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Design and Fabrication of Low Temperature Differential Stirling Engine - Gamma Type

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Abstract: NWaste heat is that heat which is generate in a process by way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose. There exist today worldwide concerns about the best ways of using the deployable sources of energy, and of developing techniques to reduce pollution. This interest has encouraged research and development for re-use of the usually wasted forms of energy. There are many methods through which waste heat energy can be recovered and utilized. Stirling engines are mechanical devices working theoretically on the Stirling cycle. It uses air, hydrogen, helium, nitrogen or even vapors as working fluids. The Stirling engine offers possibility for having high efficiency engine with less or zero exhaust emissions in comparison with the internal combustion engine. We manufactured a gamma type Stirling engine which operates at low temperature differences.
Keywords: Waste Heat, Low Temperature, Displacer Cylinder, Piston cylinder, Power Shaft

I. INTRODUCTION

Stirling engine is a closed-cycle regenerative hot air engine. It uses a working fluid which is permanently contained within the system. Power is generated by heating and cooling of the working fluid (usually hydrogen, helium or air). Invented by Robert Stirling in 1816, the Stirling engine has the potential to be much more efficient than a gasoline or diesel engine. Its efficiency theoretically can go up to the full Carnot efficiency. It is classified as an external combustion engine, though heat can also be supplied by non-combusting sources such as solar or nuclear energy. A Stirling engine operates through the use of an external heat source and an external heat sink having a sufficiently large temperature difference (of the order of 300-500K) between them. They are used particularly in cases where the primary objective is not to minimize the capital cost per unit power, but rather to minimize the cost per unit energy generated by the engine. In recent years, the advantages of Stirling engines have become increasingly significant, given the general rise in energy costs, energy shortages and environmental concerns such as climate change. The applications include water pumping, space-based astronautics and electrical generation from plentiful energy sources that are incompatible with the internal combustion engine, such as solar energy, agricultural waste and domestic refuse. If supplied with mechanical power, it can also function as a heat pump. Though Stirling engine is advantageous over other engines in terms of efficiency, minimum pollution, diversity of the heat source used and simple design, some of its disadvantages like its size and initial cost still restrict its application to certain areas. Thus, there is a need for reducing its size, which becomes the most crucial issue. It can be done by proper design of its drives, and optimizing the relative dimensions of its components.

A. Engine Types and Classifications

Broadly speaking, a Stirling Engine will fall under one of the three main categories, being alpha, beta and gamma. There are other obscure types of engine such as the thermos acoustic engine and the fluidyne engine.

1) *Alpha (α) Configuration;* The alpha configuration uses no displacer and two power pistons connected in series by a heater, cooler and regenerator. There are two cylinders, the expansion space (hot cylinder) and compression space (cold cylinder). It is a mechanically simple engine and typically produces a high power-to-volume ratio, however there are often problems related to the sealing of the expansion piston under high temperatures. The alpha engine pictured in Figure 29 is a horizontally opposed type, which has the smallest dead space but requires rather length and complicated linkages to join the pistons to the crankshaft. Another variant is the 'V' design where both pistons are arranged in a V formation and are attached at a common point on the crankshaft. This means the heater and cooler are separated which reduces thermal shorting losses, however it increases dead space through the need to have an interconnecting passageway, containing the regenerator, between them.
2) *Beta (β) Configuration:* The beta configuration features both the piston and displacer working inside the same cylinder. This makes it quite compact and there is typically a minimal amount of dead space as there are no interconnecting passageways. It is mechanically simple as both piston and displacer are connected at a common point on the crankshaft, with the only difficulty

arising from the fact that the connecting shaft for the displacer must pass through the piston where it must make a pressure-tight seal.

3) *Gamma (γ) Configuration:* The gamma configuration is similar to that of the beta type in that it uses a piston and a displacer both directly connected to a common crankshaft. The difference is that they are not in the same cylinder, meaning that the problems of sealing the displacer rod through the piston are avoided. The downside for this is the introduction of a gas flow passageway which increases dead space in the engine. This configuration is probably the easiest to build, especially out of budget materials. It is commonly seen in LTD engines.

II. REVIEW OF LITERATURE

Many works on common Stirling engines, LTD Stirling engines and solar-powered Stirling engines have been investigated by many researches, some works related to the LTD Stirling engine are as follows Haneman [1] studied the possibility of using air with low temperature sources. An unusual engine, in which the exhaust heat was still sufficiently hot to be useful for other purposes, was constructed.

This kind of engine was reported by Spencer in 1989 that, in practice, it would produce little useful work relative to the collector system size, and would give little gain compared to the additional maintenance required O'Hare [2] patented a device passing cooled and heated streams of air through a heat exchanger for changing the pressure of air inside the bellows. The practical usefulness of this device was not shown in detail as was in the case of Haneman's work. Senft [3] described the design and testing of a small LTD Ringbom Stirling engine powered by a 601 conical reflector.

He reported that the tested 601 conical reflector, producing hot end temperature of 931C under running conditions, worked very well. Iwamoto et al. [4]compared the performance of a LTD Stirling engine with a high-temperature differential Stirling engine. Finally, they concluded that the LTD Stirling engine efficiency at its rated speed was approximately 50% of the Carnot efficiency. Kongtragool and Wongwises [5] (2003) made a theoretical investigation on the Beale number for LTD Stirling engines. The existing Beale number data for various engine specifications were collected from literatures. They concluded that the Beale number for a LTD Stirling engine could be found from the mean-pressure power formula. Kongtragool and Wongwises [6] (2005) investigated, theoretically, the power output of the gamma-configuration LTD Stirling engine. The former works on Stirling-engine power output calculation were studied and discussed. They pointed out that the mean pressure power formula was the most appropriate for LTD Stirling-engine power output estimation. However, the hot-space and cold-space working fluid temperature was needed in the mean-pressure power formula. In 2005, Kongtragool and Wongwises presented the optimum absorber temperature of a once-reflecting full-conical reflector for a LTD Stirling engine. A mathematical model for the overall efficiency of a solar-powered Stirling engine was developed. Both limiting conditions of maximum possible engine efficiency and power output were studied. Results showed that the optimum absorber temperatures obtained from both conditions were not significantly different and the overall efficiency in the case of the maximum possible engine power output was very close to that of the real engine of 55% Carnot efficiency.

III. DESIGN ASPECTS OF THE GAMMA TYPE ENGINE

A. *Low Temperature Differential (LTD) Stirling Engine*

The LTD Stirling Engine is not a strict classification of engine type, but since it is of particular relevance to this thesis it is discussed in some detail here. There is no strict definition of what constitutes an LTD engine but it can be taken as being something running on a temperature difference of under 150°C. Anything running at these sorts of temperatures must typically use a heat source other than some sort of combustion, which will typically be at a temperature of several hundred degrees. LTD uses a gamma-type configuration, because this type engine can keep a large heat transfer area. With a high temperature difference it is necessary to maintain a relatively long separation between the hot and cold ends in order to avoid excessive heat loss through short conduction paths, while the heating and cooling surface area is less critical. An LTD engine on the other hand requires a large surface area for heat transfer to allow for adequate heating and cooling of the gas at such low temperatures. There is also less heat conduction from the hot to the cold end so the distance here can be shorter.

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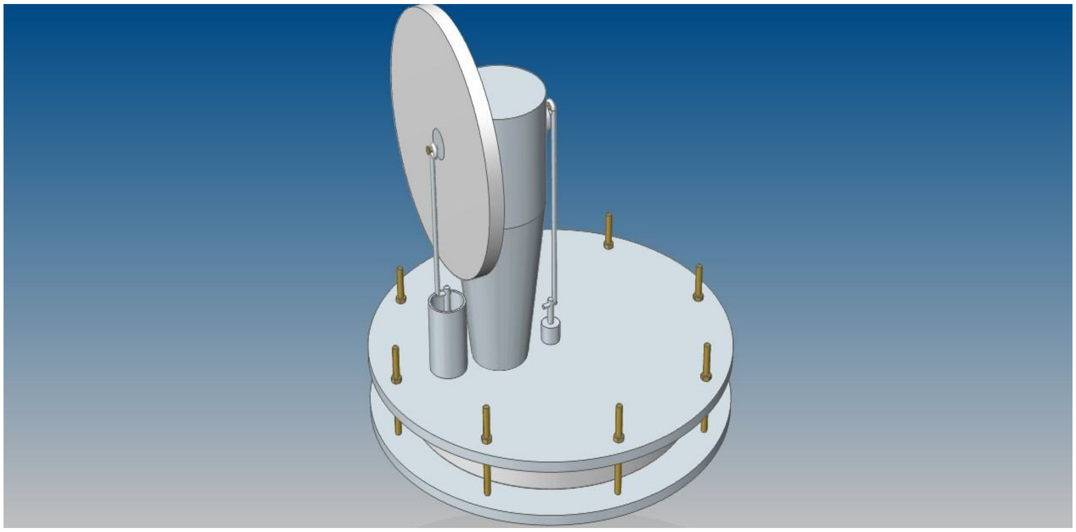

Fig 3.5 LTD Stirling Engine

The main objectives of our project are to build a working model of low temperature differential Stirling engine which will run on variety of low temperature sources. By gathering basic details and information's on Stirling engine we concluded that better knowledge on the subject and advancements in the field of Stirling engine is required to complete the project successfully.

IV. PROBLEM STATEMENT

The main aim of our project was to create an LTD Stirling engine that helps in utilizing the wasted energy or energy from various renewable sources into use full work. This section highlights the presently used methods for energy generation worldwide and the different issues concerned with them. The section also suggests the possible solutions for these problems and the potential of Stirling engines in resolving these issues**.** It is the aim of this project to design and build a prototype of a Low Temperature Differential Stirling engine which will be capable of running at any low temperature sources such as geothermal water, solar reflectors and so on. It will not even require very hot water, being able to run on low temperatures down to just 50 or 60°C. The beauty of the Stirling engine in this project is that it is able to run on any source of heat. This means that there are many areas in which it could be applied, either in scaled-up versions producing grid level electricity, small versions producing local supply or distributed generation, or as direct prime movers for pumps or motors. One such alternative application could be in an existing installation where hot waste water is a by-product of the process. An independent agency has estimated that if all waste heat was harnessed, it could provide 20% of the entire power generation needs of the Western world. Such installations include but are not limited to geothermal, coal, gas or nuclear power stations, industrial processes and food processing plants. Often this hot water is simply discharged back into a river or lake, which can raise questions about effects on local wildlife. Powering a Stirling engine off the heated water would reduce the injection temperature of the water into the river or lake, as well as being a low cost source of power which could be used to pump the water in question or drive some other load. There are also many large and minor electronic applications for this engine. Recently the MSI electronics (Taiwan) installed ltd Stirling engine on the computer motherboard which uses the heat generated to run a fan to cool the system. Also Stirling engine mobile chargers are available commercially which uses heat from the candle.

V. DESIGN OF STIRLING ENGINE COMPONENTS

This chapter deals with the design procedures conducted in the making of LTD stirling engine. Design of stirling engine components were performed based on the data's collected in the previous chapter. The details about how the engine components were machined are also mentioned.

A. Displacer Cylinder

Displacer cylinder is used hold the working fluid (air) which driver the engine. The cylinder is placed between the top and bottom plates. Cylinder should be air sealed to prevent any leakage of air. It also has to poses high thermal insulation. The cylinder is cut out from a sheet of PVC form (commercially known as multi wood). The machining was done using CAM for attaining better accuracy. Two cylinders were cut from 15mm sheet and were tightly joined to attain 30mm height. CAD drawing of the cylinder is illustrated in the figure 5.1.

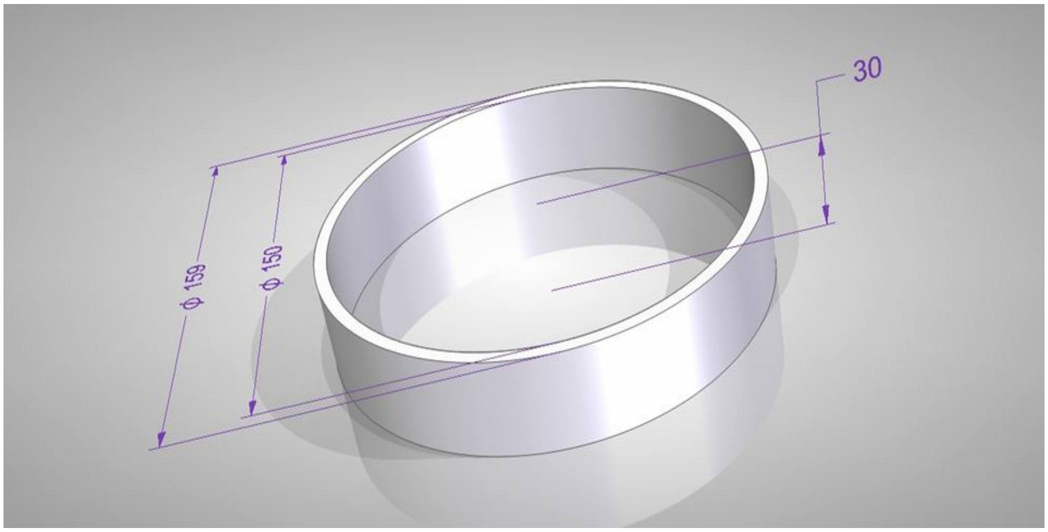

Fig 5.1 Displacer cylinder

For cylinder subjected to internal pressure alone, the safe thickness can found out by the Lame's equation.

$$\frac{t_{dc}}{r_{id}} = \left(\frac{1+\frac{P_{max}}{\sigma}}{1-\frac{P_{max}}{\sigma}}\right)^{\frac{1}{2}} - 1$$

$$= \left(\left(\frac{1+\frac{P_{max}}{\sigma}}{1-\frac{P_{max}}{\sigma}}\right)^{\frac{1}{2}} - 1\right) r_{id}$$

P_{max} = 0 .15198 N/mm^2

σ = 15N/mm^2 for PVC considering factor of safety of 2.

$$t_{dc} = \left(\frac{1+\frac{0.15198}{15}}{1-\frac{0.15198}{15}}\right)^{\frac{1}{2}} - 1\times 150 = 1.52\text{mm}$$

Actual thickness of cylinder, t_{cd} = 4.5mm

B. Surface Plates

The surface plates are the plates where the heat transfer takes place. So the plates require a high value of thermal conductivity. Area of heat exchanging surfaces should be larger than the displacer cylinder. Two plates of 6mm thickness and circular cross section where used. 200mm discs where initially machined out using lathe from two rectangular pieces of dimensions 250mm×300mm. One disc was used as the top late and other as bottom plate.

C. Top plate (Cold plate)

Top plate is the one on which the piston cylinder and the flywheel housing is mounted. The function of this plate is to dissipate heat from air that comes in contact with the bottom side of the disc to atmosphere and also to support piston cylinder and flywheel housing. CAD model of top plate is shown in the figure 5.2.

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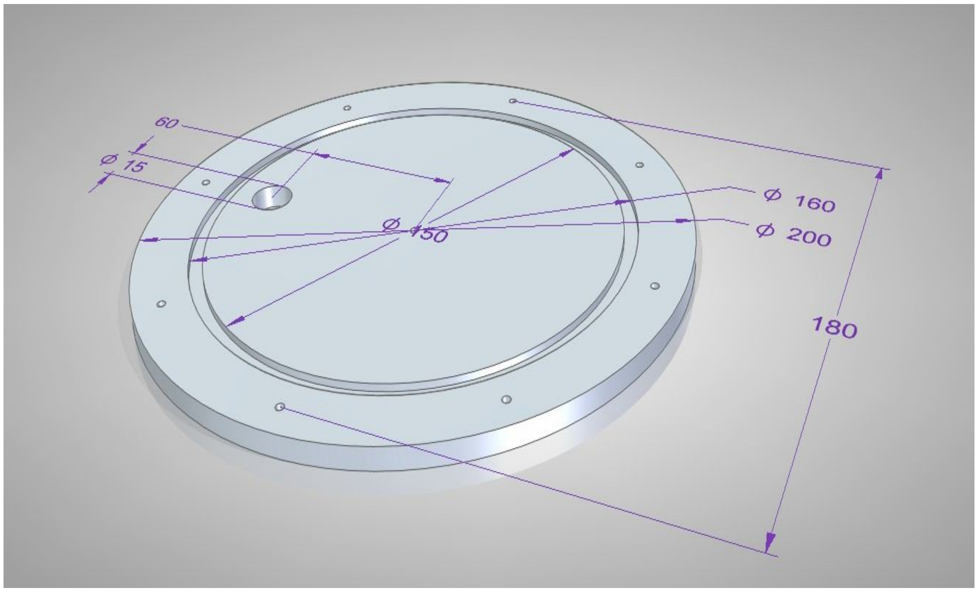

Fig 5.2 Top plate

D. Bottom Plate (Hot Plate)

The function of bottom plate is transfer heat from the external hot source to the air present inside the cylinder. So this plate also requires high thermal conductivity. It also has to support the displacer cylinder. The CAD model of the bottom plate is shown in the figure 5.3.

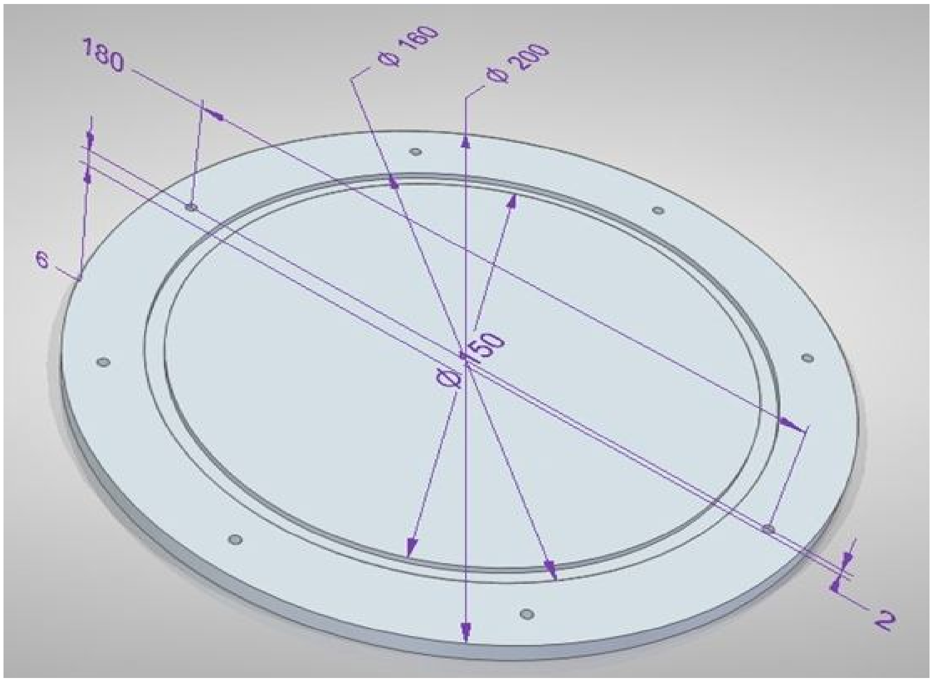

Fig 5.3 Bottom plate

E. Displacer

Displacer is used to regulate the air inside the cylinder to complete the process. As per the required properties of displacer we selected thermocol since it has very low mass and thermal conductivity. Displacer was cut from a sheet of hard thermocol of 15mm thickness. The side of thermocol was softly rubbed using sand paper to make the edge smooth. The CAD drawing of the displacer is shown in figure 5.4.

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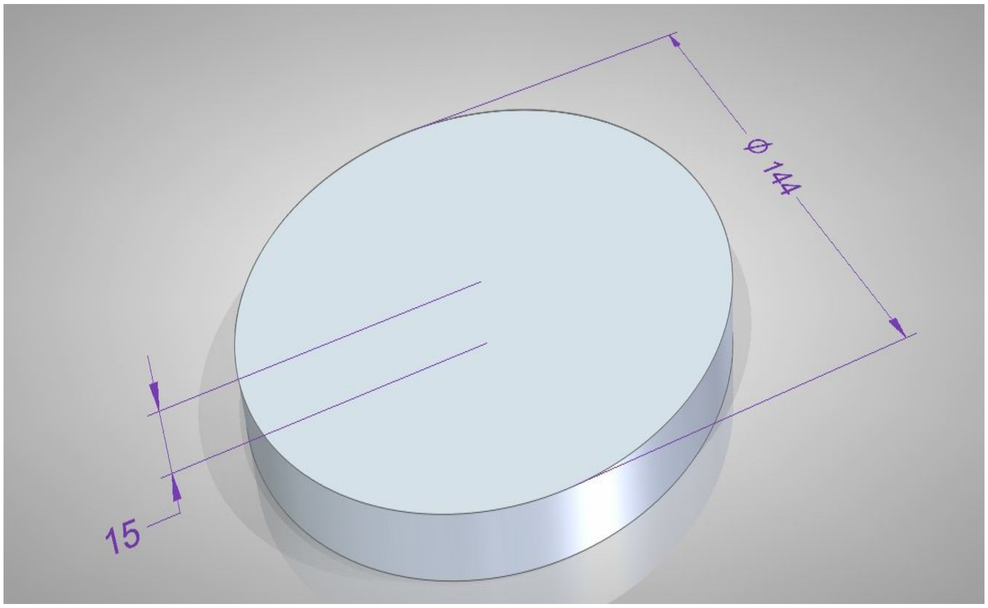

Fig 5.4 Displacer

F. Piston

Piston produces the power stroke for the engine. Piston was machined out from a Teflon rod. The machining involved tuning and thread cutting. A 25mm rod was turned out using lathe and its diameter was reduced to 18mm and was parted using a parting tool at a length of 15mm. A hole of 14mm depth was drilled axially on the piston at a depth of 12mm. This was performed to reduce its weight. At the exact center a thread of 4M was drilled for connecting the piston rod. CAD drawing of the piston shown in the figure 5.5

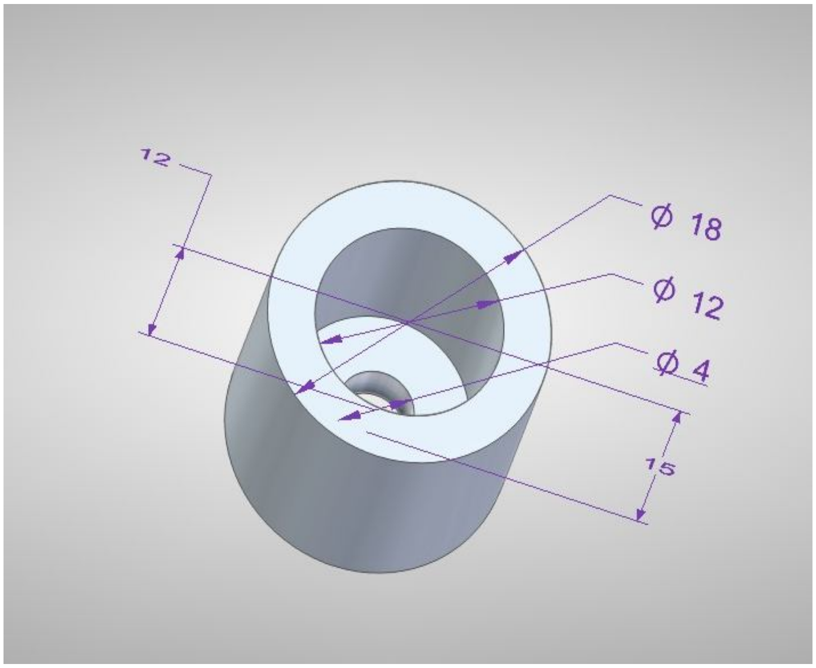

Fig 5.5 Piston

G. Piston Cylinder

The piston reciprocates in the piston cylinder. The piston cylinder was machined from an Aluminium rod of 30mm diameter. The diameter of the rod was the reduced to 25mm by turning and a hole of 18mm diameter was drilled. The hole was then bored to make the surface smooth for reducing friction. CAD drawing of cylinder is shown in figure 5.6.

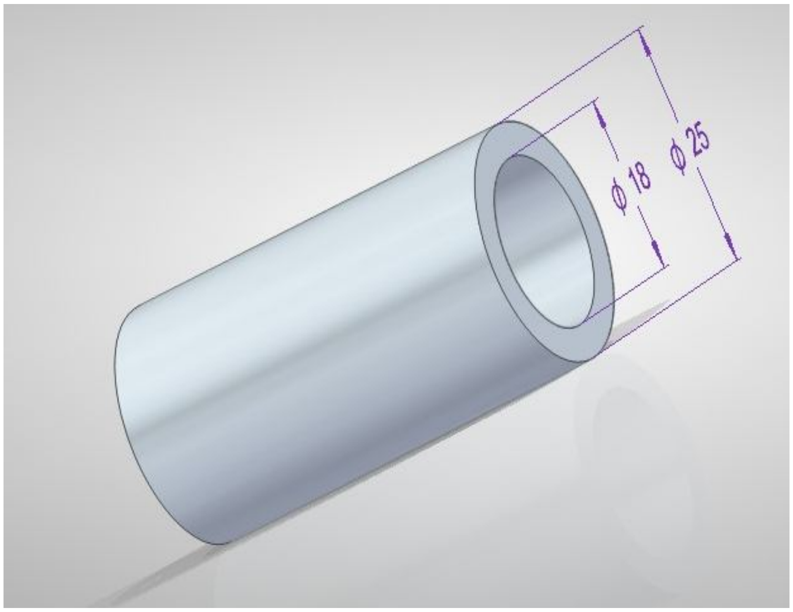

Fig 5.6 Piston cylinder

H. Power Shaft

The work done by the piston is converted into rotational power of the shaft. The power shaft should be able to withstand the torque produced by the engine. The reciprocating motion of the piston is converted into rotation of shaft by providing eccentric crank mechanism. The rotation of the shaft has to be with minimum friction for which a ball bearing is used. The length of shaft is 55mm and two threaded holes of 3mm diameter were drilled in the axial direction with an eccentricity of 5mm. This eccentricity corresponds to the crank radius of the piston. Holes were drilled with a 900 angle between them which corresponds to phase angle between the piston and displacer. CAD drawing of the shaft is shown in figure 5.7.

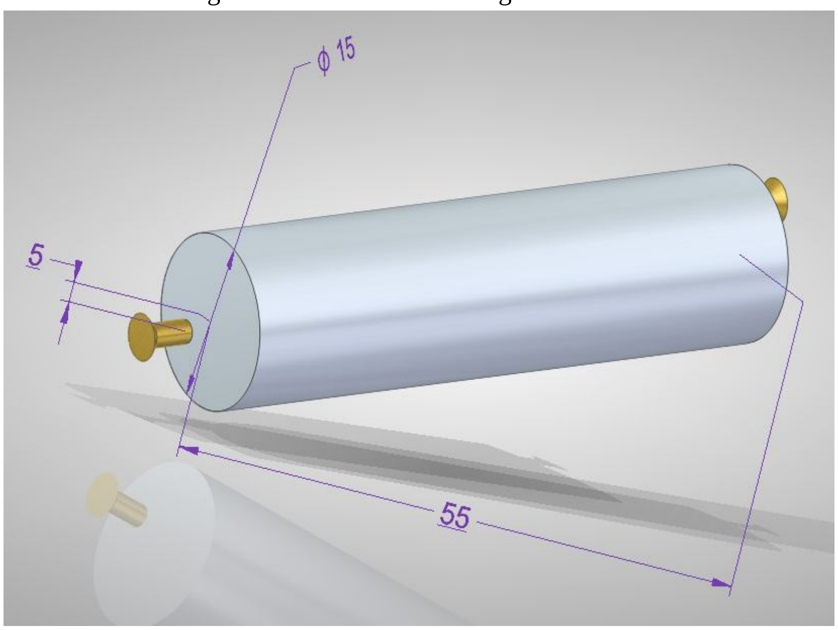

Fig 5.7 Shaft with eccentric screws

I. Bearings

The function of bearing is to make the rotation of the shaft smooth and frictionless. This helps in reducing power losses and thus work required to rotate the shaft. A single row deep groove ball bearing is used for the project. Since the internal diameter of the bearing was known it did not require any design procedures for selecting the bearing. The bearing selected was SKF 6202.

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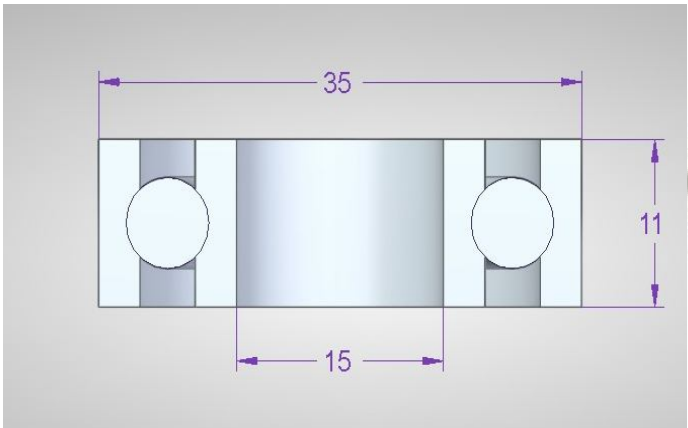

Fig 5.8 Bearing cross-section

Fig 5.9 Bearing (SKF 6202)

J. Connecting Rods

The connecting rods connect the piston, displacer and the shafts together. Two separate connecting rods were used for the displacer and piston. One end of each connecting rod was bended in semi-circular pattern. This bended end was use to hook with the piston and displacer rods. Other end was twisted to form a circular ring perpendicular to the bend in the other end. A 2mm steel rod is used as the connecting rod for both piston and displacer.

$$\text{Force due to gas pressure } F_g = \frac{\pi \times d^2 \times p_{max}}{4} = \frac{\pi \times .018^2 \times 151987.5}{4}$$

$$= 38.5N$$

Inertia force due to reciprocating parts $F_{ir} = \frac{0.01095 \times W \times r \times n^2}{g}(1 + \frac{r}{L})$

$$= \frac{0.01095 \times 1.962 \times 10^{-3} \times .005 \times 150^2}{9.81} \times (1 + \frac{95}{5})$$

$$= 0.3759N$$

Combined force on piston $F = F_g + F_{ir} = 38.5 + 0.3759 = 39N$

Component of force acting along the axis of connecting rod $F_c = \frac{F}{\sqrt{1-(\frac{r}{L})^2}}$

$$= \frac{39}{\sqrt{1-(\frac{5}{95})^2}} = 45.86N$$

For L/r< 60 Straight line formula is used to find buckling load. Here L/r is 19 and 27 for piston and displacer rods respectively.

As per Straight line formula,

Buckling load $P_c = A_{cr}[\sigma_y - \left(\frac{2\sigma_y}{3\pi} \times \frac{L}{r} \times \sqrt{\frac{\sigma_y}{3nE}}\right)]$

For piston connecting rod, $P_c = \frac{\pi \times 2^2}{4} \times [300 - \left(\frac{600}{3\pi} \times \frac{95}{5} \times \sqrt{\frac{300}{3 \times 1 \times 2 \times 10^5}}\right)] = 857N$

For displacer connecting rod, $P_c = \frac{\pi \times 2^2}{4} \times [300 - \left(\frac{600}{3\pi} \times \frac{135}{5} \times \sqrt{\frac{300}{3 \times 1 \times 2 \times 10^5}}\right)]$

$$= 821N$$

Since $F_c < F_{max}$, the design of piston connecting rod is safe and will not buckle. Considering the piston the load on displacer connecting rod is too low and can be neglected. So both the connecting rods can be considered safe.

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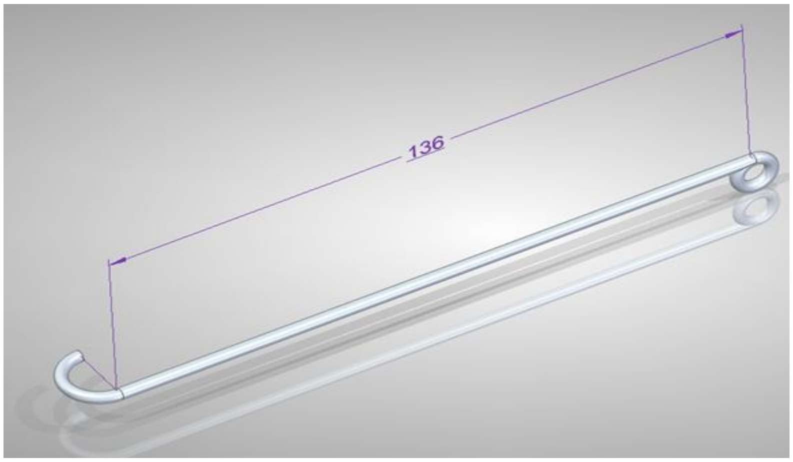

Fig 5.10 Displacer connecting rod

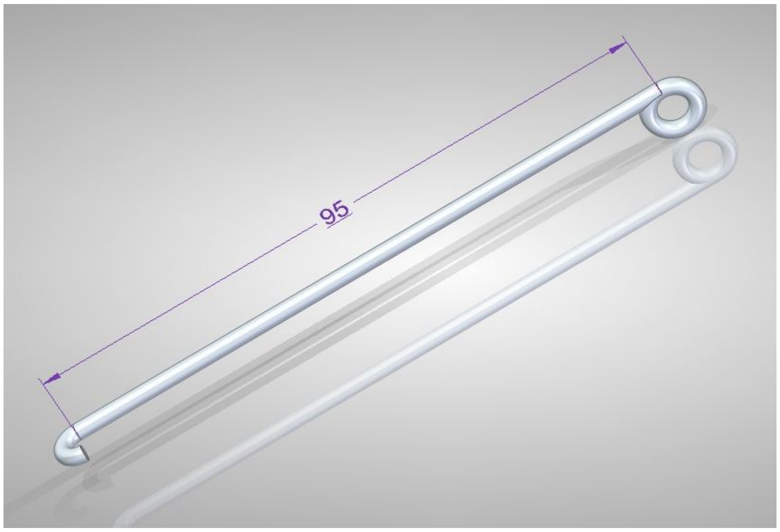

Fig 5.11 Piston connecting rod

The design of different components of stirling engine was performed in this chapter. The components were machined based on these designs. Designed components were then assembled to obtain the LTD stirling engine. The fully assembled engine was then put into test by providing the heat source under the lower plate. The detailed result on the performance parameters is given in the next chapter.

VI. RESULT AND DISCUSSION

The design and fabrication of the engine is completed successfully. After the fabrication work the engine was assembled and tested. A heat source was supplied under the lower plate of the engine, in this case we supplied steam to the bottom plate. Heat was provided for few seconds for initial warm up of engine working fluid. The engine was then started by giving an initial push by rotating the flywheel. It was observed that the engine shaft rotated at about 60 rpm when a temperature difference of about 60^0C was provided. Also an increase in engine speed was observed when higher temperature was provided at the bottom plate. For the same heat input the shaft speed increased when the top plate was cooled. We cooled the top plate by placing ice on the surface of the top plate. Since the power output and torque generated of the engine is low, we were unable to conduct a complete performance analysis. There were practical difficulties in collecting the temperature data’s which required thermocouples. As mentioned earlier, due to low torque generated we required a highly accurate loading apparatus or dynamometer for load testing of the engine. Due to these difficulties we could not conduct the load testing or performance analysis on the engine. The expected performance curves for the engine are shown in the graph below. These performance characteristic curves are quite similar to that of the piston-type internal combustion engine. The performance curves of the engine are described as follows:

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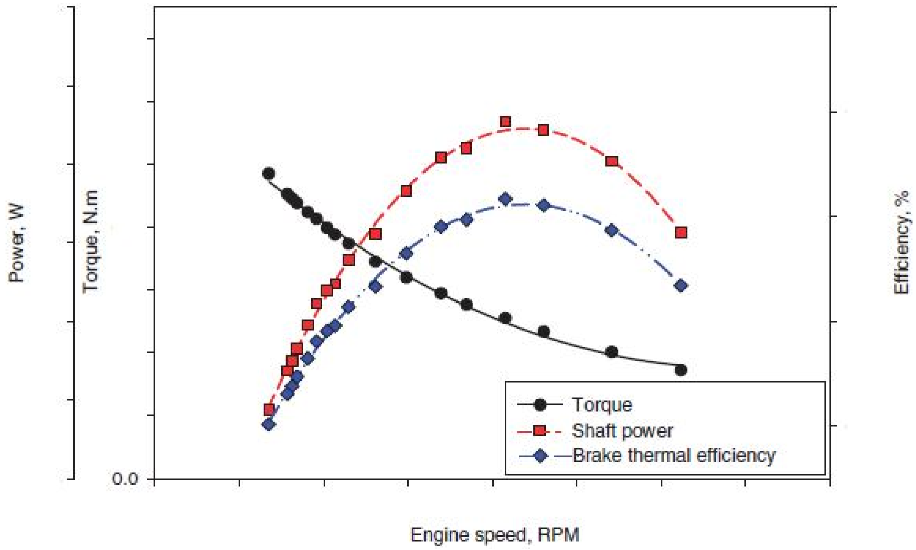

Fig 6.1 Performance chart

In an engine test, after the load is gradually applied to the engine, the engine speed will gradually reduce until a certain applied load will stop the engine. The characteristics are represented by the curve of torque versus engine speed. In these figures, it can be noted that the engine torque decreases with increasing engine speed. The variations of shaft power with engine speed are also shown in these figures. The shaft power increases with increasing engine speed until the maximum shaft power is reached and then decreases with increasing engine speed. The decreasing shaft power after the maximum point results from the friction that increases with increasing speed together with inadequate heat transfers at higher speed.

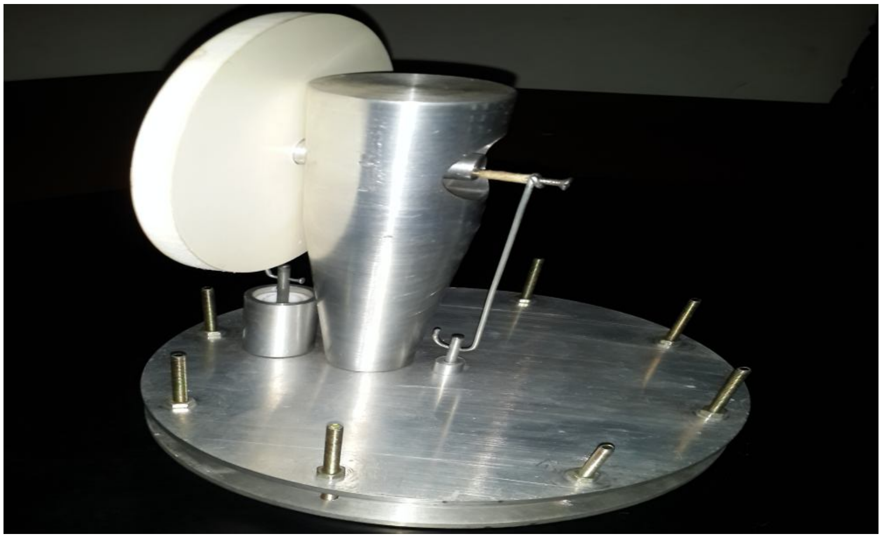

Fig 6.2 Final assembled view of engine

VII. CONCLUSION

The main aim of this engine design is to make working model of a low temperature differential stirling engine to run on a variety of low grade heat sources that are potentially free. If a small version (1-4 kW output) was able to be produced cheap enough then it could potentially find its way into applications such as off-grid domestic power generation, competing with current technologies such as solar panels, wind turbines and even other technologies. In such an application it would most likely be driven by hot water sourced from inexpensive solar collectors and may also be used in conjunction with the domestic hot water system. Other potential heat sources may include geothermal hot springs (though this would be very limiting in market potential) or direct heat from the likes of a wetback wood fireplace. The advantage stirling engine poses over solar panels is that the issue with panel life can be avoided and poses a longer life.

If a scaled up version were to be investigated then many more commercial possibilities become available. In the tens to hundreds of kilowatts range there is scope for pumps that are driven partially or wholly by the heat contained in the fluid that they are pumping. Pumps that drive hot fluid are found in many industrial processes such as production and processing plants and power stations. Some industrial processes may have such a great output of waste heat that it would be possible to drive a Stirling engine in the megawatts range, and in such applications it is an added bonus to remove this heat as it is often problematic and of environmental concern when dumping it to rivers or lakes.

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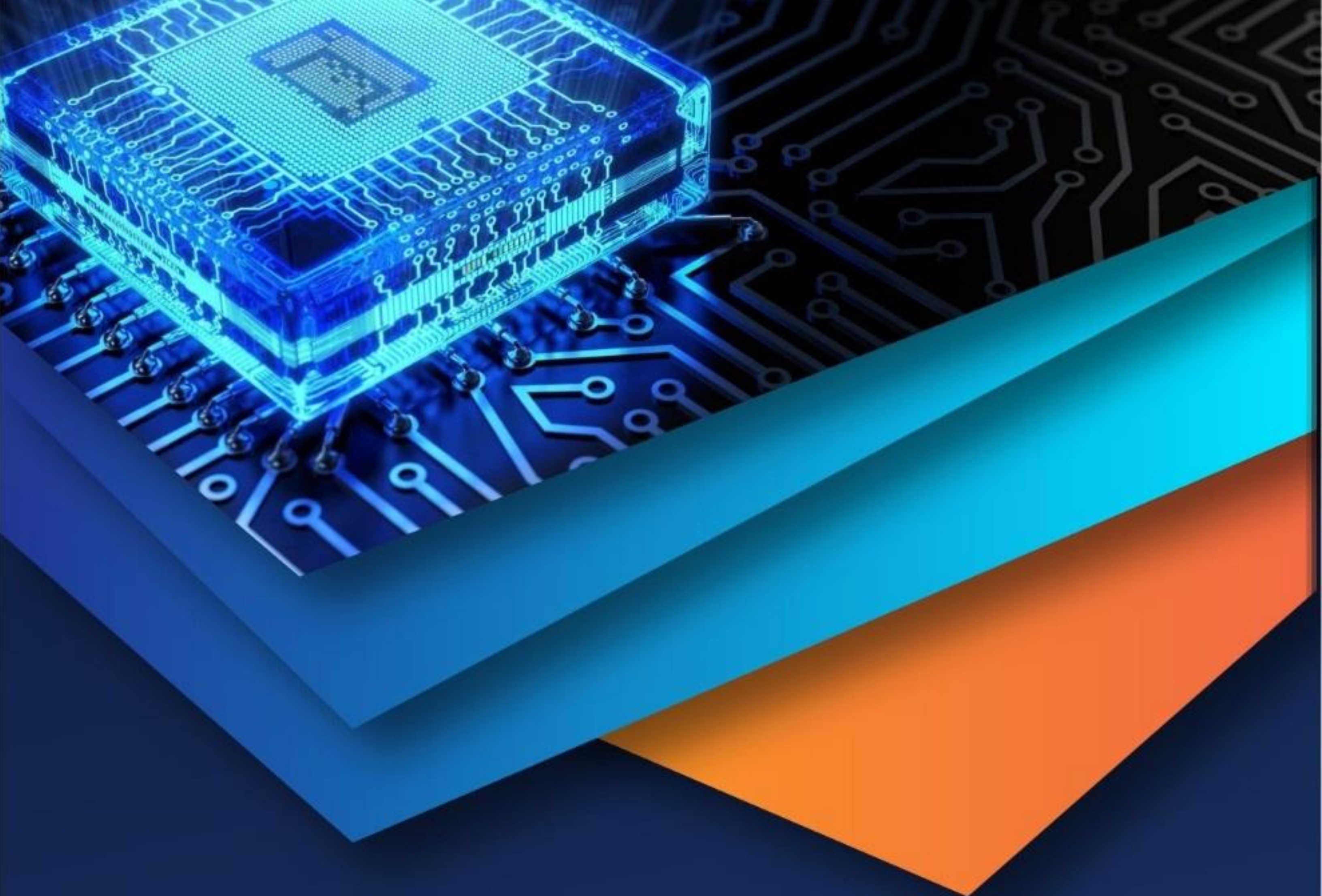

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