
					A_s (m ²)	$4 \times \pi \times r^2$

The optimization code simultaneously solves the various material and geometric properties of a thermal balloon to attain the desired ranges of maximum and minimum thermal equilibriums.

3. Results and Discussion

3.1. Results Validation

The validation results of the data received through the numerical process show great symmetry with the results drawn from the literature [3], as shown in Figure 1a. A simple model of a balloon was used to illustrate both the range of temperatures and equilibrium time that could be achieved for balloons. After the validation of the numerical code, an optimization process was carried out to obtain the maximum as well as minimum values of thermal equilibrium for the atmospheric balloon with corresponding time for various scientific and engineering applications. The combination of input values was 36, which led toward the optimization process.

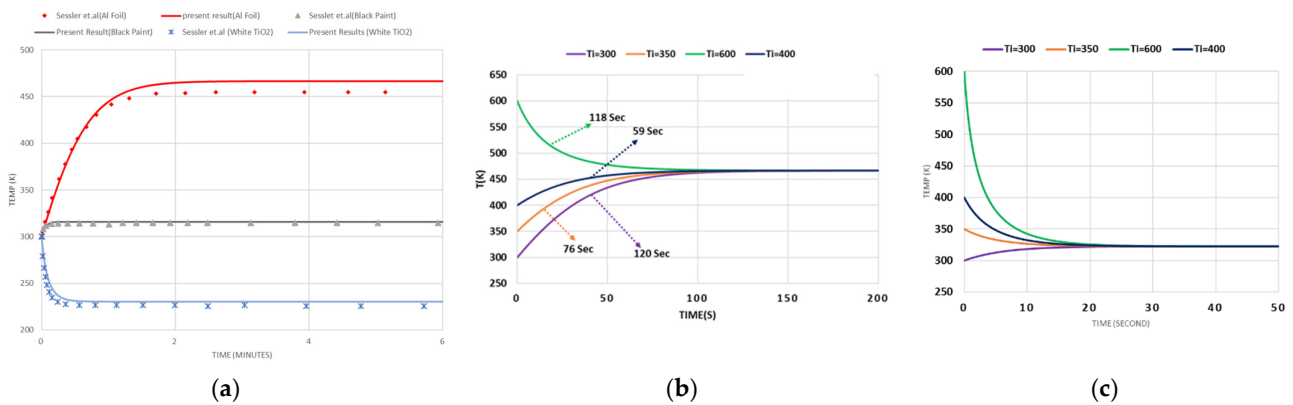


Figure 1. (a) Validation results for different coating materials (b) Temperature analysis of Aluminum foil shiny side and (c) Aluminum paint.

3.2. Initial Temperature Change

When the initial temperature of coated material was changed, the balloon thermal equilibrium achievement time also changed, depending upon its size, material and mass. Therefore, the main objective of this analysis was to attain thermal equilibrium in a significantly short interval of time. The rate of thermal equilibrium procurement was highly dependent upon the initial temperature of the material. The thermal equilibrium of Aluminum Foil Shiny Side was 454 K and the maximum time taken by the balloon to reach a thermal equilibrium state was 120 s when it was launched to the atmosphere at 600 K. Similarly, the balloon stretched very quickly to its final equilibrium state when it was launched at 400 K (very near to the thermal equilibrium, i.e., 59 s), as shown in Figure 1b. The same type of analyses were performed for black paint, white TiO₂ paint and aluminum paint (Figure 1c) coatings with a fixed diameter of 3 m and mass of 0.5 kg.

3.3. Thermal Mass Change

The thermal mass of the balloon also affected the speed needed to achieve thermal equilibrium for various material coatings. Three thermal masses (0.3 kg, 0.4 kg, 0.5 kg) were selected for four material coatings and launched in the atmosphere at a fixed initial temperature (300 K) and balloon size (3.0 m). It was perceived that the balloon with Aluminum Foil Shiny side paint attained thermal equilibriums as 53.5 s for 0.3 kg, 71.4 s for 0.4 kg and 120 s for 0.5 kg (Figure 2a).

3.4. The Effect of Size Change and Various Coating Materials

The size of the balloon was the most important parameter for the absorption and repulsion of radiation in space. The size variation analysis was carried out at a fixed mass (i.e., 0.5 kg) and an initial temperature of 300 K for all four types of coatings. It was observed that the magnitude of thermal equilibrium changes for the same material and the balloon with the largest size had a minimum value of thermal equilibrium but the shortest

time required to attain the thermal equilibrium. The results of black and White TiO₂ paint coatings for varying diameters are enclosed in Figure 2b,c, respectively.

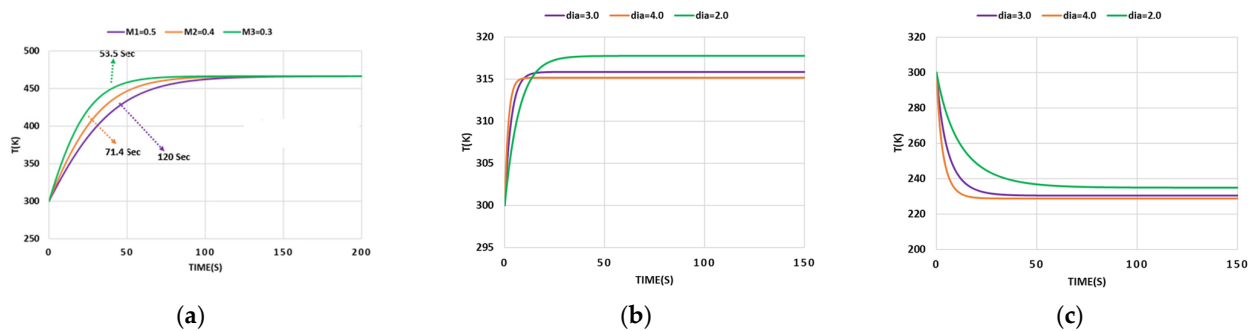


Figure 2. (a) Mass analysis of Aluminum foil shiny side, (b) Size analysis of black and (c) White TiO₂ paint coatings.

4. Conclusions

It is concluded that (1) thermal equilibrium achievement time depends on the deviation of the initial temperature from the equilibrium temperature. (2) For fixed initial temperature and balloon size, all materials with lesser thermal mass achieved thermal equilibrium at a faster rate than heavier balloons. (3) The size change of atmospheric balloons is inversely proportional to the thermal equilibrium achievement time, i.e., larger balloons reach their thermal equilibriums in a very short time interval and vice versa.

Author Contributions: Conceptualization; N.A. and M.H.; methodology; S.R. and N.A.; formal analysis; M.H. and F.U.R.; investigation; M.I. and S.R.; data curation; F.U.R. and M.I.; writing—original draft preparation; N.A.; writing—review and editing; M.H. and S.R.; supervision; N.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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