The present study requires detailed investigation about magnetic engines, their operating and working methodologies, the material used for their fabrication, material properties, losses associated with them.

2.1 Magnetic Engines

The use of magnetism to produce energy is known from decades. Magnetic energy in form of permanent and electromagnets has been used in motors, generators, switches to produce mechanical and electrical energy from last many decades.

For years people have tried to use such magnets in magnetic engines, and many designs have been developed and patents granted throughout the world, but only few engines were developed to their commercial models for micro and/or macro scale power generation units. The similar thing in almost all previous concepts is that attraction or repulsion or both attraction and repulsive force of magnets were used to drive the piston and crank. Permanent magnets or electro magnets, electrical coils and some moving mechanism like spring were used in the power generating units.

The important components of any magnetic engine or magnetic generator are combination of permanent magnets, electromagnets, magnetic shield materials or laminates, magnet and/or shield material movement mechanism, control units and piston-crank assembly. Here the magnetic engine describes the machine which produces mechanical power and the magnetic generator produces electrical power.

Broadly all type of magnetic engines can be classified into three major categories according to their working principles. The working mechanism of a magnetic engine depends upon how the power stroke is produced. The first category of magnetic engines where electro-magnets or electro magnets with combination of permanent magnets are used for power stroke, the second category of the engines is where permanent magnets are used for power stroke and, the third category where hybrid of above methods is used to produce power.

For close reflection of the gate operated magnetic engine, a detailed study of patented magnetic engines as well as commercially developed magnetic engines is made and accordingly the present study is grouped into two main parts viz. patented magnetic engines and commercially available magnetic engines. The patented engines further classified into electromagnetic engines, permanent magnetic engines and hybrid engines

The first category of the engines includes Wortham, U.S. patent no. 5,219,034 [11],Patton, U.S. patent no. 5,057,724 [13], U.S. patent no. 6,049,146 Takara [14] utilizes a magnetic piston inside a cylinder where the cylinder is alternately magnetized by electromagnetism to cause attraction and repulsion moving the piston up and down. The magnetization of the cylinder generates magnetically attracting force between the cylinder and the piston to cause the piston to move in one direction and thereafter magnetically repellent force to transfer the piston in the opposite direction. This series of action is repeated to provide a continual reciprocal movement of the piston.

The second category of the magnetic engine includes McCarthy, U.S. patent no. 7,330,094 [26], Togare, Radhakrishna, U.S. patent no. 7,667,356 [27] is based on the principles of the natural force of repulsion. The change in magnetic field from repulsion to attraction performs the piston to push up and down and turn the shaft and flywheel system.

The third category of the magnetic engine includes U.S. patent no. 7,105,958 to Elmaleh [34], is based on combination of electromagnetic engines and permanent magnet engines. –The driving mechanism of the engine maybe mechanical or electrical in nature.

2.1.1 The Electromagnetic Engines

Many engines or devices are invented where magnetic pistons or motors are coupled with electromagnetism or ceramic permanent magnets as motive force for their engines.

U.S. patent no. 5,219,034 to Wortham describes a vehicle powered by a magnetic engine includes a block fitted with the multiple cylinders for receiving magnetic pistons attached to a crankshaft and electromagnetically mounted in the engine head for magnetically operating the magnetic pistons by electric current reversal. A polarity timer is connected to the vehicle battery through a variable resistor which serves as an accelerator to vary the current through the respective electromagnets and operate the magnetic piston at a desired speed [11].

U.S. patent no 20070030671 A1 to Jon Long QianTianming is a renewable energy flashlight employing a pair of electromagnetic repulsion members to assist in reciprocating a charging magnet passing through surrounding induction coils to enhance the efficiency of manually charging a capacitor to power an LED lens amplified flashlight [12].

U.S. patent no. 5,057,724 to Patton used plurality of permanently polarized ceramic magnets is located upon a plurality of pistons, each mounted in a cylinder. An electromagnet is located at each end of the cylinder and is energized to alternatively attract and repel the ceramic magnet so that each piston is caused to reciprocate in the cylinder under the influence of electromagnetism [13].

U.S. patent no. 6,049,146 to Takara also utilizes a magnetic piston inside of a cylinder. However in this reference the cylinder is alternately magnetized by electromagnetism to cause attraction and repulsion moving the piston up and down. The magnetization of the cylinder generates magnetically attracting force between the cylinder and the piston to cause the piston to move in one direction and thereafter magnetically repellent force to transfer the piston in the opposite direction. This series of the action is repeated to provide direction. This series of the actions is repeated to provide a continual reciprocal movement of the piston [14].

U.S. patent no. 4,317,058 to Blalock used an electromagnetic reciprocating engine and method for converting an internal combustion engine to an electromagnetic reciprocating engine where the cylinders are replaced with non-ferromagnetic materials and the pistons reciprocally disposed and replaced with permanent magnet pistons. An electromagnet is disposed at the outer end of each cylinder. A switching circuit and a timing apparatus is operably connected between a DC electrical sources and the electromagnets whereby the creation of a magnetic field about said electromagnet will interact with the magnetic field about the permanent magnet pistons to effect reciprocal motion of said pistons within the cylinders. Oil rings are provided around said pistons whereby lubrication can be affected in the same manner as provided in an internal combustion engine [15].

U.S. patent to Morch, US Patent no. 2,338,005 includes the replacement of the cylinders with electromagnetic windings around the cylinders so that a piston member could reciprocate within those windings. However, a problem with this model is that the placing of the windings is within the cylinders greatly limits the size of the electromagnet since the cylinders on an ordinary internal combustion engine are typically rather close [16].

U.S. patent no. 7,557,473 B2, to Butler Kala is an electromagnetic engine comprises of an electromagnet having opposing magnetic poles at ends thereof. A non-magnetic rigid support is mounted for the oscillatory stroke movement relative to the electromagnet. A crankshaft is coupled to the support; a sensor is coupled to the crankshaft and outputs a crankshaft position signal. Permanent magnets are affixed to the support on either side of the electromagnet and are oriented so as to present the same magnetic pole. The permanent magnets are spaced from one another by a distance approximately equal to the distance between the two ends of the electromagnet plus the stroke movement of the support [17].

U.S. Patent no.3,894,599 to Murry is a bicycle powered by electrical solenoids, one of which is linked by a cable to each foot pedal of the conventional chain drive. Manually operated switches mounted on the handles control the operation of the solenoids. The solenoids are powered by a battery which maybe charged by an alternator-generator when the bicycle is coasting or going downhill. The bicycle may be propelled by normal foot action on the pedals with the solenoids supplying additional power, as required [18].

U.S. patent no. 5,637,936, to Meador is an electromagnetically powered engine apparatus and method converts pulsed alternating electrical and electromagnetic energy into mechanical energy which drives an output shaft drive. The engine apparatus produces usable mechanical power by pumping action made possible dual opposing magnetic poles disposed within a single cylinder on opposing sides of a core member end of an electromagnet, which core member is actually situated within the cylinder. The dual opposing magnetic pistons are mechanically coupled to dual axles in a manner to rotate the dual axles and the output drive shaft effects rotation of the output drive in the shaft in the same 1st direction that the dual axles are rotated [19].

U.S. patent no. 6,954,019 to Harry Paul describes an apparatus and process for generating energy through the use of rotating shaft that is moved by magnets in a single circular direction. Permanent magnets are disposed about a bottom plate member and work in coincidence with opposed polarity magnet on a top plate member. An electromagnet is disposed at an end of the row of permanent magnets to operate a continuous flow of said shaft [20].

U.S. patent no. 5,833,440 to Berling is a magnetically-powered linear displacement device utilizes a permanent magnet whose flux density can be steadily shifted from one of two parallel magnetic paths within displacement device. A pair of pole pieces made of magnetically soft magnetic materials abuts portions of the permanent magnet and conducts magnetic flux in two different magnetic paths such that the permanent magnet's flux is travelling along a 1st of these parallel paths such that the permanent magnet's flux can flow in either direction. The magnetic pathways are shifted by use of electromagnetic coils wrapped around certain portions of the pole pieces, such that when a current pulse of a given polarity is reversed, the movable magnet is forced to the opposite position of its linear displacement travel. By energizing the electromagnetic coils sequentially, with the alternating opposite polarities, the movable armatures will move in a reciprocating fashion [21].

U.S. patent no. 5,757,093 to Susliaev et al. derived an electromagnetically powered engine for powering vehicles and other devices which utilizes an engine. The inventive device includes a plurality of pistons made of a ferromagnetic material disposed for reciprocating within insulating cylinders. A conductive coil is disposed around each of the cylinder for actuating the pistons when electricity is supplied to coils. The pistons are connected with a crankshaft for converting reciprocating motion of the piston into rotational motion of the crank shaft [22].

U.S. patent no. 4,749,893 to Reynolds is an engine with reciprocating piston sliding mounted within a cylinder and connected to a rotatable shaft. The piston is driven back and forth within the cylinder by a pair of electromagnets to obtain rotator power. A secondary winding around one of the electromagnets produces an alternating

current. An anti-arc relay is also provided to prevent burning of the high voltage contacts [23].
U.S. patent no. 6,729,744 to Mah is a light generating device utilizes a large centrally located magnet which is mounted to slide past a magnet current induction wire to produce electric current. Ninety seconds of manual activation enables about five minutes of illumination [24].

2.1.2 The Permanent Magnetic Engine

U.S. patent no. 5,594,289, Minato is a rotor that is fixed to a rotatable rotating shaft, a plurality of permanent magnets is disposed along the direction of rotation such that same magnetic poles face outwards. In the same way, balancers are disposed on the rotor for balancing the rotation of this rotor. Each of the permanent magnets is obliquely arranged with respect to the radial direction line of the rotor. At the outer periphery of the rotor, with this intermittently energized based on the direction of the rotor [25].

U.S. patent no. 7,330,094 to McCarthy is based on the principles of the natural force of repulsion. A ferromagnetic slipper unit is inserted into a gap in said cylinder between the permanent magnets for attraction and repulsion of the magnetic piston which in turn is attached to shaft and flywheel system. The change in magnetic field from repulsion to attraction performs the piston to push up and down and turn the shaft and flywheel system. Two pistons in coincidence can be used so that one piston is repelling; the other is attracting causing an increase in motive force [26].

U.S. patent no. 7,667,356 to Togare, Radhakrishna relates to the "Magnetic pistons engine", hereafter called "Maps engine" or "RAT engine" or simply, an engine that works on the principle of magnetism. It is so called the RAT engine as RAT plates are used. This method provides an environmental friendly, very high efficiency engine that can complement or replace any engines that use fossil fuels, bio-fuel, solar power, hydro power, electricity, stored electricity or any other energy sources [27].

U.S. patent no. 4,129,795 to Miyada is a piston engine without cranks and crankshafts. Its principle parts include electromagnets having iron cores, electromagnets with magnetic-fluid cores, hydraulically operated turbine receiving its pressure from said pistons, electromagnetically operated polarity wheel that performs functions resembling those of commutators and special computers in the selection, reversal, and timing of currents to ensure the coordinated movements of the various parts of the engine. It maybe operated as a direct current engine, with energy derived from the portable storage batteries or generators that are independent of fossil fuels, which does not pollute the atmosphere [28].

U.S.patent no. 4,315,197 to Edwards is a magnetic piston includes a housing having a tapered bore extending along an axis having a tapered outside wall mating with tapered bore of the housing for providing radial and longitudinal movement about a rotational axis of the piston. A shaft is connected to the piston for movement along the longitudinal axis, wherein the outside wall of the piston and a second set of magnets is embedded within a surface of a wall forming a bore of the housing. The polarity for each of the magnets within the sets provides attracting and repelling forces causing rotation of the piston relative to the housing and longitudinal movement of the shaft along the longitudinal axis [29].

U.S. patent no. 4,315,197 to Studer is a linear magnetic motor/generator which uses magnetic flux to provide mechanical motion. It includes an axially movable actuator mechanism, a permanent magnet mechanism which passes through a magnetic flux generate power [30].

The GOPI engine belongs to the second category where permanent magnets are used to produce the power [31, 32].

2.1.3 The Hybrid Magnetic Engine

The hybrid engine includes the rotation of the crank shaft in a predetermined direction continuously after the initial activation of the crankshaft assembly by applying a short period of the external force, such as from as automobile starter or storage battery or some special combination of electromagnets and permanent magnets [33].

U.S. patent no. 7,105,958 to Elmaleh used electromagnetism as motive force for his engine. The electromagnetic engine includes the rotation of the crank shaft in a predetermined direction continuously after the initial activation of the crankshaft assembly of the applying a short period of the external force, such as from as automobile starter [34].

U.S. patent no. 6,278,204 to Frenette where the piston work in pairs so that when two of the solenoids are energized, they draw the associated steel plungers within the solenoid remain energized and rotate or reciprocate, due to their momentum, to a lower most position [35].
U.S. patent no. 4,631,455 to Taishoff describes an electric starter motor and generator is integrated into the structure of a internal combustion engine by making the ferromagnetic pistons of the engine the relatively moving element in the starter and the generator [36].

U.S. patent no. 5,818,132 to Konotchik describes a linear motion produced from work done by an intermittent force. A moving magnet is confined so that it can move with bi directional linear through each of at least two coils. It is useful for providing power for long life flashlight, for alarm systems and for communication devices. It is based on the principle that when a magnet is moved in between the coils, a current is induced in the coil [37].

Almost all generators or engines are having electromagnets or permanent magnets as one of their important parts. But engines based on repulsive force of magnets are very few found in the literature. To understand the behavior of magnetic engine, an intensive study of power generating devices is conducted where permanent magnets are used as main unit or in supportive unit of the engine at micro scale power generation system or macro scale power generation system.

2.1.4 Micro Power Generating Devices

The micro scale power generating units are used to produce power in micro watt for remote applications of electronic equipment. The electromagnetic generators can be classified according to their moving element parts –coil and magnet shapes, in put vibration and/or the device volume.
The electro magnet generators can be discretely assembled generators with macro scale high-performance bulk magnets and multi-turn coils or micromachined generators with micromachined magnets, aplanar coils and micromachined springs. Also, there are some generators which are partially micromachined. Themicro machined generators may have low output power and voltage compared to the assembled generators, due to the relatively poor properties of magnet, the limitations

on the number of turns of the micro coil and the restricted amplitude of vibration, but they also have the advantage of micro size for easy integration of sensingsystems.Williamset.al.[38] presented a model for an electromagnetic micro generator. The model was either for moving magnet or moving coil. This model also established the main rules to design an efficient generator.Shearwoodet.al.[39]fabricated a micromachined moving magnet generator for remote micro sensors systems based on Williams's model. They use a polyimide membrane as a moving element. This kind of spring has non-linear starching characteristics at high amplitude of vibration therefore; using patterned spring will increase the linear movement of the spring over a large displacement range and the air damping and then increased the output power. Amarithajah and Chandrakasan[40]modeled a moving coil generator. In their model they did not specify the moving element. They report a low output voltage from a macro size generator fabricated by discrete components. Therefore, their generator needs to be attached to a transformer to rectify the . As it stated by Williamset.al.the moving magnet generator design has an advantage over the moving coil one as it is simple to fabricate by avoiding making electrical connection to the mass. Chinget.al.2002[41]fabricate a moving magnet generator. They were successful in developing a spiral spring design with low resonant frequency and vibration horizontally with rotation. So, they can increase the power output from10µwto830µw,El-hamiet.al.[42]developed a moving magnet generator with a steel cantilever beam and wire copper coil. The generator was improved later by adding more magnets poles[Glynne-Joneset.al.,2004], [43]but this come to the disadvantage of increasing the overall size from 240mm^{3}to 830mm^3.

Mizuno and Chetwynd [44] present a moving coil generator. They used a silicon cantilever as a moving magnet. Their device did not offer a high output power. Kulah and Najafi[KulahandNajafi,2004] [45]developed a moving magnet silicon diaphragm generator. The output power was first estimated through simulation work and then the millimeter scale device was fabricated and tested. The diaphragm has a low resonance frequency because it has array of beams and then the electrical power will be increased according to Williams'design rules. Koukharenkoet.al. [46] presented a moving coil generator. There was a difference between the measured and simulated resonant frequencies. The difference was due to the influence of the assembly process and the bonding of the enameled copper wires along the beam or across the meander. It is also clear from the measured results that mechanical damping mechanisms are dominating. These undesirable damping effects need to be substantially reduced in order to achieve the predicted power levels. Panet.al.[47]designed a moving magnet generator. The generator was fabricated by micro machining technology and has the silicon membrane as a moving element. The amount of output power is high. Although the generator is a micromachined device, the size of the generator is still large.Wanget.al.[48] presents a moving magnet micromachined generator. They used an electroplated Cuplanar spring. The spring has a long beam due to its configuration which keeps the spring constant smaller and the amplitude of vibration bigger which makes the generator give more power. Serreet. .al.[49] present a moving magnet generator. They produced low output power due to the limited movement and the parasitic damping of the polymer film. Fabricating the spring from material with low mechanical losses like silicon will reduce the damping and increase the output power and this was in agree with the rule design suggested by Wiiliams et.al.,Sahaet.al.[50] present a moving magnet generator with no mechanical spring. The device is fabricated by assembling discrete components. The size is on millimeters. This device has high damping losses because the moving magnet directly touches the tube surface. This device has a low resonance frequency which makes the generator give low output power because the output power is proportional to the cube of the frequency as it reported by Wiliiamset.al[51].Sariet.al.[52] presented a moving coil generator. The generator is fabricated by micromachining technology. Parylene is used in this device as a structural material of the spring. The parylene spring gives large deflections and this will give larger generated power output.Kulkarniet.al.[53] presented three generators with moving magnet. The device has a low output power due to the low amplitude of vibration of the paddle and the beam. The low amplitude of vibration is due to high parasitic damping.

2.1.5 Macro Generator

Jonathan E Rucker, designed a 16 MW permanent Magnet generator for US naval applications and found that the generator module consisting of some power electronics provides an excellent alternative to traditional wound rotor synchronization machines. It is estimated by Jonathan E Rucker, in his report that the PM generator module has a 7x reduction in volume and 10x in weight compared to similar rated electromagnet rotor module.

It is observed in many studies that since power, weight and volume are interdependent. This reduction in volume and weight can provide flexibility to the Permanent Magnet device design. High speed permanent Magnet generator provides a substantial reduction in size and weight making them a logical choice for automotive industries. Reducing the size and weight of turbine generator sets offers significant advantages to naval architect. Replacing older generators with lightweight one could make it possible to decrease the size of some generator set by as much as 50% [54, 55, 56, 57].

Electromagnetic generator machines tend to be complex; weight excessive and they require field wiring which limits design alternatives. There are several drivers which cause these problems to occur. First, to generate necessary magnetic flux levels electro magnet generators have large poles pitches to support the required field winding. These pole pitch windings in turns require larger end turns and thick back iron to support the magnetic flux , both of which contribute to increase size. Second, because of the winding losses in electromagnet large cooling system can be required thus increasing the number of support components. The permanent Magnet generator is ideal for high speed application because of its simple structure and high power density [58].

Permanent magnet generator offer several advantages: they have no rotor windings so they are less complicated; they have high efficiencies; the gap field flux is not dependent on large pole pitches so the machines requires less back iron ; they require smaller and fewer support systems [59].

Beside this, the advantages of permanent magnet generators over the electromagnetic winding generators are many as, high level of automation and control is possible, the complexity of the system is reduced, easily availability of permanent magnets and low cost of the permanent magnets and hence the device. The advantages and disadvantages of the electromagnetic and permanent magnetic generators are listed in the table2.1

Table 2.1: Comparison of electromagnetic and permanent magnetic generator

Generator type	Advantages	Disadvantages
Electromagnet	Steady voltage regulation	Weight excessive
	High power capacities	Large size
	large air gap for field flux	Electromagnetic winding complication& associated losses
	Law fault current	Large support system
	Proven , robust design	Magnet losses
		Potential fault current
Permanent Magnet	Reduced size and weight	Lack of inherent voltage regulation
	High efficiency	Excessive heating
	No excitation supply	Magnetic field intensity control mechanism
	High speed applicability	Increased mass reduces speed

2.2 Magnetic Materials

Based on the above study, it can be concluded that permanent magnet is more efficient and less complex than the electromagnetic devices. The biggest limitation of the permanent magnetic based devices is their control as permanent magnetic field cannot be turned off.

While designing and developing the GOPI engine, the same problem was faced at a large extent. Further, it is found that some specially designed magnetic materials are quite useful for blocking the magnetic field intensity.

The efficiency of any permanent magnet device mainly depends upon the materials selected to develop the device. For development of any type of magnetic engine, all materials are required with specific features so they can work under very different force and loading conditions. Working of the engine and its individual components like permanent magnets, electromagnets, magnetic shield materials, laminates and even piston-crank assembly totally depends upon the material selection for their development.

As permanent magnets are used in development of the GOPI engine, so a detailed study is conducted about the material requirement for the devices where permanent magnets were used. It is found very essential to understand the basic properties and type of the magnets which are to be used for the GOPI engine development. Several basic magnetic properties are of critical important for the permanent magnets in a Permanent Magnet generator/machine are listed below [60, 61, 62, 63, 64].

- Remnant Flux Density (Br): it is the value of the flux density remaining after magnetization and it directly influences the air gap flux and magnet size.
- Coercivity (Hc): it is the value of magnetizing field needed to reduce the flux density in the magnet to zero and its gives a first order estimate of a magnet's resistance to demagnetization.
- Energy product (B *x*Hmax): it is the maximum energy product of the magnet and it is inversely proportional to the total magnet volume required.
- Recoil permeability (μrec): it is the gradient of the B-H curve and it gives the magnets ability to return to its initial magnetization after subjected to damaging forces. If the magnet goes below Hk then it will recoil along a lower line resulting in a lower magnet flux density.
- Load line: it is a line drawn from the origin to the magnet operating point on the hysteresis curve (Bm). The magnitude of the slope of the load line is the permeance coefficient.

Based upon various properties of the magnetic materials, it is observed that the size and performance of high speed permanent magnet generator depends on the permanent magnet material properties. The machine output, heat rise, weight and cost are a few of the characteristics which are directly influenced the selection of the machine materials, because of the cost and weight are interrelated the magnet must be selected to provide the necessary air gap magnetic field and ample coercive force to compensate for possible damaging effects while minimizing the volume of material.

Permanent magnet materials come in many varieties and the four most common types for machine applications are Alnico, Ferrites, SmCo material and NdFeB material. Table2.2 summarized the characteristics for these materials. Mark Rippy concluded for the use of laminate materials for permanent magnet devices [65].

But many authors used ferromagnetic materials for their machine development as these materials are the most common substances used in the construction of machines and their properties are normally described using B-H curve and hysteresis loops. These curves represent an average material characteristic that reflects the non-linear property of the permeability of the material but ignores the multi valued properties.

Table 2.2: The characteristics for magnetic materials

property	Alnico	Ferrite	SmCo	NdFeB
Remnant Flux Density (Br) (T)	0.6-1.3	0.35-0.43	0.7-1.05	1.0-1.3
Coercivity (Hc) (kA/m)	40-130	180-400	800-1500	800-1900
Recoil permeability (μrec)	1.9-7	1.05-1.15	1.02-1.07	1.04-1.1
Energy product (B *x*Hmax) (kJ/m^3)	20-100	24-36	140-220	180-320
Maximum temperature (^0C)	500-550	250	250-350	100-200
Temperature coefficient ($\%/^0C$)	-0.01 to -0.02	-0.02	-0.05	-0.08 to -0.15

It is observed that the rare-earth magnets, SmCo and NdFeB, have become more popular for high performance applications because of their greater power density, high coercivity, high flux densities, and linearity of demagnetization curve [66, 67].

No one material is optimum for every application and the normal criteria for selection are cost, permeability, core losses, and saturation flux. It is important that the material acts as a flux guide and absorb minimum amount of magnetic motive force (MMF) so that the flux is concentrated in the air gap. In addition, the material should minimize more losses including hysteresis and eddy current losses.

Technological advancement in the rare-earth magnets, SmCo and NdFeB, in recent years, these materials have become more popular for high performance applications because of their greater power density, high coercivity, high flux densities, and linearity of demagnetization curve.

2.2.1 Magnetic Dimension

The primary magnetic dimensions that affect a permanent magnet machine are the air gap and the magnet height. These two parameters play a major role in determining air gap magnetic field, the air gap magnetic flux. To a first order approximation the air gap flux density (Bg) can be represented by [68].

$$Bg = [(\frac{hm}{hm+g})Br] \tag{2.1}$$

Here,

Hm	=	Magnetic height (mm)
g	=	Air gap (mm)
Br	=	Magnet remnant flux density (T)

The use of rare earth permanent magnets (NdFeB) with their higher flux density and coercive force permits some flexibility in the size of the air gap and because of these parameters, NdFeB magnets are used for the development of the GOPI engine.

Once the magnetic material is selected, the desired air gap flux density and magnetic flux help determine the magnetic height needed. If the magnet height is too large, the air gap flux density might be significant enough to cause the material to saturate which reduces machine performance. The goal is to use the minimal amount of magnetic material to achieve the desired effect because this reduces the size and weight of the engine and decreases the magnetic material cost. Losses in the magnet can be reduced by using smaller magnets. In order to provide uniform magnetic fields, the magnetic height is usually larger than the air gap by a factor of 5-10[69].

2.2.2 Magnetic Circuit

Magnetic circuit is the sum of the total number of paths the magnetic flux may follow as it passes from and returns to its point of origin. A magnetic circuit includes the magnetic flux source (basic permanent magnet) and any pole pieces or any ferromagnetic parts that are carrying some portion of the flux. In the GOPI engine, the magnetic circuit includes permanent magnets (both fixed and movable) and the gate made of magnetic shield material.

2.2.3 Permanent Magnet

Due to the increasing availability of high energy permanent magnet materials, there has been much interest and studies in electromagnetic generators with permanent magnet excitation [70].Using the recently developed powerful permanent magnet material, Neodymium-Iron-Boron, further enhances the reliability and effectiveness of the engine. The permanent magnet establishes the flux in the magnetic circuit. To minimize the amount of magnet flux leakage, the gate in the GOPI engine should be located as close as possible to the magnets.

It is important to choose a type of magnet that will produce a strong flux density. Rare earth magnets are ideal for the electromagnetic micro generator, and offer upto five times the magnetic energy density of conventional Alnico magnets which is an alloy of aluminum (Al), nickel(Ni) and cobalt(CO) [71, 72].Much of the recent progress made in the development of permanent magnet machines can be attributed to remarkable improvement of the properties of magnet materials. Following the successful development of samarium cobalt ($SmCo_5$ and then Sm_2Co_{17}) in70s, there was some concern that the cost and availability of the principal constituents might limit the commercial success of the semagnets. Attention was drawn to find new magnetic materials with superior properties to existing ferrite and alnico types. Earlier investigations involved using iron in place of cobalt with a variety of rare earth elements, but all the R_2Fe_{17}compounds have very low operating temperature[73]. A technical term,'Curie temperature'(T_C), is introduced to describe fundamental characteristic of magnetic materials. The term T_C expresses the temperature above, which spontaneous magnetization will not exist. The practical operating temperature for a magnet is well below T_C and yet T_C itself is only around 125ºC forSm_2Fe_{17} and around 60ºC for Nd_2Fe_{17}.

Important progress was made in early1980s.$R_2Fe_{17}$was modified to the ternary compound $R_2Fe_{17}B$ which has tetragonal crystal symmetry and strong uniaxial magneto crystalline anisotropy. The Curie temperature for R_2Fe_{17} Bissome 200-300º C higher than those of the corresponding R_2Fe_{17} compounds. Then, development quickly focused on $Nd_2Fe_{17}B$. This new alloy offers the highest saturation magnetization, and its $T_C$isover300ºCs.The most compelling attribute of this compound, however, is that neodymium is considerably more abundant in the nature than samarium. It promises a significant saving in raw material cost by coupling neodymium with the use of iron as the transition metal. $Nd_2Fe_{17}B$ is the basic compound for the modern family magnets known as neodymium-iron-boron, but various partial substations and modifications are commonly made to adjust the magnetic properties to suit practical applications.

It is known that the required magnet volume is inversely proportional to the energy product, i.e. B-for a given air gap volume being magnetized to acertain flux density. Contours of constant energy product are rectangular hysteresis curve, usually drawn from property data sheet provided by magnet suppliers [74].The maximum energy product or (BH) max of a given magnet occurs where the magnetization characteristic is tangent to BHhysteresis curve. As Nd-Fe-B has a large energy density than most of permanent materials, it has widely used in various types of electric machines. NdFeB magnets, also known as a rare earth iron magnets, are produced by asintering process called rubber iso-static pressing (RIP).These high performance magnets are being used in both the electronics and power industries.

Figure 2.1shows a typical B Horhysteres is loop. The flux density *B* is displayed on the vertical axis and the magnetizing force *H* is on the horizontal axis. Note that positive and negative values of both parameters are utilized. One variation of the BH loop is the demagnetization curve commonly used to display the properties of permanent magnetic materials. The “demag” curve represents the second quadrant of the full BH loop. This is where the material has been magnetized [75].

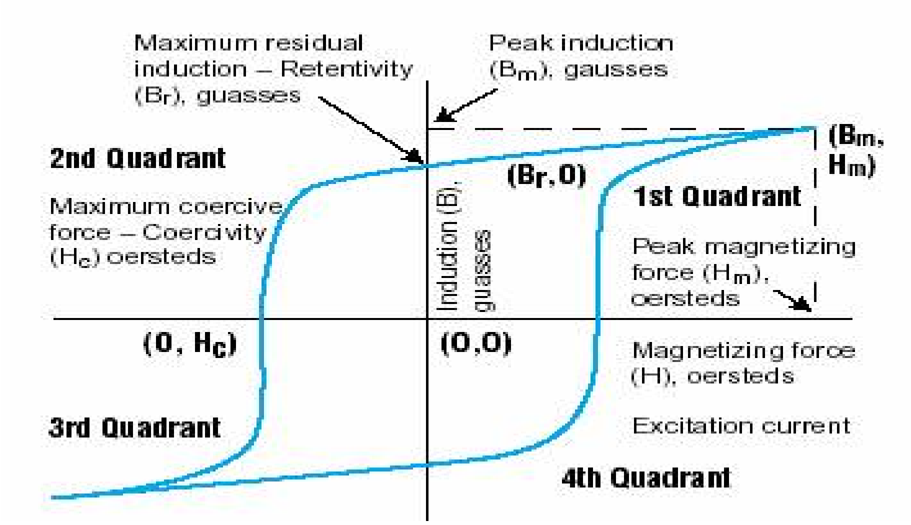

Figure2.1: BH loop for magnetic material

(Source: Jonathan E Rucker, "Design and analysis of a permanent magnet generator for naval applications" [9])

2.2.4 Magnetic Shield Material

In permanent magnet machines, the working of the machine not only depends upon the permanent magnets or flux density but also the materials used for development of the components and lamination process. As the magnetic flux near the magnets cannot be turned off, so properly lamination is of most important not only for other metallic materials not to be affected but also from human health prospective as high flux density can damage body cells. Magnetic shield material popularly known as mu-metal component is an alloy, which contains 80% nickel, 15% iron, plus copper and molybdenum (nearly 5 %).A detailed percentagewise breakup of the composition of the compound presented in the mu-metal is provided in the table 2.3. The high magnetic permeability makes mu-metal very effective at screening static or low-frequency magnetic fields, which cannot be attenuated by other methods. Mu-metal requires annealing, which is a special heat treatment in hydrogen atmosphere and one, which reportedly increases the magnetic permeability to about 40 times. Magnetic shield material is very sensitive to stress and mechanical shocks, so it should be carefully annealed. The annealing alters the material`s crystal structure, aligning the grains and removing some impurities, especially carbon. Mechanical treatment may disrupt the material`s grain alignment, leading to a drop in the permeability of the affected areas, which can be restored by repeating the hydrogen annealing steps [76].

Table 2.3: Composition of mu Metal

Composition	Percent	Composition	Percent
Carbon	0.02%	Nickel	80.00%
Manganese	0.50%	Molybdenum	4.20%
Silicon	0.35%	Iron	Balance

The effectiveness of the shielding is described by the shielding factor **S** as the relationship between external magnetic field(He) and internal magnetic field (Hi) given by Mager[77, 78] as

$$Shielding\ Factor, S = \frac{external\ magnetic\ field\ (He)}{internal\ magnetic\ field(Hi)} \quad \textbf{(2.2)}$$

The biggest limitation of the permanent magnetic based devices is their control as permanent magnetic field cannot be turned off. So gates made up of magnetic shield materials are introduced in the GOPI engine for effective working of the engine.

Magnetic properties of the material selected for the development of the gate are as follow

i. Coercive force (H) = 1.0Oe
ii. Hysteresis loss = 18 to 24 erg/cm^3 per cycle
iii. Residual Induction = 3,500Gauss

The efficiency of the GOPI engine directly depends upon the effectiveness of the gate as the engine may not work if the gate does not shields the magnetic field properly. For development of the gate, high permeability magnetic shielding material, NiFe with μ=30,000 is chosen which is an on-oriented nickel-iron-molybdenum alloy which offers extremely high initial permeability and maximum permeability with minimum hysteresis loss which meets ASTMA-753-78standard specification[79].Some physical and electrical properties of the magnetic shield material selected for the gate is listed in the table 2.4.

Table 2.4: Physical and electrical properties of the gate material

Properties	Value
Specific gravity ($kg/m^{3)}$	8747
Thermal conductivity (W/m.K)	34.6
Electrical Resistivity (Microhm-mm)	580
Temperature coefficient (per °C)	0.0011 (from-17.8/499°C)
Curie temperature (°C)	460
Melting point (°C)	1454

As the magnets in the GOPI engine are under motion continuously, temperature of the surrounding is increases and heat losses takes place. Thermal expansion takes place in the piston and gate, which further develops various stress in the material. The effectiveness of the mu metal is affected as the temperature increases [80, 81].

2.3 Losses

There are various losses associated with the permanent magnetic engines. These losses are due to flux leakage, misalignment of the magnets, demagnetization of the magnets due to their continuous movement and thermal expansion. Losses like friction losses, conductor losses, hysteresis and eddy current losses are also associated with motion of the magnets. Hysteresis losses results from the gate material not wanting to change magnetic state. As the flux density varies the material transverses the B-H curve and energy is lost. Eddy current loss is also caused by the variation in the flux density [82].

2.4 Engine Sizing Details/Methods

Because of the various stresses developed in the system, the sizing of machine matters. Whenever a machine is designed, it is important to perform some back -of-the-envelope calculations to gain insight into initial sizing estimates. As eddy current developed in a permanent magnet engine, air gap magnetic shear stress force developed per unit gap area and is constrained by magnetic design and thermal management. It is proportional to surface current density and magnetic flux density. In permanent magnet machines, the air gap flux density is approximate 60-80% of the remnant flux density. A 15 % service mass fraction is added to the total mass estimate to account for the additional services associated with large liquid cooled machines. Typical values of air gap shear stress for different types of magnetic generators are listed in the table2.5 [83, 84, 85, 86, 87, 88].

Table 2.5: Air gap shear stress for magnetic generator

Generator type	Shear stress(psi)
Small air cooled	1-5
Large air cooled	5-10
Large liquid cooled	10-20
High temperature super conducting	30-50

Once the input parameters are finalized, the first in sizing is to generate the geometry of the engine, this includes the magnetic flux density of the permanent magnets, the geometry of the magnets, the gate material. The working of the engine also depends on the size and of the gate, the distance of the gate from the magnets and the working mechanism of the gate. The length, volume, masses of components and the overall engine are calculated using basic geometric equations.

As permanent magnet engine tends to move at high speed, the permanent magnets are subject to extremely high repulsive force which will produce hoop stress. The moving components can be strengthened by enclosing them in a retaining sleeve/can for minimizing damage. The retaining sleeve can be made from many different types of material including metal alloys and composites. A disadvantage of metallic sleeve is eddy current are induced in the sleeve by variation in the flux density caused by magnet movement. The advantage of metallic sleeve is that it shields the magnets from the most of the flux density variations and it has a high thermal conductivity for heat removal.

A composite such as carbon fiber, provides reasonable strength while having lower losses since the lower conductivity reduces the eddy currents. However, the composite sleeves have low thermal conductivity and do not shield the magnets from the flux variation. This results in increased losses in the permanent magnets itself, while when the sleeve conductivity is high, the permanent magnet losses decrease and the sleeve losses increase. The material considered for use as in the retaining sleeves are listed in the table 2.6 [89].

Table 2.6: Physical and electrical properties of various materials

Material	Yield stress(ksi)	Resistivity(μΩ-m)
Stainless steel	90	0.72
Aluminum alloy	75	0.05
Titanium alloy	110	0.78
Inconel	132	0.98
Carbon fiber	100	9.25

2.5 MOTIVATION

Clearly, the prior work done in this domain demonstrates that magnetic energy producing apparatuses are well known, but that there are improvements needed in the area. Many of the advancements in this field rely upon electromagnets which complicate systems by requiring additional power sources and control mechanisms to switch current of the said electromagnets. Further, it is known that electromagnets can degrade in quality (ability to produce a workable magnetic field) over time.

Magnetic engines having permanent magnets as power generating source are also having serious working problems as, both attraction and repulsive forces are acting simultaneously on the piston head for maximum of the operational time. To eliminate these problems gates are introduced in the GOPI engine, where only repulsive force is responsible for power stroke. The gates remain in closed position and block the magnetic field between the permanent magnet and the magnetic piston all the time except the magnetic piston is at TDC. The power stroke generates only when the gate opens. Designing the magnetic geometry in a permanent magnet engine is an intricate process. It is determined that the magnet height and air gap length greatly affect the overall engine performance.

2.6 Magnetic Engine Simulation and Analysis

The finite elements of two are package ANSYS issued for calculation of the magnetic field components. This tool includes three stages: preprocessor, solver and post processor.

The procedure for carrying out a static magnetic analysis consists of following main steps: create the physics environment, build and mesh the model and assign physics attributes to each region within the model, apply boundary conditions and loads (excitation), obtain the solution, and review the results (ANSYS Documentation).

A typical magnetic field problem is described by defining its geometry, material properties, currents, boundary conditions, and the field system equations. The computer requires the input data and provides the numerical solution of the field equations and the output of desired parameters. If the values are found unsatisfactory, the design is modified and parameters are recalculated. The process is repeated until optimum values for the design parameters are obtained.

In order to define the physics environment for an analysis, it is necessary to enter in the ANSYS preprocessor (PREP7) and to establish a mathematical simulation model of the physical problem. In order to this, the steps need to follow are presented as:setGUI Preferences, define the analysis title, define the element types and options, definethe element coordinate systems, set real constants and define a system of units, and define the material properties (ANSYS Documentation).The Global Cartesian coordinate system is the default. A different coordinate system canbe specified bytheuser by indicating its origin location and orientation angles. The coordinate system types are Cartesian, Cylindrical (circular or elliptical), Spherical, and Toroid.

Some materials with magnetic properties are defined in the ANSYS material library. The materials can be modified to correspond more closely to the analyzed problem and to be loaded in the ANSYS database. Most of the materials included in ANSYS are used for modeling the electromagnetic phenomenon. The element types are used to establish the physics of the problem domain. Some element types and options are defined to represent the different regions in the model. If some laminated materials are aligned in an arbitrary form, the element coordinate system or systems have to be identified and used. The applications presented in this chapter use the PLANE53 element in the two-dimensional problem and the SOLID97 element for the three- dimensional problem.

In order to obtain the magnetic field values, the Maxwell's equations are solved by using the impute data. Then odal values of the magnetic vector potential are considered as main or primary unknowns. Their derivatives (e.g., flux density) are the secondary unknowns. After this, it is possible to choose the type of solver to be used. The available options include Sparse solver(default), Frontal solver, Jacobi Conjugate Gradient(JCG) solver, JCGout-of- memory solver ,Incomplete Cholesky Conjugate Gradient(ICCG)solver, Preconditioned Conjugate Gradient solver (PCG), and PCGout-of-memory solver (ANSYS Documentation).

The results of the calculations are shown in the post processing phase, which is a graphical program. Here, it can be observed in the applied loads affect the design, if the finite element mesh is good, and soon. The resulting fields in the form of contour and density plots are displayed by this graphical program. The analysis of the field at arbitrary points, the evaluation of a number of different integrals, and the plot of some quantities along pre-defined contoursareal so made with this program. The plotted results are saved in the Extended Metafile (EMF) format.

2.7 Need of the Present Study

For attraction and repulsion at same time McCarthy, used Slippers and Togare, used RAT plates in the magnetic piston engine developed by them for attraction and repulsion of the magnetic pistons with the fixed magnets. Slippers and RAT plates are used to introduce in the gap between the magnetic piston and the fixed magnet. But it is found that because of both attraction and repulsion forces are acting at the same place and at the same time, the thrust of the engine affected seriously. In these engines when the piston is moving towards the top dead position (TDC), repulsion force between the magnet & piston along with the attraction force between the magnet and the piston, affect the speed of the piston.

Suppose in the engines where Rat plates or Slippers are used the piston is 1/3 distanced from TDC, moving towards TDC. Then this time only 2/3 of the plate (slipper/RAT) will be introduced inside the gap to block the repulsive force between the piston and magnet. The 1/3 part of the piston and magnet will face repulsive force which is not blocked by the plates and the rest 2/3 parts of the piston and magnet will face attraction. The attraction and repulsive force acting at a place, at the same time, will reduce the total output force of the engine.

For proper thrust, the repulsive force between the magnets (fixed and movable) should apply on a concentrated area and for a very short period of time. For this a gate made up of magnetic shield material is used to operate the GOPI engine. The gate opens only when the piston is at its TDC and starts moving downward from the TDC. The gate opens at very fast rate to produce the power stroke. For all other time the gate will remain in closed position. When the gate is in its closing position, no attraction or repulsive force is acting between the magnets.

2.8 OBJECTIVE

The objective of the research is to

- Provide working mechanism of a gate operated magnetic piston engine for power generation.
- Provide modeling and simulation for the gate operated magnetic piston engine.
- Validate mathematical modeling and simulation results with experimental outcomes.