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Design and development of a controlled fuel reticulation system for a liquid rocket engine test stand

Final Year Project Report (FYP 18-25)

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Declaration

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Abstract

Rockets are developed on the core principle that mass may be moved in one direction by expelling particles in the other. Numerous techniques exist for achieving propulsion, each having its own benefits and drawbacks as well as a unique set of inherent dangers. However, the requirement for system testing prior to mission operation is something that all contemporary rocket propulsion systems share in common. To test not only each part of the system, but the operation and performance of the system as a whole, is essential. For the conducting of functional tests, complete propulsion systems are usually incorporated into a static structure - or test platform - where system processes can be remotely monitored and controlled. This is a fundamental requirement in any project and for this case our amateur rocketry project under Nakuja organisation. Complete system integration is done onto a static test platform for functional and performance testing which is an integral step in the development process. Such a platform should be designed to be relatively safe and reliable.

A controlled fuel reticulation system for a liquid rocket engine test stand was designed and developed. The test stand system includes the test stand structure, propellant and pressurant supply tanks, and feed system flow components. The test stand safely monitors and controls pressure for the Liquid Propellant Rocket Engine (LPRE) prior to integration into a flight vehicle. The system regulates fluid and pressure flow by controlling tank pressure at tank level and along the pipeline system. Pipelines for fuel and oxidizer are used to transport the propellants from the propellant tanks to the combustion chamber. Pressure regulators, pressure sensors and valves are placed along the pipelines to control and regulate flow. The test stand integrates data acquisition and control using an ESP32 micro controller. The system is portable and easily transportable. The system was tested and results obtained for the pressure and flow rates in the fuel and oxidizer line. The solenoid valves were remotely actuated using automated valve switching. System visualization of the parameters being monitored was observed on the user interface.

1 Introduction

1.1 Background

High powered rocketry is the centre of all space exploration. Owing to the increase in the interest of space exploration, advances in the field of high powered rocketry are inevitable. New technologies have been developed by the likes of NASA to allow for space exploration in the present and near future.

In Kenya, the field of rocketry and space exploration is still under research and development with no major milestones made in the recent past. In an attempt to pioneer a change in this field, the Nakuja Project, based in JKUAT seeks to design and fabricate a rocket whose aim is to get past the Kármán line (100 km altitude). Nakuja project is a multidisciplinary research collaboration comprised of students drawn from various engineering fields. Nakuja project has managed to develop and launch two rockets namely the N-1, which rose to an altitude of 32 meters, and the N-2 that was launched recently with a target altitude of 500 meters. The next development is the N-3 development. The overall goal of the N-3 rocket is to achieve an apogee of 1000m by using a solid propellant engine.

In an attempt to get past the Kármán line, the project is broken down into a number of steps that allow for the team to learn rocketry techniques in a step by step manner. This involves the development of an appropriate propulsion system, suitable avionics and flight control, all contained in an airframe.

Nakuja project aims to design and develop a liquid propellant engine rocket. This will be the first liquid rocket for the Nakuja project. The development for the liquid rocket is still in the preliminary phase. This report will discuss the design, development and fabrication of the Liquid Rocket Engine Test Stand.

1.2 Problem statement

Before any rocket mission, it is imperative that a series of tests be carried out on the engine prior to a rocket launch. The series of tests are meant to determine the ideal mixture ratios, measure the engine performance and ensure the engine is at its optimum performance. This is done by measuring parameters such as the ambient pressure and temperature, propellant flow rates as well as the pressures within the flow lines. Significant testing is necessary for the Nakuja project as it will help establish the viability of rocket propulsion concepts and develop reliable system designs. A need therefore arises to design and develop a test stand that will be used as the test rig for the rocket engine.

1.3 Objectives

1.3.1 Main Objective

To design and develop a controlled fuel reticulation system for a liquid rocket engine test stand.

1.3.2 Specific Objectives

1. To design and fabricate a safe system for a liquid rocket test stand.
2. To design and develop an electrical system to interface the microcontrollers, actuators and the physical model.
3. To develop a remotely Controlled Interface to display the real time process events and allow an operator to monitor and override the process if necessary.

1.4 Expected Outcomes

The expected outcomes include:

1. A system that can prevent unsafe conditions from occurring and persisting.
2. A simple mechanical structure for the pressure regulated fuel reticulation system.
3. A complete electrical interfacing design.
4. A control algorithm to maintain desired pressures and propellant flow.

1.5 Justification of the study

Developing a controlled fuel reticulation system that provides appropriate pressure regulation and control for the liquid test stand is essential. This will ensure consistent, stable and safe pressures within the system. Control of pressure and propellant flow during engine operation is vital for optimum engine performance.

The test stand allows for data acquisition during testing. This subsystem is the primary means by which engine performance is evaluated and failure and inefficiencies will be diagnosed.

1.6 Scope

The project will focus on developing a controlled fuel reticulation system that provides appropriate pressure regulation and control for a liquid engine test stand.

2 Literature Review

2.1 Introduction

Different designs exist for a rocket engine. It could be a solid propellant, liquid propellant or a hybrid propellant rocket engine [5]. The design of a liquid propellant rocket engine is discussed in this section. In addition, some of the work from student universities in the West involved in rocket development has been discussed in the current practice section. A summary of the bench-marking carried out, which later influenced the design process, has been highlighted in appendix D.

2.2 Design

2.2.1 Liquid propellant rocket engine

A liquid propellant rocket engine employs liquid propellants which are fed under pressure from tanks into a combustion chamber. The propellants usually consist of a liquid oxidizer and a liquid fuel [5].
A liquid propellant rocket engine consists of one thrust chamber, tanks to store the propellants, a feed system to force the propellants into the thrust chamber, a power source to supply the energy for the feed system, piping to transfer the liquids, a structure to transmit the thrust, and control devices to initiate and regulate the propellant flow and control thrust [5]. The thrust chamber is the main part of a rocket engine [5]. It is usually formed by an injector head, a combustion chamber, a nozzle, a cooling jacket, and an ignition system according to Figure 2.1.

The combustion chamber is where a fuel, and a source of oxygen, called an oxidizer are mixed and exploded. It is also known as the thrust chamber [6]. A propelling nozzle is used in a rocket engine to expand and accelerate combustion products to high supersonic velocities. The basic objective of the cooling jacket in a thrust chamber is to prevent its

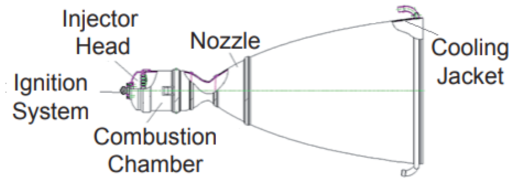


Figure 2.1: Thrust chamber [1]

walls from becoming too hot, and enable them to withstand the imposed thermal loads and stresses. The propellants are fed into the combustion chamber by propellant injectors and feed manifolds in liquid rocket engine systems. The injectors atomize the propellants as much as possible before spraying them into the combustion chamber in a pattern that aids mixing and burning [4].

Propellant

Propellant is a chemical mixture that consists of a fuel and an oxidizer that is burned to provide propulsion in rockets. Fuel is the substance that burns when coupled with oxygen-producing compounds while the oxidizer the substance that releases oxygen in order to be combined with a fuel [7].

Rocket engine propellants can be solid, liquid or hybrid propellants. Solid propellants consist of a casing, usually steel, filled with a mixture of solid compounds (fuel and oxidizer) that burn at a rapid rate, expelling hot gases from a nozzle to produce thrust. Hybrid propellant engines represent an intermediate group between solid and liquid propellant engines. One of the substances is solid, usually the fuel, while the other, usually the oxidizer, is liquid. A liquid propellant can consist of a single chemical (a mono propellant) or a mix of two chemicals, called bi-propellants. In the case of bi-propellants, the fuel and oxidizer are stored in separate tanks outside the combustion chamber [4] [5]. The liquids used may include, Oxidizer (liquid oxygen, liquid nitrous oxide, nitric acid), fuel (kerosene, ethanol, Isopropyl alcohol, liquid hydrogen),chemical compound or mixture of oxidizer and fuel ingredients, capable of self-decomposition.

2.2.2 Liquid Test stand

This is an assembly of systems that is used to safely test liquid fuel engines prior to integration into a flight vehicle [3]. The test stand comprises of tanks to store the propellants, a feed mechanism to force the propellants from the tanks into the thrust chamber(s), a power source to supply the energy for the feed mechanism, a suitable plumbing or piping system to transfer the liquids to the required areas, a structure to transmit the thrust force and control devices to initiate and regulate the propellant flow and thus the thrust.

Figure 2.2 shows a test stand developed by Copenhagen Suborbitals for their BPM100 liquid rocket engine.

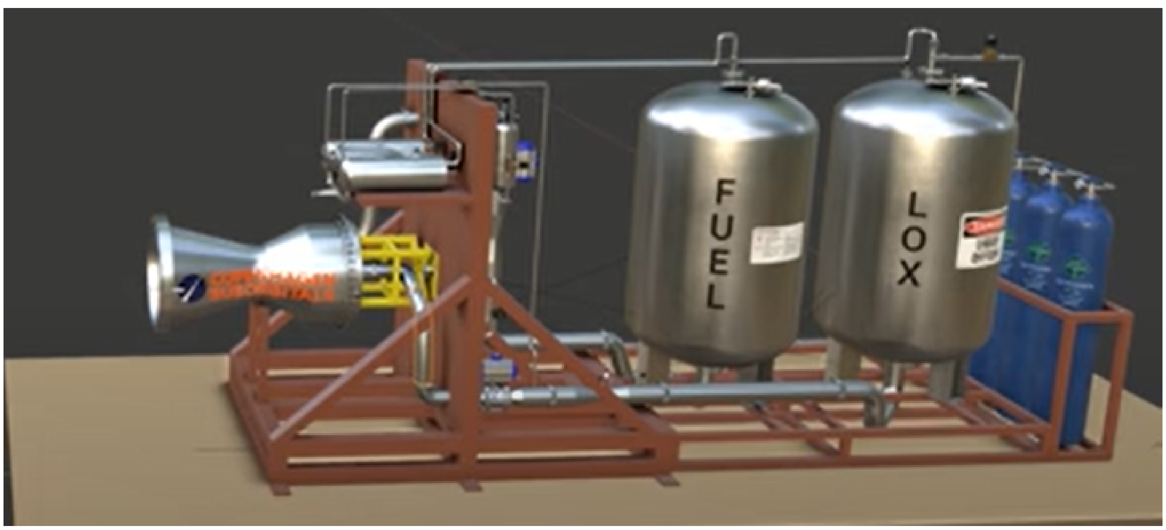


Figure 2.2: Copenhagen's BPM100 Engine Test stand

Propellant tanks

Propellants are stored in separate fuel and oxidizer tanks known as propellant tanks. In the case of a regulated pressure system, another tank known as the pressurant tank is used. This tank holds inert gas under pressure that is used to drive the propellants from their respective tanks For the usage of liquid as a propellant in pressure-fed rocket engine systems, the propellant needs to be pressurized. A separate gas supply, usually helium, pressurizes the propellant tanks to force fuel and oxidizer to the combustion chamber.

Gases used in tank pressurization systems can be pressurized in a number of ways such as, storing high-pressure inert gases at ambient temperature [1]. This is the most common method used and gases such as Helium, nitrogen, and air are typically used. Heating high-pressure inert gases (typically 93 to 427^oC) can also be used in tank pressurization.This reduces the amount of gas required and thus the inert mass of the pressurizing system.

Tank pressurization may also be achieved by creating gases by a chemical reaction using either liquid bipropellants or a monopropellant. This is done at mixture ratios that result in “warm gas. Evaporating a small portion of a cryogenic liquid propellant could also be used to achieve pressurization. This is achieved by applying heat from a thrust chamber cooling jacket or from turbine exhaust gases using heat exchangers. A part or all of this evaporated flow is then used for tank pressurization. Usually liquid hydrogen or liquid oxygen is used. Orifices or pressure regulators may be needed for attaining the desired tank pressure and mass flow rates [1].

Other methods of tank pressurization include direct injection of a small stream of hypergolic fuel into the main oxidizer tank and a small flow of hypergolic oxidizer into the fuel tank and self-pressurization of cryogenic propellants by evaporation.However, this method can be difficult to control.

Tanks can be organized in a variety of ways. The arrangement is regulated by tank design, shape, and positioning. The shapes could be spherical or cylindrical. The tank arrangement can be used to control where the test stand’s center of gravity falls [5].

Propellant tanks can be fabricated from common materials such as aluminium and its alloys, stainless steel, titanium, alloy steels, and fiber-reinforced plastics such as carbon fiber. Monocoque construction techniques are used in the construction of the tanks. Liquid propellant propulsion systems have different tank categories depending on the purpose or rather design application. The categories include, pressurized propellant tanks,

tanks for high-pressure stored gases and tanks for turbo-pump feed systems.

For pressurized propellant tanks, the pressures could range between 1.3 and 9 MPa. These tanks have thick walls and tend to be heavy. Tanks for high-pressure stored gases have pressures that are much higher. The tanks are designed and constructed having a spherical shape for minimal inert mass. Turbo-pump feed system tanks are slightly pressurized. The low pressures allow for thin tank walls.

Propellant feed systems

Propellant feed systems form the assembly responsible for supplying the propellants from their tanks to the thrust chamber. These systems increase the pressure of the propellants as well as supplying the propellants to the thrust chamber at the designed mass flow rate.

The components of a feed system consist of piping, a series of valves, provisions for filling and usually also for removing the liquid propellants, filters, and control devices to initiate, stop, and regulate their flow and operation.

There are two types of feed systems for liquid propellant rocket engines: those that use turbine pumps to force the propellants from propellant tanks to the thrust chamber, and those that employ high-pressure gas to expel or displace propellants from tanks [5].

Parameters that govern the selection of the feed system and its components revolve around the rocket application, duration, number or type of thrust chambers, past experience, mission and by the general requirements of simplicity of design, ease of manufacture, low cost, and minimum inert mass.

Selection of a type of feed system is based on different parameters that are highlighted on Table 2.1.

Table 2.1: Pressurized systems versus turbo pump system

System	Pressurized	Turbo pump
Performance	They give superior performance generally when the vehicle's total impulse is low, the chamber pressure is relatively low, the engine thrust-to-weight ratio is low.	They give superior performance when the vehicle's total impulse is relatively large, the chamber pressure is high, and the mission velocity is high.
Vehicle mission	High vehicle tank masses	Low vehicle tank masses
Power-to-weight ratio	Low	High
Size and Weight	Heavy and bulky	Compact nature and low weight
Propellant tank pressure	Usually high	Usually much lower
Propelled tank walls	Heavy-walled	Thin walls can be used
Reliability	They are traditionally far more reliable.	Unsteady cavitation instabilities that can trigger severe load and vibrations within turbo pumps cause engine thrust fluctuations and sometimes even total mechanical failure.

Pressurized systems

Pressurized sytems can be categorized as either dynamic pressure regulator or pressure blow down. Gas or dynamic pressure regulator has no significant ullage in propellant tanks as they are filled close to 100 percent. A separate pressure tank with gas under very high pressure and a set of control valves are integrated into the system which then supplies the propellant tanks with feed pressure as they are emptied.

In pressure blow down systems, propellant tanks are larger because they store not only the propellants but also the pressurizing gas, hence, there is no separate high-pressure gas tank and pressure regulator. Propellant tanks are typically filled to two-thirds capacity with liquid propellant and the last one-third with pressurized gas. The pressurized gas is then used to drive the engine.They can be lighter than a pressure regulated system. However, gas temperatures, pressures and the resulting thrust all steadily decrease as propellants are consumed [1] [8].

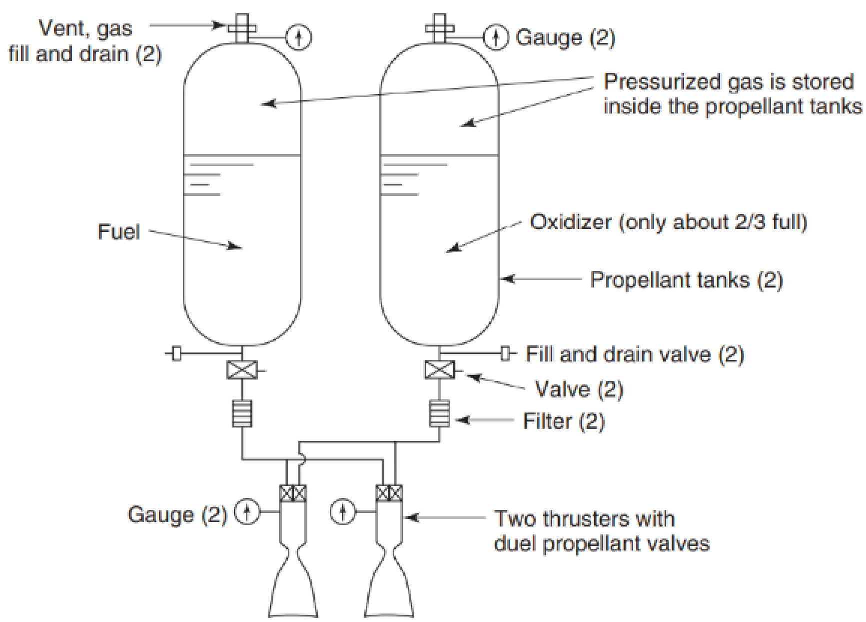


Figure 2.3: Schematic diagram of a typical bi-propellant blow-down pressurized gas feed system with two thrusters [1]

The comparison between the types of pressurized systems is as shown in Table 2.2:

Table 2.2: Regulated Pressure versus Blow Down

Type	Regulated Pressure	Blow Down
Pressure/thrust	Stays essentially constant.	Decreases as propellant is consumed.
Gas Storage	In separate high pressure tanks.	Gas is stored inside propellant at tank pressure with large ullage volume (30-60%).
Required components	Regulator, filter, gas valves and gas tank.	Larger, heavier propellant tanks.

The advantages and disadvantages of regulated pressure and blow down systems are as shown in Table 2.3 and based on this, regulated pressure was selected as the pressurizing method.

Table 2.3: Advantages and Disadvantages of Regulated Pressure and Blow Down

Pressurized System	Regulated Pressure	Blow Down
Advantages	Nearly constant-pressure feed gives essentially constant propellant flow and approximately constant thrust. Better control of mixture ratio.	Simpler system. Less gas required. Can be less inert mass. No high pressure gas tank.
Disadvantages	Slightly more complex. Regulator introduces a small pressure drop. Gas stored under high pressure, often for a long time. Requires more pressurizing gas.	Thrust decreases with burn duration. Somewhat higher residual propellant due to less accurate mixture ratio control. Thruster must operate and be stable over a wide range of thrust values and modest range of mixture ratios.

Plumbing

Plumbing refers to the flow tubes and fittings used to connect the components as they deliver the propellants from the tanks to the combustion chamber. Piping and fittings are extremely important in characterizing the extent at which an engine may be able to perform. The plumbing ensures that the feed rate mechanism design is satisfied depending on how much propellant is availed in the combustion chamber at a given time [9].

Piping and fittings

Fittings, also known as connectors or adapters, serve as standardized connections between pipes, tubes, hoses, valves, manifolds, and other components. Several types of materials are allowed for use in piping systems and serve various functions. They include; copper, cast iron, black-iron pipe, galvanized pipe, cross-linked poly-ethylene(PEX), polyvinyl chloride(PVC), chlorinated polyvinyl chloride(CPVC) and acryloitrile-butadiene-styreneac(ABS) [5] [10]. The material chosen should be compatible with the propellant being used.

Valves

A valve is a device that regulates, directs or controls the flow of a fluid by opening, closing, or partially obstructing various passageways [2].

Valves can be selected based on its function such as starting or stopping flow based on the valve state, regulating flow and pressure, controlling the direction of flow, throttling flow rates and improving safety through relieving pressure in a piping system.

They are also selected based on the pressure rating, temperature rating, flow rate, rated current, valve material, type of electrical connector as well as whether they operate as a closed or open-looped system.

Other factors that influence valve selection include the type of fluid in use, the fluid flow characteristics and the fluid head-loss.

Valves can be opened by multi-turn opening or quarter turn opening. In multi-turn opening you can open or close the valves at various speeds. Quarter opening offer motion in a 90-degree turn of the handle and this makes them ideal for situations where precision is not as important as rapid action and easy opening or closing.

Based on their mode of operation, valves can be categorized as either manual, actuated or automatic valves. Manual valves are typically adjusted by hand and use hand wheels, hand levels, gear wheels, or chains to actuate. Actuated valves are often connected to electric motors, air or pneumatic systems, hydraulic systems, or solenoids. These valves allow remote control and automation for high-precision or large-scale applications. Automatic valves activate when a specific flow condition is met.

Each valve has a flow coefficient, Cv, rating which expresses relationship between pressure drop and flow rate through a valve. The higher the Cv, the greater the flow rate through a valve.

Common valve types

There are different types of valves that are used in the piping system such as: **Butterfly valve**: It is a valve that isolates or regulates the flow of a fluid.It can be used for throttling or regulating flow as well as in the full open and fully closed position The closing mechanism is a disk that rotates.They may be hand wheel–operated or operated using a wrench or gearing mechanism.

Check valve: They are installed in pipelines to prevent back flow. A check valve is a one-way valve, in which the flow can run freely one way, but if the flow turns, the valve will close to protect the piping and other valves.

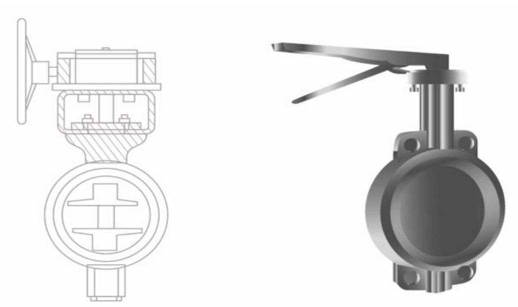
Gate valve: It is used to completely shut off fluid flow or, in the fully open position, provide full flow in a pipeline. Gate valves respond slowly, requiring numerous turns of the hand wheel, to go from fully open to fully closed. It is a valve that opens by lifting a barrier (gate) out of the path of the fluid.

Globe valve: It can be used for regulating flow or pressures as well as complete shutoff of flow. It consists of a circular orifice, usually with its axis at right angles to the pipe axis, against which a piston or disc obturator makes a seal.

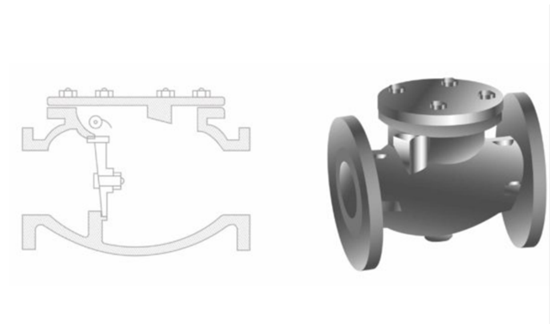
Needle valve: is a type of valve with a small port and a threaded, needle-shaped plunger. It can be used to regulate flow due to their ability to precisely control flow rates.

Pressure relief valve: It is a safety device designed to protect a pressurized vessel or system during an over pressure event. They are used as a safety measure to prevent the fuel tank and GN2 feed line or the GOx feed line - from bursting, should the internal pressure increase to unexpected levels.

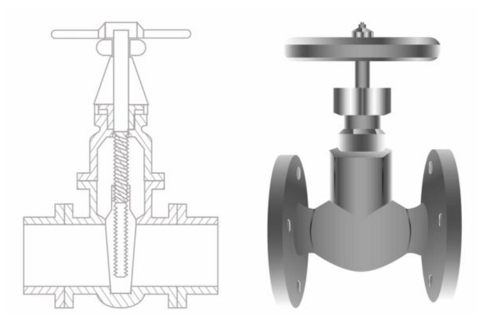
There are various valve connections and ends based on the type of application. Common valve connections and ends include screwed or threaded; often used in instrument connections or sample points, flanged end which are the most common ends for piping use, butt Welded connections typically used in high-pressure or high-temperature operations, socket welded end connections commonly used on small bore piping where threaded connections are not permitted and wafer and lug which is often used for compact valves installed in systems with limited space.



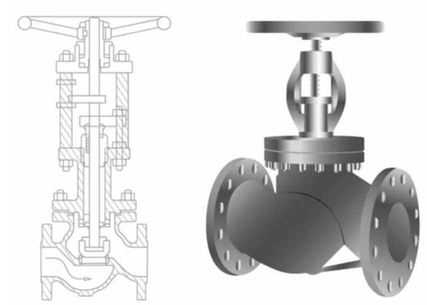
(a) Butterfly valves



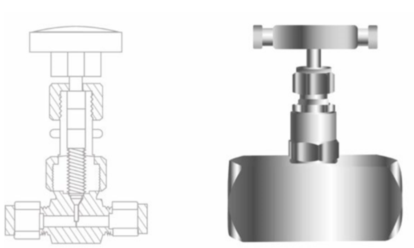
(b) Check valves



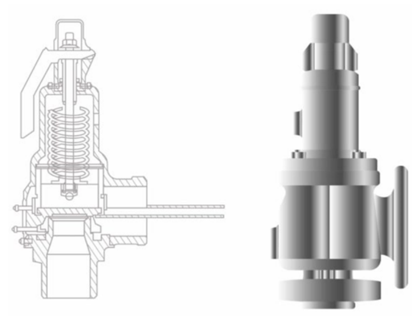
(c) Gate valves



(d) Globe valves



(e) Needle valves



(f) Pressure relief valves

Figure 2.4: Common valve types [2]

2.3 Current Practice

2.3.1 Portland State Aerospace Society (PSAS)

PSAS have developed a test stand, shown in Figure 2.10, which is a pressure-fed piping system designed to be able to supply an engine producing up to 10kN of thrust. Control and data acquisition are provided by the test stand automation and regulation subsystem(TSAR) whose goal is to automate the sensing and control instrumentation of the liquid fuel Engine Test Stand. The feed system uses a classic regulated pressure-fed thermodynamic cycle. Gaseous nitrogen is the pressurant. The propellants used are isopropyl alcohol and liquid oxygen. The piping system is designed for high pressure, cyrogenic and oxygen-compatible systems. Their LFETS Electrical Ground Support Equipment (EGSE) uses a BeagleBone Black microcontroller, the Marionette open-source DAQ, and a custom “SCADA-like” GUI.

However, valves that are compatible with the cryogenic nature of the liquid oxygen have to be used and can be really expensive and the liquid oxygen has to be pressurized.

Figure 2.5: Liquid fuel engine test stand

2.3.2 Luleå University of Technology small-scale liquid-propellant rocket engine testing platform

In this project, a bi-propellant Chemical Propulsion system, gas pressure fed with Gaseous Nitrogen and Gaseous Oxygen as oxidiser and a 70 percent concentrated ethanol-water mixture as fuel was used. The propellant assembly contained all necessary components for operating the system and performing combustion tests with it, including various types of valves, tanks and sensors. Five types of valves were used in the assembly; solenoid valves, manual valves, check valves, flow regulating valves and pressure relief valves. Pneumatically actuated pressure regulators and electrically actuated solenoid valves were used in the system as shown in Figure 2.11.

Unfortunately, the software was not implemented in a program such as LabVIEW, nor was it tested with simulated propulsion system parameters [3]. The choice of propellants can be adopted in the system as they are readily available and only the fuel has to be pressurized hence the use of less components. Gaseous oxygen is a better choice of propellant compared to liquid oxygen as it is not cryogenic.

2.3.3 Sun Devil Rocketry (Arizona St. University)

Sun devil developed a test stand which uses dynamic pressure regulation method and uses kerosene as the fuel and liquid oxygen as the oxidizer as shown in Figure 2.12. Nitrogen gas was used as the pressurant. The propellant assembly contained all necessary components for operating the system and performing combustion tests with it, including various types of valves, tanks and sensors. The design incorporated an SPDG005 pressure transducer that made use of an INA025 instrumentation amplifier. The system was also developed to allow for semi-autonomous control of these activities from a safe distance. An Arduino control unit was the micro controller used [4].

With the use of liquid oxygen, cryogenic compatible valves have to be used.

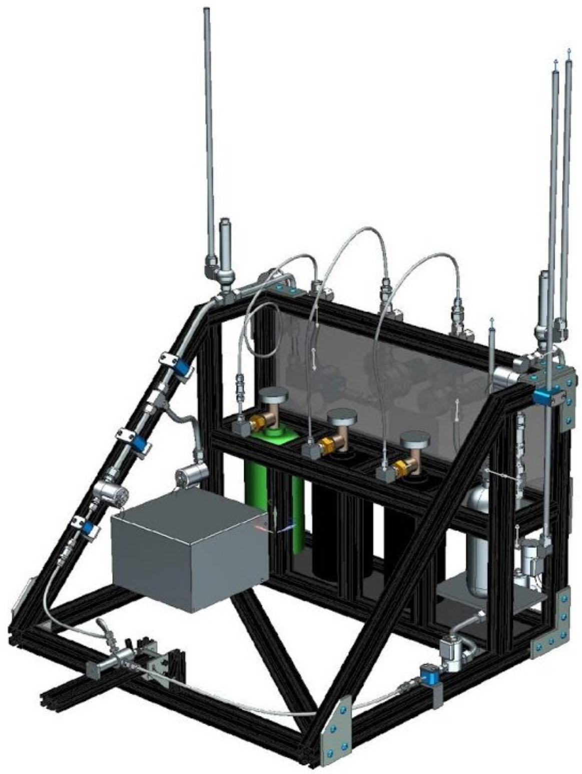


Figure 2.6: Small-scale liquid-propellant rocket engine testing platform [3]

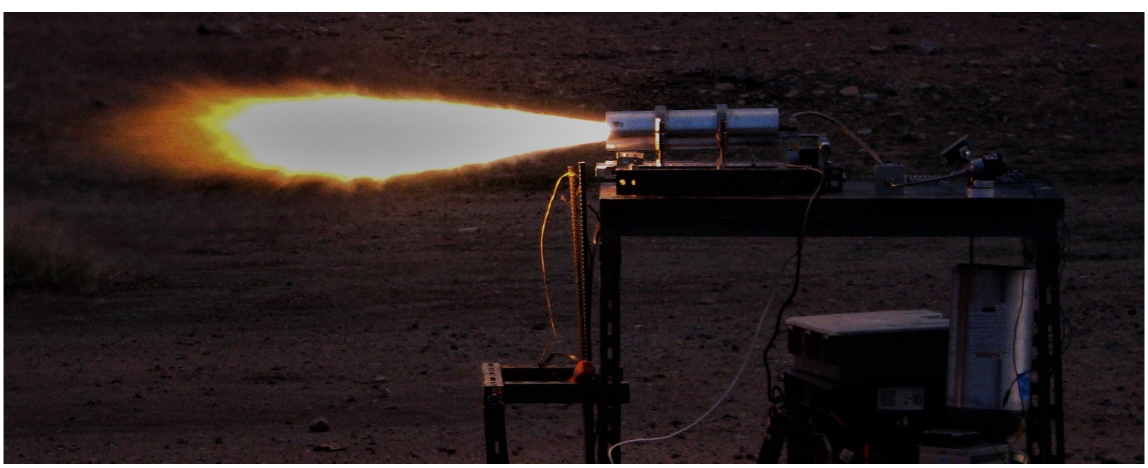


Figure 2.7: Experimental testing platform for liquid-propellant rocket engine [4].

2.4 Gaps identified

Implementing a controlled user interface capable of monitoring the pressure and automating the actuation of the valves was a challenge.

A test stand that is capable of safely and reliably testing rocket engines' performance has been a challenge as safety is paramount to both the operator and the components themselves.

3 Methodology

3.1 Overview

This section deals with a detailed description of the design considerations taken into account during the design of the controlled plumbing system for the liquid test stand. It also outlines the various parameters evaluated during the design of the controlled plumbing system.

The controlled plumbing system was designed using a modular approach. The system features the synergistic combination of the mechanical, electrical, and the control module.

3.2 Mechanical module

The controlled fuel reticulation system is made up of mechanical subsystems that carry the propellants to the injector and the structure that supports the piping system and the tank. The mechanisms consist of the test stand structure and piping system.

3.2.1 Test stand structure

The test stand structure will support all the components of the fuel reticulation system which will be mounted on it. Its design was based on the following considerations

Sizing: The size of the test stand should accommodate all the required components which include the propellant and pressurizer tanks as well as the system pipelines. The size should also be such that it allows for easy portability.

The following factors were considered for the sizing of the system:

1. The height and diameter of the tanks: The test stand should be able to hold and support standard tanks of diameter 210 mm as they are readily available and would help save on fabrication costs and time.

2. The length of the pipelines: It should allow for ample space to mount the pipes.

3. Weight of components: This is the weight of the pipelines, tanks and electrical components that need to be present in the system. The weight is kept at a minimum as the test stand should be portable.

Placement of components: The structure needs to fit all the components that would be mounted on or attached to it. It also needs to sustain the weight. It was paramount to design a frame that has a high strength-to-weight ratio. The weight here would come from the tank and the pipelines.

Material selection: The test stand structure should be made of material that is wear-resistant and strong enough to support all the components. The material used is A500 steel tubing and A653 steel sheet to provide support to the plumbing equipment.

Use of standard parts: Standard parts are readily available. They also allow for ease of interchanging components when the need arises.

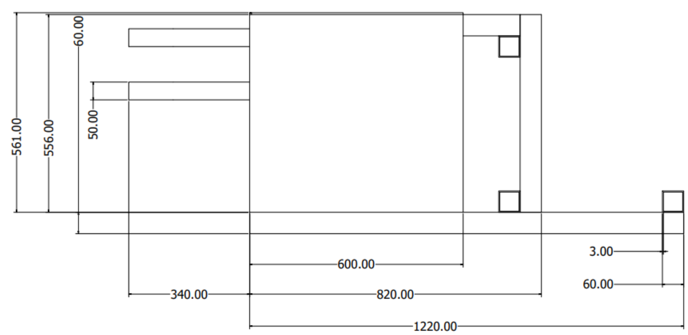
Operational safety: The test stand is to be operated remotely therefore allowing for safety during test operations.

After all the design considerations, a test stand structure made up of square tubings, panel and brackets that can be easily assembled and disassembled with a length of 1.22 m, a width of 0.68 m and an overall height of 0.61 m was designed as shown in figure 3.1.

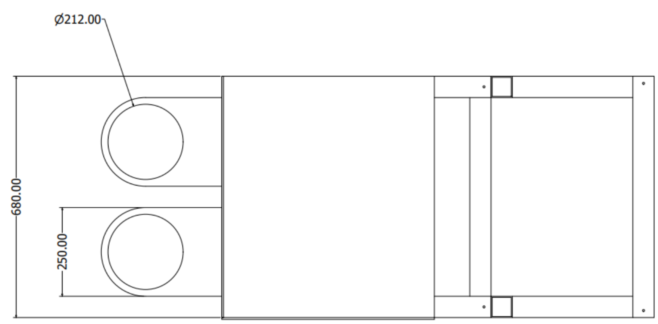
The panels are used to support the electrical components that are mounted on them while the brackets are used to hold and support the tanks.

3.2.2 Piping System

This system is responsible for transporting the oxidiser and fuel to the combustion chamber at a set pressure and flow rate. To achieve this, various components are incorporated into the system for efficient operation such as valves, filters, pipe fittings and tubings,



(a) Side view of the test stand



(b) Top view of the test stand

Figure 3.1: Views of the test stand structure

pressure regulators and pressure gauges. The piping system was designed with all the components assembled as shown in figure 3.8 below.

Valves

Check valve: Check valve A CP series check valve is used to control back pressures along the feed lines. They are placed just before the fuel tank to control the pressurant. They are also found at the end of the respective feed lines, just before the fuel and oxidizer are fed into the injector. The specific check valve has an allowable working pressure of up to 3000 psig (206 bar) a temperature range of -40 to 375° F (-40 to 190° C), flow

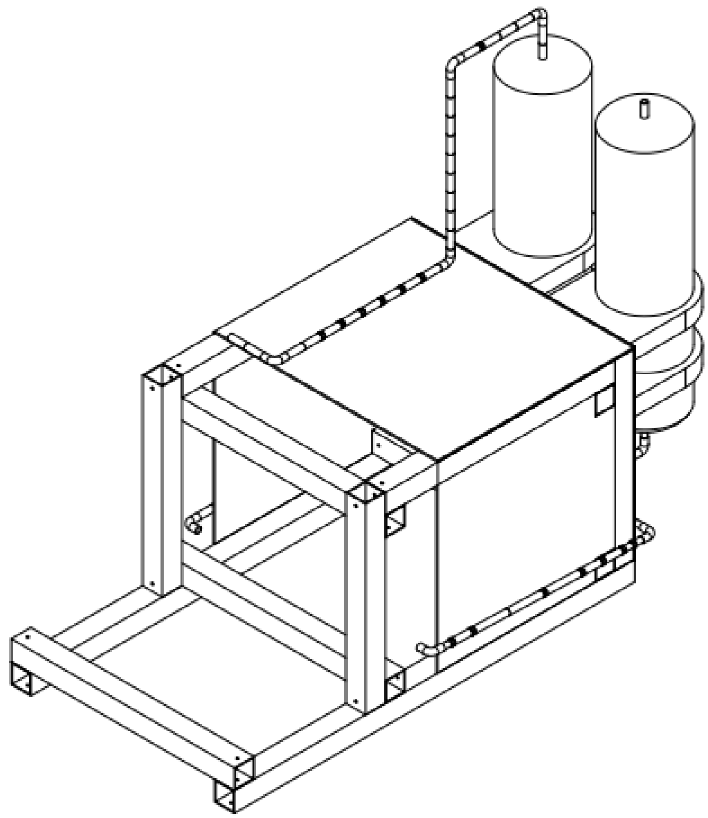


Figure 3.2: Test stand with piping system

coefficient of 0.35 and 1.20. The material used is 316 stainless steel for the body. It has end connections male and female NPT and BSPT of size 1/4 and 1/2 in.

Relief valve: They are implemented for emergency relief where pressures must be relieved quickly to reduce damage that could result from over pressure in the system. A RVC05NPT stainless steel pressure relief valve is used. It has pressure ratings of up to 5000 PSI (340 Bar).

Valve Sizing

For each of the valves to be used in the system, the size of the valve orifice has to be determined. The valve size is compatible with the size of the pipes to ensure desired mass flow rate within the system.

To determine the corresponding required mass flow rate sufficient to release over pressure the required orifice area is calculated from equation 3.1:

$$A = \frac{\dot{m}}{K_d G_o} \tag{3.1}$$

Where:

$\dot{m}$ is the mass flow rate.

K_d is the discharge coefficient.

G_o is calculated from Bernoulli's equation

Head loss can be calculated from equation 3.2:

$$h_L = f\frac{\nu^2 L}{2g_0 D} +_L i\frac{\nu^2}{2g_0 the} \tag{3.2}$$

Pressure loss can be calculated from equation 3.3:

$$\Delta P = (\Delta z + f\frac{\nu^2 L}{2g_0 D} + \Sigma K_L i\frac{\nu^2}{2g_0})\rho g_0 \tag{3.3}$$

Where: h_L is the head loss, ΔP is the pressure loss, f is the friction factor, $\Sigma K_L i$ is the sum of the resistance coefficients, ν is the velocity, g_0 is the specific gravity, L is the tubing length, Δz is the difference in elevation, D is the diameter.

Filters

Filters will be used in the assembly to remove any debris or contaminants from the fuel and coolant water. The fuel filter is especially important as particles in the fuel could easily block the fuel injector nozzle. The filter selected should be able to withstand the maximum operating pressure and the flow rate of the specific fluid.

Pressure gauges

The gauges are used in the sections close to the highly pressurised gas cylinders as a safety feature, so that these critical pressure levels can be checked directly whenever an operator is in close proximity to the assembly. This allows the operator to confirm if the system is or is not pressurised. These gauges provide a redundant pressure measurement in case of transducer failure and allow for immediate measurements during operations. The pressure range that is desired in the pipeline and the connection size determines the type of pressure gauge to be selected.

Pressure Regulator

When choosing a pressure regulator many factors must be considered. Important considerations include: operating pressure ranges for the inlet and outlet, flow requirements, the fluid, expected operating temperature range, material selection for the regulator components including seals, as well as the size and weight constraints. The regulator will maintain the downstream pressure at a lower level than the upstream pressure.

Pipe sizing

The sizing of the pipes involved using different fluid flow concepts to achieve suitable pipe sizes for use in the feed system. The mass flow rate and velocity of the fluids were some of the features used in obtaining the parameters substituted in the flow equations.

Bernoulli's equation is used to relate the fluid velocity and its effect on static pressure as pressurized fluid's potential energy. Other than that, the mass flow rate equation gives the relationship between the fluid density, liquid velocity, and cross-sectional area.

Fluid flow mean velocity: Velocity of fluid in a pipe is not uniform across its cross section area, therefore, a mean velocity is used. It is calculated by the continuity equation for the steady flow as:

$$v = \frac{q}{A} = \frac{4q}{D^2}\pi \tag{3.4}$$

where: D is the internal pipe diameter, q is the volumetric flow rate, v is the velocity and A is the pipe cross section area. The velocity for ethanol was found to be 5.16 m/s

Pipeline sizing for gases: To obtain velocity of the oxygen gas as it moves in the feed line while using pressure, temperature and flow rate as inputs; standard pipe sizes are assumed and varied to identify the flow velocity using the equation:

$$v = \frac{Q_A}{A} \tag{3.5}$$

where v is the flow velocity in m/s, Q_A is the actual volumetric flow and A is the area of the pipe.

The velocity for gaseous oxygen was found to be 20.18 m/s.

Pipe material selection

The pipelines would be used to carry propellants at different high pressures hence the material used should be able to withstand high pressures. Aluminum and stainless steel pipes were considered as the material and the comparison is highlighted in Appendix E. However, Aluminum can withstand a maximum working pressure of 1500 psi yet the gas tanks will be at higher pressures than 1500. Stainless steel tubing was then selected as it can withstand very high pressures of up to 3000psi.

3.2.3 Propellant Selection

The liquid propellant rocket engine will feature an oxidizer and fuel that will be combined at equal pressure inside the combustion chamber prior to ignition.

The choice of a propellant combination for a bi-propellant system is influenced by many factors. Physical properties, such as chemical stability and compatibility with hardware considered. It should also be decided whether the liquids used should be able to ignite and combust spontaneously at contact.

Generally, propellants are chosen based on their ability to generate thrust, i.e their value of Isp. Apart from this, what is important to consider are the many hazards that come with the handling and storing of chemical propellants for rocket propulsion. The selection criterion was mainly based on benchmarking from what has been used previously and is still in use in other liquid rocket engines.

For the oxidizer, liquid oxygen, Gaseous oxygen and Liquid Nitrous oxide were taken into consideration. Liquid oxygen is very efficient as an oxidizer. It is cryogenic in nature. Gaseous Oxygen is readily available as well as non-cryogenic. Liquid Nitrous Oxide is non-cryogenic, readily available and is approved for use in hybrid propulsion systems.

The fuel selection involved comparing and contrasting liquid methane, RP-1, Kerosene, liquid hydrogen and Ethanol. Liquid methane is highly efficient and cryogenic. Liquid hydrogen is the most efficient fuel; it is cryogenic, leaks through most seals and has extremely high vapor pressure. Ethanol is nontoxic and environmentally friendly. It has a long history as a rocket propellant and is easy to acquire. Kerosene is more efficient than ethanol and less seal friendly.

The team chose to use Gaseous oxygen as the oxidizer and Ethanol as the fuel for the engine. These propellants were selected as they are the safest to use and easiest to acquire of the propellants considered. The reason why we chose ethanol/GOX instead of kerosene is because of simulation accuracy. NASA CEA only supports RP-1 whereas kerosene in Kenya has potential impurities. The other region was due to its inefficiency in regenerative cooling. The impure material included in kerosene vapourizes and solidifies during the cooling which blocks the channel

3.2.4 Tank sizing

Oxidizer and fuel tank: This is where the oxidizer and fuel will be stored respectively, and conditioned at moderate pressure during the static test. The design considerations include ensuring tank material is compatible with the working fluid used, determining a wall thickness based on the maximum operating pressure as well as the shape of the tank that can withstand maximum stress.

Pressurant Tank: This tank holds the pressurizing gas that is required to be constantly supplied to the system proportionally for the entire duration of the operation. The design considerations were ensuring tank material is compatible with the Nitrogen gas used, determining a wall thickness based on the maximum operating pressure as well as the shape of the tank that can withstand maximum stress.

The size of the tank is a critical factor that needs careful consideration as the amount of fluid held in the tank should be sufficient for maximum duration of operation. Tank sizing is governed by the maximum operating pressures of the system which are used to determine a suitable tank wall thickness and the amounts of propellant and pressurizer required by the system during test operations

The governing equation for tank wall thickness t_w is given in equation 3.6:

$$t_w = \frac{PD}{2S} \tag{3.6}$$

Where P is the pressure in the tank, D is the outside diameter of the tank, t_w is the wall thickness and S is the allowable stress

The fuel tank, oxidiser tank and pressurizer tank each have a separate criteria that is used to determine their optimum size for the desired operation.

To calculate the required fuel tank volume $V_{fueltank}$ equation 3.7 was considered:

$$V_{fueltank} = Q * t \tag{3.7}$$

where Q is the volumetric flow rate and t is the time taken for one test. The fuel tank volume required was found to be 0.0033 m^3.

Oxidizer Tank Sizing

The gaseous oxygen, GOx, supply will consist of ready-made, highly pressurised gas cylinder. The minimum required tank volume V_{tank} for the GOx was found using equation 3.8:

$$V_{tank} = Q * t \tag{3.8}$$

To find the volume of the GOx tank the density within the tank ρ_{tank} has to be determined as shown in equation 3.9:

$$\rho_{tank} = \frac{m_o * P_o}{R_u * T_o} \tag{3.9}$$

Where p_o is the the pressure in atm, T_o is the temperature inside the oxidiser tank, $R_u =$ 0.0821 L atm/mol K and m_o is the molar mass which is 32 g/mol

Using a design safety factor of 1.5, the density was obtained as 262.4kg/m^3 The volumetric flow rate,Q was then obtained using equation 3.10:

$$Q = \frac{m_o}{262.4} \tag{3.10}$$

The volumetric flow rate and the TimeTest are then used to geta the tank size. Usipressurizedest of 5 secon ds, the oxygen tank volume required is 0.013m^3. An added safety feature involves adding dimethyl sulphide into the cylinder so that any GOx leaks are revealed by the additive's distinct odour.

Pressurant Tank Sizing

The gaseous nitrogen,GN2, supply will consist of ready-made, highly pressurised gas cylinder. According to Boyle's law, for an ideal gas with a constant temperature within a closed system the product of the gas pressure and the occupied volume remains constant in all system locations. For two arbitrary system locations, l_1 and l_1,the equation 3.11 applies:

$$P_{l1}V_{l1} = P_{l2}V_{l2} \tag{3.11}$$

The volume occupied by the GN2 inside the fuel tank increases throughout a test as the fuel is depleted. Taking the fuel tank in the state where all fuel has been replaced by

GN2 as location two. The pressure in location two, P_{l2} is equivalent to the operating pressure while the volume at location two V_{l2} equals the fuel tank volume $V_{fueltank}$. The GN2 supply tanks are taken as location 1. The pressure at location 1 P_{l1} is taken to be the pressure in the GN2 supply tank while the volume at location 1 V_{l1} is taken to be the volume in the GN2 V_{GN2}. Using a design factor of 1.5, equation 3.12 was used:

$$V_{GN2} = 1.5 \frac{P_{op} * V_f}{P_{GN2}} \tag{3.12}$$

where V_{GN2} is the Volume of the GN2 tank, P_{op} is the operating pressure, V_f is the fuel tank volume and P_{GN2} is the GN2 tank pressure. The Nitrogen tank volume required was found to be 0.00099 m^3.

3.2.5 Piping and Instrumentation Diagram

A Piping and instrumentation diagram was drawn below on figure 3.3 showing the assembly of all the piping system components.

The gaseous oxygen is supplied at high pressure of about (2000 psi) from the supply tank in its compressed form. The gaseous oxygen is filtered so as to remove any foreign particles. This pressure is then brought down to about 400-500 psi. Pressure measurement is done before and after the pressure regulators so as to confirm that the pressure has been brought down. The pressure relief valve is then used to relieve pressure in case of over pressure. A flow meter is then used to measure the mass flow rate of the propellant. If the pressure reading obtained from the pressure sensor that is downstream of the regulator has reached a set value, the solenoid valve is actuated. Pressure is measured again to detect any pressure losses. A check valve is used to prevent the back flow of the propellant before being fed to the engine.

The gaseous nitrogen is at high pressure of about (2000 psi) within the Nitrogen gas supply tank. It is then filtered so as to remove any foreign particles. This pressure is

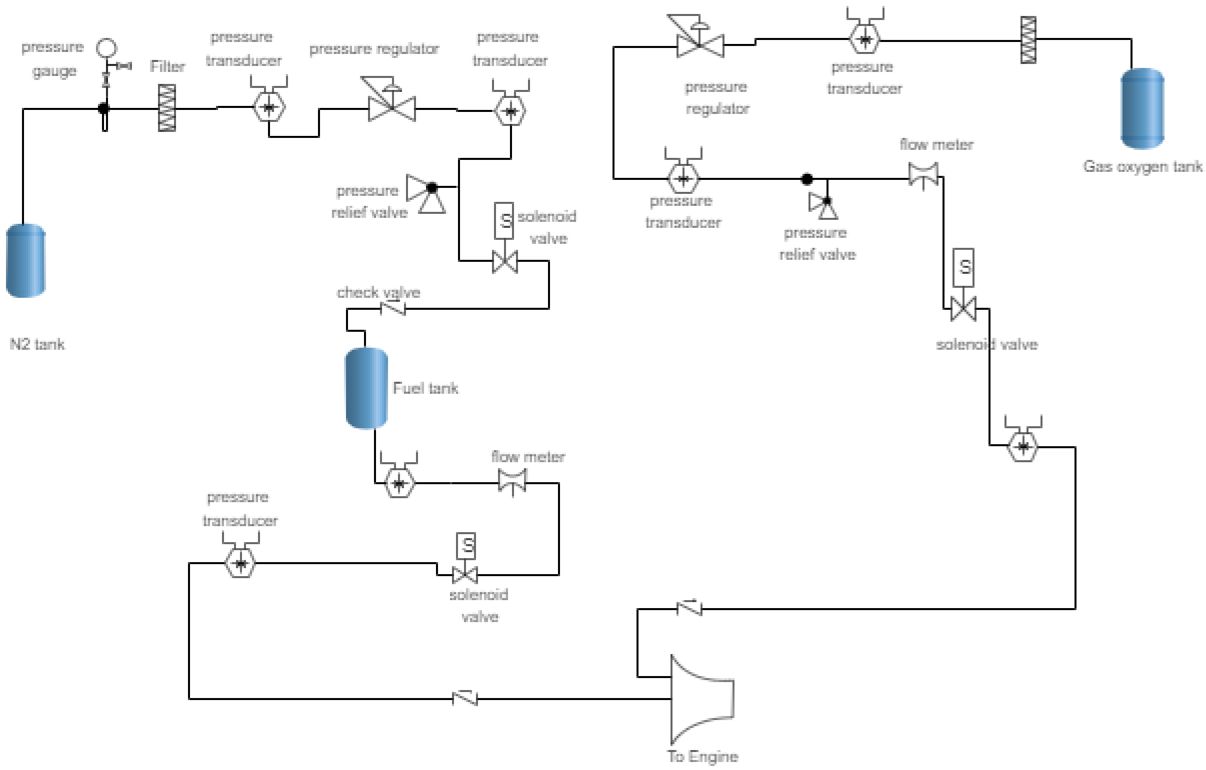


Figure 3.3: Piping and Instrumentation diagram for the fuel reticulation system

then brought down to about 400 psi as this is the desired working pressure in the system feed lines. Pressure measurement is done before and after the pressure regulators so as to confirm that the pressure has been brought down. The pressure relief valve is then used to relieve pressure in case of over pressure. If the pressure reading obtained from the pressure sensor that is downstream of the regulator has reached a set value, the solenoid valve is actuated. A check valve is used to prevent the back flow of the propellant before being fed to the engine.

The gaseous nitrogen is used to pressurize the fuel. The pressure and flow rate is then measured downstream of the fuel tank. If the pressure reading obtained from the pressure sensor has reached a set value, the solenoid valve is actuated. Pressure is then measured to get the pressure reading before being fed to the engine. A check valve is used to prevent the back flow of the propellants.

3.3 Electrical module

The electrical module is an assembly containing several power components, it consists the electrical and electronic components and their interconnection in the system. A schematic of the electrical circuit is developed after careful planning and design considerations as will be discussed in this subsection. The electrical and electronic subsystems include the power supply, input and output devices.

3.3.1 Sensors

Sensors were used in the feed system to measure the system response. Parameters monitored included the pressure along the feed lines and the fluid flow rates. The sensor measurements would be used to compare with the target or set point to determine what adjustments are needed to the actuator.

Pressure sensors: The pressure level in different sections of the assembly will be measured with electrical pressure sensors. The sensors will be utilized at key points to understand and characterize the feed system while also recording and transmitting live data during tests. Industrial pressure sensors that can be used to measure high pressures of up to 2000 psi were selected as 0-2000 psi will be the range in which the system will function at the most. The feed system pressure shall not exceed 2000 psi, and the combustion chamber nominal theoretical value is 400 psi. Therefore, any pressure transducer in that range with the chemical resistivity capable of handling the fuel and oxidizer should be capable of data acquisition.

For this design the AP020 electronic pressure sensor with a ceramic-capacitive pressure sensing element was used. The electronic pressure sensor requires a DC operating voltage of 8.5-36 V and a current range of 4-20 mA.

Flow rate sensors: The flow sensors will be used to measure the flow rate of both theoxidizerr, gaseous oxygen and fuel.

The type of fluid media was one of the factors considered when selecting the sensors. Since the oxidiser will be in gaseous form and the fuel will be in liquid state, a gaseous and liquid flow rate sensor were selected respectively.

The minimum and maximum readings required was also another criteria used as the mass flow rate should fall within that range. The mass flow rate for gaseous oxygen is 0.67093 kg/s whereas the mass flow rate for ethanol is 0.5161 kg/s.

For the design we used the FS1025-DG gas sensor whose operating voltage falls within 2.7 to 5 V and a current of 21 mA. The flow rating falls between 0 to 150 liters/min making it suitable for the gaseous oxygen feed line. A FS1027-DL liquid sensor was used whose flow rating falls between 0 to 10 liters/min. The operating voltage is 2.7 - 5.5 V and a current range of 20 - 25 mA.

3.3.2 Actuators

In the feed system, actuators would be implemented to receive a signal from the control system then respond by moving the valve to either a fully open or fully close position.

Solenoid valve: The power to the solenoid comes from the 12 V power supply circuit. The relay and the transistor are powered by the 5V circuit, which is fed from the micro-controller. When the relay coil is energized, it closes the contacts, which allows current from the 12 V supply to flow through the solenoid. When the solenoid coil is energized, the valve opens.

Relay module: A 4-channel relay is used in this circuit as an electrical switch for the solenoids. The relay module has a supply voltage of 3.75 V to 6 V, a trigger current of

5 mA, a current when the relay is active of 70 mA (single)and 300 mA (all four), a relay maximum contact voltage of 250 V AC, 30 V DC and a relay maximum current of 10 A.

3.3.3 Total power consumption

The amount of current required by the electrical system was obtained by evaluating the maximum amount of current that would be drawn by each of the components. The values were summarized in table 3.1 which shows the component description, the maximum current drawn, the number of similar components required and the maximum current.

Table 3.1: power consumption

Device	Quantity	Peak current(mA)	Total(mA)
Pressure sensor	7	20	140
Solenoid valve	4	1250	5000
Relay-4 channel	1	10000	10000
Gas flow sensor	1	21	21
Liquid flow sensor	1	25	25
Total	N/A	N/A	15186

3.3.4 Power supply

The power supply unit is required to provide desired voltages for equipment operation. Power requirements of each component are taken into consideration to determine the overall amount of power that is required by the system.

Power considerations.

Most of the devices such as the sensors; gas flow, liquid flow and pressure sensor will be powered directly by the micro controller. However, the solenoid valve requires more current for it to function optimally.

In addition, the static test would be carried out in the open and the microcontroller would not sufficiently power all components such as the solenoid valves which requires 12V DC supply. The microcontroller is limited to 5V DC supply. Therefore, an external DC power supply would be required for the system.

Different types of batteries were compared and highlighted in the table 3.2 below.

Table 3.2: Battery property

Property	Lead-acid	Lithium-ion	Lithium-polymer
Weight	Heavy	Light	Heavier than Lithium-ion
Efficiency	Low	High	High
Charging	Loses charge over time	Discharges fastest	Retains charge better than the Lead-acid and Lithium-ion
Charging time	12-16 hours	2-3 hours	1-2 hours
Cost	Cheapest	Cheaper than Li-Po	Expensive

The lead acid battery was selected to be used to power the system. It is capable of supplying 12C-24V DC voltage and its weight can be used to stabilize the platform.

3.4 Control module

The module is designed to take pressure and flow rate sensor data as input and determines the actuation required from the sensors data which depicts the current state of the system.

3.4.1 Microprocessor board selection

Different types of microprocessors were compared on table 3.3.

Table 3.3: Microprocessors

Property	Clock speed	Flash memory	Supply voltage	Digital Inputs
Arduino nano	16 MHz	32 KB	7-12 V	22
Arduino Atmega	16 MHz	128 KB	7-12 V	54
ESP32	80 MHZ/160 MHZ	4 MB	3.3 V	34
ESP8266	80 MHZ/160 MHZ	1 MB	3.3 V	17
RasberryPi	700 MHZ	8 GB SD card	5.2 V	40

The ESP32 microcontroller was selected since it has enough digital pins to satisfy the electrical circuit. In addition, it has the built in integration of both Wi-Fi and Bluetooth dual mode which allows for remote operation of the electrical circuit. The ESP32 microcontroller also has two I^2C ports allowing for serial communication with the flow sensors. Despite the RasberryPi being superior, the ESP32 microcontroller is a more economical choice.

3.4.2 Software

Arduino programming was selected because of its compatibility with the microprocessor board being used.

3.4.3 Control Interface

The control interface was designed as a means by which the operator could instruct the system as desired, and the system could respond accordingly. The interface would also allow for real time monitoring of key parameters during testing such as pressure in the propellant, pressurant tanks and along the feed lines as well as the flow rates of both the oxidiser and the fuel.

An easy-to-understand and manipulate dashboard was designed on Grafana which is an open source software as shown on figure 3.4.

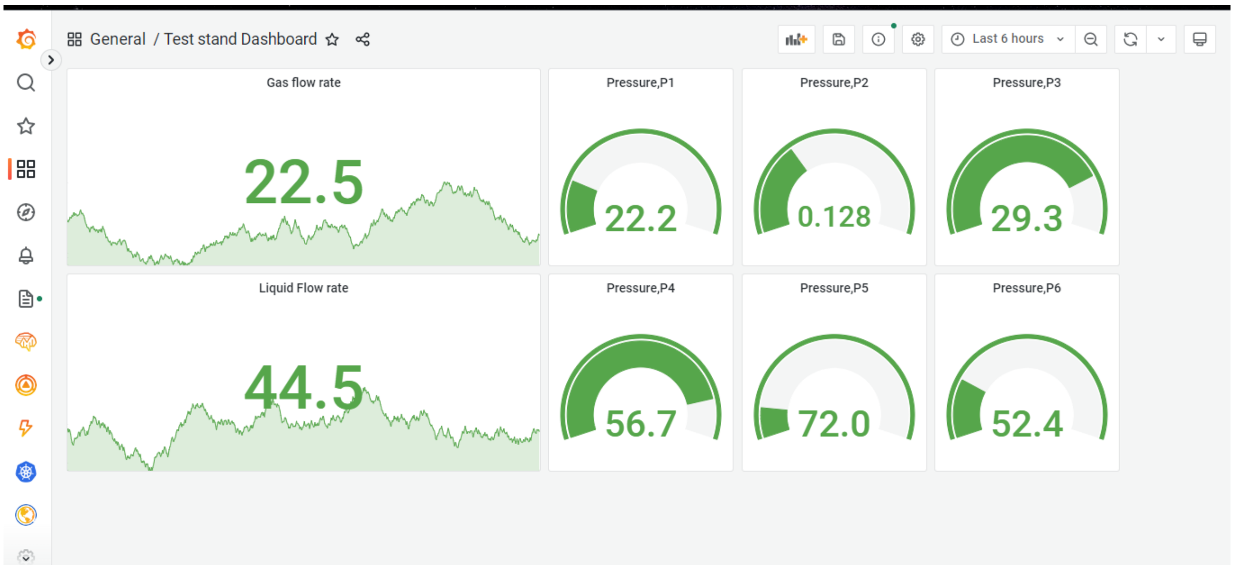


Figure 3.4: Control interface

The liquid fuel engine test stand dashboard will be a SCADA-like system for displaying the state of various actuators and sensors on the test stand to provide user interface and manual control of the hardware. The system is required in order to prepare test, and fire the various hardware in the test stand and enhance safety during operations.

3.4.4 Flowchart

A flowchart showing the algorithm of the controlled plumbing system is as shown on figure 3.5.

The tanks filled with the appropriate fluid open-source on the brackets and the fuel and gaseous oxygen are pressurized upstream. Leakages, pressure levels downstream, and mass flow are then verified. If all the criteria are met, the Gaseous oxygen and fuel are introduced into the combustion chamber and the propellant flow is regulated to achieve the desired combustion test output parameters. If the criteria are not met, the system is depressurized.

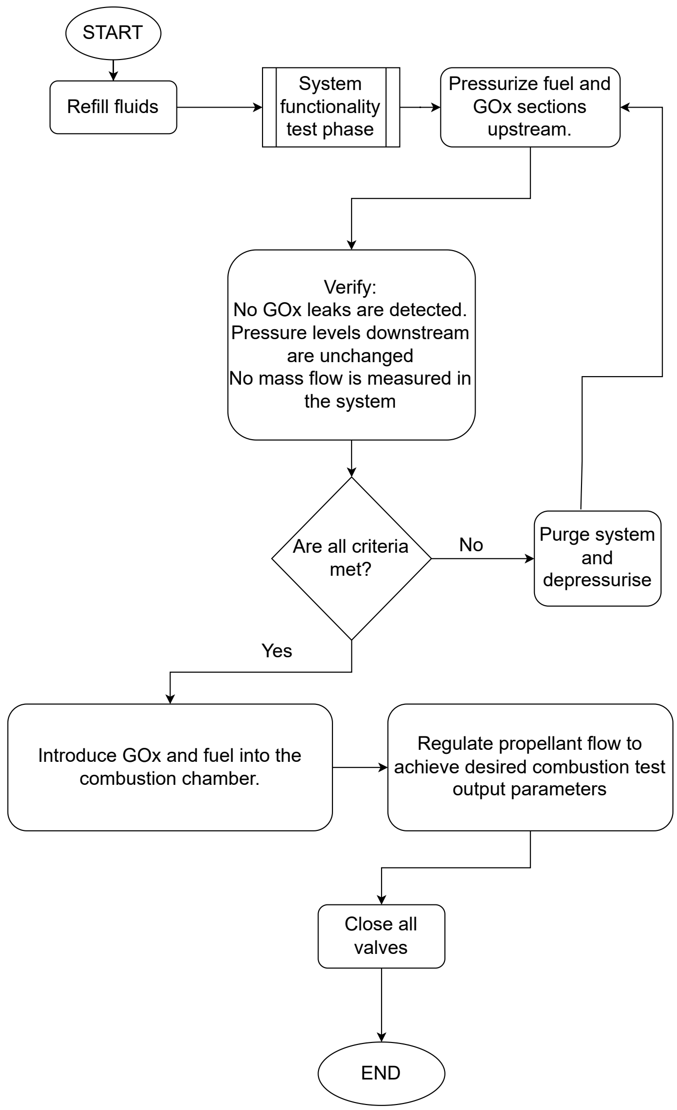


Figure 3.5: Control flowchart

3.5 Safety

One of the major design considerations of the controlled plumbing system is the safety feature. When working with fuels, high-pressure gasses, and strong oxidizers, safety must be considered as each, even on its own, has the potential to cause material damage and personal injury if mishandled. Some of the safety concerns include inter-propellant mixing as a result of fuel or oxidizer propagating upstream, system overpressure, backflow of propellant, and leakages.

Safety features that were considered during the design of the controlled plumbing system include using check valves to prevent backflow of propellant into the gas tank and inadvertent mixing of propellants inside flow passages. The pressurizing gas should be inert, clean, and insoluble in propellant and Leakage detectors incorporated to detect leaks of hazardous vapor in the plumbing system. Features that prevent an unsafe condition to occur or persist and shut down the engine safely, such as relief valve and the use of electrically actuated valves so as to enable remote control were also considered in the design of the test stand. The fuel and oxidizer panels were kept physically separate to reduce the risk of inter-propellant mixing in the case of a leak.

3.6 Redesigns and Modifications

To achieve the required thrust, the desired pressure in the pipelines is about 400 psi. However, most high pressure components required to be used in the pipeline were not locally available and had to be imported. For this reason the project was scaled down to pressures of less than 10 bar as the components could be locally obtained.

A high-pressure vessel is required to hold the ethanol and get pressurized using Nitrogen gas. During our research, a barrel was considered as it could be used to hold the ethanol at high pressures, however, no suitable filling system or station could be found. A pressure accumulator was then considered which was easily purchased and could hold a pressure of up to 3000 psi. However, the pressure accumulator is made up of Nitrile rubber which is incompatible with ethanol. Since the options available locally are incompatible with ethanol, pressurized nitrogen was used to substitute the Ethanol in order to demonstrate the capacity, pressure control, and other capabilities of the system, pressurized nitrogen was used to substitute the Ethanol. A piping and instrumentation diagram was drawn indicating the redesign and modifications on the fuel line as shown in figure 3.6.

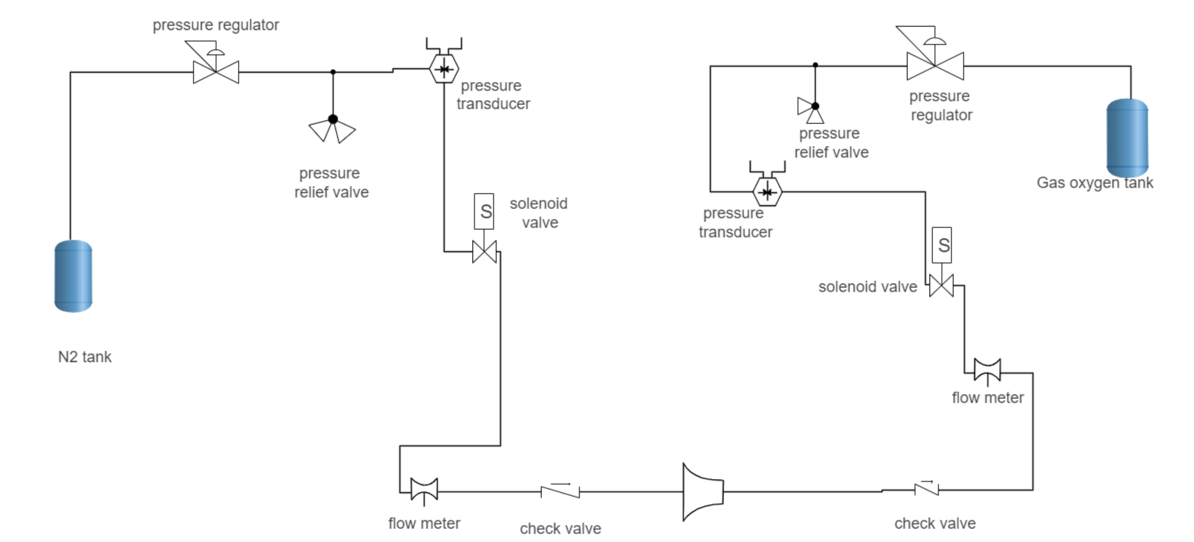


Figure 3.6: Piping and Instrumentation diagram with redesigns

During the project design stage, the test stand structure was to be fabricated from 54 * 54* 3 mm square tubes. However, angle lines were preferred for fabrication due to the ease of machining and assembly using nuts and bolts. Angle lines of 50*50*3 mm were the closest dimensions available.

The pipelines are used to carry propellants at different high pressures and the material used should be able to withstand high pressures hence stainless steel was selected. However, for ease of installation, flexible hoses were considered. In addition to its flexibility, it is also easy to route.

Our original design for the power supply was a 12V lead-acid battery. In our system, however, a 24V power supply board was used. This redesign was driven by the power rating for the available pressure sensors that required a DC supply voltage ranging between 14-30V. The power supply is connected to a 240VAC source which is then down converted to the desired 24V DC.

3.7 Fabrication

3.7.1 Test stand structure fabrication

For the test stand structure, the frame was made using 50x50x3mm stainless steel angle lines. 12m angle lines were obtained then marked out and the required lengths cut into the specific dimensions. The structure required four 556mm, two 700mm, two 1220mm, five 680mm and two 400mm angle line pieces for the complete structure assembly. With these pieces we proceeded to assemble the structure. Since the structure would require easy assembly and disassembly during transportation to testing sites, we opted for a non-permanent joining method. 8mm nuts and bolts were used for joining. We obtained two Grade 304 stainless steel sheet metals, marked them and cut them to size to obtain one piece measuring 600mm*680mm, for the top panel,two pieces measuring 556mm*600mm for the side panels and one piece measuring 560mm*680mm for the back panel. We then drilled 8.5mm holes at the panel's edges using a bench drill. The panels were then attached to the structure using 8mm, nuts and bolts.

3.7.2 Pipelines fabrication and assembly

With the test stand structure assembled, we proceeded to assemble the fuel and oxidizer pipelines. 1/2" flexible hoses were obtained and sized down in order to accommodate the down-convertedsors along the lines. End connectors,adapters, nipples and T-connectors for the pressure sensors' and relief valves' connection were used. Clamps were also used to mount and support the flexible hoses to the panels. An 11.5kg oxygen gas cylinder was used for the oxygen line and a 9.5kg Nitrogen cylinder was used in the fuel line for testing purposes, in place of ethanol. For the oxidiser line, an oxygen gas regulator was mounted on the cylinder and a 3/8" - 1/2" adapter was used to connect a 1/2" pipe to the regulator. From there, a pressure sensor is mounted followed by a solenoid valve, a flow meter, a check valve and lastly a pressure relief valve to protect the system from over pressure. The same configuration was employed on the fuel line. A Nitrogen gas regulator was mounted on the cylinder, a 3/8" - 1/2" adapter was used to connect a 1/2" pipe to the regulator. From there, a pressure sensor is mounted followed by a solenoid valve, a flow meter, a check valve and lastly a pressure relief valve to protect the system from over pressure. Clamps were then used to mount the pipeline on the panels.

3.7.3 Electrical circuitry Fabrication

Power Board: The power board circuit is made up of two voltage regulators, female header pins, 2k and 1k resistors were fabricated on a perforated board. These components were then soldered to the component providing a 24V, 12V and 5V line. The 24v power flows from the Power adapter to the pressure sensors. It is also stepped down to 12V for the solenoid valves then to 5V for the micro controller and the flow sensors. The output from the pressure sensor is a 0-10 voltage. The signal cannot be connected directly to the micro controller, hence a voltage divider circuit is used to step it down to 0 - 3.3v which can then be connected to the micro controller. Open wires are covered using insulating tape to prevent shorting of the circuit.

Solenoid Circuit Board: The circuit board for the control of the solenoid valves was fabricated from a perforated board. The components namely a TIP 120 Darling ton pair, 1K resistor and IN4001 diode and 12V power supply rails were mounted and soldered to the board to achieve actuation.

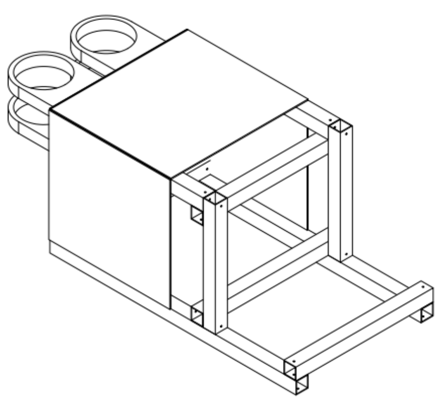
4 Results and Discussion

This chapter explains the result of the design of the controlled fuel reticulation system.

4.1 Mechanical module

4.1.1 Test stand structure

The 3D model of the test stand structure and the fabrication outcome is shown in figure 4.1. The structure was made using stainless steel G304. This contributed to the structure being stable and strong enough to support the weight of the pipelines. The angle lines and panels were joined together using nuts and bolts for easy assembly and disassembly.

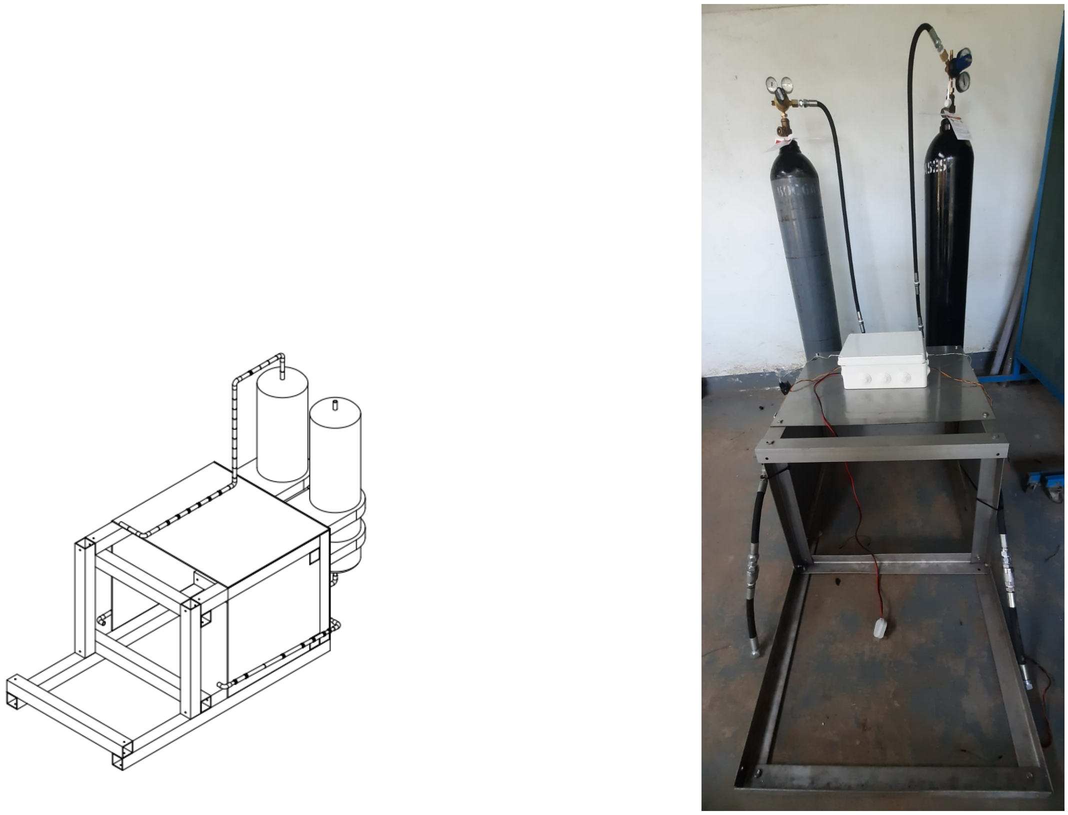


(a) Design

(b) Fabricated

Figure 4.1: Assembly of the test stand structure

The piping system consisting of flexible hoses, sensors, and valves was then assembled to the test stand structure using clamps for support. The 3D model of the piping system and the design is as shown in figure 4.2.

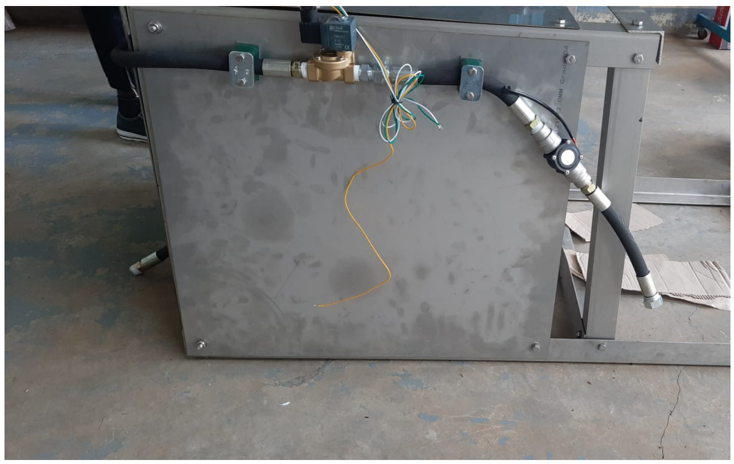


(a) Design (b) Fabricated

Figure 4.2: Assembly of the test stand structure with piping system

The different views of the test stand with the piping system for both the oxygen and nitrogen line is as shown below. The piping system is made up of check valves, pressure relief valve, solenoid valves, flow sensors, pressure sensors and pressure regulator.

(a) Back view of the piping system



(b) Piping system for the Oxygen line

(c) Piping system for the Nitrogen line

Figure 4.3: Different views of the test stand structure with piping system

4.1.2 Electrical fabrication

The power circuit fabricated in figure 4.4 was able to supply 24V to the pressure sensors, 12V to the solenoid valves, 5V to the flow sensors and the micro controller.

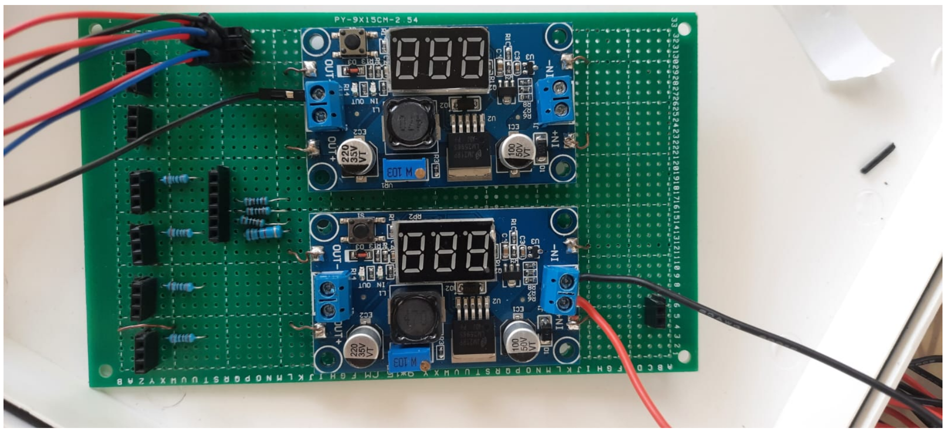


Figure 4.4: Power circuitry

The solenoid circuit, shown in figure 4.5, comprising a diode, a 1K resistor and a Darlington transistor for switching large currents was successfully used to to control the solenoid valves.

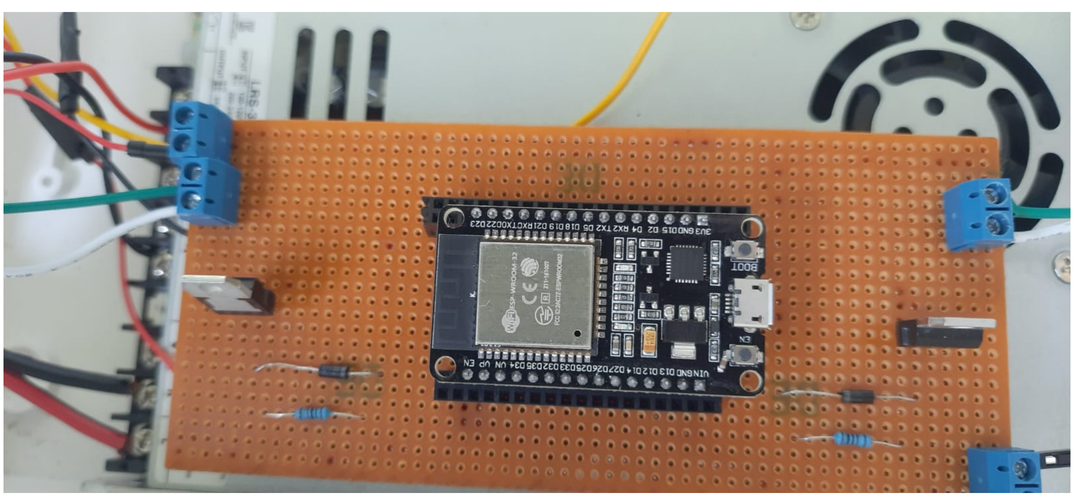


Figure 4.5: Solenoid circuitry

4.1.3 Control interface fabrication

The control interface in figure 4.6 was designed on Grafana. It was used to display oxygen and nitrogen pressure data as well as the flow rate data in the propellant lines.

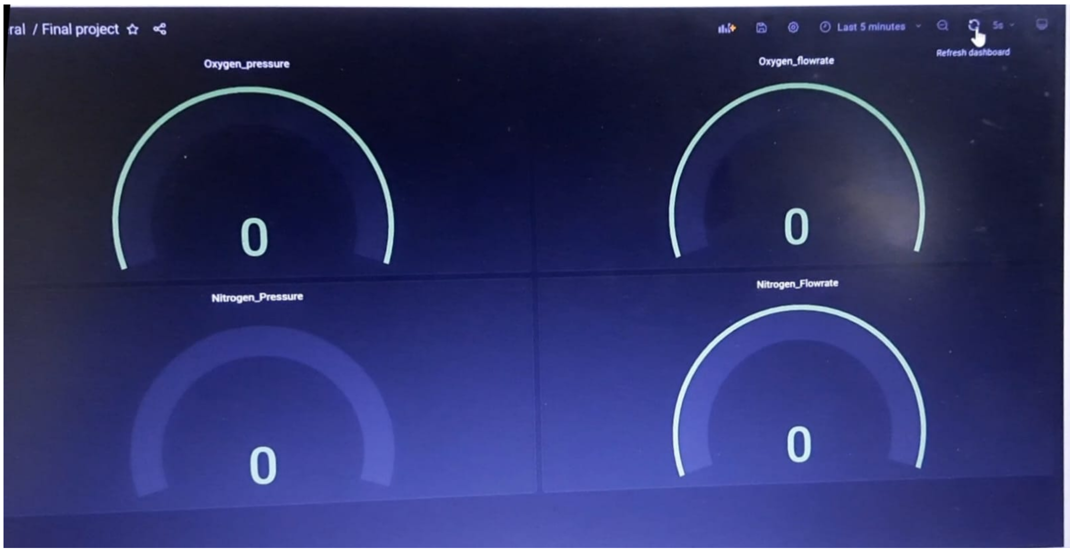


Figure 4.6: Control interface

4.2 Tests and Results

Tests were carried out on both the oxygen and nitrogen line. Results from the oxygen line were then collected and tabulated as shown in figure 4.1. The expected pressure data is indicated in the pressure gauge on the regulator. The pressure sensor reading along the pipeline was also measured and recorded.

The control interface as shown on figure 4.6 was also used to indicate the pressure and flow rate of gaseous oxygen.

Table 4.1: Oxygen line test results

No.	Expexted pressure data	Actual pressure data	Flow rate data
1	0.00	0.00	0.00
2	1.00	0.00	0.00
3	2.00	1.00	0.00
4	3.00	2.00	0.00
5	4.00	3.00	0.00
6	5.00	4.00	2.00
7	5.00	4.00	3.00

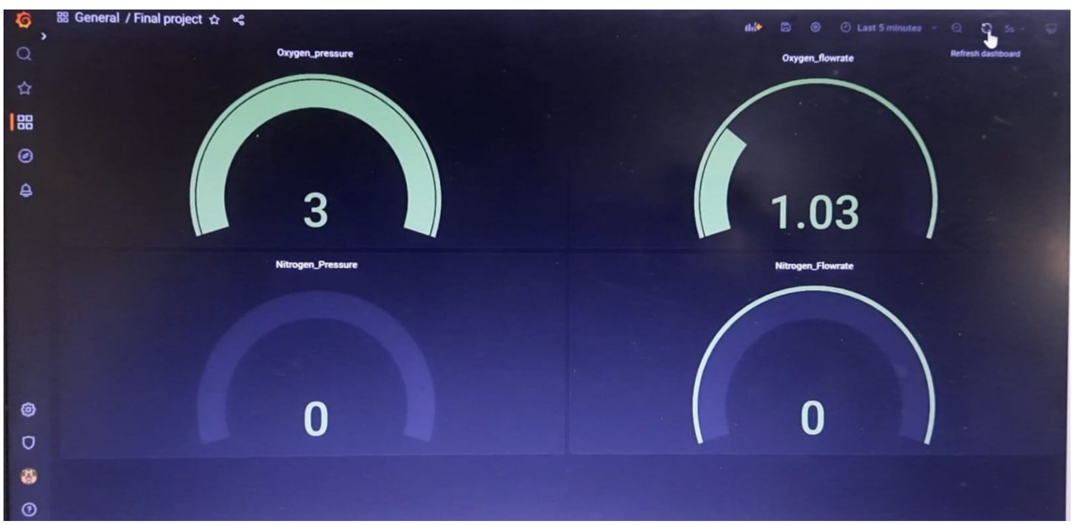


Figure 4.7: Control interface test

4.2.1 Results Discussion

From the readings obtained, it was observed that there is a pressure difference of 1 bar between the expected pressure and the actual pressure obtained. This difference in pressure was attributed to the presence of leakages along the propellant lines.

The flow rate sensor gave out different readings during each test and the flow rate obtained was not the same as the one expected. Due to the unavailability of a gas flow sensor locally, water flow sensors were used in the system and this might be have contributed to the variability in the readings.

The Nitrogen line was tested successfully. The data, however, could not be tabulated as the Nitrogen pressure gauge was faulty hence obtaining the expected pressure data for comparison with actual pressure obtained was not possible.

5 Conclusion

The purpose of this project was to design and develop a controlled fuel reticulation system for a liquid test stand. Gaseous oxygen was used as the oxidizer and Nitrogen gas used in the fuel line in place of ethanol for the purposes of testing.

The test stand structure fabricated is stable and safe and allows for easy assembly and disassembly.

An electrical system was designed and developed to interface the esp23 micro controller, sensors, actuators and the physical model. Controlled actuation of the solenoid valves was achieved using the developed control algorithm.

A user interface was designed on Grafana and successfully used to visualize and monitor the system performance.

Going forward, leakage detectors should be incorporated into the system.

6 Appendices

Appendix A:Time plan

A breakdown for the time-plan was created. This will help the team stay on track until the end of the academic year and helped keep organized with what still needs to be purchased, tested, and fabricated. The time plan is as shown.

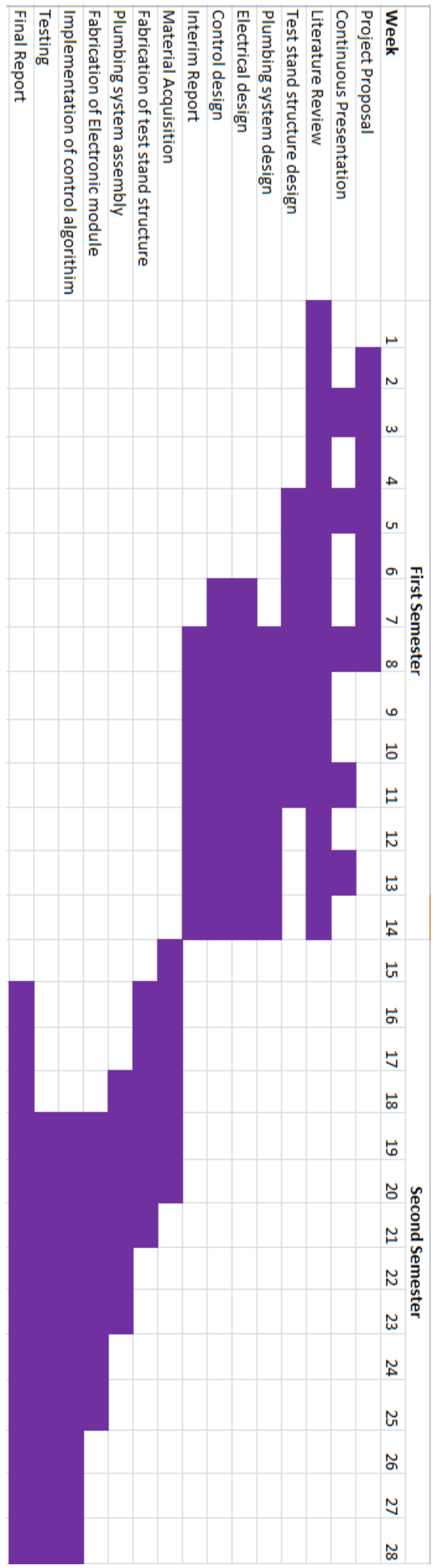


Figure 6.1: Time plan

Appendix B:Budget

The current cost estimate for the liquid rocket engine and test system is shown in table 6.1.

Table 6.1: Estimated Budget

No.	Item	Quantity	Cost per unit (Ksh.)	Total Cost (Ksh.)
1	Pipes	-	-	60112
2	Check valves	3	7620	22860
3	ethanol Pressure sensor	1	54200	54200
4	gas Pressure sensor	2	33800	67600
5	Nitrogen cylinder	1	23900	23900
6	Oxygen cylinder	1	25200	25200
7	Flow sensor	2	800	1600
8	Microcontroller	1	1400	1400
9	Angle lines	15	2343	35148
10	Metal sheets	4	7450	29800
11	Relief valves	2	7365	14730
12	Ethanol Solenoid valve	1	20860	20860
13	Gas Solenoid valve	2	16280	32560
14	Nitrogen regulators	1	13500	13500
15	Oxygen regulators	1	9200	9200
16	1/2 female tee	7	1860	13020
17	1/2 Male nipple	20	980	19600
18	1/2 X 1/4 Reducer	3	960	2880
19	Clamps	10	1600	16000
20	Adapter	2	3500	7000
21	20 Awg black and red wire	2	464	928
22	TIP 120 Transistor	4	50	200
23	Lead Acid Battery - 12V 7Ah	1	1500	1500
24	DC-DC Step-down Converter	2	500	1000
25	Miscellaneous Costs	-	-	3000
	Estimated Total			479930

Appendix C:Part drawings

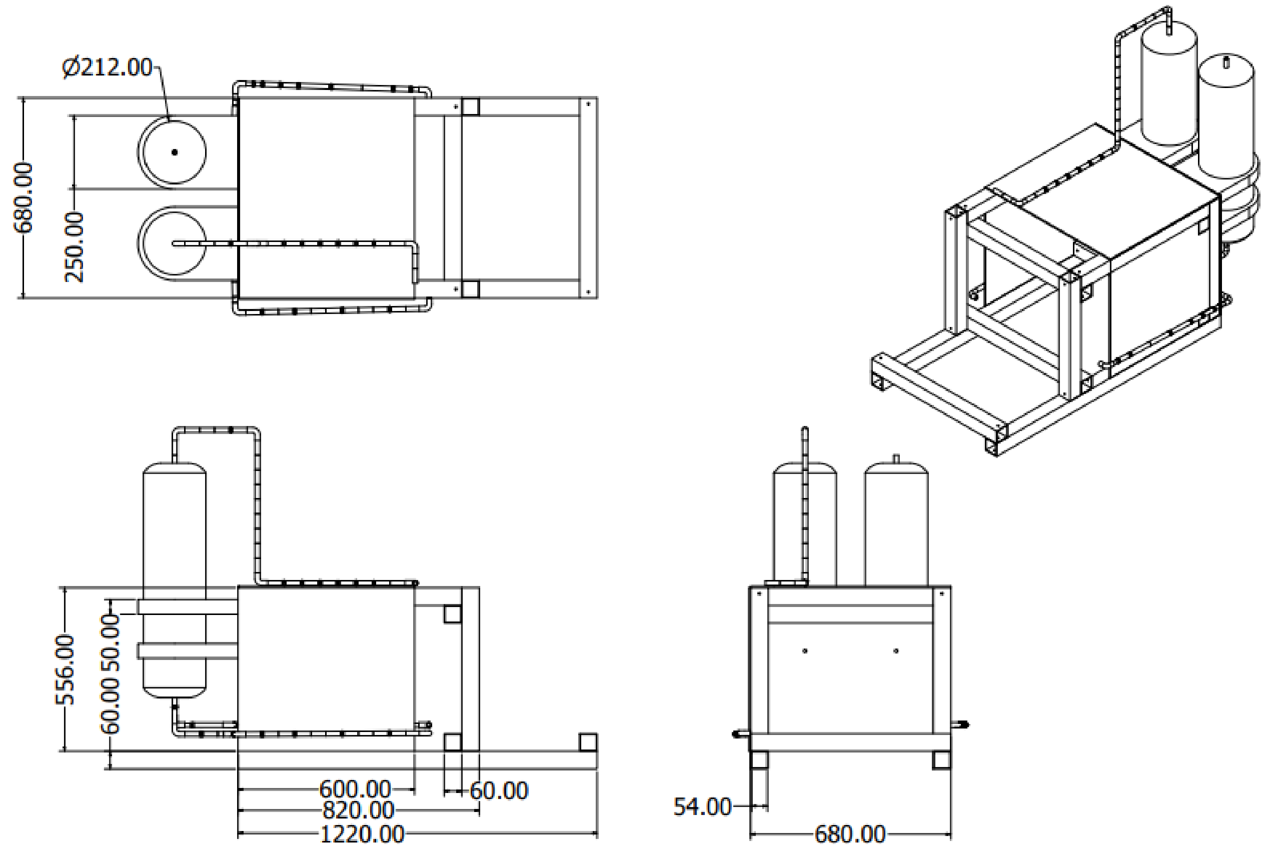


Figure 6.2: Test stand with piping diagram

Appendix D:Complete fuel reticulation system

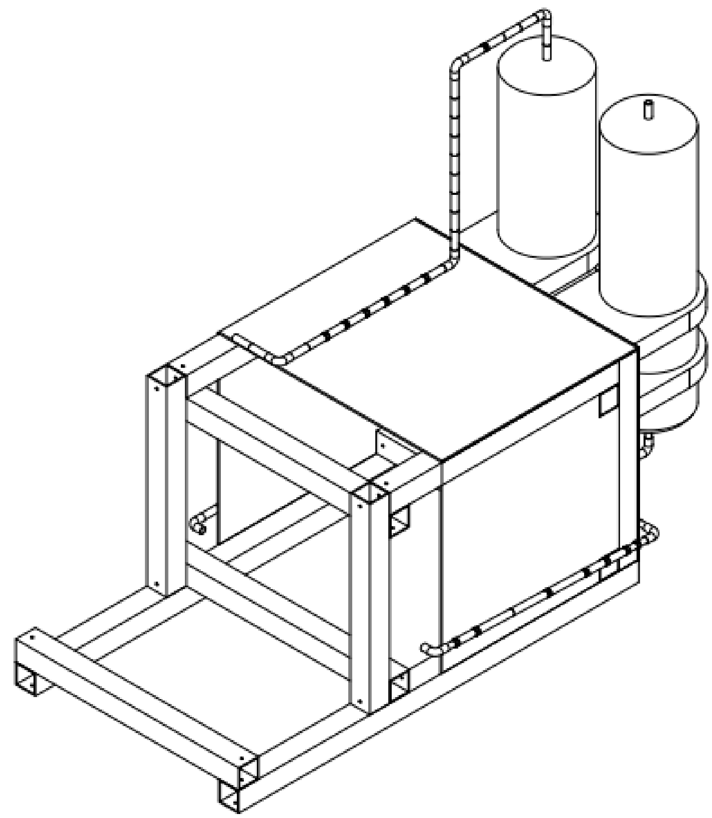
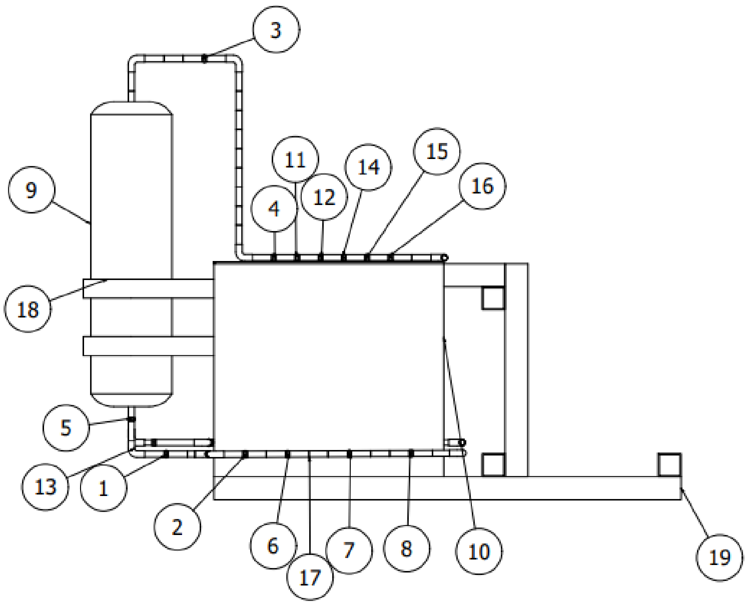
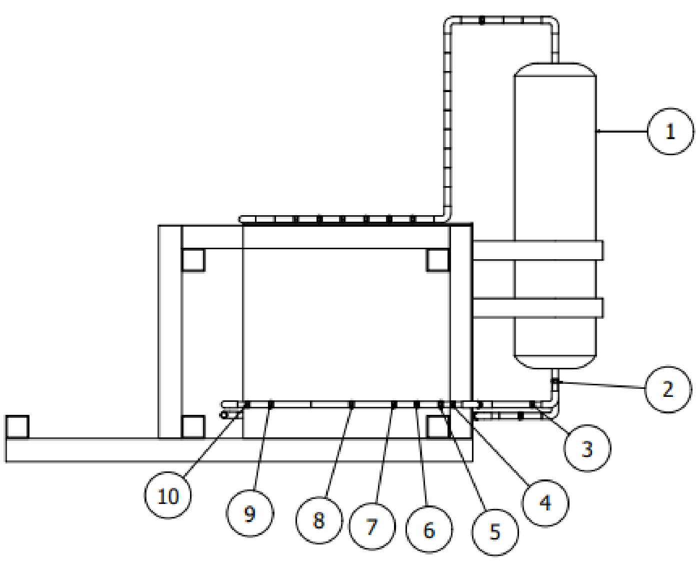


Figure 6.3: 3d diagram of the test stand with piping system



PARTS LIST		
ITEM	QTY	PART NUMBER
1	7	Pressure Transducer
2	2	Flow valve
3	3	Check valve
4	3	Solenoid
5	3	Manual valve
6	3	Solenoid
7	7	Pressure Transducer
8	4	Check valve
9	1	Fuel tank
10	1	Panel
11	2	Relief valve
12	7	Pressure Transducer
13	12	Elbow
14	2	Regulator
15	7	Pressure transducer
16	2	Filter
17	41	pipe
18	1	Brackets
19	14	Square tubings

Figure 6.4: Right view with parts list



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Oxygen tank
2	2	Manual valve
3	2	Filter
4	7	Pressure transducer
5	2	Regulator
6	7	Pressure transducer
7	2	Relief valve
8	2	Flow valve
9	3	Solenoid
10	1	Check valve

Figure 6.5: Left view with parts list

Appendix E:Comparison of Pipe material

TABLE 9-1.—*Corrosion-Resistant Steel (18-8) Annealed (MIL-T-8504 ASG) Tubing*
[Allowable working pressures in psi at 100° F; safety factor of 4]

Maximum working pressure, 3000 psi									
Tube OD, in	1/4	3/8	1/2	5/8	3/4	1	1-1/4		
Wall thickness, in	0.022	0.035	0.042	0.058	0.065	0.083	0.109		
Maximum working pressure, 2400 psi									
Tube OD, in	1/4	3/8	1/2	5/8	3/4	1	1-1/4	1-1/2	
Wall thickness, in	0.020	0.028	0.035	0.049	0.058	0.072	0.095	0.109	
Maximum working pressure, 1500 psi									
Tube OD, in	1/4	3/8	1/2	5/8	3/4	1	1-1/4	1-1/2	2
Wall thickness, in	0.020	0.023	0.032	0.035	0.042	0.049	0.058	0.065	0.095

TABLE 9-2.—*Aluminum Alloy, 5052 Round Seamless Drawn WW-T-78a Temper H34*
[Allowable working pressures in psi at 100° F; safety factor of 4]

Maximum working pressure, 1500 psi									
Tube OD, in	1/4	3/8	1/2	5/8	3/4	1	1-1/4		
Wall thickness, in	0.025	0.042	0.049	0.058	0.072	0.095	0.120		
Maximum working pressure, 750 psi									
Tube OD, in	1/4	3/8	1/2	5/8	3/4	1	1-1/4	1-1/2	2
Wall thickness, in	0.020	0.028	0.032	0.035	0.042	0.049	0.065	0.072	0.095

Figure 6.6: Comparison of pipe materials [5]

Appendix F:Component specification

Table 6.2: Component description

Item	Description
Pressure relief valve	Genebre brass High Pressure Relief Valve (Liquid and Gas). 1/2" BSPT threaded. Pressure ratings upto 10bar.
Check valve	Genebre single disk check valve, threaded ends. Maximum allowable working pressure up to 63 bar. Temperature: -20° to 240° C. End Connections: Male and female BSPT. End Connection Sizes: 1/2 in.
Solenoid valve	Brass solenoid valve, Piston pilot operated. 2/2 way Normally Closed. Operating pressure of 0-10bar.Pipe size 1/2".
Gas flow sensor	FS1025-DG gas flow sensor with solid thermal isolation technology. Gas flow 0-150litres/min. It features an Analog, 0 to 4.5V, Digital I2C output, and current consumption of 21mA.
Gas pressure sensor	A-10 pressure transmitter, Pressure rating 0-10bar. Analogue output with IO-link with ceramic-capacitive pressure sensing element. Operating voltage 14-30 V DC

Appendix G:Production plan

For the development process we came up with a fabrication plan that we used as a reference for the tasks to be done having allocated timelines to the various tasks as shown

WEEK	TASKS	MATERIAL	SPECIAL EQUIPMENT	CONCURRENT ACTIVITIES	REMARKS
1	Project presentation				Done
	Project review and redesign				Done
2	Material acquisition				Done
3	Project review and redesign			Material acquisition	Done
4	Material acquisition			Electrical Simulation	Done
5	Test stand structure fabrication (i) Scribing and cutting (ii) Drilling	(i) SS angle lines 50*50*3mm (ii) SS sheet 2mm thick		Writing solenoid code Electrical Simulation	Done
6	Tank setup (i) Gaseous Oxygen tank (ii) Nitrogen tank (iii) Ethanol tank modification	Standard gas cylinders		Build solenoid test circuits Writing sensors code	Done
7	Pipe layout (i) Intergration of valves and sensors	High pressure flexible hoses		Writing sensors code PCB fabrication	Done
8	Assembly (i) Electrical intergration and mechanical			Writing dashboard code Testing the user interface	Done
9	Dashboard implementation			Testing the user interface Combining all the codes	Done
10	Testing and modifications.				
11	Testing and modifications.				
12	Testing and modifications.				

Figure 6.7: Production plan

Appendix H:Benchmarking

Bench marking was carried out based on the parameters that are highlighted in the table below which influenced the design process of the test stand and the plumbing system.

S.No	Team name	Fuel	Oxidizer	Engine system (Pusher, Gas generator, etc.)	Tank pressure: Resorvoir tank [MPa] Fuel tank [MPa] Oxidizer tank [MPa]	Tank material Resorvoir tank material Fuel tank material Oxidizier tank material
1	PSAS (Portland St. Univ.)	Isopropyl alcohol	Liquid Oxygen	Nitrogen pressure-fed	16.89, 5.86, 4.48	
2	MASA (Univ. of Michigan)	Rocket-grade Kerosene (RP-1)	Cryogenic liquid oxygen (LOx)	Helium pressure-fed cycle		
3	USC Liquid Propulsion Laboratory (Univ. South California)	Kerosene	Gas oxygen		18.2, 8.96, 18.2	
4	SARP (Univ. of Washington)	Ethanol	Liquid Nitrous oxide	Helium gas		Aluminium
5	DARE (TU Delft)	Ethanol	Liquid oxygen		60 bar	
6	Copenhagen Suborbitals	Ethanol	Liquid oxygen	Pressure blow-down		
7	SEDS (UC San Diego)	Kerosene RP-1	Liquid oxygen	blow down		
8	MIT Rocket Team	Ethanol	Liquid oxygen			
9	Let's Build Rockets	Kerosene	Liquid oxygen			
10	Robert's Rocket Project	Kerosene	Liquid oxygen	string/stringer system		
11	Sun Devil Rocketry (Arizona St. University)	Kerosene	Liquid oxygen		2.14	stainless steel

Figure 6.8: Benchmarking

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