High Altitude Ballooning: A Comprehensive Review

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ABSTRACT
This will be re-written after the paper is completed

1 INTRODUCTION

With the recent interest in high altitude ballooning from universities, companies, and amateur scientists, many are seeking for more information on the science behind high altitude ballooning. This paper reviews some of the science, equipment and calculations behind a successful launch and features a few interesting student projects.

2 BALLOON LIFT

2.1 Net Lift

A free-floating balloon is acted upon by two major forces along the z-axis. The positive buoyant force, F_B, and the gravitational force, F_g. These forces can be combined to find the net lift force of the balloon:

$$\Sigma F = F_B - F_g \qquad (1)$$

The buoyant force, F_B, can be calculated by using the Archimedes Equation:

$$F_B = \rho V g \qquad (2)$$

where ρ is the density of the displaced fluid in kg/m^3 (in our case, air), V is the volume of the balloon in m^3, and g is the acceleration due to gravity in m/s^2. Kilograms is used for F_B instead of newtons , as it is more convenient for our application.

The density and pressure of the atmosphere changes with altitude, causing the buoyant force to change throughout the flight. The data for density and pressure is available in the 1976 US Standard Atmosphere for up to 86 kilometers. The volume of the gas at in the balloon at STP can be measured with a flowmeter attached to the gas source. Additional factors effect the buoyant force, and will be covered in section 1.2.

The gravitational force, F_g, is the mass of the entire balloon, including the payloads, the balloon itself, and the gas inside the balloon:

$$F_g = m_b - m_p - (\frac{n * M}{1000}) \qquad (3)$$

where m_b is the mass of the balloon, m_p is the mass of

the payload, n is the moles of gas in the balloon, and M is the mass of the gas in grams.

When both of these forces are combined into equation 1, we end up with the net lift, or ΣF.

2.2 Change In Lift With Altitude

During several experimental deployments, it was observed that the latex balloon was able to reach a state of neutral buoyancy without any manual modifications to the balloon during its flight. This suggests that the lift force of the balloon changes throughout the flight with altitude. Of the two forces that influence ΣF, only F_B can potentially change, assuming the mass stays constant

Two factors are involved with buoyancy: The volume of the gas and the density of the air. The density of the air changes throughout the flight due to change in altitude. The volume of the gas also changes throughout the flight, and this can be modeled with the ideal gas law.

$$Pv = nRt \qquad (4)$$

However, assuming that the pressure inside the balloon is the same as the pressure outside the balloon (the balloon expands to match the pressure), the volume of the balloon changes proportionally to the density of the atmosphere, resulting in no change in lift. This is contradictory to our observations; therefore, there has to be another factor that effects the volume. This is the back pressure of the elastic latex on the gas inside.

Various models exist for sphere rubber shells (also known as rubber balloons), including the Gent model and the Mooney-Rivlin model. This paper will be focusing on the Mooney-Rivlin model to keep the paper concise.

The modified Mooney-Rivlin model for an incompressible spherical rubber shell is as such:

$$\Delta P = 2\mu \frac{t_0}{r_0}((\frac{t_0}{r_0}) - (\frac{t_0}{r_0})^7)(1 + \frac{1 - \alpha}{\alpha}(\frac{t_0}{r_0})^2) \qquad (5)$$

Where μ is the shear modulus, α is a constant, r_0 is the unstretched radius of the balloon, r is the inflated radius of the balloon, and t_0 is the thickness of the balloon. Setting α as 1 results in the neo-Hookean model. While this is useful for small stretches, it does not accurately describe experimental data at high values of strain "Kanner". Mller

suggests values of $\frac{10}{11}$ for α and $300kPa$ for μ to accurately model the radius of the rubber balloon.

This equation can be adapted for the lift equation "lift equation reference" by solving for r, which can then be intrepreted for the volume of a sphere.

2.3   Neutral Buoyancy

Achieving neutral buoyancy is the foundation of achieving long-distance balloon flight. When a balloon is neutrally buoyant, it is able maintain suspension in the atmosphere and thus be exposed to high-altitude wind currents for a larger duration. Most trans-continental and trans-oceanic flights attain near-neutral buoyancy and maintain it for long periods of time, allowing them to travel long distances for extended periods of time.

Neutral buoyancy is achieved when the forces on the balloon along the z-axis reach a point of equalibrium so that:

$$\Sigma F = 0 = F_B - F_g \tag{6}$$

Which can be manipulated to show equivalence between buoyant force and gravity:

$$F_B = F_g \tag{7}$$

In practice, this is acheived by filling the balloon with an excess of gas that creates a small net initial upwards force (in excess of gravity) that diminishes over the course of the flight (see Section 2.2).

Initial net upwards lift is critical to the balloon's buoyancy at a target altitude. Adding too much gas at the launch point will cause the balloon to burst before it can become neutrally buoyant. A shortage of initial gas will cause the force of gravity to exceed the buoyant force at the target altitude and cause the balloon to sink.

There is no "magic amount" of extra lift that guarantees neutral buoyancy. The amount of extra lift required is dependent on the size of the balloon, atmospheric conditions, the type of lift gas used, and the mass of the payload.

Our team launched a neutrally-buoyant balloon from Mesquite, Arizona, USA, on August 4, 2013 at 16:29 UTC. Its ascent path is plotted below:
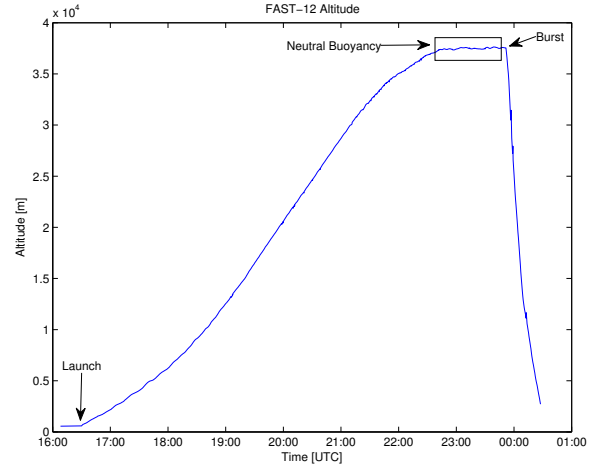
REFERENCES

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Figure 1. Altitude of neutrally-buoyant balloon vs. time