LIQUID PROPULSION ATTACHMENT REPORT NAKUJA PROJECT 3.5

TEAM

Kung'u mercy waithira
Carlos Kiti
Ilyas Osman
Churchill Okech

NAKUJA PROJECT

The Nakuja project is a technical development project based at the Jomo Kenyatta University of Agriculture and Technology (JKUAT) in Kenya, supported by the Kenya Space Agency (KSA). The project aims to build a liquid-fuel rocket to bring small satellites into orbit. The project has achieved several milestones, including the launch of the N-1, N-2, and N-3 solid model rockets, and the development of a test stand for a liquid rocket engine. The project is focused on low-cost and open-source development, with all code and work proceedings available on GitHub. The Nakuja project works in partnership with the KSA, which has supported the project's activities, including facilitating the launch of the N-2 and N-3 rockets.

Supervisor :Dr Shohei Aoki

Contact:aoki@jkuat.ac.ke

Table of Contents

INTRODUCTION

Liquid rocket propulsion represents a sophisticated domain of aerospace engineering, harnessing the principles of physics and chemistry to propel vehicles beyond the Earth's atmosphere. This report delves into the intricacies of liquid rocket engines, particularly focusing on a regenerative cooling design for thermal management. Regenerative cooling is a method where some or all of the propellant is circulated through channels or tubes around the combustion chamber or nozzle to absorb heat from the engine, effectively preventing overheating and potential damage. The engine under consideration will employ this technique, utilizing the cryogenic nature of the propellants to serve as an efficient coolant before being injected into the combustion chamber.

Furthermore, the report will explore the utilization of an augmented spark ignition system. This system is pivotal for initiating combustion in a controlled and reliable manner. It operates by injecting propellants into a pre chamber, where a spark ignites the mixture, creating a flame that stabilizes within the pre chamber before exiting into the main combustion chamber. This method ensures a consistent ignition source, which is crucial for the successful operation of the engine.

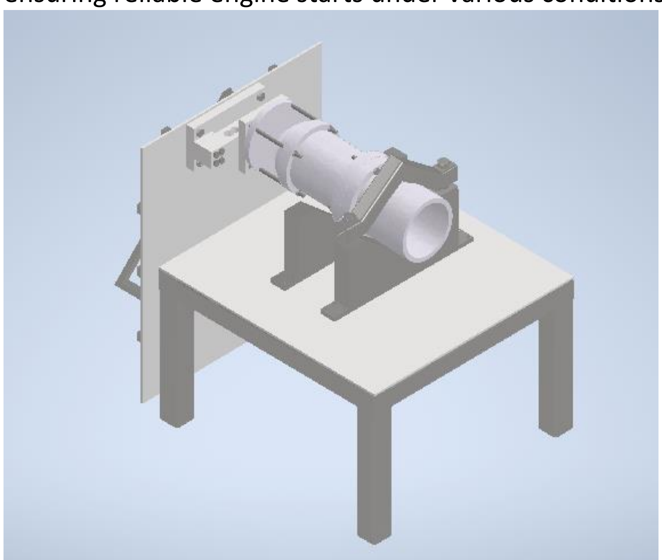
Additionally, the report will outline the procedures and findings of a water test, a critical step in the development of rocket engines. Water tests are conducted to simulate the flow of propellants through the engine's turbopump, allowing for the observation and analysis of cavitation phenomena without the risks associated with actual propellants. These tests provide valuable data that inform the design and operational parameters of the engine, ensuring its performance and reliability.

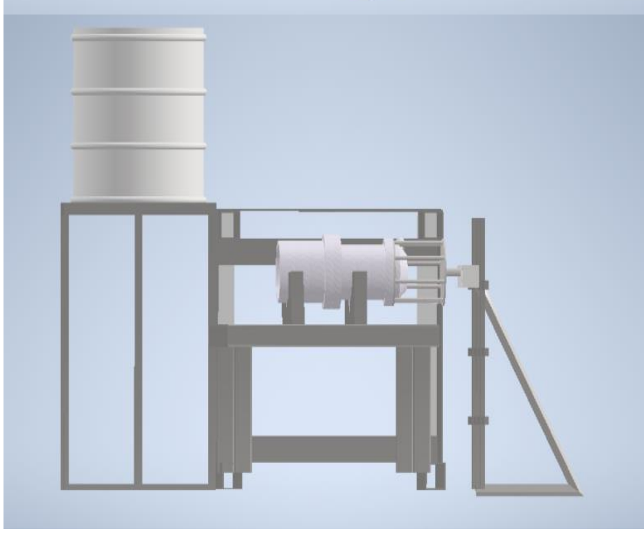
In summary, this report will present a comprehensive examination of a liquid rocket engine with regenerative cooling, augmented spark ignition, and the insights gained from water testing. Each component and process is integral to the development of a robust and efficient propulsion system, capable of meeting the rigorous demands of space travel. The culmination of these elements reflects the cutting-edge advancements in rocketry and the continuous pursuit of innovation within the field.

MECHANICAL DESIGN

Solid test stand design

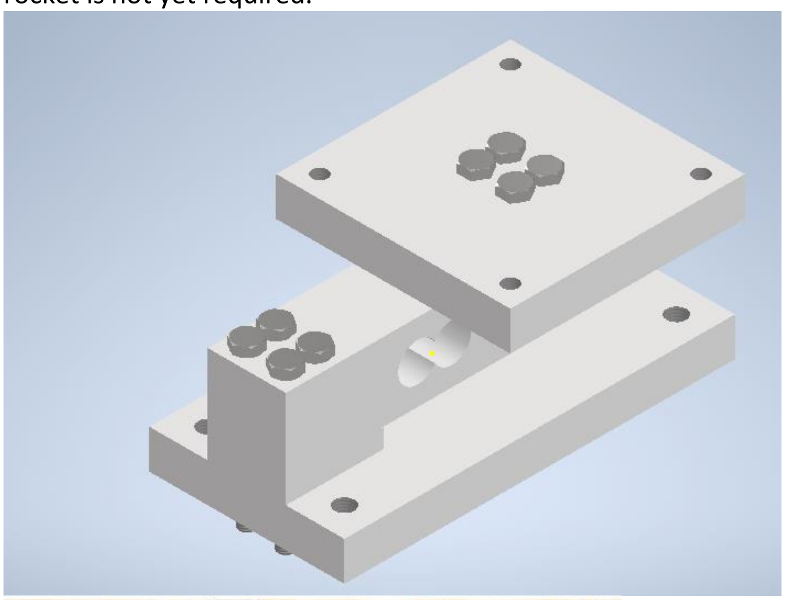
In the pursuit of advancing rocket propulsion technology, the development of a robust test stand is paramount. A test stand serves as a crucial platform for conducting experiments, validating designs, and assessing the performance of rocket engines. In this report, we will delve into the process of designing and building a liquid rocket test stand, highlighting the integration of an ignition augmented spark ignition system and the implementation of a strain gauge type load cell. The previous team's work on an ignition augmented spark ignition system provides a foundation for integrating the ignition system with the engine. This integration is critical for ensuring reliable engine starts under various conditions.





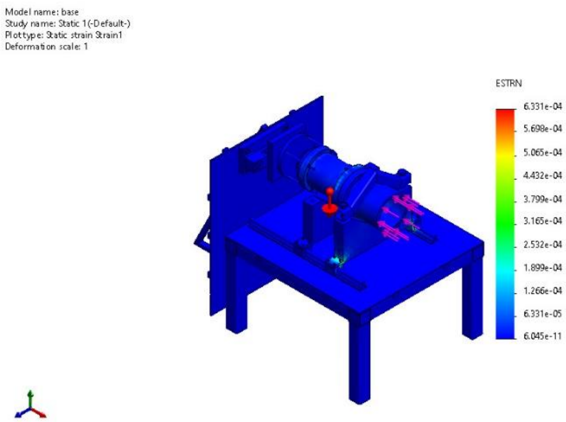
Implementation of Strain Gauge Type Load Cell

The choice of a strain gauge type load cell was driven by the need for accurate and real-time measurement of thrust forces exerted by the rocket engine during testing and since it was the most readily available in Kenya. The load cell is a crucial component that measures the thrust of the engine, which is essential for performance analysis and safety checks. The structure must not only hold the load cell in place but also minimize any interference with its readings. Integrating this load cell into the test stand posed a significant engineering challenge due to the dynamic nature of rocket propulsion. To address this challenge, we designed a specialized structure to securely hold the strain gauge load cell in place while accommodating the dynamic forces experienced during rocket engine testing. After evaluating various design options, we opted for a horizontal style configuration to optimize stability and minimize interference with the test stand components. In selecting a horizontal style for the test stand, several factors are considered. This orientation allows for easier access to the engine for maintenance and adjustments. It also facilitates a straightforward approach to scaling up the design for larger engines or adapting it for different types of tests. Moreover, a horizontal test stand can be beneficial for initial testing phases where vertical space may be limited, or where the full vertical structure of a launch-ready rocket is not yet required.

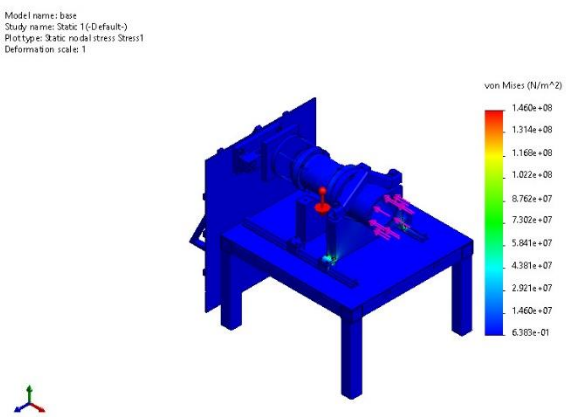


Simulations

Strain test



Stress test



Keg tank and water feed system

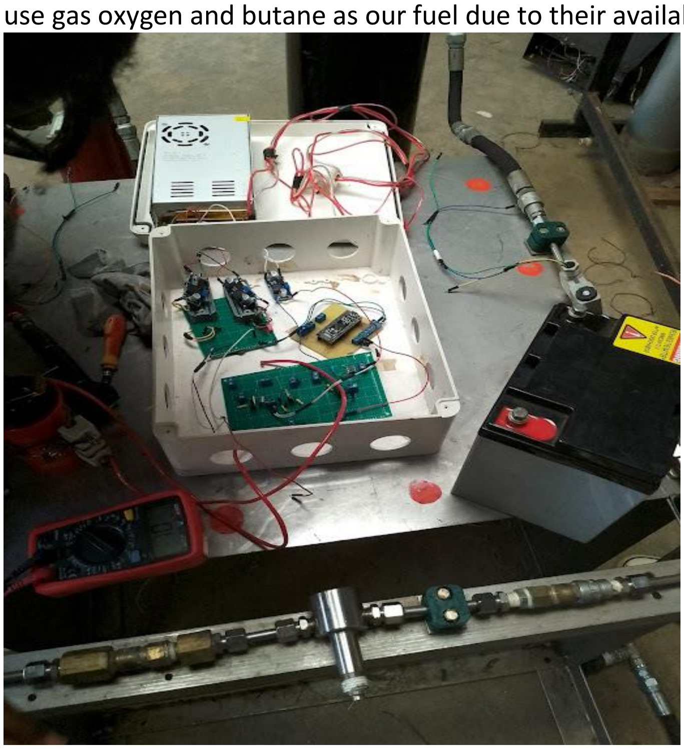
Transforming a keg tank into a storage and pressurization vessel for liquid engine propulsion involves several steps. Firstly, the keg must be equipped with a dip tube assembly, which allows the liquid fuel to be drawn from the bottom of the tank. This is crucial during the ignition phase to ensure a consistent supply of fuel. The dip tube typically consists of a tee fitting and a modified compression fitting that allows a tube to pass through and extend to the near bottom of the tank. When pressurizing with nitrogen gas, a regulator is attached to a nitrogen cylinder and connected to the keg tank's inlet. The regulator controls the flow and pressure of nitrogen into the tank's ullage space—the area above the liquid fuel. As nitrogen is inert, it effectively pressurizes the tank without reacting with the fuel. The pressure must be sufficient to overcome the liquid head and any friction in the dip tube to drive the fuel towards the engine. It's essential to ensure that the pressure does not exceed the tank's maximum service pressure to maintain safety and integrity of the system; this can be tested in the water test. The process must be conducted with appropriate safety measures, including the use of personal protective equipment and adherence to safety guidelines provided in the material safety data sheets for both the fuel and nitrogen gas. This setup is typically used for ground testing and not recommended for flight vehicles due to the complexity and safety concerns associated with pressurized systems in dynamic environments.

ELECTRONICS DEVELOPMENT

Ignition circuit

When we started the attachment the main focus was on working with the team that was developing the ignition circuit and ensuring that the circuit did fire. The team focused on the design and development of an augmented spark igniter (ASI) for the liquid rocket engine. They aimed to address the limitations of small-scale engines by offering a more streamlined and efficient solution compared to conventional ignition systems. The ASI system was developed as an alternative to direct-spark systems in rocket engines, aiming to achieve widespread ignition and withstand high-pressure environments. The team designed an augmented spark igniter that could be fabricated in-house, contributing to the development of a reliable ignition source for the rocket engine. Additionally, they emphasized the importance of proper microcontroller selection for the ignition system, ensuring performance, reliability, and safety. The team also developed a control algorithm to accurately estimate the ignition timing by monitoring the flow rate of the oxidizer into the ignitor, ensuring safe and efficient ignition of the liquid rocket engine.

From the p&id in the next chapter we get a view on how the flow of the fluids would be. In this case we use gas oxygen and butane as our fuel due to their availability in the Kenyan market.



Pressure sensor and solenoid control

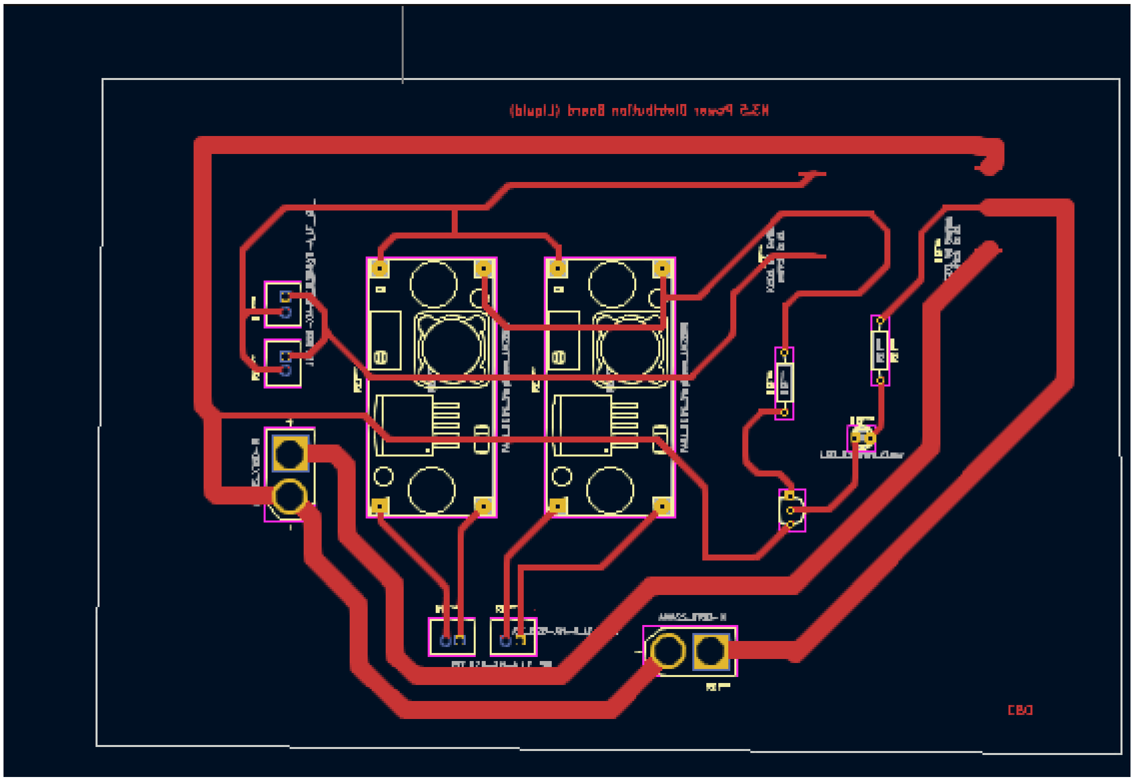
With the success of the ignition circuit, the team sought to modularize the ignition circuit.
This was considered because it enables the circuit to be broken down into small components that can be isolated and worked on separately after which they can be integrated into a complete system.
Also the debugging phase is easier when the circuit is modularized.

The circuit was thus broken down into:
1. Power distribution module
2. Control module.

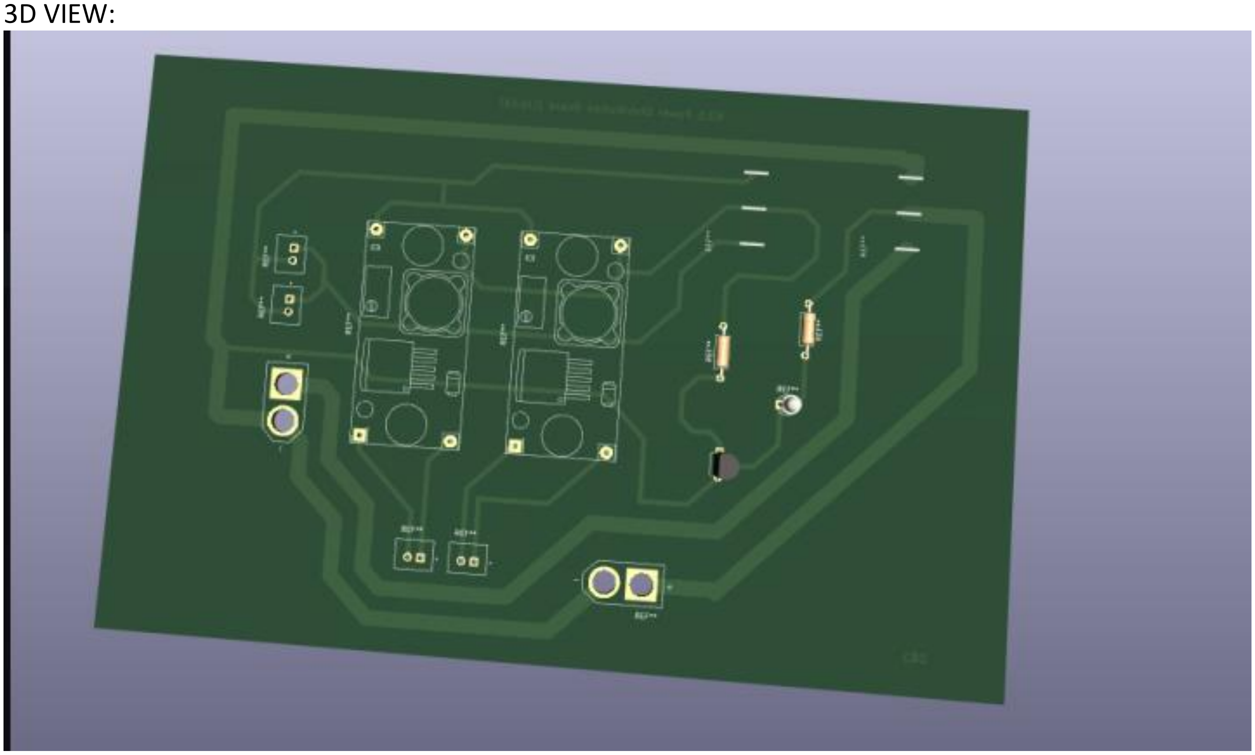
Power Distribution Module (Board)
This module powers the control board and the Spark plug (ignites the fuel).
The spark plug draws a high-voltage current while the electronics onboard the control circuit, primarily the microcontroller, requires delicate power feed; neither excess nor deficient, just precise as stipulated in the microcontroller data-sheet.
Also it was worth considering that in the long-run if needed to use another microcontroller type, the voltage supply would require regulation to the amount specified in the specific microcontroller data sheet.
Therefore, the power distribution board should feature a voltage regulation mechanism.
Similarly, the solenoid valves need around 12 V to be open.

Putting these into consideration, the team designed a simple power distribution board that encapsulated all of the above needs.

Below is the PCB design of the board:



3D VIEW:



Breakdown explanation of the board:

The Power distribution receives power from two sources:

1. SMPS
2. 12 V car battery

The two sources combined, provide power to the control board. The power from the SMPS gets fed to two buck converters; each buck-converter is configured to provide different DC voltages. (explanation coming in while.).

Likewise, the two power sources i.e. SMPS and Battery, have separate switches that enable them to feed their respective power to the Power Distribution board prior to distribution to the control board. This enables the ability to cut power manually to components that get power from this board in case there is a malfunction during tests (Safety feature).

The SMPS

The SMPS' power is fed to two buck converters; each configured to provide different voltages; one provides 5V, to power the microcontroller in the control board and the other provides 12 V to power the solenoid valves.

The voltage from these bucks is sourced from different terminals provided in the Power distribution board.

The Battery

The battery provides power meant to power the spark plug.

There is the provision of the input terminal to feed the Battery's power to the Power distribution board as well as an output terminal from where the control board sources this power and feeds it to the spark plug.

Control module

Objectives of the board

- Houses the microcontroller board that controls the ignition Circuit i.e.: firing
- Has override switches for manually overriding the microcontroller in case it malfunctions during the engine operation.
- Is modular enabling extension of other circuitry.

Design

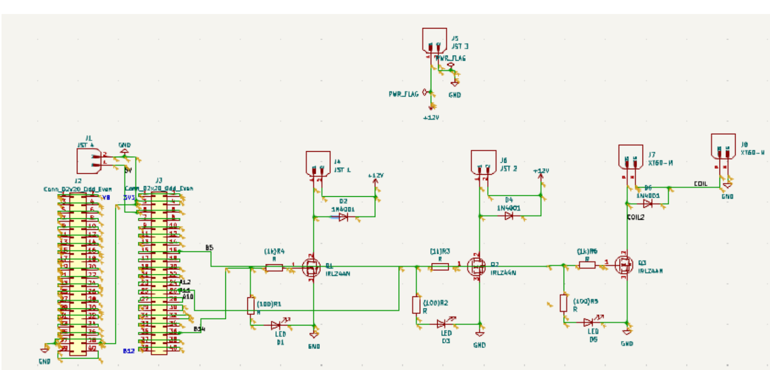


Figure 1 schematic of the control circuit PCB

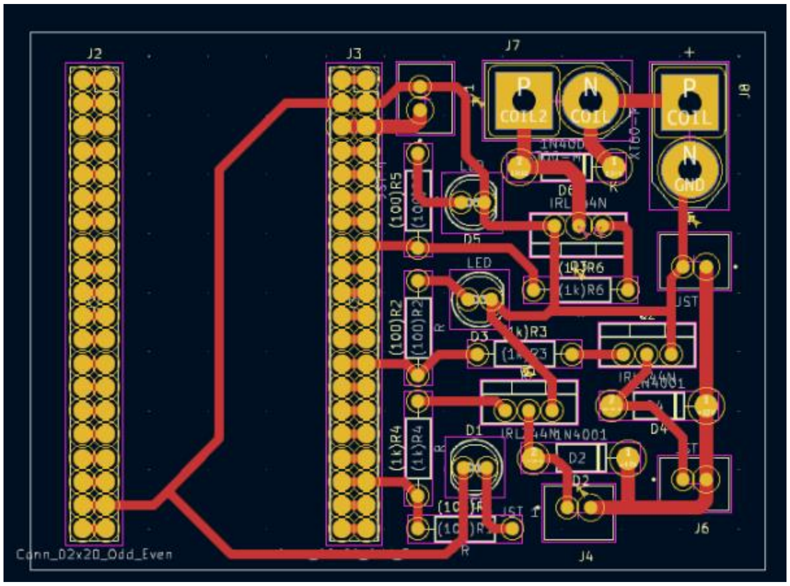


Figure 2copper tracks for the control circuit pcb

Fabrication

Steps for fabricating a PCB

- **Print the Design on Transparent Film:** Print each layer of the PCB design onto a transparent film. This film will be used to transfer the design onto the PCB substrate.
- **Clean the PCB:** Clean the copper-clad board to remove any oxidation and ensure a smooth surface for photoresist application.
- **Align the Film:** Place the transparent film with the PCB design over the photoresist-coated board.
- **UV Exposure:** Expose the board to ultraviolet (UV) light through the film. The UV light hardens the photoresist on areas that should remain, leaving unexposed areas soft.
- **Develop the Photoresist:** Use a developer solution to wash away the unexposed (soft) photoresist, revealing the copper beneath.
- **Etch the Board:** Submerge the board in an etching solution, typically ferric chloride or an ammonium persulfate solution, to remove the unwanted copper, leaving only the copper traces protected by the hardened photoresist.
- **Clean the Board:** Rinse the board to remove the etching solution and remaining photoresist. Add the components.

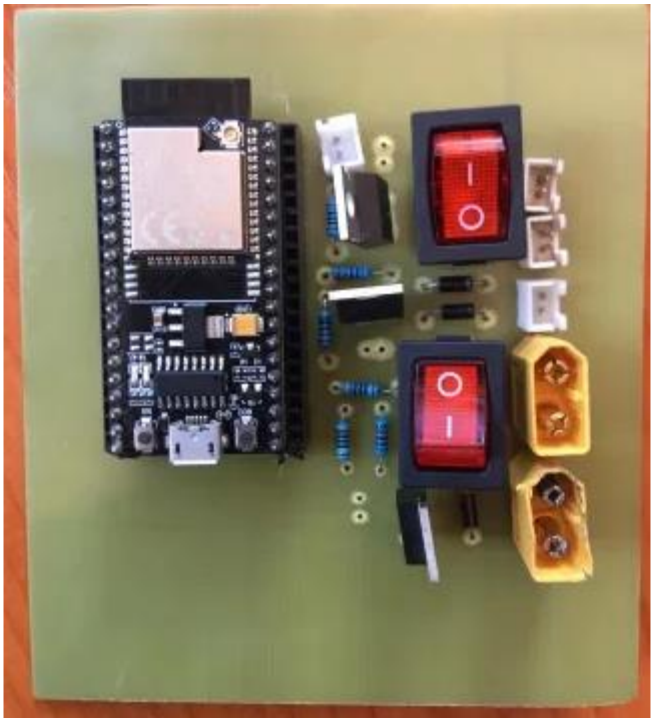


Figure 3control board

The control board is integrated with the power board to operate all the components in the circuit that is the solenoid valves ,the pressure sensor , the flow meters and also the spark plug .

TESTING AND VALIDATION

P&ID Diagram

In the realm of liquid rocket testing, precise instrumentation and control systems are essential for ensuring safety, efficiency, and performance. One crucial tool used in the design and operation of liquid rocket test stands is the P&ID diagram. In this section, we will elucidate what a P&ID diagram is and its significance in the context of liquid rocket testing. And also show the designs we came up with for our rocket design.
P&ID stands for Piping and Instrumentation Diagram. It is a schematic representation that illustrates the piping, instrumentation, control devices, and process flow of a system. In the context of liquid rocket testing, a P&ID diagram provides a comprehensive visual depiction of the test stand setup, including the rocket engine, propellant supply systems, instrumentation, valves, sensors, and control mechanisms.

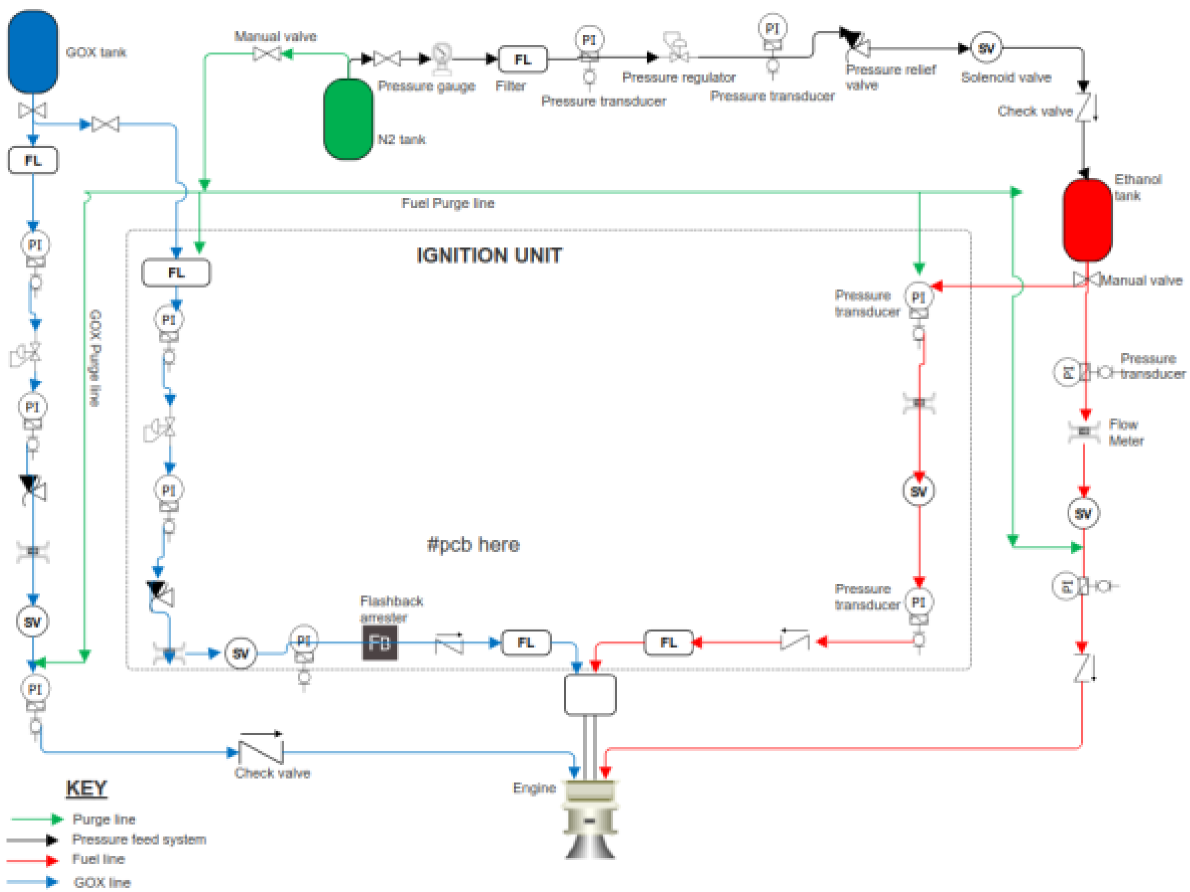
Components of a P&ID Diagram

1. Piping: The P&ID diagram depicts the piping network that carries propellants (such as liquid oxygen and liquid fuel) from storage tanks to the rocket engine. It illustrates the routing, connections, and specifications of the piping system, including pipe sizes, materials, and fittings.

2. Instruments and Sensors: Various instruments and sensors are incorporated into the P&ID diagram to monitor and control critical parameters during testing. This may include pressure gauges, temperature sensors, flow meters, level indicators, and safety devices. Each instrument is represented by a specific symbol with annotations detailing its function and measurement range.

3. Valves and Control Devices: Valves play a crucial role in regulating the flow of propellants and controlling the operation of the rocket engine. The P&ID diagram delineates the type, location, and function of valves within the system, such as isolation valves, control valves, relief valves, and emergency shutdown valves. Control devices, such as actuators and solenoids, are also depicted to illustrate their interaction with the process.

4. Process Flow: A key feature of the P&ID diagram is the depiction of process flow, illustrating the sequence of operations and the direction of propellant flow within the system. This helps engineers and operators visualize the test stand dynamics and identify potential bottlenecks or safety hazards.



RPA Data Simulation

While the previous team had conducted simulations for the liquid rocket engine, our task was to reevaluate and confirm these simulations using advanced tools. We utilized RPA software, which stands for Rocket Propulsion Analysis, renowned for its sophistication in liquid rocket engine design and analysis. In this section, we will elucidate the capabilities of RPA software and present the results of our simulations.

Understanding RPA Software:

RPA software serves as a powerful tool in the realm of liquid rocket propulsion, providing engineers with invaluable insights into engine performance and design optimization. It employs advanced algorithms and computational methods to predict various aspects of engine operation, including thrust chamber sizing, nozzle wall contour optimization, and engine cycle power balance. One of the key functionalities of RPA software is its ability to calculate chemical equilibrium compositions from a diverse range of propellant components. By analyzing thermodynamic properties of reaction products, the software facilitates precise estimation of engine performance metrics such as specific impulse, thrust, and combustion efficiency. Additionally, RPA software aids in determining engine mass and optimizing critical parameters to enhance overall propulsion system efficiency.

Presentation of Results:

In the subsequent section, we will present the results of our simulations using RPA software.

Rocket engine characteristics:

Table 3. Theoretical (ideal) performance

Parameter	Sea level	Optimum ex	Vacuum	Unit
Characteristic velocity	0.0000	1846.9100	0.0000	m/s
Effective exhaust velocity	2622.7500	2627.6000	2994.0400	m/s
Specific impulse (by mass)	2622.7500	2627.6000	2994.0400	N·s/kg
Specific impulse (by weight)	267.4500	267.9400	305.3100	s
Thrust coefficient	1.4201	1.4227	1.6211	

Table 4. Estimated delivered performance

Parameter	Sea level	Optimum ex	Vacuum	Unit
Characteristic velocity	0.0000	1795.5400	0.0000	m/s
Effective exhaust velocity	2474.6200	2479.4800	2845.9100	m/s
Specific impulse (by mass)	2474.6200	2479.4800	2845.9100	N·s/kg
Specific impulse (by weight)	252.3400	252.8400	290.2000	s
Thrust coefficient	1.3782	1.3809	1.5850	

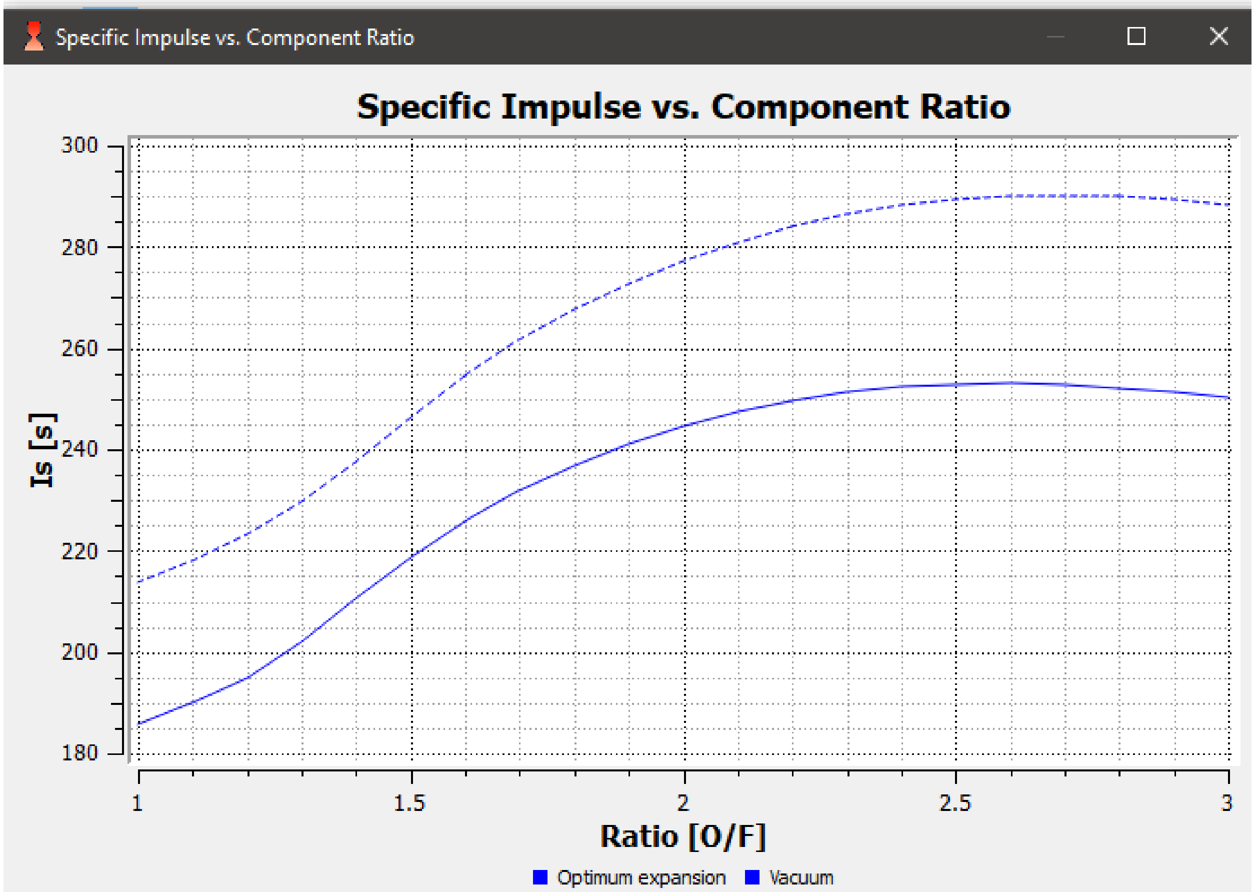
#Ambient condition for optimum expansion: H=0.11 km, p=0.987 atm

Optimum O/F Ratio:

```
Exploded formula:  (O)1.432 (C)0.568 (H)1.704
             O/F:    2.6823988
           O/F 0:    3.7246217 (stoichiometric)
           alpha:    0.7201802 (oxidizer excess coefficient)
```

Graph of specific impulse against o/f ratio:

From the graph we deduced that the optimum o/f ratio for our system is 2.5 but as advised by the supervisor we were to conduct successive test using ratios from 1.5-2.5 to test which ratio was well suited for the piping of or system



Graph of the temperature against o/f ratio:
The issue of temperature being the main concern as to why the precious team chose a lower o/f ratio but as can be seen from the graph still even if we reduced the o/f to 1.5 we still get temperatures up to around 2200k which is higher than the melting point of aluminum 6061 which is at around 800k here are some of the considerations and explanations we got from some literature:
Heat transfer occurs through several mechanisms to manage the high temperatures generated during combustion. Here's a summary of how heat transfer occurs:

1. Combustion Chamber: In the combustion chamber, the fuel and oxidizer are mixed and ignited to produce high-temperature, high-pressure gasses. The heat generated by combustion raises the temperature of the chamber walls.

2. Convection: Hot gasses from the combustion process come into direct contact with the chamber walls, transferring heat through convection. This heat transfer mechanism is the primary contributor to the high temperatures experienced by the chamber walls.

3. Radiation: Heat is also transferred through radiation, where electromagnetic waves emitted by the hot gasses are absorbed by the chamber walls, raising their temperature further.

4.Regenerative Cooling: To manage these high temperatures, the former team employed regenerative cooling. In regenerative cooling, a coolant (usually the fuel or an alternative fluid) is circulated through channels or tubes embedded within the chamber walls. As the coolant flows, it absorbs heat from the chamber walls, carrying it away from the combustion chamber. The heated coolant is then passed through a heat exchanger or radiator to dissipate the heat before being recirculated back into the chamber. This process effectively removes heat from the combustion chamber, preventing excessive temperature buildup and maintaining the structural integrity of the engine components.

Our engine is of the regenerative type a below is how that works:

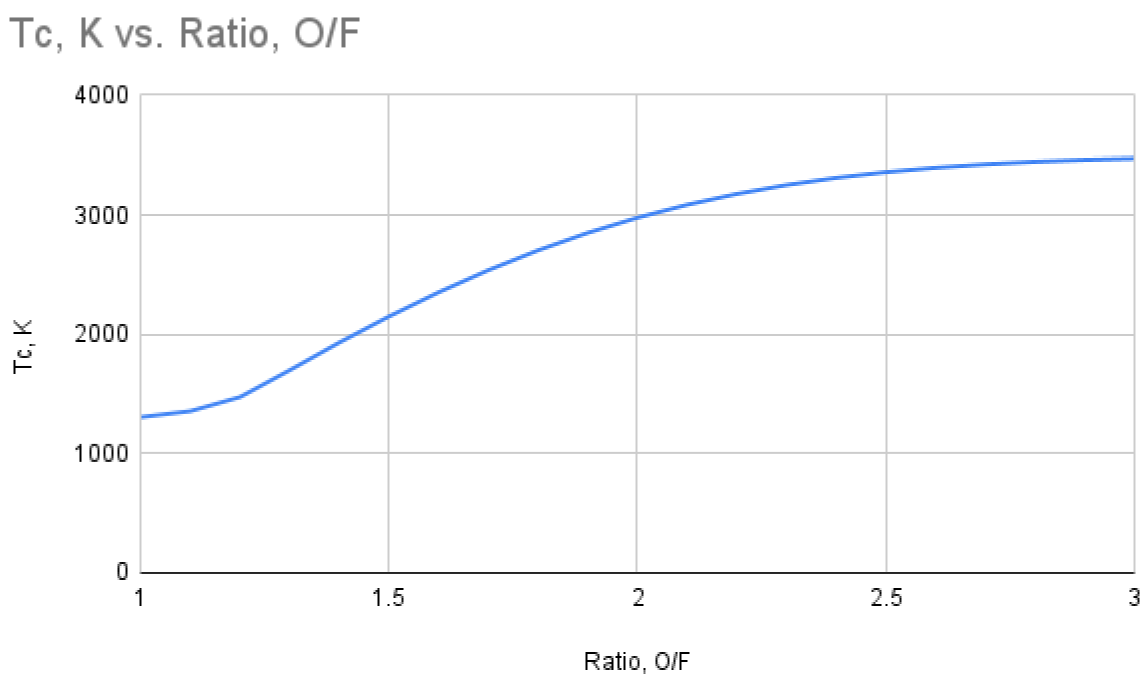
Even though the melting point of a material may be lower than the temperatures expected in a specific environment, it can still withstand those temperatures under certain conditions, primarily due to heat transfer methods like regenerative cooling in a rocket engine. Here's how it works:

1. Heat Transfer Rate: The rate at which heat is transferred from the hot gasses to the chamber walls is crucial. In a well-designed rocket engine with efficient cooling mechanisms like regenerative cooling, the heat transfer rate from the combustion chamber walls to the coolant is high. This rapid heat transfer helps keep the temperature of the chamber walls below their melting point, even though the gasses themselves may reach temperatures far higher than the melting point of the material.

2. Temperature Gradient: The material experiences a temperature gradient across its thickness. While the inner surface of the chamber wall is exposed to the high-temperature gasses, the outer surface is in contact with the relatively cooler coolant. This temperature gradient ensures that the material does not reach temperatures close to its melting point, even though it may experience high temperatures internally.

3. Thermal Conductivity: The thermal conductivity of the material also plays a significant role. Materials with high thermal conductivity can efficiently dissipate heat away from the hot spots, spreading it across a larger surface area and reducing the temperature gradient within the material.

4. Coolant Properties: The properties of the coolant circulating through the regenerative cooling channels are crucial. The coolant absorbs heat from the chamber walls and carries it away, effectively cooling the walls and preventing them from reaching temperatures close to their melting point. The flow rate, temperature, and specific heat capacity of the coolant all influence its effectiveness in heat removal.



Mass flow rate calculations

From the deduced o/f ratio below is how we calculated the mass flow rate for both the fuel and the oxygen:

MASS FLOW RATE

Target thrust=2KN

Target chamber pressure=2Mpa

Exit pressure=0.1Mpa

$V_e = \sqrt[2]{2\frac{RK}{K-1}\frac{T_0}{M}\left[1-\left(\frac{P_e}{P_0}\right)^{\frac{k-1}{k}}\right]}$

I_{sp}(from the simulation) = 252.34s

$V_e = I_{sp} * g$=2474.62 m/s

$\dot{m} = F_{thrust}/V_e$=2000N/2474.62=0.8082 kg/s

Optimum O/F ratio from simulation chosen as from the graph=2.5

$$\dot{m}_{oxygen} = \frac{\dot{m}}{1+O/F}$$

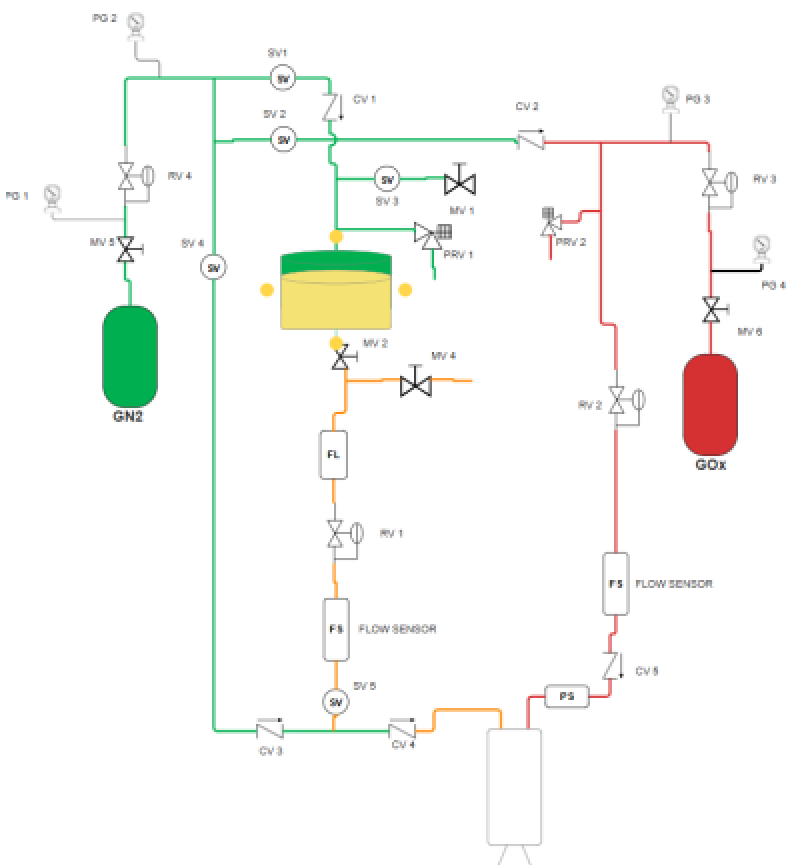
$=\frac{0.8082}{1+2.5}$=0.23091kg/s

$$\dot{m}_{fuel} = \dot{m} - \dot{m}_{oxygen}$$

=0.57729kg/s

Water test procedure

A water test in the context of liquid rockets typically involves using water as a stand-in for rocket fuel to test various components of the rocket, such as the turbopump, under simulated operating conditions. This is crucial for validating the design and ensuring the reliability of the propulsion system without the risks associated with combustible and cryogenic fuels. The procedure generally includes filling the system with water, then pressurizing it to simulate the conditions the rocket will face during launch. The purpose of such tests is to identify any potential issues, such as leaks or cavitation, and to verify that the system can withstand the pressures and stresses of actual operation. For our system we would use the feed system described above. When using pressurized water with nitrogen, the nitrogen gas is used to pressurize the water in the system, which then allows for the testing of the rocket's components at the required pressures without the need for mechanical pumps. This method can provide a more controlled testing environment and can be particularly useful when evaluating the performance of the system under various pressure conditions. Below is a diagram for the water test p&id diagram which now doesn't include the ignition bit that will be used in the fire test. For our case only the fuel it is replaced by water since for the oxidizer we will use gaseous oxygen.



When conducting water tests for liquid engine rocket tests, several requirements and procedures are typically followed:

1. Pressure Simulation: To simulate the pressures that the fluid in the rocket's fuel will experience, specialized equipment such as pumps and pressurized tanks are used to inject water into the test system

at the desired pressure levels. This ensures that the test conditions closely mimic those experienced during actual rocket operation.

2. Safety Measures: Strict safety protocols must be in place to prevent accidents during testing. This includes proper training for personnel involved, use of safety equipment, and adherence to established procedures to handle pressurized systems safely.

3. Test Setup: The rocket engine and associated components are securely mounted in a test stand or rig. Instruments for monitoring pressure, temperature, flow rates, and other relevant parameters are installed to collect data during the test.

4. Water Injection: The water, often dyed for visibility, is injected into the system at controlled rates and pressures. This process is carefully monitored to ensure that the desired test conditions are achieved without exceeding safety limits.

6. Data Collection: Throughout the test, data is continuously collected from the monitoring instruments to assess the performance of the rocket engine and verify that it meets the desired specifications.

7. Post-Test Analysis: After the test is completed, the collected data is analyzed to evaluate the engine's performance, identify any issues or anomalies, and inform future design iterations or modifications.