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TASK : DESIGN OF FUEL INJECTOR FOR A LOW ALTITUDE LIQUID PROPELLANT ROCKET

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1. TITLE: DESIGN OF FUEL INJECTOR FOR A LOW ALTITUDE LIQUID PROPELLANT ROCKET

2. ABSTRACT

The write up below highlights the process of designing a fuel injector for a liquid propellant rocket for the Nakuja project. The rocket is expected to achieve an average of 1 KN of thrust. This paper will include a selection process of the design. A conceptual design of a coaxial swirl injector was selected and the paper follows the design of the injector using Computer Aided Design using Autodesk Inventor. Master CAM is also used to simulate the process fabrication process of the parts designed. Design for manufacture and assembly were highly considered in the selection process of the injector as it would determine manufacturing ease and cost. The resulting coaxial swirl injector is highly modular and simple in its design thus meeting both goals to reduce costs and allow for easier manufacture.

2.1. INTRODUCTION

In a liquid propellant rocket engine, one of the most important elements are the propellant injectors. There is a need to design an injector for a small rocket engine that will be used on the Nakuja project N3 rocket. The injector needs to deliver enough propellant into the combustion chamber to produce the desired thrust as well as atomize and mix the fuel. There are three proposed designs: coaxial, swirl injector, pintle injector and self-impinging injector. From the proposed designs the coaxial swirl injector was selected due its ease of fabrication compared to the pintle injector and self-impinging injector. The coaxial swirl injector was then designed using computer aided design and the individual parts were assembled. The injector is expected to deliver propellant with ideal flow characteristics and atomize the fuel adequately.

2.2. LITERATURE REVIEW

The injector implementation in liquid rockets determines the percentage of the theoretical performance of the nozzle that can be achieved. A poor injector performance causes unburnt propellant to leave the engine, giving poor efficiency.

Injectors can be a number of small diameter holes arranged in carefully constructed patterns through which the fuel and oxidizer travel. The speed of the flow is determined by the square root of the pressure drop across the injectors, the shape of the hole and other details such as the density of the propellant.

Injectors consist of a number of small holes which aim jets of fuel and oxidizer so that they collide at a point in space a short distance away from the injector plate. This helps to break the flow up into small droplets that burn more easily.

The mass flow rate of the two-phase mixture in the recessed chamber is M, and the density of the two-phase mixture is $\rho = \rho_g \beta + \rho_l(1-\beta)$, where ρ_l, ρ_l are the density of the liquid and gas, respectively, and is the volumetric fraction of the gas phase. Because the flow is considered to be inviscid, the viscous term is neglected and the momentum equation in the recessed chamber can be written as

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} \quad [1]$$

2.3. PROBLEM STATEMENT

As described above a fuel injector is an integral part of a rocket engine. The fuel injector performs the primary function of feeding fuel to the combustion chamber. The design of a fuel injector for a low altitude rocket has the following functional requirements;

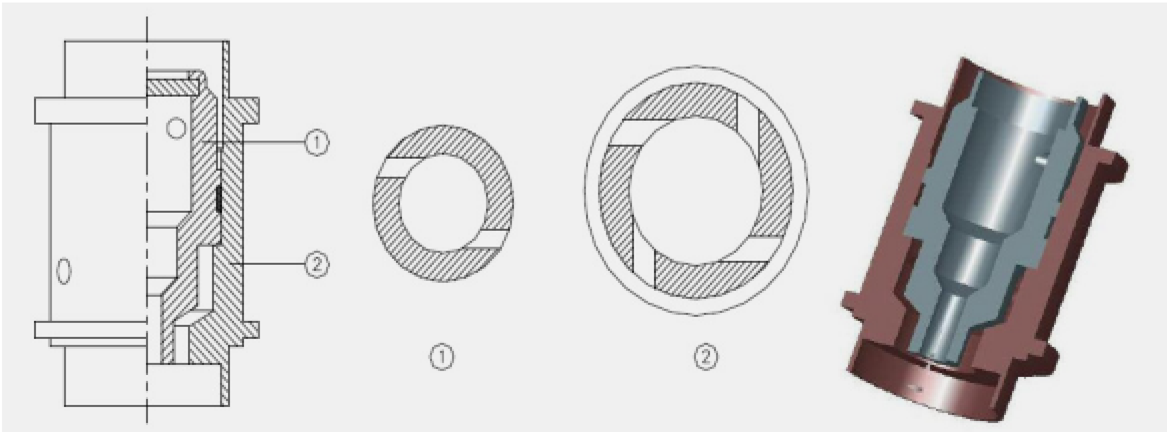
1. The fuel injector must be able to inject fuel into the combustion chamber at the correct oxidizer to fuel ratio and the correct flow rates. For this reason the discharge coefficient of the injector must be determinable.
2. The fuel injector should ensure complete mixing of propellants to avoid undesired hotspots on the chamber wall that may cause failure of the engine
3. The fuel injector must facilitate a primary pressure drop of between 10-20% to prevent discharged fuel from flowing back into the injection system and causing an explosion.
4. The fuel injector should also facilitate the atomization of the propellants to ensure optimal conversion of chemical energy to thermal energy.
5. The fuel injector should have tunable parameters to allow for fuel rich or oxidizer rich discharge. This is important to facilitate fuel film cooling on the walls of the combustion chamber and oxidizer rich combustion in the center of the combustion chamber.
6. The fuel injector should be able to handle isopropyl alcohol as it has low density .

The fuel injector also has to meet the following non- functional requirements:

1. It should be easy to construct as the technical capabilities of the Nakuja project are limited.
2. It should be scalable as the project will commence with a small rocket that can then be scaled to a bigger rocket. It is important that the injector design be scalable to reduce the design variables as the rocket engine is scaled upwards.
3. The fuel injector should be made from locally available material as the purpose of the Nakuja project is to make rockets from locally sourced materials.

2.4. PROPOSED SOLUTION

Our proposed solution is a coaxial swirl element in assembly separating fuel and oxidizer input by use of a separator plate.The swirl injector consists of two primary parts; the inner element and the outer element. The two elements are placed on different levels separated by a separator plate. The inner element takes in Liquid Oxygen tangentially which causes the liquid to swirl along the wall of the inner section. The fuel enters the outer section tangentially as well and swirls along the wall of the outer element. This results in the LOX leaving the inner element in the shape of a cone which collides with the cone formed by the outer element. In this way the fuel and then oxidizer leave each of the elements in a cylindrical manner colliding and atomizing due to the high pressure and velocity of the flow. The configuration is as displayed in figure 1.



This configuration meets the functional requirements of the fuel injector system .The efficiency of the injector for low density and gaseous fuels can reach as high as 95%. The swirl injector has the following advantages;

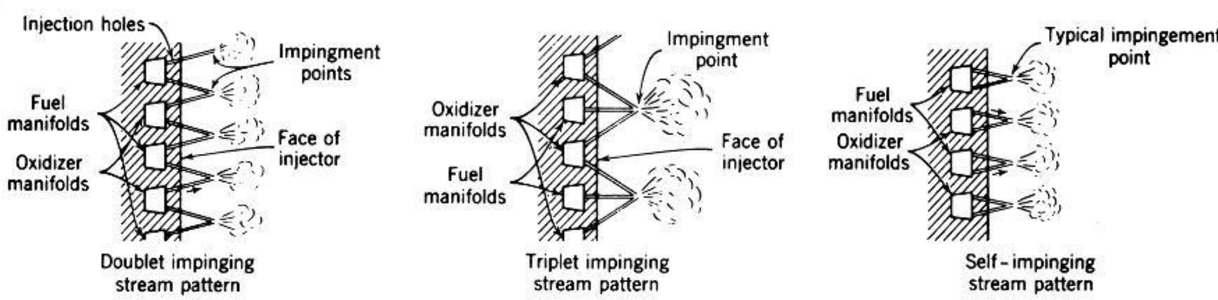
1. The design is highly scalable since the assembly can be made bigger by adding the number of swirler elements in the assembly.
2. The swirler and assembly are relatively easy to machine
3. The swirler offers high atomization which is crucial for the conversion of chemical energy to thermal energy
4. The swirler element offers adjustable flow parameters allowing the assembly to create oxidizer rich zones and fuel rich zones.
5. Swirler elements offer the ability to vary the velocity of the propellants which can enhance the mixing of the fuel and oxidizer
6. The parrots a highly modularized allowing for Design for manufacture and assembly.

The disadvantages of swirl injectors are:

1. They are a relatively new type of injector with fewer developed optimization characteristics
2. They require high dimensional accuracy for high performance

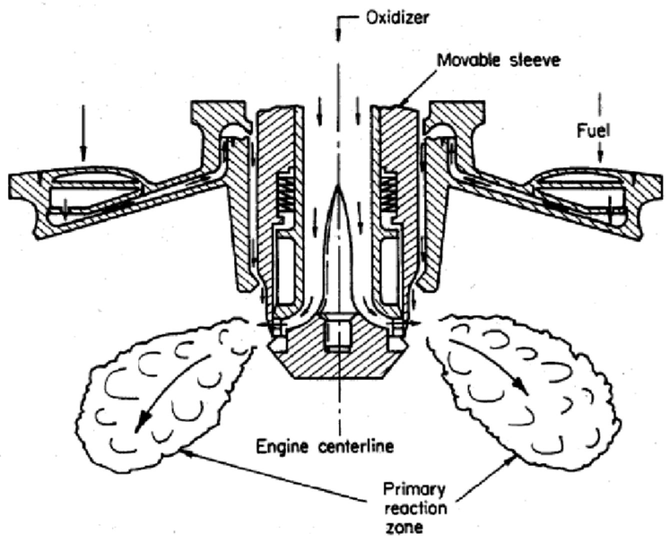
The other types of injector designs considered were;

Cross impinging injectors/jet injectors-



These types of injectors were not chosen because they require a high degree of accuracy to machine and they are prone to explosions as the contents of the combustion chamber can move upstream.

Pintle injectors-



These types of injectors are known for their performance and reliability. They achieve a high degree of atomization. This type of injectors were not chosen as they offer a difficulty in analysing the discharge coefficient, they are very difficult to scale up and they require very close dimensional tolerances.Pintle injectors are also ideal in their number of processes involved. They however include an actuated part that might reduce the simplicity of construction as well as raise costs.

2.5. METHODOLOGY

The injector will consist of two parts:

1. The individual swirl elements
2. The injector plate assembly

Swirl elements

The conceptual design of each element was divided into two main parts: the inner element and the outer element. They were divided in the given configuration to ease the fabrication process. The inner element is used for the oxidizer (liquid oxygen). It consists of a cylindrical chamber which decreases diameter in the direction of through a conical section. It has four tangential holes that provide the tangential entry of the liquid into the cylinder as shown in the figure below.

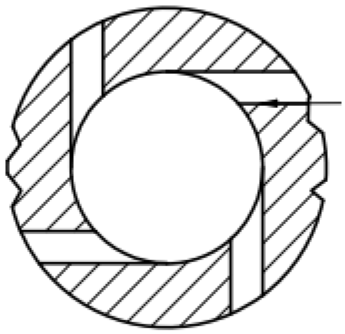
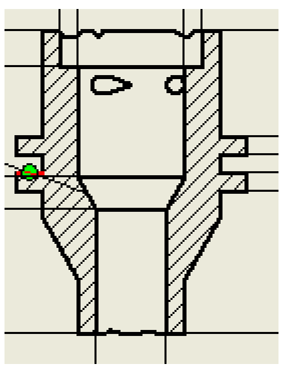
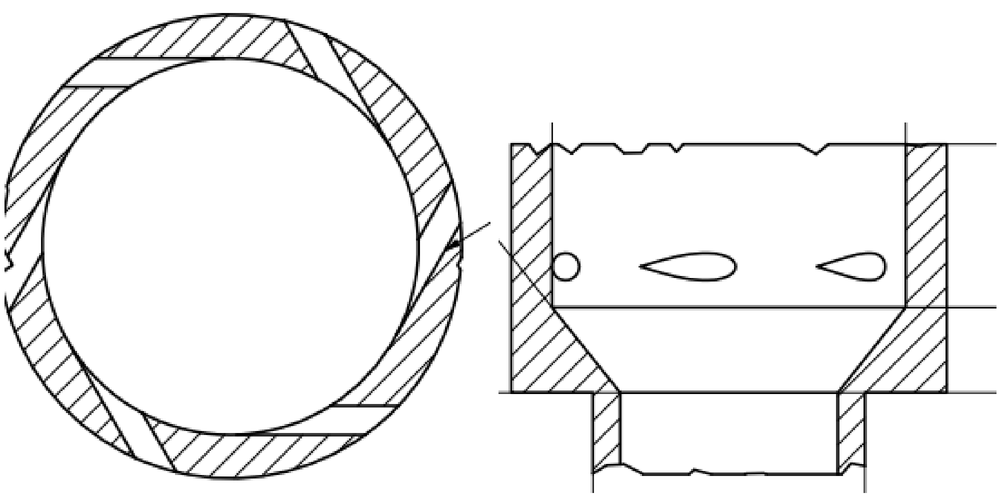


Fig. 4 Section view of swirler element

The liquid follows the curve of the chamber as it swirls within the chamber before exiting in a conical shape as shown in the figure below. The inner element also has a flange which is used to solder the inner element to the outer element.



The outer element is the same as the inner element but has more tangential holes (six) as shown in the figure below. The inner element is mated to the outer element. The outer element is used for the fuel (ethanol).



The individual flows impinge on each other and droplets are ejected into the combustion chamber. This results in mixing as well as atomization of the propellant.The design process of the swirler element involves selecting the dimensions of the inner and outer element as well as the size and number of the tangential holes used in the swirler.The concept designs of the swirl element are attached:

Injector assembly base and plate
Consist of a separator plate as well as a base with holes. The separator plate forms the boundary between the LOX and the fuel. The dimensions and type of material are parameters to be determined. The concept designs for the injector assemble base and separator plate are attached.

3. DESIGN SELECTION PROCESS

The requirements of the fuel injectors were defined and the coaxial swirl injectors selected as the appropriate injectors.During the design selection process a number of factors affected the selection of a design.These factors included:

- The required thrust of the eventual rocket
- Safety of use and construction
- Reliability
- Repeatability of the design
- Ease of manufacture
- Thermal properties of injector material and assembly.
-

The Design of these injectors for use in the Nakuja project followed the following process.

1. **Determining the type of material to be used**

The material to be used to make up the injector elements has to be:

- able to withstand high combustion temperatures of the combustion chamber
- strong enough to endure chemical and thermal corrosion for multiple firings
- dissipate heat rapidly to avoid development of hotspots
- easy to clean
- Easy to weld to make connections

Common injectors are made from brass and mild steel. Brass is used when the injector is to be made via subtractive manufacturing while the steel is used when the injector is to be made using additive manufacturing.
For this reason brass was chosen as the material of choice as it meant all the design requirements.

2. **Determining the dimensions of the swirl elements.**

The inner and outer swirl elements had to be dimensioned for our specific use for the Nakuja project. The dimensions of both elements were determined based on the desired flow rate. The required thrust is used to set the dimensions of the combustion chamber as well. The elements had to be small enough to fit within the assigned plate area. The injector plate also had to be able to fit along with the combustion chamber as well as align with the nozzle.

3. Determining the number of swirler elements

The number of swirler elements are determined depending on the desired thrust. The number was chosen as 19 to maximize the area of the combustion chamber .The value suits the desired combustion chamber required to produce 1KN of thrust.

4. Determining the geometry of the swirlers.

The geometry of the swirlers was chosen to maximize the area of overlap of the two cones produced by the swirlers. Maximum area of overlap increases the degree of atomization offered by the swirler. They also needed to be able to withstand 3 MPa of pressure.

The above process resulted in the design in the attached drawings.

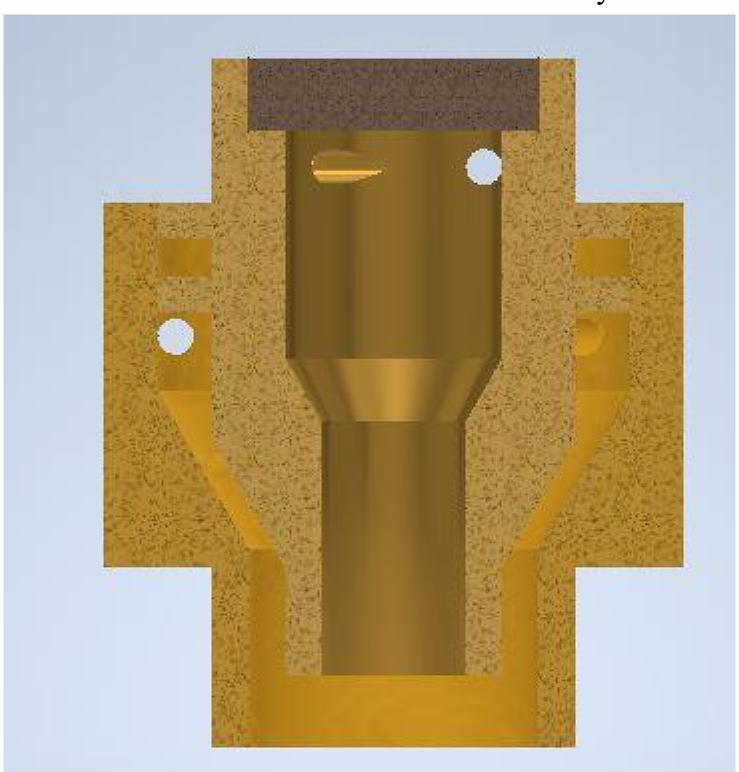
4. DESIGN DEVELOPMENT

The development of the design was done by separating the assembly into five distinct parts:

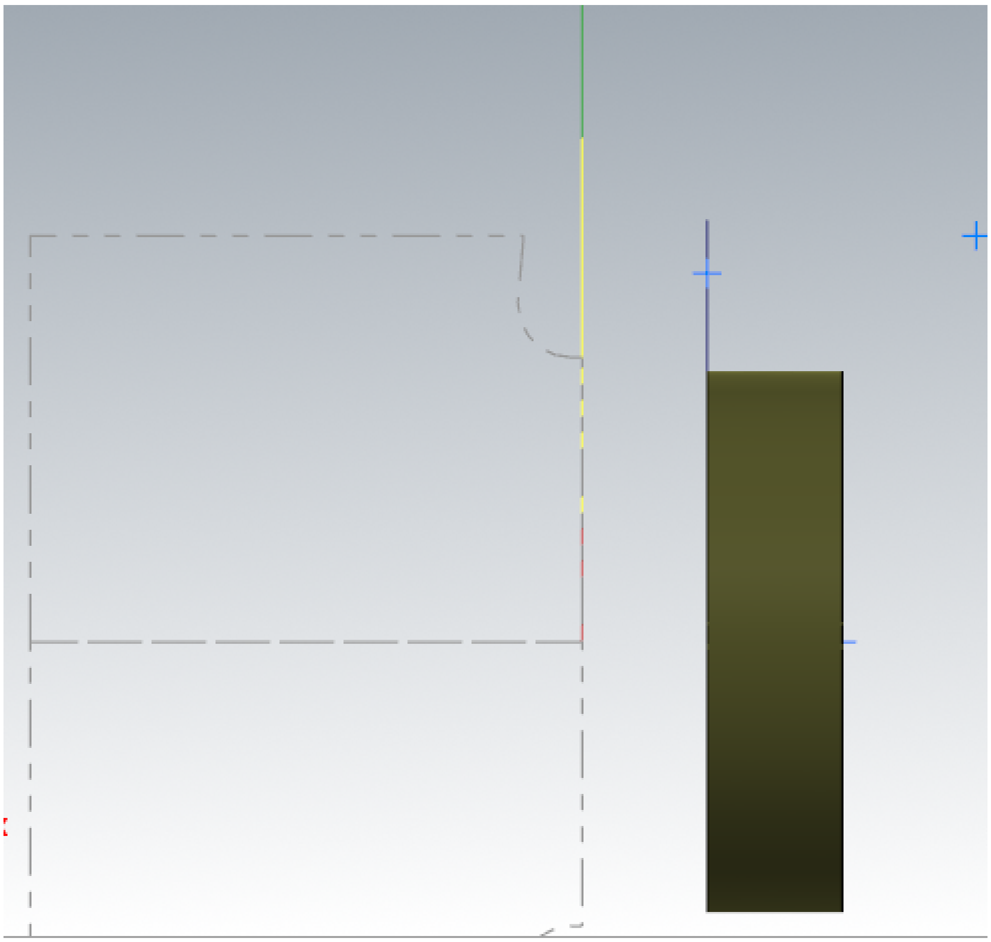
1. Separator plate
2. Base plate
3. Swirler cap
4. Inner swirl element
5. Outer swirler element

Swirler Assembly

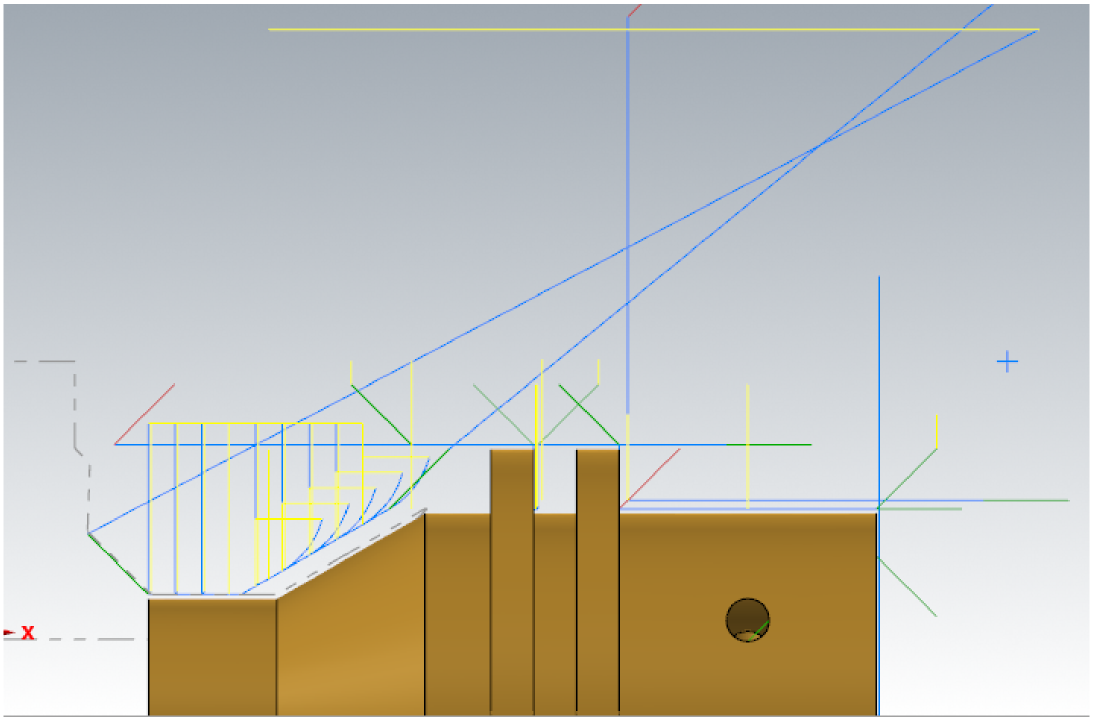
The parts were drawn on Autodesk Inventor for the 3D representation. The individual parts were then assembled. A cross section of the assembly is shown below.



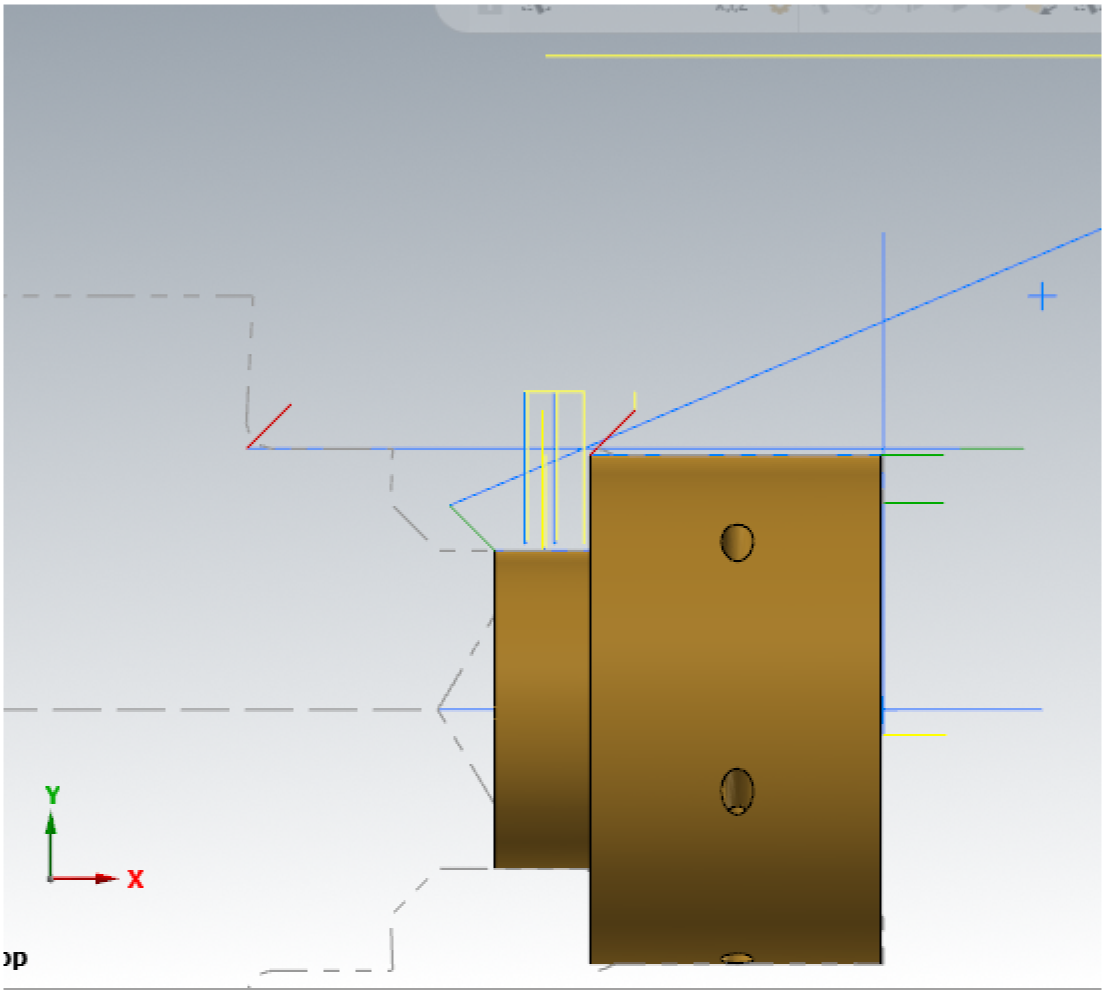
MasterCAM was then used to show the fabrication processes.
The cap was machined using a CNC lathe. The first process was facing the stock. This was followed by a rough surface turning on the outer diameter profile followed by a finishing process on the surface. The part was then cut off from the stock using a grooving tool. The tool paths are shown below:



The inner element was machined using a CNC lathe. The first process was facing using a right hand turning tool. A rough turning operation was then used to bring the dimensions to closer tolerance of the desired profile. A grooving operation was then used to machine the flanges on the profile. A grooving tool was also used to finish the tapered turning on the end of the part. A finishing turning operation was then done to bring the part to the required dimensions. A diameter 4 drill was then used to drill through the entire part. A diameter 8 drill was then used to a depth of 9mm. An internal grooving tool is then used to finalize the internal profile. The part was then cut off from the stock using a grooving tool. The figure below some of the generated tool paths.

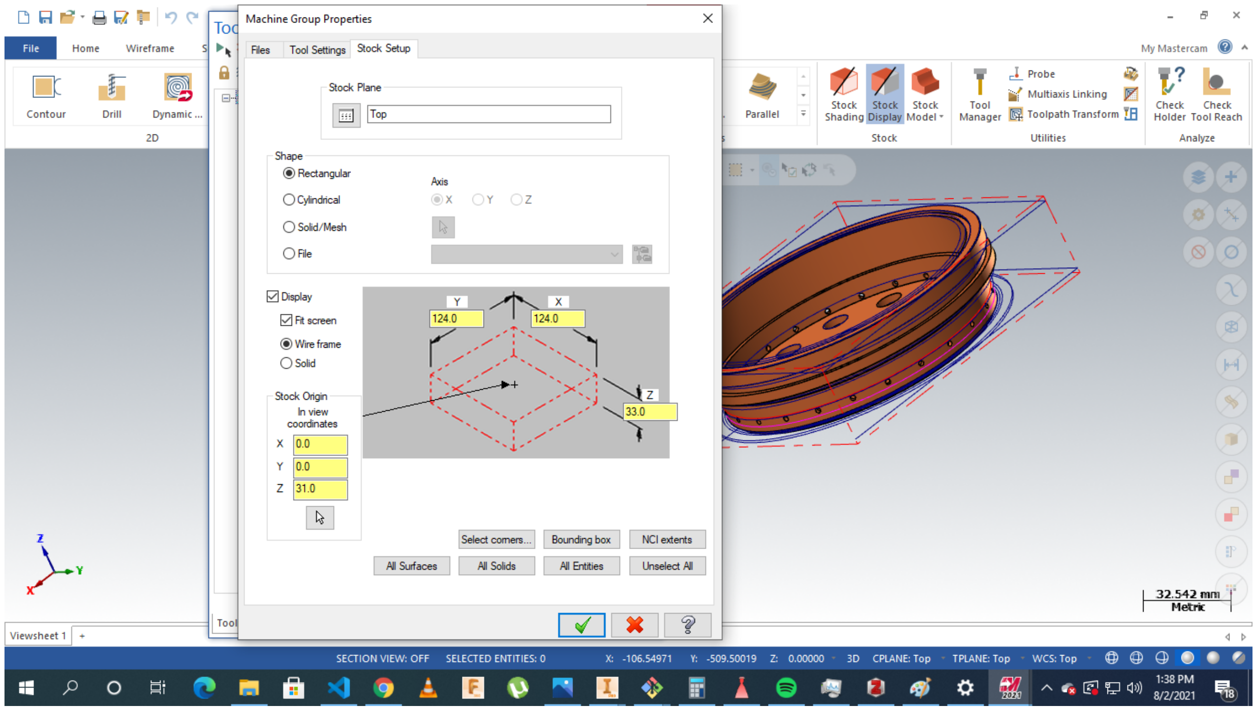


The outer element was machined using a CNC lathe. The first process was facing. This was followed by a rough turning operation on the profile. A grooving tool was then used to machine the end on the profile where there is a diameter change. The outer element was then finalized with a finishing turning operation. For the internal profile a drill of diameter 8 is passed through the entire stock. THis is followed by a drilling with a 12 mm drill to a depth of 12.12mm. The internal profile is then finalized by an internal turning operation. The part was then cut off from the stock using a grooving tool.

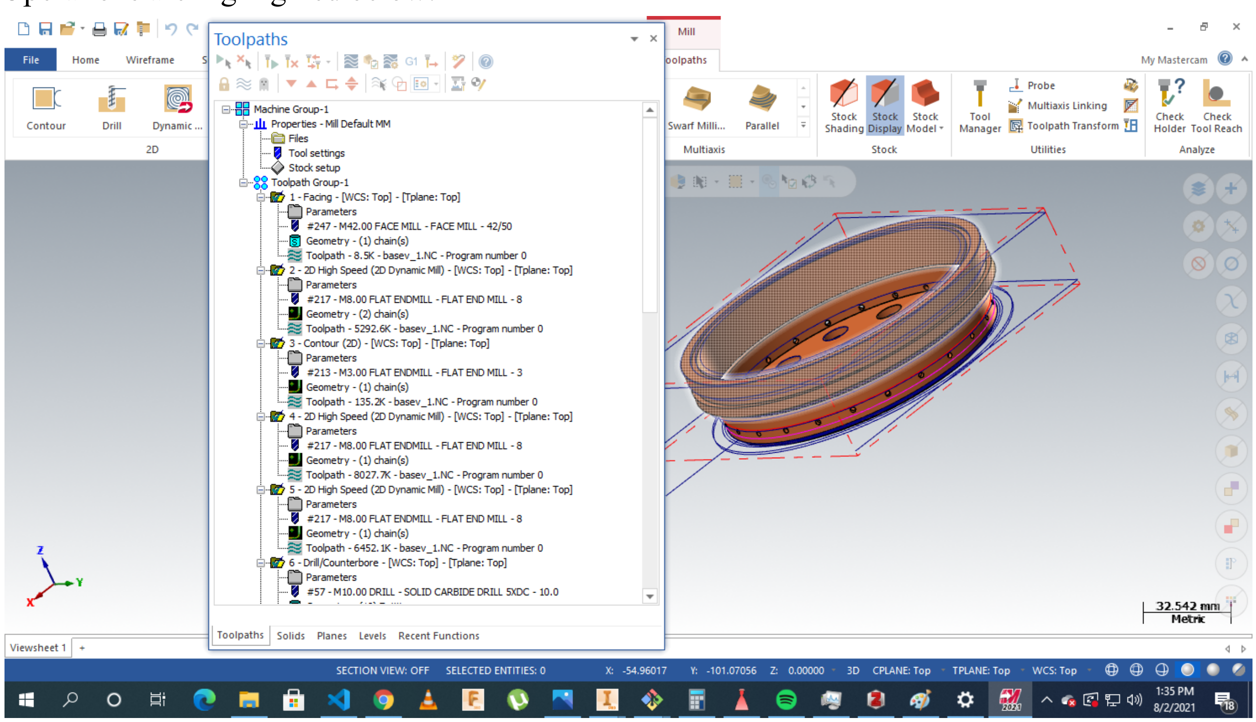


Base plate

The stock of this part was as defined:

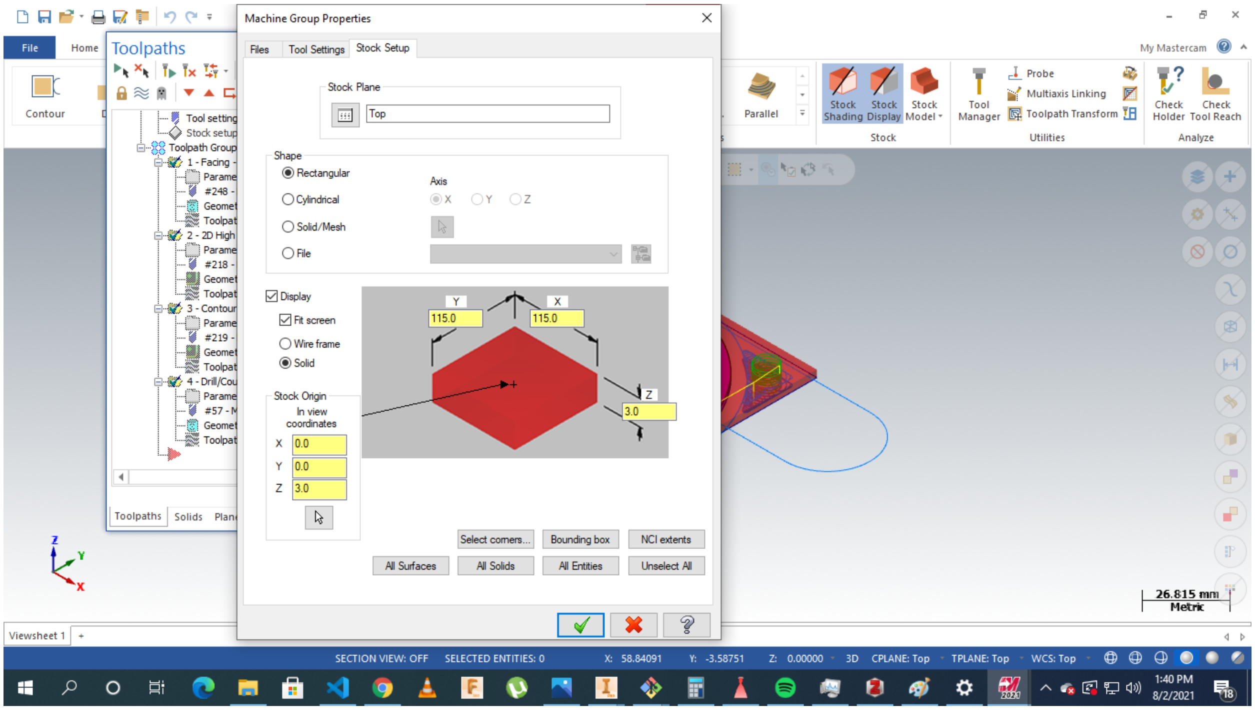


The operations were to conducted on a five axis milling machine. The processes involved include: facing, contour milling drilling slot milling and multi-axis drilling.
The parts were milled as the material to be used was brass.
Operations are highlighted below:



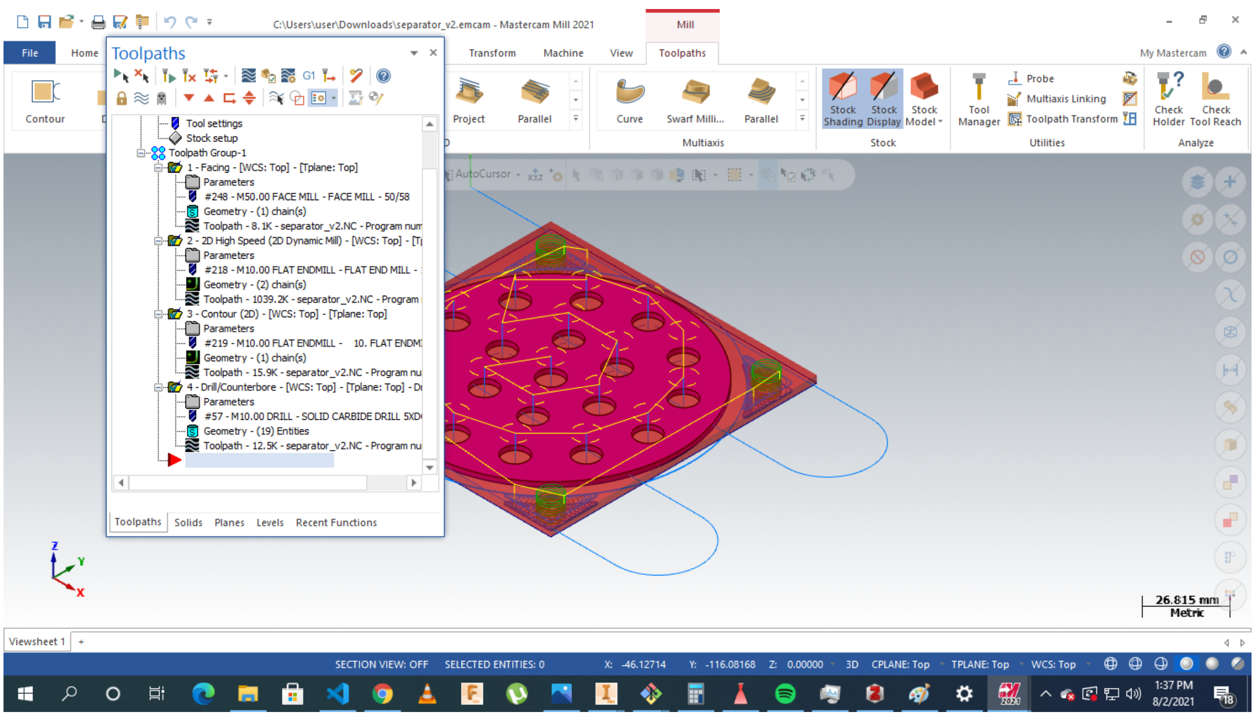
Separator plate

The stock was as defined:



The operations involved: facing, drilling,contouring and parting.

The processes were as displayed :



References

[1] L.-J. Yang and Q.-F. Fu, ‘Theoretical Investigation on the Dynamics of a Gas-Liquid Coaxial Swirl Injector’, *J. Propuls. Power*, vol. 27, no. 1, pp. 144–150, 2011.

2. [1]H. Belal, A. Makled, and M. Al-Sanabawy, “Vaporization-controlled simplified model for liquid propellant rocket engine combustion chamber design,” IOP Conference Series: Materials Science and Engineering, vol. 610, p. 012088, Oct. 2019, doi: 10.1088/1757-899X/610/1/012088.