Laboratory

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Aerostatics
Observations of Archimedes Principle

Introduction

In this laboratory, we will explore the nature of lighter-than-air flight by measuring the lifting capacity of several large helium balloons. The data and knowledge gained in this experiment will be used to answer design-oriented questions regarding aerostatics.

Balloon Flight

The first manned flight in history was accomplished with the use of a hot-air balloon on November 21, 1783. Frenchmen Jean-François Pilâtre de Rozier and François Laurent, Marquis d'Arlandes ascended over Paris in a 100-foot diameter balloon built by Joseph and Étienne Montgolfier. Their flight lasted approximately 23 minutes, covered 5.5 miles, and required them to burn wool and straw to keep the balloon's air temperature high enough for lift.

Early experiments with hydrogen and hydrogen-filled balloons were conducted by such notable scientists as Cavendish, Black, and Cavello. Physicist Henry Cavendish (1731-1810) determined that hydrogen was seven times lighter than air and that it would be useful for designing lighter-than-air flight vehicles. Then in December of 1783, J. A. C. Charles and Nicolas-Louis Robert of France were carried aloft and traveled 27 miles in a hydrogen-filled balloon.

Archimedes Principle

Aerostatics involves vehicle flight that is not dependent upon relative motion of the air. By contrast, aerodynamics involves the motion of air over a surface, which generates a lifting force. In aerostatic flight, a buoyancy phenomenon is responsible for generating a lift for such vehicles as weather balloons, blimps, and dirigibles. The Greek mathematician, physicist, and inventor Archimedes was the first to observe the behavior of buoyant objects and is credited with describing the fundamental principle of buoyancy:

> *"A body immersed in a fluid will be buoyed up by a force equal to the weight of the fluid that the body displaces."*

When this concept is applied to a balloon, we consider the displacement of the total volume occupied by the enclosed gas and the balloon membrane. This total volume is known as the balloon's envelope.

Derivation of the Buoyant Force

Mathematically, the buoyant force (F_B) represents the gross lift on the system, or the total positive contribution to the vertical force. It is expressed in units of pounds and can be represented by the equation:

$$F_B = \rho_{ext} \cdot g \cdot \mathcal{V} = L_{gross} \tag{2.1}$$

In this equation, the displaced (external) fluid density is expressed as ρ_{ext} (in units of slugs/ft³), the gravitational acceleration is expressed as g (in units of ft/sec²), and the enclosed volume of the envelope is expressed as $\mathcal{V}$ (in units of ft³). The product $\rho_{ext} \cdot g$ is often called the weight density of the fluid because is it expressed in units of lbs/ft³. L represents the lift in units of lbs.

To determine the *net lift* of the system, we must add the negative contribution to the vertical force to the gross lift. This contribution involves the weights of the following balloon components: the weight of the gas

in the envelope (W_{gas}), the weight of the envelope material (W_{env}), and the weight of the payload (W_{pay}), all in units of lbs. Thus:

$$L_{net} = L_{gross} - W_{total} = F_B - \left(W_{gas} + W_{env} + W_{pay}\right) \tag{2.2}$$

When the balloon is in a steady state, it is not accelerating in any direction. Thus, it is neither ascending nor descending and the total system is in equilibrium. In this case, the net lift equals zero and thus equation (2.2) becomes:

$$F_B = \left(W_{gas} + W_{env} + W_{pay}\right) \tag{2.3}$$

However, we know that the weight of the gas in the envelope is a function of its density (i.e., the internal gas density, expressed as ρ_{int}) and the volume of the envelope. Thus:

$$W_{gas} = \rho_{int} \cdot g \cdot \mathcal{V} \tag{2.4}$$

Substituting equations (2.1) and (2.4) into equation (2.3) and rearranging a bit yields the following equation:

$$g\left(\rho_{ext} - \rho_{int}\right)\mathcal{V} = W_{env} + W_{pay} \tag{2.5}$$

The left-hand side of this equation represents the theoretical force produced by displacing a volume of air with an equal volume of another gas (e.g. helium). This would be the envelope's overall ability to lift a vehicle.

The right-hand side represents the gross weight of our vehicle. This gross weight consists of the envelope material itself and the weight of the payload. For the helium balloon experiment, the payload weight will consist of the actual cargo weight (i.e. steel shot) and the weight of the support structure (i.e. cup, string, paper clips).

For this experiment, the internal fluid is gaseous helium. At standard temperature (59°F) and pressure (29.92″ Hg), the density of helium is 0.0003282 slugs/ft³. For non-standard days, use the equation of state with the proper value of the specific gas constant to determine the actual helium density:

$$\rho_{int} = \rho_{He} = \frac{p_{atm}}{R_{He} T_{room}} \tag{2.6}$$

Note that the pressure and temperature of the helium are assumed to be the ambient conditions.

Procedure

Follow these steps to inflate your balloon and determine its buoyancy:

1) Record the room temperature and the day's barometric pressure.
2) Inflate your balloon with helium and tie it off tightly (use a bowline or a slipknot). Keep a good grip on it, especially as it nears capacity. The buoyant force may exceed one pound.
3) Measure the circumference using a sewing tape. Make your measurements along three different orientations and average them, since the balloon won't be perfectly spherical.
4) Connect the payload cup with string and paper clips and fill it with steel shot until the total vehicle reaches a steady state. You will probably need to trim out your cargo with scraps of paper. Be careful of slight air currents in the room, as they may cause the balloon to gradually rise or fall.
5) Deflate the balloon and make a separate measurement of the mass of the deflated balloon membrane using an analytic balance. Now determine your total payload mass (shot + cup + string + paper clips).
6) Tabulate the circumference of your balloon and the measured weights on the chalkboard with the data from the other teams.

Data Reduction

Your data reduction should involve the following calculations for all the balloons used in your class section:

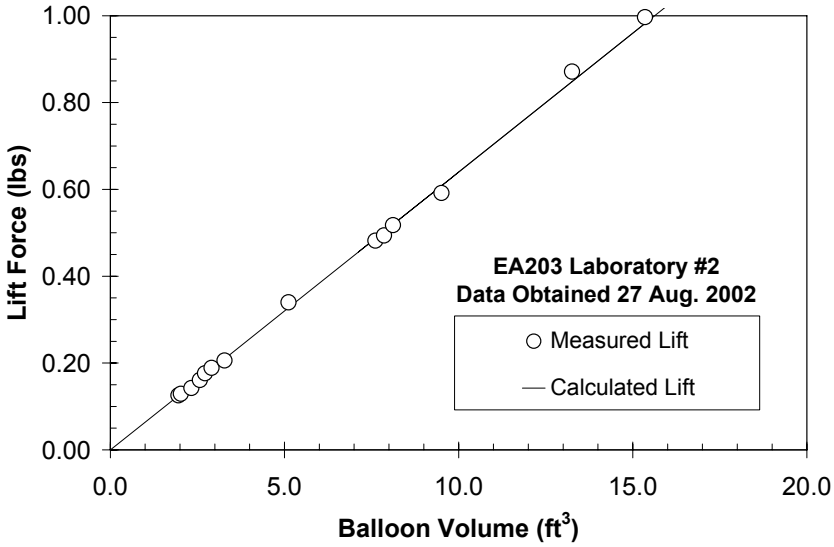
- Tabulate the volume of the balloon in cubic feet.
- Calculate the density of the air in the room and that of the contained helium.
- Calculate the theoretical lift in pounds, L_{theory}, based on the circumference. This comes from the value of the left-hand side of equation (2.5).
- Determine the total weight lifted in pounds, $\left(W_{env} + W_{pay}\right)$. This is the measured lift of the balloon.
- Using the appropriate graphical conventions for experimental and theoretical data, plot the calculated and measured lift against the balloon volume. NOTE: If you're using Microsoft Excel, you should NOT be using the trendline function! You will need to plot two separate data series on the same set of axes.
- Calculate and tabulate the percent error between the theoretical predictions and the actual weight lifted.

Creating a Data Table and Plot

Use the examples below to create your table of data and a plot. Clearly label all columns and axes and indicate the engineering units used.

• Table 1. Sample table: The lift of helium balloons

Experimental Measurements					Calculations	
C (in)	**Volume (ft^3)**	**W_{env} (lb)**	**W_{pay} (lb)**	**W_{total} (lb)**	**L_{theory} (lb)**	**% Error**
-	0	-	-	-	0.0000	-
66.75	2.91	0.1004	0.0886	0.1890	0.1859	1.65
69.50	3.28	0.0720	0.1340	0.2060	0.2099	1.84
80.60	5.12	0.0715	0.2684	0.3399	0.3273	3.84
92.00	7.61	0.1003	0.3815	0.4818	0.4868	1.03
93.00	7.86	0.0704	0.4234	0.4938	0.5028	1.80
94.00	8.12	0.0650	0.4528	0.5178	0.5192	0.28
99.10	9.51	0.0986	0.4930	0.5916	0.6084	2.76
110.70	13.26	0.1094	0.7618	0.8712	0.8481	2.73
116.25	15.35	0.1048	0.8918	0.9966	0.9821	1.48
-	20	-	-	-	1.2794	-



- Figure 1. Sample plot: Measured and calculated lift of helium balloons

Deliverables

Although the data were gathered in teams, each write-up must be done and submitted on an individual basis. You must hand in the following deliverables to complete this laboratory:

- A formal abstract for this experiment
- A plot and data table of the whole section's data (follow the technical graphics guidelines)
- Sample calculations for your balloon that are used to obtain your graphical results
- Answers to the following questions

Questions

1) If we cut the payload loose (cup, string, shot), but keep the envelope tied off, how high would your balloon rise (to the nearest 10 ft)? Assume constant balloon volume and standard atmospheric conditions, for both the air and the helium.

2) Based on Archimedes' Principle, will a balloon have a higher buoyant force in air or in water? What is the ratio of water/air buoyancy for a fixed volume?

3) A hot air balloon rises to a maximum altitude of 2,000 ft. If the entire vehicle weighs 550 lbs and the balloon volume is 33,510 ft^3, what must be the average air temperature inside the balloon? Assume standard atmospheric conditions.