A Feasibility Study on Altitude Control System Development for Rubber High-Altitude Balloon†

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ABSTRACT

Rubber weather balloons are low-cost, commercially available, capable of stratosphere flight, and commonly used for various purposes. With an ultimate objective of using rubber balloon to develop a controlled balloon system which satisfy operation requirements, it is necessary to obtain the performance requirements of altitude control system. This paper investigates the feasibility of altitude control system development for Helium-filled, spherical weather rubber balloons to satisfy specified operation requirements. Two different altitude control methods of adjusting buoyancy and adjusting weight are considered. Both methods use the technique of compressing gas into pressurized reservoir and releasing storing gas for altitude control. Theoretical derivations are used for assessing the performance requirements of the altitude control system. Simplified analysis for quasi-steady flights under design points (operation requirements) which include altitude change, heat transfer options (i.e. convection and radiation), vertical speed, and weather tolerance was made to obtain required initial Helium mass for the launch. Finally, the performance requirements of the altitude control system are analyzed based on all design points and initial Helium mass filled in the balloon. The results show feasibility of altitude control system with a large reservoir or with relaxation of operation requirements from both methods for the selected rubber balloon.

Keyword: Altitude Control, Rubber Balloon, HAB

1. INTRODUCTION

High-altitude balloons (HAB) are typically free-fly balloons capable of carrying instruments to the stratosphere at 20−30 kilometers above the sea level. weather balloons are the most common type of high-altitude balloons, normally filled with helium or hydrogen, and frequently used by meteorologists, hobbyists, and researchers for studies and operations. These balloons are normally equipped with sensing and communication instruments and parachute. After weather balloons are released, they continuously gain altitude until they reach bursting points. Then, the instruments fall down slowly with parachute. Due to the low-cost and availability of weather balloons and equipment, these balloons are normally discarded after released [1].

Weather balloon is typically preferred to be nature rubber for biodegradability. Nature Rubber is an elastic material which can elongate up to 650%. [2] Physical response of rubber balloons had been modelled and used in many applications [3−6]. Using of rubber balloon models to simulate balloon flights and compare with real flight data are in [6, 7].

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Generally, altitude control of a balloon is achieved by either changing the balloon’s lift force or mass. Changing of the balloon’s lift force is commonly obtained by changing of its volume and can be done by using mechanism or heat. Changing of the balloon’s mass is commonly obtained by collecting air from surrounding. In [8], an altitude control system which releases lifting gas to maintain altitude and descend is designed and implemented for a rubber balloon platform. However, few works on design and implementation of altitude control for rubber balloons can be found in the literature, the topic still presents difficulties and challenges due to the uncertainty of weather and material properties, such as nonstandard atmosphere and constantly changing of temperature and pressure gradients, as well as unique stretching behavior and limitation of enclosed pressure of rubber balloons [8].

The objective of this paper is to investigate the feasibility of altitude control development for rubber balloon using two different altitude control methods. The scope of the study covers Helium-filled, spherical rubber balloon systems with combined payload weight of 4 kg. (ICAO light, unmanned free balloon) and operating at the altitude of 0−20 km in standard calm weather condition. Two methods of adjusting buoyancy and adjusting weight are considered in the development of altitude control system. For the study, governing equations are simplified to represent the quasi-steady state of rubber balloon flight. Design points are specified based on operation requirements of balloon systems. The performance requirements of altitude control system are obtained using analysis of quasi-steady flight under all design points and simplifying assumptions. Finally, the results of simplified quasi-steady-flight analysis are present and the feasibility of altitude control system development is determined by the realistic performance requirements of altitude control system in satisfying the operation requirements.

2. METHODOLOGY

In this work, we consider a spherical rubber weather balloon with initial radius, r_0, and skin thickness, t_0. When Helium is filled into the balloon, the gas pressure, P_g, increases as the gas quantity, m_g, inside the balloon increases. This gas pressure can be computed by assuming that Helium is an ideal gas. When the gas pressure is higher than the combination of surrounding air pressure, P_a, and rubber restoring pressure, P_b, the balloon starts to inflate and increases its radius, r. Assuming standard atmospheric condition, the properties of surrounding air can be obtained using barometric formular [9]. The rubber restoring pressure can also be computed by assuming that pressure-radius characteristic of the rubber balloon follows the Mooney-Rivlin model [5, 6]. The stable balloon radius is at the point in which the compressing and expanding pressures are balanced.

The motion of a balloon system is depended on the resultant of forces acting on the balloon. In the quasi-steady flight (i.e. constant speed, pressure, and temperature), the forces acting on the balloon are lift (or buoyancy), weight, and aerodynamic drag. The lift force of a balloon depends on the its volume, V_b, and density of surrounding air, ρ_a. An increase of the balloon volume increases its lift force, and vice versa. The weight of a balloon depends on its mass, m, and gravitational acceleration, g. The gravitational acceleration is assumed to be constant in the work.

Figure 1 illustrates the rubber balloon system with altitude control module considered in this work. The altitude control system consists of two set of gas compressor, gas reservoir, and release valve. The first one is used for enclosed Helium inside the balloon. The other is used for the surrounding air. Relocation of enclosed Helium between balloon and gas reservoir changes the quantity of gas inside the balloon while the balloon total mass is maintained. Compressing the gas into the gas reservoir decreases the gas quantity inside the balloon, decreases the gas pressure, and reduces the balloon volume and its lift force. Releasing the gas from reservoir into the balloon increases the gas quantity inside the balloon, increases the gas pressure, and increase the balloon volume and its lift force. The collecting the outer air into the air reservoir increases the total mass of balloon, while releasing the collected air to the surrounding decreases the total mass of balloon.

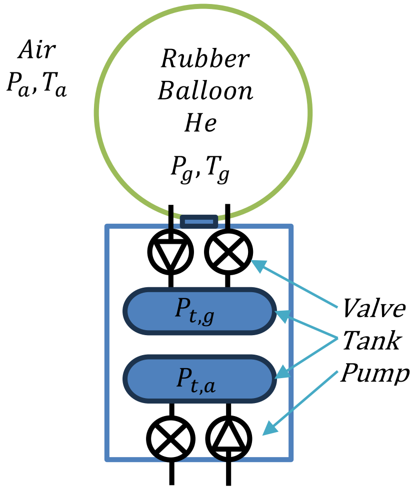

Figure 1. the rubber balloon system with altitude control module

For the feasibility study of altitude control development for rubber balloons, the developed altitude control must satisfy the desired operation requirement of the controlled balloon system. Table 1 presents the operation requirements for the developed balloon system.

Table 1. Operation requirements for developed balloon system

Parameters	Value
Payload mass	4 kg
Balloon stretch limit	600%
Balloon vertical speed	±5 m/s
Balloon altitude	0−20 km
Air pressure uncertainty	±5%

To assess the performance requirements of the two altitude control methods, quasi-steady flights of the balloon under design points specified based on the operation requirements are analyzed. Motions of the balloon in horizontal plane is not considered for the simplicity of analysis. The quasi-steady flight of balloon is the flight condition in which the balloon has constant speed, pressure, and temperature and can be simplified as

$$0 = \rho_a V_b g - 0.5\rho_a v_h |v_h| A_b C_d - mg$$

where ρ_a is the density of surrounding air, V_b is the balloon's volume, v_h is vertical speed, A_b is projection area of balloon, C_d is the drag coefficient, m is the total mass of balloon, and g is gravitational acceleration.

Design points are specified to ensure operation requirements of developed balloon system and consist of four dimensions (i.e. vertical speed, altitude change, tolerance to weather (pressure) uncertainty, and heat transfer option). The range of vertical speed, altitude, and pressure change of the balloon flights are presented in Table 1. The temperature range of balloon flights are determined by the heat transfer option. Considering a floating balloon, its temperature (including lifting gas) can be changed due to heat convection and heat radiation. If there is no radiation, the balloon temperature in quasi-steady flight will be equal to surrounding air temperature. With radiation, the balloon temperature is affected by sunlight, surface temperature, and sky temperature, which are different during day and night. Therefore, four design points of without radiation in day time, without radiation in night time, with radiation in day time, and with radiation in night time are considered. The steady temperature of the balloon in the present of radiation is at the point in which heat convection and radiation are balanced and can be determined by

$$hS_b(T_b - T_a) = \epsilon A_b Q_{sun} + \epsilon\sigma S_b\left(T_b - \frac{T_s}{2} - \frac{T_{sky}}{2}\right)$$

where h is the convection coefficient, S_b is the surface area of balloon, ϵ is the emissivity of the balloon material, A_b is projection area of balloon, Q is the energy of sun light (1000 W/m^2), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2·K^4), andT_b, T_s, T_{sky} are temperatures of balloon, earth surface, and sky, respectively.

It is assumed that the surface temperature in day time is 35°C, while the surface temperature in night time is 25°C and there is no sunlight in the night time. The effective sky temperature follows the Swinbank's model [10].

From analysis of the balloon's quasi-steady flights with all design points, the Helium mass (filled at the launch) required to satisfy balloon system's operation requirement can be determined. Then, the performance requirements of altitude control system are determined by capabilities of pump and reservoir which require to achieve quasi-steady flights with the initial Helium mass under all design points. Finally, the feasibility of altitude control system development is determined by the realistic performance requirements of altitude control system equipment.

3. RESULTS AND DISCUSSION

For the study, we begin with the rubber balloon modelling. The physical characteristic of rubber balloon based on [5, 6] is affected by the initial radius and skin thinkness of balloons. The corresponding value of initial radius and skin thinkness of balloons are determined by analyzing commercial weather balloon available in the market. Analysis of commercial weather balloon specification shows a tendency that the initial skin thickness of a balloon is constant regardless of its size. Figure 2 present calculated results for initial skin thickness of samples of commercial weather balloons. Figure 3 present restoring pressure characteristic for different sizes of commercial weather balloons from the Mooney-Rivlin model. The commercial weather balloon size of 1kg is selected for the development of controlled balloon system and used in the following analysis and results in this paper.

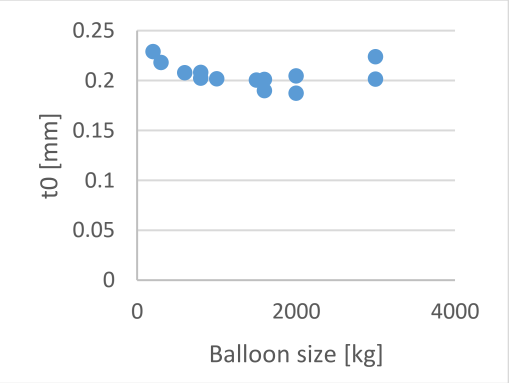

Figure 2. initial skin thickness of samples commercial weather balloons that

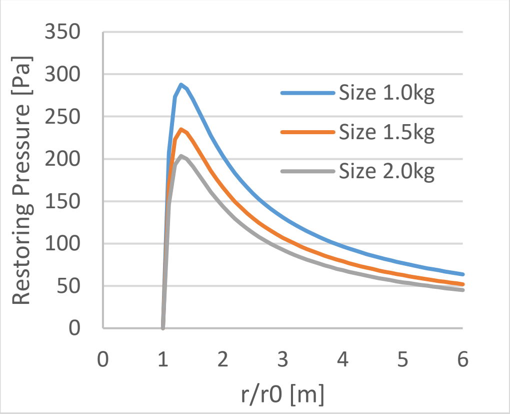

Figure 3. restoring pressure characteristic for different sizes of commercial weather balloons

For the analysis of balloon flight at altitude of 0−20 km, an atmospheric model is developed based on barometric formular [9]. Figure 4 presents the temperature at different altitude based on standard atmospheric condition and given surface temperature. Figure 5 presents the density of air and Helium at different altitude based on standard atmospheric condition, given surface pressure, and given surface temperature.

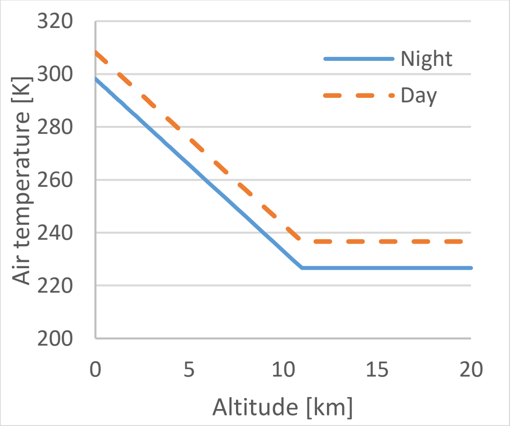

Figure 4. surrounding air temperature at different altitude based on standard atmospheric condition and given surface temperature.

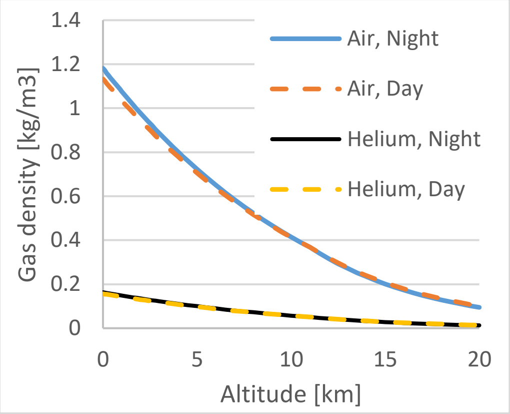

Figure 5. density of surrounding air and Helium at different altitude based on standard atmospheric condition, given surface pressure, and given surface temperature.

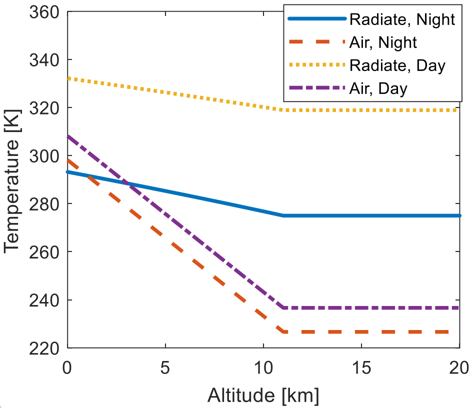

Figure 6. temperature of surrounding air and equilibrium heat transfer point at different altitude during day time.

Figure 6 presents the temperature of surrounding air and temperature of balanced heat convection and radiation at different altitude during day and night time. It is observed from the result that a rubber balloon leaving under the sun in clear sky can reach the temperature of over 60 degrees Celsius.

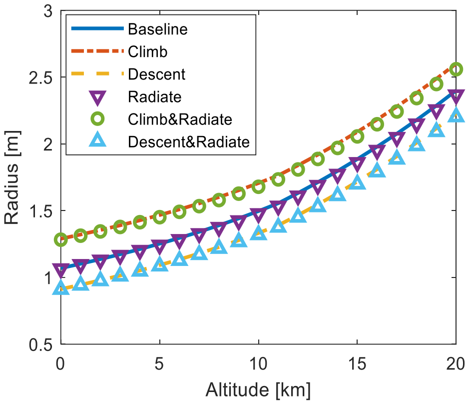

Figure 7. radius required for 1-kg balloon to satisfy the vertical speed and heat transfer option design points at different altitude during day time.

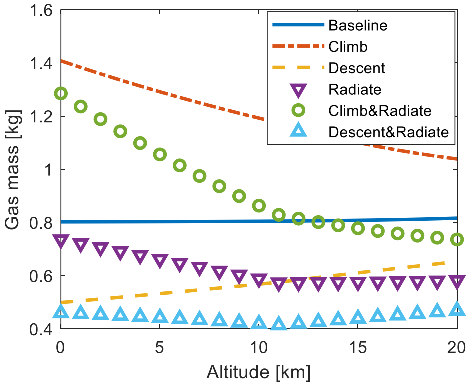

Figure 8. Helium mass required for 1-kg balloon to satisfy the vertical speed and heat transfer option design points at different altitude during day time.

Figure 7 and 8 present samples of required amount of radius and Helium mass for the selected 1-kg balloon to satisfy the vertical speed and heat transfer option design points at different altitude during day time. It can be seen that the change in radius and mass requirements are mainly due to the vertical speed design point.

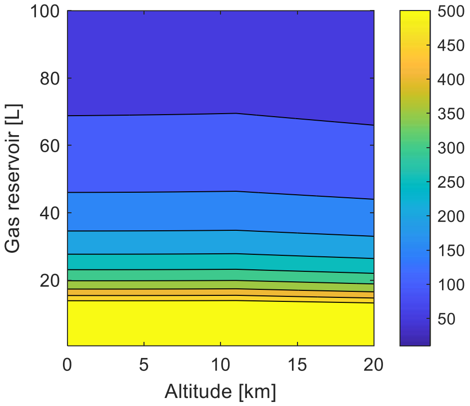

Figure 9. performance requirement of the Helium pump system for different gas reservoir and altitude.

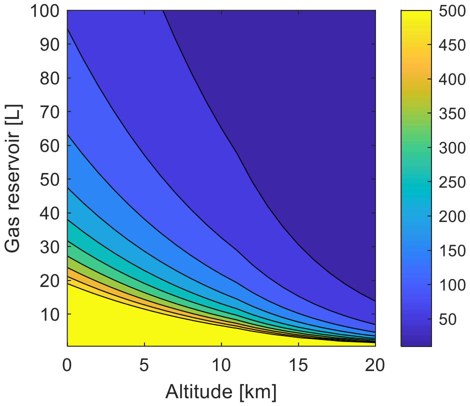

Figure 10. performance requirement of the air pump system for different gas reservoir and altitude.

Figure 9 present the performance (pressure [bar]) requirement of the Helium pump system for gas reservoirs of 1−100 liters and altitudes of 0−20 km. The requirement on Helium pump system for a given reservoir is observed to be the same for different altitude. Figure 10 present the performance (pressure [bar]) requirement of the air pump system for gas reservoirs of 1−100 liters and altitudes of 0−20 km. The results in Figure 9 and 10 show that the pump system of the two considered methods requires to generate a pressure difference of about 100 bars for a 100-liter reservoir. This requirement decreases as the reservoir capacity increases.

4. CONCLUSIONS

In this paper, the feasibility study of altitude control implementation for Helium-filled, spherical weather rubber balloons is presented. Two methods of changing balloon's buoyancy by storing enclosed Helium and changing balloon weight by storing surrounding air are considered in the development of altitude control for a balloon system. Design points of vertical speed (±5 m/s), weather tolerance (±5%), Operation altitude (0−20 km), and heat transfer options (including or excluding radiation in day or night time) are used to obtain the performance requirement of altitude control system (pump pressure and reservoir volume) using the balloon's quasi-steady flight analysis. The results can be used for the selection of pump, valve, and reservoir for an altitude control system. The feasibility of altitude control system with a large reservoir is observed. The performance requirement of altitude control system is mainly resulted from the operation requirement on vertical speed. The performance requirement of altitude control system can be greatly reduced with the relaxation of vertical speed requirements. For altering buoyancy method, the requirement of pump system is indifferent for all altitude. For altering weight method, the requirement of pump system decreases as altitude increases. Comparison between two altitude control method shows that the performance requirement of altering buoyancy method is lower at low altitude while that of altering weight method is lower at high altitude.

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