Performance Analysis of a Stirling Engine Heated by Two Individual Heat Sources (Solar and Fossil Fuel)

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ABSTRACT

To meet the continuously increasing demand in electricity, while conserving our natural resources and the earth as a whole, more effective and alternative energy sources must be utilized. For an alternative source of energy to be attractive, it must be both economical and have the ability to be interconnected with existing grid. Stirling engine can achieve and implement the highest efficiency of all the practical heat engines and theoretically up to the Carnot efficiency. In addition, Stirling engine is fuel flexible, and is not limited to any one specific heat sources.

The purpose of this thesis is to effectively and efficiently convert thermal energy from two different heat sources (solar and fossil fuel) into electrical energy via Stirling heat engine. The comparison and performance of these two heat sources under Northern Cyprus climate conditions analyzed. The proposed work is designed and developed a prototype and manufactured alpha Stirling engine operates at temperature range of 70℃ to 200℃. The engine first tested and heated by fossil fuels and secondly by solar radiation. Two working fluids (helium and air) are considered in this prototype to compare the working principles of the engine.

Keywords: Stirling engine, Stirling cycle, low moderate temperature, helium, fuel flexible, engine performance, thermodynamic simulation.

ÖZ

Doğal kaynakları muhafaza ederken, artan elektrik talebinin karşılanması için daha etkili ve alternatif enerji kaynakları kullanılmalıdır. Bununla birlikte, kullanılacak alternatif kaynağın ekonomik ve mevcut dağıtım sistemine uyumlu olması gerekmektedir. Stirling motoru diğer ısı motorları arasında pratik olarak en yüksek, teorik olarak Carnot verimine yakındır. Ayrıca Striling motoru yakıt kullanımında esnektir ve herhangi bir özel ısı kaynağı ile sınırlı değildir.

Bu tezin amacı etkin ve verimli bir şekilde iki farklı ısıl enerji kaynağını (güneş ve yanan yakıt) elektrik enerjisine dönüştürmek için Stirling kullanılmasıdır. Kuzey Kıbrıs iklim koşulları altında bu iki ısı kaynağının karşılaştırılması ve performans analizinin yapılmasıdır. Bir diğer amaç ise 70℃ - 200℃ sıcaklıkları arasında çalışabilen bir prototipin tasarlanıp üretilmesidir. Prototip önce fosil yakıt sonra da güneş enerjisi kullanarak test edilmiştir. Çalışma akışkanı olarak hava ve helyum gazı kullanılarak karşılaştırma yapılmıştır.

Anahtar kelimeler: Stirling motor, Stirling döngüsü, düşük orta sıcaklık, Helyum, esnek yakıt, motor performansı, termodinamik simülasyon

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LIST OF ABBREVIATIONS

LTD	Low Temperature Difference
CHP	Combined Heat and Power
PV	Photovoltaic
IC	Internal Combustion
CPS	Concentrated Power Solar
SES	Stirling Engine System
LOX	Liquid and Oxygen
TDC	Top Dead Center
BDC	Bottom Dead Center
HHV	High Heating Value
LHW	Low Heating Value
RPM	Revolution per Minute

LIST OF SYMBOLS

A	Area [m^2]
B_n	Beale number
d	Distance [m]
dx	Phase angle [°]
F	Force [N]
f	Operating frequency [Hz]
h	Hypotenuse of triangle
m	Mass of gas [kg]
η_c	Carnot efficiency
P	Power [W]
P	Engine pressure [Pa]
P_{mean}	Average pressure [Pa]
P_o	Indicated power [W]
ΔT	Temperature difference [℃]
V_R	Regenerator volume [cm^3]
V_E	Expansion volume [cm^3]
V_{SE}	Swept expansion volume [cm^3]
V_{DE}	Expansion dead volume [cm^3]
V_C	Cooler volume [cm^3]
V_{SC}	Swept compression volume [cm^3]
V_{DC}	Compression dead volume [cm^3]
V_C	Cooler volume [cm^3]
W	Work [J]

W_{cyc}	Energy of cycle
W_n	West number
X	Dead volume ratio

Chapter 1

INTRODUCTION

The highest world energy demand belongs to fossil fuels, since they are facing quick reduction and environmental issue; there is huge interest in finding a right alternative for them. Figure 1.1 shows the power generation of various sources in the world.

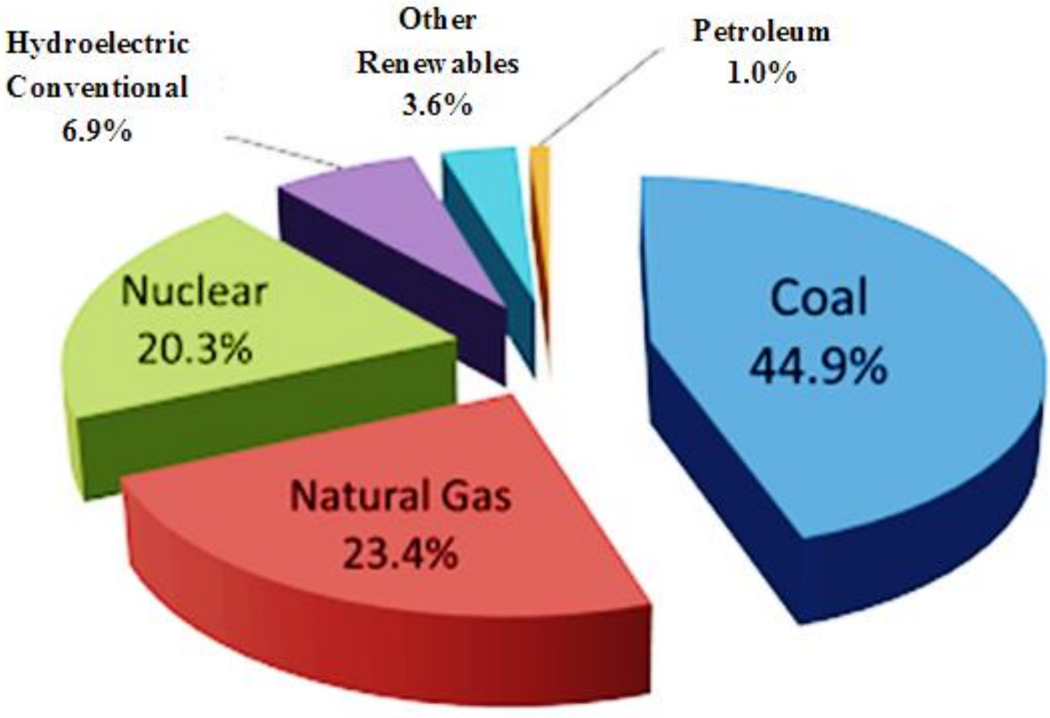

Figure 1.1. US power generation by various sources [1]

The purpose of this chapter is to provide an introduction showing the overview of this research, in four different parts. First it describes the motivation of the research. Then, the determined objectives of the research will be explained. Finally the approach, which is based on the objective, will be explained in outline.

1.1 Motivation

A Stirling engine is a heat engine which was invented by Robert Stirling in 1815. It is based on gas properties and thermodynamic laws. The engine uses an external heat source in contrast with internal combustion engines so that there is no explosion inside the cylinder while working. The gas is expanded and compressed cyclically and continuously to produce motion to transforming energy. Fluid gas remains inside the system and it is displaced from the hot side to the cool side and vice versa when the engine is operating.

A Stirling engine development falls into two categories:

- Fossil fuel fired engines
- Solar or waste heat powered, for generation of “green” and renewable power

Stirling engine is unlike an internal combustion (IC) engine where the fuel is injected into the cylinders and burned intermittently. The compressible gas can be air, hydrogen, helium, nitrogen or even vapor depending on the design of the engine. The Stirling engine has several potential advantages over internal combustion engines:

- Lower emissions that are more easily controlled
- Quieter operation due to the absence of a valve train and intermittent firing
- A wider variety of fuel sources, including combustion of fossil or biomass fuels, concentrated solar heat, and high grade waste heat from industrial processes, for different configurations of the same basic design.
- Higher theoretical efficiencies
- Higher torque across a wide range of engine speeds

Figure 1.2 shows that solar radiation can be focused on the heater of a Stirling engine and convert the solar energy to mechanical energy.

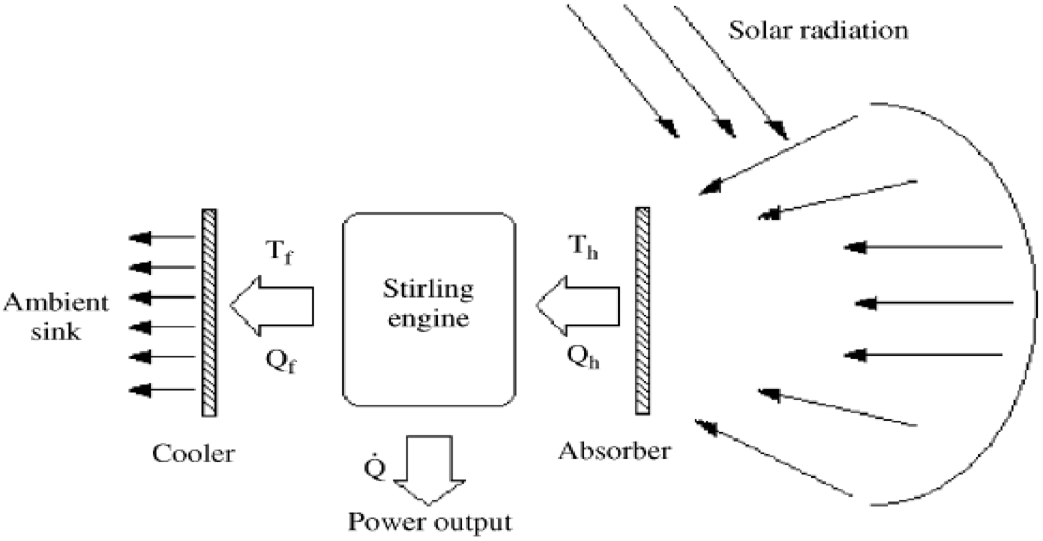

Figure 1.2. Schematic diagram of solar powered stirling engine [2]

1.2 Objective

The objective of this study is to design, build and investigate the performance of the Stirling engine which runs by using several individual heat sources such as solar and fossil fuel. One of the aims is to show that the developed Stirling heat engine can successfully work with alternative sources. Also the comparison and performance analysis of these heat sources will be investigated. To present this work an alpha type prototype Stirling engine is designed, manufactured and tested.

1.3 Approach

The work presented in this thesis is the performance analysis of a Stiling engine heated by two individual heat sources. Therefore, an alpha type Stirling engine prototype is designed and manufactured. The engine operated at relatively temperature range of 70°C to 200°C. For increasing the efficiency and performance of the engine, two types of working fluid (helium and air) individually used in the engine. Additionally water pumped in the aluminum tubes around the engine to cool the engine as well.

The general approach in this study is shown in Fig 1.3. The performance analysis between heat sources were done on the developed prototype and by the Stirling engine software analyzed and the results were compared. At the end the simulated analysis were considered to verify the efficient result.

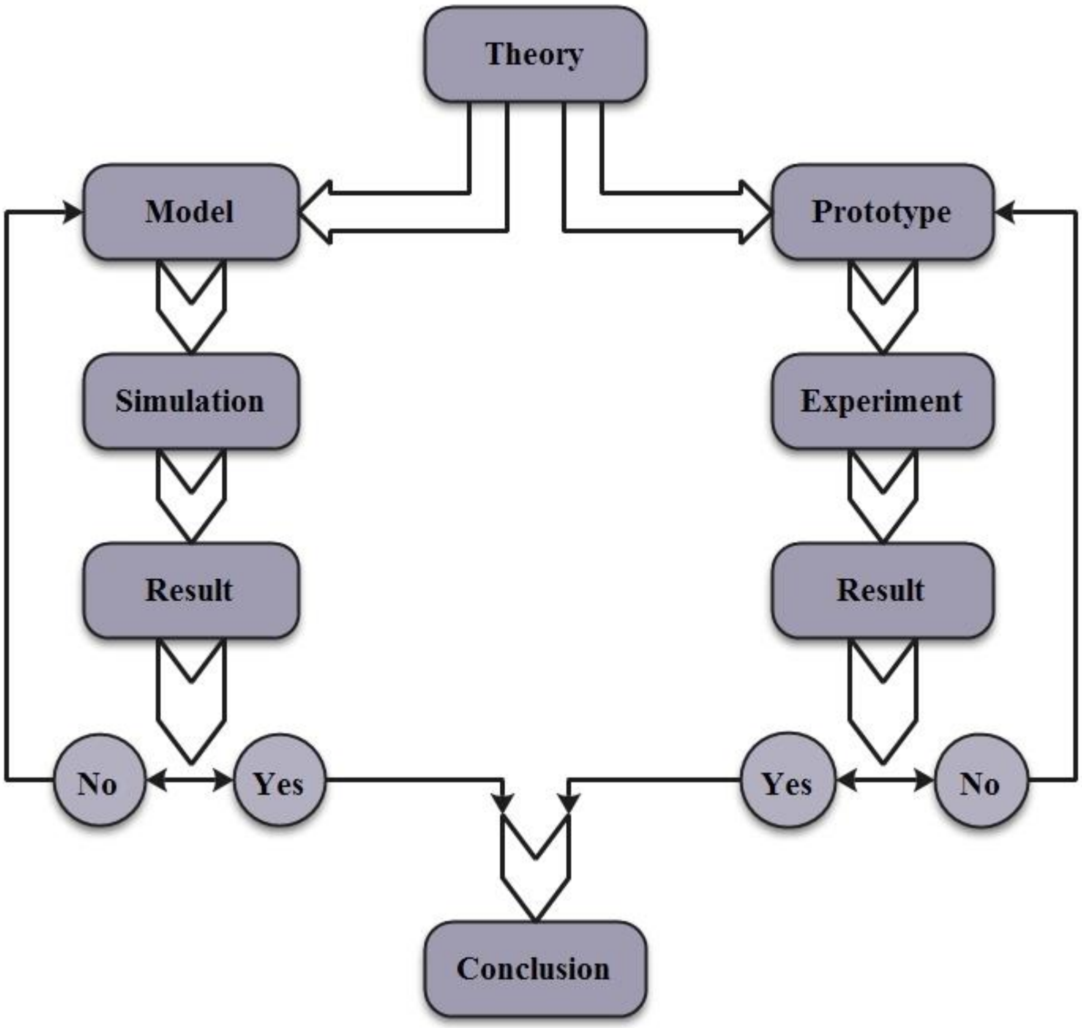

Figure 1.3. A schematic of research approach

1.4 Outline

The work presented in this thesis is mainly makes an exposition of the Stirling engine. In order to achieve the objective of this investigation, four steps were performed. In harmony with these steps, this thesis is organized in five succeeding chapters. The first step of the study is the background and literature review of the Stirling engine. This is made in the subjects of the operating principles, thermodynamic cycle and classification types of Stirling engine. These subjects are presented in the chapter 2 of this thesis. First the history and operating principles of the Stirling engine are explained. Then, the ideal thermodynamic cycle and classifications of the Stirling engine are described.

The chapter 3 is designing prototype of proposed Stirling engine. The prototype is used for the experimental study of this research. The design overview, methodology and engine construction are considered in this chapter. At first there is an overview about the investigation, then, methodology consist of mathematical modeling of the engine is described. Finally the engine construction included prototype engine components is explained.

Chapter 4 is the study of the results of the simulation and experimental tests. The experimental data of the prototype Stirling engine are described in this chapter. First engine tested by fossil fuels, secondly engine tested under the solar radiation. The performance analysis and comparison of the engine are considered by Stirling engine software. Finally the calibration instruments which used for the experimental data and their specifications are demonstrated.

Finally all results are used in order to determine the conclusion of this study and provide some recommendations for future works. Therefore, in chapter 5 the results of this study are concluded. The highlights, significant results and the summary of the main work are presented. In addition recommendation for future work is given. At the end the drawings of the manufactured prototype and the raw data showed in the appendixes.

Chapter 2

BACKGROUND AND LITERATURE REWIEW

2.1 History

Steam engines started being used in wide range during the industrial revolution of the 18th century. It’s been used in different industrial applications some of which can be called pumping, lifting heavy weighted machines and driving rotating machinery [3].

Steam engines developed by 19th century, the technological improvement in new engines made them able to have the same outcome as work of teams of horses or giant water wheels, however beside all these advantages steam engines failed in few majors such as being inefficient, according to researches these engines had efficiency of 2% to maximum 10% [1]. Even though coal was cheap at the time it still made sense to factory owners to strive for more efficient machines to maximize their profits. The main drawback of the steam engine however was their safety, or rather lack thereof. Violent boiler explosions were a matter of course, reported on a day to day basis. These explosions would release scalding high pressure steam and often led to fatalities, promoting engineers and inventors to search for a new alternative type of engine.

During 19th century Stirling engines, also known as hot air engines became the most attracted type of engine for variety of people from engineers and researchers to entrepreneurs and investors. Hot air engine is a device which expands gas when it’s heated and contracts when it gets cool and it can convert heat into mechanical applications. These types of engines has been in used since 1699, however it has been said that most workable type of these engines was open cycle gas furnace that was invented by English inventor George Cayley on 1807.

2.1.1 Stirling Brothers

Invention of Stirling engine has been related to Robert Stirling who was on minister position for about 53 years and had no background on the field of engineering, but it's been highly suspected that his brother was related to this invention since he had wide knowledge in thermodynamic and mechanical engineering. James was Robert's brother who believed to be responsible in design and production of the engine. The main patent of Stirling brothers was divided into two different inventions: the basic invention called "Economizer" or regenerator, second part was real engine that employs economizer to minimize fuel consumption.

Through the period between 1815 and 1845 Stirling brothers developed first five types of Stirling engines. "Gamma" was the first version that was invented on 1815. This engine was so simple and included two different separated cylinders containing open fire heating and air cooling system. Second version of Stirling engines known as "Beta" came out on 1816 which contained two extra parts "displacer and power piston" in a cylinder to help declining loss of flow among cylinders. Even though "economizer" was introduced and patented by Stirling brothers in 1816, it wasn't employed in a working engine till 11 years after the invention (About 1827) [4]. In the original description of regenerator there are some information about a space that been filled by successive layers of thinnest steel plates, pierced with holes, distance of which from each other is two or three. Regenerator's duty is to reduce the necessary heat needed to be given to heat exchangers and increase the whole efficiency of the engine. To do so they need to act as temporary heat storage base, to send the heat of the gas back to regenerators while hot and cold gas pass through them.

Two other main developments in engine design also have been done by Stirling brothers in 1840 [3], to maximize the heat transfer space they built an engine containing an outer regenerator and tubular heat exchangers. In 1845 they built an engine that employed a separate pump to fill up the engine with compressed air. You can see this pressurized cycle engine in Fig 2.1.

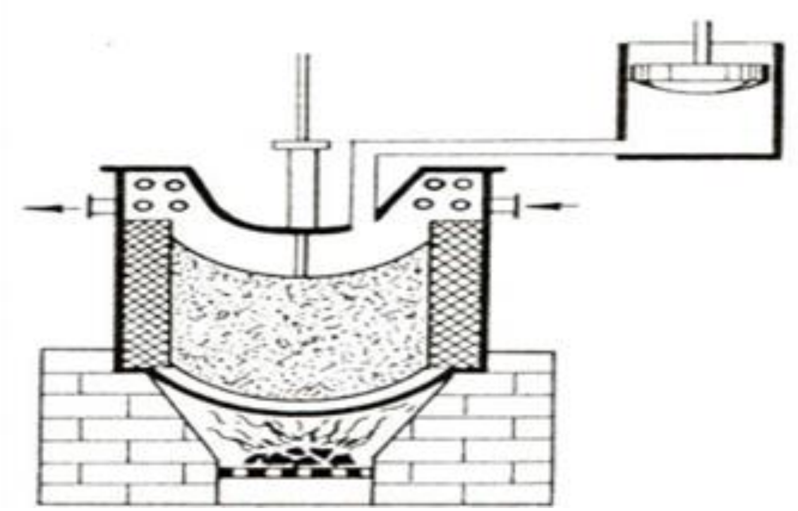

Figure 2.1. Stirling brothers 1845 pressurized cycle engine [3]

This pressurized cycle engine use to support energy for all the machinery at a foundry in Dundee, Scotland for months with 2.5 HP (1.8kw) produced energy till it was exchanged with newer and larger version of it. 30 years after the Stirling engine invention, there came out many inventions in that area, on 1860, Ericsson built an open cycle engine that was able to refill the hot air with fresh cold air in each cycle. Although it was functioning good with cooling air but it was causing great heat loss and had just 2% efficiency.

2.1.2 The Philips Contribution

During 1930's [4] Stirling engine was still useful and not forgotten till 1973 where Philips found great market in Europe to sell their Radios and was also trying to find demand in Africa and Asia. Since Radios used to work with batteries and they were expensive, this barrier was the main reason of decrease in Demand and it wasn't easy to afford the prices of batteries. On the other hand the vacuum tubes inside the radios caused the higher battery consumption. All these reasons together made Philips to realize the need of a generator hence it could be small in size and needed less after care and maintenance and could be safer and less noisy and away from all of these reasons they were using paraffin oil which was easily available.

Throughout three years of experimenting and developing new engines in Nat. Lab in Eidhoven, Netherland, Philips designed and engine in power output from 6W to 745W. Some of the experiments were using engines that could increase the working fluid and also using hydrogen instead of air. Both of these experiments increased the output power but decreased the life of the engine. During 1941 they designed an efficient engine Called Type 10 [5] engine with special application of transferring heat to the cylinder head through liquid metal (K-Na eutectic) pumped with an electromagnetic pump. Although this technology was not applicable for Stirling engine but it found to be useful in cooling of fast-breeder reactors in nuclear power sites. They also tried hot sodium heat pipes experiment of which found to be unstable and caused explosion in their lab.

They also did many experiments on type 10 engine itself, during 1941 to run it as a heat pump they tried through driving the shaft of the engine with electric motor. The reason they tried this experience was to find a replacement or an alternative for cooling systems used in refrigerators and air conditioners (Freon compression-evaporation) cooling system. However not so far from struggle they found out Stirling cycle cooler was much more efficient and useful and with which they could reach the temperature as low as -100°C and during 1945 the small change in engine helped them reaching temperature less than -200°C.

During World War II Germans invasion of Netherland lead the lab slow down their technological progresses. During this period type 19, engine shown in Fig 2.2 was designed and guarantees working two times more than Stirling engine. The engine was Philip's 19th prototype engine and was small in size and had high power output. After Type 19th engine in 1943 type 20 was produced, this engine had output equal to 50 HP and contained a swept volume of 2.9 liters plus 4 cylinders. The engine was 15% efficient and worked smoothly [1].

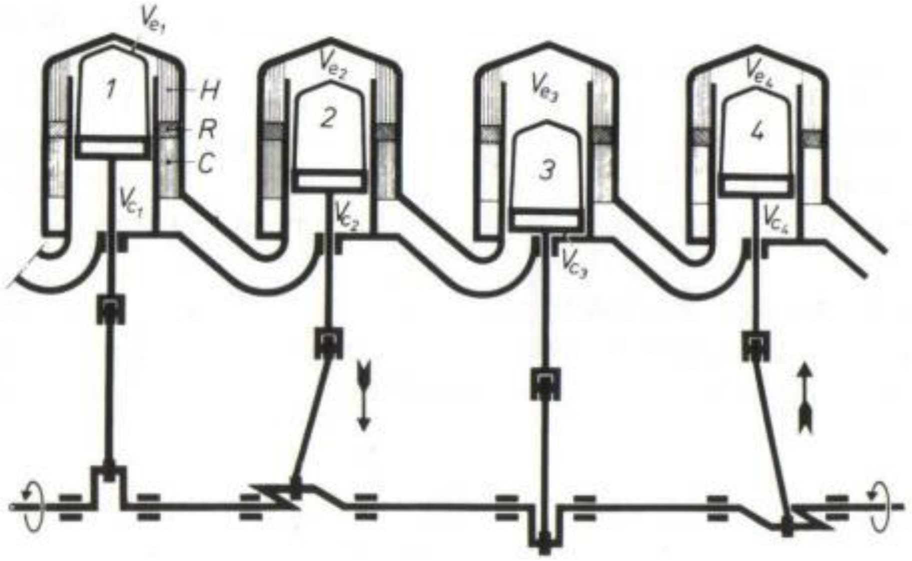

Figure 2.2. Philips type 19 double acting engine with 4 cylinders [1]

In 1948 Philips designed type 24 (V- engine) containing 2 cylinders and following variation types 24b, 24c, 24d. The latest one being 24d was the most successful with output ability of 20HP, however showed problem with sealing and lubrication. This type was predesigned to be used in cars engine but it never found its way to that.

During 1949 [4] the result of Philips and S.M.F group cooperation was an engine called SMF-Kroon, that was a successful engine with ability of making 45HP via 4 liter shift and with efficiency around 20%, but during 1949 engine experienced a sudden explosion and killed one person. The reason of which was investigated to be caused by oil steam that forced into hot chamber and caused explosive mixture under 5MPa engine air pressure and set off by hot piston head. After this accident they increased the safety tests and preferred to use nitrogen and helium or hydrogen which is safer than air.

During 1953 Philips [4] found a solution for balancing a small displacer type engines and a kind of better piston sealing via invention of rhombic-drive mechanism applied in small Beta type engine. Another good feature of this engine was minimizing cost and weight of the engine through pressurizing engine working gas not crankcase. All these positive characteristics were because of a perfect seal around the piston rod that’s due to no lateral thrust work upon them. Other benefits noticed later were higher working pressure, well set design and fewer vibrations. The engine is shown in Fig 2.3.

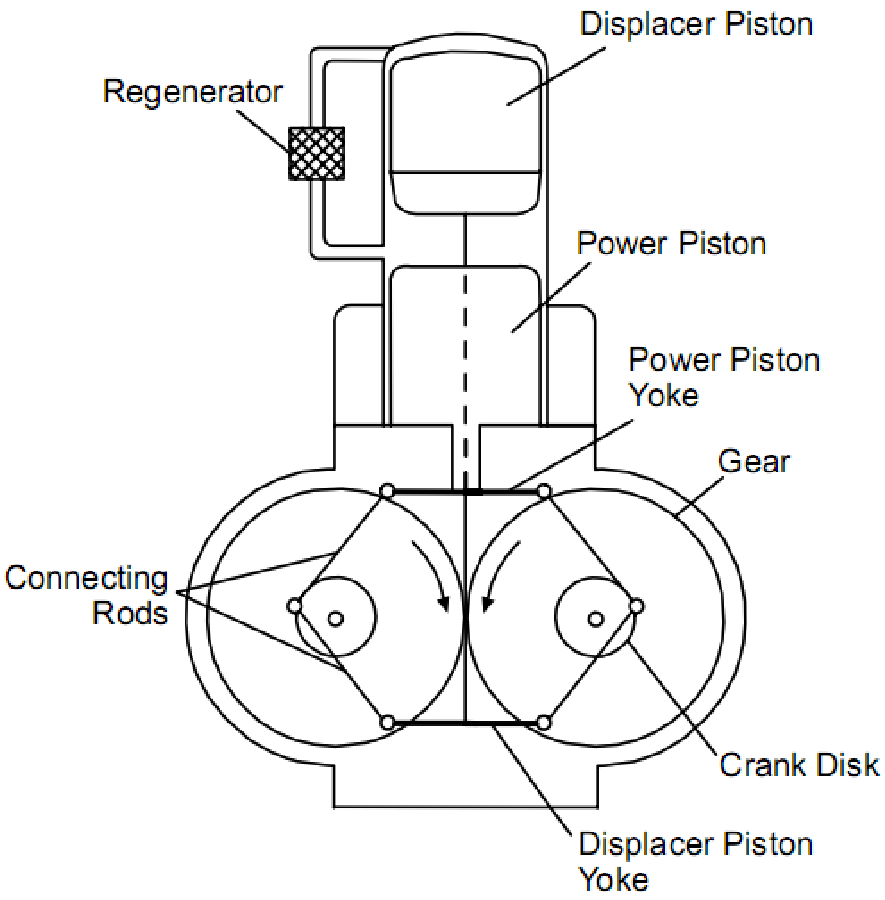

Figure 2.3. Philips beta type Stirling engine with rhombic drive mechanism [4]

Loads of engines were built even years after, production and design of which found to be costly and finally in 1953 Philips stopped designing new engines in favor of continuing working on Stirling cycle refrigerators.

2.1.3 Modern Advances

In 1970 [5] a different design was out by D. West who was a research scientist at Harwell laboratories. The schematic of this designed engine can be seen on Fig 2.4. The engine used liquid piston arrangement and was so simple and it used bent tubes and taps and could pump water. It simply works the same as Stirling engine with Hot and cold area and some amount of water which changes the location of heated or cooled air.

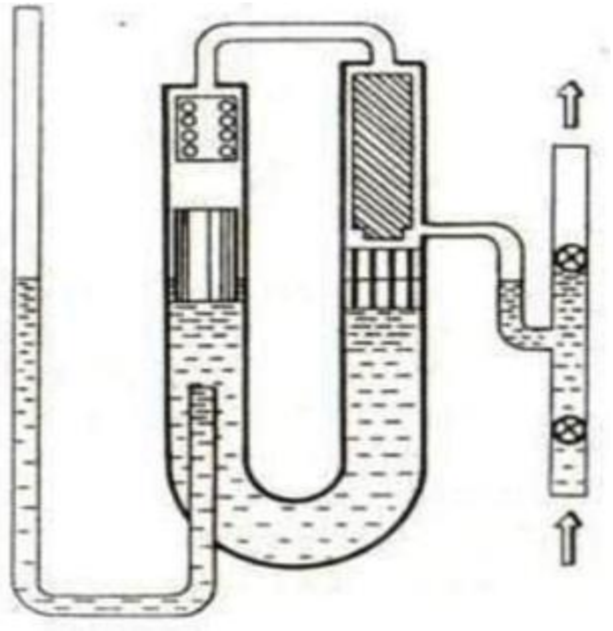

Figure 2.4. Stirling engine built by D. West in 1970, with liquid piston [5]

William Beale [6] was also follower of Stirling engine, who invented free piston Stirling engine. The engine that had few moving parts and no crankshaft and in this engine both piston and displacer motion rely on Oscillations that are controlled through gas pressure and springs on dampers. On 1978 a totally different engine with different usage was made. The application of which was for powering a submarine. Since Stirling engines are very silent and free of vibrations, they found to be more suitable in this purposes and beside they don’t need air for inflammation and they are surrounded by very effective heat sink, sea.

Mc Donnell Douglas in 1985 invented a huge parabolic solar mirror that could follow sun through sky and focusing its energy on mounted Stirling engine that could reach up to 1430°C [7]. To use Stirling engine they made a deal with united Stirling, and the engine was capable of producing 25KW and had a good efficiency of 31%. These large parabolic mirrors have been used worldwide and most famous of it is Joint Venture between electricity supplier Southern California and Edison and

Stirling manufacturer Stirling energy systems on 2005. The advantages of solar Stirling system can be listed as high efficiency, low cost per KW in compare with other solar Technology and high life expectancy. Figure 2.5 showed the invented solar Stirling engine system by McDonnell Douglas.

Figure 2.5. Solar Stirling engine system by McDonnell Douglas (1985) [8]

Thermo acoustic Stirling engine is very different type of Stirling engine which converts heat into strong vocal or acoustic power with no moving part. Through the sound waves the engine was able to produce electricity using electro-acoustic power transducer or using them directly in acoustic refrigerators.

2.2 Operating Principles of Stirling Engine

2.2.1 Stirling Thermodynamic Cycle

In its simplest form a Stirling engine consists of a cylinder containing a gas, a piston and a displacer. The regenerator and a flywheel are other complimentary parts of the engine.

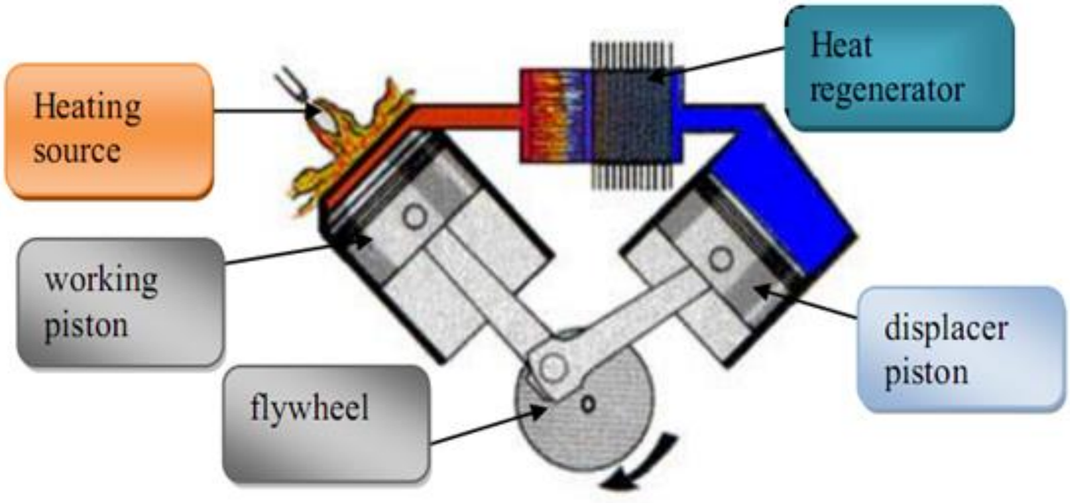

Figure 2.6. Stirling engine components

The temperature rises and gas expands related with the temperature of the heat side when heat part of the cylinder’s temperature is high by external heat sources Fig 2.6. Total volume is constant and restricted by a piston therefore expanded gas pushes the piston down, so the volume of the pressured gas is increased and the gas loses its pressure and temperature. Later, the piston backs to the heat side and compresses the gas by momentum force of the flywheel, when it reaches near its up limit the displacer also pushes the cooled gas to the heat side of the cylinder so that the gas is compressed and it can be prepared to do another cycle. Since the gas expands, the piston pushes down which produces mechanical energy. Thus, this repeats itself until an external heat source is accessible. Engine’s performance is mainly affected by the generator and the flywheel. The flywheel’s duty is to transmit the linear movement of the working piston to rotary movement. This provides the required momentum for the cycle procedure. Engine's efficiency improves by the regenerator taking the incoming heat from gas during the expansion and releasing heat to the gas during the compression.

The classification of the Stirling differs based on the way that they displace the fluid from hot and cold places of the engine. The alpha engine type is the one that contains two pistons attached and connected by regenerator in different (hot and cold) cylinders. The cold cylinder is where working fluid is compressed and expands in hot cylinder. Beta and Gamma both use a single piston and cylinder in which a thermally insulating displacer has the responsibility of pushing working fluid from the hot to cold sides of cylinders. Without considering configuration, Stirling engines follow a special thermodynamic cycle [2], including 4 related stages as shown in Fig 2.7.

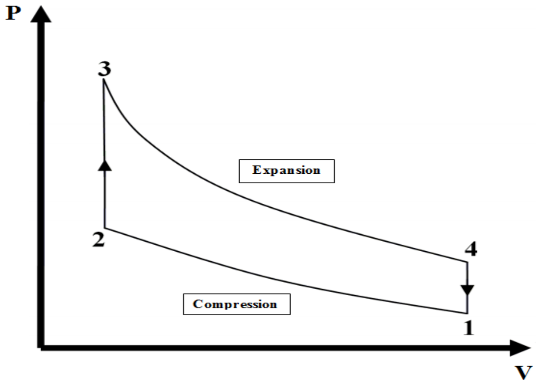

Figure 2.7. Ideal Stirling thermodynamic cycle

1. State 1 to 2 is Isothermal compression; in the cold end the gas transfers its heat to the surroundings to keep the same temperature during compression from the piston.
2. Stage 2 to 3 where constant volume heat is added and thus pressure on the piston increases and in this part inner heat converts from regenerator to working fluid.

3. Stage 3 to 4 is Isothermal expansion stage where the gas expands as heat is added in order to maintain temperature.
4. Heat rejection from stage 4 to 1 where the air has expanded as far as the piston can move back, volume can no longer increase so air must now lose heat and internal heat will be transferred from working fluid to regenerator.

2.3 Stirling Engine Types and Classifications

The Stirling engine has several mechanical configurations for different purposes which are classified into four important distinct types: Alpha, Beta, Gamma and Free piston configuration. The working mechanism of all configurations approximately is same and based on thermodynamic laws and gas expansion at higher temperature.

2.3.1 Alpha Stirling Engine

The alpha Stirling configuration uses no displacer and two power pistons attached 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 Fig 2.8 is a flat opposed type, which has the smallest dead space but requires rather length and complicated linkages to join the pistons to the crankshaft.

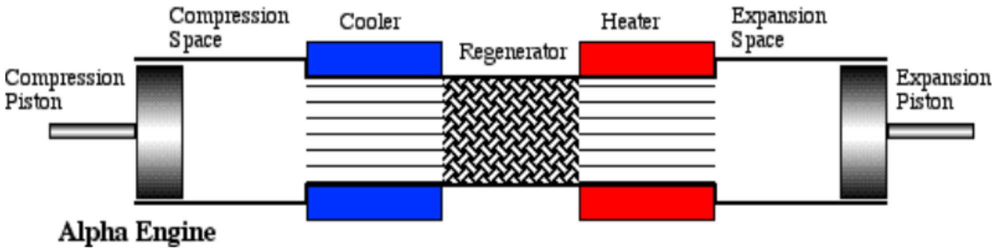

Figure 2.8. Alpha engine configuration[9]

The ‘V’ design is another variant, where both pistons are arranged in a V formation and are connected 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.

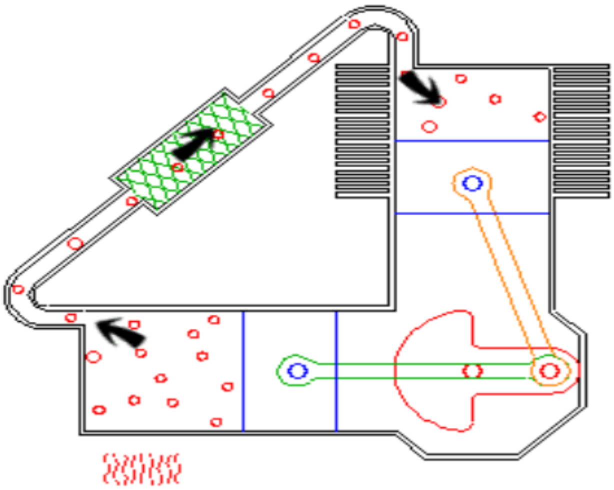

Figure 2.9. V type alpha engine configuration[9]

2.3.2 Beta Stirling Engine

Beta engine is formed with the displacer and the piston on an in-line cylinder system. The aim of the single power piston and displacer is for the constant volume to move the working gas and therefore to transmit it between the expansion and compression spaces.

Displacer piston and beta Stirling are placed in the same cylinder and have a single power piston. Displacer piston works to transmit the working gas from the hot heat exchanger to the cold heat exchanger. Moreover, displacer piston is moveable and does not extract any power. Figure 2.10 showed a typical beta Stirling engine.

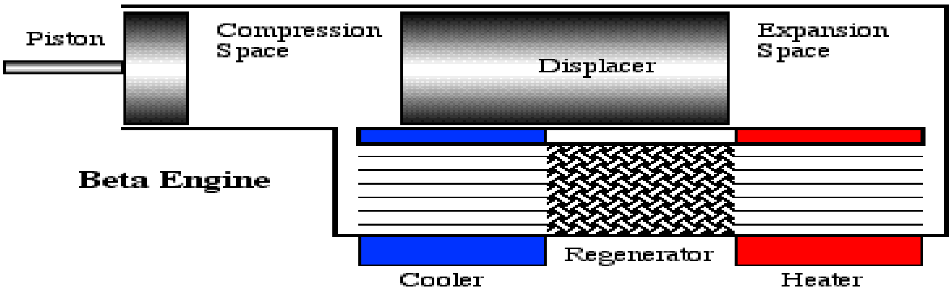

Figure 2.10. Beta engine configuration[9]

When the working gas is moved to the hot end of the cylinder it expands and pushes the power piston. When it is moved to the cold end of the cylinder it contracts and the momentum of the machine is usually improved by a flywheel which forces the power piston to the other way in order to compress the gas. The alpha engine type and the beta engine type evade the technical problems of hot moving seals.

2.3.3 Gamma Stirling Engine

A gamma Stirling is simply a beta Stirling in which attached in a separate cylinder together with the displacer piston cylinder; also it is connected to the same flywheel. The gas can flow freely between the two cylinders and remains a single body. There is lower compression ratio in this configuration but is mechanically simpler and often used in multi- cylinder Stirling engines.

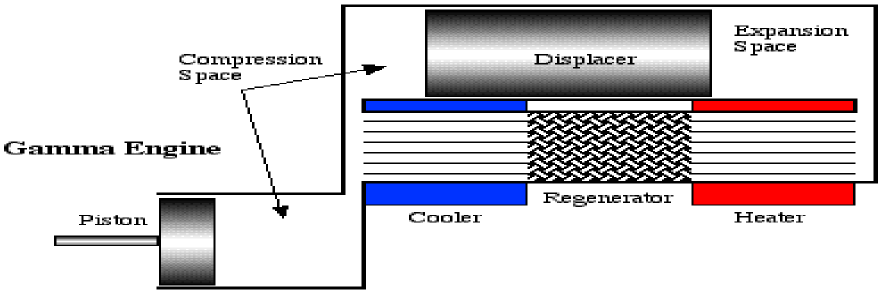

Figure 2.11. Gamma engine configuration[9]

Gama type engine which is shown in (Fig 2.11) consists of a displacer and a power piston in which it is very similar to beta type engine. This allows a suitable complete separation between the heat exchangers associated with the displacer cylinder and the compression and expansion work space associated with the piston.

2.3.4 Free Piston Stirling Engine

Free piston Stirling engines are however different in the case that there is no crankshaft in this engine and the displacers are not attached to each other. Fluid forces control the motion of the piston and the displacer. Figure 2.12 represented a section view of free piston Stirling engines.

Linear alternator is used to remove the energy from the engine. However, from time to time, piston motion is used directly in pumping applications. The advantages of this engine configuration are fewer moving parts, meaning greater reliability and simplicity, which also reduces the costs of production. They can also be compact and lightweight by comparison with more traditional designs. Non-contact gas bearings and planar springs can bring friction down to almost zero in these designs [10].

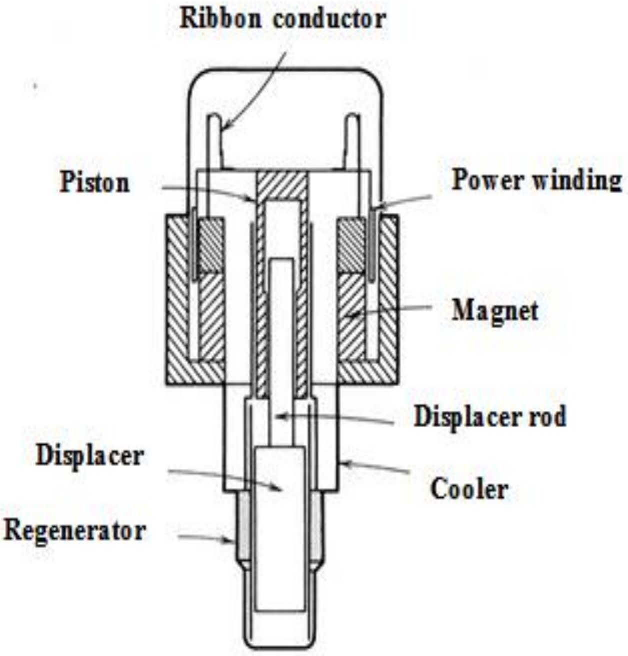

Figure 2.12. Sun power 100 W free piston Stirling engine (section view)[6]

Chapter 3

DESIGNING PROTOTYPE OF PROPOSED STIRLING ENGINE

3.1 Design Overview

Due to the low temperature difference given, naturally power and efficiency is low. Therefore, the engine needs to be pressurized so that the targeted power could be reached as well as keeping the engine at a reasonable size. Essentially, pressurizing the engine puts more moles of working gas into the same space, meaning higher specific power output per liter. This necessitates strong and completely sealed engine housing in order to maintain a high working pressure safely. The only connections into and out of the engine are the heating and cooling water and the electrical connections, including the power output from the generator which is sealed inside the engine. A nominal value for engine pressure, P_o of 1.0Mpa (10bar) was chosen as an achievable pressure level for what was predicted to be a large pressure vessel. A cylindrical shape is a good choice as it has great strength for a given material type and thickness. A cylinder can be formed easily by putting end caps on a length of pipe, and pipe can be bought that is already manufactured and tested, cutting down on costs and time for custom fabrication of a housing.

Due to this engine being a research prototype it was desired for a range of adjustments to be possible to adjust and test certain parameters of the engine. One such adjustment is the stroke length of the power piston, which in turn affects the compression ratio. The compression ratio, or volume ratio V_R, is defined as the gas volume with the piston at top dead center (TDC) divided by the gas volume with the piston at bottom dead center (BDC).

It is typically very low in (LTD) engines due to the large overall gas volume that is generally required for these engines to operate. "Rule of thumb" formula is ideal for balancing the volume ratio, which used depending on the temperature difference of the engine. The formula states:

$$V_R = \left(1 + \frac{\Delta T}{1100}\right) \tag{3.1}$$

Where V_R: Volume ratio

The motion of the displacer in a traditional LTD engine design is limited to sinusoidal motion as it is driven off the same shaft as the crankshaft. In addition, the phase angle is almost always fixed at 90° however this is not necessarily the optimum value, as indicated by the graph in Fig 3.1 which describes a numerical analysis of a certain Philips Stirling engine. It would be useful to be able to easily alter the phase angle to find the optimum value, and it is partly for this reason that it was decided to operate the displacer in the prototype engine via an electronically controlled motor or actuator. The second major advantage of doing this is the ability to move the displacer in a non-sinusoidal or discontinuous motion. It will also be possible to do a direct comparison of sinusoidal vs. discontinuous motion and study the effects on power and efficiency. Further to these benefits, it will allow the losses associated with regenerator and heat exchanger pressure drop and bearing and seal friction to be directly and accurately measured simply by looking at the average power consumed by the motor/actuator.

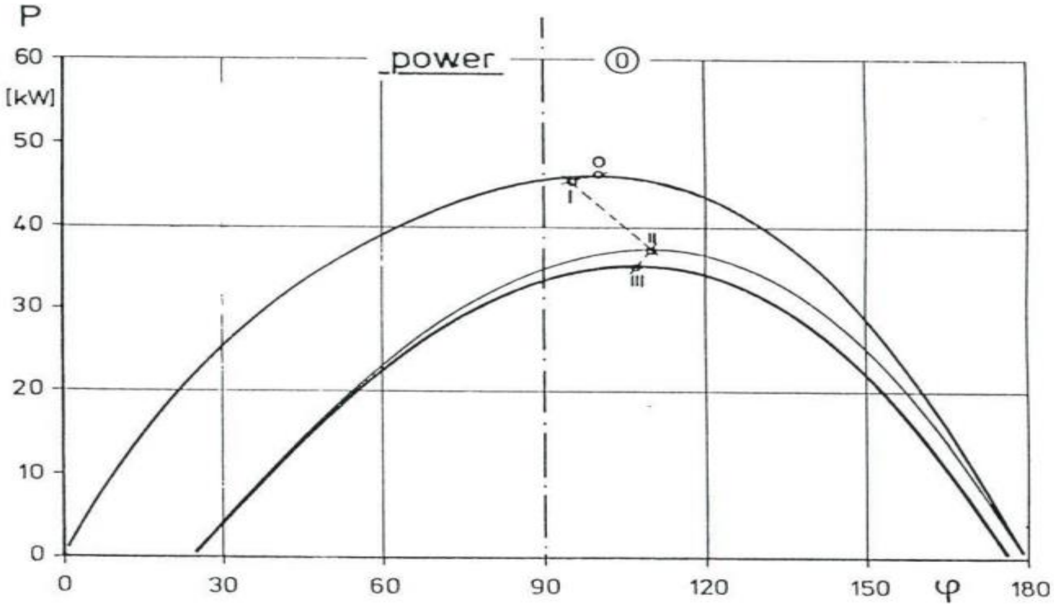

Figure 3.1. Power output vs. phase angle for three different dead volumes [11]

3.2 Methodology

The practical Stirling cycle consists of two isothermal and two isochoric processes, rather different from the ideal Stirling cycle. For this reason, it is used as a more realistic approach to calculate thermodynamic values during designing stage.

In this study design details of the manufactured engine were obtained by using Stirling engine simulation software developed by Franco Normani. Table 3.1 shows the technical specifications of the manufactured Stirling engine.

The assumptions used in analysis method are as following:

- Each cell is an open system from a thermodynamic point of view and the cell working fluid inlet and outlet under periodic conditions.
- Pressure differences arising negligible during the displacement of the working fluid by hydrodynamic frictions compared to the thermodynamic pressure.
- There is a linear and stable temperature distribution in the regenerator and provides the heat balance for the regenerator.

- Helium and air is considered as ideal gas and used as working fluid.
- The total mass of the system is constant and does not change with time.
- The heater and hot cylinder side wall are as hot source temperature and the cooler and cold cylinder side wall are as cold source temperature.
- The heater, cooler and regenerator volumes are constant, the hot and cold cylinder volumes change according to the crank angle.

Table 3.1. Technical features of the Stirling engine

Engine type	Alpha ($\propto$)
Hot cylinder volume	40 cm^3
Cold cylinder volume	10 cm^3
Regenerator volume	2.5 cm^3
Heater dead volume	32.6 cm^3
Cooler dead volume	5 cm^3
Total dead volume	38.6 cm^3
Cold source temperature	23 ℃
Hot source temperature	200 ℃
Phase angle	90°
Maximum engine speed	320 rpm
Working fluid (gas material)	Air- Helium
Stroke length	23 mm
Mass of air	0.000048 kg
Mass of Helium	0.0000056 kg

The performance of the engine calculated by the SCHMIDT theory [12, 13]. It is isothermal calculation method for Stirling engines and help to calculate the engine parameters based to the isothermal expansion and compression of an ideal gas.

$$PV = mRT \tag{3.2}$$

Figure 3.2 shows the calculation model of the alpha type Stirling engine.

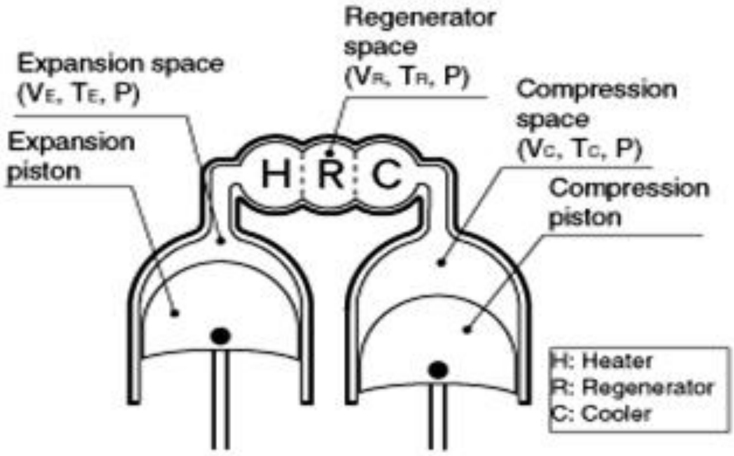

Figure 3.2. Alpha Stiling Engine type [12]

First, the expansion and compression cylinder volume determined at a given crank angle. The volume described by a crank angle (x). When the expansion piston is at the maximum position, the crank angle is defined as x = 0.

By equation (3.3) the expansion volume describes V_E with a displacement volume of the expansion piston V_{SE} and expansion dead volume V_{DE}.

$$V_E = \frac{V_{SE}}{2}(1 - \cos x) + V_{DE} \tag{3.3}$$

Where:

V_E: Expansion volume $[cm^3]$

V_{SE}: Swept expansion volume $[cm^3]$

V_{DE}: Expansion dead volume $[cm^3]$

With a displacement of compression piston V_{SC}, compression dead volume V_{DC} and a phase angle dx, the compression volume V_C is found by equation (3.4).

$$V_C = \frac{V_{SC}}{2}\{1 - \cos(x - dx)\} + V_{DC} \tag{3.4}$$

Where:

V_C: Cooler volume [cm^3]

V_{SC}: Swept compression volume [cm^3]

V_{DC}: Compression dead volume [cm^3]

The total volume is showed by equation (3.5).

$$V = V_E + V_R + V_C \tag{3.5}$$

Where:

V_E: Expansion volume [cm^3]

V_C: Cooler volume [cm^3]

V_R: Regenerator volume [cm^3]

Total mass of the engine using the engine pressure P, temperature T, every volume V, and the gas constant R, each calculated.

$$m = \frac{PV_E}{RT_E} + \frac{PV_R}{RT_R} + \frac{PV_C}{RT_C} \tag{3.6}$$

Where:

m : Total mass of gas [kg]

P : Pressure [Pa]

R : Gas constant

T : Temperature of the engine [K]

By using the following equations the temperature ratio t, founded a displacement ratio v and other dead volume ratios.

$$t = \frac{T_C}{T_E} \tag{3.7}$$

$$v = \frac{V_{SC}}{V_{SE}} \tag{3.8}$$

$$X_{DE} = \frac{V_{DE}}{V_{SE}} \tag{3.9}$$

$$X_{DC} = \frac{V_{DC}}{V_{SE}} \tag{3.10}$$

$$X_R = \frac{V_R}{V_{SE}} \tag{3.11}$$

The regenerator temperature T_R is calculated in equation (3.12) under the assumption.

$$T_R = \frac{T_E + T_C}{2} \tag{3.12}$$

When Equation (3.6) using Equation (3.7) and (3.11) is replaced, the total mass of gas will be described in the next equation, by using the equations (3.3) and (3.4).

$$m = \frac{P}{RT_C}\left(tV_E + \frac{2\pi V_R}{1+t}\right) + V_C \tag{3.13}$$

$$m = \frac{PV_{ES}}{2RT_C}\{S - Bcos(x - a)\} \tag{3.14}$$

$$a = tan^{-1} \frac{v.\sin dx}{t + \cos dx} \tag{3.15}$$

$$S = t + 2tX_{DE} + \frac{4tX_R}{1+t} + v + 2X_{DC} \tag{3.16}$$

$$B = \sqrt{t^2 + 2tv\ cosdx + v^2} \tag{3.17}$$

Next equation (3.13) is defined as engine pressure P.

$$P = \frac{2mRT_C}{V_{SE}\{S - Bcos(\theta - a)\}} \tag{3.18}$$

The average pressure P_{mean} may be calculated as follows:

$$P_{mean} = \frac{1}{2\pi}\oint P\,dx = \frac{2mRT_C}{V_{SE\sqrt{S^2-B^2}}} \tag{3.19}$$

$$h = \frac{B}{S} \tag{3.20}$$

As a result, the pressure P, the average engine pressure based P_{mean} calculated in equation (3.21).

$$P = \frac{P_{mean}\sqrt{S^2 - B^2}}{S - B\cos(x - a)} = \frac{P_{mean}\sqrt{1 - h^2}}{1 - h.\cos(x - a)} \tag{3.21}$$

On the other hand, in the case of equation (3.18), if cos (x-a) = 1, the engine pressure P change to the minimum pressure P_{min}, the next equation is introduced.

$$P_{min} = \frac{2mRT_c}{V_{SE}(S+B)} \tag{3.22}$$

Therefore, the engine will be described pressure P based to the minimum pressure P_{min} in equation (3.23).

$$P = \frac{P_{min}\,(S+B)}{S-B\,\cos(x-a)} = \frac{P_{min}\,(1+h)}{1-h.\cos(x-a)} \tag{3.23}$$

Similarly, when cos(x-a) =1, the engine pressure P becomes the maximum pressure P_{max}. The following equation is introduced.

$$P = \frac{P_{max}\,(S-B)}{S-B\,\cos(x-a)} = \frac{P_{max}\,(1-h)}{1-h.\cos(x-a)} \tag{3.24}$$

3.2.1 Power Output

Performance can be expected, using a variety of methods which take into account such things as effectiveness temperature difference operating speed and pressure, expansion and compression space volumes and regenerator. Such an estimate is made by using Beale number and the number later called William Beale, free piston Stirling engine inventor. He noted that the performance of many Stirling engines is to comply with the following simple equation:

$$P_o = B_n\, p\, f\, V_e \tag{3.25}$$

Where:

P_o: Indicated power [W]

P : Pressure [Pa]

f : Operating frequency [Hz]

V_e: Expansion volume [cm^3]

B_n : Beale number

Figure 3.3 shows a graphical representation of measured data from many Stirling engines designed. The solid line in the middle is typical of most Stirling engines, while the upper and lower lines represent strange high or low performance engines. According to this chart with a heater temperature of 90℃ (363K), it would be reasonable to expect a Beale number in the range 0.002 to 0.008. Beale number is used as 0.005 for further calculations[6].

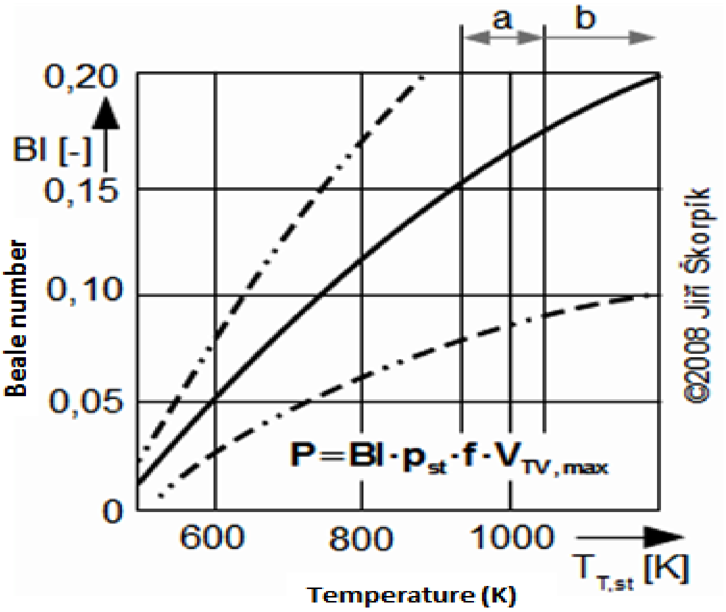

Figure 3.3. Beale number vs. heater temperature for a range of engines [6]

The second power approximation method is called the West number and is comparable to the Beale number apart from what it takes direct account of the temperature diversity. The formula is articulated as:

$$W_o = W_n\, p\, f\, V_e \left(\frac{T_h - T_c}{T_h + T_C}\right) \tag{3.26}$$

Where W_n is the West number, which has an average value of 0.25 and where a higher number represents greater competence engine.

The most important factor in the overall competence of the engine is the temperature difference. In 1824, a working Sadi Carnot [3] published including a formula that later became very famous, the formula with the following, which is the maximum hypothetical competence of a heat engine States or the effectiveness η_c Carnot a function only of the temperature difference between the hot side temperature T_h and the cold side temperature T_c (both temperatures in K).

$$\eta_c = \frac{T_h - T_c}{T_h} \tag{3.27}$$

3.2.2 Efficiency of Stirtling Cycle

Once a work is carried out for a period of time, we can determine performance as a rate of energy supplied in a certain time. Stirling engine followed thermodynamic laws and principles; its power is a function of pressure in the cylinder, volume and temperature, and thus energy developed by the following formulas;

Once a work is done for a phase of time, we can determine power as a rate of provided energy in a certain time. Stirling engine pursues thermodynamic laws and principles, its power depends on pressure within the cylinder, volume and temperature, and thus power can be designed from following formulas;

$$P = \frac{F}{A} \tag{3.28}$$

As work is equal to force multiply by travelled distance the;

$$W = Fd \tag{3.29}$$

By replacing pressure and area instead of force in the formula it becomes;

$$W = PAd \tag{3.30}$$

When pressure is inserted on a constant area like cross section area of a piston the work will depend on distance travelled by piston directly, here volume is equal to;

$$V = Ad \tag{3.31}$$

So final obtained formula of instantaneous work in a cycle is;

$$W = PV \tag{3.32}$$

power as a rate of supplied energy by Stirling cycle for doing work is equal to production energy or work in a cycle multiply by rotational pace of engine per second so;

$$P = W(E)cyc.rps \tag{3.33}$$

Where:

V: Volume [m^3]

A: area [m^2]

F : force [N]

d : travelled distance [m]

W : work [J]

P : power [W]

rps : revolution per second

W_{cyc}: energy of cycle

3.3 Prototype Engine Construction

The engine represented in Fig 3.4 is designed and manufactured as alpha type with a single displacer and power piston. In alpha type engine, there is a 90° phase angle between the cylinders. This phase angle can enable the cycle processes. A Stirling engine always has five main parts that are essential to its operation, also the designed and manufactured engine is consists of these five parts, which are: power piston, displacer, hot side heat exchanger, Regenerator and cold side heat exchanger.

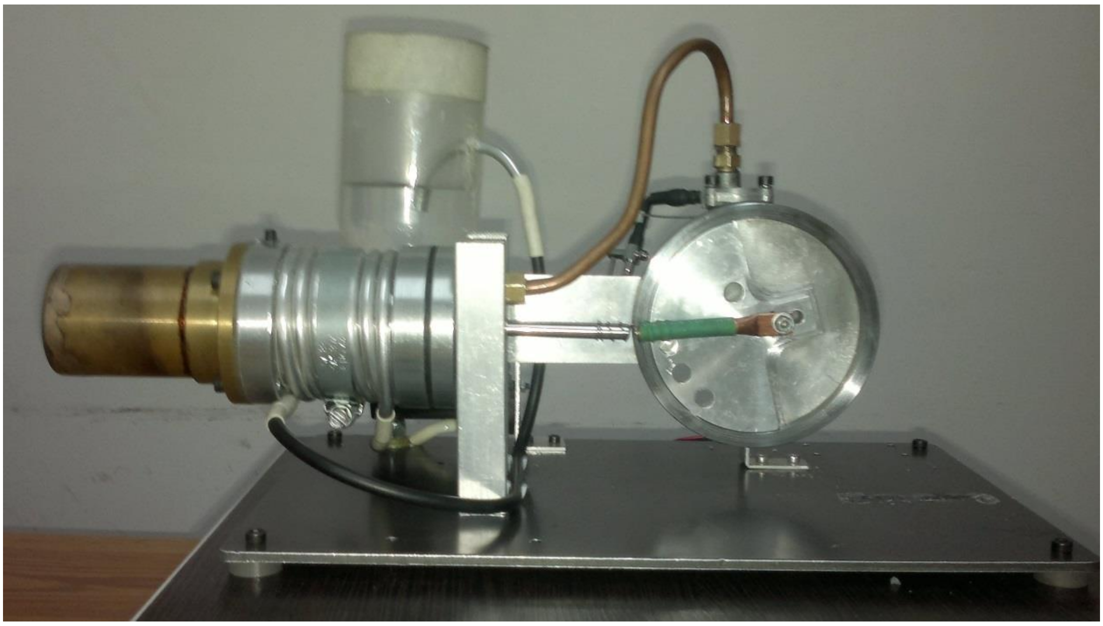

Figure 3.4. Designed and manufactured prototype

3.3.1 Heat Exchangers

The heat exchangers are charge of transferring all the heat into and out of the engine. There are always two heat exchangers, one to heat the working gas and other one to cool it.

The designed heat exchangers are connected together by cupper pipes to transfer the working fluid from one side to another side. The hot side of engine consists of 70mm end welded brass tube combined with 73mm aluminum closed ended to absorb the suitable expanded working fluid. Because of high thermal conductivity of brass, it’s suitable for this purpose to absorb the heat. One end of the brass tube is closed and welded to well vacuumed and do not let any leakage of working fluid. Figure 3.5 shows manufactured heat exchangers.

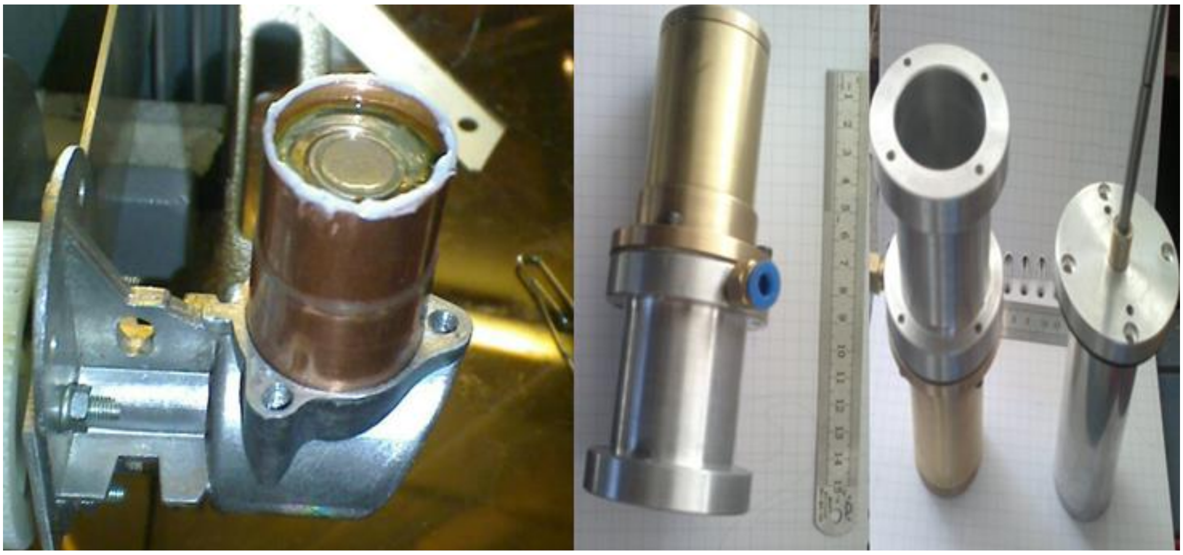

Figure 3.5. Cold side and heat side exchangers of designed prototype

3.3.2 Displacer

The importance of the displacer is to shift the working liquid inside the engine. The heat exchangers create two divided regions inside the engine; a hot region and a cold region. These regions dwell in the majority of the volume inside the engine. It is the role of the displacer to carry the working liquid presumably between these regions in order to alternately heat and cool the liquid. Ultimate faces of a displacer are to be lightweight so that it can speed up and slow down rapidly without including too much power from the engine. It should be thermally non-conductive to avoid irritating heat transfer, and it should be firm and offer minimal stream resistance while keeping dead space around its edges to a minimum. Figure 3.6 shows the light weight displacer used in the manufactured engine.

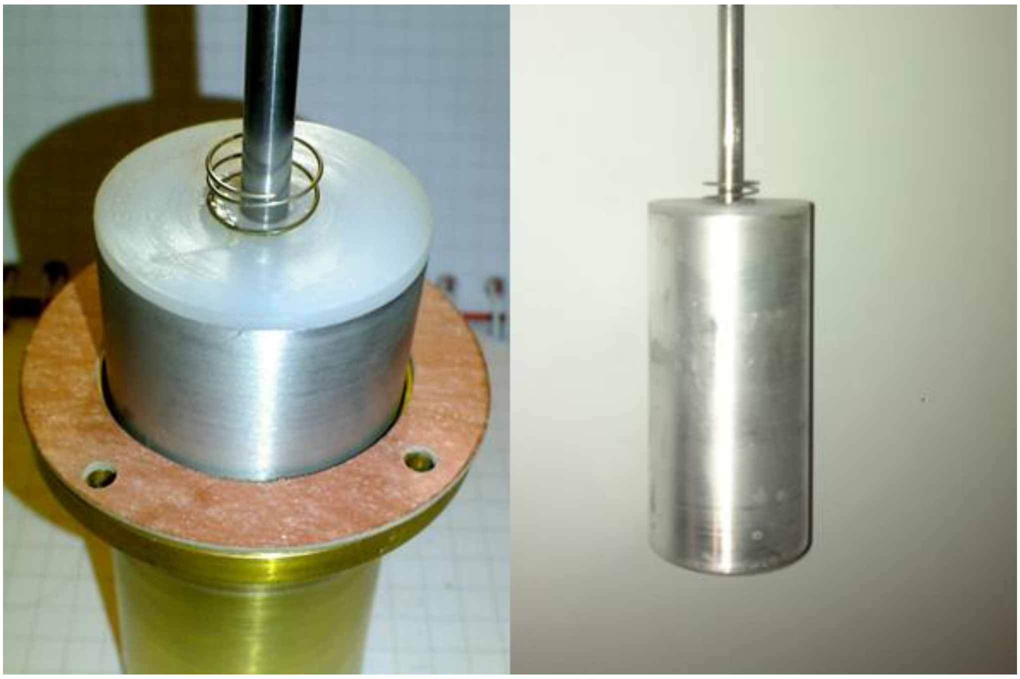

Figure 3.6. Light weight displacer

3.3.3 Regenerator

The fact of regenerator is to act as a temporary heat storage element that is able to quickly absorb heat from the hot working fluid and transfer it back again into the cold working fluid. This deeply decreases the quantity of thermodynamic work required to be performed by the heat exchangers and in turn significantly enlarges the overall competence of the engine.

The prototype regenerator is formed of circular aluminum tube which rounded around the aluminum body of hot side heat exchanger and the water with an electrical pump flow inside the tube and cool the heat absorbed by the heat exchanger. As it is shown in Fig 3.7 the aluminum tube cools exchanger body and does not allow absorbing too much heat. Each time when the pump starts to circulate the water inside the tubes, at least about 5℃ reduce the temperature of the heater cylinder; even it will be more by adding cubes of ice to the water and allow the engine to work on a constant temperature.

Figure 3.7. Circular tube regenerator

Figure 3.8 exemplifies a distinctive relationship between the effectiveness of a regenerator (with 0 being no regenerator and 1.0 being the ideal regenerator) versus the overall efficiency of a Stirling engine.

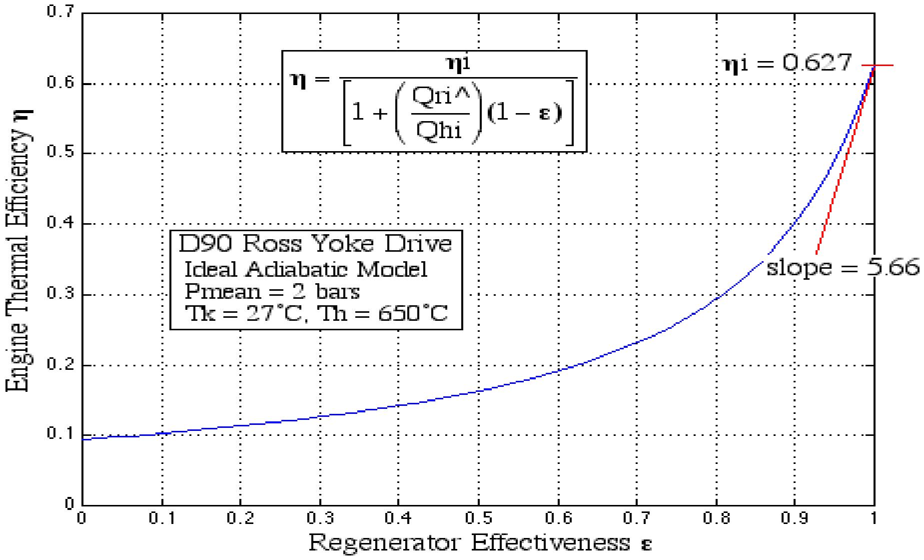

Figure 3.8. Influence of regenerator effectiveness on engine efficiency [11]

3.3.4 Power Piston

The power piston’s responsibility is to transmit power created by pressure acting on the piston face to the crankshaft of the engine. The piston moves inside a cylinder and is strongly sealed against the cylinder walls by the piston rings in order to maintain the necessary pressure differential across the piston for motive power.

Planned criteria for the piston is light weight and perfectly balanced (this is actually achieved by counterbalancing the crankshaft), as well as being made of a material suitable to use at the intended temperature. In some situations thermal expansion must be considered where it can mean that the piston expands to the point of grasping in the cylinder. The piston rings can be made of metal, rubber or other suitable materials. They need to be able to seal against the design pressure difference, which is typically quite low for a Stirling engine. To avoid unnecessary resistance between the cylinder wall and the piston rings, generally some types of lubricant is used, though care must be taken to guarantee that the lubricant will not vaporize and then condense inside the regenerator which will cause it to become blocked and lose effectiveness.

As shown in the Fig 3.9 the designed power piston is smaller than the displacer, so the volume of the displacer cylinder is more than cold cylinder. It causes to have more pressurized working fluid in displacer cylinder to apply into the power piston. Figures 3.10 and 3.11 showed the power piston cylinder and crank mechanism.

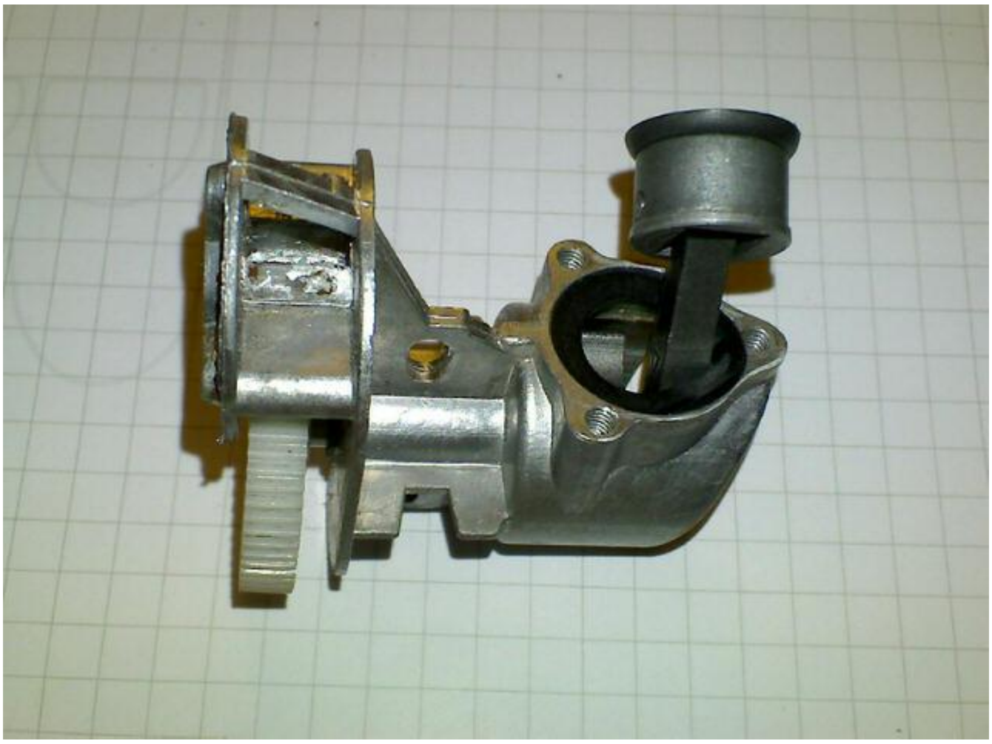

Figure 3.9. Power piston components

Figure 3.10. Power piston and cylinder

Figure 3.11. Crank, con-rod and piston

3.3.5 Other Components

There are some other components that were not able to run the engine without them, these components also helped to the better performance of the engine, such as: main shaft, spring, and flywheel.

Main shaft which is connected to the one end of displacer and transfer the movement to the balanced flywheel. When the working fluid inside the displacer cylinder expanded it pass the displacer to the backward and shaft which connected to the displacer transmit the force to the flywheel. The flywheel also is connected to the power piston, so when the power piston pushing up the displacer will be moved to opposite side, such process needed a frictionless contact of shaft with bearing which designed at the end of the displacer cylinder. The shaft was manufactured from chromed steel in order to avoid bearing friction. The another thing as showed in the Fig 3.12 is the use of spring between the shaft and flywheel, that makes better free and rigid movement of the displacer shaft without making any angle and again eliminates the chance of having friction between the displacer shaft and bearing.

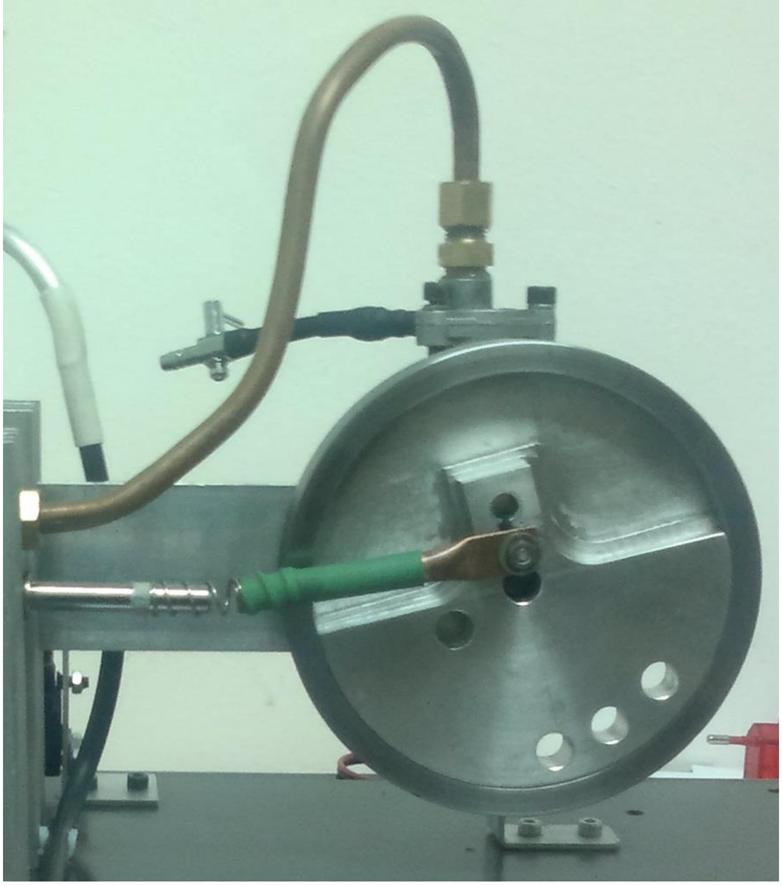

Figure 3.12. Chromed steel shaft, frictionless spring and balanced flywheel

Chapter 4

EXPERIMENTAL DATA

This study attempts to explore the performance of moderate temperature Stirling engine at different values and wall temperature of the heater section. Two different analyses were used to test the performance of Stirling engine. Firstly engine has tested with burning fuels such as ethanol, diesel. Secondly engine got tested under solar radiation.

To simulate the application in solar application, the heating is set in wall temperature between 70 and 200 ℃. The input power to the heater is set to be same as atmospheric pressure for working fluid such air, and for helium working fluid the pressure was calculated according to the inserted mass of helium inside the cylinder.

The surface temperatures are measured by using type T thermocouples. The water tubes at the cooler sections are supplied to reduce the temperature at the cooler section.

4.1 Burning Fuel

4.1.1 Ethanol as Fuel

Ethanol is a colorless liquid and volatile found in alcoholic beverages and thermometers, but it can also be burned in combustion applications for significantly cleaner emissions due to its very low particle content. High volatility of ethanol makes it as fuel for the evaporative burner of the Stirling engine. Low energy density of ethanol in comparison to diesel indicating that, higher volumetric rate of fuel would be required to provide the same power output during combustion. Similar to diesel, ethanol containing a little water and only very few particle, However ethanol is partially oxidized due to the presence of the OH pair in the fuel molecule and thus its heating value is lower to that of diesel. Ethanol is higher heating value (HHV) is 29.8 MJ / kg and its lower heating value (LHV) is 28.9 MJ / kg.

Experiment was operated at several stages. At the first test of the engine the displacer cylinder heated around 100 ℃ and number of revolution of the flywheel counted as 180 rpm. The performed test was without using the regenerator and with use of air as working fluid inside the system. Figure 4.1 represented the engine tested by ethanol.

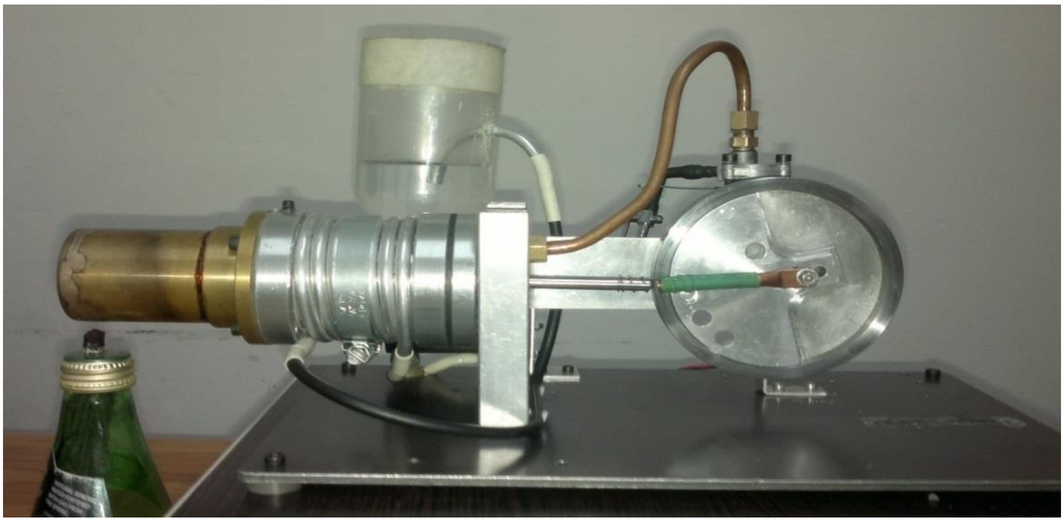

Figure 4.1. Prototype Stirling engine, tested by fossil fuel

The second running of the engine was with using of regenerator, the regenerator assumed to be between the heater and cooler. There are several types of regenerators although for this engine there are aluminum tubes which by helping of electrical pump circulate the system and increase the engine performance. In this time by using the regenerator the system at temperature of 100℃ has 190 rpm and also at the 200℃, engine has the maximum performance of 310 rpm.

At the third run of the engine, the helium gas is used. Helium has the lowest melting and boiling points. After hydrogen, helium has the second most abundant element in the atmosphere. To express helium, one should mention it’s colorless, odorless, tasteless and properties of that element. The boiling point of helium is very low and remains monoatomic. This element is very small and very light; it also is the least reactive element among all elements. Through the use of helium in the system, engine run faster at temperature level of 100℃, disc was turning about 200 revolutions per minute (RPM). During this period, engine runs without the use of the regenerator and the engine does not benefit from the cooling system.

The last experiment tested with burning of ethanol was with use of helium inside the engine, turning on the regenerator and helping the engine by cooling system. This was the best condition of the engine and engine got the revolution of 320 rpm after getting the constant temperature of 200℃. Figures 4.2 and 4.3 shows the performance of the engine with working fluids of helium and air inside the engine.

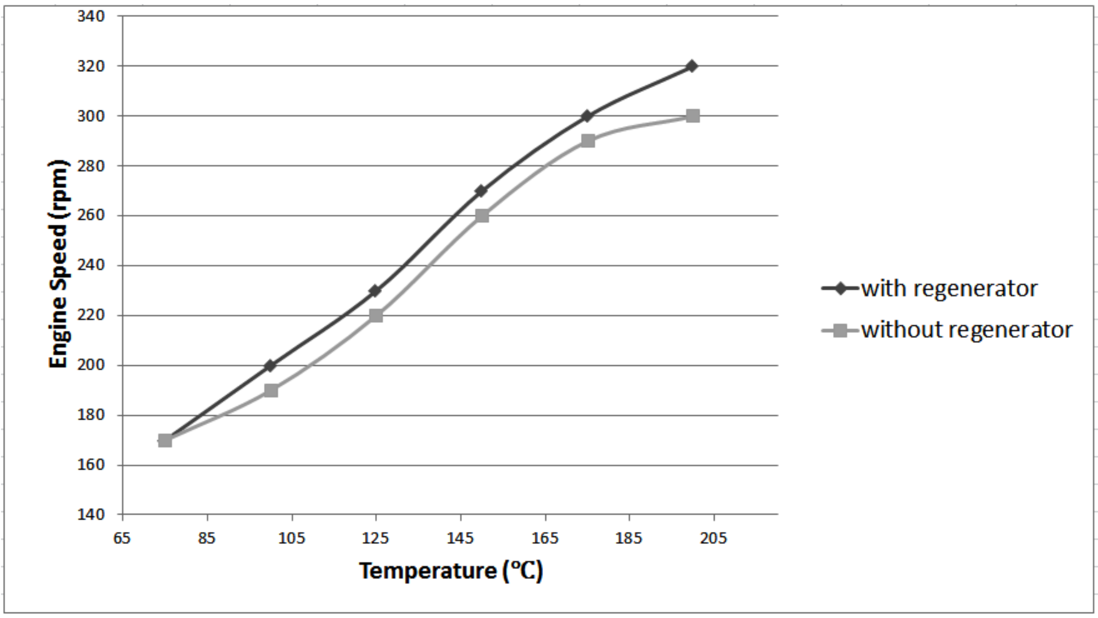

Figure 4.2. Performance of the engine when helium used as working fluid

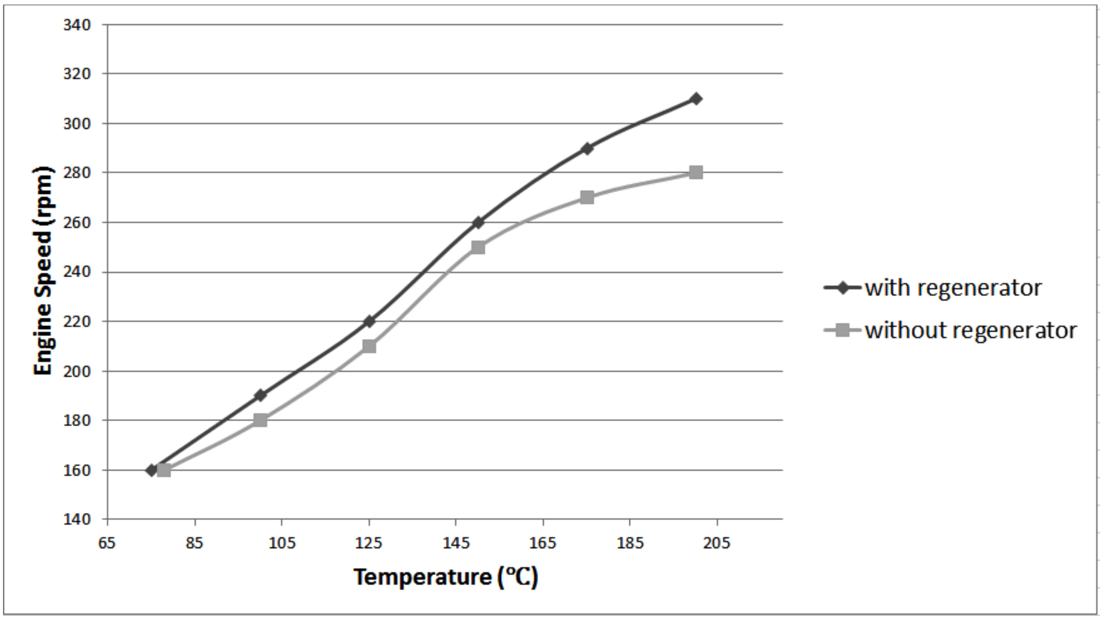

Figure 4.3. Performance of the engine when air used as working fluid

4.1.2 Diesel as Fuel

Diesel fuel has low combustion properties such as low water and oxygen content (both are less than 1% weight), and low particulate content. The combination of these properties provides a diesel fairly high calorific value, of the amount of energy which is free from fuel combustion.

The HHV of a fuel is released by combustion devices that recover the enthalpy of vaporization of the exhaust water vapor. On the other hand, the LHV is released when the exhaust water vapor does not condense. Consequently, the algebraic difference between the HHV and LHV will be the water’s evaporation latent heat of vaporization. For diesel, the HHV is 45.9 MJ / kg and the LHV is 43.0 MJ / kg.

The engine was operated under four stages for diesel fuel same as ethanol. The performance of the engine by heating diesel is higher than ethanol fuel due to having higher HHV and LHV. But when heating the cylinder by diesel, it makes a thin film layer of diesel smoke on the cylinder and that cause to do not transfer the real amount of heated value to all surface of the cylinder. Figure 4.4 shows the variation of air and helium when regenerator not used as cooling.

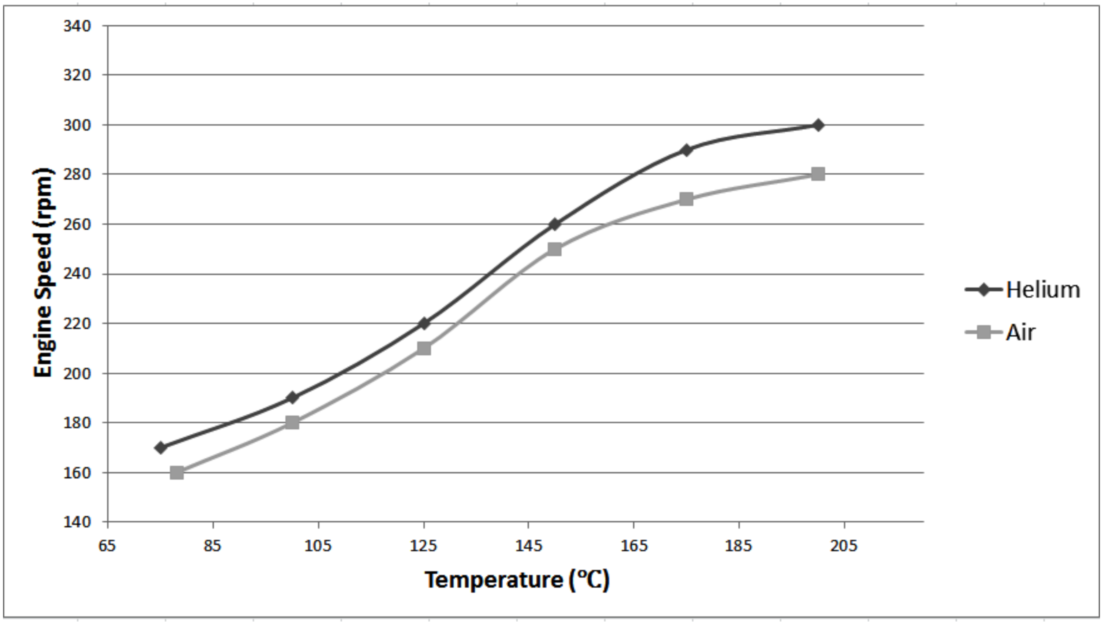

Figure 4.4. Engine speed vs heat side temperature (without regenerator).

As the electrical pump of the regenerator start working and circulating the cold water into the pipes, the engine starts to cool and reduces the constant temperature. As shown in the Fig 4.5 when regenerator circulating the water, the engine has the maximum speed of 320 rpm.

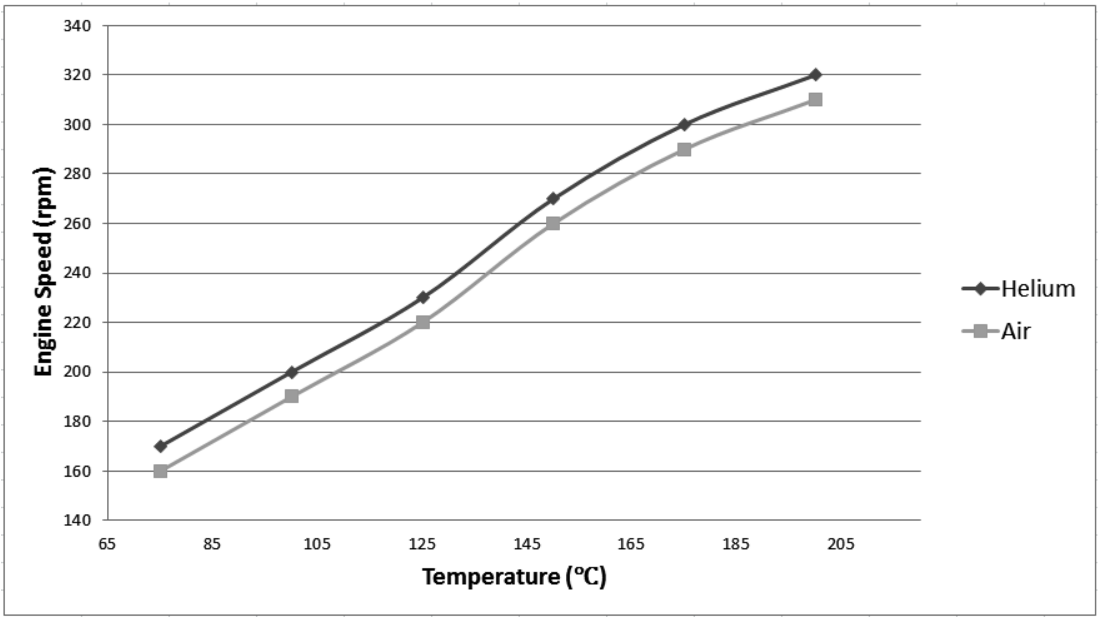

Figure 4.5. Engine speed vs heat side temperature (with regenerator).

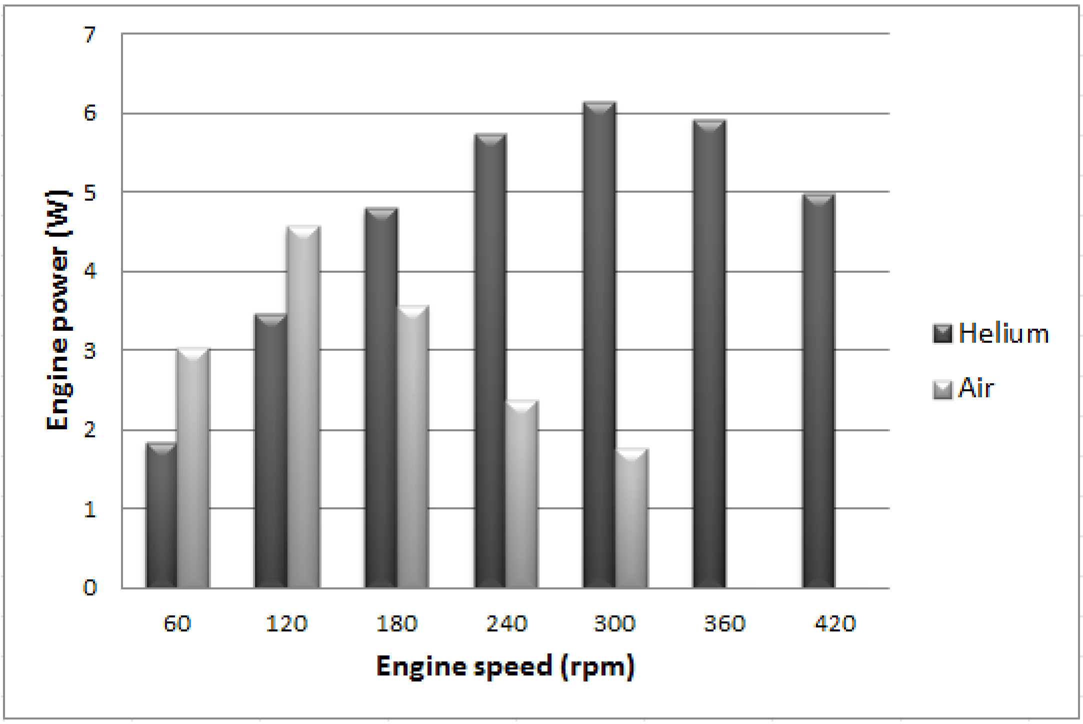

Figure 4.6. Variation of engine power with engine speed

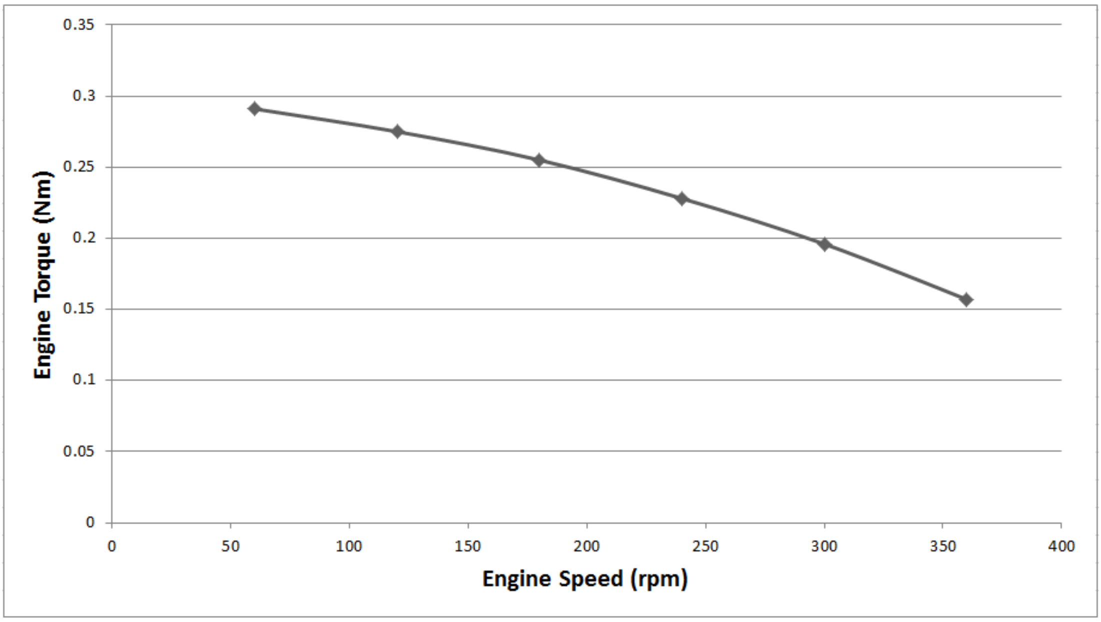

Figure 4.7. Variation of engine torque with engine speed

4.2 Solar Radiation

For the cost reduction of the output current, it is necessary to provide a system for a given cost, at a temperature to make the peak power supplying system. This temperature is a function of the collector characteristics and the ambient temperature and the intensity of the sunlight. The engine designed to adjust its load, in order to obtain an optimal temperature, and the collector efficiency of the system.

The designed and manufactured prototype tasted under Northern Cyprus climate and weather condition of Famagusta. The city is located at 35 $°N$ latitude and 33 $°E$ longitudes. The engine test conducted between 16/11/2013 and 18/11/2013 from 12.00 pm to 1.00 pm. Figure 4.8 shows the prototype Stirling engine tested by solar radiation.

Figure 4.8 Prototype Stirling engine tested by solar radiation

By founding the focus point of sun light and measuring the intensity of the sun light using pyranometer, and get helping of mirror and magnifying glass the sun light focused on the hot end displacer cylinder. In this type of experiment it takes time to heat up by sun light but once finding the focus point and making constant conditions it was possible to run the engine. Because of the weather on this season of year, it’s a little hard to have enough temperature for heating the exchanger cylinder. Each 10 minutes the temperatures, number of revolution of disk and solar intensity were measured. As showed in Fig 4.9 the engine hot end cylinder achieved the average temperature of 90°C, with revolution of 150 rpm. in an ambient temperature of 24°C.

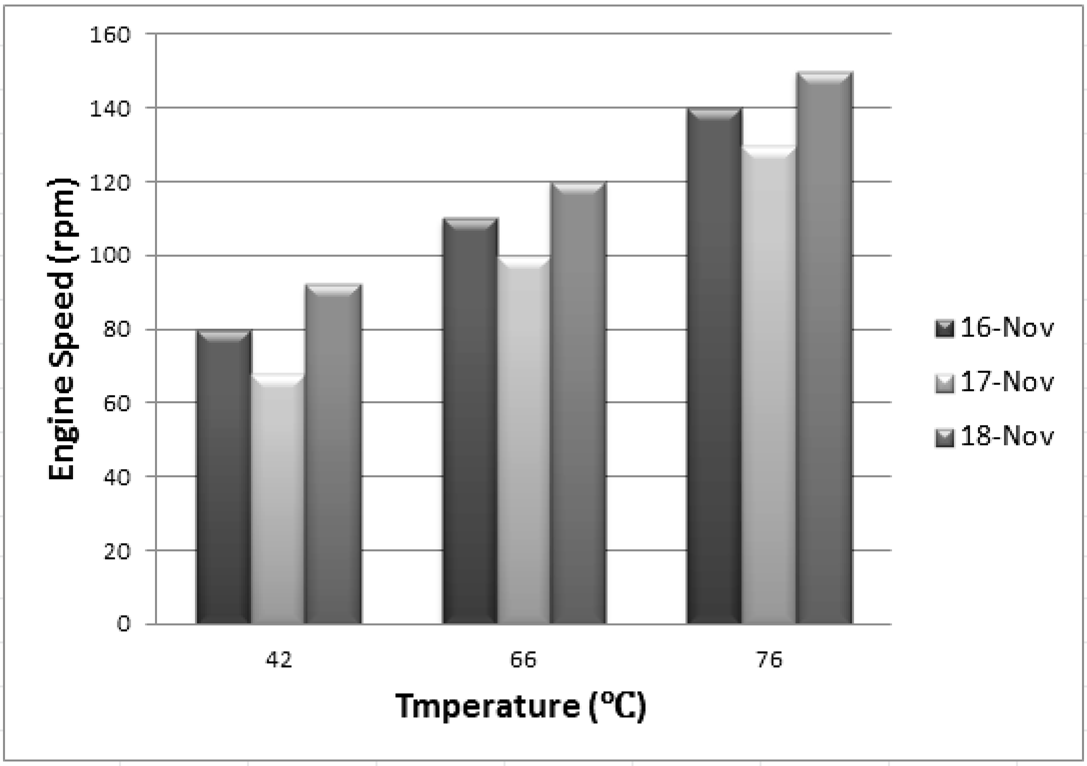

Figure 4.9. Sun light variation of engine speed depending on temperature

4.3 Calibration Instruments

One of the devices that are used in this experiment was stroboscope, used to measure the number of revolutions of the disc in RPM. It is showed in Fig 4.10.

Figure 4.10. Stroboscope

The specifications of the used stroboscope demonstrated in table 4.1.

Table 4.1. DAWE Stroboscope specifications

Stroboscopic Flash Rate	100 to 15,000 flashes per minute (FPM) Low range: 100 to 1,000 RPM/FPM High range: 1000 to 15,000 RPM/FPM
Accuracy	±(0.05% + 1 digit)
Resolution	0.1 FPM/RPM (less than 1,000 FPM/RPM) 1 FPM/RPM (> 1,000 FPM/RPM)
External Trigger Input	Input signal : 5V to 30 V rms 5 to 15,000 RPM/FPM

Another device is data acquisition system (Thermometer) Fig 4.11, to measure the temperature of the thermocouples. Two thermocouples used in this experiment, one for measuring the heater temperature and one for measuring the temperature of water which used to cool the system in the regenerator. The thermocouples are ANSI ‘T’ (Cu, Ni) type and supplied by Omega Ltd. and measure the temperatures within range of -270℃ to 400℃.

Figure 4.11. Data acquisition system

Omega Digital Thermometer specifications 10 Channel Dedicated temperature and Process Inputs:

Accuracy: ±0.5°C (±0.9°F) temp; 0.03% reading process

Resolution: 1°/0.1°; 10 µV process

Temperature Stability

- **RTD:** 0.04°C/°C
- **Thermocouple @ 25°C (77°F):** 0.05°C/°C (cold junction compensation)
- **Process:** 50 ppm/°C

NMRR: 60 dB

CMRR: 120 dB

A/D Conversion: Dual slope

Reading Rate: 3 samples per second

Display: 4 digit, 9 segment LED, 10.2 mm (0.40")

Pyranometer shown in Fig 4.12 is an instrument for measuring solar irradiance from the solid angle 2π onto a plane surface. When mounted horizontally facing upwards it measures global solar irradiance. If it is provided with a shade that prevents beam solar radiation from reaching the receiver, it measures diffuse solar irradiance. This kind of sensors creates a voltage signal proportional to the solar irradiance.

Figure 4.12. Pyranometer

Table 4.1 shows the specifications of the pyranometer device used in this experiment.

Table 4.2. Pyranometer specifications

Response Time	< 15 s	Sensitivity	approx. 8 μV / Wm^{-2}
Zero Offset a)	± 7 Wm^{-2}	Impedance	approx. 700 Ω
Zero Offset b)	± 2 Wm^{-2}	Calibration	less than 1%
Non-Stability	± 0.8%	Measurement (Instant)	less than 10 Wm^{-2}
Non-Linearity	± 0.5%	Measurement (Hourly)	approx. 2%
Directional Response	± 10 Wm^{-2}	Measurement (Daily)	approx. 1%
Tilt Response	± 0.5%	Spectral Selectivity	± 3%
Temperature Response	± 2%		

Chapter 5

CONCLUSION

The design and performance of a low temperature difference Stirling engine are described. The hot end temperature is investigated between 70 and 200℃. This work choose for low cost design choices including low pressure, helium and air working fluid and utilization of standard parts in construction and standard material selection.

The designed and manufactured prototype engine by using diesel fuel as heat source and helium as working fluid inside cylinder at the ambient temperature tested. The engine started to run at 75℃ hot end temperature and at 200℃ obtained the maximum output power of 6.5W and 320 rpm, engine speed. The thermal efficiency corresponding to maximum power was determined as 37%.

Another time by using sunlight as heat source and helium as working fluid, at the ambient temperature of 24℃, engine achieved the maximum temperature of 90℃. At this time engine achieved the speed of 150 rpm, and maximum power of 3W. The thermal efficiency corresponding to power was determined as 18%.

One area in which a large improvement could be potentially made in the operation of the engine is by pressurizing the engine. In this experiment because of lack of equipment, it was not able to charge the pressure inside the engine, but by charging the pressure inside of the engine can knowingly increase the performance of the engine.

Another way to improve performance would be using of stainless steel shaft and bushes in the displacer mechanism of the engine. Material selection is the most important part of designing of this engine but due to time and budget constraints hindering the fabrication process.

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APPENDICES

APPENDIX A: Material drawings

The following drawings represented the manufactured parts in the workshop.

APPENDIX B: Experimental data of the engine

The following tables represented the raw data of the prototype Stirling engine.

Table B-1: Engine performance by helium with cooling system

$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)	T_{Water} (℃)
75	170	22.8	5.2
100	200	22.8	5.8
125	230	23.00	7.00
150	270	23.00	8.3
175	300	23.2	10.6
200	320	23.4	13.3

Table B-2: Engine performance by helium without cooling system

$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)
75	170	22.8
100	190	22.8
125	220	23.00
150	260	23.2
175	290	23.2
200	300	23.3

Table B-3: Engine performance by air with cooling system

$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)	T_{Water} (℃)
75	160	22.8	5.2
100	190	22.8	5.7
125	220	23.00	7.3
150	260	23.00	8.5
175	290	23.2	10.8
200	310	23.3	13.6

Table B-4: Engine performance by air without cooling system

$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)
75	160	22.8
100	180	22.8
125	210	23.00
150	250	23.00
175	270	23.2
200	280	23.3

Table B-5: Engine performance by solar radiation, 16 Nov 2013

$Time$ (min)	$Intensity$ (mv)	$Radiation$ (W/m^2)	$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)	T_{Water} (℃)
20	5.66	539.04	42	0	24.3	5.3
30	5.66	539.04	63	0-30	24.3	6.6
40	6.23	593.33	75	80	24.6	8.5
50	6.23	593.33	84	110	24.6	11.3
60	6.48	617.14	90	140	24.8	13.7

Table B-6: Engine performance by solar radiation, 17 Nov 2013

$Time$ (min)	$Intensity$ (mv)	$Radiation$ (W/m^2)	$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)	T_{Water} (℃)
20	5.67	542.85	42	0	24.3	5.3
30	5.67	542.85	61	0-30	24.3	6.6
40	6.09	580.00	75	68	24.5	8.5
50	6.20	590.47	80	100	24.6	11.3
60	6.20	590.47	85	130	24.6	13.7

Table B-7: Engine performance by solar radiation, 18 Nov 2013

$Time$ (min)	$Intensity$ (mv)	$Radiation$ (W/m^2)	$T_{Hot\ end}$ (℃)	$Speed$ (rpm)	$T_{Ambient}$ (℃)	T_{Water} (℃)
20	6.12	582.85	42	0	24.5	5.3
30	6.12	582.85	66	0-30	24.5	6.6
40	6.27	597.14	76	92	24.7	8.5
50	6.71	639.04	85	120	24.9	11.3
60	6.71	639.04	90	150	24.9	13.7

The engine test conducted every 10 minutes between 16/11/2013 and 18/11/2013 from 12.00 pm to 1.00 pm.