ASEN 2002 Design Laboratory Assignment 1: High-Altitude Scientific Balloons

Jeffrey Thayer

Department of Aerospace Engineering Sciences

University of Colorado at Boulder

1. Project Overview

1.1. Goal

To design and model a high-altitude zero-pressure balloon carrying a payload with minimal altitude variation caused by thermal heating and cooling.

1.2. Societal Context & Relevance

Many scientific experiments and measurements require the use of long endurance high-altitude balloon systems to ferry a payload to specific altitudes. Zero-pressure balloons will rise and fall with the heating and cooling of the inside gas, usually changing altitude cyclically with the day/night cycle. However, some measurements may require the balloon/payload to remain within a specified altitude range, and thus engineers must optimize a balloons design to stay within a close range of the target altitude.

1.3. Integration

Students in ASEN 2002: Introduction to Thermodynamics and Aerodynamics are assigned into teams of 5-7 students for a 5-week design lab. These students will implement the thermodynamic principles encountered in class lectures in their study of, analysis, modeling, and design of a zero-pressure high-altitude balloon. Students will have lab time as well as additional time outside of class/lab to meet and work on the lab.

1.4. Description

The objectives of this lab are to study scale-model balloons, understand their physics and to design a balloon proposal meeting with "customer" specified requirements in altitude, endurance, and payload capacity. Students are expected to learn the required fundamentals of thermodynamics including the First and ideal gas laws, and incorporate them into engineering analysis, modeling, and design work as a team.

1.5. Learning Activities and Tasks

Students will experiment with a scale model of a zero-pressure balloon to observe its underlying characteristics and become more familiar with its design aspects. After establishing the basics of zero-pressure balloon design, they are tasked with designing a payload-bearing balloon to fly at a specified attitude and endurance with a minimal amount of altitude variation caused by thermal heating and cooling. Their final design and model will need to be presented professionally within a final report and presentation.

2. Learning Objectives

2.1. Technical Objectives

2.1.1 Skills

- Construct balloon scale models
- MATLAB coding
- Mass and volume measurements
- Report writing
- Presentation preparation and delivery

2.1.2 Processes

- Balloon experimentation and data collection
- Data analysis and model validation
- Design trade-studies
- Sensitivity analysis
- Design optimization

2.1.3 Procedures

- Project planning/scheduling
- Problem breakdown
- Balloon-payload system construction
- Experimentation and data collection
- System modeling and validation
- Balloon design optimization and final proposal

2.2. CDIO Outcomes

The students are able to develop engineering design and reasoning skills throughout this balloon design lab. Decisions that must be made by the students include: material choice, optimum combination balloon volume, thickness, and mass etc.

Students will be required to implement important engineering skills such as planning, design, implementation, testing, and data analysis. The design of a zero-pressure balloon is labor intensive with many obstacles impeding an 'obvious' design including balloon material, thermal effects, energy transfer, max payload mass, required flight endurance, and more.

Thus students will be forced to not only understand each component of design and the physics involved, but also learn to perform design trade-off and optimizations to meet requirements while working within a team environment stressing the need for strong intra-team communication and organizational skills.

3. Student Instructions

3.1. Project Description

High-altitude balloon design is thermodynamically intensive but requires knowlege of multiple other disciplines incncluding: gas laws, material sciences, and structural design. A background and introduction into the physics and design issues involved with this payload-bearing vehicle system is provided in the following Introductory Document attachment. Each group is to perform a design analysis of a high-altitude Zero-Pressure balloon for carrying a research payload. The design requirements and acceptable assumptions are as follows:

Attachment: High-Altitude Balloon Introduction.doc (7 pages)

Requirements:

Payload: A 2000 kg research instrument

Altitude: The balloon should be able to reach an altitude of 30 km

Duration: The balloon should be able to stay in residence for 2 weeks or more

Assumptions:

Shape: Assume the shape of the balloon at target altitude is a sphere

Transients: Ignore transient effects during ascent

Stresses: Ignore stresses on balloon due top payload attachment and wind loading

The following four suggestions/statements are offered to help students clarify the issues that will be involved in this lab assignment.

1. This lab will require a scale model of a zero-pressure balloon in order to develop the mechanical and thermal analysis used in evaluating balloon characteristics. This should provide some insight into an actual balloon system design.
2. Research zero-pressure balloons. Formulate a "homework problem" that computes the volume of a research balloon at the required altitude – do this for a zero-pressure balloon. Discuss margins of safety before the balloon fails.
3. Write a MATLAB 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 example code is available on the Mathworks website.
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.

3.2. Learning Objectives

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

1. Learn about the requirements and design assumptions for developing lighter-than-air vehicle designs.
2. Integrate knowledge of the first law of thermodynamics within a practical design analysis. The design should include factors of safety, for example on material stresses, imposed by the characteristics of the design and the environment.
3. Develop skills in thermodynamic and material engineering reasoning required for analysis and design.
4. Use MATLAB for plotting engineering calculations and for performing necessary model numerical integration.
5. Learn the process and importance of design trade studies and sensitivity analysis.
6. Learn research skills, both in the Library and on the Web/electronic.
7. Further develop team-based project and presentation skills.

3.3. Learning Activities

3.3.1 Scale Model Balloon System

Prior to developing a design for a high-altitude research balloon, a scale model of a zero-pressure balloon must be constructed and a mechanical and thermal assessment of the system must be developed. Prepare a brief group report addressing all of the following questions and submit this report in lab on September 16.

Construct Helium Balloon with Payload:

Gather all balloon materials and determine their mass. With the assistance of a lab technician, fill the balloon with helium gas. Record the estimated mass of gas for your system – note this source has a large uncertainty. 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 the local temperature and pressure from ITLL reading or website.

Make the 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 heat to be transferred to the balloon. Release the balloon and record any observations. Define your thermal system and describe thermodynamically the processes taking place during your observations.

Re-establish Neutral Buoyancy:

Record all required measurements and readings. 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.

Determine Mass of the Balloon 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. Also, compare numbers with the TA's recording of the gas flow meter. What are the total mass budget and the fractional percent of the balloon system components to the total system mass?

Design Modifications:

In order to lift a larger payload, what design modifications are possible and what would be the impact? To make an originally designed balloon neutrally buoyant in water, what would be the required mass of the payload?

3.3.2 Zero-Pressure Gradient Balloons

The lab's primary analysis will involve designing a zero-pressure balloon to satisfy the clients design requirements. Each team should determine the following design aspects for their balloon designs:

- Select internal gas and support the decision– know its properties and characteristics given the expected environment
- Volume of the balloon at target altitude
- Constraints imposed by solar heating and radiative cooling
- Balloon material properties

The following steps can help outline the design process of a zero-pressure balloon so that all required design parameters and deliverables are met.

1. 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.
2. Once at altitude, account for heat transfer and work processes. Assume the sun illuminates the balloon for 12 hours while the balloon also radiates and then the next 12 hours with only the balloon radiating. Assume the only work that takes place is expansion or compression, i.e. boundary work. What is the height variation of the balloon over a 24 hour period?
3. Provide a design solution that would reduce the height perturbation over the 24 hour period to within 500 m of the required altitude while sustaining a duration of two weeks. The design solution does not have to be overly developed but must make sense. Remember the simpler the better, as you add complexity your solution may raise more questions and uncertainty about its appropriateness, cost, or feasibility.
4. Provide thermodynamic plots to illustrate the processes and various states the lifting gas experiences throughout the balloon life time.

3.3.1 Planetary Mission

A client would like to consider your zero-pressure balloon design for possible planetary missions. To illustrate the design modifications required, provide sensitivity plots of the following: (These sensitivity plots would include your results above but be sure to provide a range of values that straddle earth values)

- Balloon final volume versus atmospheric gas molecular weight
- Balloon height variation versus distance from the sun (Assume same atmosphere as earth so simply move the earth through the solar system)

3.4. Assessment Criteria and Standards

Group grading will be based on delivered write-up and presentation outlining assignment procedures, analysis and results. Individual team effort grade breakdowns will be based on peer evaluations. Failure to submit an evaluation form results in no credit for that part of the assignment.

3.5. Equipment, Tools, and Materials

3.5.1 Electronic Equipment

Students must have access to electronic scales to weigh their balloons and payloads. Because of helium's positive buoyancy, the best way to measure mass input into the balloon is with an electronic pressure regulator/flow meter mounted directly to the pressure vessel. To conclude the experimental portion of the lab assignment, students must also use a heater to transfer energy into the system and achieve neutral buoyancy. Because this is a largely theoretical study, the most important piece of electronic equipment is a computer with computational (MATLAB) and symbolic algebra (MathCad or Mathematica) software.

3.5.2 Tools

The only non-electronic equipment required for this lab is a pressure vessel containing helium gas and a graduated water tank for computing balloon displacement. Methodology for estimating balloon dimensions is up to the students but it is satisfactory to assume a certain shape and measure dimensions with a ruler and then mathematically deduce volume.

3.5.3 Materials

Materials needed for the experimental portion of this assignment are black Mylar balloons. String is used to tie off the end of the balloon and attach washers as ballast.

3.6. Safety and Risk Mitigation Procedures

The pressurized helium tank must be handled under instructor or course assistant supervision. Safety eye wear must be worn at all times when dealing with pressurized gas.

3.7. Deliverables

3.7.1 Group Presentation

Each group will prepare a 15-minute presentation reporting the results of their balloon design investigation. Include the group's scale model results and your high-altitude balloon design. This presentation must report how each requirement is met by your design *in a quantitative manner supported by analysis and research*. It must also provide some rationale for major design decisions.

3.7.2 Individual Peer Reviews

Each student must submit an email with their individual confidential peer reviews of their team mates to the professor by email. This is due on the date of your final presentation. In the email, provide the following for each person in your group:

Attachment: Team Member Evaluation Form.doc (1 page)

4. Instructor Guide

4.1. On Conducting the Project and Student Instructions

As this lab is an introduction to team-based engineering design projects, the students are expected to work as independently (from teaching staff) as possible. Instructors, TAs, and faculty should maintain either an advisory or customer role to the team, and emphasize team self-dependence while following the outlined project guidelines. However in recognition of the early level of students within this course, additional guidance may be required to groups from stalling or falling behind. Guidance and trouble-shooting should be readily available to student teams during their mandatory weekly meeting/updates with professors and TAs.

4.2. Team Organization and Management Suggestions

- Students are free to organize their groups (of about 5-7) according to their wishes.
- Each group should adapt their own variation of team management according to the following suggestions.
    - Week 1: Organize groups. Brainstorm ideas. Draw pictures of the problem, to ensure understanding of the parameters for this the assignment. Build scale model and develop analysis. Try to distill the problem into a few equations.
    - Week 2: Formulate a "homework problem" for the design to compute final volume. Research information needed while others work on MATLAB code.
    - Week 3: Work out the radiative transfer analysis. Begin to draft presentation. Identify missing pieces that require further work.
    - Week 4: Finish presentations. Revise, revise, and revise!
    - Week 5: Presentations during Lab sessions. All Presentations must be submitted to class folder by assignment due date.
- Students are expected to attend each laboratory session. Each group will be expected to present weekly update briefings to the faculty and staff of the class.

Attachment: ASEN 2002 Balloon Experiment (Example Schedule) (2pages)

4.3. Assessment

4.3.1. Criteria

Assessment of student performance should emphasize fundamental understanding of thermodynamics theory and application for a payload-bearing balloon design. In addition to the thermodynamics, an understanding of material and structural/stress significance should be displayed by the team's design proposal.

The assessment criteria include soundness in balloon design reasoning, correct testing and analysis of scale model balloon, correct design and optimization procedure, understanding of balloon design limitations, and well-placed effort into accurately modeling and predicating the balloon dynamic system. Each team's efforts and achievements can be ascertained from their weekly meetings, lab report, presentation, and student peer reviews.

4.3.2. Methods and Materials

Attachment: Hybrid Altitude Balloon Grading Rubric.doc (1 page)

5. Resources

5.1. Budget

- Recurring
- Helium gas
- 18 inch Black Mylar Balloons
- Paper Clips
- Nylon Washer Kits (as Payload Weight)

5.1.1 Non-recurring

- Mica Space Heaters
- Large (10" x 24" x 20") Aquarium Tanks
- Aquarium Pump

- SI-124 0.1mg Resolution Mass Balance
- Mass Flow Meter
- Tubing, Air Fittings, Connectors, Regulators, Valves

5.2. Equipment and Tools

- Rulers
- Mass Balance/Scale
- Mass Flow Meter
- Aquarium + Pump
- Helium Gas Tubing/Connectors
- Office Tools

5.3. Materials and Supplies

5.3.1 Reusable Parts

Quantity	Part	Acquisition
1 box	Paper clips	Hardware Store
1 box	Nylon Washer Kit	Hardware Store

5.3.2 Tooling

Quantity	Part	Acquisition
2	Mica Space Heater	Hardware Store
2	10" x 24" x 20" Aquarium Tanks	Aqua Imports
1	Aquarium Pump	Hardware Store
1	SI-124 0.1mg Res. Mass Balance	Chem. Store
1	Mass Flow Meter	Micromotion

Attachment: SI-124 Balance Literature (2 pages)

Attachment: PS-00371 Flow Meter Data Sheet (24 pages)

5.3.3 Consumable

Quantity	Part	Acquisition
1	Helium Gas Tanks	Airgas Intermountain
30	18” Black Mylar Balloons	Balloons Everywhere

5.4. Staffing

5.4.1. Instructors

Instructors should avoid giving direct project instruction, and should instead act as an adviser that helps guide the project progress, provide resource ideas, and troubleshoot major issues. Experience with scientific balloon research is useful for providing students with real-world examples of benefits and realities involved in balloon vehicle systems.

5.4.2. Technical staff

Technical staff with expertise and/or experience in balloon construction and manufacturing, balloon design, and compressed gas handling is recommended but not required.

5.5. Spaces

5.5.1. Design

Lab-stations or student workstations with at least one computer per group.

5.5.2. Build

Benches or tables for scale model balloon construction and handling during experimentation

5.5.3. Storage

Sensitive equipment and any compressed gases, such as the mass scale, mass flow sensor, and helium should be locked in a protected location for storage. These were stored within the ITLL facility at CU. Other equipment such as the aquarium tanks, heaters, and materials should also have some safe storage location.

5.5.4. Operation

Indoor location to prevent balloon loss with helium access, water bath for volume measurements, and measurement tools

5.6. Other Resources

- MATLAB software required.
- Anderson, John David. "Chapter 3." *Introduction to Flight*. Boston: McGraw-Hill Higher Education, 2005. Print.

6. Safety and Risk Mitigation

6.1. Operational Safety

- Helium tank must be secured in an upright position and clamped securely to the wall of a fume-hood room when being rented/used during the lab.

Attachment: Helium General Information(2 pages)

6.2. Governing Policies and Regulations

6.2.1. Governmental

- N/A

6.2.2. Institutional

- Health and safety training required for Teaching Assistants and Staff.

7. Additional Information

7.1. Possible Project Variations

As it stands, the design project is a static system. A possible variation for this assignment is adding of built in heating or cooling. This may be too advanced for students for which this design lab is originally intended but would be appropriate for more advanced courses.

7.2. Supplementary Multi-Media and Other Resources

N/A

7.3. Sample Student Products from Previous Project Iterations

Attachment: Sample Student Presentation.ppt

7.4. List of Attachments:

In order of appearance

High-Altitude Balloon Introduction (7pages)

Team Member Evaluation Form (1 page)

ASEN 2002 Balloon Experiment (Example Schedule) (2pages)

Hybrid Altitude Balloon Grading Rubric.doc (1 page)

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Helium General Information(2 pages)