ARTICLE NO. 77-1183R

Performance Theory for Hot Air Balloons

Karl Stefan*
The Balloon Works, Inc., Statesville, N.C.

An analytical model is developed describing external and internal heat transfer processes. The model is utilized for illustrating the effects of various parameters, especially with respect to fuel consumption. It is shown that in general for the same load, a large balloon has much better fuel economy than a small balloon. A black balloon offers superior fuel economy when flying in sunshine, and when lightly loaded, may not require any fuel. However, without sunshine the black balloon is inferior to an aluminized balloon.

Nomenclature

A = balloon surface area
a = vertical acceleration
C_d = aerodynamic drag coefficient
C_p = specific heat of air
D = aerodynamic drag
d = proportion of solar radiation reflected by Earth or clouds
E = efficiency of combustion
F_s = solar radiation flux incident on balloon
G = gross weight, excluding weight of lifting gas
g = acceleration due to gravity
H_f = heating values of fuel
h_i = internal convection coefficient
h_o = convection coefficient
I = inertial force or unbalanced forces causing acceleration
L = aerostatic lift force
m = mass being accelerated
Q = heat transfer rate
Q_{Ad} = Earth reflected solar radiation (albedo) absorbed by balloon
Q_{Ae} = Earth emitted infrared radiation absorbed by balloon
Q_{As} = solar radiation absorbed by balloon
Q_{Am} = infrared radiation emitted by atmosphere and absorbed by balloon
Q_c = heat added to skin by convection from ambient air
Q_E = infrared radiation emitted from balloon surface
Q_{ic} = heat added to internal gas by convection from skin
Q_{ir} = net heat gain by gas through radiation exchange with the skin
Q_k = rate of heat loss through leakage
Q_p = amount of heat carried away by the overflow of hot gases from the bottom due to injection of additional gas by the torch
Q_t = heat supplied by torch
 = horizontal cross sectional area of balloon at maximum diameter
T_a = ambient air absolute temperature
T_e = absolute temperature of Earth's surface
T_g = absolute temperature of internal gas balloon
T_s = absolute temperature of balloon surface
U = vertical velocity of balloon
V = volume of balloon
V_k = volumetric flow rate from leakage
W_f = rate of fuel usage
W_i = the weight of air induced to flow into the balloon for each unit of fuel used
w_a = ambient air density
w_{ao} = air density at sea level
w_i = density of internal air
α_s = solar absorptivity of the balloon outside surface
ϵ_a = infrared emissivity of the atmosphere
ϵ_b = infrared emissivity of the inside surface of the balloon
ϵ_e = infrared emissivity of the earth's surface
ϵ_s = infrared emissivity of the balloon outside surface
ϵ_g = infrared emissivity of gas in the balloon
σ = Stefan-Boltzman constant $= 0.1714 \times 10^{-8}$ BTU/(h-ft^2)(°R^4)
τ_a = infrared transmissivity of atmosphere

Presented as Paper 77-1183 at the AIAA Lighter-than-Air Systems Technology Conference, Melbourne, Fla., Aug. 11-12, 1977; submitted Sept. 16, 1977; revision received Jan. 26, 1979.

Index categories: Lighter-than-Airships; Solar Thermal Power; Thermal Control.

*Vice-President, Engineering. Member AIAA.

Introduction

HOT air balloons such as the ones which are becoming popular in sporting activities have performance possibilities far beyond what has been explored to date. The sport balloon has been a useful experimental tool in correlating analytical methods with flight results and in understanding practical limitations and costs. This paper presents the analytical method and some results in applying it to hot air balloon systems.

The lift and hence the flight path of a ballon is in general closely associated with the thermal environment. In a conventional gas balloon, that is, a balloon filled with a lighter-than-air gas, control is exercised by overriding the thermal effects by dropping ballast or valving off gas. In a conventional hot air balloon, the thermal correlation is intensified by the fact that both total lift and control are maintained by thermal energy regulation.

The energy factors affecting a hot air balloon are shown in Fig. 1. The affect of all these factors on the balloon depend upon the properties of the balloon itself. Radiation emitted from the balloon depends upon the emissive properties and temperature of the skin. The skin temperature, in turn, is an equilibrium point established by heat removal through radiation and convection, by heat addition through solar and Earth radiation and by the internal hot gases.

An analytical model is illustrated in Fig. 2. It is a spherical shell representing the balloon skin temperature T_s. The shell is filled with air which is heated by a torch Q_t, to temperature T_g, and it floats in an atmosphere at temperature T_a and density w_a. The aerostatic lift force L, is balanced by gross weight G, aerodynamic drag D, and inertial force I. To make the model realistic, two holes are provided, one for leaks and one for spilling. Spilling occurs when heat in the form of hot gas is added from the torch thus displacing cooler gas in the balloon which spills or overflows out the opening in the bottom of the balloon.

Parameter Evaluation

The parameters of Fig. 2 may be evaluated as follows:

1) External thermal factors (heat flow into skin is plus)

$$Q_{As}=F_s\alpha_s A/4 \tag{1}$$

The solar flux F_s, varies from 0 to a maximum of about 400 BTU/h-ft^2. The absorptivity of the balloon fabrics is about 0.4 for light colors to 0.9 for dark colors, and 0.15 for metallic aluminized surface.

$$Q_{Ad}=F_s d\alpha_s A/2 \tag{2}$$

d, albedo, is roughly 0.3 over desert, 0.8 over snow or ice, 0.6 over clouds, 0.1 over other surfaces. Since reflection is generally diffuse, effective area of the balloon is $A/2$.

$$Q_{Ae}=\epsilon_e T_e^4 \epsilon_s \tau_a A/2 \tag{3}$$

Earth radiation effects are quantitatively quite significant, but ϵ_e and τ_a are both difficult to assess except where specific values are available. A value of 0.9 for ϵ_e appears valid for most situations. τ_a can vary from 0 to 1 depending on altitude and atmospheric conditions. At 5000 ft on a clear day 0.8 appears to be a reasonable value. In Ref. 2, this and other incident IR effects are integrated into one measurement by a "Gergen" black ball radiometer.

$$Q_{Am}=\epsilon_a T_a^4 \epsilon_s A\ 2/3 \tag{4}$$

The comments on Eq. (3) also apply here. ϵ_a will vary with atmospheric conditions. If the balloon is near the ground, the area effective in receiving this radiation is closer to $2/3A$. However, the short path length for Earth radiation compensates for this decrease of atmospheric radiation. A value of 0.8 for τ_a has been used for low altitude calculations in this paper.

$$Q_E=\epsilon_s T_s^4 A \tag{5}$$

Since Q_E varies as the 4th power of temperature, fuel economy obviously is enhanced by low temperatures.

$$Q_c=h_o A(T_a-T_s)^{4/3} \tag{6}$$

Convection coefficient data has been developed for this paper, from Ref. 1, and modified to obtain better correlation with flight data points. A value of 0.4 BTU/h-ft^2 °R has been used in these calculations.

2) Internal thermal factors (heat flow into gas mass is plus)

$$Q_{ic}=h_i A(T_s-T_g)^{4/3} \tag{7}$$

h_i has been evaluated by fitting this model to flight test results; $h_i=0.51$ BTU/h-ft^2 °R has been satisfactory.

$$Q_{ir}=A(\epsilon_b T_s^4 f-\epsilon_g T_g^4 (1-f)) \tag{8}$$

where

$$f=\epsilon_g/(\epsilon_g+\epsilon_b-\epsilon_g\epsilon_b)$$

This expression was derived by analysis of the internal radiation exchange between gas and balloon skin involving reradiation and reflections.

ϵ_g for the internal gas of a hot air balloon containing products of combustion and with a path length of about 50 feet has been calculated to be about 0.45. However, fitting to flight test data indicates 0.3 to be a more satisfactory value.

$$Q_k=V_k w_i C_p(T_a-T_g) \tag{9}$$

Although nonleaking balloons are generally preferred, hot air balloons do tolerate a reasonable amount of leakage with increased fuel usage as the only penalty. The calculations for this paper assume zero leaks.

$$Q_t=W_f E H_f \tag{10}$$

H_f for propane as used in a balloon is about 18,600 BTU/lb.

$$Q_p=W_f C_p W_i(T_a-T_g) \tag{11}$$

W_i, the mass of air entrained by the fuel, is estimated at 18 lb of air per lb of fuel, for propane torches.

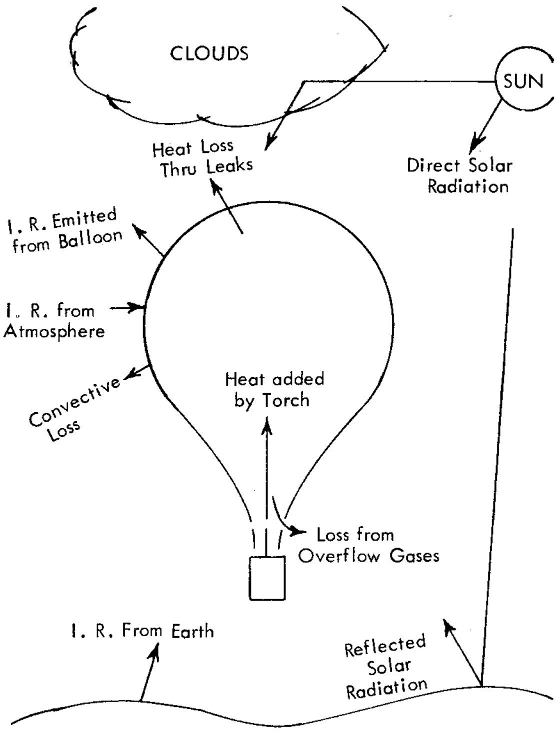

Fig. 1 Energy factors affecting a hot air balloon.

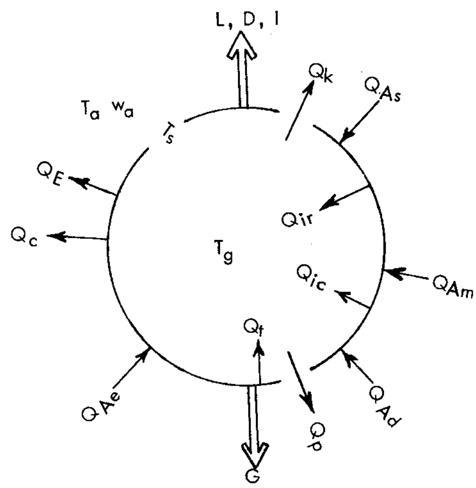

Fig. 2 Analytical model for hot air balloons.

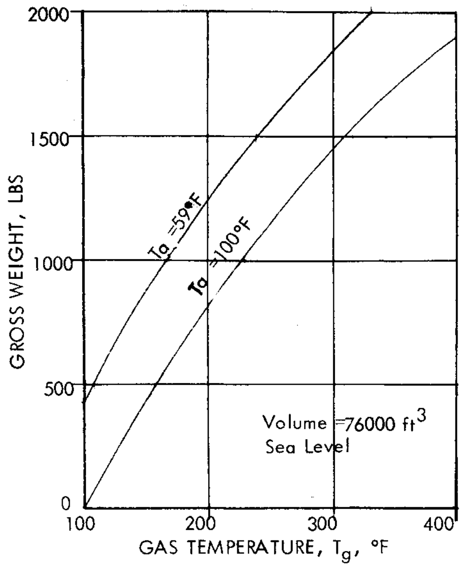

Fig. 3 Gross weight vs gas temperature.

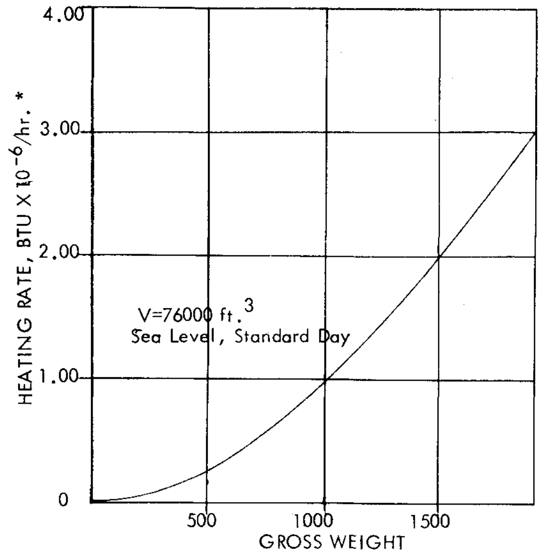

Fig. 5 Gross weight vs heat requirement.

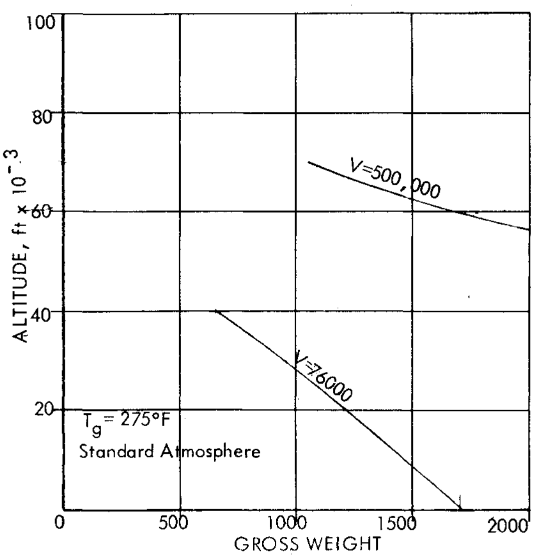

Fig. 4 Gross weight vs altitude.

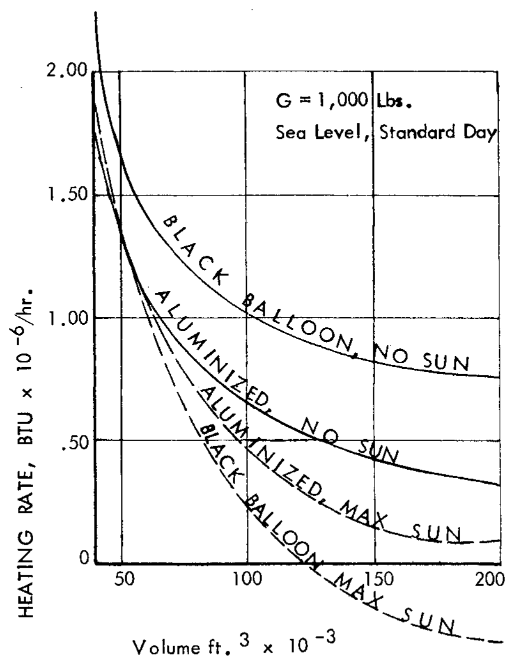

Fig. 6 Heat requirement vs volume for various surface finishes.

3) Force factors

$$L = Vw_a(1 - T_a/T_g) \qquad (12)$$

This expression for aerostatic lift is derived from Archimedes' principle.

$$G = \text{gross weight, excluding weight of lifting gas} \qquad (13)$$

$$D = 0.5\, C_d (w_a/g)\, U^2 S \qquad (14)$$

Wind tunnel measurements for the natural shape balloon in vertical motion give a value of about 0.4 for C_d. Generally speaking, results of drag calculations for balloons in flight have not been satisfying, probably due to undetected ambient air motion and temperature variations as well as changes of internal gas temperature.

$$I = ma \qquad (15)$$

where

$$m = 1.5\, Vw_a/g$$

The 1.5 factor in m accounts for the 50% additional or virtual air mass involved in acceleration of a sphere.

4) Equilibrium conditions

The condition for thermal equilibrium of the balloon skin is

$$Q_{As} + Q_{Ad} + Q_{Ae} + Q_{Am} + Q_c - Q_E - Q_{ic} - Q_{ir} = 0 \qquad (16)$$

Likewise, conditions for thermal equilibrium of the mass of gas inside the balloon is established when

$$Q_{ic} + Q_{ir} + Q_k + Q_t + Q_p = 0 \qquad (17)$$

The equation for vertical motion of the balloon is

$$L + G + D + I = 0$$

Performance Capabilities

The above expressions have been evaluated for a range of steady state, zero motion balloon conditions. These illustrate performance capabilities of currently practical balloon systems.

Figure 3 illustrates the relationship of gross weight and gas temperature. The degradation of lift capability on a hot day, $T_a = 100°F$, is real and appreciable, as any balloonist will testify. Fabric properties limit conventional balloon temperature to 250 to 300°F.

Figure 4 shows the effect of altitude on balloon lift. A popular sport balloon size, 76,000 ft^3, tops out at around 40,000 ft, while a half million cubic ft balloon could be operated in the 60,000 ft range. Tropospheric lapse rates are very helpful for hot air balloon altitude performance, but once into the stratosphere, the requirement for additional volume increases drastically.

Fuel consumption is the limiting factor for many aspects of hot air balloon performance. For a given balloon, the most significant fuel factor is the gas temperature T_g, at which it must operate, and this is dictated by the load it must carry and the ambient air density in which it must fly. Figure 5 illustrates the relationship for a 76,000 ft^3 balloon on a standard day. A hot day would result in a much lower load for the same fuel consumption.

The curve of Fig. 5 indicates the possibility of saving fuel by using a larger balloon. Figure 6 verifies this idea and also illustrates the effect of surface finish on the fuel requirement. The general conclusion is that fuel consumption is decreased by increased volume. The black balloon and aluminized balloon present extremes in the range of available surface finishes. The black balloon presents a dilemma for the balloonist in that it is the worst of cases for "no sun" and the best for "maximum sun." Since balloonists generally fly when sun elevation is low (for low winds), its overall performance may be as good as that for the aluminized surfaces. All fabrics tend to have high infrared emissivity, but solar absorptivities may be low in the light colors. It would therefore appear that a dark colored balloon would have better fuel economy that a light one. If a balloon must be flown very hot, the curve shows that aluminized is better than black. Note that the curve for the black balloon with "maximum sun" crosses the line to zero fuel consumption. The balloon at that point becomes solar powered, with flight totally sustained by solar energy.

References

[1] Kreith, F., *Principles of Heat Transfer*, International Textbook Company, Scranton, Pa., 1965.

[2] Morris, A., *Scientific Ballooning Handbook,* NCAR TN/IA-99 Sec. II, "Theory of Balloon Flight," Sec. III, "Energy Balance and Flight Model," National Center for Atmospheric Research, Boulder, Colo., 1975.

[3] Dingwell, I.W. et al., *Vertical Motions of High Altitude Balloons*, Office of Naval Research, Technical Rept. II, A. D. Little Inc., Cambridge, Mass., 1963.

[4] Gergen, J.L., "Black Ball, A Device for Measuring Atmospheric Infrared Radiation," *Review of Scientific Instruments,* Vol. 27, 1956, pp. 453-460.