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DESIGN A SOLAR POWERED STIRLING ENGINE PROTOTYPE TO PRODUCE ELECTRICITY

Lee Shee Yao[1] , Hanani Abdul Wahab[1, *]

[1]Faculty of Mechanical Engineering and Manufacturing, University of Tun Hussein Onn Malaysia,
Batu Pahat, Johor, Malaysia
[*] nani@uthm.edu.my

ABSTRACT For the concerns of environmental issue such as global warming, sustainable and green way to produce energy is highly in demand. Dish Stirling system is one of the most efficient system among others concentrated solar power technologies. However, the system is in disadvantage in terms of cost and reliability when compare to others CSP technologies. In this study, a fundamental prototype of solar powered dish Stirling engine is designed, manufactured, and tested. One component of the prototype which is the power piston is malfunctioning. It was found that the accuracy requirement of the manufacturing of the prototype was high and it requires high skill and experience in machining process.

Keywords: Parabolic dish, free piston Stirling engine

INTRODUCTION

Our world that relied on non-renewable energy source such as fossil fuel has caused many environmental issues such as pollution and global warming. This urges the exploitation of renewable energy sources for the ever growing energy demand. Solar energy is one of the most promising alternatives that can curb these issues.

A conventional power generator system uses fossil fuel as their source of thermal energy. However, there is an existing approach which uses solar energy to power a Stirling engine coupled with an induction generator. Such system is commonly known as dish-Stirling system, has shown promising result in terms of its performance. A dish-Stirling system is one of the concentrated solar power (CSP) technology that uses parabolic dish concentrator to reflect the sun light to a point focus receiver of a Stirling engine to generate power. Currently, dish-Stirling system has the highest solar conversion efficiencies of all current CSP technology[1]. Besides, a dish concentrator also achieved highest optical efficiencies, highest concentration ratio of all other CSP concentrator.

Dish Stirling system has been researched and developed mainly in large scale for generating electricity and constructed as power plant. Despite all the advantages of high efficiency over the other CSP technology, the technology of dish Stirling system is still not matured to be commercialized. However design of the engine can possibly overrule what has been found as the theoretical economic optimum. To increase the system's competitiveness with other CSP technology, thermal storage and hybrid operation are interesting options but they are still technically challenging and not yet proven [2].

BRIEF HISTORY

Stirling engine is a closed-cycle external combustion engine which was invented by Reverend Robert Stirling, D.D., of Cloag, Methvin, Perthshire, in 1816. In comparison to an open-cycle engine, closed-cycle and exhaust of the working fluid into each other, and while part of the working fluid need to be heated at one part of the engine and simultaneously cooled in another part. Figure 1 shows the reproduced description from the original patent specification of 1816.

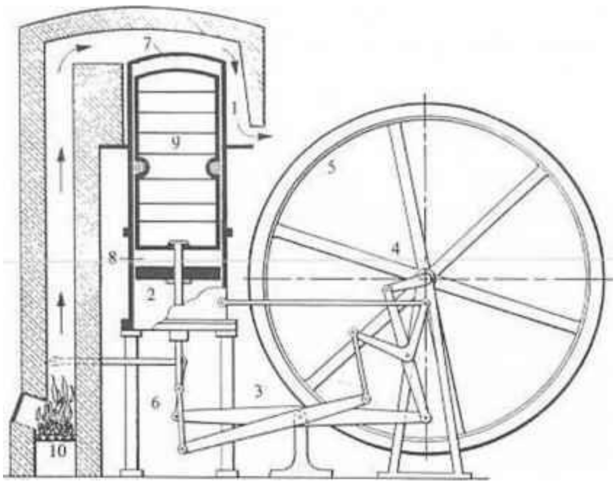

Figure-1: Original drawing of Stirling engine based on patent specification of 1816.

WORKING PRINCIPLES

The working principle of a Stirling engine is shown in Figure 2.2 while Figure 2.3 shows the P-V and T-s diagram of a Stirling cycle.

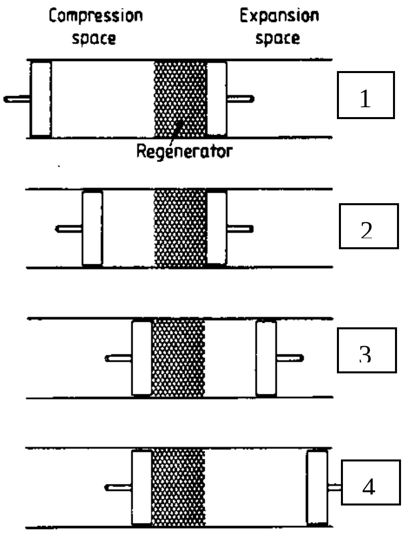

Figure-2: Working principle of a Stirling engine.

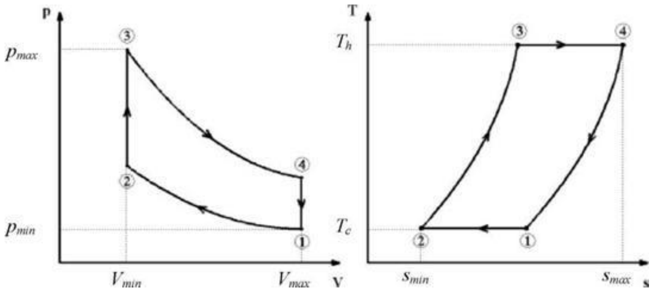

Figure-3: P-V and T-s diagram of a Stirling cycle.

First, the compression-space piston is at the outer dead point, and the expansion-space piston is at the inner dead point, next to the regenerator. In this positions (represented by 1 in the Figure 2.3), the volume is maximum while the pressure and temperature values are at their minimum. For process 1-2, cold isothermal compression occurs, when the compression piston moves towards the inner dead point while the expansion piston remain stationary. The working fluid is compressed and its pressure increases. However, the temperature remains constant due to heat is abstracted by the cooler at the compression space to the surrounding (heat sink). For process 2-3, isochoric heating occurs, when both piston move simultaneously (the compression piston towards the regenerator while the expansion piston away from the regenerator), such that the volume remain constant during the process. As a result, the working fluid will pass through the regenerator and gain heat from the regenerator. Subsequently, the temperature of the working fluid will increase from Tc to Th in the expansion space. As temperature increases at constant volume, pressure increases. For process 3-4, isothermal expansion occurs, when the expansion piston moves toward the outer dead point of the expansion space, while the compression piston remains stationary. During the expansion, the pressure of the working fluid decreases gradually, and the volume increase to Vmax. The temperature remain constant due the heat added by the external heat source to the expansion space.

Lastly, for process 4-1, isochoric cooling occurs, when both piston move simultaneously (the expansion piston towards the regenerator while the compression piston away from the regenerator), such that the volume remain constant during the process. As a result, the working fluid will pass through the regenerator and restore heat back to the regenerator. Subsequently, the temperature of the working fluid will decrease from Th to Tc in the compre 1 pace. As temperature decreases at constant volume, pressure decreases [3].

TYPES AND VARIATION

2 g engine can be classified by their restoring mechan… there are basically two types. The first type is kinematic, which the piston is connected to linkage, cranks or flywheel which is then connected to say a generator. The second type is free piston, which there is no linkage 3 her mechanism connected to the piston. Therefore the pistons can drive a linear alternator directly. Without linkage mechanism, a spring or damping system is used instead in order to the system to move at natural frequency and the engine only have two moving parts. Free piston S 4 engine has the advantage of simple design, however, it is still far less developed compared to the kinematic type [4].

The Stirling engine can be further classified by their structural configuration of pistons and the processes occurred to the working fluid.

1. Alpha

Alpha configuration has two separate cylinders for hot working fluid and cold working fluid respectively. The two cylinders are usually arranged in 90 degrees to each other and are joint to the same point on a flywheel as show in Figure 2.4. This configuration is suitable for high temperature application and has high efficiency and output [4].

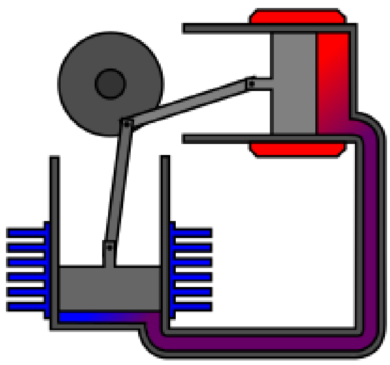

Figure-4: Alpha Stirling engine.

2. Beta

Beta configuration has only one cylinder which contains both the displacer and the power piston. The working fluid will alternate between the hot space and the cold space, regulated by the displacer and power piston together (see Figure 2.5) [4].

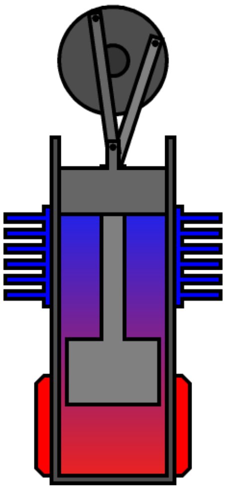

Figure-5: Beta Stirling engine.

3. Gamma

Gamma/ low temperature difference configuration is similar to the Beta configuration except that the power piston and the displacer are place in separated but interconnected cylinders. Besides, the power cylinder's diameter is smaller compared to the displacer and therefore tend to have large dead space which lowers the power output (see Figure 2.6) [4].

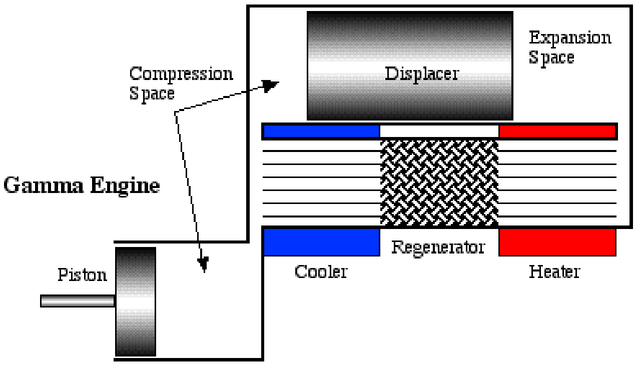

Figure-6: Gamma engine.

SOLAR POWERED DISH STIRLING SYSTEM

The solar powered dish Stirling system consist of parabolic dish, mounting structure, solar tracking system, receiver, Stirling engine, cooling system and electric generator or alternator. These components works together in order to produce electricity from sun light. The function of these components are describe below:

The solar tracking system will track the sun's position so that the axis of the parabolic dish will always be parallel to the sun light. The parabolic dish will reflects and concentrates the sun light to a focus point where the receiver is placed. The receiver will absorb the heat from the concentrated sun light and transfer the heat to the working fluid in the Stirling engine. The working fluid in the engine can be either air, hydrogen or helium heats up and cools down in a cyclic way to convert thermal energy to mechanical energy [5].

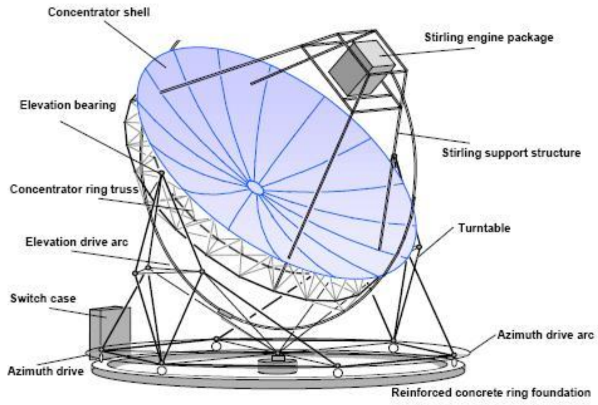

Figure-7: Schematic diagram example of a dish Stirling system.

METHODOLOGY

Figure 3.1 shows the flowchart of this study.

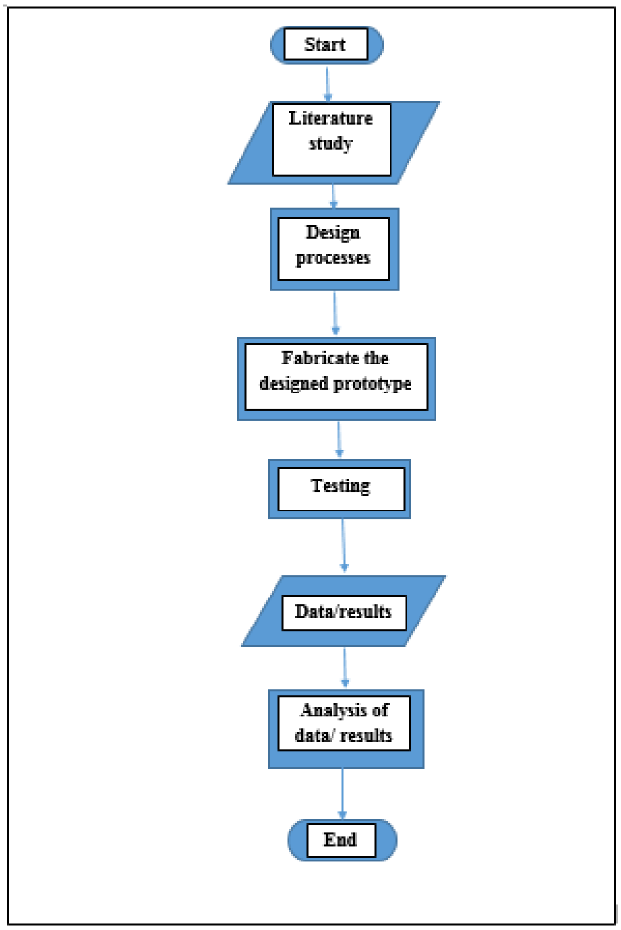

Figure-8: Flow chart of this study.

IDEA SELECTION

The idea selection process is applied to select from the various configurations and linkage mechanism of Stirling engine. There are three main configurations of Stirling engine, namely alpha, beta and gamma configurations, and two types of linkage mechanism namely kinematic and free piston. Table-1 shows the pros and cons of each criteria mentioned. These criteria is weighted against the constraint and technical requirement shown in Table-2.

Table-1: Pros and Cons of Stirling engine configuration and linkage mechanism.

Configuration	Pros	Cons
Alpha	• High power • High temperature differential • High efficiency.	• Piston seal difficulty at hot end. • High cost
Beta	• High power • High temperature differential • Seals are less crucial	• High cost
Gamma	• Low temperature differential • Low cost	• Low power
Linkage mechanism		
Kinematic	• Better control of working fluid	• Require more parts • Sealing problems
Free piston	• Less moving parts	• Hard to design and manufacture

Table-2: Evaluation of Stirling engine's configuration based on manufacturing cost, durability and power output. (Rating from 1-10, 1 for undesirable, 10 for most desirable)

	Alpha			Total
Design criterion	Manufacturing cost	Durability	Power output	
Kinematic	5	6	9	20
Free piston	6	7	9	22
	Beta			
Kinematic	6	7	9	22
Free piston	7	8	9	24
	Gamma			
Kinematic	9	5	5	19
Free piston	10	5	5	20

From Table-2 above, free piston, beta configuration has the highest overall rating. Therefore, a free piston, beta Stirling engine will be design as the prototype.

FABRICATE THE PARABOLIC DISH CONCENTRATOR

The parabolic dish concentrator can be created using a recycled standard direct TV satellite sold by ASTRO Malaysia. They can sometimes be found in the trash site of a neighborhood where people throw it after they unsubscribed for the direct TV services. Firstly the surface of the satellite dish is sanded down using 180 grit grinding sand paper and a hand grinder as shown in Figure-9. Figure-10 show the parabolic dish after it had been sanded.

Then, the solar reflective film is cut to about an inch wide strip and is pasted on the sanded surface of the parabolic dish. With the solar reflective film, the parabolic dish can now work as a concentrator. Figure-11 shows the parabolic dish concentrator that has been produced.

Figure-9: A 180 grit sandpaper and a hand grinder.

Figure-10: ASTRO satellite dish that has been sanded.

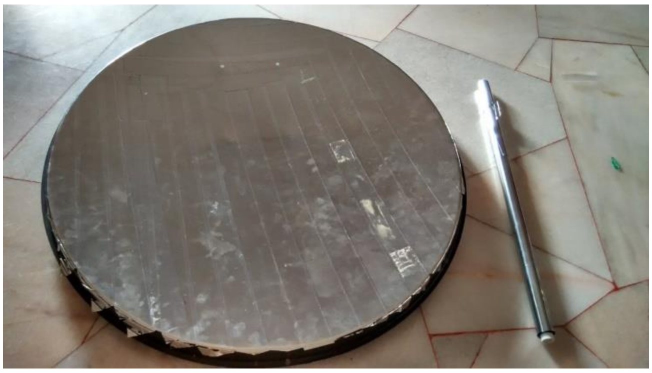

Figure-11: Parabolic dish concentrator made from Astro satellite dish by pasting the surface with solar reflective film.

FABRICATE THE FREE PISTON STIRLING ENGINE

In this section, the fabrication processes of the free piston Stirling engine will be summarized in Table-3 and Table-4. Standard parts like bolt and nuts, and springs are bought from hardware shops.

Table-3 Fabrication methods for each part of the free piston Stirling engine.

Part no.	Name	Fabrication methods
1	Displacer cylinder	Lathe and milling
2	Displacer	Lathe
3	Displacer rod	Lathe
4	Power piston cylinder	Lathe and milling, lapping and polishing
5	Power piston	Lathe and milling, lapping and polishing
6	Annular regenerator	Cut using scissors
7	Radiator	Lathe
8	Cylinder top flange	Milling and EDM wire cut
9	Top cover flange	Milling and EDM wire cut
10	Top cover	EDM wire cut
11	Top cover cylinder	Lathe
12	Spring holder	Lathe and grinding.

The joining methods for each part are summarized in Table 3.4.

Table-4: Joining methods for each part.

Part no.	Name	Joining methods
1, 4	Displacer cylinder and power piston cylinder	Sealed with RTV silicone gasket maker, joint using bolts and nuts (size M5).
2, 3	Displacer and displacer rod	MIG welding, bench grinding finishing
4, 7	Power piston cylinder and radiator	The power piston is fitted into the hole of the radiator
4, 9	Power piston cylinder and cylinder top flange	MIG welding, use hand grinder for finishing
9, 10, 11	Top cover flange, top cover, top cover cylinder	MIG welding, use hand grinder for finishing
8, 12	Cylinder top flange, spring holder	Joint using bolts and nuts (size M6).
8, 9	Cylinder top flange and top cover flange	Joint using bolts and nuts (size M6).

Figure-12 shows all of the parts fabricated in their disassembled state. One of the spring is welded to the power piston and the other spring is to be join with the displacer rod using super glue. Figure-13 shows the fully assembled free piston Stirling engine prototype and the top cover is to be joint to the cylinder top flange using bolts and nuts to provide hermetic seal to the system. A Schrader valve is attached to the top cover so that the system can be charged to higher operating pressure. Figure-14 shows the stator coil and Figure-15 shows the N50 grade neodymium permanent magnet that is used for making a simple linear alternator.

Figure-12: Parts before joining them with bolts and nuts.

Figure-13: The fully assembled free piston Stirling engine prototype and its top cover.

Figure-14: Stator coil.

Figure-15: Two pieces of N50 (D25mmxH5mm) strong magnet.

EXPERIMENT

After the prototype has been fabricated, test run will be carried out on the prototype. If the prototype is working, experiments will be carried out to obtain the required parameters for analysis.

For the testing of the parabolic dish, it is carried out on 27th November 2016 at time about 1230 at Parit Raja, Batu Pahat. During that time, the sky was clear and direct solar radiation can be received. The parabolic dish concentrator is adjusted until it face the sun and produce a nice focal point when the plywood is place at the focal point. Then after about 30 seconds, the plywood would start giving out smoke and black burn mark is observed on the plywood. The temperature of the plywood at the focal point and temperature of the surface of the parabolic dish concentrator were measure using an infrared thermometer, and the readings were recorded (see Figure-16 and Figure-17).

For the testing of the free piston Stirling engine, the prototype was placed in the flame of a cooking stove. When the temperature and the hot end reach above 300 degree Celsius, the power piston is pushed pulled to give the engine a kick start. The temperature of the hot end and cold end are measured and recorded (see Figure-18).

Figure-16: Temperature of concentrator measured using infrared thermometer (44.6 degree Celsius).

Figure-17: Temperature of concentrator measured using infrared thermometer (428 degree Celsius which is greater than the flash point of wood 400 degree Celcius).

Figure-18: Temperature measured at heater end and cooler end.

RESULTS

The measurements of the parabolic dish concentrator needed for the analysis of the focal point are recorded in Table-5.

Table-5: Measurements of the dish.

Measurements of the dish	
Long axis length (mm)	660
Short axis length (mm)	610
Depth (mm)	50

The surface temperature if the dish and the plywood is measured after the 30 seconds. Smoke was observed and as if the plywood was burning (see Figure-19). The measurement of temperatures are recorded in Table-6

Table-6: Surface temperature of dish and plywood.

Parts	Surface temperature(℃)
Dish	44.6
Plywood	428.1

Figure-19 shows the parabolic concentrator that is placed under the sun while a piece of plywood is placed at the focal point. Then the approximate distance from bottom edge to the focal point is measured to be 500 mm.

Figure-19: Focal length measured from the bottom edge of the parabolic dish (approximately 500 mm).

The prototype heater end is place on a gas stove and let to be burn until the temperature rise until about 390 degree Celsius. At the same time, the temperature at the cooler end is measure to be about 62 degree Celsius. The temperature difference is need for the engine to start working. Then, the spring connected to the power piston is pushed or pulled to give the engine a kick start. However, the prototype did not start up or run.

Further diagnosis of the problem with the prototype is done and is discussed in the following chapter. However, in ideal condition, given the temperature difference in a heat engine, the maximum efficiency of a thermal cycle can be calculated using Carnot's efficiency equation:

$$\eta_{Carnot} = \left(1 - \frac{T_L}{T_H}\right) \times 100\%$$

$$= \left(1 - \frac{62 + 273}{388 + 273}\right) \times 100\%$$

$$= 49.32\%$$

According to Allan J Organ[6], the most efficient engine achievable now is about half of that of Carnot's efficiency, i.e: 49.32/2=24.66%.

Due to the prototype is unable to run, the linear alternator which in original plan is not able to be coupled to the prototype to produce electricity.

DISCUSSIONS

In this section, the problem faced during the design and fabrication process and the countermeasures or suggestions for them are discussed thoroughly in order to provide a guideline for future work.

The parabolic dish concentrator produce a focal point of solar flux that is not uniform or is scattered. This may due to the accuracy when manufacturing the dish by the manufacturer. As the requirement of accuracy increases, the cost of manufacturing will also increases. The dish used is an Astro direct TV antenna which cost about RM200 for the dish including the stand. Another factor is when applying the solar reflective film onto the dish, some of the dish surface are not even due to the rough sanding process which can reduce the performance of the dish concentrator. The suggestion for improvement is to sand the dish surface with finer grits sand paper such P200 and above. Also, the dish can be sent to be chrome plated in shop, but the cost will definitely increase as well.

Another aspect which is important for the dish concentrator to function at maximum efficiency is its ability to track the sun. Therefore, it is recommended to design an adjustable solar tracking mechanism for the dish concentrator.

The fabrication of the free piston Stirling engine was mainly done by machining process such as lathe and milling. One of the requirement for the parts of free piston Stirling engine is that every parts are needed to be manufactured to great accuracy and high surface finish especially parts that are moving in the engine. In order to achieve that, good fabrication procedure or planning need to be laid out to reduce error. The quality of machining product is also affected by human error, environmental condition and tool condition.

For instance, one of the mistake made was when boring the power piston cylinder and clamping its thin section in the chuck. The clamping force of the chuck will deform the cylinder by a little say a few micron which is invisible to our eyes, and it is this small tolerance that matters when trying to fit the piston into the cylinder. Therefore, it is necessary to leave extra length to the work piece to be clamped in the chuck while the extra length can be removed later. In addition, it is common practice to use two cutting tools which one is for roughing and one is for finishing. Always use coolant in high speed cutting.

There is a process of sanding and polishing of power piston and power piston cylinder in order to fit them together. The clearance is best when it is less than 6 micron. The mistake made was using a P600 grit sand paper for the process of sanding and polishing. This causes the clearance between the power piston and the power piston cylinder is approximately 50micron. Therefore, it is recommended to use at least P1200 grit sand paper and higher for the finishing process to get close tolerance fitting and P2400 grit to P3000 grit for final polishing.

However, the process of sanding using sand paper may not produce a truly uniform and accurate finishing for a work piece that require very tight tolerance and high surface finish. The machine capable of doing the work is called cylindrical grinder which is available but is under maintenance in UTHM. By using the suitable grinding wheel with fine grits, surface with very low roughness can be produced.

The parts which require tight tolerance and high surface finish are power piston, power piston cylinder and displacer rod. Due to improper technique in manufacturing them, the pressure essential for the free piston Stirling engine is unable to be achieved due to high leakage at the power piston and the displacer rod which subsequently causes the free piston Stirling engine is unable to run.

The material selection for the different parts of free piston Stirling engine will also affect the performance and reliability of them. Basically, the materials need to be able withstand high temperature oxidation due to high temperature. Iron materials that will rust easily at high temperature should be avoided. Besides, the materials used for parts that is close to the linear alternator which have strong magnet should not be ferromagnetic materials, as they will pull the magnet and cause the linear alternator unable to work. It is recommended materials to be used are stainless steel, aluminium or its alloy, and cast iron. These unique materials requirement will naturally increase the manufacturing cost and overall cost of the prototype as well.

The material used for mechanical seal is RTV silicone gasket maker, which provides good seal, however, it is recommended to use high temperature O-ring for easier assembly or disassembly of the prototype.

CONCLUSION

As a conclusion, doing this project has gained me a lot of valuable experience and knowledge. I have also been able to apply engineering knowledge to design the free piston Stirling engine prototype. I have gain some experience in machining process using a lathe and milling machine. The requirements for producing high quality machining product are having great patient, ability to put attention into fine details, careful usage of suitable tools, ability to control the environment of the manufacturing process and also experience in doing the job. It is also a good learning process for me as I had to seek advice from the technicians or the head of the machining lab.

Even though the end product is not as expected result, that it will run and produce electricity, the refinement needed to be done in future are clearly discussed in Chapter 4. This can provide a guideline for future student who wish to manufacture a dish Stirling engine prototype. It is also recommended that this design project can be assign to three to five final year students as many core disciplines such as dynamics, statics, thermodynamics, heat transfer, computer aided design, computer aided manufacturing, fluid mechanics, basic electric and manufacturing technology.

REFERENCES

[1] W. S. K. Lovegrove, "Introduction to concentrating solar power (CSP) technology," *Conc. Sol. power Technol. Princ. Dev. Appl.*, p. 10, 2012.

[2] W. S. and T. Keck, "Parabolic dish concentrating solar power (CSP) systems," *Conc. Sol. power Technol. Princ. Dev. Appl.*, pp. 284–322, 2012.

[3] M. A. B. Yunus A. Cengel, "9-7 Stirling and Ericsson Cycles," in *Thermodynamics: An Engineering Approach, Seventh Edition in SI Units*, New York: McGraw-Hill Education, 2011, pp. 499–502.

[4] A. J. O. Theodor Finkelstein, "Reassessment," in *Air Engines*, London and Bury St Edmunds, UK: Professional Engineering Publishing Limited, 2001, pp. 87–102.

[5] R. B. D. William B. Stine, "'A compendium of solar dish/Stirling technology', Report SAND93-7026," Sandia National Laboratories, Albuquerque, NM, 1994.

[6] A. J. Organ, *Stirling Cycle Engines*. West Sussex: John Wiley & Sons, Ltd, 2014.