

HYBRID ROCKET IGNITION SIMULATION AND EXPERIMENTS



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Abstract

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1

Introduction

It's not rocket science.

The following report contains simulations and observations of the hybrid rocket MEOWTH II (**M**echanical **E**ngineering **O**bservational **T**utoring **H**ybrid rocket) created by *Team Rocket* [1] at Navitas, Aarhus University. The first rocket was built in 2014 by a previous group of students, but has since been passed along to other pupils, with the intent of teaching the basics of rocket science.

During the previous MEOWTH's tests, a large pressure spike during the startup phase has been observed. This can be seen in the old video here: bit.ly/1SYp1Ug in the timespan of seconds 5-7. From the video, it appears that just as the rocket exhaust reaches supersonic speeds, *something* explodes, extinguishing the flame. We know it happens before the rocket goes supersonic due to the lack of shock diamonds prior to the event. [2, chapter 18, p. 643]

This bachelor thesis attempts to simulate the rocket's startup condition in order to explain and understand the event. My advisor, Gorm Bruun Andresen, proposed a hypothesis that the pressure spike occurs at the point where mass-flow is choked in the throat. As the flow is sub-sonic, the amount of matter exiting through the nozzle is gradually increasing. When the flow goes sonic or beyond, it is suddenly capped. This abrupt change in physical properties may be able to explain this event, and the following contains the theories and thoughts that went into simulating the rocket engine's startup.

1. Introduction

In order to create a safer rocket with more measurements options, MEOWTH II was built. Alex Nørgaard, Gorm Bruun Andresen and I personally assembled and water-tested the rocket. The rocket can be seen on the frontpage and on figure 2.1, and each section contains at least four possible points measurements for various instruments.

The purpose of these simulations are ultimately to improve the rocket and rid it of large pressure variations. To see improvements, it is necessary to measure how the rocket behaves under different conditions. Therefore, setup and calibration of various measurement equipment is essential in order to retrieve excellent data. This is also covered in this report, as the experimental part is of equal importance. Measuring the rocket chamber's temperature is of great inconvenience, as the several thousands of kelvin are too much for even the strongest of thermocouples. [3] This issue and it's solution is discussed thoroughly in the sections below.

All measurements and tests could not have been carried out if not for the test facilities provided by Peter Madsen of Raketmadsen's spacetlaboratory. MEOWTH II's tests were carried out on the 3rd to the 4th of May, 2016 in Copenhagen.

The entire project is publicly available on https://github.com/carlegroen/bachelors_degree, where all work files, data and various notes can be found.

2

Theory

Understanding the theory behind the rocket's flow requires a basic knowledge on rockets. Therefore, the first theoretical segment concerns basic rocketry, followed by a more advanced segment of nozzle theory.

2.1 Basic Rocket Science

A rocket engine consists of a few fundamental elements. A rocket engine is a type of jet engine that, in contrast to duct jets, carry their own rocket propellant. Jet engines as seen in aeroplanes are usually situated with a duct, confining the air flow. Rocket engines on the other hand carry a supply of oxygen and rocket propellant, which allows them to function even in vacuum.

Rocket engines work by obtaining thrust in accordance with Newton's third law. The internal combustion chamber accelerates fluids through a propelling nozzle to high speeds. The fluid is most often a gas created from mixing fuel and oxidizing components in the combustion chamber. The exhaust is accelerated to supersonic speeds by expansion in the nozzle, which forces the engine in the opposite direction.

Most rockets used today are liquid rockets which store their propellant and oxidizing component in separate tanks. The liquid fuel is then forced into the combustion chamber for consumption. Solid-fuel rockets contain propellant prepared with a fixed fuel and oxi-

2.2. Theoretics of the Hybrid Rocket Engine

dizing component. The fuel is called 'grain', and the storage compartment for the grain is the combustion chamber. A hybrid rocket is the mixture between the two. Most often, hybrid rockets contain a solid fuel, or 'grain' and liquid or gaseous oxygen, thus earning the name hybrid engine. Variations of this engine type do exist, but this configuration is the most often used [2, chapter 16, p. 605]. Solid oxidizers are uncommon as they are problematic and have worse performance than liquid oxidizers.

Liquid and hybrid engines both use injectors to disperse oxygen and propellant into the combustion chamber. For a hybrid engines, this means spreading oxygen to the grains surface to allow combustion.

Hybrid rockets are inherently safer than its two counterparts, and accidents are less volatile as accidental fuel mixing is a non-issue. The oxidizer and fuel are almost always contained in separate chambers, which also reduces the mechanical complexity of the rocket in comparison to liquid rockets.

2.2 Theoretics of the Hybrid Rocket Engine

The hybrid rocket engine consists of three parts: The combustion chamber, the converging into a throat, and diverging section after called the nozzle. A rocket's effectivity is highly dependent on the shape, size and ratios between these three segments. Accordingly, it is imperative to study these parts of the rocket's design.

The rocket in question is seen in figure 2.1 which is divided into a tank, three chambers and a nozzle. From the left: The tall tank contains the oxidizing agent, which is injected into the first part of the rocket. The longest part of the rocket, as seen on figure 2.1, contains potassium permanganate engulfed in a flame retardant foam. This creates oxygen, which is forced through the rocket's second part: the grain chamber. The heat from decomposition heats the inside material to roughly 485K, which is close to MDF's autoignition point of 492K at atmospheric oxygen levels. [4] With almost pure oxygen being created in the decomposition, the autoignition temperature drops and combustion takes place. The exhaust exits through the nozzle after it has passed the mixing chamber.

2.2. Theoretics of the Hybrid Rocket Engine

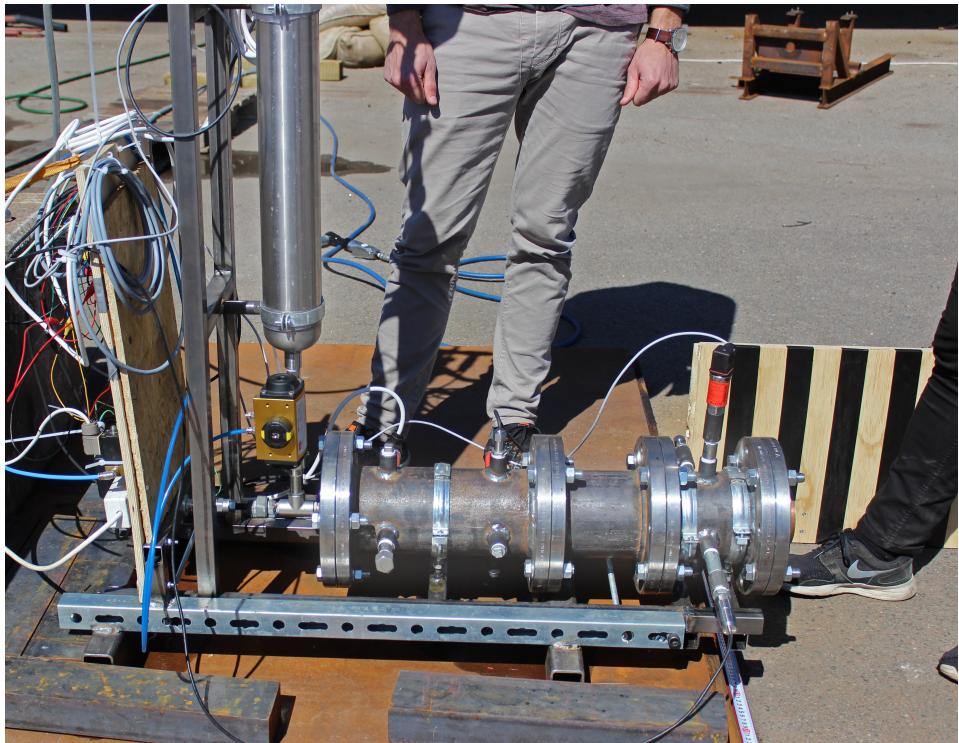


Figure 2.1: The hybrid rocket build at Navitas in Aarhus for educational purposes.

All calculations and considerations made in the report is in regard to this particular rocket. The following subsections elaborates each individual segment of the rocket, with the purpose of providing the necessary background knowledge to understand the simulations and results. The explanation is given step by step, starting with injection and ending with exhaustion.

2.2.1 Injection

To initiate combustion in the hybrid engine, an oxidizer is injected into the combustion chamber. The rocket in question creates its oxidizer by mixing an oxidizing agent with potassium permanganate. The agent is contained in a pressurized tank containing an 80% H_2O_2 rich mixture with the remainder being H_2O . The oxidizing agent is assumed to be injected at a constant rate of:

$$\dot{m}_{\text{injection}} = 0.273 \text{ kg/s.} \quad (2.1)$$

in accordance to data collected at the recent launch .

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2.2. Theoretics of the Hybrid Rocket Engine

The oxidizing agent is injected into the first chamber where decomposition into O₂ is aided by potassium permanganate. The hydrogen-peroxide (H₂O₂) decomposes into dioxygen (O₂) as it reacts with the potassium permanganate (KMnO₄), which is encased in a flame retardant foam. The unbalanced chemical reaction is as follows:



The specific enthalpy released during decomposition is:

$$\Delta h_{\text{decomposition}} = \frac{\Delta H_{\text{H}_2\text{O}_2}}{M_{\text{H}_2\text{O}_2}} \quad (2.3)$$

Where ΔH is the change in enthalpy. The energy released heats the grain's surface to autoignition temperatures of approximately 260 °C in this extremely oxygen-rich environment. The increased temperature increases the pressure, in accordance to the ideal-gas law:

$$PV = nRT \quad (2.4)$$

The ideal gas law is crucial in our description of the rocket. Describing the rocket's upstart phase requires coupling the changes in temperature T , pressure P and amount of substance n . During injection and decomposition, combustion occurs simultaneously.

2.2.2 Combustion Chamber

The combustion chamber contains two important theoretical aspects. First, the propellant grain has significant effects on the rocket's thrust over time. Secondly, the theoretical description of the rocket's combustion allows us to estimate different working parameters, and deciding the rocket nozzle's size and area ratios.

Propellant Grain

The combustion chamber consists of an approximate 3 liter cavity which is filled with the grain. The actual volume in a hybrid rocket depends strongly on the initial condition of the grain and the fuel's combustion rate. Holes have to be carved in the grain to allow oxygen to reach the grain's surface, and transport exhaust towards

2.2. Theoretics of the Hybrid Rocket Engine

the throat. The combustion rate is largely determined by the exposed surface area of the grain, and the flux of the oxidizer. The surface gradually expands as the outer regions are burned away, thus changing the rocket's effective thrust over time [5, chapter 12, p. 174]. *The propellant's increase in burning area during the first second is assumed to be negligible, compared to the rapid increases in pressure and temperature.*

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The shapes and sizes of the holes in the grain has a large impact on the initial ignition and thrust ratios. [6] Therefore, several different grain geometries are being tested . Depending on the surface areas, the different grain's regression rate varies greatly over time. Unless oxygen is the limiting factor, the regression rate will be proportional to the thrust. The generated thrust is directly proportional to the instantaneous burning area, and as this area increases, so does the thrust.

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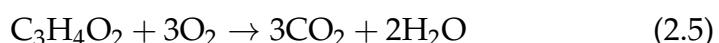
An alternative explanation to the pressure spike could therefore be a very fast increase in regression area. The grain's specifications from the previous tests are not mentioned, but a wagon-wheel design with several holes could allow ignition in single canals before all of them. This could allow hot pyrolytic fuel and oxygen to accumulate, causing an eventual explosion.

Autoignition

An effect that appears to be an important piece of the puzzle is the autoignition of the grain. As soon as decomposition occurs, the material begins to heat up, until it spontaneously ignites. This point can be found by reading the datasheet of the material, albeit the value is listed for atmospheric air. [7]

Combustion

As temperatures reach the MDF's autoignition point, and oxygen levels increase, combustion starts taking place. The combustion reaction can be described chemically by the formula:



Energy released in this reaction heats up the chamber's fluids towards a design temperature of 2498 K. Assuming a *closed* chamber,

2.2. Theoretics of the Hybrid Rocket Engine



Figure 2.2: Cross section of the throat area.

the rise in temperature and amount of substance yields an exponential increase in pressure over time. This is not a desired property, as that would eventually lead to engine destruction. The accumulated decomposed and combusted material leaves through the rocket's throat, which allows the rocket to reach pressure-equilibrium. The throat's area is essential to the rocket's pressure and thus stability, hence the advance to the throat.

2.2.3 Throat

The throat begins at the end of the combustion chamber, at the opposite side of where injection occurs. The throat is characterized by the convergence of the rocket chamber into a small passage called the throat, followed by a diverging section: The nozzle. The throat's cross-sectional area is what determines the maximum flow rate, as the speed of sound restricts the flow of matter. In order to calculate the amount of matter contained in the chamber, it is crucial to know how much is flowing out. Due to conservation of mass, the flow rate \dot{m}_t must be proportional to the density of the material, the

2.2. Theoretics of the Hybrid Rocket Engine

velocity and the throat's area:

$$\dot{m}_t = \rho \cdot v_t \cdot A_t \quad (2.6)$$

[8] The velocity v_t is thus roughly proportional to the mass flow as the area and density are approximately constant in this case. Hence, as the matter approaches the speed of sound, the flow rate out of the rocket stagnates. This is called mass flow choking, which must be at a maximum when the velocity is equal to the speed of sound. This condition is satisfied when the mach number $M = 1$. For an ideal compressible gas, this becomes:

$$\dot{m}_t = \frac{A_t P_c}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (2.7)$$

Where P_c is the pressure in the combustion chamber, T_t is the temperature in the throat, γ is the specific heat ratio and R is the gas constant. [8] Three outcomes are possible:

$\dot{m}_t < \dot{m}_{in}$, less mass is coming out than is flowing "into" the rocket.

$\dot{m}_t = \dot{m}_{in}$, mass outflow equilibrium.

$\dot{m}_t > \dot{m}_{in}$, more mass is flowing out than is being created.

The first outcome would yield increasing pressure until the rocket has burned all of its fuel, or it explodes. The second option is what we know as a safe and steady rocket, assuming the designed mass flow equilibrium is within the rocket's boundaries. The final outcome will yield a slow decrease in pressure over time, until the rocket has been exhausted for material inside and combustion ceases.

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In order to describe the initial pressure spike it is necessary to not assume any of these conditions. The abrupt change from the first to the second condition is what is hypothesized to cause the spike in pressure. Therefore, simulating the mass flow out of the rocket is essential to our understanding of the phenomenon. This does however require knowledge of several key parameters within the rocket, which are difficult to calculate, unless some things are assumed, such as conservation of entropy. However, in order to combine this knowledge, we first have to look at the final piece:

2.4. Isentropic Flow

2.2.4 Nozzle

The rocket nozzle's primary function is to channel the combusted propellant out of the rocket and accelerate it. The optimal nozzle maximizes the velocity of the exhaust, preferably to supersonic values. The most well-known nozzle is a convergent-divergent nozzle called a deLaval Nozzle, which performs all of these things through simple geometry. An important part of maximizing the nozzle's performance is ensuring that the flow stays isentropic. At optimal ratios, the flow is frictionless and adiabatic, which ensures entropy is conserved. Isentropic flow is considered to *only* be dependent on the cross-sectional area of the nozzle that the fluid moves through. [9]

As the fluid is pushed through the throat it is highly pressurized. The nozzle is in contact with the surroundings, which acts as a reservoir of low-pressure gas between atmospheric pressure (101.3 kPa). and no pressure (in space!), depending on the rocket's whereabouts. The expansion of course depends on the surrounding pressure, but in general, the plume can be over- and underexpanded and ambient. Ambient is the preferred expansion of the plume, where the exhaust gas is in pressure equilibrium with the surrounding air. If the exhaust has the same pressure as the surroundings, the gas is optimally expanded, and provides the maximum amount of thrust to the rocket. [10]

2.3 Heat Capacity

$$\gamma = \frac{C_p}{C_v} \quad (2.8)$$

2.4 Isentropic Flow

In order to effectively describe the rocket's behavior, we have to assume a few things:

1. Entropy is conserved.
2. Decomposition and combustion products obey the perfect gas law.



Figure 2.3: Isentropic flow between two points x_1 and x_2 in the rocket.

3. All chemical reactions are adiabatic: No heat is lost to the surroundings.
4. The fluid velocity inside the chamber is approximately zero, allowing us to assume stagnated pressure. The velocity is *not* assumed to be zero when entering the throat and nozzle, however.

The assumption of isentropic flow stems from the idea that the process is reversible. The fluid will, after moving through the nozzle, have the same original values. The second law of thermodynamics states that reversible flow maintains entropy, and this allows us to calculate almost any value related to the rocket's flow. It is therefore an essential piece to the project. [9]

If supersonic flow is not achieved by gradual means, isentropic flow is not a valid assumption. If shock waves occur abruptly, isentropic flow is not a valid assumption. Hence, exit values are simulated before any normal or oblique shock relations occur. [11]

The simulation is based on four valuable equations: The conservation of energy, the continuity equation, the momentum equation and equation of state.

Conservation of energy requires that for adiabatic flow, between

2.4. Isentropic Flow

two any points x_1 and x_2 , as seen in figure 2.3:

$$h_1 - h_2 = \frac{1}{2}(v_2^2 - v_1^2) = C_p(T_1 - T_2) \quad (2.9)$$

where h again is the enthalpy of the fluid, v is the flow velocity and C_p is the heat capacity, T is the fluid's temperature. From the continuity equation, we can find a pseudo-steady state from looking at the stagnation temperature in the chamber. Setting $v_2 = 0$ yields the stagnation temperature:

$$T_0 = T + \frac{v^2}{2C_p} \quad (2.10)$$

This yields several key relationships between stagnation properties for pressure, density and temperature:

$$\frac{T_0}{T} = \frac{P_0}{P}^{\frac{\gamma-1}{\gamma}} = \frac{\rho_0}{\rho}^{\gamma-1} \quad (2.11)$$

[12, chapter 3, p. 60-63] Using this, we can find the temperature at the exit:

$$T_e = \frac{P_e}{P_0}^{1-\frac{1}{\gamma}} \cdot T_0 \quad (2.12)$$

As P_e is the exit pressure, which is equivalent to the ambient pressure. The exit temperature allows us to calculate the density of the exiting fluid ρ_e :

$$P_e = \rho_e R T_e \Rightarrow \rho_e = \frac{P_e}{R T_e} \quad (2.13)$$

Bernoulli's equation provides us with the exit velocity v_e :

$$v_e = \sqrt{2 \frac{P_0 - P_e}{\rho_e}} = \sqrt{2 \frac{P_0 - P_e}{\frac{P_e}{R T_e}}} \quad (2.14)$$

$$\Rightarrow \sqrt{2 \frac{(P_0 - P_e) R T_e}{P_e}} \quad (2.15)$$

Exit velocity and density yields the mass outflow per second:

$$\dot{m}_{\text{out}} = A_e \cdot v_e \cdot \rho_e \quad (2.16)$$

2.4. Isentropic Flow

and knowing how much matter is flowing "into" the rocket (see injection and combustion chamber sections) yields the total enthalpy contained in the rocket at all times. Therefore, we can now approximate the temperature in the rocket's chamber, knowing the different material's abundances.

(2.17)

3

Simulation

The rocket's simulation can be explained relatively simply through a series of flowcharts. The first one describes how all constants and flows are defined, and how reference values are calculated.

3.1 Implementation

The rocket engine's ignition algorithm is based on the previous assumptions. Figure 3.1 show a flowchart of the ignition algorithm. The implemented algorithm is divided into four parts, which determine the rocket's performance at various stages. The first stage is the rocket's pre-launch conditions, eg. amount of substance n , pressure P and temperature T . The second stage is injection of oxidizer into the pre-combustion (or decomposition) chamber. The amount of injected oxidizer is equivalent to the injection nozzle's flow per time step Δt in every iteration. This is followed by recalculating the rocket's conditions. After the initial matter has been injected, decomposition starts. This is the third stage of the algorithm. Post decomposition, the temperature, pressure, exit velocity v_e and exit mass can be found. The temperature is compared to the autoignition temperature T_{auto} : If higher, combustion of material still contained inside the rocket starts. Otherwise, more oxidizer is injected and decomposed until the energy released during decomposition heats the interior to autoignition temperatures. The final stage occurs when temperatures are large enough to allow combustion. Combustion takes place using *all* the available oxygen inside

3.1. Implementation

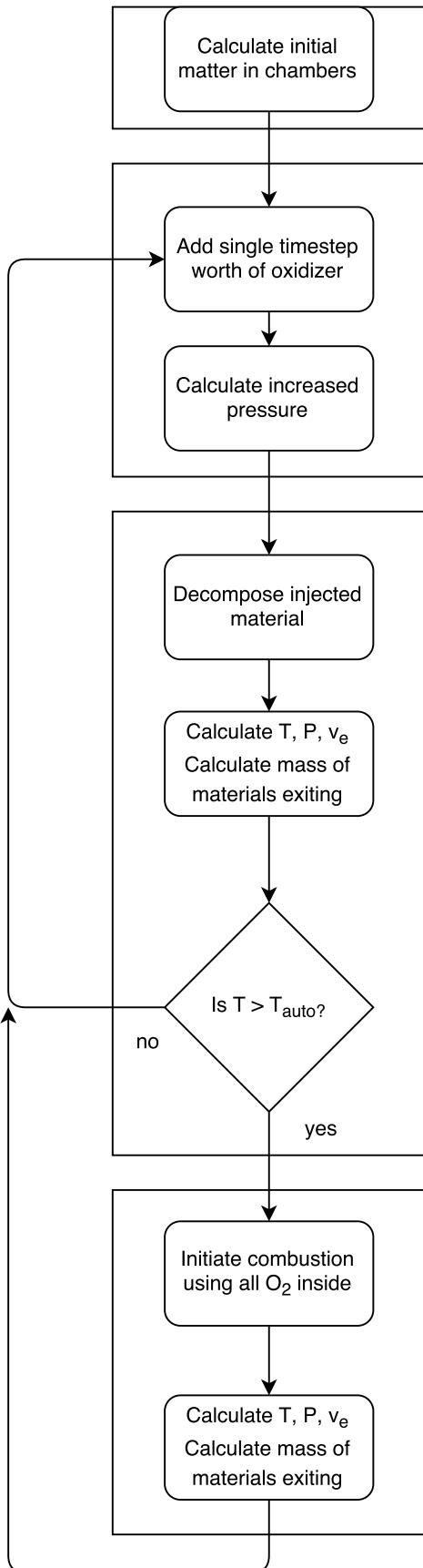


Figure 3.1: Scheme showing the implementation of the rocket's ignition algorithm.
16

3.1. Implementation

the rocket during every iteration. This means, that if $T_{\text{auto}} \approx T_{\text{amb}}$, combustion occurs instantaneously, using only the oxygen released by the first time step's oxidizer. If, however, $T_{\text{auto}} > T_{\text{amb}}$ (as it is in our case), combustion occurs a certain time later, allowing oxygen to accumulate inside the chamber.

4

Rocket tests

Testing of the rocket engine ensued at "Raketmadsens Rumlaboratorium" in Copenhagen on the 3rd to the 4th of may 2016. The tests were carried out by me in company by my advisor Gorm Bruun Andresen, and seven other students from Navitas.

4.1 Logbook

4.1.1 Day 1

The test setup consists of the rocket engine with several piezoelectric and piezoresistive pressure sensors, as well as a force sensor at the back. The pressure sensors sit at various sites on the rocket, allowing us to detect any pressure waves travelling through the chamber, and measuring the rocket's pressure throughout the firing. The force sensor (henceforth mentioned as ForceLink) measures the rocket's thrust.

The equipment is set up with LabVIEW, which Gorm spent most of the first day configuring. The rocket setup was tested on day 1, otherwise, the day consisted mostly of setting up the tent and establishing a remote connection to a new computer and installing the necessary programs.

4.1. Logbook



Figure 4.1: Foam permeated with KMnO_4 dust inserted into the decomposition chamber, inside a tube of MDF, in order to avoid accumulation of liquid H_2O_2

4.1.2 Day 2

Day 2 started early with preliminary water tests at 12:13, 12:33, 12:57 and 13:21. Two injectors, a low-flow and a high-flow, were brought along and tests of both ensued. Following the preliminary water tests, the rocket chambers were assembled and foam permeated with KMnO_4 was prepared and inserted into the decomposition chamber, as seen in figure 4.1. Initial rocket test started almost two hours after the final water test at 15:20 with 15L of H_2O_2 at 24bar pressure. After the test, the stand was quite smokey as the rocket flanges were *not* tightened correctly and an O-ring was missing. A leak between the grain's chamber and the after-burn chamber seared the underside of the protective casing, thankfully without harming any of the measurement equipment. After the

small upset, three additional tests were carried out.

The three first tests were all done with the low-flow nozzle with a total radius of 15mm per injector hole, of which there were three. The final tests were carried out with the large injector with hole radii of 2mm. The second test happened at 17:22 with a H_2O_2 pressure of 24bar, the next at 18:32 with 31bar. The final test was done

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at 20:19, with a H₂O₂ pressure of 31bar, with the high-flow nozzle.

All tests were done with the same hexagonal patterned grain, with masses pre- and postburn noted.

The day concluded with Peter Madsen using our test rig to test his own rocket based on a catalytic pack, with no combustion present.

The firing procedure was meticulously planned out, in order to avoid any eventual dangers. Thus, including a such list is essential for future rocketeers:

4.2 Firing Procedure

Launching the rocket requires several crucial steps in order to safely ignite the engine. Safety is the number one priority, thus, a stepwise checklist is necessary.

PRELAUNCH

1. Insert grain
2. Insert foam permeated with KMnO₄
3. Assemble rocket chambers
4. Establish remote access to control computer
5. Ensure measurement options are correct
6. Check signal and restart ManuWare
7. Create new data-log file

ALL CLEAR AREA EXCEPT FUEL RESPONSIBLE PERSON

1. Equip H₂O₂ safety equipment
2. Fill tank with H₂O₂
3. Pressurize tank
4. CLEAR THE AREA
5. Start data-collection and cameras
6. Arm the rocket
7. Fire the rocket
8. Stop data-collection and cameras

4.3. Results

9. Remove external pressure compressor
10. Depressurize tank
11. Area is safe

Peter Madsen and his assistant Stefan Eisenknappel are the only two people present when loading the rocket with H₂O₂. The procedure is executed from start to end at each launch, and has several areas where it can be improved if time permits.

The control computer should be replaced by a microcontroller, such as an arduino or raspberry pi. As of this project, the data bandwidth is too low in either alternative, but it is a viable solution in the near future.

In order to reduce reload time, adding more piping to the christmas tree is necessary, as air leaving the H₂O₂ tank flows back, spilling the H₂O₂ concentration out of the funnel. When a suitable final design is done, welding the pieces together is a superior alternative to using bolts and nuts. Welding removes any chance hydrogenperoxide leaking, damaging the rocket and measurement equipment.

The rocket's arming and controlpad needs to be set up in a smarter, more convenient way. The ideal setup is to have a single controlbox, that when starts data-collection as soon as the rocket is armed, and notes when it is fired. This would allow everything to be controlled from a single box, with measurements being saved to a raspberry pi situated at the base of the rocket. Data can then instantaneously be read from a secondary computer through cable or wireless connection. As the rocket's final destination is space, continuously improving data-transfer and making the rocket an individual unit is paramount.

Removing additional noise from measurements can easily be done avoiding ground-loops. The ignition controlpad was grounded differently than the other equipment, which introduced another way for electricity to run to ground.

4.3 Results

A total of ten measurements were collected at every test. The most essential is the Piezoelectric pressure sensors located at the front.

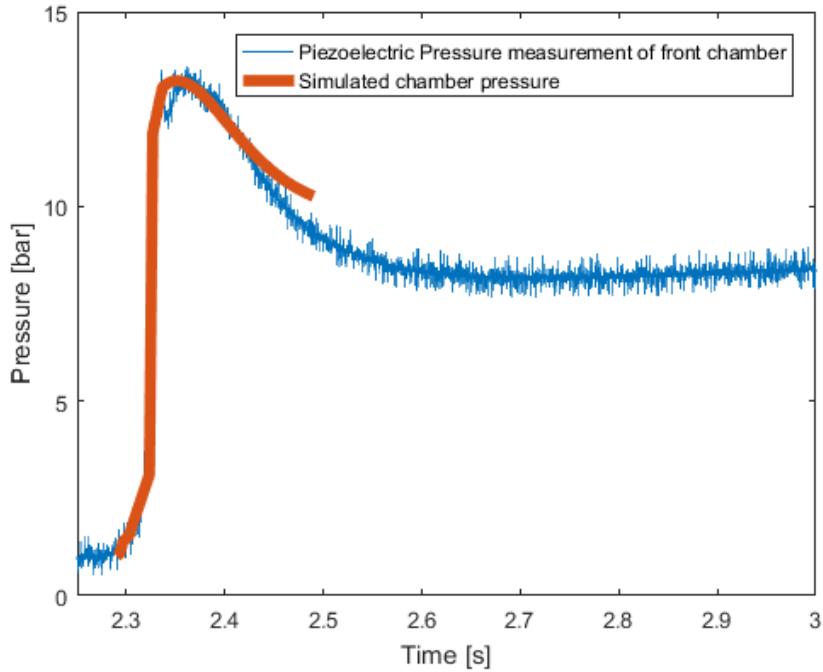


Figure 4.2: The second burn's front chamber peak, as found by the Piezoelectric pressure sensor. Plotted on top is the simulation created in this bachelor's thesis.

The simulation calculates the pressure after the combustion chamber, and at the nozzle's exit.

The experimental and simulation results are seen in figure 4.2, where the blue line is the experimental results, and the red is the simulated pressure. The simulation assumes no combustion until a temperature of 220 celcius, at which all of the oxygen inside the combustion chamber is instantly consumed, followed by a steady burning phase. The instantaneous combustion looks like an explosion, as more oxygen is available at this point than at any other. The experimental front pressure dips shortly after initial combustion, which may be due to a shockwave moving through the rocket, forcing new oxygen from flowing to the grain's surface for a short period of time. The pressure then drops rapidly to a steady state, where the simulation ends just prior. The abrupt ending is due to a bug in the current version of the simulation software EES, which crashes after a certain number of iterations. Future versions may allow the calculation of the steady state. Take note of the simulation's timescale, as the duration of the peak is very small, almost only two tenths of

4.3. Results

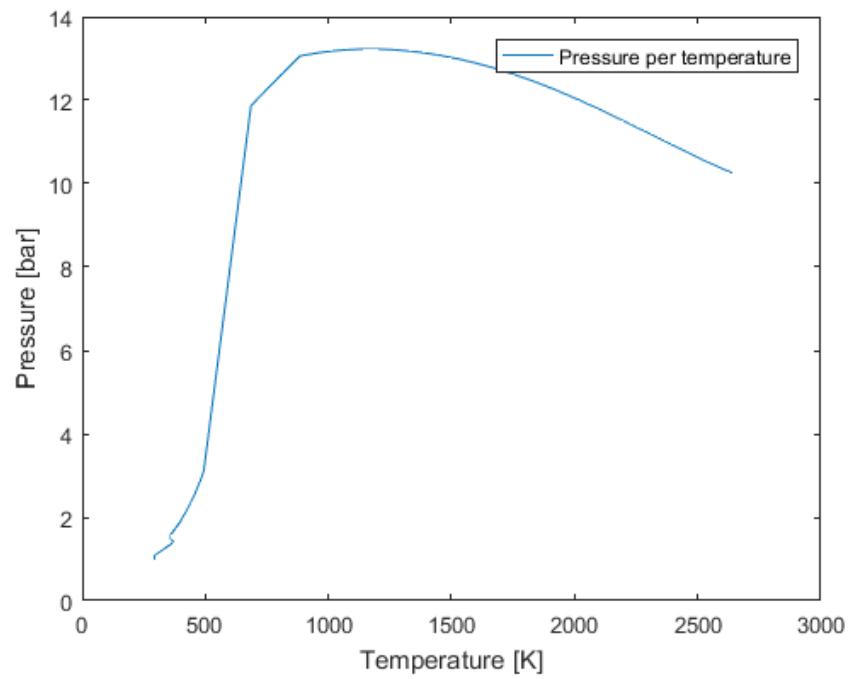


Figure 4.3: Pressure per temperature plotted over the simulated timespan in figure 4.2. As the temperature rises, the pressure falls.

a second.

5

Discussion

Comparing the simulated rocket engine and the experimental data allows us to compare real life with theory.

6

Conclusion

7

The Project's Future

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7. The Project's Future

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Additional figures

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Bibliography

- [1] Bulbapedia. http://bulbapedia.bulbagarden.net/wiki/Team_Rocket, may 2016.
- [2] George P. Sutton and Oscar Biblarz. *Rocket Propulsion Elements*. Wiley, 8th edition, 2010.
- [3] Thermocouples: Using Thermocouples to Measure Temperature. <http://www.omega.com/prodinfo/thermocouples.html>, 2016.
- [4] SierraPine. *MDF Material safety data sheet*, January 2005.
- [5] John D. Clark. *Ignition!: An informal history of liquid rocket propellants*. Rutgers University Press, 1st edition, 1972.
- [6] Richard Nakka. Propellant Grain. http://www.nakka-rocketry.net/th_grain.html, july 2001.
- [7] James G. Quintiere. *Principles of Fire Behaviour*. Delmar, 1st edition, 1997.
- [8] Nancy Hall. Compressible Area Ratio. <https://www.grc.nasa.gov/www/k-12/airplane/astar.html>, May, 2015.
- [9] Richard Nakka. Nozzle Theory. http://www.nakka-rocketry.net/th_nozz.html, April 2014.
- [10] Robert A. Braeunig. Nozzle. <http://www.braeunig.us/space/propuls.htm>, 2012.
- [11] Nancy Hall. Isentropic Flow. <https://www.grc.nasa.gov/www/k-12/airplane/isentrop.html>, May, 2015.
- [12] Seppo A. Korpela. *Principles of Turbomachinery*. Wiley, 1st edition, 2012.