CHAPTER 3 THEORY, MATHEMATICAL MODELING AND PROTOTYPE DESIGN OF GOPI ENGINE

Comparing with traditional engine, the GOPI engine is very simple in design as the complex mechanism of fuel burning process of the traditional engine has been eliminated permanently from it. Even though the GOPI engine has its own complexity and mechanism on which it works and, it has numerous components which have their own unique designs and working features. For designing and fabrication of the engine and further modeling and simulation of the engine, the understanding of the basics of the engine and its working principles are of utmost important.

3.1 GOPI Engine Basics

When one magnet is fixed and another magnet of the same polarity is brought near to the fixed magnet then the movable magnet can be brought to a maximum approach distance. After that distance a huge force is required to bring the movable magnet nearer to the fixed magnet. From the maximum approach distance, if the movable magnet is made free to move, then it will move in the opposite direction. The covered distance by the movable magnet depends upon the power of the magnets. Let the fixed magnet be m_1 and movable magnet be m_2. The arrangement is made in such a way that the same pole of the m_1 and m_2 are facing each other. If the m_2 is brought from a long distance (at this place both magnets feel no force of any kind between them) to the m_1, then the value of external force to bring the m_2 near to the m_1 will increase in proportion to the reciprocal of the distance square. This external force will increase the potential energy of the system. After reaching the maximum approach distance, if the m_2 is released then it will move in opposite direction (180^0) with greater kinetic energy, which will reduce as the distance increases. Now if m_2 can bring back to the fixed magnet m_1 and released again, then the kinetic energy and potential energy of the system can be maintained and kinetic energy can be attained at the cost of the potential energy of the system.

In the Gate Operated magnetic Piston Engine (GOPI Engine) one magnet (m_1) is kept fixed and other magnet (m_2) is brought again and again near to the m_1 (after a fixed interval). In GOPI engine the moving magnet m_2 is arranged in such a way that when it is to be moving away from the m_1 the kinetic energy can be used as output of the engine. When m_2 is to be brought near m_1 then also the engine should work in the same direction and net work is gained. So the output of the engine works in same direction and is gained both when the m_2 is moving away from m_1 and when m_2 is to be brought near m_1.

In GOPI engine, only repulsive force of the magnets has been used to produce thrust or power stroke. For this, gate of magnetic shield material is introduced between the fixed magnet and the movable magnet. A fixed magnet (m_1) and other movable magnet in form of magnetic piston (m_2) are arranged in such a way that m_2 is brought again and again near to the m_1 (after a fixed interval). The gate remains in closed position except when the piston is at its TDC.

In ordinary piston engine, piston is powered by fuel and then it rotates the crank which is attached to it. After one complete cycle, the piston will be at its initial position. For continuous motion, the power to the piston should be supplied at fixed interval to produce power stroke in the GOPI engine at fixed interval duration, the movement of the magnetic piston is synchronized with the gate movement. For this very purpose in the GOPI engine the fixed magnet is clamped at the place, which is just above the Top Dead Center (TDC) of the piston and the movable magnet is clamped on the piston head combined known as magnetic piston. Now, when the piston moves up and down in the piston cylinder then the m_2 will also move up and down with the piston head. After a fixed interval m_2 will come very near to the m_1 where it will experience repulsive force from m_1 and will produce power stroke and will start moving down wards. The magnet m_2 should experience the repulsive force only when it approaches the maximum approach distance, a magnetic shield material in form of a gate which covers the gap between the m_1 and m_2 is used. This gate remains in closed position all the time except when the piston is at TDC. This gate will open when the piston just starts moving downward from TDC. The reciprocating movement of the piston is converted in to rotation motion with help of the crank –shaft arrangements. The rotation of the crank can be used as the output of the engine. This motion is continuous by arranging more pistons in rows and columns.

3.2 Terminology of the Engine

Some Important terminology which is to be understood before discussing working principles of the engine is described here…

3.2.1 Gate System

Gates are to be fabricated with magnetic shield materials specially treated with hydrogen annealed. The properties of the material are to be blocked magnetic field between two magnets if placed between these two magnets.

Gates are used in between the air gap of maximum approach distance of the magnet system. If gate system is not there then the approaching speed of the movable magnet towards fixed magnet will reduce and this will affect the overall efficiency of the engine. Gates are operated in such a manner that these will open only when the movable magnet approaches its maximum approach distance.

3.2.2 Gate Cycle

When movable magnet approaches to the fixed magnet then corresponding gate of the engine unit opens and closes according to the position of the magnetic piston. The opening and closing of the gate is synchronized with the piston position. The opening and closing of the gate in one complete rotation of the attached crank will be known as gate cycle. In single piston configuration, the frequency of opening and closing of the gate is one in one gate cycle while in multi piston configuration, frequency in one gate cycle depends upon piston matrix.

3.2.3 Power Stroke

When the movable magnet approaches the fixed magnet, the gate opens and the repulsive force between the movable magnet and the fixed magnet acts. Because of this strong repulsive force, so-called the power stroke, the movable magnet will start moving downwards and output is gained. The power stroke happens only when the movable magnet approaches its maximum approaches distance and faces the repulsive force stroke. Here two types of powers are used as input to operate the GOPI engine. The one within the magnets as magnetic power to produce the power stroke and the second one is external power to operate the gate mechanism

3.2.4 Magnetic Piston

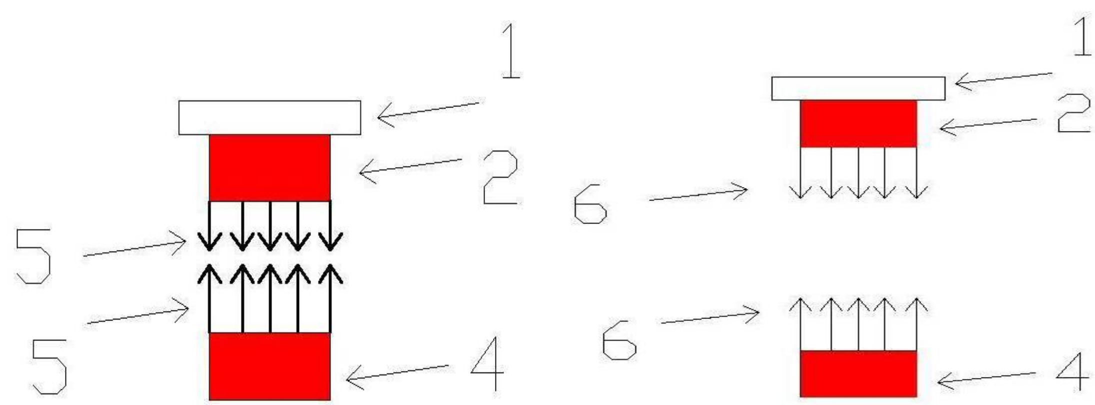
When a magnet is clamped on the head of a piston, then this arrangement is known as Magnetic Piston. Here, movable magnet is housed in a semi hollow non-magnetic, non-metallic cylinder so that the cylinder will serve both purpose of magnetic piston and linkage between the piston and connecting rod. Engine embodiment is the skeleton of the engine which contains all parts/components of the engine. It is also to be known as engine unit which can produce power.

3.3 Working Principles of the GOPI Engine

When magnets are placed at a distance where they do not feel any force will remain in stationary condition. The magnetic force lines coming out from the magnet shows the direction of the magnetic force produced by the magnet. The gap between the two magnets indicates that there is no repulsive force between these magnets because of large distance between them. When these magnets are brought near to each other, there will be strong magnetic force between them. Magnets can be brought near to each by moving both magnets towards a common point or by keeping one magnet in fixed position and moving second magnet towards the first one.

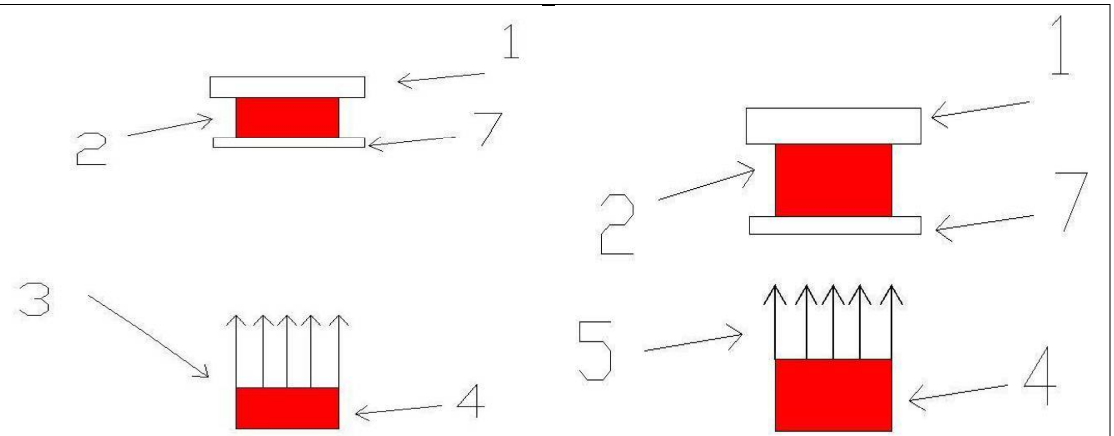
In GOPI engine, one magnet is kept in fixed position and the other magnet is brought near the first magnet after a fixed interval. When the distance between two magnets is large, the magnetic field between these magnets will be very weak as the magnetic field between the two magnets varies according to the reciprocal of the distance square. As the movable magnet is brought near the fixed magnet, repulsive force between the magnets increases as shown in the figure3.1 (a). This force of repulsion between these two magnets depends on the distance between them. As the distance decreases, the repulsive force between them increases, the work done on the magnets to bring them closer is stored in the system as magnetic potential energy of the system. The thicker lines of force of the magnets represent strong repulsive force between the magnets. After approaching to the maximum approach distance, the movable magnet will return back to its path by 180^0 with greater velocity if it is made free to move, because of the repulsive force between the magnets. When the magnet starts moving apart from the fixed magnet, the magnetic repulsive force between them will decrease as the distance between them increases, the intermediate value of the magnetic force in between maximum repulsive force (minimum distance between the magnets) and minimum repulsive force (maximum distance between the magnets) is represented by thinner lines between the magnets as shown in the figure 3.1 (b).

External force is required to bring the magnets near to each other, this external force should be more than the repulsive force between the magnets, and otherwise the magnets cannot approach to their maximum approach distance. This external force applied on the system converts into the potential energy of the system. This energy can be regained by releasing the non-fixed magnet to move. Hence this process does not produce excess energy than the applied energy since the net energy generated is always zero. Therefore generating energy by the application of direct external force on the magnet (s) is not useful. To get net output from the system, it is important that the energy releasing from the system should be more than the energy applied to the system or the system potential energy and kinetic energy should work in the same direction so they can be added to get useful output. To run the GOPI engine and to get output, it is tried to keep the system potential energy lesser than the system kinetic energy.



a: Strong magnetic force **b: weak magnetic force**

Figure 3.1: Magnetic Field Between Magnets

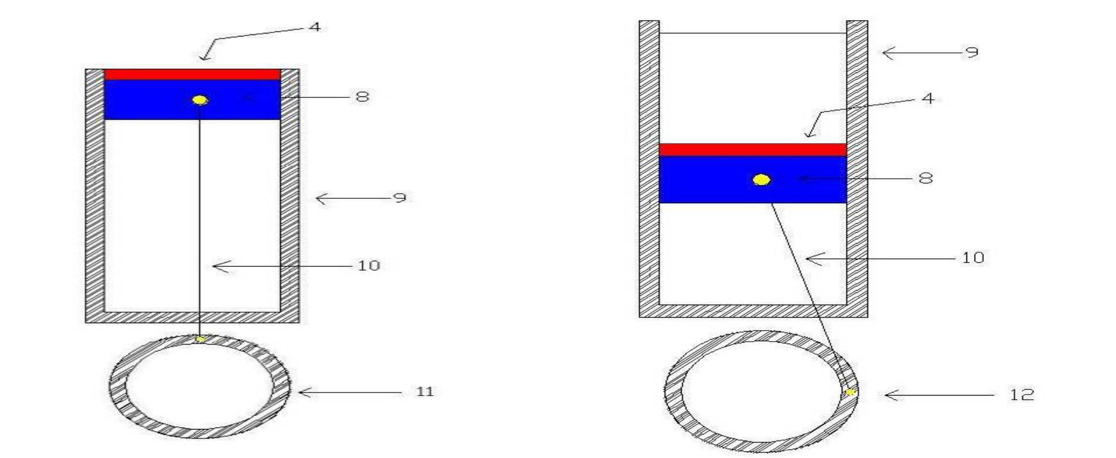


a: Shield effect when magnets are apart **b: Shield effect when magnets are closer**

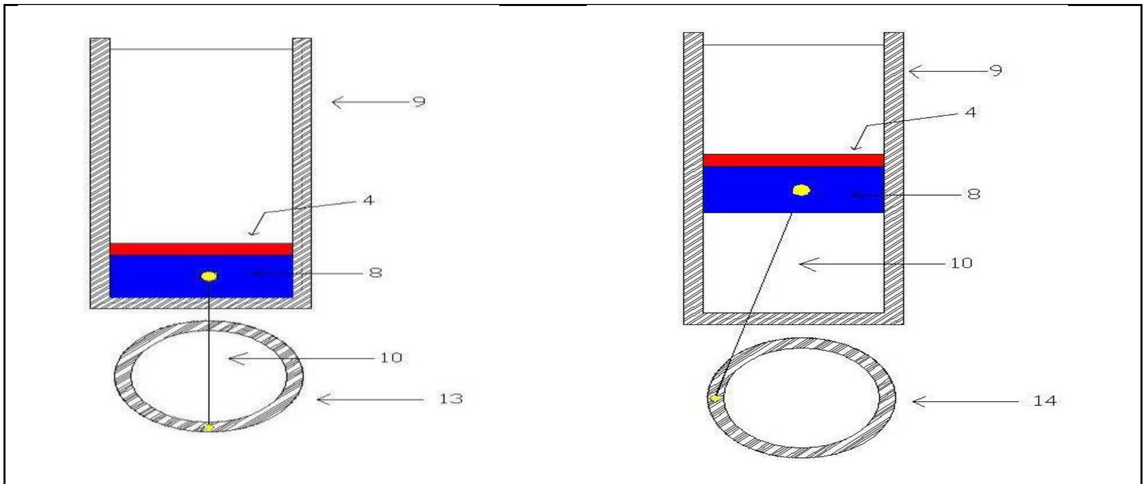
Figure 3.2: Magnets and Shield Material

It is well understood that when any magnet is covered with magnetic insulation material properly (magnetic shield material or mu metal), then there will be no force exerted between these magnets as the property of the magnetic insulation material is to block magnetic force lines coming out from the target magnet, and because of this, there will be no magnetic force beyond the insulating material. For the designing of the GOPI engine, the fixed magnet is insulated. The magnetic flux lines of the magnet will be negligible beyond the insulating material as the insulating material insulated the magnetic field efficiently as shown in the figure 3.2(a). In this condition, if the movable magnet is brought near the fixed magnet then it will feel no repulsive force at all as shown in the figure 3.2(b) At the time when the magnets are at maximum approach distance, if the magnetic insulation cover is removed from the fixed magnet then the strong repulsive force will act between the magnets and the movable magnet will start moving down wards immediately with greater velocity.

To design the GOPI engine, this phenomenon of repulsive force acting between the magnets is used. The movable magnet is brought again and again near the fixed magnet and when the distance between them is minimum the repulsive force starts acting between them and by this the movable magnet is forced to move downward. To perform continues movement of movable magnet or to bring back to maximum approach distance again and again, the movable magnet is clamped over traditional piston-crank configuration as piston head as shown in the figure 3.3.



a: crank rotation angle 0^0 **b: crank rotation angle 90^0**



c: crank rotation angle 180^0 **d: crank rotation angle 270^0**

Figure 3.3: Magnetic Piston and Crank angle

As the piston moves up and down in the cylinder, the magnet also completes to and fro cycle with the piston. Various locations of the piston and magnet in terms of crank angle are shown in the fig 3.3(a), fig 3.3(b) and fig 3.3(c) and fig 3.3(d). The magnetic shielding material in form of gate is inserted between these two magnets to minimize the repulsive force between them when the movable magnet approaches TDC. The magnetic shielding material in form of gate is inserted between these two magnets to minimize the repulsive force between them when the movable magnet approaches TDC.

When the magnetic piston reaches TDC, the gate will be opened by some mechanical or by other means and a repulsive thrust will act between these magnets. Because of this repulsive force, the magnetic piston will start moving downwards as shown in the figure 3.4. After this action happens, the gate will close and will remain in closed position till the magnetic piston comes back to TDC after one complete cycle. For smooth working of the engine, four magnetic pistons maybe used in four different magnetic cylinders and fixed magnets are placed on each of the top of the cylinder. The pistons are arranged in such a way that the related cranks will form an angle of 0^0, 90^0, 180^0, 270^0 and 360^0. This means when power stroke happens in first piston (engine unit) then the second magnetic piston will be at middel of the cylinder in the down ward direction motion.

This respective crank will form 90^0 angle. At this time the third magnetic piston will be at bottom dead center (BDC) and the related crank will form 180^0 angle but after a moment the piston will change its direction and will start moving in the upward direction. The fourth magnetic piston will be at middel of the cylinder in the upward direction motion and the crank will form 270^0 angle as shown in the fig 3.4 (a), fig 3.4(b), fig 3.4 (c) and fig 3.4(d) respectively. When the magnetic piston reaches to TDC after completion of one rotation , the gate cycle completes. Moving magnet m_2 is clamped on each of the piston head and one fixed magnet m_1 is clamped in each cylinder just above the TDC. The positions of pistons in their cylinder are arranged in such a way that the cranks are positioned at 0^0,90^0, 180^0, 270^0, 360^0 /0^0 respectively.

IN multi piston configuration, the magnets which are clamped on the piston1 (P_1), piston 2(P_2), piston3 (P_3) and piston 4 (P_4) are m_{21}, m_{22}, m_{23}, m_{24} respectively. The magnets clamped in the cylinder 1, 2, 3, 4 are m_{11}, m_{12}, m_{13}, m_{14} respectively as shown in the figure 3.5. In the fig 3.5 (a), figure 3.5 (b), figure 3.5 (c) and 3.5 (d), power stroke occurs on associated piston at every 90^0 rotation of the crank angle. The repulsive force between the fixed magnets and the moving magnets should be operative only then when the corresponding piston is at its TDC. For smooth running of the engine, the opening of the gate and the TDC of the corresponding piston should be synchronized. To operate opening and closing of the gates, a micro-processor based control system is used. These pistons and cranks can be used in matrix of any number of column and rows. For development of the GOPI engine, one engine unit is clamped to a common shaft

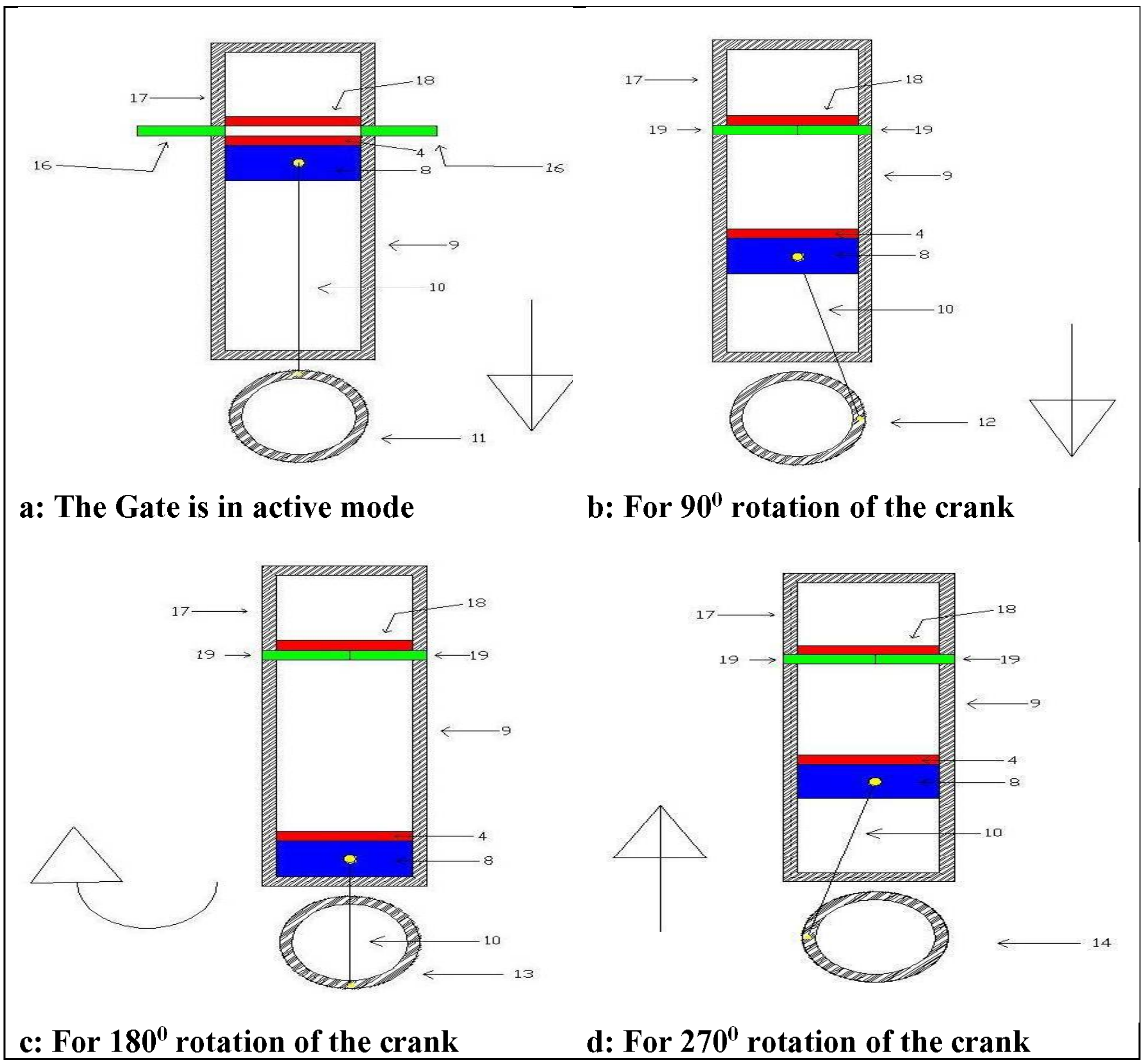
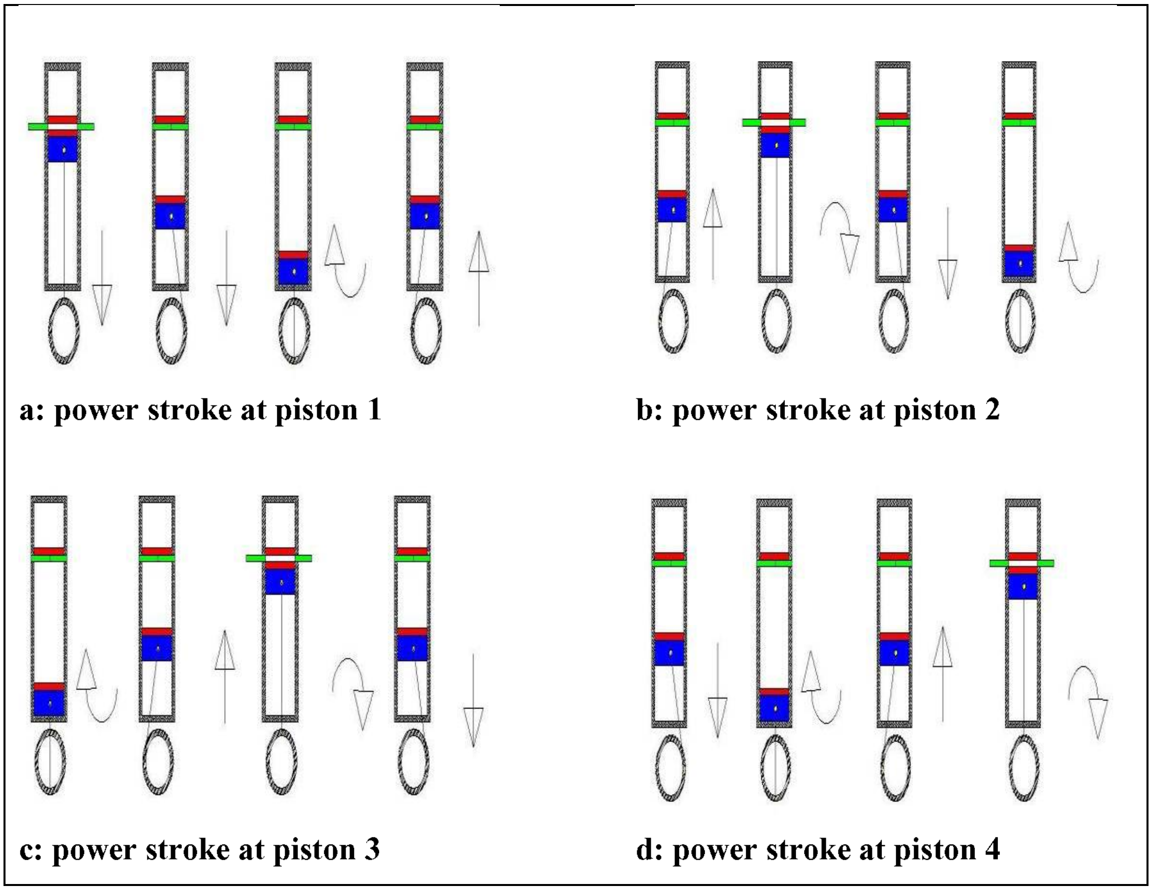


Figure 3.4: Magnetic Piston and the Gate cycle



a: power stroke at piston 1 **b: power stroke at piston 2**

c: power stroke at piston 3 **d: power stroke at piston 4**

Figure 3.5: Multi Piston Engine Unit

For uniform motion and out put, the cranks are coupled with a common shaft. The mechanical output is gained at this shaft. The figure 3.6 represents schematic diagram represents the control system, gate operating system and signal system Tr and Rr to detect the location of the piston. When the piston crosses the sensors to its upward motion, a signal will be sent to the gate control mechanism which will activate the gate operating mechanism and will open the gate to produce the power stroke. After the stroke, the piston will tend to move downward towards the BDC. The control system will generate a signal again as the piston crosses the semsors during the downward motion and the gate will be closed. In multipiston configuration, individaul control system will operate the gate operating mechanism and. In four piston system, power stroke will happen at every 90^0 of crank rotation.

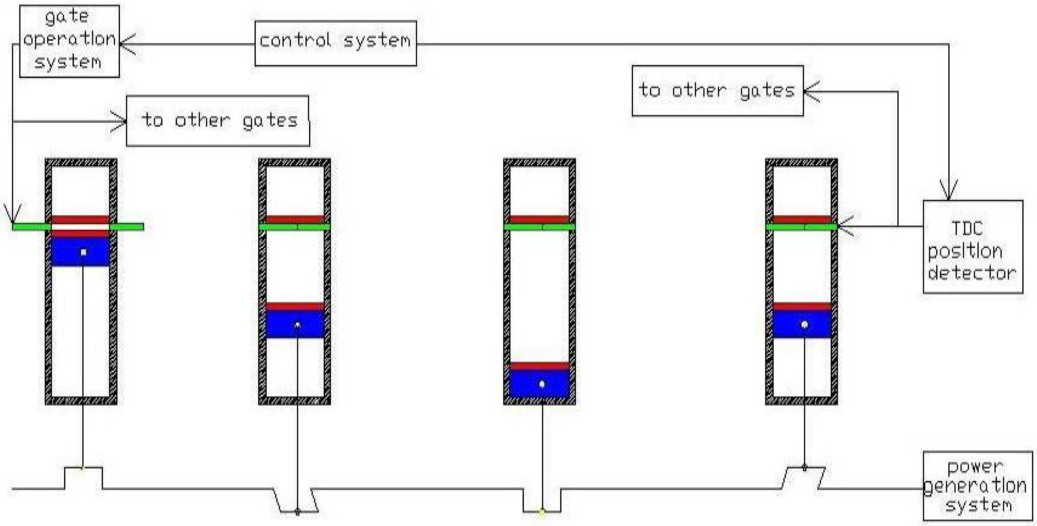


Figure 3.6: GOPI engine with Control Units

The numeric numbers mentioned in the figure 3.1 to figure 3.5 are described here

1	Fixed support
2	fixed magnet (m_1)
3	magnetic field lines
4	movable magnet (m_2)
5	strong magnetic field lines between the magnets
6	weak magnetic field lines between the magnets
7	magnetic shield material
8	magnet on piston head
9	piston cylinder
10	connecting rod
11	crank
12,13,14	crank at different positions
16	gate in opened position (power stroke happens)
17	mounting structure for fixed magnet in engine unit
18	magnet and gate configuration
19	gate in closed position

3.4 Mathematical Modeling

The amount of research, specifically addressing the modeling of magnetic engine where magnetic piston is a part, is small even though a numerous number of patents have been granted and filed worldwide. The GOPI engine working process is similar only in crank rotation and piston movement with conventional engines. The engine does have some specific operating characteristics compared to the conventional engine, which need to be treated with some caution.

In this section, the modeling of GOPI engine is presented, and the feasibility of the implemented model is discussed. The engine can be subdivided into numerous important parts. Designing and modeling of each part is unique in nature. Modeling of various parts of the GOPI engine is done which are described in the following sections

i. Piston dynamics and control
ii. Gate mechanism
iii. Engine frequency control
iv. Operating condition of the engine
v. Operating power requirement

3.4.1 Piston Dynamics and Control

In conventional engine, the power stroke happens because fuel burns in combustion chamber and the chemical energy of the fuel produces high thrust on the piston head which rotates the attached crank and flywheel. In GOPI engine, the power stroke produces thrust with help of repulsive force between the fixed magnet and the magnetic piston. Magnetic force remains there for all the time but the intensity of the field is changed with help of the gate.
The piston motion can be derived from Newton's second law, avoiding complex mechanism of the crank rotation, given by the following equation.

$$\sum F = Mp\frac{d^2x}{dt^2} \qquad \textbf{(3.1)}$$

Where $\sum F$ is the net force acting on the piston head and it can be given as
$\sum F = Fm - Fa - Fr - Fn$ **(3.2)**
Here,

Fm	Magnetic force between the m_1 & m_2
Fa	Attach force between the gate and m_1& gate and m_2
Fr	Frictional force between the engine components
Fn	Reduced magnetic strength of the magnet in due course of time and
Mp	Moving mass (piston crank assembly)
x	position of the piston in the time frame with respect to the fixed magnet

There may be some more factors on which the net force on piston head depends. Theoretically the above equation for the net force satisfies the working of the engine. Now, a detailed discussion of the individual component of the equation 3.1 is described here

i. Fm is the magnetic force between two identical cylindrical bar magnets placed end to end is approximately given by the equation 3.3.
ii. Fa is the amount of force required to pull away the gate from m_1 or m_2 as the gate will virtually attach with the magnets. This happens because magnetic field of any strength attracts each and every material in their magnetic field range to some extent. Detailed modeling is covered in the coming sections

iii. Fr is the frictional force between the engine track and the magnetic piston and between other components of the engine. Obviously the magnetic piston moves on the track in a non-packed situation, even though there will be frictional force between each and every contact.

iv. Fn is the value of magnetic strength which reduces in due course of time. Generally it is found that a magnet in stationery condition does not lose it magnetic strength in time frame but there is no experimental relation available between the magnetic strength reductions with its continuous movement in time frame.

$$F = \left[\frac{B_0^2 A^2 (L^2 + R^2)}{\pi \mu_0 L^2}\right] \left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \quad \textbf{(3.3)}$$

Where,

B_0 Magnetic flux density very close to each pole

A Area of each magnetic pole

L Length of each magnet

R Radius of each magnet

v. Mp is active mass of the piston. As the magnetm2 is housed in the piston cylinder by removing the material of the cylinder equal to the volume of the magnet.

Let Vc is the volume of the cylinder when there is no magnet is housed inside it. Then the weight of the cylinder will be

Mc=(ρc)Vc **(i)**

Where ρc is the density of the cylinder material. When magnets are inserted inside the cylinder then the cylinder material is to be removed equal to the magnet volume. Now, total mass of the piston cylinder (Mct) after inserting n number of magnets

Mct = (ρc)Vc- ρc(n.π.r.r.t) +n.Mm **(ii)**

Thickness of the piston head (L) can be given by total number of magnets used as piston head multiplied thickness of single magnet.

L = n.t (iii)

Total magnetic flux is the cumulative sum of individual magnet's magnetic field

B = n.B_0 **(iv)**

(ii)

Total moving mass (Mp) is the sum of actual mass of the cylinder when no magnet is housed into it and mass of the magnets which are housed into the cylinder minus mass removal from the cylinder to house magnets. The total moving mass also includes mass of crank assembly.

$$Mp = Mph + Mc + Mcr + Mcn \quad \textbf{(v)}$$

Here,

Pc density of cylinder material
Vc volume of the cylinder
N number of magnets housed into the cylinder
t thickness of the magnet
Mm mass of the magnet
Mph mass of the piston head
Mp moving mass
Mc mass of the cylinder
Mcr mass of the connecting rod
Mcn mass of the crank
Ms mass of single magnet and
n number of magnets

3.4.2 The Gate Mechanism

The total force required to operate the gate is the sum of force required to operate the mechanical inertia of the gate and force required to operate the magnetic inertia of the gate. The magnetic inertia of the gate is proportional to its virtual attachment of the gate with the magnets. The total force required to operate the gate is given by the equation. Total force required to operate the gate= Force required to pull the gate from its virtual attachment with m_1 and m_2 + Force required to pull the gate from its rest position. Mathematically,

$$Fgt = Fag + Fmg \quad \textbf{(3.4)}$$

Where,

Fgt Total force required to operate the gate
Fag Force required to counter balance the magnetic inertia of gate
Fmg Force required to counter balance the mechanical inertia of gate

Because of the Fa, the magnetic field blocked by the gate between the magnets, the Fag, the magnetic inertia force is required because the gate will virtually attach to the magnets m_1 and m_2. This happen because when the gate is placed in between or near the magnets, the magnetic field lines coming out from the magnets may retain on it, may diverted from it or may passes through it completely or may be partially blocked, retained and diverted from the gate. In any of the situations stated above, some external force is required to pull the gate away from the neutral mode, known as Fag, and theFa is the attached force between the m_1 and gate & m_2 and the gate. In other words, the Fa is the blocked magnetic field by the gate and Fag is the amount of force required to pull away the gate from its neutral mode (the gate is in closed position) to produce power stroke when the m_2 (magnetic piston) approaches the TDC.

The Fa,F'a and Fag entirely depend upon the shielding nature of the gate material. The shielding of a magnetic material can be described in the terms of permeability of the material. The Fa depends upon many parameters like type of shield material used for gate fabrication, thickness of shield material, geometry of gate and virtual attachment of gate with m_1& m_2. The effectiveness of the gate mainly depends upon the permeability of the material and the annealed process. More the permeability of the gate material, more will be the shielding nature of the gate. A high permeable material as NiFe (mu metal) will be chosen for the gate fabrication.

The Fm depends upon the magnetic properties of the permanent magnet used for the engine development. Before selecting magnets, it is very essential to understand the basic properties and type of the magnets. Several basic magnetic properties like Magnetic field intensity, magnetization and demagnetization are of critical importance for the permanent magnets in a permanent magnet engine. Various forces acting on the gate are described in the figure 3.7. When there is no gate between the magnets, only magnetic force, Fm (or F) will be there. But as the gate is inserted between the magnets, the magnetic force or the magnetic field line start acting as described in the equation 3.6.

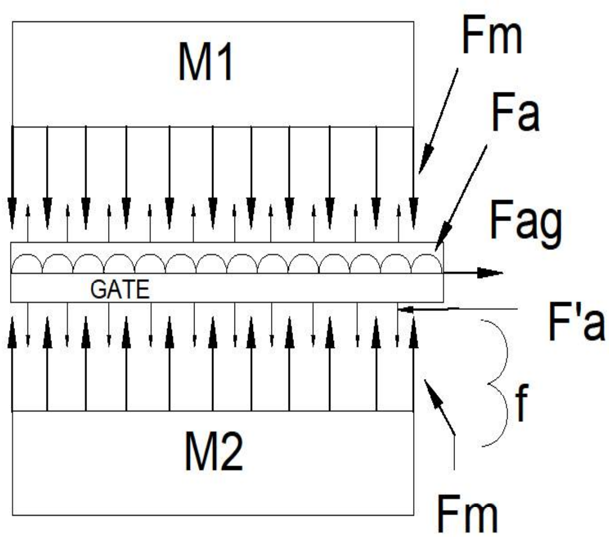


Figure 3.7: The Gate and the Magnetic Forces

The operating mechanism of the gate may be understood by taking an example of a light beam passing through a material sheet where a part of light transmitted through the sheet, a part is reflected and a part of the light is absorbed by the sheet as shown in the figure3.8.

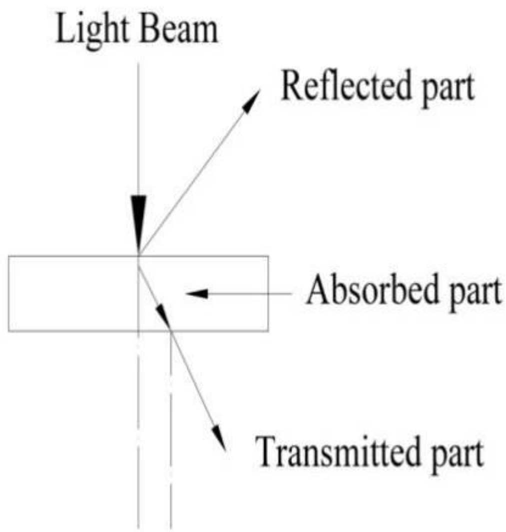


Figure 3.8: Light beam passes through a material sheet

The values of light which pass through the sheet, or reflected, or absorbed by the sheet can be presented in their coefficient values as coefficient of absorption(a), coefficient of reflection(r) and coefficient of transmission(t). Mathematically,

Absorption coefficient (a)+reflection coefficient (r)+transmission coefficient (t)=1 **(3.5)**

To understand the working mechanism of the gate, the magnetic field very close to the gate can be treated in same manner as that of light beam near the material sheet and the gate itself as material sheet. The magnetic field lines may be blocked or retained (absorbed) by the gate, or may pass (transmitted) through the gate or may get diverted (reflected) by the gate depending upon the magnetic properties of the material as shown in the figure 3.9. The total value of the magnetic field near the gate can be given by the equation 3.6.

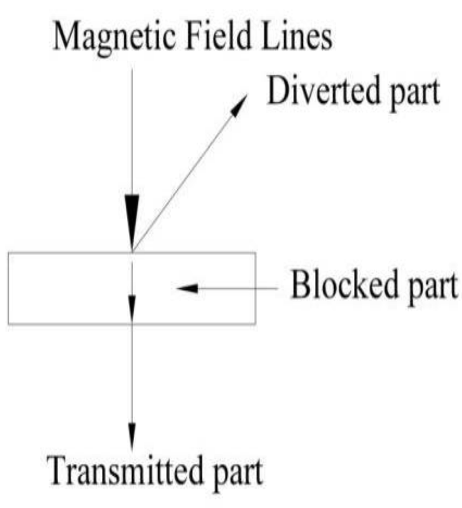


Figure 3.9: Magnetic field lines passing through a shield material

$b+d+p=1$ **(3.6)**

Here,

b coefficient of blocked (retaining) magnetic field by gate
d coefficient of diverted magnetic field from the gate
p coefficient of passing (transmitting) of magnetic field through the gate

3.4.3 Frequency Control

Frequency of the engine directly depends upon the gate opening and closing speed or gate cycle of the engine. The power stroke of the engine is directly related to the gate cycle. The power stroke produces when the piston is at TDC, the minimum distance between the fixed magnet (m_1) & the piston head (m_2). At this moment, the gate will open and the repulsive force will act between the fixed magnet and the magnetic piston. This force will push the magnetic piston down ward. When the piston moves by certain distance in its downward direction, the gate will close. The closing and opening are controlled by advanced microprocessor based control units.

3.4.4 Operating Conditions

The engine works when the gate cycle is synchronized with the piston movement. Synchronization can be achieved only if gate shields the magnetic field properly. The design of the gate is very important in this regard. If the design of the gate is not done properly, then the engine may not work. To produce power stroke, it is most important that the gate should be in active mode and the gate cycle should be synchronized with the piston movement. The condition for working of the engine maybe given by following relation.

$$F = a.Fm \qquad \textbf{(3.7)}$$

Or

$$F = a.F$$

Fm or **F** is the magnetic force between the fixed magnet (m_1) and the magnetic piston (m_2) (when there is no gate between the m_1& m_2 or magnetic field lines are passing through the gate completely), **F'** is the magnetic force between the fixed magnet (m_1) and the magnetic piston (m_2) (when there is gate between the m_1& m_2 or the magnetic field lines are blocked or diverted completely) and **a** is the gate factor. The value of gate factor ranges between 0 and 1. i.e. $0 \le a \le 1$. Here, gate factor is a variable that indicates how efficiently the gate is performing i.e. how much magnetic field is diverted or blocked or passing through the gate. The gate factor itself depends upon many parameters like type of gate material, thickness of material, distance of gate from the m_1 and m_2, magnetic pole strength of the m_1 and m_2.When the magnetic field is blocked or diverted completely by the gate then the value of the gate factor is one and when there is no gate in between the magnets or the magnetic field lines is passing through the gate completely, then the value of gate factor will be zero. In other situations its value remains between 0 and 1.

When the engine is performing efficiently, the value of gate factor will be equal to one. This time the magnetic field is either diverted or blocked completely by the gate. The value of p coefficient in equation 3.6 will become zero and the values of b and d coefficients combined together will be one. Mathematically, When $a=1$ **(vi)**

$p=0$ and $b+d=1$;

Here, $0 \leq b \leq 1$ and $0 \leq d \leq 1$

Further if $b=1$, the gate is blocking the magnetic field lines completely. The engine will work but the efficiency will be less as the value of Fa will be more in this situation and hence more input power is required to operate the gate.

If $d=1$, the gate is diverting magnetic field lines completely. The engine will work with highest efficiency as the Fa will be equal to zero and the power required to operate the gate is minimum. When the gate is performing with least efficiency or not working at all, the value of gate factor will be equal to or near to zero. This time most of the magnetic field lines pass through the gate. The value of d coefficient will be equal to zero and value of b and p coefficients combined will be equal to one. Mathematically,

When $a=0$ **(vii)**

$d=0$ and $b+p=1$;

Here, $0 \leq b < 1$ and $0 < p \leq 1$

It is to be noted that when $a=0$; the not working condition of the engine, the value of b will be very close to zero and p will be near to one, further if the value of b approaches to one, the gate will start blocking maximum of the magnetic field lines but even the magnetic piston may stuck to somewhere in its upward motion as some magnetic field lines may passes through the gate all the time and the nonzero value of counter force f ($f \neq 0$) as shown in the figure 3.7 will produce hindrance in the piston movement in upward direction. The gate cycle cannot be matched with the piston movement and the engine will stop working after few cycles. And if $p=1$, the magnetic field lines passes through the gate completely and the engine will not work at all in this situation.

When the magnetic piston moves in upward direction and approaches to TDC, there maybe some repulsive force between the m_1 and m_2 if the gate is not blocking the field completely. Let this repulsive force be known as counter force and represented by f, then the counter force can be given by

$f = F - F'$ **(3.8)**

$f = F - a*F$ **(3.9)**

Now, the operating mechanism of the engine can be described under two conditions which are discussed here.

(I) When there is no gate in between the magnets m_1 and m_2 (or magnetic field lines passes through the gate completely), then

$f = F - F' = F$ as $a = 0$; or ($p=1$; $b=d=0$)

$f = F$ **(viii)**

This means, the counter force between the magnets m_1 and m_2 will be maximum and equal to F. In this condition, the magnetic piston will get stuck to somewhere in its way and the attached crank will not complete its cycle. So for complete rotation of the crank the counter force f should be less than the torque produced by the magnetic force of the engine at every point of the motion otherwise the engine will not work at all.

(II) when gate block the field completely or divert the same completely i.e. a=1, then

f=F-F'=F-F as a=1; (p=0; b+d=1)

f=0 **(ix)**

This means, there will be no repulsive force or counter force between m_1& m_2 when the magnetic piston is moving upward towards TDC. The piston will move upwards without any restriction and in this condition the speed of the piston will not be affected.

The efficiency of the engine depends upon the value of b and d coefficients. The efficiency of the engine may be very less if b=1 i.e. the gate attaches with the magnets fully and the Fa will be maximum and when d=1, engine will work with highest efficiency as all magnetic field lines are diverted from the gate and the value of Fa will be minimum, the power required to operate the gate will be less as minimum attachment is there between the gate and magnets.

3.4.5 Power Required for Operating the Engine

Power required for operating the gate mainly because of two reasons: the gate attached with the magnets and it needed momentum for continuous motion. The power can be supplied by some storage means like battery. The power required to operate the gate can be given by the following equation,

Pg is the sum of the power required to pull the gate from its virtual attachment with m_1& m_2 (Pag) and power required to pull the gate from its rest i.e. Neutral state (Pmg). Mathematically,

$$Pg = Pag+Pmg \qquad \textbf{(3.10)}$$

Pag is proportional to Fag and depends upon a, b, d and p; the gate factor and the gate coefficients.

3.5 Development of the Prototype Engine and its Components

Development of the engine is mainly divided into two major classes: one is development of the engine components and the other is mathematical modeling of the engine. The various components of the engine which are to be developed and designed for modeling are described in this section.

3.5.1 Magnet Configuration

This part of the engine includes permanent magnet (m_1), fixed cylinder. The fixed magnet is in fixed position above the gate in the cylinder. This magnet is housed in a non-metallic, non-magnetic cylinder.

The permanent magnet kept in the fixed position to produce power stroke with the magnetic piston. The magnet and the cylinder are clamped together with wooden block so that it cannot perform any movement with respect to its position when it faces repulsive force from the magnetic piston. Rare earth magnet NdFeB magnet is used which is strong enough to bear the stresses and can produce desired magnetic flux. The magnetic field intensity of the chosen magnet for engine development is 1.2 T. The magnet is in the form of solid cylinder having diameter of 60 mm and thickness 10 mm.

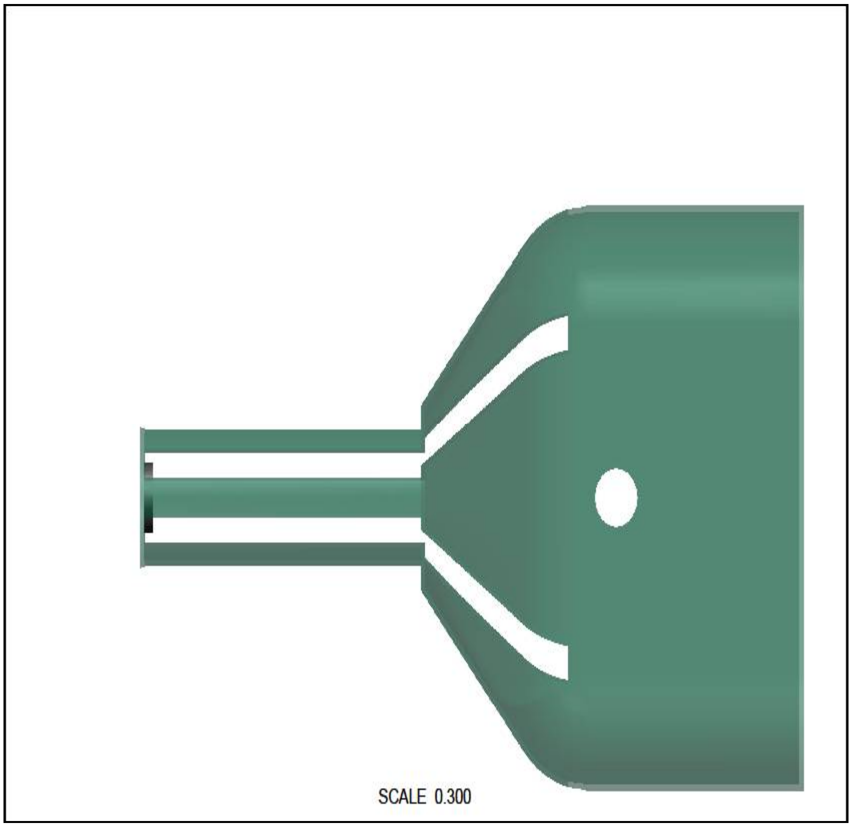


Figure 3.10: Piston Cylinder

The fixed cylinder is simply a non-metallic, non-magnetic cylinder in which the permanent magnet m_1 is housed. The internal diameter of the cylinder is 60 mm equal to the diameter of the magnet to be housed in the cylinder. The outer diameter and the length of the cylinder depends upon many factors such as, stress developed due to repulsive force between the magnets, thermal expansion. After finalizing the design parameters of the permanent magnet and the cylinder, no further change in the designed value of the pole strength of the permanent magnet is possible. The cylinder and the fixed magnet, as a single part, are shown in the figure 3.10.Fixed cylinder is designed as a part of the embodiment of the engine. At the top of the cylinder, the fixed magnet is mounted in such a way that the north pole of the magnet is projected inside. The grooves are provided here to minimize the frictional losses as net contact between the piston and the cylinder is reduced.

The grooves in the cylinder of the GOPI engine is achieving many benefits like

i. Mass is reduced so more rpm can be achieved at the same power input
ii. Contact surface is reduced so the friction is reduced
iii. Temperature stress is reduced as air can flow through the grooves
iv. Manufacturing and maintenance cost is reduced

The fixed magnet is shown in the top of the cylinder. The engine skeleton is also used for the crank and shaft stand.

Table 3.1: GOPI engine cylinder detailing

Sr. No	**Particular**	**Dimension**	
1	Bore(mm)	60	
2	Total Length(mm)	315	Including fixed cylinder
3	Cylinder Head Thickness(mm)	75	Including magnet cover

3.5.2 Gate Mechanism

This part of the engine includes the gate material, the gate geometry and the gate operating mechanism. The gate is used for changing the intensity of the magnetic flux to reduce the approach distance of the magnets, the gate opening and closing mechanism which further includes some advanced micro-processor based control units with some mechanical arrangement. The purpose of the gate is to block magnetic field between the fixed magnet and the magnetic piston when the magnetic piston is moving towards the TDC.

Design of the gate is very crucial and important among all parts of the engine. The efficiency and working condition of the engine entirely depends upon the gate and its operating mechanism. The material which is to be selected for gate development should be highly permeable, light in weight, cost effective and should be capable of bearing all stresses and other forces acting on it while performing in moving conditions. The material selected for the gate is having 30,000 permeability and annealed with hydrogen process. The thermal expansion of the selected material is provided by the manufacturer and it is provided in the table 3.2.

The intensity of magnetic field in a magnet (circular) is maximum at its center and decreases as moving towards circumference from the center of the magnet. The power in the stroke depends upon many factors but it mainly depends upon the geometry of the gate. The geometry of the gate is important as when it is used in single paneled form, then only 2/3 of the gate would be introduced inside the gap to block the repulsive force between the magnetic piston and fixed magnet of the engines when the piston is at 1/3 distance from TDC, moving towards TDC.
The 1/3 part of the piston and magnet will face repulsive force which is not blocked by the gate and the rest 2/3 parts of the piston and magnet will face no force or the attraction force. The attraction and repulsive force acting at a place at the same time will reduce the total output force of the engine. For proper torque, the repulsive force between the magnets (fixed and movable) should apply on a concentrated area and for a very short period of time. To produce strong power stroke, the rate of repulsion between the m_1 and m_2 should be very high.

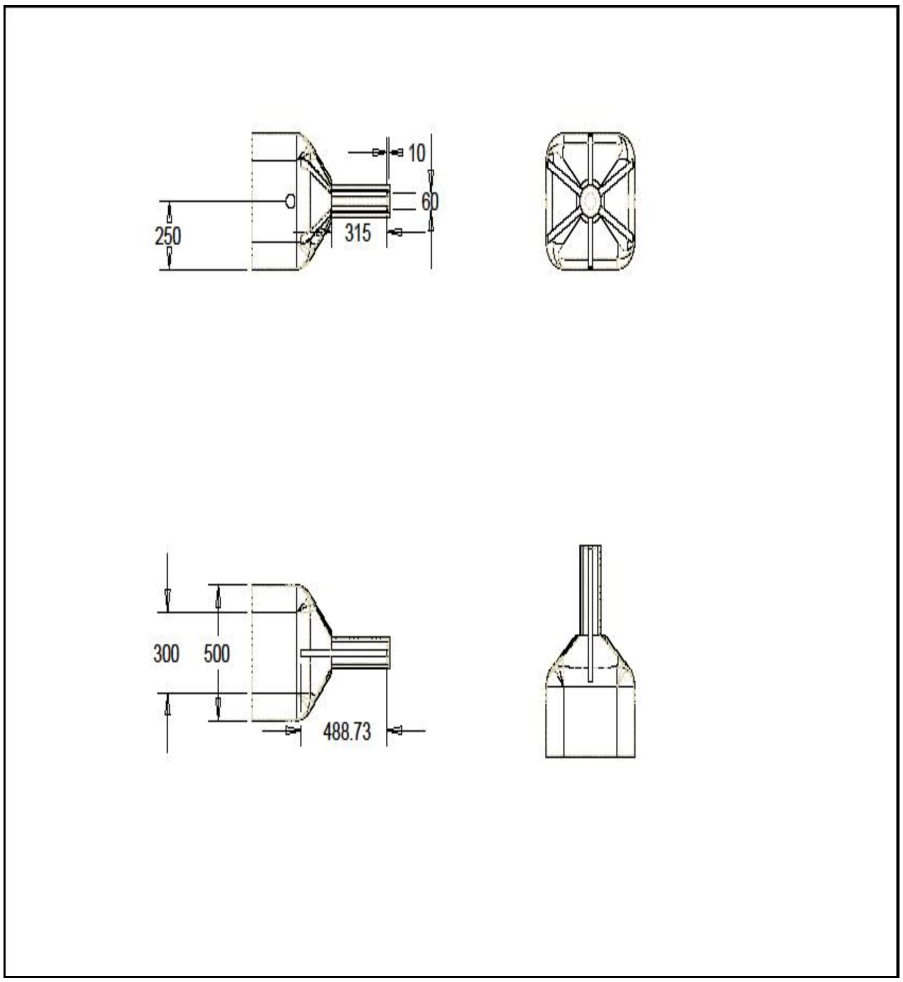


Figure 3.11: Piston Cylinder detailing

As the magnetic flux inside a cylindrical magnet concentrated at its center, so it is very important that the centers of the magnets (m_1& m_2) should be faced at the very moment as the gate pulled away from its neutral position for maximum power in the stroke. For this reason, the multi paneled gate is used. For the multi paneled gate, area of each panel is equal to the total surface area of the gate divided by the number of panels. Effect of 2 paneled gate and 4 paneled gate is studied for the GOPI engine

Table 3.2: Coefficient of thermal expansion

Temperature (°C)	Coefficient (10^{-6}/°C)
-75to25	10.80
-50to25	10.70
-25to25	10.40
25to50	12.30
25to100	12.40
25to200	12.76
25to300	13.00
25to400	13.30

It is found that intensity of power stroke depends upon the opening and closing speed of the gate from its neutral position. Higher the operating speed more will be intensity of the power stroke. The opening and closing of the gate is controlled by microprocessor with infrared receiver (Rr) and transmitter (Tr) signal system. In it aRr and Tr is placed in fixed position below the TDC inside the piston cylinder. When the piston crosses the Rr and Tr in its upward direction, a signal will generate and will be sent to the gate opening control device. At this moment the gate will open and a repulsive thrust will be produced between the m_1 and m_2. With this force the piston will start moving downwards. In its downward motion, when the piston crosses the Rr and Tr position again, a signal will generate and this time the gate will be closed. Individual Rr and Tr system is used for all gates in multi piston engine. For proper working of the engine, the opening and closing of the gates must be synchronized with the piston position.

3.5.3 Magnetic Piston Configuration

In traditional engines, fuel burns over the piston head and because of this huge pressure and temperature generated over there, the piston moves in the piston cylinder which further rotates the attached crank. In GOPI engine, no such mechanism takes place but the purpose of the piston configuration is to transfer the reciprocating motion of the piston to the attached crank in form of rotational motion. To perform the power stroke

with the fixed magnet, the movable magnet is housed in a non- metallic, non-magnetic cylinder, which performs reciprocating motion on the engine track.
The magnetic pistons are used to move on this track. It is made up of non-metallic, non-magnetic material. In traditional engine the pistons are used to move in the piston cylinder in a filled situation, but in GOPI engine the pistons are moved on the track in non-packed situation. It gives us a lot of benefits to overcome the frictional losses and lubricating mechanism. Here the cylinder itself provides the function of the engine track. The main objective of the engine track is to provide smooth movement of the magnetic piston and to minimize frictional losses.
Magnetic piston of GOPI engine has two important parts viz. piston head and connecting point. The head part of the piston is acted as piston head where the permanent magnet is clamped in the cylinder and tail part of the piston act as link between the magnetic piston and connecting rod. The design of the magnetic piston maybe single piston or multi piston depends upon matrix of the pistons used in the engine in form of m*n, where m represent column and n represent row. To design the magnetic piston of the GOPI engine, rare earth bar magnets are used.

In one design, a wooden cylinder has been taken to fabricate the magnetic piston. The cylinder is kept hollow from one side so that magnet can be placed into it. The depth of the hollow part of the cylinder is kept equal to the thickness of the bar magnet and the inner diameter of the cylinder is kept equal to the diameter of the magnet. Total length of the piston cylinder is the sum of piston head length and the piston tail length. In other design approach, non-metallic, non-magnetic material is used for the same purpose. Metallic material has high mechanical strength to bear all stresses.

A. Piston Configuration

GOPI engine can be divided into numerous designs based on the piston –crank configuration. Each design has its own advantages and limitations. The common thing between all designs is the Engine Unit as shown in the figure 3.12. Engine unit is the smallest embodiment of the engine which can produce power.

a. Single piston

A single piston GOPI engine is the smallest embodiment which can produce power. It consists of the following parts: a magnetic piston, a gate assembly, fixed magnet, a crank and flywheel system and control units. The arrangement of all these parts in their particular places is to be known as Engine Unit. The power stroke happens once in 360^0 rotation of the crank.

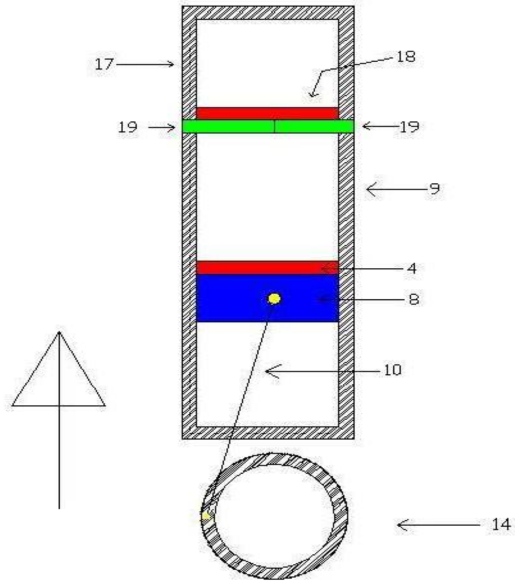


Figure 3.12: Engine Unit

b. Multi- piston

Multi piston configuration may consist dual piston attached to a common crank in opposite phase or four pistons attached to a common shaft or any number of pistons can be used in a matrix of m*n where m represents column and n represents row. In any configuration, each magnetic piston will be arranged with individual engine unit. Power stroke in two pistons system occurs at 180^0 rotation of the crank and at 90^0 rotation of the crank in four pistons system. The power stroke in the engine when more than four pistons are used depends upon arrangement of the pistons in the matrix of m*n.

The benefit of multi piston design is that more power stroke can be arranged in one rotation of the crank and multiple power strokes can be attained at particular phase (rotation angle) of the crank. This helps in to get more power in the stroke.

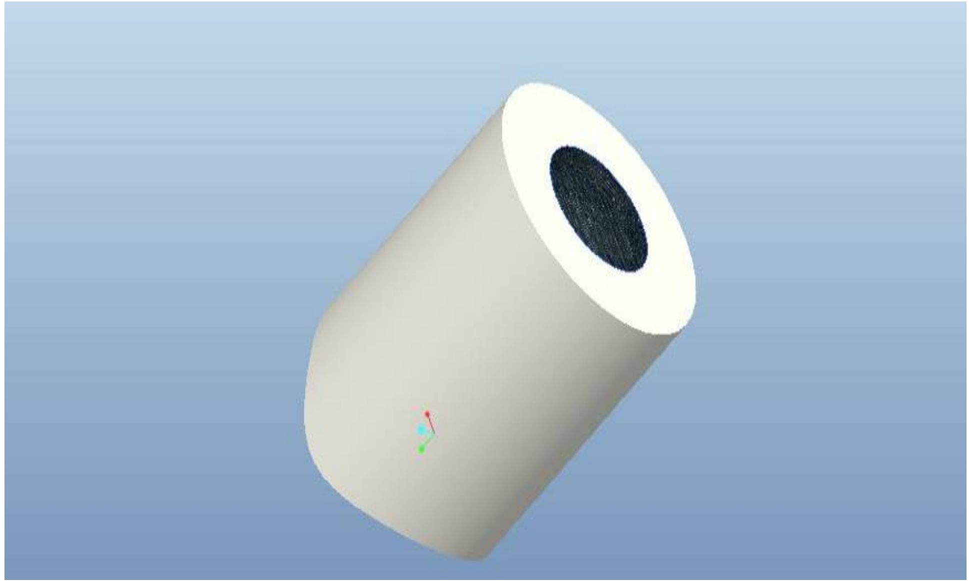


Figure 3.13: Magnetic Piston

Dimension detailing of the magnetic piston is provided in the figure 3.13 and figure 3.14

Piston head is the projected portion of the movable magnet housed in the magnetic piston. Power stroke happens at this place when the piston head approaches the TDC. The magnet is fixed with glue or by some other means inside the hollow part of the piston cylinder in such a way that one pole of the magnet is projected outward and other pole will be hidden in the cylinder. This combination of the magnet and piston of the magnetic piston which serves both the purpose of piston and cylinder as shown in the figure 3.13. The projected part of the magnet will act as piston head. The other side of the cylinder is used to clamp with crank with help of connecting rod.

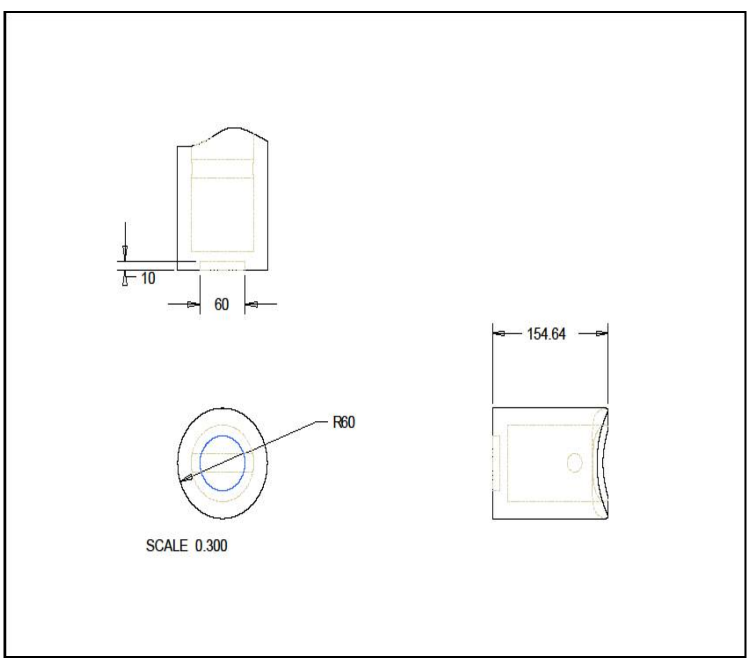


Figure 3.14: Dimension detailing of magnetic piston

At the tail end of the piston cylinder, a pin joint is provided where one end of the connecting rod is pinned. Table 3.3 represents the piston detailing.

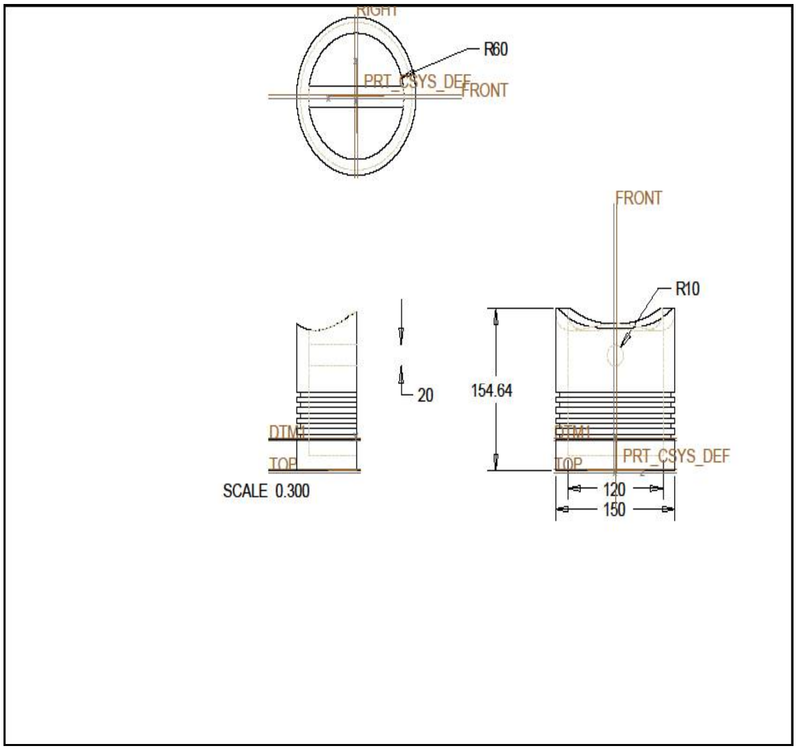


Figure 3.15: Dimension detailing of piston tail

Table 3.3: Piston Detailing

Sr. No	**Particular**	**Dimension**	**Explanation**
1	Bore(mm)	60	Magnet diameter
2	Piston head length(mm)	20	Magnet thickness
3	Piston head thickness(mm)	75	Including magnet cover

3.5.4 Crank Shaft Configuration

To convert the reciprocating motion of the piston into rotational motion of the shaft, crank shaft configuration is used. The working mechanism of the crank shaft of the GOPI engine is as same as that of the IC engines but there is a significant difference in selection of the materials. The crank shaft configuration includes connecting rod, crank shaft and crank stand. The material selected for the connecting rod should be non-metallic; non-magnetic so it should not be affected by nearby magnetic field otherwise the engine will not work properly.

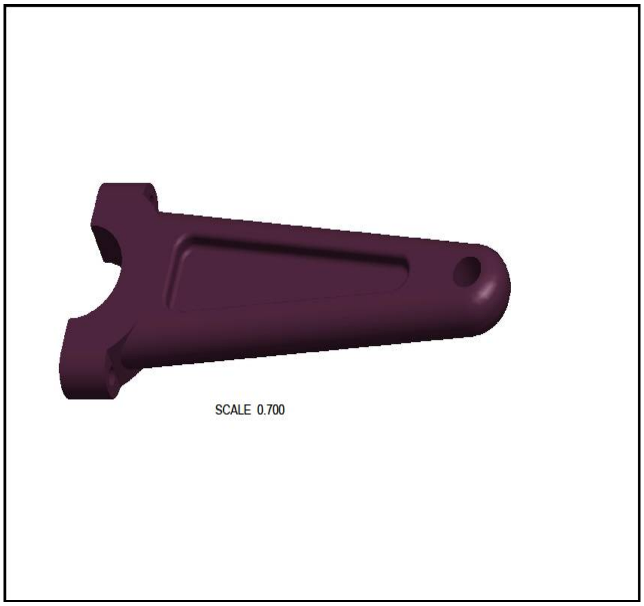


Figure 3.16: Connecting Rod

The working location of crank shaft is quite far from the magnetic field produced by the magnetic piston and fixed magnet so the material of the crank will not be affected by the nearby magnetic field and hence there is no limitation on the material chosen for fabrication of the same but it is advisable that magnetic laminating sheets should be used to protect the engine components from strong magnetic field. Crank stand is used to hold the crank and shaft of the GOPI engine. It also holds the engine track on which the magnetic piston is used to make up and down movement. Generally non-metallic, non-magnetic material should be chosen for its fabrication.

3.5.5 Control Units

Control units are important components of the engine as without proper control units, the engine may not work properly. Synchronization of the gate movement with the piston position is very –very important as without it the working of the engine will be affected seriously. An advanced micro-processor based technique is used to design the control units of the engine. The exploded view of the GOPI engine is shown in the figure 3.20.

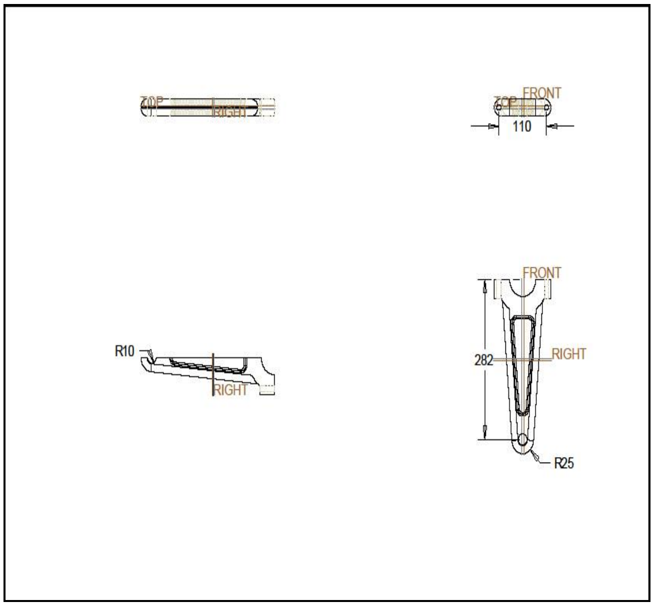


Figure 3.17: Connecting Rod detailing

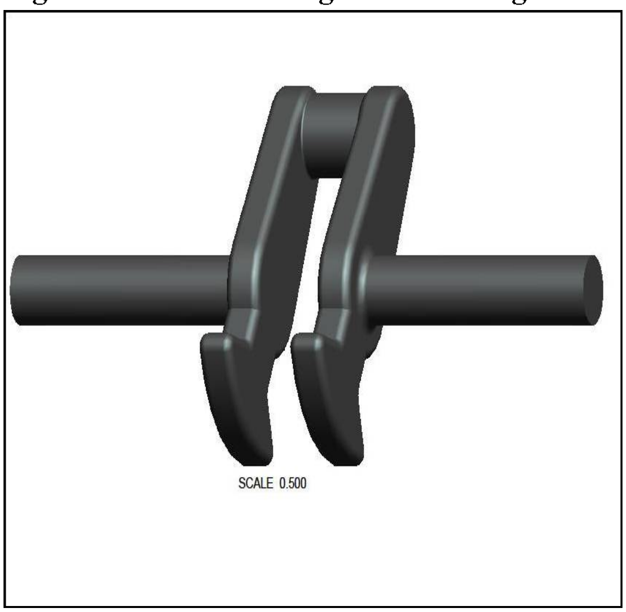


Figure 3.18: Crank and Shaft

3.5.6 Input Power

Input power is required to operate gates and the control units of the engine. It can be a battery or some mechanical or other form of energy which will be capable to operate the engine control units smoothly.

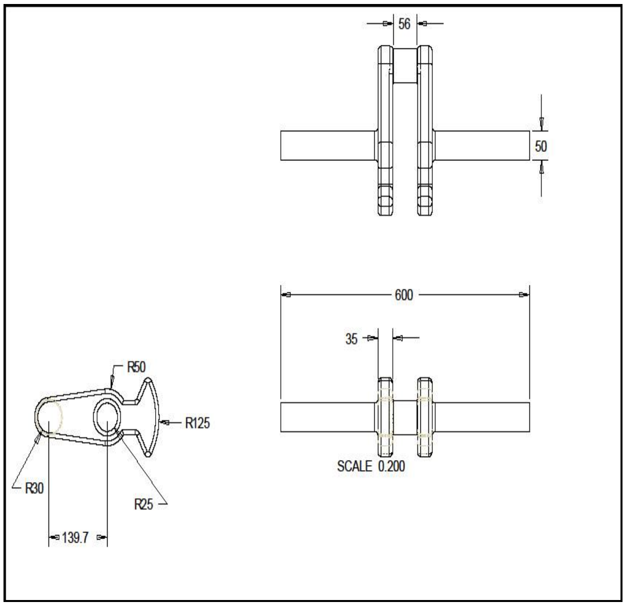


Figure 3.19: Crank and Shaft detailing

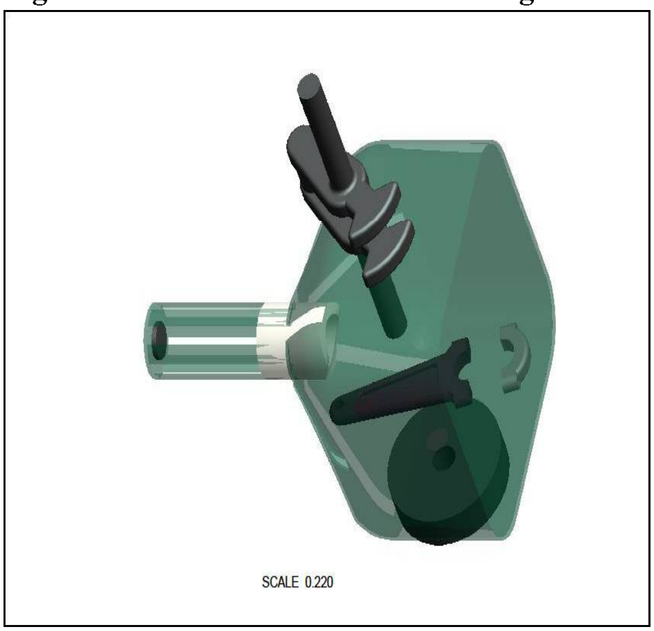


Figure 3.20: Exploded view of GOPI engine