Thermodynamics Design Laboratory Assignment: Atmospheric Satellites

ASEN 2002: Introduction to Thermodynamics and Aerodynamics
University of Colorado at Boulder

Assigned: Wednesday, Aug. 26th, 2020
Midpoint Status Quiz Due: 11:59PM Wednesday, Sept. 23rd, 2020
Presentation Due: 8:00AM MDT Wednesday Oct. 14th, 2020
NEW DUE DATE: Tuesday Oct. 20th, 2020

Figure 1: Redbull Stratos Balloon

(a) Felix Baumgartner prepares to jump

(b) Felix Baumgartner moments after jumping

1 Learning Goals

In this Design Lab, you have the opportunity to achieve the following learning goals:

1. Learn about the requirements and design assumptions for developing lighter-than-air vehicles and the approach using intensive/extensive properties.
2. Integrate your knowledge of the first law of thermodynamics in a practical design analysis. Include factors of safety, for example on material stresses, imposed by the characteristics of the design and the environment.
3. Learn about the utility of scale models and the insight provided in developing the final system design.
4. Incorporate models to establish design feasibility and credibility.
5. Use MATLAB for engineering calculations and plotting.
6. Learn trade studies and sensitivity analysis.
7. Learn research skills.
8. Further develop your teamwork and presentation skills.
9. Develop engineering reasoning and communication skills.

2 Background

2.1 Lighter Than Air Vehicles

There are only two practical methods of producing a buoyant aircraft. If the air inside a suitably large and lightweight envelope is heated to a high temperature, the gas expands and a sufficient amount of fluid (air can be considered a fluid) may be forced out of the interior so that its weight decreases and the total weight of the craft becomes less than the amount of fluid (or air) displaced. Hot air balloons were flown by the brothers Joseph and Etienne Montgolfier as early as the spring of 1783. While the materials and technology are very different, the principles used by the earliest eighteenth-century experimenters continue to carry modern sport balloons aloft.

The other means of achieving buoyant flight is to fill the envelope with a gas that is sufficiently lighter than air. The first hydrogen-filled balloon was designed and constructed by Jacques A.C. Charles and launched from the Champs de Mars in Paris on August 27, 1783. Jean Pierre Blanchard, a French aeronaut, made the first free flight with a gas balloon in the United States from Philadelphia in January 1793.

Today, research balloons capable of reaching high-altitudes ($>$ 30 km) for extended periods of time (weeks to months) are being deployed by NASA. These balloons carry research payloads that enable scientific measurements that are otherwise hindered on the ground by atmospheric effects. These balloons also serve to test spacecraft instrumentation prior to satellite deployment while mitigating the significant forces incurred during launch. Scientists use scientific data collected during balloon flights to help answer important questions about the universe, atmosphere, the Sun and the space environment. Questions such as “How did the universe, galaxies, stars, and planets form and evolve?” and “Are there Earth-like planets beyond our solar system?” are being answered by NASA with the help of experiments flown on scientific ballons. One such mission is slated for launch in 2023 which will carry a 8.4 foot telescope over 40 km to observe light wavelengths that aren’t visible on the ground. ASTHROS

In October 2012, the Red Bull Stratos project set new records by carrying Austrian skydiver Felix Baumgartner to an altitude of 37,640 m (123,491 ft) where he leapt into the record books, Red Bull Link. A less publicized feat by Google Exec, Alan Eustace, broke the record of highest free-fall again in October, 2014 setting the record at 135,890 feet, Eustace Link. The Eustace jump spawned a Netflix documentary “14 Minutes from Earth” which contains several appearances by CU Aerospace Alumni and Pressure Suit Assembly Lead, Jared Leidich.

Renewed interest in inflatable systems is occurring with the push towards space commercialization. NASA contests such as the 2017 exploration Habitat (X-Hab) Academic Innovation Challenge, X-Hab Link, and Bigelow Aerospace's space habitats, such as the BEAM deployed on the International Space Station, BEAM Link are current examples of recent developments in inflatable space systems. New endeavors involving commercial companies, such as Google, are exploring lighter-than-air vehicles for aerial wireless network connectivity in rural and remote areas. Google's Project Loon involves developing high-altitude balloons placed in the stratosphere at an altitude of about 20 mi (32 km) to carry the companies' electronics aloft, Loon Link. In 2021, Space Perspective, a Florida based company, plans to offer tickets priced at $125,000 each to board their high altitude balloon, Spaceship Neptune, and reach an altitude of 100,000 feet during a 6 hour flight. Space Perspective.

Figure 3: Google's Project Loon research balloon

3 Balloon Design: An Application of the Ideal Gas Law and First Law

There are two types of research balloons: zero-pressure balloons (Red Bull Stratos) and super-pressure balloons (Google's Project Loon). A more appropriate name would be zero-pressure gradient balloons and super-pressure gradient balloons but the word "gradient" is commonly dropped or implied. Research these balloon types and understand their differences as you will be reporting on those differences in your presentation. The most basic design question about high-altitude balloons is how to achieve and maintain a desired altitude for a given payload. This needs to take into account the following issues:

- The density, pressure and temperature conditions of the atmosphere.
- The Ideal Gas Law and Archimedes' Principle.
- Material properties and their design limits
- The mass budget of the balloon system and final volume.

In this lab activity, your group will make a first order approximation of the design of a high altitude zero-pressure balloon capable of achieving the requirements listed in section 3.4.1. Due to time and budget constraints you will make a few simplifications and assumptions detailed in section 3.4.2. To aid in the understanding of the governing principles a scale model balloon system will be analyzed with empirical data (see: section 3.1). The results from this scale model experiment will inform your team on the relevant design parameters and allow you to explore the principles of buoyancy and the ideal gas law. The scale model system will also help your group develop a model for the system using first principles and an understanding of thermodynamic systems. The main deliverable of this lab assignment is a group presentation that will allow you to: 1. demonstrate your understanding of the principles associated with high altitude balloon systems, 2. detail the design of such a system at a Preliminary Design level.

3.1 Scale Model Balloon System

Prior to developing a design for a high-altitude balloon system, your task is to review the scale model video of a zero-pressure balloon and develop a mechanical and thermal assessment of the system. Though not required, if you have access to similar materials you are encouraged to conduct the same type of experiment remotely. Again, it is not required to conduct your own experiment as the video and accompanying data is sufficient for the learning objectives. The following instructions were used to create the scale model video these instructions are also here to help those students that wish to recreate the scale module experiment.

3.1.1 Construct a helium balloon with payload.

Gather all balloon material and determine their masses. With the assistance of a lab technician, fill the balloon with helium gas. Attach a payload and achieve neutral buoyancy in the lab. Draw a free-body diagram of the system and perform a force analysis identifying all forces involved. Record local temperature and pressure from PILOT reading or NCAR website (http://www.eol.ucar.edu/cgi-bin/weather.cgi?site=fl).

3.1.2 Make your balloon "slightly" negatively buoyant

Add additional payload to your balloon to make it fall. Place the balloon system in front of a heater and hold it to allow sufficient time for energy to be transferred to the balloon. Release the balloon and record your observations. **Define your thermal system and describe thermodynamically the processes taking place during your observations that includes processes and energy conversions.**

3.1.3 Re-establish neutral buoyancy with your balloon

Record the mass of your payload (string, washers, etc. . .). Remove payload and estimate the balloon volume by making careful measurements of the balloon dimensions. Use a water tank to provide another means of estimating balloon volume. Determine the volume of the balloon by recording the volume of water displaced in a graduated tank after fully submerging the balloon in the water tank. **Contrast your tank results with your dimensional estimate for volume.**

3.1.4 Determine the mass of the gas

Using the neutrally buoyant force balance analysis, estimate the required mass of the gas. Contrast this estimate with estimating the mass of the gas using the measured volume and the Ideal Gas Equation. **Evaluate errors and discrepancy between the two estimates. What is the total mass budget and the fractional percent of each balloon system component to the total system mass?**

3.1.5 Consider Modifications

If you wanted to lift more payload, what design modifications would you make and what would be the impact? If you were to make your originally designed balloon neutrally buoyant in water, what would be the required mass of the payload?

3.2 Mid point status quiz

On 9/16/2020 a quiz will be posted to Canvas that will help gauge your progress and understanding of the principles of this design lab. The quiz is to be completed using any resources except for your peers. The quiz will ask questions using the concepts developed by the assessment of the scale model balloon system; therefore, it is highly encouraged that you clearly record your balloon system analysis and utilize MATLAB as a computational tool. The quiz will be centered on two real events (Lawnchair Larry and Balloon Boy) research in to these events is not required but left as an exercise to the interested students.

3.3 Final design quiz

On 10/14/2020 a quiz will be posted to Canvas that will help gauge your understanding of the entirety of the lab material. The quiz format will be the same as the mid point status quiz in terms of length and allowed resources. The quiz will ask questions related to any aspects of the balloon analysis and design so it is highly encouraged that you are familiar with your group's MATLAB code to the point that you can modify it enough to quickly solve related problems. Lawnchair Larry and Balloon Boy may appear in this quiz as well.

3.4 Design a High-Altitude Balloon

In your groups, perform a design analysis of a high-altitude balloon for carrying a payload. Your group will decide whether the payload is a research instrument or life forms.

3.4.1 Requirements

1. **Payload** The balloon shall be able to carry a payload of 500 kg.
2. **Altitude** The balloon shall reach an altitude of 25 km.
3. **Duration** The balloon shall stay at 25 km altitude $\pm$ 1 km for no less than one day.
4. **Safety Factor** The balloon material safety factor should be consistent with relevant missions of similar payload types. Your group will provide information validating your chosen safety factor.

3.4.2 Assumptions:

1. **Shape** Assume the shape of the balloon at target altitude is a sphere.
2. **Transients** Ignore transient effects during ascent.
3. **Stresses** Ignore stresses on the balloon material associated with attaching the payload or wind loading.
4. **Payload mass** Assume the payload mass includes the primary payload aspects, all payload support structure, and all systems necessary to attach the payload to the balloon.

3.5 Zero-Pressure Gradient Balloons – Design Expectations

Your primary analysis will involve designing a zero-pressure balloon to satisfy the client's design requirements. You should determine the following design aspects for the balloon:

- Select and support use of your internal gas – know its properties and characteristics given the expected environment
- Determine the volume of the balloon at the target altitude
- Research and describe balloon material properties
- Evaluate your full-scale balloon system's mass budget and compare to the scale-model mass budget. Display this information as a table.

3.5.1 FBD

Provide a free-body diagram and perform a force analysis of the balloon applying Archimedes Principle. Determine the lifting gas and its properties, balloon material and thickness, the final volume of the balloon, the necessary mass of your lifting gas. Provide material stress analysis to indicate possible balloon failure – i.e., plot factor of safety values of your material versus balloon volume.

4 Required Deliverables

4.1 Quizzes

You will complete two quizzes that demonstrate your findings and understanding from the scale model experiment described in section 3.1, the provided video recording and data, and questions related to the governing principles and design of the balloon system.

4.2 Group Presentations

Your group will prepare a 15-minute Preliminary Design Review (PDR) level presentation video reporting the results of your design investigation. Include in your presentation how the scale model results were used in developing your high-altitude balloon design. This report must present how each requirement is met by your design in a quantitative manner supported by analysis and research. The presentation must also provide rationale for your decisions. Each person in your group must speak during the presentation. If a video recording is not possible for your team, a paper report may be submitted with instructor's consent prior to 9/30/2020 at 11:59 PM.

5 Suggested Study Questions/Issues

The following statements are offered to help you clarify the issues involved in this assignment.

1. The scale model experiment of a zero-pressure balloon and accompanying mechanical and thermal analysis should provide some insight into the actual balloon system design. Consider the mass budget of the scale model and what implications it has on the full system.

2. Research zero-pressure balloons. Formulate a "homework problem" that computes the volume of the balloon at the required altitude – do this for a zero-pressure balloon. Discuss margins of safety before the balloon fails.

3. Write a MATLAB routine that calls the function that computes the pressure, density and temperature from the 1976 Standard Atmosphere Model. A description of this atmospheric model is given in Chapter 3 of Anderson, Introduction to Flight and code can be found on the Mathworks website: atmoscoesa.m.

4. Develop your analysis code to enable flexibility in your design parameters. That way, you can study how changes in design parameters affect the output design specifications.

6 Suggested Activities

You are free to organize your group as you wish, the following set of weekly objectives can be used to help guide your development. Every group may adapt their own variation of these suggestions. You are encouraged to attend each laboratory session either in-person or remotely. Your group may be expected to present weekly update briefings to the instructional team.

Week 1 – Aug 26

Read over the lab description and requirements. Begin to research zero-pressure gradient balloon systems. Review all posted material to prepare for meeting your group next week.

Week 2 – Sept 2

Organize your groups. Discuss how group coordination and communication will work. Exchange necessary contact information. Establish a schedule for required assignments. Brainstorm ideas. Draw pictures of the problem, to make sure you understand the parameters of the assignment. Review scale model video and begin to develop analysis based on provided data. Try to distill the problem into a few equations.

Week 3 – Sept 9

Review lab documents, formulate a "homework problem" for the design to compute final volume. Research needed information and begin to write the MATLAB code. *Should have completed basic neutral buoyancy relationship.*

Week 4 – Sept 16

Prepare for midpoint quiz and begin to develop a presentation outline. Continue working on your presentation and MATLAB code. Identify missing pieces that require further work. *Should have completed neutral buoyancy relationship with factor of safety and thickness determined.*

Week 5 – Sept 23

Submit quiz to Canvas. Continue working on your presentation. Begin analysis using solar radiation. Identify missing pieces that require further work. *Should have solar radiation analysis complete before next week.* Begin exploration of design methods to achieve requirements with solar radiation.

Week 6 – Sept 30

Continue working on your presentation. Identify missing pieces that require further work. *Should have a complete analysis formulated including solar radiation effects on the day/night altitude.* Finalize design method to achieve requirements with solar radiation effects.

Week 7 – Oct 7th

Finalize presentations and prepare to submit on due date. *Should have design and analysis mostly complete. Presentation should be nearly final.*

Week 8 - Oct 14th

Submit presentation recording to Canvas.