# Floating Performance Analysis and Extended Lifetime for High Altitude Zero Pressure Balloon

# Sherif Saleh

Abstract—This paper presented modeling and simulation for zero pressure balloon trajectories. The simulation was validated by real flight data. Most effective parameters on altitude stability at floating area were investigated. Variation in temperature was the responsible mainly for change in altitude levels. Cloud cover was taken into consideration to demonstrate its influences on climbing rate during ascending and on altitude stability during floating altitude. Initial lift gas quantity was estimated and optimized. The necessary amount of ballast drops was optimized. Results showed the best launching time to improve balloon performance in floating area. Also, cloud cover was very important in balloon simulation and revealed a serious effect on floating altitude more than climbing rate in the ascending process. New estimation for lift gas quantity was useful to keep climbing rate almost constant and reasonable maintaining ascending without ballast drops to support longer lifetime aloft. Another aspect to enhance longer lifetime at floating altitude was the ballast mass consuming per night. It was optimized to avoid losses in ballast masses.

*Index Terms*—High altitude balloons, ascending trajectory, lift gas, ballast mass.

#### I. INTRODUCTION

Scientific balloons are widely used in different applications that stimulate applicants to explore the innovations in this field. Zero pressure balloons are kind of the scientific balloons that carry different payloads to high altitudes according to application purposes. The major disadvantages in zero pressure balloons are the short lifetime and the altitude instability during day and night times at floating area. Discovering influences on balloon trajectory lead to predicting a successful real flight, and save efforts and time. Furthermore, reduces the failure reasons and costs of balloon design as [[1]]. Indeed, variation in temperatures and heat transfer influence directly on climbing rate during the ascending process and altitude stability during floating area. Both results lead to the balloon unbalance and the necessity to find solutions; such as overthrowing ballast masses in the case of reduction of the climbing rate during ascending or floating altitude lower level. On another hand, initial lift gas inflation affects mainly on climbing rate during the ascending process.

Reference [1] introduced the influence of gas inflation on ascending zero pressure balloon trajectories. Reference [2] investigated the basic concepts and background of zero pressure balloons such as geometry, shape and balloon design parameters as the differential pressure at the base of the

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S. Saleh is with the School of Astronautics, Beihang University, 37 Xueyuan Road, Beijing 100191, China (e-mail: shmtcg40@hotmail.com).

balloon, payload, and buoyancy at the float. Reference [3] implemented a new tool analysis code to describe the successfully flight trajectory prediction with an error less than 1% and mean error rate of climb less than 0.5 m/sec. Reference [4] discovered the influence of convection factor around balloon during ascending as a thermal load. Reference [5] investigated the thermal and dynamical numerical model for zero pressure balloons during ascending and floating compared to experimental data. The accurate simulation was one of the objectives of this work. Reference [6] developed the analytical thermal model to describe the gas and film temperature and heat transfer. Thermal equilibrium equations were demonstrated. The results of new model and flight testing data were compared. Reference [7] referred to absorptivity to emissivity ratio was very important to show the influence of heat transfer during day and night on the altitude stability. Reference [8] established the thermal analysis for flying bodies owing to its significant effect. Reference [9] presented the numerical and dynamical models describing the thermodynamic characteristics for high altitude balloons. Inflation quantity was considered a significant factor that affected on balloon ascending speed and differential pressure. Reference [10] optimized the ascending parameters to get the best flight trajectory with minimal error and achieve the balloon reaching successfully its target area. Also, Reference [11] interested in minimizing the errors in trajectory simulation to get an accurate simulation. Reference [12] aimed to decrease or eliminate the effect of ballasting in zero pressure balloons to prolong the floating time endurance. Also, it showed that undetermined amount of ballast release per night was considered one of the significant problems in floating altitude.

It has been concluded that researchers seek to obtain an accurately simulated trajectory close to real flight, as [13]. There are parameters that affect directly on thermal and heat transfer such as cloud cover in [14]. Consequently, the climbing rate is changed during ascending or altitude level at floating area. So, obtaining stable reasonable climbing rate during the ascending process and prolong the lifetime of the balloon at floating area are significant goals. These attempts are performed to develop zero pressure balloon performance practically.

This paper concerns on four aspects: 1) it investigates the influence of the cloud cover on altitude stability at floating area in different times within day and year. 2) It explains the discrepancy in altitude stability at floating altitude due to variation in temperatures and observes the most useful launching time. 3) It contributes a method to estimate the initial lift gas inflation so that ensure balloon ascending in reasonable climbing rate and time without ballast masses dropping to maintain the expected lifetime in floating area. 4)

It optimizes and predicts the accurate necessary amount of ballast masses release per night to save unneeded masses for extra days.

Finally, this work aims to improve the performance of high altitude zero pressure balloons to prolong lifetime aloft supporting future applications. Also, keeps precise simulation of the balloon in ascending process with reasonable climbing rate and time avoiding obstacles in this region. Besides, it shows the importance of controlling ballast mass release accurately avoiding constant ratio of ballast mass consuming, [15] to save mass losses.

# II. ENVIRONMENT DESCRIPTION

# A. Atmospheric Model

Atmospheric model is categorized by three parameters; pressure, temperature, and density. These parameters are calculated from sea level to 32 Km altitude according to [16] as follows:

$$T_{air} = \begin{cases} 288.15 - 0.0065.z & 0 < z \le 11000 \text{ m} \\ 216.65 & 11000 \text{ m} < z \le 20000 \text{ m} \\ 216.65 + 0.0010.(z - 20000) & 20000 \text{ m} < z \le 32000 \text{ m} \end{cases}$$
(1)

$$P_{air} = \begin{cases} 101325.((288.15-0.0065z)/288.15) & 0 < z \le 11000 \text{ m} \\ (-(z-11000)/6341.62) & 11000 \text{ m} < z \le 20000 \text{ m}. \end{cases}$$
(2)  
$$\frac{22632e}{5474.87((216.65+0.0010(z-20000))/216.65)} & 20000 \text{ m} < z \le 32000 \text{ m}. \end{cases}$$

Also, air density at different altitude can be calculated from ideal gas low,

$$\rho_{air} = \frac{P_{air}}{R_{air}T_{air}}.$$
(3)

where  $P_{air}$  is the atmospheric pressure,  $R_{air}$  is the specific gas constant of air and  $T_{air}$  is the air temperature and Z is the balloon altitude.

#### B. Solar Elevation Angle Model

Elevation angle of sun radiation represents the angular height of the sun and the horizontal as shown in Fig. 1. This angle changes during daytime dependent on latitude and the arrangement of this day in the year, [[17]].



Fig. 1. Elevation angle of sun radiation.

Sun elevation angle  $\alpha_{ELV}$  can be found using the following formula:

$$\alpha_{ELV} = \sin^{-1} [\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos(HRA)].$$
(4)

where; HRA is the hour angle,  $\varphi$  is the location latitude, and  $\delta$  is the declination angle, which depends on the day of the year.

$$\delta = \sin^{-1} [\sin 23.45^{\circ} \sin \frac{360(day - 81)}{365}].$$
 (5)

Day is the day number of the year (example Jan  $1^{st}$  is day=1).

$$HRA = 15^{O} (LST - 12).$$
 (6)

LST is the local solar time [hour]

# C. Cloud Cover Model

Cloud cover is an obstacle to quite heat transfer from direct solar radiation and reflected radiations on lift gas and balloon skin. Cloud cover influences on solar model formulation according to a thickness of cloud in altitude; it is selected about 0.15 to 1, [18].

 The influence of cloud cover on the intensity of direct solar radiation is

$$q_{sun} = \begin{cases} I_{sun, z} (1 - CF) & altitude \le 11000m \\ I_{sun, z} & altitude > 11000m \end{cases}$$
(7)

 $q_{sun}$  is the intensity of sun radiation,  $I_{sun,z}$  is the product of the intensity of sun radiation at this altitude  $I_{sun}$  and  $\tau_{atm}$  atmospheric transmittance. CF is the cloud factor.

2) The influence of cloud cover on the intensity of reflected radiation is

$$Albedo = \begin{cases} Albedo ground (1 - CF) & alitude \le 11000m \\ Albedo ground (1 - CF)^2 + (Albedo cloud CF) & alitude > 11000m \end{cases}$$
(8)

*Albedo*<sub>ground</sub> and *Albedo*<sub>cloud</sub> are the radiation reflection factor for earth ground and cloud, respectively; as in [19].

# III. GOVERNING EQUATIONS OF BALLOON ASCENDING

There are five differential equations that derive high altitude zero pressure balloons in the ascending and floating processes; change in heat transfer of lift gas and balloon skin, change in lift gas mass, change in altitude, and change in climbing rate. In addition to the equation of balloon volume is addressed.

#### A. Balloon Geometry

The balloon shape is assumed to be spherical; zero pressure balloons consider  $P_{gas} = P_{air}$ , so, balloon volume is expressed as,  $[m^3]$ 

$$V = \frac{M_{gas} R_{gas} T_{gas}}{P_{air}} \tag{9}$$

where  $M_{gas}$ ,  $R_{gas}$ ,  $T_{gas}$  and  $P_{gas}$  are the mass, specific gas constant, the temperature in K and pressure of the lift gas, respectively.

Balloon diameter, [m]:

$$D = 1.24V^{\frac{1}{3}}$$
(10)

Surface area of balloon,  $[m^2]$ :

$$A_{eff} = \pi D^2 = 4.83 V^{\frac{2}{3}}$$
(11)

Top projected area,  $[m^2]$ :

$$A_{top} = \frac{\pi}{4} D^2 = 1.21 V^{\frac{2}{3}}$$
(12)

#### B. Thermal Models

Thermal models of stratospheric balloons should express on two systems; balloon film and inner lift gas temperatures. Heat is transferred throughout three media; air, balloon film, and inner lift gas as shown in Fig. 2. Firstly, heat transfer from and to balloon film skins is presented. Then, heat transfer of inner lift gas is demonstrated which represent an effective part in balloon thermal model.



Fig. 2. Heat transfer sources for High altitude balloon

#### 1) Heat transfer on balloon film skins

There are several factors that determine balloon skin temperature. These factors are external and internal convection between air, outer and inner balloon skin, direct and reflected sun radiation, IR radiation, and heat emissivity to the surrounding air, as in [18], [19], and [20]. Film temperature skin differential equation is

$$C_{film}M_{film}\frac{dT_{film}}{dt} = Q_{film}$$
(13)

Here,  $C_{film}$  is the specific heat of film material,  $M_{film}$  is the mass of film material,  $T_{film}$  is the film temperature in [K], and  $Q_{film}$  is the heat transfer into balloon film.

# 2) Heat transfer on lift gas

There are several factors that determine lift gas temperature. These factors are internal convection, direct and reflected sun radiation, IR radiation, and heat emissivity to the inner balloon film, [19]. Lift gas temperature differential equation is

$$\frac{dT_{gas}}{dt} = \frac{1}{\gamma C_V M_{gas}} \left( \mathcal{Q}_{gas} - \frac{g M_{gas} R_{gas} T_{gas} V_Z}{R_{air} T_{air}} \right)$$
(14)

 $\gamma$  is the heat capacity ratio  $\left[\gamma = \frac{C_P}{C_V}\right]$ ,  $C_P$  and  $C_V$  are

the specific heat of lift gas at constant pressure and volume, respectively,  $Q_{gas}$  is the inner lift gas heat transfer, g is the gravitational acceleration and  $V_z$  is the relative vertical velocity.

#### C. Lift Gas Mass Differential Equation

At float altitude, maximum balloon volume accessibility is achieved. Balloon continues ascending by its momentum and inertia, hence; pressure inside balloon grows strongly. Consequently, gas should leaks gradually from ducts to prevent balloon explosion causing a reduction in lift gas mass. Therefore, the change of lift gas mass in time is calculated dependent on volume change in time over maximum volume and lift gas density. Lift gas mass differential equation is

$$\frac{dM_{gas}}{dt} = -\rho_{gas} \Delta \dot{V}$$
(15)

 $\Delta \dot{V}$  is a volumetric change in time,  $\Delta \dot{V} = \frac{V_{altitude} - V_{max}}{\Delta t}$ 

After a reduction in lift gas mass, balloon descends again under its float altitude by inertia, then ascends again and repeat this cycle many times. Lift gas mass leakage is a method to control balloon ascending and descending during the day. Besides, there is another method at night; that is dropping dummy masses in zero pressure balloon system (ballast masses release).

#### D. Dynamic Model

The dynamic model represents the forces that help balloon to ascend and forces that resist it. So, buoyant force, balloon gross weight, and drag forces should be introduced. Buoyant force is the force that responsible on balloon lifting overcoming gravitational force due to gross weight. This force comes mainly from lift gas inflation inside the balloon which gas density lighter than air density. Once this force exceeds the gross weight; ascending occurs and difference is called the free lift. The drag force is the aerodynamic force that resists the balloon ascending dependent on balloon shape, volume, velocity, and drag coefficient.

Firstly, free lift depends on gross inflation that able to carry balloon system into atmospheric layers.

Gross inflation is  $GI = gV(\rho_{air} - \rho_{gas})$ ,  $\rho_{gas}$  is calculated from lift gas mass and balloon volume. The free lift force is  $F_{freelift} = gV(\rho_{air} - \rho_{gas}) - gM_{gross}$ . Then, the drag force is  $F_{drag} = \frac{1}{2}C_d\rho_{air}A_{top}V_Z^2$ ,  $C_d$  is the drag coefficient.

Equation of motion is represented by [20] as follow

$$M_{virtual} \frac{dV_Z}{dt} = F_{freelift} - F_{drag}$$
(16)

 $M_{gross}$  is the gross mass (payload+film+ballast),  $M_{virtual}$  is total balloon mass that is balloon gross mass and lift gas mass, in addition to air virtual mass that represents load above the balloon head.

 $M_{virtual} = M_{gross} + M_{gas} + C_{virtual}\rho_{air}V$ .  $C_{virtual}$  is the

virtual mass coefficient,  $C_{virtual} \approx 0.5$  [18],  $C_d$  is f (Re), [[19]].

#### E. Altitude Differential Equation

Differential equation of altitude depends on relative vertical velocity as follows

$$\frac{dZ}{dt} = V_Z \tag{17}$$

#### IV. MODELING AND SIMULATION

### A. Matlab M-File

Simulation of zero pressure balloon is established on MATLAB M-file. This code consists of the main program of initial conditions lift gas mass, lift gas temperature, balloon film temperature, altitude, and velocity; and numerical fourth orders Runge-Kutta (ode45) solver for thermal and dynamic differential equations. In addition, the subroutine of thermodynamic non-linear ordinary differential equations as described in section III. This code predicts new parameters of trajectory every second. Also, simulate balloon through ascending and floating area with cloud cover effect, and ballast drop every night to compensate altitude at night.

# B. Genetic Algorithm

The genetic algorithm (GA) toolbox is applied twice in this work as additional subroutines. Firstly, it is used to optimize and predict the initial lift gas quantity at launching during sunset to ensure approximately constant climbing rate without ballast drops. Secondly, it seeks about an accurate amount of ballast release every night without wasting that prolongs lifetime endurance for balloon system.

GA is a global search technique. It strikes a reasonable balance between exploiting the available information and searching through unexplored regions. It depends on the performance of a population of recommended solution. The population is created from the variable that will be optimized. Genetic Algorithm operation close to the laws of nature uses a population of potential solutions represented by a string of binary digits, called chromosomes or individuals, which is submitted to many transformations, called genetic operations such as selection, crossover, and mutation. The population is going to evolve during the generations according to the fitness value of the individuals; then, when a stationary state is reached, the population has converged to the solution of the given optimization problem.

The basic structure of a GA consists mainly of the following steps:

1) Random initialization of a population of individuals.

- 2) Evaluation of the individuals (variables).
- 3) Application of genetic operators (selection, crossover, and mutation) to the population and return to step (2) until the best individual is reached.
- The first subroutine to predict initial lift gas quantity consists of objective function, variable, and constraints as follows:

function

is 
$$f_{\min}(x) = \frac{\left(\rho_{air}V - x(1) - M_{gross}\right)g - \frac{1}{2}\rho_{air}C_dA_{Top}V_Z^2}{M_{virtual}}$$
 Variabl

e is  $x(1) = M_{gas}$  The constraint is positive free lift all the time and velocity is constant to find almost minimum acceleration. Volume depends on lift gas mass. In this case, ascending velocity is selected to be 5 m/s.

• The second subroutine to predict ballast mass release every night consists of objective function, variable, and constraints as follows

Objective function is

Objective

$$M_{ballast} = M_{ballast} - x(1),$$

$$M_{gross} = M_{ballast} + M_{payload} + M_{film}$$

$$f_{min}(x) = \frac{\left(\rho_{air}V - M_{gas} - M_{gross}\right)g - \frac{1}{2}\rho_{air}C_dA_{Top}V_Z^2}{M_{virtual}}$$

Variable is Variable is x(1) = ballast drop where,  $M_{ballast}$  is the remained ballast mass,  $M_{payload}$  is the payload mass, and  $M_{film}$  is the balloon film mass.

The constraint is positive free lift and positive ballast mass drop quantity so that keep acceleration is zero or a little bit higher as minimum as possible at night and initiation of this loop at negative velocity occurring.



V. RESULTS AND ANALYSIS

#### A. Model Validation

Thermtraj NASA model and real flight 167N data were adopted to validate this code, [21]. These models represented high altitude zero pressure balloon with design volume of 66375  $m^3$  to float at an altitude of 36.7 Km carrying a payload of 196.82Kg. Balloon gross mass was 381 Kg and initial lift gas mass was 69.221Kg. It was launched at local time 11:35 Am from Palestine, Texas on July 24, 1980. This

code represents the complete flight simulation with ballast dropping stages and predicts balloon trajectory for several days and nights until descending at no ballast masses. The code has the ability to add several subroutines to precise simulation.



Fig. 3 and Fig. 4 represent balloon trajectory in the ascending phase and whole flight throughout the first day and night, respectively. Real flight, ThermTraj, and present models are almost closed with each other. The reason for the discrepancy in some points belongs to change in ascending and descending velocity, which is influenced by several parameters such as initial lift gas mass, wind velocity prediction, location, time and atmospheric models are identical owing to ascending velocity tends to zero. Meanwhile, there is a significant observation below tropopause layer; three models also are almost identical. This refers to few numbers of uncertainties below tropopause layer.

# B. Heat Energy and Cloud Effects on Altitude Stability

Variation in temperatures within day/night or summer/winter influence on altitude stability in floating altitude area. The main reason in the differential temperature belongs to the sun radiation, also belong to the amount of heat that reaches to balloon film and lift gas. Clouds are very important factor in the gained amount of heat. It obscures the direct or reflected sun radiation according to a thickness of clouds attenuating their effects. So, the following results demonstrate the importance to take cloud factor into consideration. Furthermore, the effect of launching time on altitude stability at floating area.





Fig. 5. Temperature variation in summer during sunrise (a) cloud, (b) clear cloud.

Fig. 5(a, b) and Fig. 7 (a, b) show the effect of cloud cover on the temperature variation in the summer at launching time 11:35 Am (sunrise) and 8:00 Pm (sunset), respectively. It is observed that the cloud cover obscures heat radiation during sun appearance diminishing lift gas and balloon film temperatures. Also, reveals an insignificant effect at sunset launching time due to sun disappearance. Solar radiation is considered the main source of heating. Fig. 5(a, b) and Fig. 7explain the effect of cloud cover on altitude stability. Cloud cover causes a difference in altitude mainly at floating area through the launching during sunrise. Also, no serious effect is observed on altitude stability through launching during sunset owing to sun disappearance. Similarly, the same effect in winter is deduced but at lower temperatures degree. So, the cloud factor is an important parameter to get more accurate simulation.







Fig. 7. Temperature variation in summer during sunset (a) cloud, (b) clear cloud



Fig. 8. Balloon floating altitude stability in summer during sunset.

2) Season temperatures effect on floating altitude stability



x 10<sup>4</sup>



Time Fig. 10. Balloon floating altitude stability during sunrise launching time.

Fig. 9 (a, b) shows the variation in temperatures between the summer and winter months at the launching time of (11:35 Am). Fig. 10 shows the difference in altitude stability due to variation in temperature that is higher in the summer. From the conclusion in Fig. 10, it had been generated an idea of the influence of launching time on altitude stability at floating area. While the balloon ascends at sunset, the differential in temperature decreases achieving more altitude stability at floating area. In the following section, this idea has been represented.

# 3) Launching time effect on floating altitude stability



January.

Fig. 11 (a, b) shows the variation in temperature between the summer and winter months at the launching time of (8:00 Pm) noting that at sunset launching time lifting gas and balloon film temperatures are lower than atmospheric temperature until sunrise because of sun disappearance. At sunrise, lift gas and balloon film temperatures absorb heat from surrounding to increase resulting in a small change in the altitude as shown in Fig. 12. So, it has been concluded that the launching time at sunset is better than at sunrise owing to a low differential temperature at floating area. But sunset time has a negative effect on climbing rate during balloon ascends; so, in the next section, an estimation and optimization for initial lift gas mass are presented to ensure climbing rate at a reasonable value during ascending.



Fig. 12. Balloon floating altitude stability during sunset launching time.

#### C. Initial Lift Gas Inflation Effect

Genetic Algorithm is used to optimize and estimate the best initial lift gas quantity during launching time at the sunset about 8:00 Pm, so that ensures no descending, ascending along total excursion without any ballast drop and achieve a reasonable ascending time. Ascending without ballast drops supports long endurance time in the floating altitude.



lift gas quantity.

Fig. 13 establishes the balloon trajectory at optimized initial lift gas mass that keeps velocity is almost constant (selected 5 m/s). A new estimation of lift gas mass starts climbing rate more stable and keeps climbing rate variation not exceed 1 m/s. In contrast, the original value of lift gas mass causes marked decrease in climbing rate during sunset ascending. Decreasing in climbing rate during ascending is critical because it may lead to balloon descending or need to release ballast masses to keep ascending process resulting in a shortage of floating lifetime.

# D. Ballast Release Control

This section concerns on the optimization and accurate prediction of ballast masses release at floating altitude to diminish the loss in ballast masses per night supporting longer floating lifetime.



Fig. 14. Variation in climbing rate due to ballast mass release.



Fig. 15. Variation in altitude due to ballast mass release.

Fig. 14 shows the difference between the random ballast dropping and optimum prediction for ballast release. Optimum ballast mass dropping causes a smooth variation in climbing rate and avoids the loss in ballast mass which enables altitude compensation for extra days. Fig. 15 shows the variation in altitude corresponding to optimum and random ballast masses release. Low random ballast mass release leads to a little bit decreasing in climbing rate, high random ballast drop leads to a loss in ballast masses. Optimum ballast mass has been selected to keep acceleration a little bit higher than zero to ensure ascending process. In addition, it saves the ballast mass losses about 2% per night to extend the lifetime of floating balloon.

# VI. CONCLUSIONS

This paper simulates thermal and dynamic balloon integrated system in high altitudes. Nonlinear ordinary differential equations of ascending zero pressure balloons are described. It aims to improve the balloon performance in ascending and floating areas for a longer lifetime. This work has been summarized in the following steps:

- Precise modeling and simulation for high altitude zero pressure balloons.
- 2) Studying the effective parameters on altitude stability in high altitudes such as cloud cover and launching time.
- 3) Investigating the significant influence of differential temperature on balloon performance.
- Optimization and prediction for the lift gas quantity that keeps climbing rate almost constant and support balloon ascending without ballast drops in the desirable time.
- 5) Optimization the ballast amount release per night to save these masses for extra days enhancing longer lifetime.

Lastly, control an accurate ballast mass dropping allows to prolong endurance floating time, as well as starting launching time at sunset that causes more altitude stability in floating area avoiding descending or ballast drops in the first night to compensate altitude level due to high differential temperature.

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**S. Saleh** was born in Egypt in 1980. He received his bachelor in mechanical engineering at Military Technical College, Cairo, Egypt, 2003.

He received her master of science in mechanical engineering at Military Technical College, Cairo, Egypt, 2010.

He works as a researcher and a assistant lecturer, Egypt.

Currently, he is a Ph.D. a researcher in Beihang University, Beijing, China. His research interest is in design of flight vehicles.