Lab 4

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Lab Section 102

Methods and Materials

Rocket Design

When we started this lab, we received a 2L bottle as our “rocket” as well as a can of butane. When first designing and testing the rocket without any modifications, we noticed that the bottle did not hold up well against the wind. If there was a breeze, especially during strong gusts, the bottle would move in the direction of the wind. This, thereby, made our launches very unpredictable and non-replicable. While researching possible solutions to mitigate the effect of the wind, one thing that kept popping up was to use fins at the bottom of the bottle to maintain stability. To keep the rocket the most stable, the fins are angled at 45 degrees from the rocket body, and it stretches out 2.5 inches from the body. We then added a second bottle cut in half to act as the nose of the rocket and attached a 50g weight at the front to make the bottle’s center of mass closer to the nose than the nozzle. This allowed for a more streamlined design, reducing our drag and resulting in straighter launches. In the end, our rocket’s total empty mass was 190g with a center of mass 17.2cm from the nose close to the center as the 3 fins negated some of the effects of the 50g mass at the nose. By moving the center of mass closer to the nose, it made sure that the center of pressure was further behind the center of mass. The addition of the fins added more surface area and it was important to have the center of pressure further back to help ensure our rocket had a more stable launch and ballistic phase. This would help prevent spinning or flipping which we saw in the original 2L bottle rocket. All these features can be seen in Figure 1.

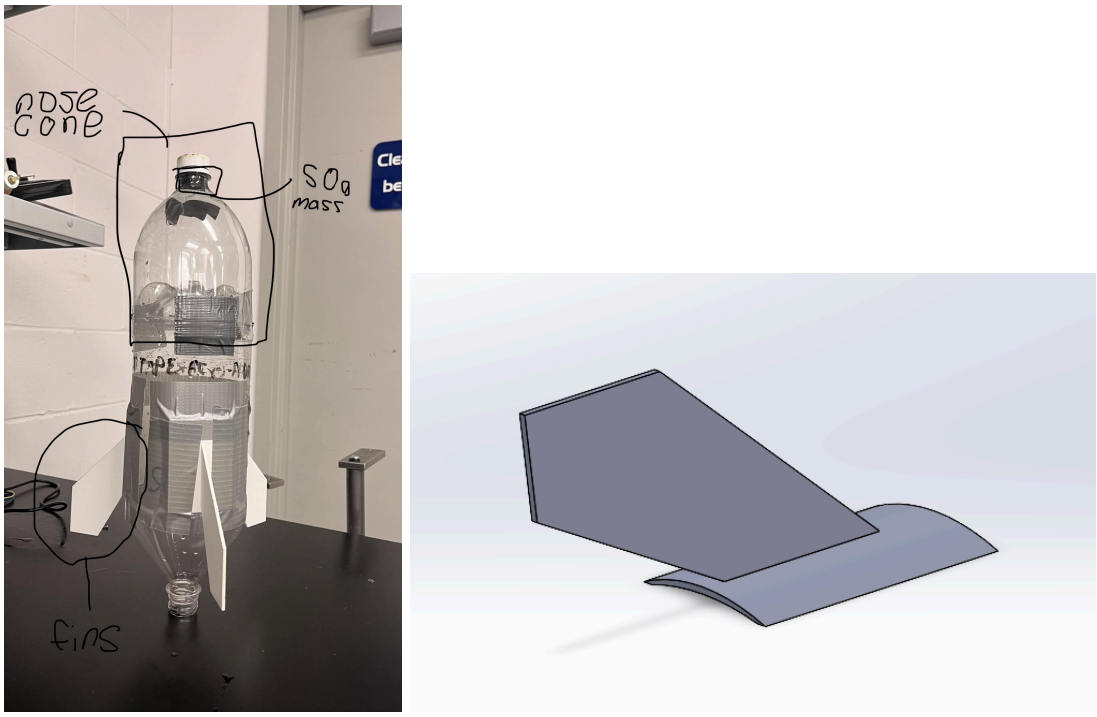


Figure 1: Annotated image of our rocket. Included is the CAD design of the fins

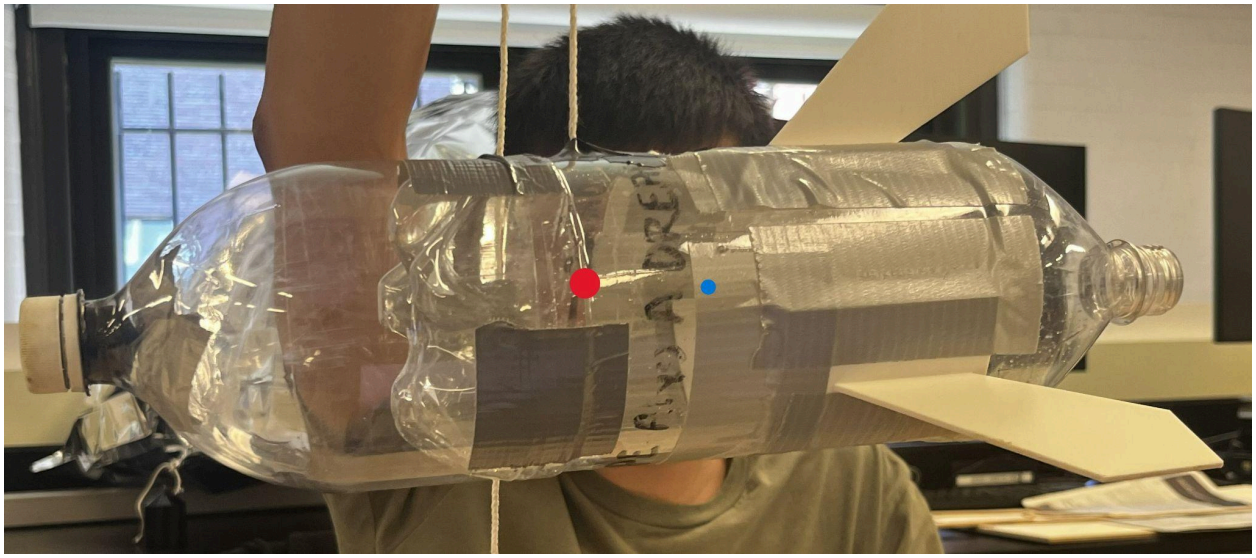


Figure 2: Rocket CoM 17.2cm from nose (red dot) CoP 21 cm from nose(blue dot)

In the beginning of the rocket design, we ran an assortment of experiments. We started by testing the plain rocket with different water masses and butane masses and couldn't gather much helpful data as the launches were very inconsistent. We used this to learn how to launch our rocket more consistently without failed launches by observing how the rocket reacted to wind with different water masses. After these tests, we figured out what changes we needed to make to our rocket and ran more tests afterwards varying water mass, butane mass, water temperature, and recording raw distance. We used this data to make a draft of our model and refined the model by running more tests with specific parameters aiming for a certain distance and seeing how far off our model was, aiming for it to be within 10% for each launch. It worked very well for lab 3 as we had consistent predictions that were within that 10% range when tested.

To prepare for lab 4, we flipped our model by inputting the target distance with the wall and wanted it to give us rocket specs for launch. We repeated the same experiment by running test numbers and calibrating our model accordingly.

From all of our experiments and data, we estimated that the drag was approximately 0.42 on stable flight conditions but between 1.1-1.45 for unstable flight conditions. A stable flight meant the rocket was stable as the center of mass was in front of the center of pressure and the rocket would self-correct and wobble slightly on its trajectory. An unstable flight meant the center of pressure was in front of the center of mass and the rocket would flip and spin during the launch.

Model

Our model simulated launches and outputted the one closest to the given launch specs. While creating the model, it was split into 2 phases: the thrust and ballistic phase. The thrust phase calculated the pressure that we built up in the rocket from the butane and water mixture and also accounted for the decreasing mass during the thrust phase.

We used the Antoine Equation to determine the vapor pressure inside the rocket, thereby finding out how much power the rocket has based upon the butane and water amount. The equation $\log_{10} p = A - \frac{B}{C+T}$ states that A, B, and C are constants and P is vapor pressure and T is temperature. The pressure value found is plugged into our thrust equation which will determine how far we predict the rocket to fly. The ballistic phase simulated the rocket after there were no more liquids inside, which utilized solely the drag coefficient we calculated from our tests.

In our first iteration, we treated the rocket as a particle mass but later updated it to be more realistic. The model accounts for the decreasing mass over time and the rocket accelerates as it gets lighter. It also treats the rocket as a rigid body which has drag. The model goes through potential input specifications from angles of 25-65degrees, water volume of 200-700mL and butane amounts of 10g-17g to see which one will have a trajectory that will be close to the target distance and gap. We chose these metrics in order to ensure our model wasn't looking at combinations that were either too drastically leaning to the extreme on one variable or too narrow to find a complete flight value.

The code prioritizes getting through the gap entry to maximize points as the gap bonus is 1.25. This is done by manually adding the 1.25 bonus to the gap, which helps the model find the maximum possible model score. The model also accounts for the initial height being slightly above 0m by setting py = 0.1 as the angle launched was slightly off the ground.

We also recorded how long it took from the bottle flip to launch to track how long it took the butane and water to mix. This was done to track the pressure and energy inside of the bottle. We noticed there was an optimal time between 1 - 1.5 seconds which resulted in the best launches. This was helpful in seeing how long we can hold pressure and how long it took to mix.

To correctly manage both the thrust multiplier and the drag coefficient, a multitude of launches were tested at both short and long distances to help isolate both the thrust multiplier and drag coefficient values. The short and long distance had the same butane mass value, same launch angle, and same temperature of water, which helps eliminate lingering variables which could inadvertently affect the thrust and drag coefficients as well. This meant that we were only changing the mass of the water to affect distance. The longer distance launches had more of an effect from the drag coefficient while the shorter launches had more of an effect from the thrust

multiplier. We used the shorter launches to first test for the thrust coefficient and the longer launches to modify the drag coefficient.

Results

The butane rocket performance varied more than expected during Demo Day. The parameters given were: Target at 22m, Wall at 8.15m, and Gap Center at 6.4m tall. Our initial prediction was for the model to go 21.99m and fit through the gap, and our launch results can be seen in Table 1 and our model outputs can be seen in Table 2.

Trial	Targeted Distance (m)	Actual Distance (m)	Hit Gap	Distance Percentage Error (%)
1	22	38	No	72.7
2	22	14.69	Yes	33.2

Table 1: Table of rocket performance during demo day

Trial	Water Mass (mL)	Water Temperature (℃)	Butane Mass (g)	Angle (Degrees)
1	400	35	12	45
2	350	35	10	45

Table 2: Table of Model Outputs

In Trial 1, the rocket traveled 38 m, overshooting the target distance by 16 m and resulting in a percentage error of 72.7%. The rocket also failed to pass through the gap. This was primarily caused by an overestimation of the boil-off rate of liquid butane during preparation, which led to more propellant being added than intended. As shown in Table 2, the rocket was loaded with 12 g of butane and 400 mL of water, producing significantly greater thrust than predicted by the model.

A major challenge throughout testing was structural damage to the rocket. During pre-launch testing, one of the fins snapped after a hard impact and had to be repaired with duct tape because a replacement fin could not be manufactured in time. The repaired fin was less rigid and introduced additional aerodynamic drag and instability, causing the rocket to wobble laterally during flight. To account for this behavior, the drag coefficient in the model was increased.

However, this made the system much more difficult to predict accurately, since the rocket no longer behaved consistently between launches.

For Trial 2, the butane mass was reduced to 10 g and the water mass was reduced to 350 mL in an attempt to compensate for the excessive thrust observed during the first launch. The rocket successfully passed through the gap and followed a more controlled trajectory, but it only traveled 14.69 m, undershooting the target by 7.31 m and resulting in a percentage error of 33.2%.

Overall, although the rocket was able to achieve the desired gap trajectory in Trial 2, the launches showed that the model was highly sensitive to changes in propellant mass and aerodynamic behavior. Small variations in butane measurement and rocket stability produced large differences in launch distance and trajectory.

Discussion

Parameters Affecting Consistency

1. **Thrust Multiplier & Inconsistent Manual Release Technique**
   When testing the model, one of the variable parameters which drastically affected the model was the thrust multiplier. The multiplier accounts for the energy loss from the nozzle and rail friction. Because we were using a hand as our cork, there was human error for each launch and we couldn't be perfectly consistent. This meant each launch had a different friction and release timing as well as a differing time for the butane to mix.. While we did practice a lot, there were still inconsistent manual releases resulting in a different thrust multiplier for each launch meaning our model couldn't be entirely predictable. To improve this, we could have designed a cork to make pressure release more consistent. We did try using a couple objects to hold in pressure but none went as far as our human launches.

2. **Drag Calculations**
   Another variable parameter which greatly affected the model was the drag calculations. Since the coefficient of drag of the rocket is not a perfectly known number – like how the average sphere has a Cd of .47 – the calculations to find the drag coefficient were more complex than initially understood. In addition, while testing the rocket, the nose cone kept getting damaged by the impact on the ground. This resulted in irregular bumps, which made the calculations for the drag coefficient more difficult. Furthermore, since the velocity of the rocket varies both with the mass of the water, the mass of the butane, and a variable thrust multiplier, the calculations became increasingly more challenging.

   Moreover, while testing the bottle rocket, one of the fins snapped due to the force from hitting the ground. As this was the final few calibration tests before Demo Day, we had no time to print a new fin. The duct-tape, while the best feasible idea at the time, subsequently added surface roughness and an asymmetric profile. The "repaired fin" was not as stable and rigid as the other ones. This irregularity may have increased the drag coefficient in one section of the rocket, making it not fly completely straight. It may also have increased the total drag of the rocket, making all the prior tests worthless. In addition, it may have also changed the center of pressure, making the flight more wobbly and shortening the total flight distance.

3. **Propellant Measurements and Reaction Inefficiencies**
   When testing the rocket outdoors, wind interference and the low resolution to the field scale cause both inaccurate scale tarings and butane measurements. The difference in readings, specifically during Demo Day, made the butane visually show much less condensed liquid butane compared to other launches. There was also no way to account

for the butane evaporation from being sprayed to when we launched. This led to consequential errors with regards to flight distance and gate flight height.

Another error here was that we could not reach thermodynamic equilibrium every launch. Because we only flipped the bottle upside down, there was no way for the butane to completely mix with the water. While we could have theoretically "shook" the bottle and done more manual shaking, it would have been extremely difficult to hold bottle pressure via our hand and not release any liquid prior to launch. This meant that not all the butane would reach the rapid boiling state and remain in liquid form. This inefficiency meant that the mass of butane put into the bottle was not entirely accurate as not all of it was being used for a reaction and we couldn't hit the theoretical values predicted from our Antoine Equation model. We also had no way to track the pressure inside the bottle so all of our pressure testing was done theoretically.

Demo Day Performance

Even though both equations introduced a considerable amount of noise into the data, the model proved to be fairly resilient to real-world imperfections. When creating the model, we decided that successfully passing through the gap was more important than landing exactly at the target distance, which the model ultimately achieved during Trial 2. Although the rocket successfully passed through the gap as intended, the model still over-predicted the flight distance by about 7.31 meters, as the rocket only traveled 14.69 m instead of the predicted 21.99 m.

In contrast, Trial 1 greatly overshot the target distance, traveling 38 m and missing the gap entirely. As elaborated in the Results Section, this was likely caused by excess butane being added due to incorrect estimation of the boil-off rate, which significantly increased the thrust generated during launch, and an overestimation of the new Coefficient of Drag after the structural damage to one of the fins. Together, these results suggest that the model may have underestimated how sensitive the rocket's trajectory was to small changes in propellant mass and aerodynamic conditions. Additionally, the discrepancy could have resulted from differences between testing conditions and Demo Day conditions, particularly wind effects, inaccurate butane mass measurements due to varying evaporation rates, inconsistent time elapsed between dispensing the butane and launching the rocket, and the damaged fin introducing additional drag and instability during flight.

Improvements

While the manner we collected testing data would be adequate for a launch of smaller degree, for a model which needs to be accurate by mere centimeters, the means of testing should have varied even more.

Alternative Tests

1. **Vertical Launch Test**
   One way in which the drag coefficient specifically could have been better altered is by a vertical launch test. Since – after the butane and water mass has dissipated – the bottle only experiences the forces of gravity and drag, one could record a video of the launch to calculate the drag coefficient. In addition, one could add extra weights to the rocket, like coins on the nose cone, to vary the mass of the rocket and thereby create more data points for the coefficient to accurately represent.

2. **Testing with Telemetry Device**
   Another way the model could have been improved is by adding a telemetry device inside the rocket to measure both the pressure and temperature. One overlooked area of model analysis was finding the pressure and temperature of the bottle at specific points within the flight. In theory, if these values were found, the mdot value could have an extra known value that can accurately change the value. In addition, it could also track the butane content and determine how long the thrust phase is (rather than guessing). This can help determine the drag coefficient. Since the thrust forces are absent after the thrust phase, any variance from the pure theoretical model can be attributed solely to the drag coefficient. This will allow for a more accurate profile of the drag coefficient, and thereby a more accurate representation of the real-life rocket.

3. **Testing for heat dissipation through walls**
   One more way the model could be improved is by adding an equation and subsequently testing for the dissipation of heat through the plastic walls. While initially thought of as negligible, upon further notice, the heat dissipation through the walls could yield an adverse change in the rocket's flight path. As the liquid butane evaporates within the rocket, the plastic walls absorb heat, causing the temperature of the system to increase, as well as the butane losing efficiency. By adding an additional heat equation, the model can adjust for both the vapor pressure and the butane efficiency, thereby leading to a more nuanced prediction of the thrust duration.

Design and Procedural Modifications

1. **Standardized Mechanical Release**
   From the first rocket test, we came to the understanding that we needed to keep the pressure of the rocket system constant throughout the loading process. Within the tests

and Demo Day, we decided to use a hand to manually block the pressure within the bottle. While this resulted in the rocket being able to launch, it hindered our ability to keep the initial launch pressure constant. To improve this, we will replace the hand release technique with a mechanical launch plug (such as a pull-pin mechanism). The mechanical release ensures that the initial launch pressure for two identical launches will be identical due to the friction on the exit being the same. This launch process would yield in highly consistent initial pressures, thereby constant initial velocities and overall launches.

2. **Standardized Thermodynamic Mixing Protocol**
   Since the butane's point of evaporation is lower than the average temperature of air, when out of the bottle, butane is always evaporating. This makes measuring the condensed liquid butane's mass a difficult ordeal. It especially makes it tough to make sure the difference between the butane on the scale and the butane in the rocket is negligible. Alternatively, if we were to stick with a hand release technique, we would enforce a stricter, timed protocol for shaking and agitating the bottle prior to launch. Ensuring that the water and butane fully emulsify guarantees the closed system reaches true thermodynamic equilibrium. This complete emulsification allows for a complete and predictable flash-boiling phase change that accurately matches our Antoine Equation predictions.

3. **Accurate Propellant Measurement**
   When measuring the mass of the butane, one problem we ran into was the sensitivity of the scale itself. In the first few trials, while the scale would read differences in masses, it was not sensitive enough to be able to understand the difference between hundreths of grams. This made for the volatile butane readings to have small yet significant inaccurate readings. To ensure that these differences become negligible, a highly sensitive digital scape equipped with a wind-shield will be used. This will help measure the highly volatile butane accurately in an outdoor environment and keep our launches constant.

4. **Accurate Mass Accounting**
   During Demo Day, one of main procedures necessary prior to launch was to add padding on the front of the nose cone to prevent damaging buildings. When testing the rocket prior, the added mass of the padding was not calculated into the system, nor calibrated for in the model. This led to the model in Trial 2 to compensate for an extra 50mL of water. In the future, we will add padding prior to Demo Day, and collect calibration data with the padding attached to ensure that the model's dry mass input matches the physical rocket, and the variables within the code are synced up correctly to the real-world system.

Appendix

Videos of Launches on Demo Day

Model Code

Test Data Labs 3 and 4

LLM

Synopsis of LLM Use