# WANKEL ROTARY ENGINE

A Final Year Project Report

Presented to

**SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING (SMME)**

Department of Mechanical Engineering

National University of Sciences & Technology (NUST)

ISLAMABAD, PAKISTAN

---

In Partial Fulfillment

of the Requirements for the Degree of

Bachelor of Mechanical Engineering

---

by

BILAL AZIZ

NIBRAS SALMAN

HAREEM FATIMA

LAIBA REHMAN

June 2022

# EXAMINATION COMMITTEE

We hereby recommend that the final year project report prepared under our supervision by:

| | |
|---|---|
| Bilal Aziz | 255382 |
| Nibras Salman | 244065 |
| Laiba Rehman | 243153 |
| Hareem Fatima | 245135 |

Titled: “Wankel Rotary Engine” be accepted in partial fulfillment of the requirements for the award of Mechanical Engineering degree with grade ___

| | |
|---|---|
| Supervisor: Dr. Sami ur Rahman Shah, Title (faculty rank)<br>School of Mechanical and Manufacturing Engineering (SMME) | ____________________<br>Dated: |
| Committee Member:<br>School of Mechanical and Manufacturing Engineering (SMME) | ____________________<br>Dated: |
| Committee Member:<br>School of Mechanical and Manufacturing Engineering (SMME) | ____________________<br>Dated: |

______________________ ___________

(Head of Department) (Date)

## COUNTERSIGNED

Dated: ________________ __________________________

(Dean / Principal

# Abstract

This paper emphasizes how Wankel Rotary Engine can potentially compete with the conventional Piston engine following its prime advantages over the competitor. Few of which include, the higher power output, greater torque delivery, elevated power to weight ratio, a smaller and simpler engine design, and culminated vibrations. These rewards, however, weigh less in the eyes of industrialists when the cost of running the engine bounces on the stage. The Rotary engine holds a bad reputation for gulping fuel and lubricant; however, this notorious fame is exaggerated since following its inception in 1957, the globe was struck by a drastic oil crisis in 1973, which led the manufacturers to completely disregard this alluring machine. Mazda remained the only company that stuck with the rotary and kept using it in their RX series automobiles, which the car enthusiasts kept on adoring. We chose to design, build, and test a model of the Wankel Rotary engine since we believe that due to its simpler design it could serve as a steppingstone for Pakistan to move towards vertical integration of such engines (rather than simply assembling modern engines). Moreover, the rotary engine has much more potential to be modified and flourished to improve its defects. We used an iterative technique to design our engine, the initial step was to formulate the dimensions of each part such that the assembly is kinematically correct. The next step was to calculate whether each part could mechanically resist failure under the given loading conditions. If it could, the dimensions would be kept, otherwise, new dimensions were assigned, and the process repeated. The fundamental parts will initially be sand cast by using wooden patterns, these include the engine's housing, end plates, rotor, and the eccentric shaft. These sand cast parts will then be precisely machined via a 3-axis milling CNC. The engine can only operate if the auxiliary components are correctly identified and employed. These additional systems include ignition (spark plugs, CDI unit), lubrication (oil pump, oil filter), and starting the engine (starter motor), just to name a few. After assembling all the engine components with the auxiliary systems, we are testing the engine on the dynamometer for the brake horsepower and torque.

# Acknowledgements

This project would not have been possible without the grace of Allah. Amongst the people we would like to express our deepest gratitude towards our parents, who supported us financially and mentally along the journey. Their prayers and love for us gave us the strength to carry this work forward, work harder than we ever could and achieve what we are achieving. We would like to acknowledge the sheer help by our supervisor Dr. Sami ur Rahman Shah guided and illuminated us along this escapade. His will to propel us and search things in the field, and his technical acumen are golden nuggets which we were fortunate enough to realize. His advice along the way and judgement calls saved us a lot of time and capital. We are particularly thankful to the people at MRC especially Faisal Sahab and Nisaar Sahab who did most of machining work and helped in practically building the engine. We present our utmost gratitude towards Mr. Asad Zia who explained the working principles of a lot of the auxiliaries that we have used.

# Table of Contents

# List of Figures

# Chapter 2 Introduction

## Problem Statement

3D Modelling, Simulation, Fabrication, Assembling & Testing of a Wankel Rotary engine while comparing its response to a similar sized Piston engine.

## Motivation behind the Project

Since its inception in 1876, the piston engine has ruled over our streets and the same fundamental design is being used so far. Imagine the same being said for a telephone, computer, or building. How did these things look back in the 1800s and how do they look now? Is the flourishing of these things due to some pivotal reason? The answer is YES, and the reason is Competition. Something the Piston engine did not encounter, hence the IC engine race had not much of diversity.

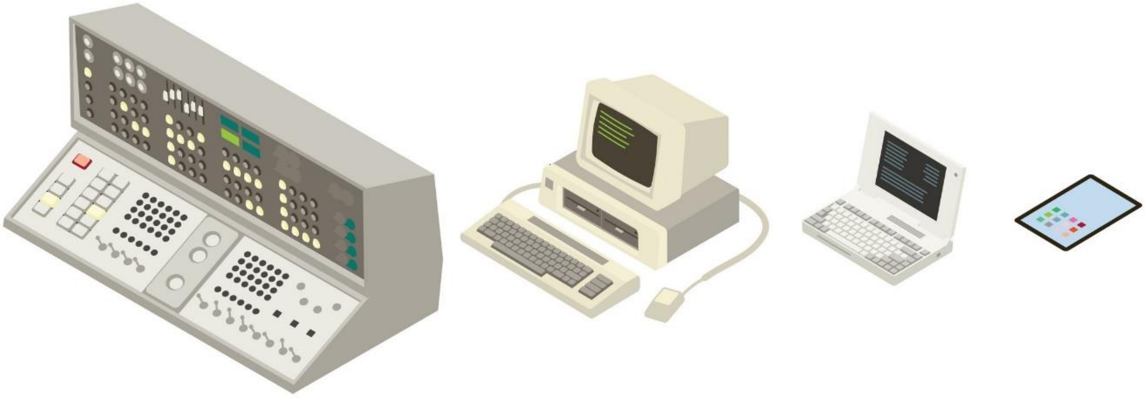


*Figure 2-1 A gradual betterment of the computer over the course of a century*

One true competitor jumped in the ring of the piston engine, which did hold numerous potential advantages. However, it also had a bad repute of gulping down fuel and lubricant. Soon the piston engine became unwaveringly strong, when an oil crisis in 1973 made the Rotary seem as an even bigger fuel drinking monster than it was. Consequently, despite its various upsides, it has not been worked on enough and room for potential improvement is still there.

We believe that due to its simpler design, less complexity of parts, cheap manufacturing cost, higher torque delivery, better power to weight ratio and culminated vibrations, the rotary engine can:

1. Serve as a steppingstone for countries like Pakistan to initiate Vertical Integration.
2. Moreover, Rotary engines have very less mechanical vibration and a great flexible compact packaging form factor which allows us to utilize them in space as auxiliary power sources.
3. Their ideal applications include primary & hybrid propulsion for UAVs, auxiliary power units for aerospace and land-based vehicles., automotive hybrid power systems and ultra-portable generators.
4. Speaking of power source, they are also very compatible to use in sports automobiles like snowmobiles, jet skis, motorcycles, and track cars.
5. AIE has made a meaningful change and a step forward in the 'air-cooled rotor' rotary engine by having developments and advancements in the old design of SPARCS cooling technology.

Other than that, in Pakistan, the rotary engine manufacturing had no scope for which this step will be a milestone towards renewing the rotary engine manufacturing industry. This will provide a place to start the initiative to overcome the challenges that have been in our way of using this reliable source of energy in our applications.

## Objectives

The objectives of the manufacturing of Wankel engine include

1. modelling of the engine parts and their assembly,
2. identification of rotor's motion and thermal analysis of the engine assembly via the determination of impact forces and temperature increment at various places,
3. kinematic motion analysis
4. measuring torque and power of the rotor engine, and,
5. overshooting the whole structure comparing its result to a Piston engine

# Chapter 3 Literature Review

## History

The design was firstly presented by a German Engineer Felix Wankel as the first patent presented was in 1929. This engine has been the only long-term competitor to the reciprocating Wankel engine. NSU helped him to bring changes within its design and make advancements so that the design was then accepted as a modern day Wankel engine design. Further improvements are made by each company looking at the requirements needed to fulfil the industry desires. They can even prepare some sort of cooperating mechanical system that will provide the back-up energy source for each connecting system.

From the start of the industrial evolution, the application of Diesel and Otto cycle on reciprocating engines has been a successful market development. Apart from this fact, this engine has all the advantages like higher torque, lower weight with minimum parts along with it and fewer reciprocating imbalance.

We will be working on an existing idea for an alternative of a reciprocating engine which is known as the Wankel engine. The engine has been used in motor vehicles and in some other applications but has never been widely adopted. This will be a naturally aspirated, spark ignition, single-rotor, air cooled engine.

The Wankel Engine is the result of research of over 30 years of Felix Wankel, a German Engineer. In 1926, Wankel began searching for the prospect of a positive displacement rotary engine and by 1951 he concluded that three problems that were being faced had prevented the rotary engine from achieving success so far.

1) The range of possibilities of arrangements and cycles for rotary engines which almost inundated the designers.
2) The challenge of sealing high pressure chambers. This involved sealing in several planes, with the sealing of corners as the most difficult.
3) The difficulty of developing a proper thermodynamic and gas cycle with adequate port areas and timing of events.

Thus, a combination of a proper geometric and kinematic arrangement which offered good sealing possibilities and could integrate an efficient cycle within one design had to be found. Wankel eventually arrived at two rotary combustion engine configurations which appeared superior and were subsequently built and operated fittingly. In both the arrangements the engine has two fundamental parts, an external rotor with a hole inside within which an inner rotor can rotate. Here, the external rotor ideally comprises of a center housing and two side housings (front and rear). The two rotors have spaced but parallel axes. The internal surface of the center housing is an epitrochoid while the external surface of the internal rotor approximates the internal surface of this epitrochoid during their relative revolution. The vertices of the internal rotor are in contact with the epitrochoid profile consistently.

The rotors are rotated in the same direction about their corresponding axis at a speed ratio of the outer rotor to the inner rotor of $n - l/n$, where ‘$n$’ is equal to the number of lobes of the epitrochoid. Here, the speed ratio suitable for an efficient is 1.5.

In one arrangement, both rotors rotate at this speed ratio, while in the other arrangement the outer housing is stationary, and the inner rotor has a planetary motion about the axis of the outer rotor. The relative motion of the two rotors, however, is the same in both the cases. The arrangement in which both the rotors rotate is devoted to the dual rotation type and the engine based on this is called Drehkolbenmaschine, or D.K.M. type. This design permitted easier sealing procedure and balancing this engine proved to be advantageous but resulted in a costly and complicated design.

The engine based on the other arrangement and titled Kreiskolbenmaschine, or K.K.M. type, was designed by Wankel and Walter G. Froede, built and tested by N.S.U. Notorenwerye A.G., Germany. K.K.M. is a kinematic inversion of the D.K.M. design. In this engine only the rotor and eccentric output shaft rotate at suitable distinct speeds; the intake and exhaust ports are in the center housing or side housings. A spark plug is fitted to the center housing and no-slip rings for the ignition. In the D.K.M. engine, both the rotor and casing were rotating in the same direction. The speed ratio of these two parts was 2:3, resulting in a velocity of the rotor relative to the casing of l/3. The same relative velocity between the rotor and housing is maintained in the new engine with a planetary motion of the rotor. To meet these requirements an inventive design has been implemented. While the rotor revolves physically about the mathematical fixed point which is the center of symmetry of the center housing, it also rotates about its own axis, eccentric to that of the main axis, but in opposite direction and with an angular velocity of 2/3 of the main axis. A positive angular displacement of 90° of the latter corresponds to a 60-degree negative angular displacement of the rotor relative to its own axis. The positive angular velocity of the rotor relative to the main axis is therefore only 30 degrees. This implies that three revolutions of the main shaft relate to one revolution of the rotor. The correct ratio of the two angular velocities is influenced by a reduction gearing, comprising an internally geared annulus attached to the rotor and a fixed externally gear fixed at one side cover of the casing, coaxially with the main shaft. This engine has proved to be better than the other. Hence work is being done on the design and development of this engine.

The Wankel engine uses an oval-shaped housing with epitrochoidal inner surface and a curved triangular-shaped rotor on an eccentric shaft as compared to the standard reciprocating type Internal Combustion engine with a crank-slider mechanism. The rotor rotates within the chamber in such a way that it forms three separates chambers. As the rotor turns, the volume of each chamber changes. In successive chambers fuel and air mixture is filled then compressed and ignited, and the expansion of the hot gases turns the rotor to allow this chamber to expand again and expel the exhaust gases.


shutterstock.com · 1609239667

*Figure 3-1. Cross section of a typical 2 rotor (13-B) Wankel Rotary engine*

## Principle of Operation

The principle of operation of the K.K.M. type of Wankel engine is that since the rotor, while being rotated forward, counter rotates at two-thirds of the shaft speed, its actual speed relative to the casing is only one-third that of the shaft, a fact which is significant as it implies a comparatively low sliding speed even at a high rate of revolution of the output shaft. It also means that there is one working 'stroke' during each revolution of the shaft. The rotor intercepts three spaces between its faces and the epitrochoidal inner surface of the housing. As the rotor rotates, these spaces grow and diminish like the volume inside the cylinder of a reciprocating engine as the piston moves up and down, but with a mutual phase difference of 120 degrees. While one working space is in the suction phase the next is undergoing compression and ignition, while the third goes through the stages of expansion and exhaust. No valves or valve gear are required since the rotating piston itself covers and uncovers the inlet and exhaust ports in turn. By the positive division of the working spaces due to the adoption of four-stroke operation, even running at all loads and low specific consumption are obtained. The adequate cooling and absence of hot spots make the engine insensitive to a low octane number. A balancing mass and flywheel are provided to compensate the inertia forces arising from the planetary motion of the piston and to provide more even running. Water cooling is used although it is thought that air cooling may be possible later. The only suitable method of lubrication is by a petrol and oil mixture, as with two strokes.

## Engine Cycle

The rotary engine works on Otto cycle. Figure below shows the engine operating under ideal conditions on P-V coordinates. For the reciprocating engine the equivalent cylinder volume and the corresponding piston position below the volume axis could be indicated. But for the rotary engine this may not be done, and it may be correlated by position numbers.

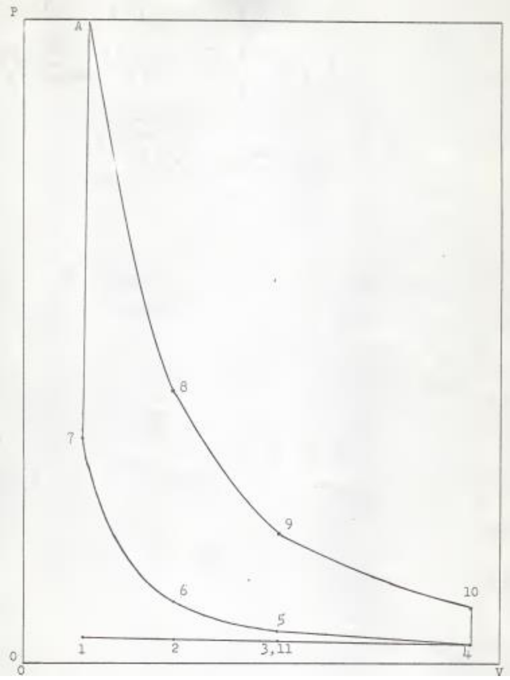


*Figure 3-2 Ideal P-V diagram for Rotary Engine.*

Here, Fuel-air induction takes place through 1-2-3-14, next compression of the fuel-air charge through 4.-5-6-7. Ignition of the mixture takes place at 7 for a sharp pressure rise to A. Then expansion and work take place through A-8-9-10. Most of the gas blows out of the cylinder as the exhaust port is uncovered after position 10. Then the rotor squeezes the rest of the spent gas from the compartment through 10-11-12-1. The actual engine cycle will differ from this ideal due to irreversibility and heat transfer.

The operation of the rotary internal combustion engine is illustrated below.

- The intake process occurs highlighted as blue in figure.
- It is followed by compression indicated by green.
- Then the combustion and expansion stage take place indicated by red in figure
- Finally, the exhaust stroke takes place indicated by yellow in figure
  .

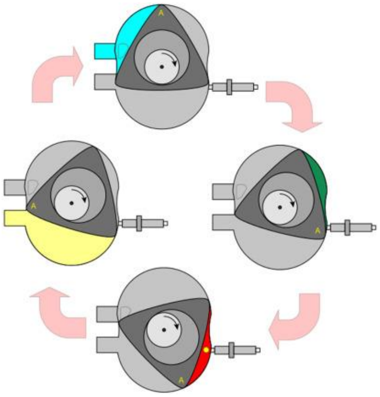


*Figure 3-3 cycles of the rotary engine*

The Wankel engine operates with the four-stroke cycle principle. As illustrated from figure below, the reciprocating engine fulfills the four-stroke cycle in two crankshaft revolutions which is 720°. However, the Wankel engine's eccentric shaft completes three revolutions at each rotor revolution which is 1080 °. At each rotor revolution, every side of the rotor fulfills its own four-stroke cycle. Hence, each rotor revolution has three four-stroke cycles in total. This means that every eccentric shaft revolution corresponds to one four-stroke cycle

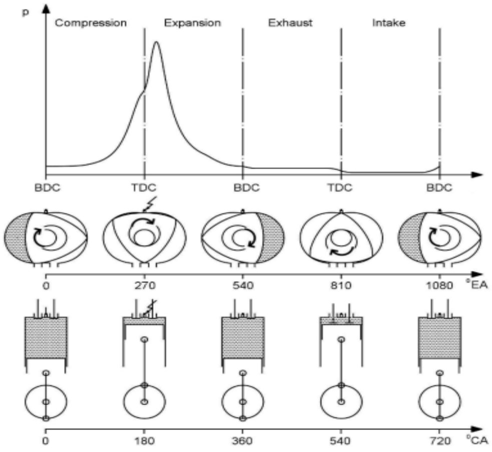


*Figure 3-4 Comparison of the four strokes in b/w rotary and piston engine.*

By this way, Wankel engine produces power for per eccentric shaft revolution, which is the basis of its high specific power output

From the design point of view, the rotary Wankel engine differs from the reciprocating piston engine in four primary ways:

i. The rotor substitutes for the piston.
ii. The housing substitutes for the cylinder.
iii. The eccentric shaft substitutes for the crankshaft and connecting rods.
iv. Valves, camshaft, and timing belt are removed due to intake and exhaust ports in the housing where their opening and closing are achieved directly by the motion of the rotor.

The following main differences between Wankel and Piston Engines that affect their performance can be mentioned:

• Difference in patterns of working chamber volume and surface dependence on the angle of shaft rotation

• Duration of the Wankel working cycle is 1.5 times longer in comparison to a 4-stroke piston engine in terms of the angle of shaft rotation. The complete working cycle of a Wankel engine takes place in each working chamber per one rotor revolution, or per three shaft revolutions. In other words, one working cycle in a Wankel engine occurs during 1080 degrees of shaft rotation or 360 degrees of rotor rotation, compared to 720 degrees of the crankshaft rotation in a 4-stroke piston engine.

• 'Hot' and 'cold' stator zones of the Wankel working chamber surfaces are separated as compared to in a piston engine, where the same working chamber surfaces are heated and cooled in-turn. This, in combination with rotational movement together with a working chamber, leads to differences in the heat transfer conditions.

• Unfavorable shape of the Wankel working chamber leads to the high surface-to-volume ratios and larger relative value of crevice volumes where flame quenching can take place which then results in difference in combustion patterns.

• Wankel working chamber has more complicated design of seals which include both apex seals and rotor side seals. This usually results in higher possibility charge leakage values.

• Wankel engine differs primarily from piston engine in its kinematic mechanism which leads to differences in internal friction power losses.

Here, the rotary engines have various significant advantages over piston engines :

- Reduced size and weight, competitive with the gas turbine.
- Low vibration with as few as one or two rotors.
- Higher speed capability by virtue of complete balance.
- High volumetric efficiency through porting without the limitations of valve dynamics.
- Sizing flexibility.
- Mechanical simplicity.

In addition, due to the longer intake stroke duration in the rotary engine, high volumetric efficiency can be attained even at high speeds resulting in a flat ‘torque versus engine speed’ curve. Additionally, the rotary engine is less susceptible to knocking and therefore more bearable to the fuel quality. Another feature of the rotary engine is that its geometry is very suitable for charge stratification, as the rotor always moves the air charge past the stationary location of the spark plug the necessary flow distribution for charge stratification within the chamber. Finally, in recent years there has been an increased interest in developing rotary engines fueled by hydrogen. While the reciprocating four-stroke engine fueled by hydrogen is prone to preignition and backfiring through the intake ports, in the rotary engine the intake ports are separated from the combustion zone, so there are no hot spots during intake process.

The two main disadvantages of rotary engines are the increased emission of unburned hydrocarbons and higher fuel consumption. Both drawbacks are related to the long and narrow shape of the combustion chamber, resulting in high surface-to-volume (S-V) ratio resulting in large volume of the quenching layers, increased sealing perimeter which increases gas leakage from the combustion chamber, and long flame travel leading to lower thermodynamic efficiency.

At the same time, the content of $NO_x$ in the exhaust gases of rotary engines is lower than in reciprocating engines. Regarding carbon monoxide, the level of its emissions is like that from piston engines. Figure below illustrates a comparison of the exhaust emission characteristics between rotary and reciprocating engines.

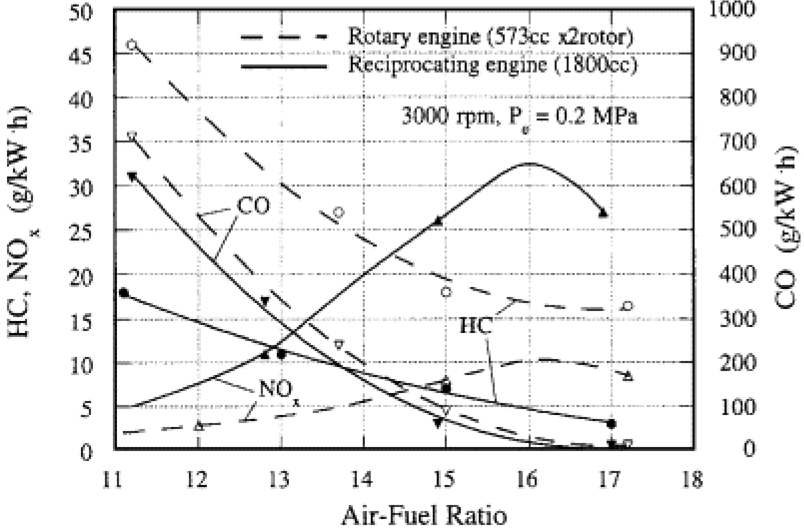


*Figure 3-5 Comparison of Exhaust Emission Characteristics*

In the late 1970s, a detailed study of the sources of hydrocarbon emissions was carried out by General Motors . The study was critical to the future of rotary engines, for unless the base engine hydrocarbon emissions and fuel consumption could be reduced to that of a reciprocating engine, it would have been extremely difficult for rotary engines to enter the engine market.

A short comparison on the low $NO_x$ emission rate in the rotary and piston engines is made below. Plots shown in Figures below illustrate a comparison between nitrogen oxide emissions from carbureted rotary and piston engines. The tested engines were a four-cylinder, in-line 2300-

cc displacement, 8.44 compression ratio, water-cooled engine manufactured by Ford Motor Company and a two-rotor 1308-cc displacement, 9.4 compression ratio, water-cooled Model 13B engine manufactured by Mazda. In this study, the catalytic converter and exhaust gas recirculation apparatus was removed from both engines. The fuel used was synthetic coal-derived gasoline. In the entire range of tested engine speeds and loads, the $NO_x$ emissions from rotary engines were about two to three times lower. As the engine speed increased, the measured $NO_x$ emissions from the rotary engine remained almost constant.

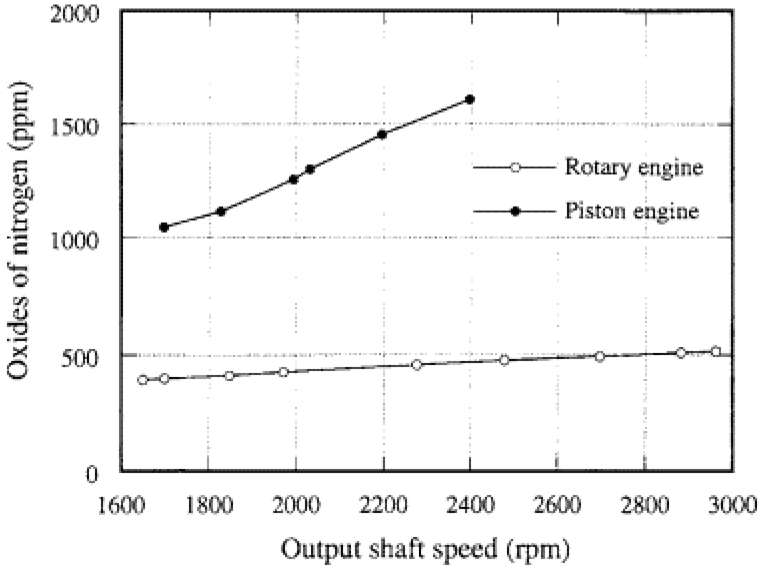


*Figure 3-6 Engines Speed effects on the Nitrogen oxides emissions*

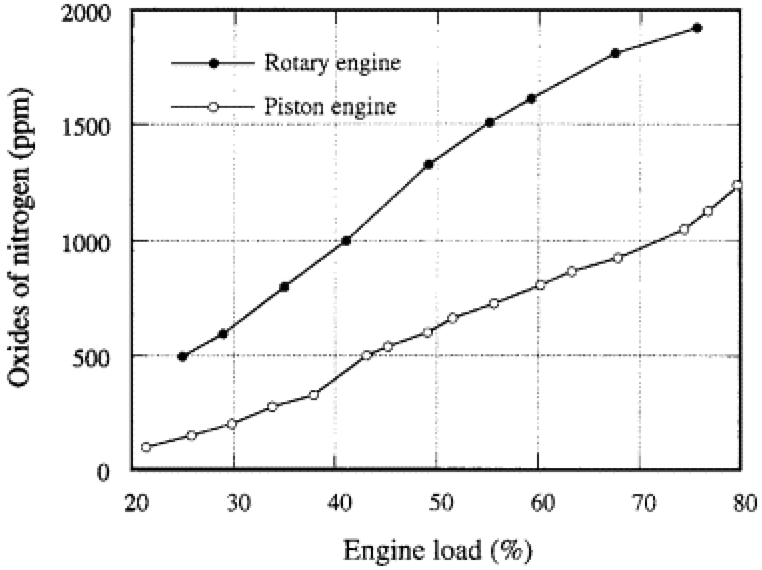


*Figure 3-7 Variation in Nitrogen Oxides emissions with engine load*

One of the reasons for the low $NO_x$ emission rate underlined in the study is the high concentration of burned gas in the fresh mixture. This is due to the leakage across apex seals, which creates a built-in exhaust gas recirculation system in the rotary engine. Another important reason is the high rate of heat transfer into the walls of the combustion chamber caused by its high S-V ratio. Both phenomena lead to low maximum combustion temperatures and, therefore, a low rate of $NO_x$ generation.

## Research & Their Analysis

The rotary engines' old designs had lower volumetric efficiencies, the undesirable exit air temperature leakage due to internal air leakage and the wearing of distinct parts along with the most damage to the seals. These disadvantages have made the use of this engine difficult, which has not been addressed physically on the engine yet. Also, the more extended pressure stroke rotation angle (330°) improves the fuel-air blending as fuel is infused by a carburetor close by the air intake stage. Even though, heat motors have gotten no modern consideration, for more than fifty years, sliding vane revolving blowers have taken a significant spot in everyday designing applications, particularly in the limit scope of 10-1000 cc/sec and for conveyance pressures in the scope of 2-18 bars.

A high compressor air delivery temperature decidedly adds to the temperature rise prerequisite in the combustion chamber. As less fuel input is required to reach the higher allowable turbine inlet temperature, therefore, the specific fuel consumption is lowered significantly. Air and oil-cooled sliding vane engines have extra hugely beneficial elements for example, almost steady air flow processing, less pressure changes, lower noise levels and smooth-running characteristics.

Many companies have been doing research on how to make an efficient energy source out of a rotary engine. The fuel consumption by an engine has a significant impact on the efficiency of that engine and for how long that engine is going to survive the market. In the early days, the engines were used to produce mechanical power burned gas. Gasoline and lighter fractions became available in 1800s as fuel usage. Also, for using these fractions, different carburetors were designed to vaporize the fuel and mix it with air. Using Gasoline, tough compression ratios were low (<=4) to avoid knock, due to its high volatility and good cold-weather performance. During the fuel shortage between 1907 to 1915, the yield of crude oil had to be increased.

From the discovery of William Burton and his associates, the heavy oils have been decomposed into less volatile compounds via a thermal cracking process. But this discovery was not even sufficient in this fuel shortage.

During the WWI period, there were certain improvements made i.e., anti-knocking agent advancement was made by passing oil over a catalyst at 450-480 $^0$C and that was possible due to the thermal cracking of oil.

There are many factors related to the design and the way an engine operates. Firstly, there is need to save the environment by the automotive contribution to the urban air pollution and secondly, the need to control the fuel consumption in automotive industry. The operation and design of all the internal combustion engines have been affected by the emission-control requirements and the fuel developments.

Since all the systems working inside an engine are related to noise production. The intake, exhaust, cooling system, block surface of the engine are sources for engine noise. These noises can be the effect of the forces caused by the mechanical rotation of reciprocating engine components or by the mechanical excitation or by the forces resulting from the combustion process.

During the 1970s, the crude petroleum price rose rapidly. The improvement of engine efficiencies included pressures have become substantial whereas emission control requirements have made improving engine fuel consumption more difficult and the reason for the pollution, lead in gasoline has forced spark ignition engine compression ratios to be decreased.

To date, only Rolls Royce has built a Diesel Rotary Engine. Single Rotor CI Wankel engine need K factor to produce the compression ratio for auto-ignition in long and thin chamber at TDC.

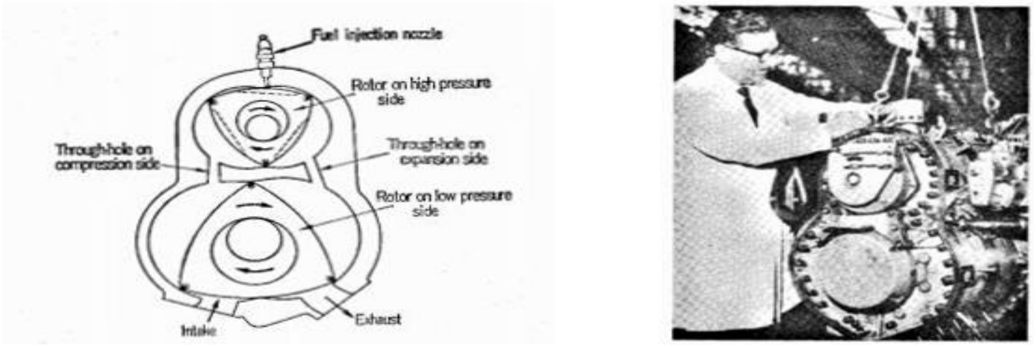


*Figure 3-8 Rolls Royce Diesel Engine*

Shigera Ohnishi at Nippon Clean Engine Research Institute Co. Ltd discovered for the first time, Low temperature combustion. The process where auto-ignition consumes lean premixed charge rather than deflagration flame out and the combustion process is called Active-Thermo Atmosphere Combustion (ATAC). What happens in this engine is that the fuel faces rapid auto-ignition without flame which causes lower cylinder temperatures. Figure below shows Kamimoto’s work which was later updated by Sun.

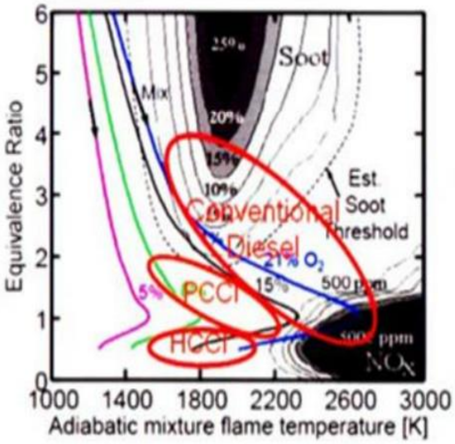


*Figure 3-9 Combustion Strategies on $\phi$-T Diagram*

This figure shows the soot and NOx production ranges. The HCCI process offers engine efficiency like a diesel engine. The ignition start can be uncontrolled, variation of combustion cycle from time to time, vibrating pressure waves, like knock, high-pressure reduction due to sudden release of heat, these all factors can limit the maximum load achievable to an HCCI engine. The problems we face with HCCI can be overcome by mixing fresh air charge with Exhaust Gas Recirculation (EGR). The already mixed EGR gases pose two major effects on the combustion of this type of engine, first the ignition timing advanced, and the species found to affect the heat release rate and lower the temperature for combustion.

After this, there was another development in the approach called Multiple Premixed Compression Ignition (MPCI) raises the low load limit of HCCI. The working principle for this type goes like this: flowing of lean mixture into the chamber, combustion, injection, and mixing of a second spray of fuel and combusts again. All these events of combustion happen to take place separately.

The scalability studies done by Sher give us different calculations that an engine as small as 0.3cc displacement with 20:1 compression ratio is possible. Assumptions for understanding the clearance height between the piston and chamber would be engine is square implies bore and stroke are equal. Then use the below formula by inserting clearance height as 0.38mm (about 0.01 in).

$$\frac{Clearance\ Volume + Displacement\ Volume}{Clearance\ Volume} = CR$$

In Aceves' paper, Analysis and Experiments on HCCI combustion gave two results of analysis by using single and multi-zone models. The properties of the single zone model included the accurate prediction of the start of ignition and being a good indicator of peak pressure. The multi-zone model was beneficial for predicting the emissions of Hydrogen and Carbon Monoxide gases which a single zone model cannot do. HCCI engines have been known for the application range from motorcycle to ship engines. Basic combustion process has been told when HCCI happens to have the absence of propagating flame when localized reactions are dominant. The turbulence has an insignificant effect on the combustion and would affect temperature gradients mostly due to the homogeneity of the reactions. Equivalence ratios, percent EGR and intake conditions are the factors affecting HCCI operation.

The two effects which are caused by adding EGR are: ignition delay and peak temperature reduction, according to Chen's study. This study also deals with the calculations of species mass fraction and premixed temperature with a given percent EGR recirculation.

Compression ratios as high as 21:1 with gasoline fuel have been achieved. Using EGR recirculation, HCCI range of operation can be extended. The diesel engine fuel would not be able to run on this type of mode due to the short ignition delay time. Miniaturization limits of HCCI internal combustion engines shows that HCCI will allow for small scale engine operation, to engine size 0.3 cubic centimeters. From the Understanding HCCI characteristics in Mini HCCI engines by Collar, the small engines studies showed that thermal stratification affect pressure rise rate and peak pressures.

CFD model showed the strong thermal gradient as a 'cascade' within the chamber for combustion, implying that there will be gradual combustion instead of rapid combustion. The combustion propagation remains above the narrow epitrochoid housing in spark ignition, as indicated by Mazda Rotary Engine Technology paper. The separate zones can be working within the same chamber at the same time. The knock in the HCCI mode was studied by Andreae and his findings that structural vibration radiations cause audible knock transmissions. Rapid heat release rate tends to vary the cylinder pressure in the absence of knock. Andreae found that 5MPa/ms is a suitable limit for pressure rise rate.

The computational optimization of a Heavy-Duty compression ignition engine fueled with conventional gasoline found that the chamber limiting load in a reciprocating engine has high pressure oscillations caused by HCCI combustion, performed by Dempsey at Wisconsin Madsion’s Engine Research Center. He found that thermal efficiency at high load, Partial Premixed Compression Ignition (PCCI) allows for low NOx with 50% gross, but soot particulates were increased due to large variations of equivalence ratio.

## Sealing Design

The material used for apex seals is the same as that of a piston ring. It is shown in the figure below:

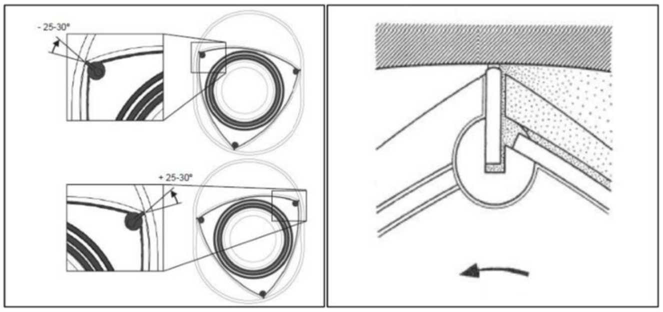


*Figure 3-10 Conventional Apex seal design in a Wankel Engine*

Rotor design uses 3 of the top apex seals. A retainer flat strip of flexible material is used to get constant contact between flat plate and the housing wall. working chamber has a depth related to the length of the plates. Mostly, the height of the plate is three times longer than the thickness of the plate. Then the thickness depends on the size and proportions of the trajectory of the apex seal's plate.

The sealings we are using are apex seals made of SS steel material. We cut the string of this material into small 8 cm parts. After cutting the parts, we quenched the parts by heating them first with welding torch as too red-hot and then we deformed them to our desired curvature of ape seals. After the deforming process, the seals were put into the cold water to retain the shape and strength of the seals. The seal curvature is normal enough to fit into the corners of the rotor and protect the corners from wearing out.

The SS material is used for the apex seals because it has a lower friction coefficient layer which makes it suitable. T The COF value of HLS 316L SS compared to wrought 316L SS can be ascribed to the hard oxidative particles formed upon sliding at the interface during the wear test as the result of these microstructural features.

## Ignition System

The engine turns over and then cranks when you turn the key in the ignition. Getting it to spin up, on the other hand, is a lot more difficult than you may expect. It necessitates the entry of air into the engine, which can only be accomplished through suction (the engine does this when it turns over). There's no air if your engine isn't turning over. Fuel cannot combust in the absence of air. The starting motor is in charge of turning the engine over and allowing everything else to happen during ignition. The starter motor engages when the ignition is turned on, turning the engine over and allowing it to draw in air. A flywheel with ring gear mounted around the edge is installed on the engine. The pinion on the starter is designed to fit into the ring gear's grooves. The magnetic inside the body engages and pushes out a rod to which the pinion is attached when the ignition switch is turned on. The starter motor turns when the pinion strikes the flywheel. This causes the engine to rotate and draw in air (as well as fuel). The starter motor disengages, and the electromagnet ceases as the engine rolls over. The rod returns to its original position in the starter motor, removing the pinion from contact with the flywheel and preventing damage. There are several components of a starter motor which help ignite the engine, which are:

- Armature
- Commutator
- Brushes
- Solenoid
- Plunger
- Lever Fork
- Pinion
- Field Coils

The ignition system we are using in our engine is a Honda CG 125 ignition system, consisting of the following components:

- Ignition switch
- Generator
- Pick-up coil
- Points Contact Breaker
- HT Ignition coil
- CDI unit
- Regulator
- Spark plugs

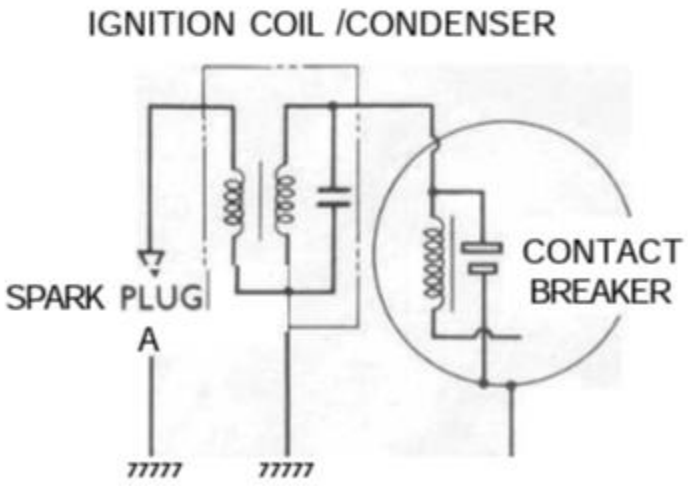


Fig. 3.1 Ignition system: schematic diagram

Here is the schematic diagram of the ignition system of Honda CG 125 from its official manual.

### 1. General Description

**The spa**rk required to ignite the petrol/air mixture in the combustion chamber is generated by an ignition coil mounted on the frame and a flywheel generator attached to the engine's left crankshaft. A contact breaker assembly within the generator determines when the spark will occur; as the points separate, the electrical circuit is interrupted, and a high-tension voltage is developed across the points of the spark plug, which jumps the gap and ignites the mixture. **2.Generator: Checking the Output**

The generator coil is instrumental in creating the power in the ignition system, and any failure or malfunction will affect the operation of the ignition system.

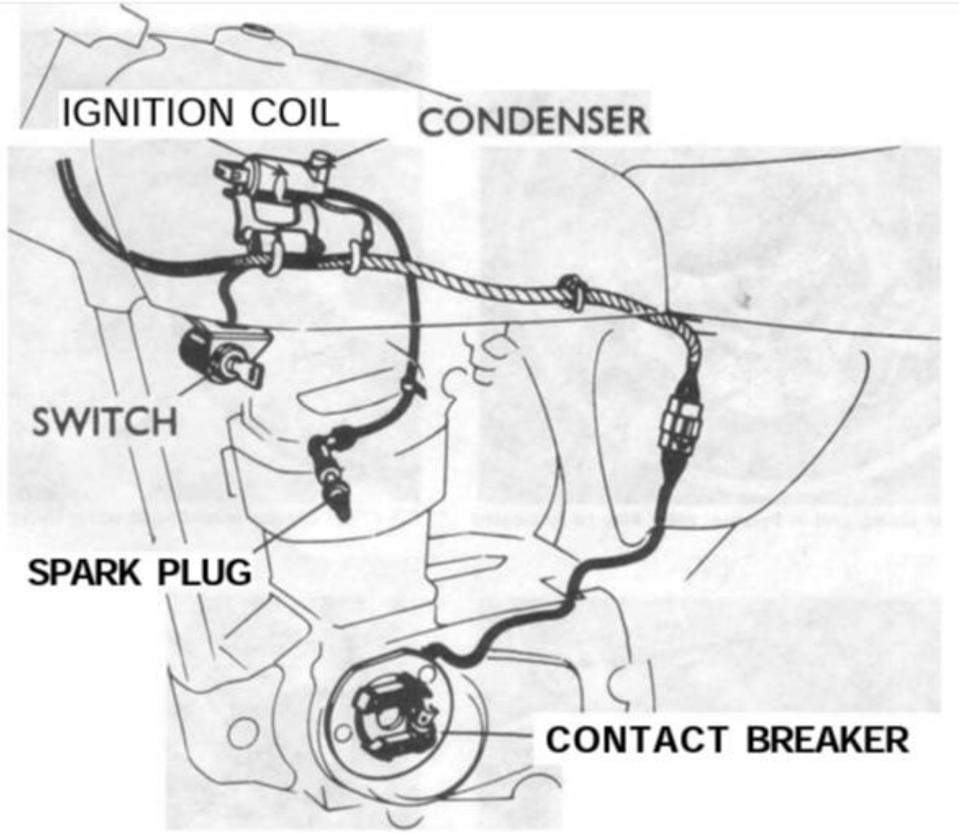


Fig. 3.2 Ignition system: component location

## Lubrication System

Continuous friction poses a great challenge and a big need to lubricate the engine entirely, specifically the rotor and the housing wall. To achieve this purpose, there are some lubricating holes built in the housing wall of the engine, connected to the lubrication pump directly. SO, keeping up with this design, the lubricant injects inside the chamber and the whole rotor walls and housing is covered with the lubricant. The lubrication equation, pressure boundary equation and the mass conservation equations are shown in the figure below. These equations are a characterization of the lubrication properties and the indication of different forces on the engine parametric qualities.

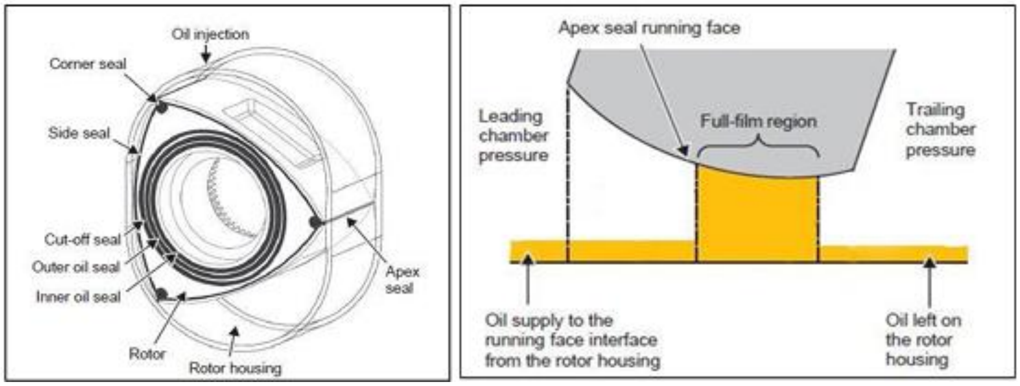


*Figure 3-11 Lubrication system and Wankel engine contacts*

Disadvantages, on the other hand, of this lubricating system are requirement of excessive lubricating oil all the time, loss of lubricating oil during combustion process, increment in emission level, total maintenance increment, and unnecessary lubrication of all engine parts.

Oil provided per requirement is a system that will be proven economically sustainable and better lubrication. so, the system should be helpful to prevent oil loss by burning the oil inside the chamber while combustion process.

## Functions of Engine Lubrication system

There are some of the important and obvious functions which a lubrication system has in engine, given below:

- The primary purpose of the lubrication system is to reduce the wear by securely closing the clearance between moving parts like bearings and shafts etc. Lubrication also avoids the moving parts that do not come directly in contact with each other.
- Oil serves as a cleaning agent and a detergent to eliminate dust particles. Smaller particles are filtered out by the oil filter while the larger dust particles are retained in oil pan.
- Clearance between the rotating journals and bearing is filled with oil. The oil acts as cushioning agent when the bearing suddenly experiences heavy loads.
- It also provides its function as a cooling system. The oil circulation moves the heat from the moving parts around and cools down the moving parts in engine.

## 2-Stroke Lubrication System

One part of the oil is injected into the air-fuel mixture to lubricate the wall of the epitrochoid surface and the seals of the Wankel rotary engine. Another component circulates on the shaft bearings and cools the rotor.

In both cases, the problems to be solved are different, and the lubricant must be a compromise to meet the various requirements.

There are ports in a two-stroke lubricating system that allow air-fuel mixture into the crankcase and exhaust gases to exit.

At this stage, the best lubricant is a synthetic mineral oil blend with an appropriate additive combination. Synthetic oil is a petrochemical product created by polymerizing a monoolein C4 cut; its molecular weight is comparable to that of conventional mineral oils.

Deposits in the combustion chamber are kept to a minimum with this lube oil formulation, preventing preignition and seal sticking. Apex seal wear has been significantly reduced, and engine life has been extended.

The performance of such a formulation has been tested on the bench and in the field in water- and air-cooled engines.

Certain 2-stroke lubricants are diluted with solvents in order to provide "clean burning" and "deposit control." This is usually done to compensate for the base fluid's lack of performance. A fully synthetic 100 percent ester-based lubricant is the best choice for a modern 2-cycle engine for the best balance of performance and protection. This 100% synthetic ester base fluid has a high level of detergency to ensure the removal of carbon deposits and the prevention of the formation of new performance-robbing deposits.

When it comes to 2-stroke oils, the most important factor to consider is the base oil. A 100 percent synthetic ester product is the best choice among current technologies for achieving maximum performance and protection for a machine.

## Cooling System

Our engine's cooling system is an Air-Cooling System. Heat is dissipated directly into the air after passing through the cylinder walls in the air-cooling system. On the outer surfaces of the cylinders, air cooling systems have fins and flanges. The heads increase the area exposed to the cooling air, thereby increasing the rate of cooling.

The basic idea behind this method is to have a continuous current of air flowing over the heated surface of the engine where the heat is to be removed. The amount of heat dissipated is determined by the following variables.

1. The surface area of metal into contact with air.
2. The rate of air flow.
3. A temperature difference between the heated surface and the air.
4. The conductivity of the metal.

### Advantages of air-cooling system engine:

1. Anti-freezer not required.
2. Can be used in areas with scarcity of water.
3. This system can work in cold climates where water’s availability is difficult.
4. No leaks to guard against.
5. No topping up the cooling agent.

## Planetary Gear Set

The working chamber changes in volume twice per revolution, thus the four processes of the internal combustion engine could be achieved. With the Wankel-type rotary engine, the rotor’s apices follow the oval contour of the inner periphery of the engine casing while remaining in contact with the gear on the output shaft which is also in eccentric orbit around the center point of the engine casing. A phase gear mechanism dictates the orbit of the triangular rotor. The phase gear consists of an inner-toothed gear ring fixed on the inside of the rotor and an outer-toothed gear fixed on an eccentric shaft. If the rotor gear were to have 30 teeth inside it, the shaft gear would have 20 teeth on its perimeter, so the gear ratio is 3:2. Due to this gear ratio, the rate of turning speed between the rotor and the shaft is defined as 1:3. The rotor has a longer rotation period than the eccentric shaft. The rotor rotates one turn while the eccentric shaft rotates three turns. With the engine running at 3000rpm, the rotor will run at a mere 1000rpm.

# Chapter 4 Designing the Engine's Dimension

The design of prototype in hardware is as significant as its software design. Just like software design serve as core or foundation of a project, its hardware design is necessary procurement for project to physically exist and work. The idea of the design of the model along with its software design although forms the major steps in initiation of the design phase but having a physical model (hardware design) realistically demonstrates working of project. Basically, constructing a prototype marks the development phase of the design. For our project, we focus on the complete modelling of Wankel engine on **SolidWorks**. It includes all the parts necessary for the construction of a Wankel engine and the sub-assemblies needed to assemble all the parts into a final design.

There are two fundamental pathways to design a new engine from scratch, you either,

1. Set a designated power and torque rating, and build an engine around these parameters, such that in the end it gives these designated deliverables.

OR

2. Designate peculiar dimensions for the engine and then iteratively work your way through perfecting the design, and then calculate & measure the torque & power.

We chose to go with the latter approach, which gave us flexibility in changing the dimensions as per need. The engine was built in accordance with ISO standards, and each part of the engine needed to be coherent with the other, thus, the dimensioning phase was extremely iterative; Changing one dimension of a single part had its impacts on the dimensions of another part which in turn influenced the part it engaged with further. Consequently, after certain trial and errors we were able to form the geometry of each part such that the entire engine assembly was neither too big, for which manufacturing cost would go up, neither too small, for which the intricacy of parts would have been a problem.

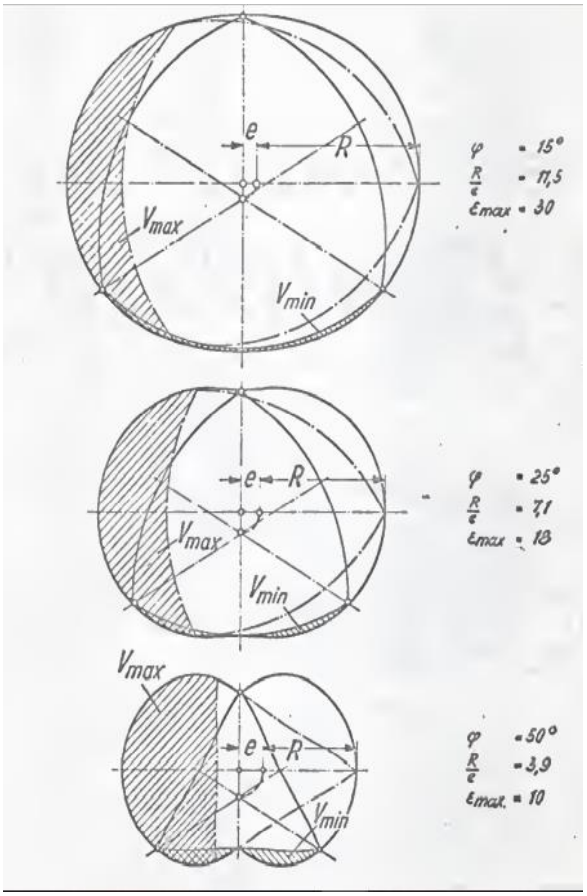
The dimensions and design for each component are based on dimensioning of the rotor and the cubic capacity required. The initial phase in designing was to produce the dimensions of rotor and housing that supports our required air/fuel capacity.

This section discusses each component, subassemblies, and the whole engine assembly to provide insight into the dimensions behind the rotary engine.

## Components:

We will explain in detail how these components are organized to make the prototype work.

**Optimum Shape of Rotor and Housing**



Epitrochoid is one of the numerous varieties of epicyclic curves and represents the path traced by a point on the radius of a circle, rolling without sliding on the outer circumference of another fixed circle. The hypotrochoid is generated in an analogous way by a point on the radius of a circle rolling on the inner circumference of a fixed circle. If an epitrochoid or a hypotrochoid is rotating about an axis, and another appropriate body, representing either the inner or the outer envelope of the trochoid, rotates on another parallel axis in the same direction but with a different angular velocity, then spaces are formed between the trochoid and the envelope, the area of which varies between a minimum and a maximum according to a sine function. The difference between these volumes constitutes the displacement of the engine and their ratio the theoretical compression ratio. A cut-out in the inner rotor provides the actual desired compression ratio and a gas transfer passage at the top dead center. The shape of the epitrochoid is determined by the ratio of the eccentricity '*e'* to the length of the generating radius *'R.'* Figure below shows how, for the given volume of one chamber, the size, and the shape of the trochoid casing

can vary considerably. For the ratio R/e = ∞ it is obviously a circle, for a ratio of 11.5:1 it resembles an ellipse, while for smaller ratios the curve has two indents in. its small axis which are small at the ratio R/e =7.1 but very pronounced at the ratio R/e = 3.9. The R/e ratio also determines the maximum angle of obliquity α, which the generating radius forms with the normal to the curvature. It is necessary to keep this angle small to facilitate the scaling between the apex of the rotor and the path of the casing. The maximum deviation of α from the normal should not exceed + 30 degrees, which corresponds to an R/e ratio of something between 6 and 7. The figure also shows the influence of the R/e ratio on the variation of the area of each individual cell during the rotation of the rotor, and thus on the theoretical compression ratio ε.

### i. MID HOUSING

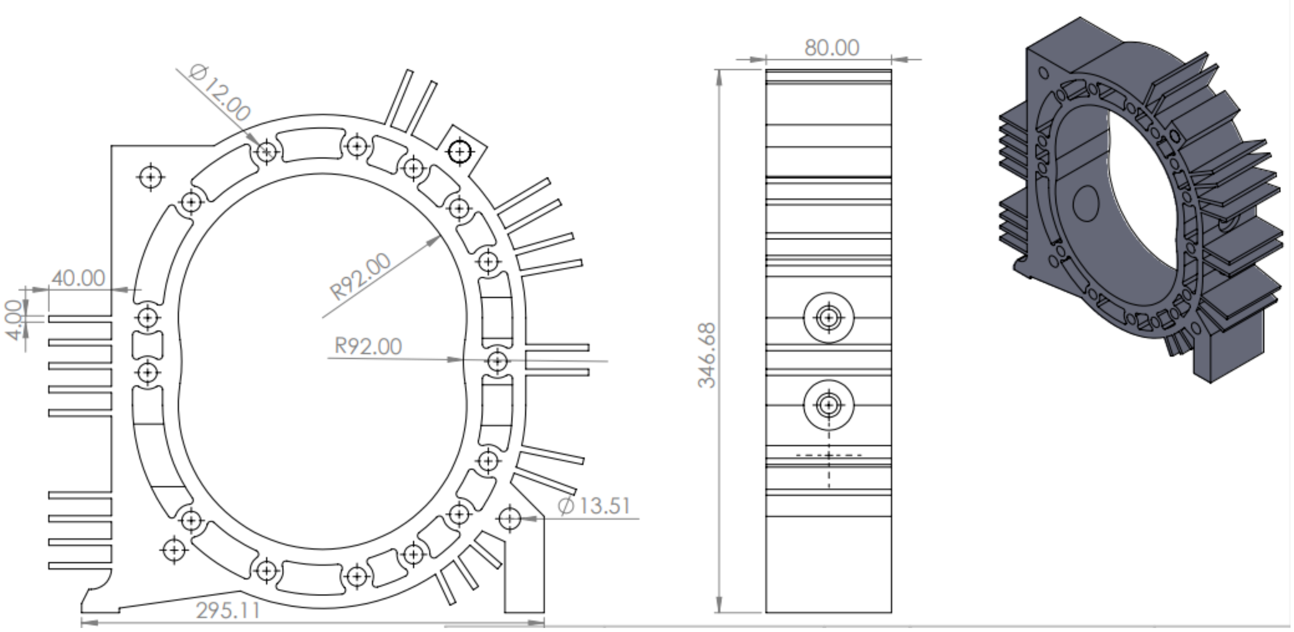


*Figure 4-1 An engineering drawing of Mid housing.*

The rotor housing is the workplace where the whole compression cycle takes place i.e., contains the combustion cycle. During the engine's operation, the rotor housing is made as such to remain stationary. The slots in the boundary walls of the housing admits and exhaust the air flow providing suitable conditions for combustion. (stoyanAPC, n.d.)

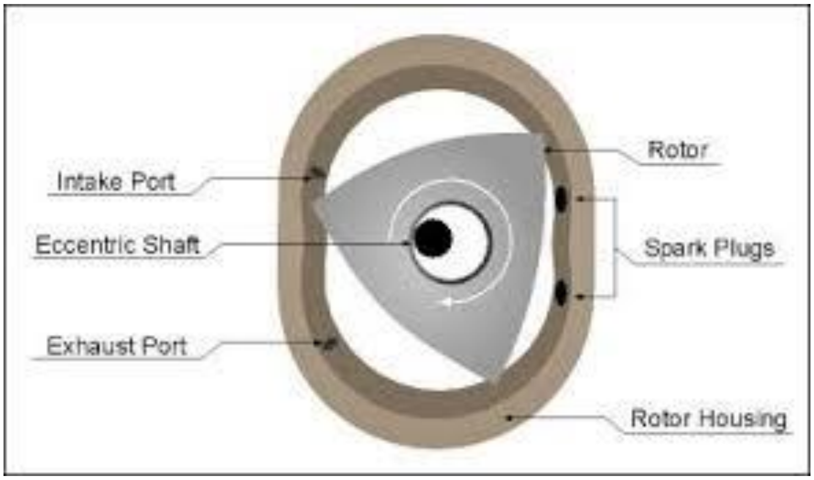


*Figure 4-2 Displaying the main components to be considered Within the housing*

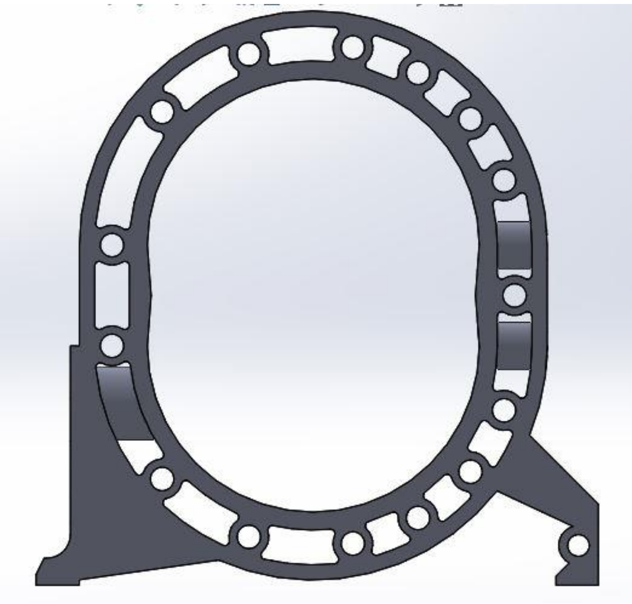


*Figure 4-3 Front view of Housing*

The step-by-step method adopted to create a 3D model is explained below.

1. Creating a Center Slot with 55.75 mm (about half the length of the long edge of a credit card) gap between the two centers and a diameter of 184 mm (about twice the length of the long edge of a credit card)
2. Offsetting the inner surface boundary by 10mm (about 0.39 in) to give the inner part of housing its thickness.
3. Offsetting the inner surface boundary by 29.19mm (about 1.15 in) and 37.69 mm (about 1.48 in) to define the inner and outer boundaries respectively for the outer part of the housing.
4. The inner and outer part is extruded on midplane by 80mm (40mm (about half the length of the long edge of a credit card) on each side of the plane)
5. To create the epitrochoid shape we drew three circles of 92 mm (about the length of the long edge of a credit card) with the first 2 concentric with the two centers used to make the slot. These two circles' boundaries coincide with that of inner surface
6. The third circle is made tangent with both circles and its center is made horizontal with the center

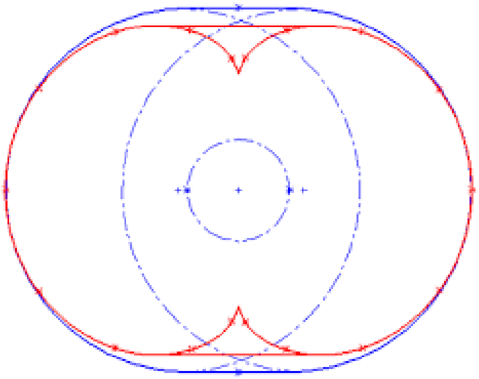


*Figure 4-4 Epitrochoid*

slot midpoint. The geometry from inner surface to the three tangent boundaries of 3 circles formed are extruded on mid plane by 80mm (40mm (about 1.57 in) on each side of plane)

7. 13mm (about 0.51 in) diameter hole for studs are then made between the inner and outer parts of the rotor housing and joined to them by extruding it 4.54mm (about 0.18 in) along its diameter. These are then extruded on mid plane by 80mm (40mm (about 1.57 in) on each side of plane).
8. The hole for studs is made in upper part and the mirrored onto lower part using the horizontal axis through center slot. Here a total of 15 stud holes are formed.
9. The external edges of stud hole are filleted with the inner and outer part of the housing
10. The base for the housing is then made so that it can be kept straight up.
11. A 36 mm (about 1.42 in) diameter hole is made on the right edge of the housing using the extruded cut feature to the inner surface of inner part to allow for exhaust of combustion products
12. A 26 mm (about 1.02 in) diameter 2 holes are made for spark plugs using extruded cut feature. These holes have centers horizontal to the two centers of slot made initially.
13. The design is saved as block, after converting the identities that need to be kept for front and back plate, in library

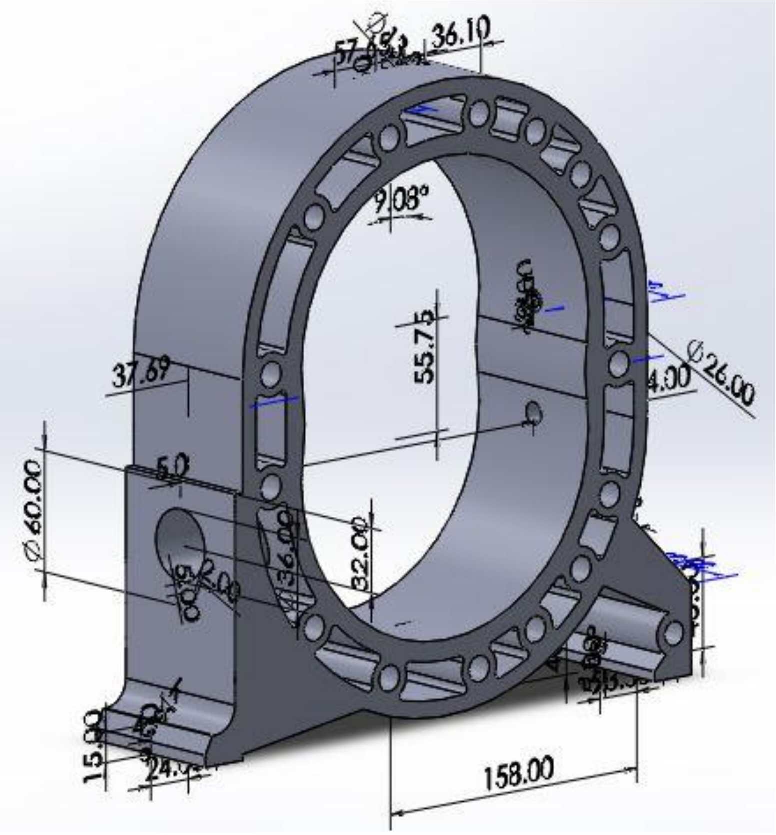


*Figure 4-5 Rotor Housing with Dimensions*

## ii. **ROTOR**

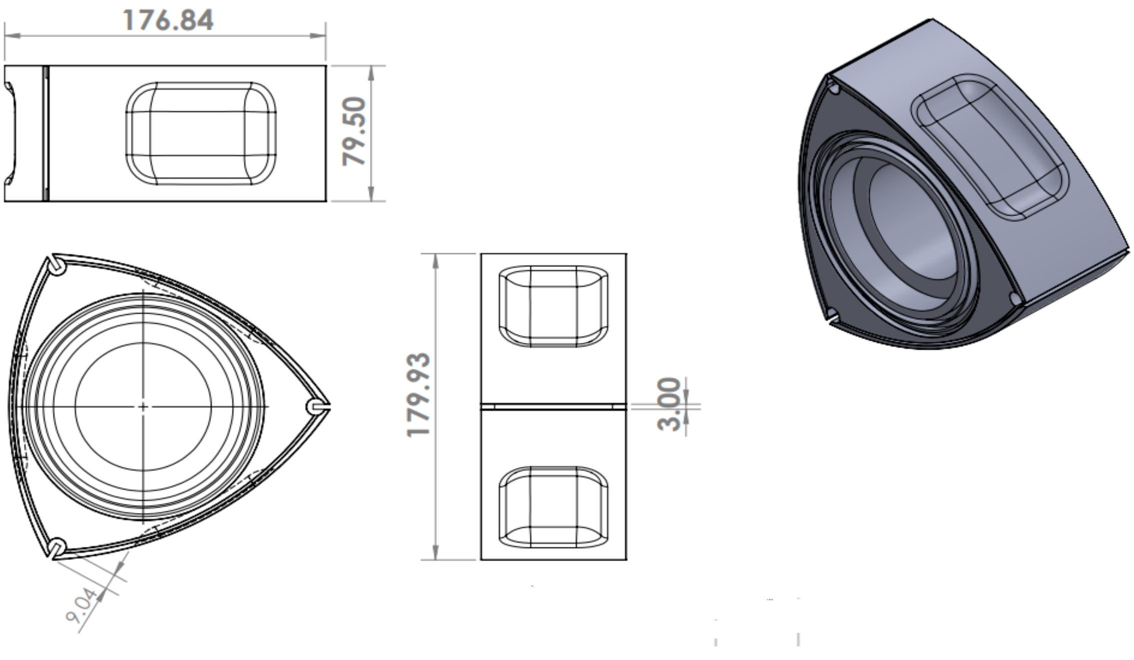


*Figure 4-6 ED of the rotor*

The rotor is the major rending part of the assembly. The rotor is sits in the housing but is a little smaller in size than the volume of the housing, the shape of the rotor imparts an important property enabling it to fill the housing's full volume when in motion. The rotor only fits in a single position within the housing based on how it is angled, and the only way to move it around the housing requires both rotation and translation. The motion of the rotor can necessarily be categorized as circular, but the center of the rotor or the centroid moves in a complete circle as the rotor motions a full cycle around housing. This property of the motion of is translated to as circular motion of rotor.

The rotor also contains an internal ring gear which meshes with a spur gear (called a stationary gear) attached at the engine's backplate. The ring gear and the spur gear are designed such that they have a gear ratio of 1.5, and the size chosen such that both the gears are monotonic with the engine's size.

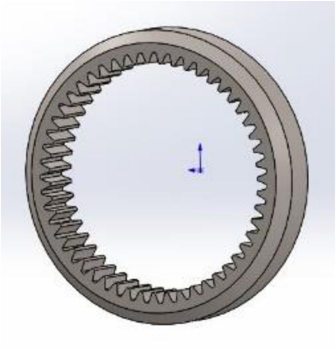


*Figure 4-7 Internal ring (Spur) Gear*

The Rotor dimensions were taken as the foundation of parameters for all other parts. After considering all the objectives and design boundaries, the dimensions for rotor were decided. Initially, an equilateral triangle is as a reference for further modification into crescent shaped sides of the rotor. The sketch is then protruded to a thickness of 80mm (about the length of the long edge of a credit card), considering the compression ratio required.

Intrusions are made on the front and rear faces of the protruded body for the placement of seals. A circular extrusion is made at the centroid of the body to provide a passageway for the eccentric shaft.

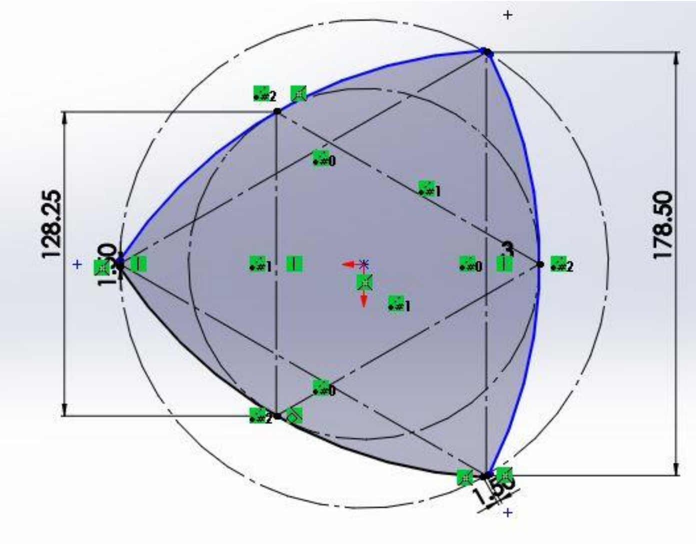


*Figure 4-8 Rotor's peripheral dimensions*

The internal gear was then mated to the rotor. It would be done via a couple of saddle keys. The internal gear makes the circular motion stay connected with the external spur gear attached to the eccentric shaft.

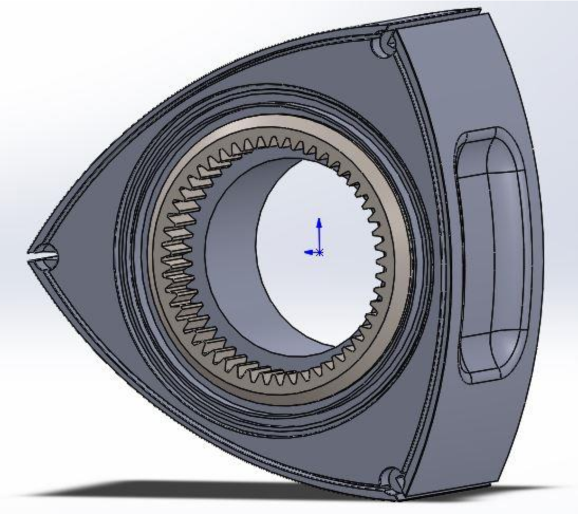


*Figure 4-9Rotor assembly*

### iii. Eccentric Shaft

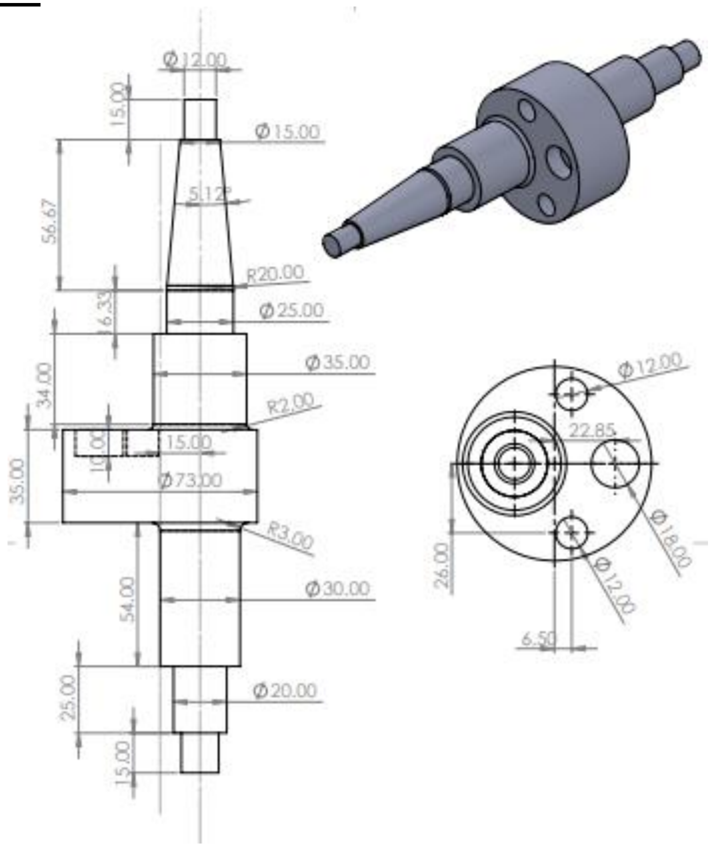


*Figure 4--10 ED of the Eccentric Shaft*

The eccentric shaft is the integral part that transmits the power from the rotor further. The shaft is eccentric to convert the complex motion of the rotor into pure rotation at the ends. The shaft was made in correspondence to the other parts, so that it may align effectively with them, and the entire engine runs coherently. The main parameters to be considered were,

1. The journal’s diameter and the length which would fit into the bearing housing (within the rotor).
2. The eccentricity of the protruding shaft from the journal, which ensures that this (protruding) shaft remained in pure rotation.
3. The axial lengths of the shaft, which assure that the shaft adjusts appositely in between the housing and the two end plates
4. The taper at one end where the CDI magnet would sit and be press fitted.
5. The diameters of the journals which will be mounted in the 2 needle bearings at each plate.
6. Shoulders that ensure that the flywheel can be nutted tightly to the shaft.

Once we knew the design boundaries, and requirements, the job was simple; the software was steered to produce a viable design. We started off by making a general layout of one of the shaft's ends. It included a chamfer of 175 followed by a shoulder. The lengths were chosen so that the shaft may pass through the endplates and have enough length so that a flywheel may be mounted on the shoulder. This shoulder would be threaded in the future, and it is where the flywheel would be placed and bolted down against. The revolve command about the axial axis produced one of the shaft's ends.

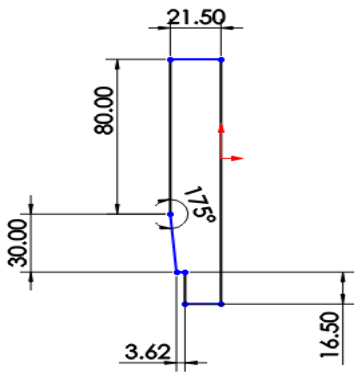


*Figure 4-11(a) Dimensions of one of the shaft's end*

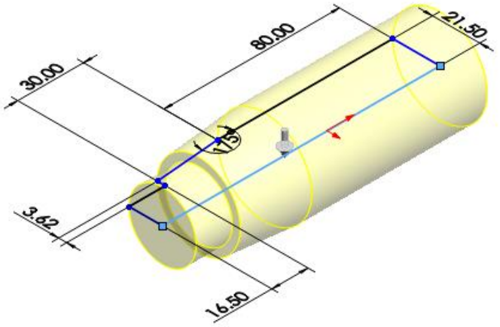


*Figure 4-11(b) Applying the revolve command*

The next step was to include the journal, which segregates the shaft into 2 ends. To produce pure rotation, the journal needed to be offset from the shaft's axis by 15mm (about 0.59 in). The journal's dia needed to match the bearing dia present in the rotor, thus a 74mm (about 2.91 in) circle was sketched with its center 15mm (about 0.59 in) away from the shaft's central axis. Next, this circle was extruded by 52mm (about 2.05 in) giving rise to the journal on top of the shaft's end.

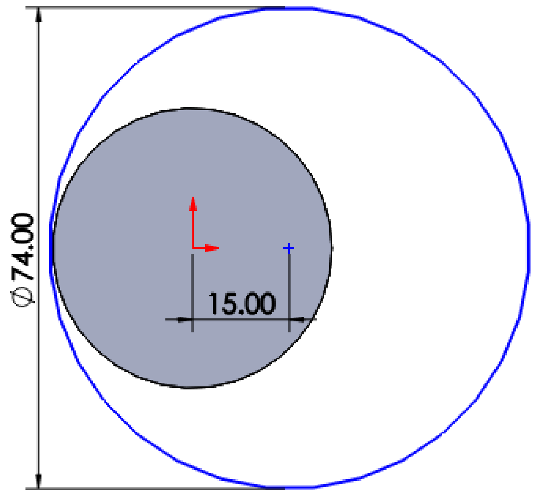


*Fig 3.12(a). Top view of shaft, showing an eccentricity of 15mm (about 0.59 in) from the shaft's axis*

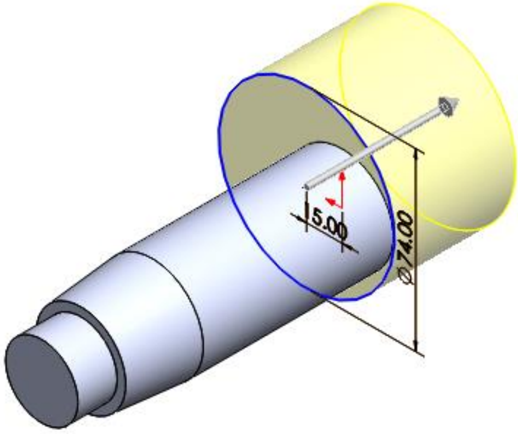


*Fig 3.13(b). Eccentric journal formed*

Using simple extrusion, the second half of the shaft is also made, it was made concentric to the 1st end so that it may be in pure rotation as well. This end was made to protrude out from the endplate, and is where all the auxiliaries (ignition system, gear pump, etc.) would be connected.

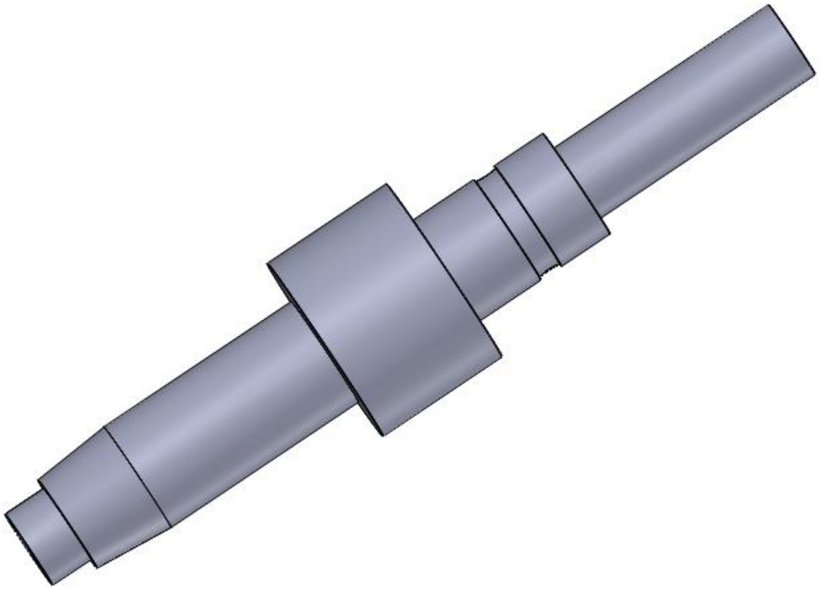


*Figure 4-12 Full length of the shaft*

Since the shaft would carry the lubricant and deliver it at critical locations, it must be hollow, moreover, it must have holes perpendicular to the axial lengths at the journal to form a hydrodynamic lubricant layer in the bearing. Similarly, the gear mesh must be covered with lubricant and thus a hole perpendicular to the axial axis where the gears mesh is made. These holes extend to the surface from both sides, and since the shaft is hollow, these holes ensure lubricant travels from the shaft's center to these locations. These holes are represented in Fig4 below:

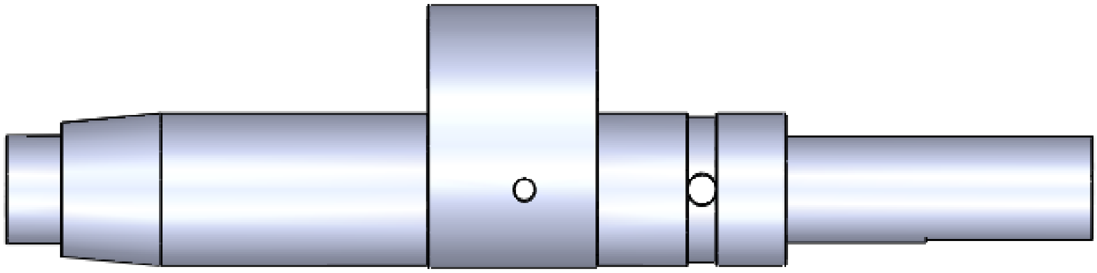


*Figure 4-13 Highlighting the location and size of holes to lubricate the bearing and the gears.*

Next, we made 3 holes within the journal's length that retain oil. The size and location of these holes were arbitrarily chosen such that they may be big enough to hold enough oil but not too large that their size effects the strength of the journal. 3 holes of length 47mm (about 1.85 in) were extruded, 2 of them were 12mm (about 0.47 in) and one was 18mm (about 0.71 in) in diameter.

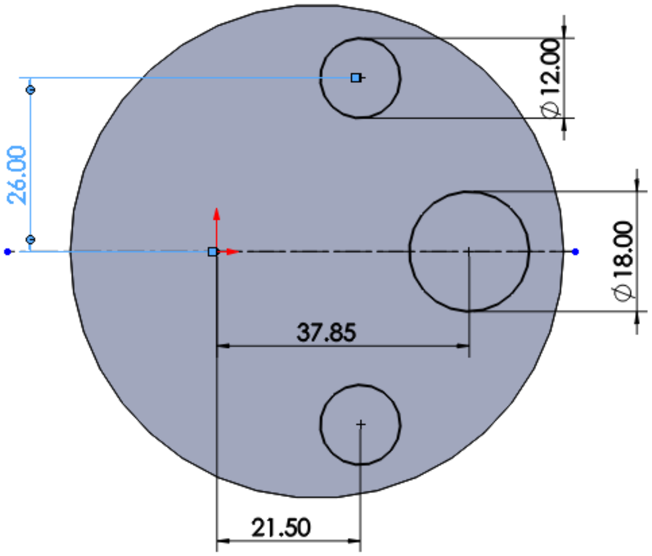


*Figure 4-14 Location and sizes of the 3 holes for lubricant retention.*

The internal diameter of the shaft was designated to be 15mm (about 0.59 in). This inner diameter runs throughout the length of the shaft. This embarks the foundation of the complete design of the shaft. The sizes and dimensions were related to the other parts (the rotor, the end plates, and the housing) such that the shaft may align perfectly with them and mates at appropriate places. Dimensions that not needed to be mated were initially arbitrarily selected and then iteratively tuned to the most comprehensive options.

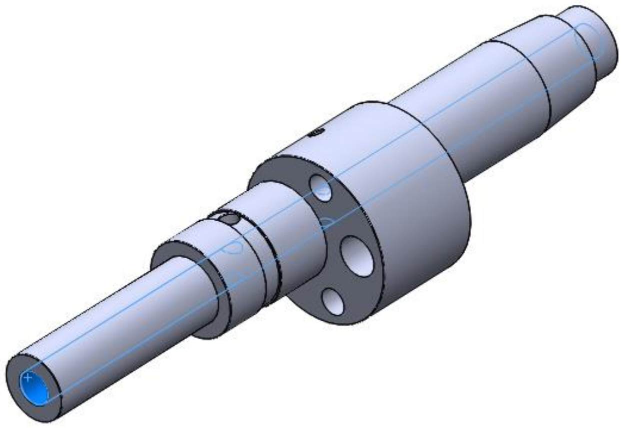


*Figure 4-15 internal diameter highlighted*

### iv. <u>Front Plate</u>

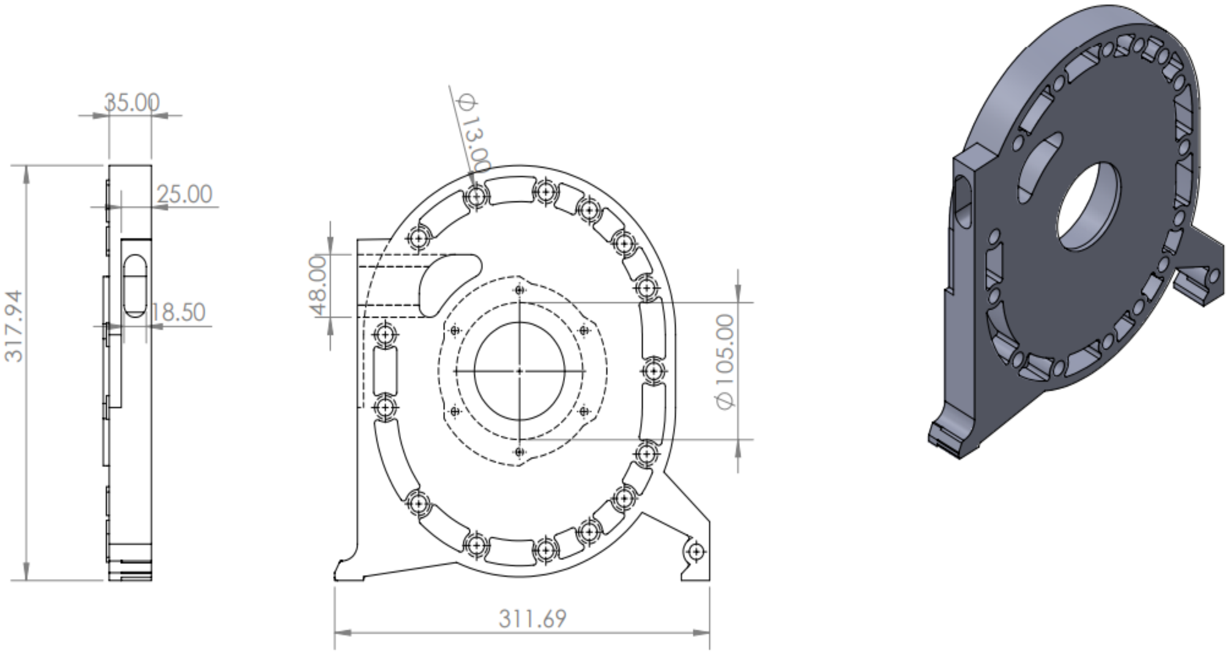


*Figure 4-16 End plates Engineering Drawing*

1. For the Front plate, it is made using the block designed saved in library.
2. In it we make a 105 mm (about 4.13 in) diameter to allow for insertion of stationary gear.
3. We also make six 6.25 mm (about 0.25 in) diameter holes on the outer surface of the front plate to allow us to secure the stationary gear.
4. A 76.25 mm (about 3 in) diameter hole is made for insertion of shaft in the Rear plate.
5. Along with this a curved slot on inner face of Rear plate is made having 8.75 mm (about 0.34 in) diameter at edges to allow intake of air.
6. Other slots are made using extruded cut feature on right side of the Rear plate to connect to the slot made on inner face of Rear plate.

## Assembling The Engine:

Assembling the parts together gives us a clearer vision of what we are working with and highlights the problems in the sizing of components. After assembling the parts, motion study is done which shows the movement of rotor as pure rotation.

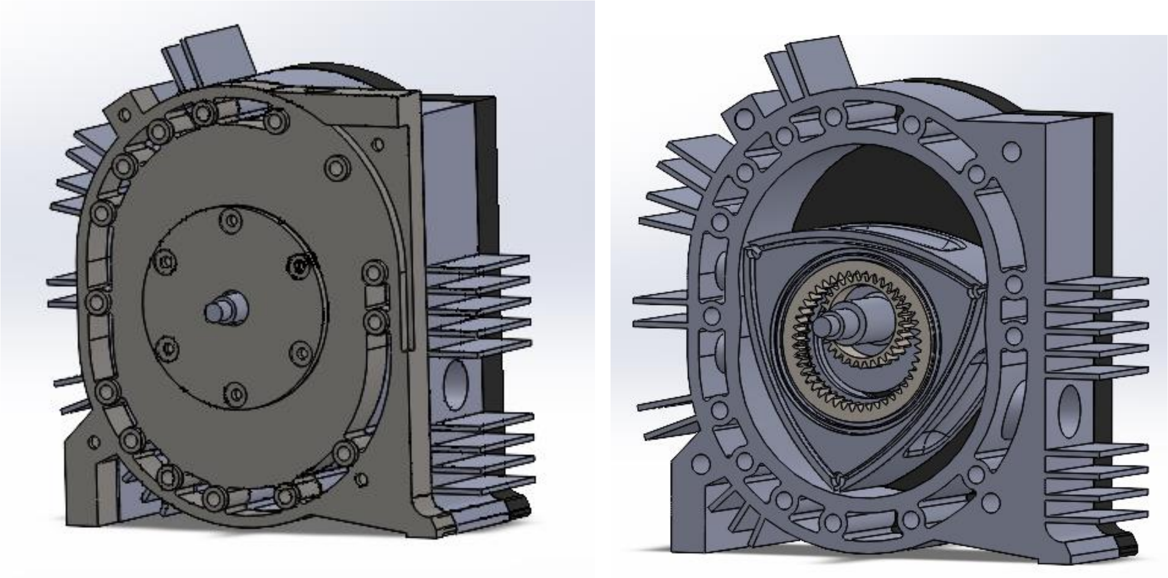


*Figure 4-17 Highlighting the complete assembly of our 1 rotor Wankel Rotary engine on Solid Works.*

The main issue while assembling parts in CAD software was to keep the rotor in pure rotation and to keep the gears meshed. Following steps were followed to get the desired working of shaft and rotor.

1. The eccentric shaft and rear plate were imported, and concentricity was established between the hole in rear plate and the circular surface of the shaft. For the assembling part, the rear plate was kept fixed.
2. Rotor is imported into the assembly file and concentricity is established between the bearing hold on the rotor and the journal on the rotor.
3. Distance command on the mate is employed to get the required position of shaft and rotor. Following mates were done.
    a) 1mm (about 0.04 in) distance between rotor face and face of rear plate
    b) 19 mm (about 0.75 in) distance between face of journal of rotor and face of rear plate
4. Rear front gear plate is imported and mated with rear plate.
5. The chamfered curved surface act as the resting surface for external spur gear, which is mated using gear mate with the internal spur gear on the rotor.
6. The housing and the front plate are mated onto the assembled parts using fixed and conc

# Chapter 5 Methodology

It is one thing to design an engine, but the game gets many folds tougher when one must physically manufacture what is only on paper, let alone with limited resources and capital. Our approach for erecting the engine was initially discretizing each part required into 2 distinct categories, namely, those parts that were standardized and could be brought from the market directly, and those which we would need to manufacture (either due to their unavailability or price). This simplified the pathway for us since we were able to design an engine that revolved around standards and materials that were commercially cheap and available. Initially we discuss the parts we intended on making ourselves, this included the crux of the engine: the main housing, the rotor, the end plates, the eccentric shaft, and even some of the sealing.

## 1. Housing

The Wankel engine uses an oval-shaped housing with epitrochoidal inner surface. The shape of the combustion chamber is designed so that the three tips of the rotor will always stay in contact with the wall of the chamber, forming three sealed chambers.

Each part of the housing is dedicated to one part of the combustion process. The four sections are:

- Intake
- Compression
- Combustion
- Exhaust

For manufacturing of our Housing, we will be using cast iron as the material and using sand casting to form the housing. This is because of cast iron’s low cost and its formidability. The iron used for this block is the gray cast iron having a pearlite-microstructure. The iron is called gray cast iron because its fracture has a gray appearance. Ferrite in the microstructure of the bore wall should be avoided because too much soft ferrite tends to cause scratching, that can leak air between chambers. As the housing will be made from sand casting, it involves making the mould for the cast iron block with sand. The preparation of sand and the bonding are a critical and very often rate-controlling step. Permanent patterns made of wood will be used to make sand molds. Molten metal will be poured immediately into the mold and after solidification, the mold is destroyed, and the inner sand is shaken out of the housing.

The bonding of sand can be done using two main methods:

(i) Green Sand Mold: It consists of mixtures of sand, clay, and moisture

(ii) Dry Sand Mold: It consists of sand and synthetic binders cured thermally or chemically

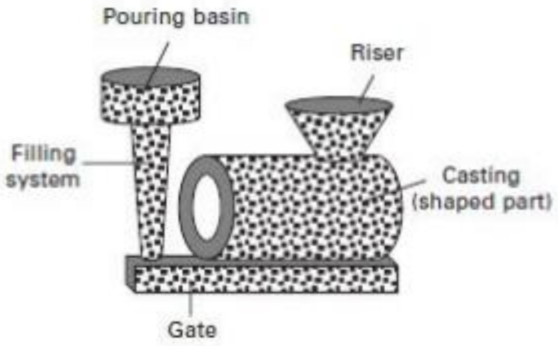


*Figure 4- 1 Fundamentals of Sand Casting*

This mold includes a sand core to make the housing inner cavity. The casting obtained from using this mold illustrated in figure above. Usually, molten iron in a ladle is gently poured into the cavity under the force of gravity using a filling system. The sand core forming an inside hollow shape is made from a dry sand component. For the efficient performance of a housing's inner surface, we will require high dimensional accuracy. A finishing process called honing can be used here to give accurate roundness and straightness to the cavity but depends on the possibility of process being carried out in MRC. The whetstone will grind the surface of cavity by exerting an expanding pressure. The vertical motion of the head together with revolution will generate a crosshatch pattern where the profile of the crosshatch pattern is determined by the sharpness of the whetstone. The advantage is that grooves of the crosshatch hold the lubricating oil during engine operation. The resulting oil film on the surface of the cavity generates hydrodynamic lubrication.

A finished surface of the cavity exposes the graphite without burr. The quality of the honing is measured by surface roughness value. The graphite in the cast iron block surface works as a lubricant during machining as well as during the engine operation. The lubrication offered by graphite on the wall surface reduces the frictional force between the wall and the contacting surfaces. The low frictional force of graphite comes from the fact that the crystal structure has an extremely low frictional coefficient during slip at the basal plane. The graphite decreases friction for tools during machining. The brittle nature of graphite makes chips discontinuous. The resultant high machinability gives high dimensional accuracy to cast iron parts. The micro-burr of the crosshatch disrupts the oil film to obstruct hydrodynamic lubrication.

Here although aluminium housing could have a weight about 40% less than a cast iron housing which could help in fuel consumption reduction. The thermal conductivity of aluminium alloy is 150 W/(m.K) while that of the cast iron is about 50 W/(m.K). This gives aluminium alloy high cooling performance at a lower weight. However, using aluminium is not suitable for us due to limited capital and inexperience. Moreover, cast iron is capable of lubricant retention which will greatly ease us in reducing friction within the engine.

The pattern of the housing was made of lasani wood at MRC in NUST with a conservative approach using CT 13 tolerances and keeping in mind the shrinkage and machining allowance. A draft angle of 2 degrees was also used. The pattern had a minimalistic design which mitigated much of the complex features which would have been onerous for a wood worker to make manually by hand tools. The casting was done in Okara where the rate was Rs.190/Kg and the part weighed around 45 Kg.

*Figure 4- 2 Housing Pattern*

The part was then shot peened, which is a technique where small metal balls are hammered at high speeds on the surface of the part to remove any dirt, sand and the upper oxide layer. To put the part on a CNC though, even more of the sand engrained on the top layer must be removed, for which we grinded the part. This was followed by hand working the complex geometries with sand paper. Where possible, a more appropriate method of simply milling the surface to a straight surface finish was adopted by machining 2 mm of the surface. CNC machines cannot filter out sand particles as they have a strainer and not a filter, for which if we needed to put our part on the CNC, the sand must have been completely removed.

## 2. Rotor

The rotor has three convex faces, each of which acts like a piston. Each face of the rotor has a pocket in it, which increases the displacement of the engine, allowing more space for air/fuel mixture. At the apex of each face is a metal blade that forms a seal to the outside of the combustion chamber. There are also metal rings on each side of the rotor that seal to the sides of the combustion chamber. The rotor has a set of internal gear teeth fixed into the center of one side. These teeth mate with a gear that is fixed to a side housing. This gear mating determines the path and direction the rotor takes through the housing.

The rotor will also be manufactured using sand casting process and be made of cast iron. The rotor's pattern is made of wood in MRC at NUST with a conservative design that is a balance in reducing weight, mitigating complexity for the wood worker and keeping machining tolerances intact. The design of the wooden pattern was a conservative one made according to the CT 13 on the casting scale which is ideal for handed sand casting parts. The casting was done in Okara at a local shop since the rate was minimum there with Rs 190/Kg compared to Rs 300/Kg in Islamabad. The total weight of the casted rotor part came out to be 15 Kg.

*Figure 4- 3 Sand Casted Rotor*

The part was then shot peened, similar to the housing described above and the same further procedure of cleaning the surface was adopted. For the CNC machining, the rotor was undoubtedly the most complex part, as it needed initial fixtures to be made to clamp the part in position.

## 3. Eccentric Shaft

It is the useful part that is used to convert the eccentric motion of the rotor into concentric motion and take it out of the engine. The rotor rotates around the eccentrics and make an orbital rotation around the eccentric shaft. The eccentric shaft is made via mild steel which is an ideal material concentric to its job. It is not brittle like cast iron, hence can resist higher bending and torsional moments and radial loads (axial loads are trivial). The maximum diameter of the shaft is 73mm and the length of the entire shaft is approximately 28cm. Thus, we bought a mild steel rod of 75mm dia and length of 35cm. This was then given to the lathe machinist at MRC NUST with the engineering drawing containing all the required dimensions and the tolerance associated with each part. Note: The tolerances of all the parts are an extremely essential aspect of mating any 2 parts and thus is discussed in detail in a separate chapter.

*Figure 4- 4 Eccentric Shaft*

For our casting process of Rotor and Housing we need to keep in mind some tolerances to allow for surface finishing and allow the casting process to be straightforward. The tolerances are divided into two categories

### i. <u>Functional Dimensions</u>

This includes the following BS 6615: 1996 - Rough Casting Tolerances for Cast Iron can used. Here, for Shell molding process we can allow till CT8 degree. The machine molding and automatic molding can reach CT9 degree. The resin sand casting can reach CT9 to CT10 degree. The manual green sand casting can reach CT10 to CT12 degree.

| **Raw casting basic dimension mm** | | **Total casting tolerance (mm)** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| over | up to and including | Casting tolerance grade CT | | | | | | | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 6 |
| - | 10 | 0.09 | 0.13 | 0.18 | 0.26 | 0.36 | 0.52 | 0.74 | 1 | 1.5 | 2 | 2.8 | 4.2 | - | - | - | - |
| 10 | 16 | 0.1 | 0.14 | 0.2 | 0.28 | 0.38 | 0.54 | 0.78 | 1.1 | 1.6 | 2.2 | 3 | 4.4 | - | - | - | - |
| 16 | 25 | 0.11 | 0.15 | 0.22 | 0.3 | 0.42 | 0.58 | 0.82 | 1.2 | 1.7 | 2.4 | 3.2 | 4.6 | 6 | 8 | 10 | 2 |
| 25 | 40 | 0.12 | 0.17 | 0.24 | 0.32 | 0.46 | 0.64 | 0.9 | 1.3 | 1.8 | 2.6 | 3.6 | 5 | 7 | 9 | 11 | 4 |
| 40 | 63 | 0.13 | 0.18 | 0.26 | 0.36 | 0.5 | 0.7 | 1 | 1.4 | 2 | 2.8 | 4 | 5.6 | 8 | 10 | 12 | 6 |
| 63 | 100 | 0.14 | 0.2 | 0.28 | 0.4 | 0.56 | 0.78 | 1.1 | 1.6 | 2.2 | 3.2 | 4.4 | 6 | 9 | 11 | 14 | 8 |
| 100 | 160 | 0.15 | 0.22 | 0.3 | 0.44 | 0.62 | 0.88 | 1.2 | 1.8 | 2.5 | 3.6 | 5 | 7 | 10 | 12 | 16 | 0 |
| 160 | 250 | - | 0.24 | 0.34 | 0.5 | 0.7 | 1 | 1.4 | 2 | 2.8 | 4 | 5.6 | 8 | 11 | 14 | 18 | 2 |
| 250 | 400 | - | - | 0.4 | 0.56 | 0.78 | 1.1 | 1.6 | 2.2 | 3.2 | 4.4 | 6.2 | 9 | 12 | 16 | 20 | 5 |
| 400 | 630 | - | - | - | 0.64 | 0.9 | 1.2 | 1.8 | 2.6 | 3.6 | 5 | 7 | 10 | 14 | 18 | 22 | 8 |
| 630 | 1000 | - | - | - | - | 1 | 1.4 | 2 | 2.8 | 4 | 6 | 8 | 11 | 16 | 20 | 25 | 2 |
| 1000 | 1600 | - | - | - | - | - | 1.6 | 2.2 | 3.2 | 4.6 | 7 | 9 | 13 | 18 | 23 | 29 | 7 |
| 1600 | 2500 | - | - | - | - | - | - | 2.6 | 3.8 | 5.4 | 8 | 10 | 15 | 21 | 26 | 33 | 2 |
| 2500 | 4000 | - | - | - | - | - | - | - | 4.4 | 6.2 | 9 | 12 | 17 | 24 | 30 | 38 | 9 |
| 4000 | 6300 | - | - | - | - | - | - | - | - | 7 | 10 | 14 | 20 | 28 | 35 | 44 | 6 |
| 6300 | 10000 | - | - | - | - | - | - | - | - | - | 11 | 16 | 23 | 32 | 40 | 50 | 4 |

*Table 5-1 Casting tolerances for basic dimensions of parts*

### ii. Non-Functional Dimensions:

| | |
|---|---|
| **Wall Thickness Tolerance** | ± 0.20mm |
| **Straightness/ Flatness Tolerance** | 0.10 mm per 25.4 mm |
| **Angular Tolerance** | ± ° up to 76.2 mm (about 3 in) |
| **Typical Surface Finish** | 2.0 μm |
| **50 % Additional Tolerance up to** | ± 127 mm |
| **33 % Additional Tolerance above** | ± 127 mm |

*Table 5-2 Non-functional Dimensions*

The housing and rotor once cast will be sent to the CNC shop, where a 3-axis CNC milling will intricately refine the parts with minimal tolerances of 0.01mm (about 0 in). The E-shaft on the other hand, will be delivered to an operator on a lathe machine which can then be refined to the intended size and surface finish. Initially using Sand casting for the parts and then proceeding with machining operation, instead of directly machining billets is done due to the unavailability of cast iron billets and to reduce workload and work time on the CNC, which would have used up quite a lot of tooling when machining a complete billet into the desired shape.

## 4. Flywheel

The rotors drive an output shaft running through their center. This shaft is linked to a flywheel to smooth out the power impulses of the engine. The basic working principle of a flywheel is that initially the electric motor gives power to the flywheel which causes the rotor to rotate and burn fuel inside the combustion chamber. Once the power stroke is activated the flywheel absorbs rotational energy during the power stroke and uses it for the other three strokes. In this way, it helps in stabilizing the rotational movement of the transmission system.

The energy equation depends on the angular velocity and moment of inertia of the flywheel.

$$E_k = \frac{1}{2} I\omega^2$$

$\omega$ = angular velocity

I = Moment of Inertia of Mass

$$I = \frac{1}{2} mr^2$$

Thus, it is obvious that the energy stored in a flywheel will increase with the increase in weight, size, and angular velocity.

The flywheel will be made of cast iron as it is cheap and there is minimum or no need for machining as it can directly be used after casting operation.

# 5. SEALS & SPRINGS

The apex seals and the corner seals are what trap the fluids from one chamber to another and thus are extremely preeminent to carry out the process of combustion and expansion in the engine. Ineffective sealing leads to decreased efficiency and in worst cases engine failure and seizure. The rotary engine uses a set of special seals named Apex seals and corner seals, each of which comes with its own spring that helps in pushing these seals against the rotor housing to ensure proper shutting off fluid transfer. We were unable to get our hands on these apex seals, thus we decided to fabricate them on our own.

The apex seals were made by initially getting hands on cast iron plates that were 7 mm thick. We got them from the same place from where we casted our parts. The plates were milled down to 4mm (the required thickness for the apex seal). Cast iron is a very viable material to be used for this purpose. It has lubricant retention properties which will allow smooth transitioning in the housing. Moreover, law of material hardness dictates that when 2 surfaces are in contact and rubbing together, the material with lower hardness will eventually be chipped off (start to degrade), and since the housing (which is made of cast iron) cannot bear a seal made of steel. The only 2 compatible metals that can withstand the high temperatures of the engine and also are not harder than the housing material are aluminum and cast iron. Aluminum brings an exaggerated expansion coefficient hence is also undesirable for high temps. This cutdown method chooses cast iron as the preferred material.

Once the plates were cleaned at milled to the desires thickness of 4mm, they were wire cut into shape at MRC by the EDM machine. We need 3 such seals for the 3 apexes of the rotor.

*Figure 4- 5 Apex Seal*

This seal is to be pushed towards the housing, so that it may maintain a sealing channel to separate the fluids in each chamber conformed, which ultimately ensures the proper working of the engine. This push is provided by a leaf spring that sits behind the seal in the rotor's apex cavity. A wire of SS of diameter 0.5mm was cut into small pieces of length 8cm and then heated till it was red hot using a flame torch. The red-hot wire was hammered and pressed into an arc shape of required diameter and then quenched into water at room temperature. The whole process is known as Quenching.  Since the workpiece was still brittle to be a spring the process was repeated by heating it to a temperature of 293$^{o}$C and quenching it in hot oil.

Next, we discuss the auxiliary equipment that are imminent for our project to function. These parts are commercially available, and it is undoubtedly wise to purchase and incorporate them in the design (instead of going for vertical integration). Parts made in bulk by renowned manufacturers are both reliable and cheap (when compared to manufacturing these parts individually). Deciding which size and designated part to use was our burden and this is what we went with.

## 6. Starting Motor

To start the engine, the crankshaft must be turned at some speed, so the engine sucks air-fuel mixture and compresses it. The flywheel at the shaft output end has teeth on the surface of its rim. The drive gear of the starter engages with it and does the rotating the crankshaft, initiating the duty cycle of the engine. A starter motor is a special device used to rotate crankshaft an internal-combustion engine.

When the ignition key will be turned on current is fed to the solenoid and starter will switch on. The return spring will then serve to switch off the starter when the key is released. By the current feeding to the solenoid, the electromagnet attracts an iron rod. Two heavy contacts close the rod movement and the circuit form battery to the starter is completing. Starter motor must turn no more time than need, to start the motor. The electric motor of the starting system creates torque, and its body is made of steel and has the appearance of a cylinder. Inside the housing there are field windings wound around cores attached to the housing. These windings are made of thick conductive wire capable of withstanding strong electric current. The windings generate an electromagnetic field that can rotate the starter armature. One of the elements of the anchor is the core, with grooves along which are located the turns of the windings of the anchor. Both ends of each winding are connected to the collector. The torques created by each of the windings add up so that you can rotate the armature, more precisely the armature shaft. If you look at the starter from the side of the collector, you can see the brush holder at the anchor.

This mechanism transmits torque from the electric motor to the flywheel. A drive gear is installed on the armature shaft. The action of the electromagnetic switch forces the drive lever to translate the drive gear into engagement with the gear rim of the flywheel so that the rotation is transmitted to the motor shaft.

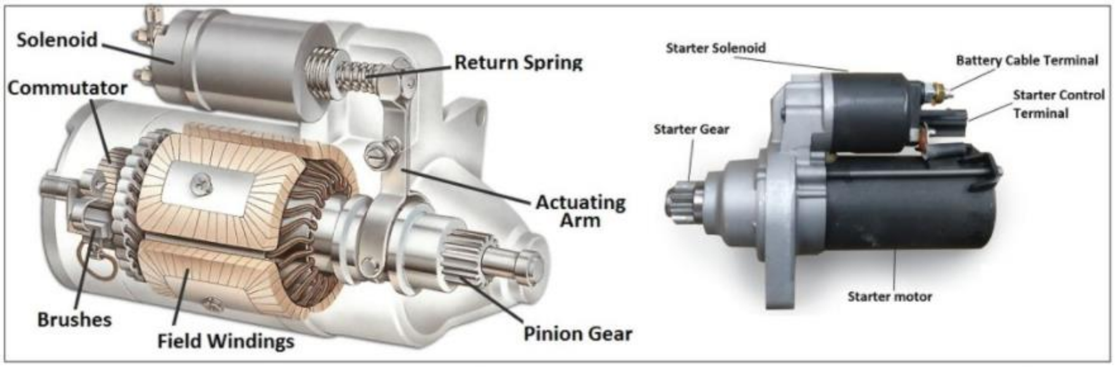


*Figure 4- 6 Starter motor*

## 7. Carburetor

Carburetor is the device that used to mix air and fuel in an internal combustion engine. The main objective of the carburetor is to provide quality air-fuel mixture for cruising range and for other unique requirements like at starting, idling, acceleration, variable load, and speed operation condition. The main parts of a simple carburetor are carburetor air filter, float chamber, fuel discharge nozzle, metering orifice, choke valve, throttle valve and venturi.

The float chamber is vented to the upstream side of the venturi or to the atmosphere. Float and needle valve maintains the constant gasoline/ petrol level inside the float chamber. The float goes down because of the decreasing amount of fuel inside the chamber. When the fuel level goes down to the designed level, the floats go down, actuate the fuel supply valve, and admits fuel into the chamber. When fuel reached the designed level, float closes the fuel supply valve. The tip of fuel discharge nozzle from the float chamber is located to the throat of venturi. The tip will be slightly above the level of fuel in the float chamber to avoid overflow. The throttle valve is regulated by the mechanical linkage (cable) or pneumatic link to the accelerator pedal of the vehicle.

A Carburetor work on the Bernoulli's principle. During the suction stroke, air is drawn into the cylinder through venturi or choke tube. Venturi tube is designed in such a way that it offers minimum resistance to the air flow. When air passes through the venturi the velocity of air increases and the pressure decreases. At venturi throat the velocity of air reach maximum and the pressure reach minimum. There will be a pressure difference between the float chamber and venturi throat. This pressure difference is known as carburetor depression. Because of this pressure difference fuel is discharged to air stream through fuel discharge nozzle. The amount of fuel discharged depend upon the size of fuel discharge nozzle/ fuel discharge jet.

The throttle of vehicle does not directly control the fuel supply. Instead, it actuates a mechanism that controls the air flow into the engine. The speed of air drawn into the cylinder determines the amount of fuel mixed in the air. The amount of charge delivered to the gasoline engine cylinder varies with varying power output. This is achieved by using a throttle valve after the venturi. When the throttle valve opening varies, the air flow rate also varies. The increase in air flow rate decreases the pressure at the throat that makes the flow of fuel vary in a comparable manner. However, as the decreasing pressure at throat decrease the density of air whereas the density of fuel remains unchanged. This results the simple carburetor produce a progressively rich mixture with increasing the throttle opening.

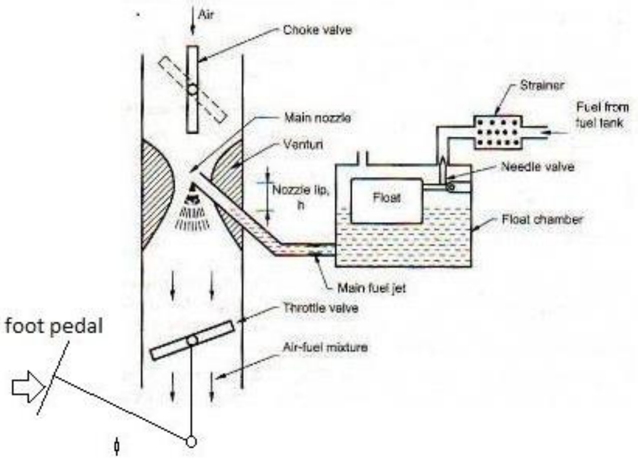


*Figure 4- 7 Basic working of a Carburetor*

## 8. Ignition System:

In spark ignition engines, the electrical discharge produced between the spark plug electrodes by the ignition system starts the combustion process. A spark can arc from one electrode to another when sufficiently high voltage is applied. Ignition system used in this engine to provide the necessary spark is the battery system where the spark energy is stored in a capacitor and transferred as a high voltage pulse to the spark plug by means of a special transformer which is called as capacitive discharge ignition system.

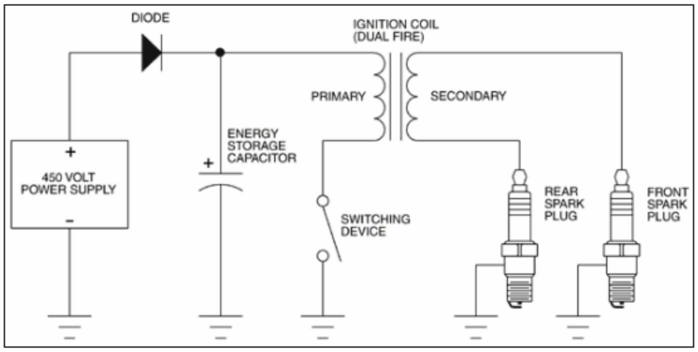


*Figure 4- 8 Showing the principle behind CDI ignition systems used in bikes and 2 stroke engines.*

## 9. Spark Plugs:

The Wankel engine uses two spark plugs, that is a leading, and a trailing spark plug. The leading plug located at the side of the rotor housing burns up to 95% of the air/fuel mixture providing much power. We will be using two NGK DPR8EIX-9 IRIDIUM Spark Plug usually used for Honda CG125 motorcycle.

## 10. Lubrication:

The journal bearing, the O-rings and the seals, require generous amounts of lubrication, (which is also a downside of the rotary) to prevent failure due to excessive wear. For this, a dry sump lubrication method is employed, whereby the E-shaft is hollow, and has holes at critical locations perpendicular to the axial length, which deliver the lubricant to these locations within the housing, namely, the journal bearing, the stationary & ring gear mesh, and the O-ring seals. An oil pan will enclose the E shaft externally which will be filled with the lubricant. An oil pump drives the lubricant in a loop, ensuring continuous supply of oil at these locations. An oil filter precedes the oil pump, which collects all the debris and abraded material that the oil picks up during its harsh escapade around the inside of the engine. We will not be coupling the oil pump directly to the E-shaft, i.e., to reduce complexity, we will drive the oil pump externally from a motor. A strong geared motor hooked up to the 12-Volt battery will be able to power the oil pump just correctly.

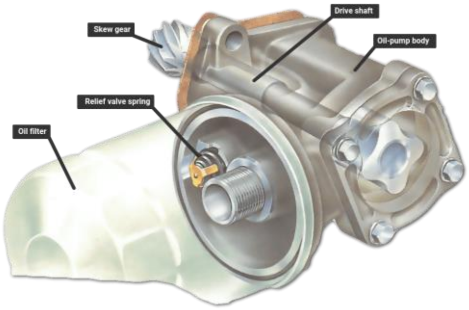


*Figure 4- 9 A typical oil pump used to drive lubricant*

## 11. Internal and External Spur Gears

These are made from mild steel of Grade 2 which are heat treated to resist bending and pitting failure. The gears were made by an experienced machinist in Quetta. We chose a simple module system to manufacture the gear set instead of the ANSI counterpart. Since the 2 gears, (an internal ring gear and a stationary spur gear) were to engage, they must have had the same module. The design of our Wankel Rotary engine dictated that the gear ratio be 3:2.

The design calculations for the gears to sustain the bending stresses (at root) and contact pitting resistance is shown further in the report. Through those calculations it is proved that a module of 1.75 for both the gears can be used. The ring gear has 51 teeth and the spur gear has 34. The ring gear was made via a shaper machine with a cutter of module number 1.75. As the machine moves to and fro it creates slots within the metal rod that complement the insertion of spur gear teeth. The stationary gear was made via a milling machine coupled to a cutter of module number 1.75.

*Figure 4- 10 Internal and External Spur Gears*

## 12. Bearings:

The Wankel rotary engine usually has 3 journal bearings. One in the rotor and 2 in each of the end irons. Due to a lack of substantially powerful lubrication system and an absence of sump, we could not use journal bearings. We then had to resort to use other typ eo fdynamic mechanical bearings. To conserve space and size we opted to go with needle bearings at each of these locations. The needle bearings chosen were open ended from the inside which allowed us to use bigger needles in the bearings. The bearings were bought online after a rigorous iterative approach to select them so that they correspond to our design. The 3 bearings bought had the sizes as follows:

- NK 73/35
- HK 30/38
- HK 3520

Apart from the conventional radial bearings, we also needed 2 axial thrust bearings to accommodate any axial movement of the shaft, or else in a high rpm situation, the shaft might escape the press fit and slide out. Axial bearings used were of needle type, with thin washers to reduce size. Their employment was based on their capacity to withstand dynamic loading which was measured by SKF charts and was well under lethal limits. The axial bearings we bought were:

- AXK+2AS 2542 YFB
- 51205 YFB

# ASSEMBLING THE ENGINE

The engine assembly involves a ton a specific steps, each one should be in a correct order. Once the CNC parts came, we initially used tap and dies in the specific holes to form internal threads. Specifically one of the side plates has the internal threads for 12mm long bolts.

We first shrink fitted the stationary spur gear on the gear plate and then arc welded to ensure the gear is firmly held in place on the hub. The gear was heated in an oven upto a temperature of 400 deg and then paced in the hub by using pliers quickly. A boring dead weight was placed atop the gear which allowed it to go down the hub. Once it cooled and the hole of the gear contracted, it tightly grasped the hub.

Next, the gear plate was bolted to its position on the back of the front plate by using 6 8mm bolts. The plate was flipped down and the rotor placed such that the ring gear inside the rotor meshed with the stationary gear. We made sure to use a lot of assembly lube to form a lubricant boundary layer between the gears. 2 dowel pins were placed in their respective holes. This allowed us to correctly drop the mid housing down. Once the housing engulfed the rotor, we inserted the apex seals and the leaf springs.

The eccentric shaft was then inserted inside the rotor’s bearing in the correct orientation, the tapered part of the shaft pointed upwards. The bearings were also laced with Vaseline and assembly lubricant.

The CDI side plate was then placed, again using the dowels as guides. Long tension bolts were then inserted and torqued lightly in a crisscross pattern. The ignition coil plate was then screwed on its place on the back of the CDI plate. This was followed by clamping the magnet of the CDI unit using a 12mm nut. We had placed the carburetor channel on the top of CDI plate. A short elbow was first clamped on the top which was further connected to the carburetor.

The 2 spark plugs were then clamped to their position. The engine was then rotated, and the other end of the shaft was clamped to the flywheel by a 14mm nut and washer. The starter motor was then placed and engaged with the flywheel. The electronics were attached and the engine ignition switch turned around again to clamp the tension bolts to their designated torques.

# Chapter 6 Design Calculations

Once the initial dimensions were given, we then proceeded to the calculation phase, where each part was tested against a certain failure criterion (based on its application & type of loading). If the calculations exhibited that the structure would yield, a new dimension was chosen, and the calculations repeated. This was done until the optimum sizes could be determined which would allow the engine to operate without malfunctioning.

## INTAKE

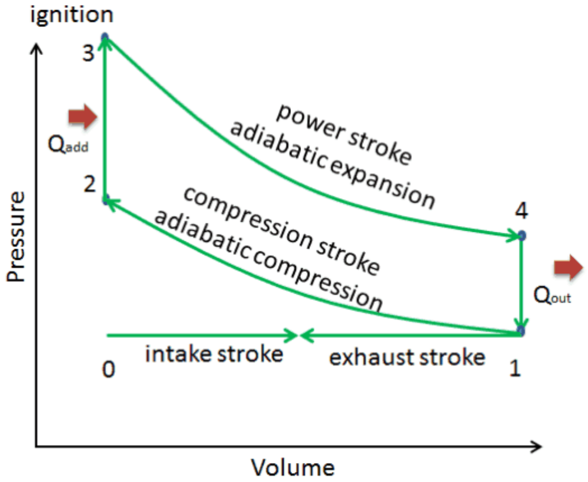
The process of combustion is what delivers the output power to the engine. The intake phase is the prerequisite to the combustion and hence our calculation starts with determining the salient variables in this process. As the rotor moves across the intake manifold, it creates a vacuum, drawing in air from the atmosphere and into the engine. The volume of air sucked in is extremely important and let it be $V_{intake}$. This volume is equal to the volume displaced by the rotor moving across the intake manifold. This volume of air although comes from the atmosphere outside, but carries fuel with it, this is possible by the admission of a carburetor before the intake. Air coming in initially travels through the carburetor and picks up fuel by venturi effect. For the sake of calculations, we assumed that the air fuel mixture is at stochiometric ratios which ensures maximum load on the parts. Since the fuel is High octane $C_8H_{18}$, the stochiometric combustion equation comes out to be

$$5\ O_2 + 2\ C_8H_{18} \rightarrow 16\ CO_2 + 18\ H_2O + energy$$

The air fuel ration is thus $A.F_{ratio}$ = ***14.7 grams of air / gram of fuel***. Note that the equation above is the stochiometric equation with oxygen, Air contains 21% Oxygen, thus more air needs to be fed for complete and ideal combustion.

The calorific value of High octane $C_8H_{18}$ is 46 MJ/Kg.

## Otto Cycle Calculations:



From Solidoworks model and prior calculations, we know that for our engine;

$$Compression\ ratio = r = 5.12$$

$$Intake\ Volume = V_{in} = V_1 = 425\ cm^3$$

$$Clearance\ Volume = V_c = 83\ cm^3$$

$$C_v = 1.005\frac{kg}{K}$$

$$Calorific\ Value = 47.9\frac{MJ}{kg}$$

$$k = 1.4$$

$$T_{1=}25^oC = 298K$$

From State 1 to 2:

$$\frac{T_2}{T_1} = r^{(k-1)}$$

$$T_2 = 298 \times (5.12)^{(1.4-1)}$$

$$T_2 = 572.69\ K$$

From State 2 to 3:

$$Q_{in} = Calorific\ Value \times m$$
$$m_a \times C_v \times (T_3 - T_2) = Calorific\ Value \times m_f$$

$$\frac{m_a}{m_f} \times C_v \times (T_3 - T_2) = Calorific\ Value$$

Putting in values in the equation, gives us the value for $T_3$;

$$T_3 = 3814.98\ K$$

From State 3 to 4:

$$\frac{T_3}{T_4} = r^{(k-1)}$$

$$T_4 = 1985.11\ K$$

Efficiency:

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \times 100$$

$$\eta = 47.9\ \%$$

# VOLUME

## Housing

$$Area\ of\ housing = A_{housing} = \pi r^2 + bh$$

$$A_{hosuing} = 0.97[\pi 0.092^2 + (0.184 * 0.05575)]$$
$$= 0.03574\ m^2$$

$$Thickness\ of\ the\ housing = 80mm\ (about\ 3.15\ in)$$

$$Volume = Area * thickness = 0.03547 * 0.08$$

$$Volume = 0.002844\ m^3 = 2.844\ liters$$

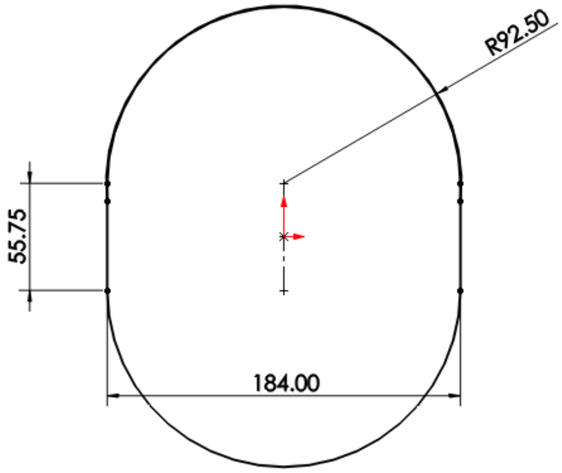


*Figure 6-1 Approximate shape of rotor housing*

## Rotor

$$Area\ of\ sector = \frac{\theta}{360} * \pi r^2 = \frac{60}{360} * \pi(0.1951^2)$$

$$Area\ of\ sector = 0.01993\ m^2$$

$$Area\ of\ shaded\ region\ X = A_{sector} - A_{triangle}$$

$$A_X = A_{sector} - \frac{\sqrt{3}}{4}a^2$$

$$= 0.016683 - \frac{\sqrt{3}}{4}(0.1951)^2$$

$$A_X = 0.0034478\ m^2$$

$$Total\ Rotor\ Area = A_{rotor} = \frac{\sqrt{3}}{4}a^2 + 3A_X$$

$$A_{rotor} = \frac{\sqrt{3}}{4}(0.1785^2) + 3(0.0034478)$$

$$= 0.02414 m^2$$

$$V_{rotor} = A_{rotor} * thickness = 0.02414 * 0.08$$

$$V_{rotor} = 0.00193124 m^3 = 1.9312\ liters$$

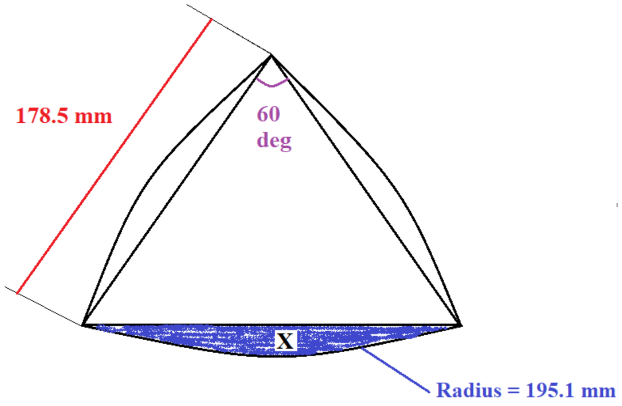


*Figure 6-2 Peripheral cross section of rotor*

**Note:** The rotor also has 3 combustion cavities, which aid in the combustion process and increase the overall engine's volume. Thus, the volume of these cavities must be considered when considering the total engine's volume. The shape of these cavities is quite complex due to the addition of fillets to make it smoother and culminate stress concentrations, hence, we will be using an approximation technique to calculate its volume. The depth of these cavities is 7.5mm (about 0.3 in).

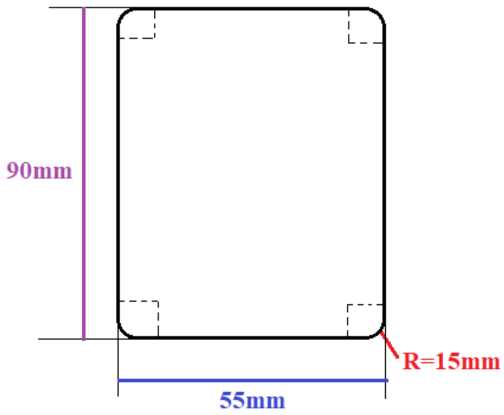


*Figure 6-3 Approximate Cross Section of Combustion Cavity*

$$Area\ of\ cavity = A_{cavity} = \pi r^2 + 2(b_1 h_1) + b_2 h_2$$

$$A_{cavity} = \pi 0.015^2 + 2(0.025 * 0.015) + (0.055 * 0.06)$$
$$= 0.004757\ m^2$$

$$V_{cavity} = 0.004757 * 0.0075$$

$$V_{cavity} = 0.00003567\ m^3 = 0.03567\ liters$$

**Note:** 3 of such cavities are present, moreover due to fillet addition 15% reduction factor is applied. Now the net volume of 3 such cavities is:

$$V_{cavities} = 3(0.03567) * 0.085$$

$$V_{cavities} = 0.090975\ liters$$

### Total Engine Volume

$$V_{total} = V_{housing} + V_{cavities} - V_{rotor}$$

$$V_{total} = 2.84443 + 0.090975 - 1.9312$$

**$V_{total}$ = 1.004 liters = 1004cc**

## FORCES & TORQUES

### FORCE

We now find the forces that are generated within the engine by combustion. This initially requires the compression ratio of the engine. The compression ratio can be easily computed via measuring the intake volume $V_{in}$ and the compression volume $V_c$. Since the assembly is quite complex, calculating these two volumes would have been utterly onerous. Thus, a much simpler approach was adopted. We used Laser Cutting on acrylic sheets to fabricate an initial prototype of our project to check whether the kinematic motion of the assembly works accurately as we wish or not. This model was positioned for the max intake volume & the minimum compression volume separately, and then these volumes measured. The volume was measured by pouring in known quantities of water that filled these spaces. The results came out to be:

$$\mathbf{V_{in} = 0.425\ liters = 425\ cm^3}$$

$$\mathbf{V_c = 0.083\ liters = 83\ cm^3}$$

Compression ratio = $\mathbf{r = V_{in}/V_c = 5.12}$

Maximum force on the rotor occurs at the instance of ignition, i.e., when the pressure on rotor's face is 5.12 times the atmospheric pressure.

$F = P.As$

The area A is the surface area of one of the 3 sides of the rotor:

$A_s = arc\ length * width$

$$arc\ length = s = 2\pi r * \frac{\theta}{360}$$

$$s = 2\pi(0.1951) * \frac{60}{360}$$

$$= 0.2043\ m$$

$$A_s = 0.2043 * 0.08$$

$$= 0.016345\ m^2$$

$$P = r.P_{atm}$$

$$= 5.12 * 101325$$

$$= 518784\ Pa$$

$$F = P.A_s$$

$$= 518784 * 0.016345$$

$$\mathbf{F = 8.4795\ KN}$$

**TORQUE**

The force is spread over the entire surface; however, we can assume that it acts as a single point in the middle. The torque generated is a result of the force due to the compression pressure & the eccentric distribution of weight (of rotor & shaft) which does not acts through the centroid. The maximum torque produced is thus:

$$Torque = T = (F + W).e$$

- Where W = weight of rotor and shaft
- e = eccentricity = 15cm (about 5.91 in)

$$m_{rotor} = V_{rotor} * \rho_{cast\ iron}$$

Volume of the rotor can be evaluated via solid works to be: $V_{rotor} = 1117016\ mm^3$

Density of cast iron = 7200kg (about 15873.26 lb)/$m^3$

$$m_{rotor} = 1.117016 * 7.3$$

$$= 8.1542\ Kg$$

Combining the mass of the ring gear, seals and springs in the rotor, the new rotor mass turns out to be: $m_{rotor} = 9.1\ Kg$

Similarly, mass of shaft comes out to be:

$$m_{shaft} = 3.24\ Kg$$

$$W = 9.81(3.24 + 9.1)$$

$$= 121.05\ N$$

$$T = (8479.5 + 121.05) * 0.015$$

**T = 129.008 Nm**

## GEAR ANALYSIS

Although the gears introduced in our design were correspondent to ISO standards (metric units), their analysis is much more efficient and detailed in US Customary Units, by the aid of **AGMA** (American Gear Manufacturers Association) **Stress equations**.

Spur gears are known to yield under **bending stresses** at the root or by **pitting** at the tooth surfaces. Bending failure initiates when the bending stresses exceed the yield strength or the bending endurance strength of the gear material. On the other hand, surface failure commences when the contact stresses surpass the surface endurance strength of the gear material. We thus need to calculate each of these stresses and compare them with the endurance strengths to assure that the gears will not fail under the given loading conditions.

We start by visualizing the bending stress and contact stress equations:

- **Bending Stress:**

$$\sigma_b = W^t \frac{K_o K_v K_s P_d K_m K_b}{F.J}$$

- **Contact Stress:**

$$\sigma_c = C_P \sqrt{W^t \frac{K_o K_v K_s K_m C_f}{d_P F . I}}$$

We only need to analyze the forces on the stationary spur gear, since it would be subjected to higher stresses compared to the inner ring gear. Hence, if the calculations exhibit that the stationary gear is viable and does not fail, doing the same calculations for the ring gear would be trivial. The 1st step is to convert our ISO based spur gear into a US customary based gear.

**Stationary Gear**

$\varphi = 14.5^o$ (Pressure angle)

Module = m = 1.75

Face width = F = 18mm (about 0.71 in) = 0.70866in

N = 34 teeth

$d_P = m.N = 1.75 * 34 = 59.5\text{mm} = 2.3425\text{in}$ **(**Pitch circle dia)

$$P_d = \frac{N}{\pi d_P} = \frac{34}{\pi * 2.3425} = 4.62 \text{ teeth/in}$$

Note that we will be using '***Shigley's Mechanical Engineering Design Eighth Edition'*** for the Tables and Figures used in our analysis. We start our analysis by defining the maximum bending stress $\mathbf{S_t}$ and maximum pitting resistance contact strength $\mathbf{S_c}$ for our gear materials.

From Table 14-3: For mild steel carburized and hardened, Bending strength $\boldsymbol{S_t = 70,000psi}$

From Table 14-3: For mild steel carburized and hardened, Contact strength $\boldsymbol{S_c = 225,000psi}$

Note that both strengths are for a reliability of 99% and a service life for $10^7$ cycles. However, since we need a greater life cycle, we will be suing stress cycle factors for bending and contact pitting to consider higher life cycle.

We initiate by calculating all the factors involved one by one.

**i. Bending Strength Geometry Factor: J**

It accounts for the shape of the gear teeth and stress concentrations in it for bending stresses developed at the root curvature. For a spur gear having 34 teeths to be engaged with a ring gear of 51 teeth, we use a geometry factor figure with a pressure angle of $14.5^o$ to measure:

**J = 0.42**

### ii. Surface Strength Geometry Factor: I

$$I = \frac{cos\varphi * sin\varphi}{2m_N} * \frac{m_G}{m_G - 1}$$

$m_N = 1$ (For spur gears)

$$m_G = \frac{N_{ring}}{N_{spur}} = \frac{51}{34} = 1.5$$

$$\varphi = 14.5\ deg$$

$$I = \frac{cos 14.5 * sin 14.5}{2(1)} * \frac{1.5}{1.5 - 1}$$

**I = 0.36361**

### iii. Elastic Coefficient: $C_p$

From Table 14-8, against gears of steel vs steel:

**$C_p = 2300\ (psi)^{0.5}$**

### iv. Dynamic Factor: $K_v$

Dynamic factors are used to account for inaccuracies in the manufacture and meshing of gear teeth in action. Transmission error is defined as the departure from uniform angular velocity of the gear pair.

We can use Fig 14-9 to find $K_v$ however, the graph is a function of pitch line velocity $\boldsymbol{V_t}$ & $\boldsymbol{Q_v}$. We can choose $Q_v = 9$, for a commercially made gear with average precision. Note that we do need precise gears however, to be on a safer side we have chosen $Q_v$ as 9.

Now to find the pitch line velocity! We are designing the engine to run on a max rpm of 9000. Due to the physics behind the engine's working, the rotor completes 1/3rd of a cycle, for each complete rotation of the shaft. Consequently, the rotor is moving with a speed of 3000rpm. Now note that, rotor's cycle is not circular, in fact it follows the epitrichoidal perimeter of the housing.

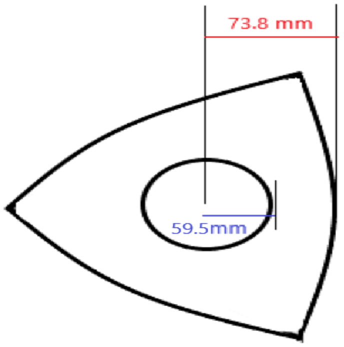


*Figure 6-4 Distance of Pitch circle dia from center and tip ends*

$$Perimeter = 2\pi r + 2b = 2\pi(0.092) + 2(0.057) = 0.692053\ m$$

$$Speed\ at\ rotor\ tips = rpm * perimeter$$

$$Speed\ at\ rotor\ tips = 3000 * 0.692053 = 2076.16$$

$$Speed\ of\ gear = Pitchline\ velocity = V_t = 2076.16 * \frac{59.5}{73.8}$$

$V_t = 1673.86\, m/min = 3876.5\, ft/min$

From Fig 14-9 against an approximate $V_t$ = 4000ft (about 1.22 km)/min &

$Q_v$ = 9, we get,

**$K_v$ = 1.36**

### v. Size Factor ($K_s$) & Surface Condition Factor ($C_f$)

For non-detrimental surface finishes and anomalies, we can approximate both these factors as:

**$K_s$ = 1**

**$C_f$ = 1**

### vi. Load Distribution Factor: $K_m$

Load-distribution factor modified the stress equations to reflect nonuniform distribution of load across the line of contact.

$$K_m = 1 + C_{mc}(C_{pf}C_{pm} + C_{ma}C_e)$$

$C_{mc}$ = 1 (for uncrowned teeth)

For face width F < 1in

$$C_{pf} = \frac{F}{10d} - 0.025$$

$$F\,\frac{F}{10d} = \frac{0.70866}{10 * 2.3425} = 0.03025 < 0.05$$

Hence, we use F/10d =0.05

$$C_{pf} = 0.05 - 0.025 = 0.025$$

$C_{pm}$ = 1

$$C_{ma} = A + BF + CF^2$$

Values of constants A, B & C are determined from Table 14-9, against precision enclosed units.

A = 0127

B = 0.0158

C = $-0.93 * 10^{-4}$

$$C_{ma} = 0.127 + 00158(0.70866) - 0.93 * 10^{-4}(0.70866)^2$$

$C_{ma}$ = 0.13815

$C_e$ = 1 (for non-lapped gearing)

$K_m = 1 + 1[(0.025 * 1) + (0.13815 * 1)]$

**$K_m$ = 1.16315**

### vii. Hardness Ratio Factor: $C_H$

Since the inner ring gear and the stationary spur gear, both will be made from identical materials, and will undergo concurrent heat treatment methods, their hardness is equal. Since the ratio of hardness of stationary gear and hardness of ring gear $H_{BP}/H_{BG} < 1.2$:

**$C_H$ = 1**

### viii. Rim Thickness Factor: $K_B$

When the rim thickness is not sufficient to provide full support for the tooth root, the location of bending fatigue failure may be through the gear rim rather than at the tooth fillet. To accommodate this, the rim thickness factor is employed.

Back up ratio = $m_b = t_r/h_t$

$$m_b = \frac{2.56}{3.94} = 0.64975$$

For $m_b < 1.2$

$$K_B = 1.6 \ln\left(\frac{2.242}{m_b}\right) = 1.6 \ln\left(\frac{2.242}{0.694975}\right)$$

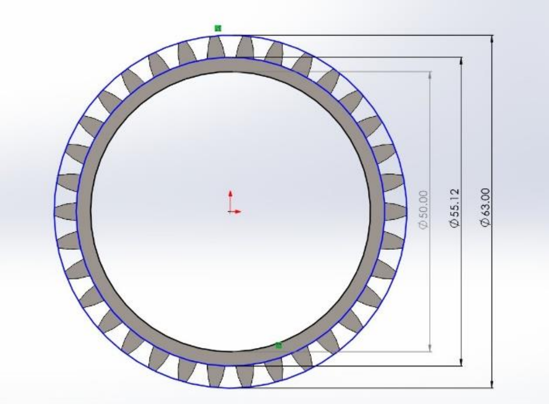


*Figure 6-5 Spur gear dimensions for rim thickness factor*

**$K_B$ = 1.874**

### ix. Transmitted Load: $W^t$

We can calculate the transmitted load $W^t$ from the torque of the engine calculated previously. The ring gear rotates with the same torque as the rotor. The transmitted load can be calculated simply by dividing the torque by the pitch circle radius:

$$W^t = \frac{T}{r_p}$$

$$W^t = \frac{129.008}{(\frac{0.0595}{2})}$$

**$W^t$ = 4373.15 N = 983.12 lbf**

### x. **Temperature Factor: $K_T$**

For oil or gear-blank temperatures up to 250°F (120°C), use,

$$\mathbf{K_T = 1.0}$$

### xi. **Reliability Factor: $K_R$**

The reliability factor accounts for the effect of the statistical distributions of material fatigue failures. The gear strengths St and Sc are based on a reliability of 99 percent. We are also designing our gears on a reliability of 99%. From Table 14-10:

$$\mathbf{K_R = 1.0}$$

### xii. **Bending Stress-Cycle Factor: $Y_N$**

This stress is designed for $10^7$ cycles; however, we tend to design the gear for $10^9$ cycles. To incorporate this change in our bending stress, we employ the repeatedly applied stress cycle factor:

$$Y_N = 1.6831N^{-0.0323}$$

$$Y_N = 1.6831(10^9)^{-0.0323}$$

$$\mathbf{Y_N = 0.8618}$$

### xiii. **Pitting Resistance Stress Cycle Factor**

Like the bending stress cycle factor, incorporating fatigue strength for $10^9$ cycles, we get the pitting resistance stress cycle factor as:

$$Z_N = 2.466N^{-0.056}$$

$$Z_N = 2.466(10^9)^{-0.056}$$

$$\mathbf{Z_N = 0.7727}$$

**Bending Stress:**

$$\sigma_b = W^t \frac{K_o K_v K_s P_d K_m K_b}{F.J}$$

$$\sigma_b = 983.12 \frac{1 * 1.36 * 1 * 4.62 * 1.1635 * 1.874}{0.70866 * 0.42}$$

$$\boldsymbol{\sigma_b = 45255.7\ psi}$$

Corrected maximum bending stress = $\sigma_b{}'$

$$\sigma_b' = \frac{\sigma_b\ K_T K_R}{Y_N}$$

$$= \frac{45255.7 * 1 * 1}{0.8618}$$

$$\boldsymbol{= 52513\, psi < S_t = 70000\, psi}$$

Since the maximum bending stress is smaller than the gear bending strength (which was determined earlier), the gear will not fail under bending.

**Pitting Contact Stress**

$$\sigma_c = C_P \sqrt{W^t \frac{K_o K_v K_s K_m C_f}{d_P F.I}}$$

$$\sigma_c = 2300 \sqrt{983.12 \frac{1 * 1.36 * 1 * 1.1635 * 1}{2.343 * 0.70866 * 0.36361}}$$

$$\sigma_c = 116756\, psi$$

Corrected maximum pitting resistance contact stress = $\sigma_c{}'$

$$\sigma_c' = \frac{\sigma_c\, K_T K_R}{Z_N}$$

$$\sigma_c' = \frac{116756 * 1 * 1}{0.7727}$$

$$\boldsymbol{\sigma_c' = 151101\, psi < S_c = 225000 psi}$$

We can see that the applied maximum contact stress is less than the contact strength of the material, the gear will not fail by pitting either. Thus, the design of gear is safe to use.

# Chapter 7 Results & Discussion

Up till now we are extremely pleased with the results which are directing us into a forward direction. The first result came in the form when each individual part designed in SolidWorks was coherent and the mates fit perfectly. This displayed that the iterative technique adopted to choose the ultimate size was a success. Secondly, during the assembly phase within SolidWorks, again each part sat perfectly.

The next success came during the motion analysis which was done to check pure rotation of the main shaft induced from a complex motion of the rotor. This required precision in gear meshing, since the assembly needed to be in certain shapes, while the mate was applied. Nonetheless, once the right assembly was done and the main shaft rotated, we saw that the rotor followed the contour of the mid housing, remaining in contact with the surface of the housing at every moment. Moreover, since no interference was seen, the design was kinematically correct.

However, we were rightly advised by our supervisor to practically test the model kinematically to visualize any inaccuracies the software might ignore. Consequently, we made an excessively simplified DXF model of our design, and laser cut it just to see whether the rotor's motion is optimum as needed. Fortunately, the model exhibited that the design was kinematically correct and we can proceed with CNC machining of cast iron.

The calculations on the other hand show that the design is safe to operate with the given loading conditions, and that the specific parts will not fail.

# Chapter 8 Bibliography

[1] Huichao Jiao, Run Zou, Nana Wang, Baoyang Luo, Wenchao Pan, Jinxiang Liu,Optimization design of the ignition system for Wankel rotary engine considering ignition environment, flow, and combustion, Applied Thermal Engineering,

Volume 201, Part A, 2022, 117713, ISSN 1359-4311,

https://doi.org/10.1016/j.applthermaleng.2021.117713.

(https://www.sciencedirect.com/science/article/pii/S1359431121011376)

[2] F. Amrouche, P. Erickson, J. Park, S. Varnhagen, An experimental investigation of hydrogen-enriched gasoline in a Wankel rotary engine, International Journal of Hydrogen Energy,

Volume 39, Issue 16,2014, Pages 8525-8534, ISSN 0360-3199,

https://doi.org/10.1016/j.ijhydene.2014.03.172.

(https://www.sciencedirect.com/science/article/pii/S0360319914008647)

[3] C.H. Lee, K.C. Jiang, P. Jin, P.D. Prewett, Design and fabrication of a micro Wankel engine using MEMS technology, Microelectronic Engineering,Volumes 73–74,2004,

Pages 529-534, ISSN 0167-9317,

https://doi.org/10.1016/j.mee.2004.03.030.

(https://www.sciencedirect.com/science/article/pii/S0167931704002060)

[3] Leonid Tartakovsky, Vladimir Baibikov, Marcel Gutman and Mark Veinblat Technion Israel Inst. of Technology (2012). Simulation of Wankel Engine Performance Using Commercial Software for Piston Engines

[4] Hiriyur Veeranna Chandra (1958) A Survey of Rotary type Internal Combustion Engines with particular emphasis, on the N.S.U.-Wankel Engine.

[5] TAYLAN ERCAN (2005) THERMODYNAMIC AND STRUCTURAL DESIGN AND ANALYSIS OF A NOVEL TURBO ROTARY ENGINE (188)

[6] Osman Akin Kutlar and Fatih Malkaz (2019) Two-Stroke Wankel Type Rotary Engine: A New Approach for Higher Power Density.

[7] https://www.newkidscar.com/starting-system-engine/

[8]https://mechstuff.com/how-does-a-wankel-engine-work/#:~:text=When%20a%20tip%20of%20the,being%20taken%20away%20for%20combustion.

[9] https://www.mecholic.com/2018/09/design-and-working-principle-of-carburetor.html

[10] http://www.iron-foundry.com/castings-ISO8062-rough.html

[11] Amrit Kumar. Flywheel: Definition, Function, Construction, Working Principle, Material, Advantages, Application

[12]https://prog.lmu.edu.ng/colleges_CMS/document/books/MCE544%20-%20LECTURE%202.pdf

[13] Mark Dulger, in Handbook of Air Pollution From Internal Combustion Engines, 1998.Pollution from Rotary Internal Combustion Engines

[14] https://www.autoelectro.co.uk/starter-motors#:~:text=When%20you%20turn%20the%20ignition%20switch%2C%20the%20electromagnet%20inside%20the,(as%20well%20as%20fuel).