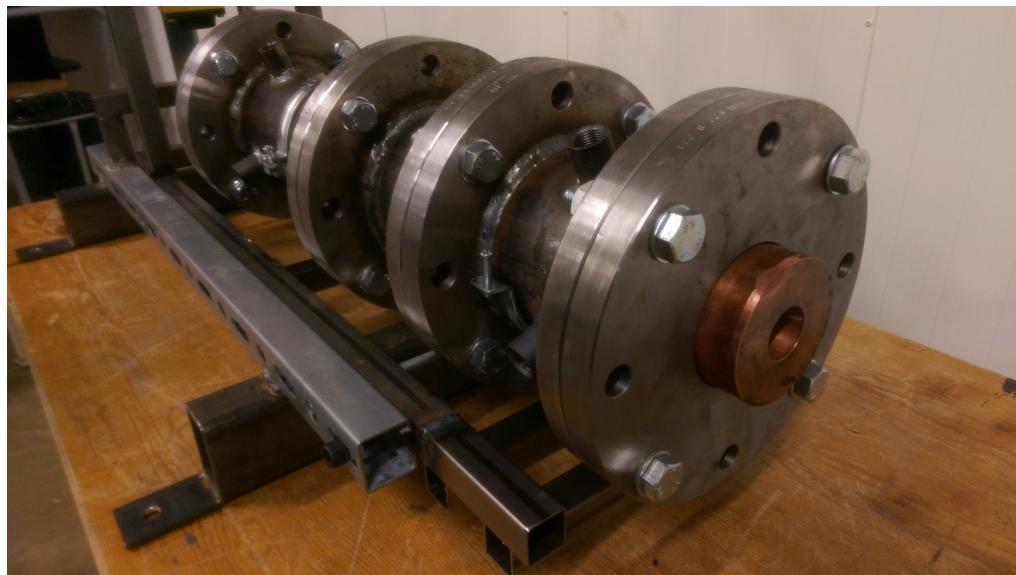


HYBRID ROCKET ENGINE



Carl-Emil Grøn Christensen
Department of Physics and Astronomy, Aarhus
University

Supervisor:
Gorm Bruun Andresen
Department of Engineering, Aarhus University

June 2016

Abstract

.5Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

.5Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Contents

1	Introduction	1
2	Theory	3
2.1	Basic Rocket Science	3
2.2	Theoretics of the Hybrid Rocket Engine	4
2.2.1	Injection	5
2.2.2	Combustion Chamber	6
2.2.3	Throat	7
2.2.4	Nozzle	9
2.2.5	Isentropic Flow	10
3	Simulation Results	11
4	Rocket tests	15
5	Conclusion	19
A	Additional figures	21
B	Sensitivity analysis	23
	Bibliography	25

1

Introduction

It's not rocket science.

The following report contains simulations and observations of the hybrid rocket M.E.O.W.T.H II (**M**echanical **E**ngineering **O**bservational **T**utoring **H**ybrid rocket). created by *Team Rocket* 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 M.E.O.W.T.H.'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. [1, 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, M.E.O.W.T.H 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. [2] 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 Raketauditoriet's spacelaboratory. M.E.O.W.T.H 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

2.2. Theoretics of the Hybrid Rocket Engine



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

oxidizing 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 [1, 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 effectiveness 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. This is the largest part of the rocket, as seen on figure 2.1, which 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. [3] 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.

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% H₂O₂ rich mixture with the remainder being H₂O. 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 .

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

Fixme Note: Hvordan angiver jeg kilde/skal jeg ændre dette til at være tidsafhængig?

2.2. Theoretics of the Hybrid Rocket Engine

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 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 [4, chapter 12,

2.2. Theoretics of the Hybrid Rocket Engine

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.

Fixme Note: Er det her en god antagelse?

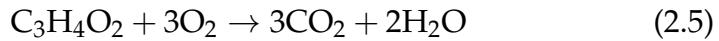
The shapes and sizes of the holes in the grain has a large impact on the initial ignition and thrust ratios. [5] Therefore, several different grain geometries are being tested. Depending on the surface areas, the different grain's regression rate varies greatly over time. Unless oxygen is the limiting 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.

Fixme Note: SKRIV OM DE FORSKELLIGE HVILKE HAR VI VALGT? HVORFOR?

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.

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, 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

2.2. Theoretics of the Hybrid Rocket Engine



Figure 2.2: Cross section of the throat area.

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 velocity and the throat's area:

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

[6] 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:

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

2.2. Theoretics of the Hybrid Rocket Engine

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. [6] 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.

Fixme Note: Passer det med masse?

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:

2.2.4 Nozzle

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.

2.2. Theoretics of the Hybrid Rocket Engine

2.2.5 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.
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.

3

Simulation Results

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis.

3. Simulation Results

Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

3. Simulation Results

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

4

Rocket tests

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis.

4. Rocket tests

Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

5

Conclusion

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis.

5. Conclusion

Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetur adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetur.

A

Additional figures

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

B

Sensitivity analysis

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Bibliography

- [1] George P. Sutton and Oscar Biblarz. *Rocket Propulsion Elements*. Wiley, 8th edition, 2010.
- [2] Thermocouples: Using Thermocouples to Measure Temperature. <http://www.omega.com/prodinfo/thermocouples.html>, 2016.
- [3] SierraPine. *MDF Material safety data sheet*, January 2005.
- [4] John D. Clark. *Ignition!: An informal history of liquid rocket propellants*. Rutgers University Press, 1st edition, 1972.
- [5] Richard Nakka. Propellant Grain. http://www.nakka-rocketry.net/th_grain.html, july 2001.
- [6] Nancy Hall. Compressible Area Ratio. <https://www.grc.nasa.gov/www/k-12/airplane/astar.html>, May, 2015.