Fluids Midterm Project

James Lee

Fluid Mechanics

Doctor Krishan Bhatia

October 19, 2024

Part 1 - External Flow

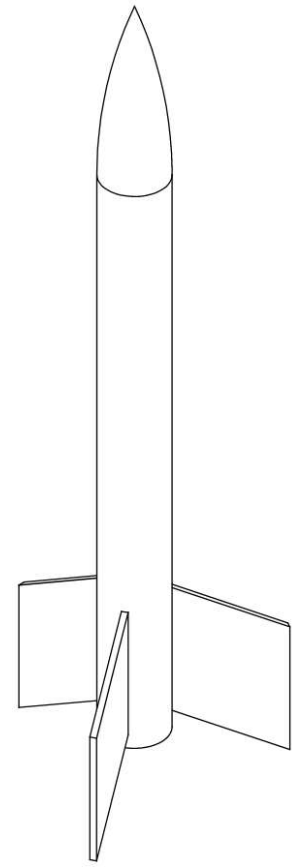
Overview

In this section, I will be designing, analyzing, and optimizing a model rocket with a specific focus on its fins to better understand external flow. The dimensions and proportions of the fins will be adjusted to minimize drag and optimize the required horsepower for the rocket's flight.

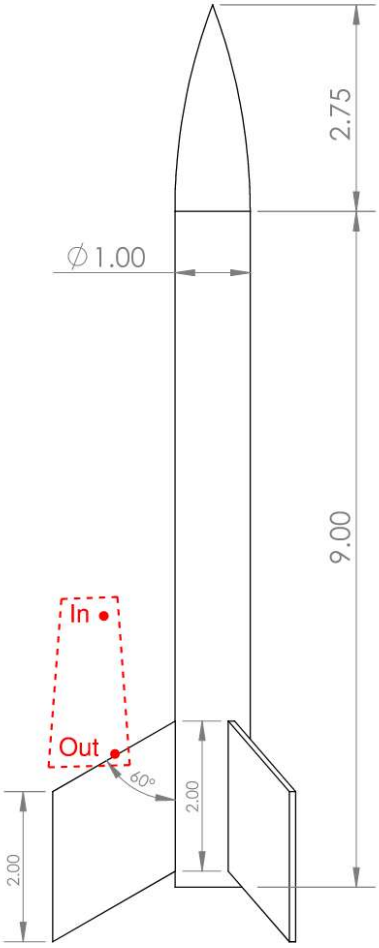
I chose this project because I am currently a member of the Rowan Rocketry Clinic, where I've been developing a payload subsystem that includes an Arduino-powered rover capable of autonomously deploying after the rocket touches down. While this project is highly interesting, it does not involve the actual rocket dynamics that I am eager to explore. This fluid mechanics project presents a valuable opportunity for me to research and analyze the external flow of a rocket, which I haven't had the chance to do so far.

To begin, I had to decide what type of rocket would be best to analyze. Given that rockets typically travel at high speeds, analyzing the external flow could be complex, since the air would have to be treated as a compressible fluid. A NASA article explains that for fluid analysis, the density of air can be assumed constant below 250 mph (Hall, 2021). To simplify my analysis, I found another NASA source that compares the speeds of model rockets to real rockets, noting that model rockets usually travel at speeds lower than 250 mph (Dasilva, 2023). Based on this information, I have chosen to analyze a model rocket traveling at a maximum speed of 250 mph, which allows me to treat the air as an incompressible fluid, greatly simplifying the analysis.

Overview



ISOMETRIC VIEW



FRONT VIEW

As shown in my drawing, I have chosen a trapezoidal design for the rocket fins. While there are numerous possible fin shapes, I selected this design because it was successfully used in last year's rocket for my clinic project. Given my familiarity with this shape, I'm eager to explore its performance further and find ways to optimize it.

Control Volume Analysis

Bernoulli Equation to find Outlet Pressure, Drag Force, and Power for a Single Fin:

$\rho = 1.225 \frac{kg}{m^3}$ $g = 9.81 \frac{m}{s^2}$

$l = 2.125$ in $w = 0.09375$ in $A = l * w = 0.199$ in^2

All my "inlet" terms:

$P_{in} = 0$ psi (gauge) $v_{in} = 250$ mph $z_{in} = 0$ m

All my "outlet" terms:

$v_{out} = 0$ mph $z_{out} = 0$ m

I have elected to make z_in and z_out both 0 m, as they would cancel out on both sides of the equation. In my control volume analysis, the difference in height would be so small that, compared to the magnitudes of the pressure and velocity, it can be ignored without sacrificing too much accuracy.

v_out will be set to 0 mph for the sake of simplicity. Though the air will not actually lose all velocity when it hits the rocket fin, we can make this simplification to make the equation easier to work with.

$$\frac{P_{in}}{\rho * g} + \frac{v_{in}^2}{2 * g} + z_{in} = \frac{P_{out}}{\rho * g} + \frac{v_{out}^2}{2 * g} + z_{out}$$

$$F_d = \left(P_{out} - P_{in}\right) * A$$

$$\text{Power} = F_d * v_{in}$$

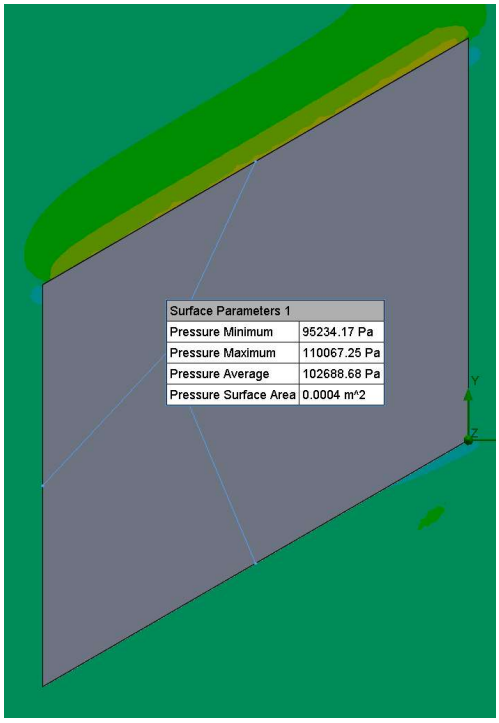
$P_{out} = 1.110$ psi
$F_d = 0.221$ lb
Power = 0.147 hp

$P_{out,absolute} = P_{out} + 14.7$ psi $= 109.003$ kPa

We will use the average absolute pressure on the rocket fins (in kPa) to provide a point of direct comparison with the flow simulation results. CFD will provide average, minimum, and maximum absolute pressure of the rocket fin.

While it was quite challenging to find a source of comparison for drag force or horsepower on a model rocket fin (as all designs are unique), I did want to comment on the low drag force. Drag force is proportional to the cross sectional area of the object pushing through the air (University of Waikato, 2011). Because I went with very thin fins (0.09375 in), I was able to achieve a very low drag force of 0.221 lbs.

Flow Simulation Results



Pressure Minimum	95.23417 kPa
Pressure Maximum	110.06725 kPa
Pressure Average	102.68868 kPa
Pressure Surface Area	0.0004 m^2

Let's take the average pressure from the flow simulation, and compare to the pressure derived from the hand hand calculations.

P_{CFD} = 102.68868 kPa

P_{BPad} = 109.003 kPa

$$\text{PercentDifference} = \left(\frac{\left| \left(P_{CFD} - P_{BPad} \right) \right|}{\frac{P_{CFD} + P_{BPad}}{2}} \right) * 100 = 5.966$$

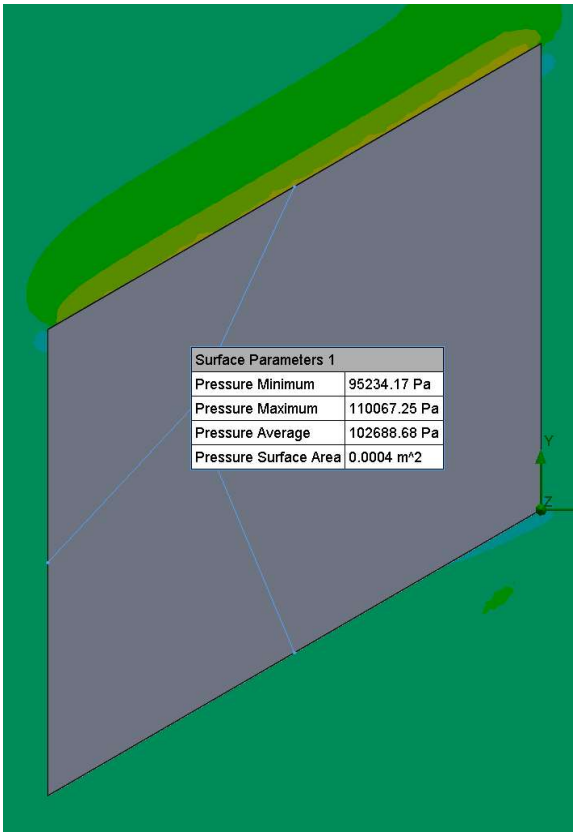
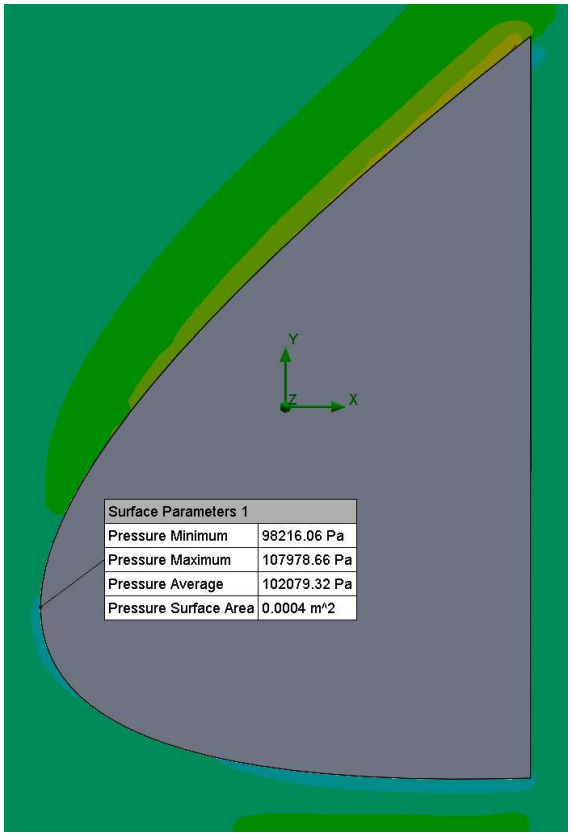
Optimization

When performing the control volume analysis, I used the front projection of the face. In other words, I assumed that the front of the fin was perfectly flat, for the sake of the equation– I did not account for the fact that the front of the fin is tapered. This, of course, would have an effect on the results, typically in the form of the drag coefficient C_D. This can be seen in the simulation results, which features a lower average pressure than the hand calculations.

To optimize this further, I suggest expanding on this idea. A fin design that, while maintaining the same front profile area (so the hand calculations would still yield the same results), would have a more efficient design so as to minimize the drag coefficient. I suggest an ellipsoidal shape that lacks the hard edges shown on the current trapezoidal design. This should allow the air molecules to more efficiently travel around the fin, minimizing the drag force and the required horsepower for the rocket to travel through the air.

As demonstrated with the following cut plot, this proposed shape reduces the pressure on the front of the fin, meaning that the air is traveling around it more efficiently.

Optimization

Original Design	Optimized Design
	

	Original	Optimized
Pressure Minimum	95.23417 kPa	98.21606 kPa
Pressure Maximum	110.06725 kPa	107.97866 kPa
Pressure Average	102.68868 kPa	102.07932 kPa
Pressure Surface Area	0.0004 m^2	0.0004 m^2

Part 2 - Shaft Work

Overview

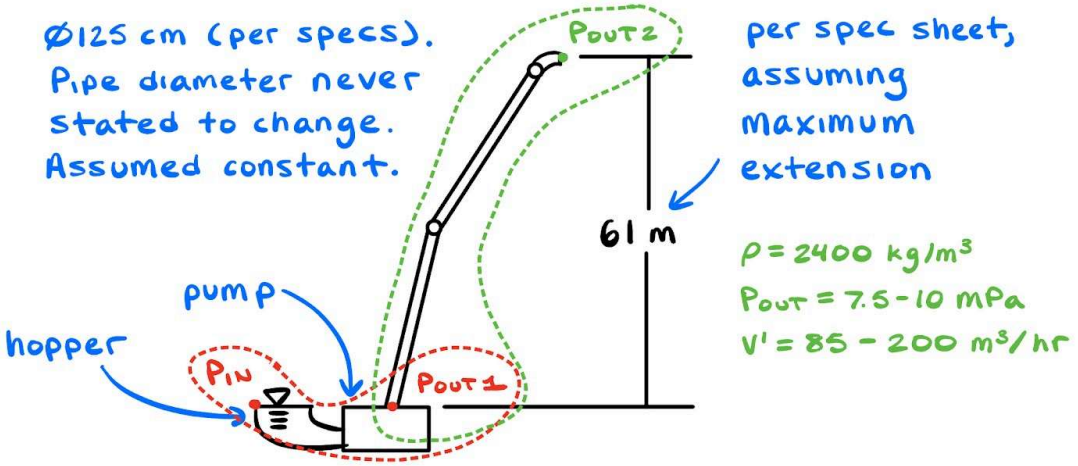
For this section, I will analyze a real-world fluid system that incorporates shaft work to accomplish a fluid task. I will begin by performing a control volume analysis, defining all relevant terms, inputs, and outputs. Next, I will compare my theoretical results to the actual specifications of the same fluid system in practice, and analyze any discrepancies between the two.

I have chosen to examine a concrete boom pump, a construction machine used to transport and place concrete in hard-to-reach areas. It consists of a truck-mounted pump and a long, articulated boom that delivers concrete from the truck to the target location via a series of pipes (LTGroup, 2024).

For the past three years, I've worked as an assistant project manager at Tri-State Construction, a concrete subcontractor in Millville, New Jersey. We own a concrete boom pump, and I've always been intrigued by its operation. This project provides an excellent opportunity to conduct fluid research on equipment I've regularly encountered.



Drawing



P_{IN} is right before pump, in concrete hopper. Exposed to atm. pressure.
P_{OUT1} is right after pump, used to find shaft work.
P_{OUT2} is the pump outlet at max vertical extension. Find pressure

Spec Sheet



Max. Theo. Concrete Output	85-200 m3/h
Vertical Height of Boom	30m~61m
Turntable Rotation Angle	±210° ~ ±360°
Max. Pumping Pressure	7.5~10 MPa
Diesel Engine Model	YUCHAI / YC6J200-52 Cummins / ISGe5-400 / ISGe5-430
Inside Diameter of Delivering Pipe	Φ125
Folded Form	4Z, 5RZ, 6RZ, 7R

Control Volume Analysis

Mechanical Energy Equation to find Shaft Work (in hp) of concrete pump:

$\rho = 2400 \frac{kg}{m^3}$ $g = 9.81 \frac{m}{s^2}$ $V' = 200 \frac{m^3}{hr}$ $m' = \rho * V' = 480000 \frac{kg}{hr}$

All my "inlet" terms:

$P_{in} = 0$ atm (gauge) $v_{in} = 5 \frac{m}{s}$ $z_{in} = 0$ m

All my "outlet" terms:

$P_{out} = 7.5$ MPa (gauge) $v_{out} = 5 \frac{m}{s}$ $z_{out} = 0$ m $W'_{out} = 0$ hp

The value of 5 m/s for v_in and v_out were chosen arbitrarily. This can be done because the system being analyzed is in steady state- the mass flow rate in is the same as the mass flow rate out-and the diameter of the inlet and outlet are assumed to be the same. In addition, there is assumed to be no height difference between both sides of the pump.

$$\frac{P_{in}}{\rho * g} + \frac{v_{in}^2}{2 * g} + z_{in} + \frac{W'_{in}}{m' * g} = \frac{P_{out}}{\rho * g} + \frac{v_{out}^2}{2 * g} + z_{out} + \frac{W'_{out}}{m' * g}$$

$W'_{in} = 558.759$ hp

Bernoulli Equation to find Gauge Pressure (in atm) of boom's peak:

All my new "outlet" terms:

$v_{out2} = 5 \frac{m}{s}$ $z_{out2} = 61$ m

Again, 5 m/s was chosen for the outlet velocity, for similar reasons mentioned above. It is assumed that the diameter has not changed, and the system is still in steady state.

$$\frac{P_{out}}{\rho * g} + \frac{v_{out}^2}{2 * g} + z_{out} = \frac{P_{out2}}{\rho * g} + \frac{v_{out2}^2}{2 * g} + z_{out2}$$

$P_{out2} = 6.064$ MPa

Comparing Results



X15 Productivity Series (2024)

Power	430 - 605 hp
Torque	1650 - 2050 lb-ft
Certification	EPA 2024



X15 Performance Series (2024)

Power	525 - 565 hp
Torque	1650 - 2050 lb-ft
Certification	EPA 2024



X15 Efficiency Series (2024)

Power	400 - 500 hp
Torque	1450 - 1850 lb-ft
Certification	EPA 2024

The required horsepower needed for the shaft work within the concrete pump that was calculated in the control volume analysis falls within three Cummins engine models demonstrated here (Cummins, 2024).

One factor that could be limiting the pressure on the control volume analysis is the fact that concrete is a non-newtonian fluid. Viscous effects were not considered in the mechanical energy equation, however they would definitely be a factor in real life. This would mean that the horsepower needed in real life would be a little higher than what was calculated. These engines provide some overhead as a safety factor.

The pressure calculated at the peak of the boom was higher than atmospheric. Again, the viscous nature of concrete likely has an influence on this. A lot of energy would be lost in heat when pumping the concrete through the boom.

Sources Cited

1. Hall, N. (2021, May 13). *Role of Mach number in compressible flows*. NASA. https://www.grc.nasa.gov/www/k-12/airplane/machrole.html
2. Dasilva, M. (2023, November 20). *Model rockets and real rockets*. NASA. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/model-rockets-and-real-rockets/
3. University of Waikato. (2011, November 30). *Rocket aerodynamics*. Science Learning Hub. https://www.sciencelearn.org.nz/resources/392-rocket-aerodynamics
4. LTGroup. (2024, September 11). *Concrete pump rates - Luton Group*. LT Concrete Pump. https://ltconcretepump.com/concrete-pump-rates/
5. Cummins. (2024). *ISG12 euro IV/V (export markets) | Cummins inc.*. https://www.cummins.com/engines/isg12-euro-ivv-export-markets