PERFORMANCE CHARACTERISRIC IMPROVEMENT OF AN UPSCALED GAMMA-TYPE STIRLING ENGINE BY USING HEAT REGENERATOR.

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DECLARATION

I hereby declare that this dissertation is my own investigation and study. The experiment data and fabrication has originally conducted by me.

Signed.. (MUHAMMAD ZAEEM BIN MOHAMAD ZAN)

Date ....

STATEMENT 1

This dissertation is the result of my own investigation and study, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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Title of thesis: Performance characteristic improvement of an upscale gamma-type stirling engine using heat re-generator.

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NOMENCLATURE

Name	**Symbol**	**Unit**
Hot source temperature	TH	□C
Cold temperature	Tc	□C
Hot temperature	Th	□C
Torque	T	Nm
Power	Pi	Watt
Mean Pressure	PM	Bar
Operating frequency	F	Hz
Swept Volume	VSE	m3
Radius of flywheel	R	m
Mass of load	M	kg
Gravitational force	G	ms-2
Thermal expansion	α	□C-1
Change of length	δ	m
Temperature difference	ΔT	□C
Thermal conductivity	k	Wm-1K-1
Heat transfer coefficient	h	Wm-1K-1
Thickness	x	m
Beale number	Bn	
Area of plate	A	m2

ABSTRAK

Kepentingan penggunaan dan kelestarian tenaga semulajadi telah menarik minat para pengkaji untuk menghasilkan sebuah enjin pembakaran luaran seperti enjin Stirling. Dalam kajian ini, sebuah Stirling enjin jenis Gamma yang berskala besar dengan isipadu keseluruhan 85 cc, nisbah mampatan isipadu 1.5 dan sabut besi sebagai regenerator haba telah diuji prestasinya. Regenerator haba tersebut diperbuat daripada bulu keluli (steel wool)mempunyai garis pusat sepanjang 3.2cm dan panjang 1.5cm dan dipasang diantara silinder displacer dan silinder omboh. Cecair kerja yang digunakan untuk operasi enjin adalah udara, sumber haba adalah Gas Petroleum Cecair (LPG) dan jaket penyejuk untuk menstabilkan suhu sejuk menggunakan ais. keputusan kajian menunjukkan bahawa input haba ialah 65J, enjin gamma dapat beroperasi dalam mod bertekanan diri pada suhu sumber panas 280C dan suhu sejuk 32C . Prestasi keseluruhan enjin menggunakan regenerator haba telah bertambah baik berbanding prestasi enjin tanpa regenerator haba. Untuk ujian tanpa beban, kuasa brek dari formula Beale telah meningkat sebanyak 1%, kecekapan termal brek (BTE) telah meningkat sebanyak 0.9% pada perbezaan suhu yang lebih tinggi di antara sumber panas dan suhu sejuk sebanyak 1% berbanding prestasi enjin tanpa Regenerator haba.

ABSTRACT

The rise of concern on green and sustainable power production system has led to a rise of interest among researchers in developing external combustion engines such as Stirling engine. In this study, an up-scaled gamma-typed Stirling engine with the total swept volume of 85cc., volume compression ratio of 1.5 with the use of mesh-wired heat regenerator has been tested for its performance. The heat regenerator is mesh-wired, made of steel wool with the diameter of 3.2cm and height of 1.5cm which is placed inside the working fluid flow passage in between the displacer cylinder and the power piston cylinder. The working fluid used for the engine operation is air, the heat source is Liquefied Petroleum Gas (LPG) and the cooling jacket to stabilize the cold temperature is using water. Based on the experimental results, it shows that at the heat input of 65J, the gamma engine was able to operate in self-pressurized mode at the hot source temperature of 280C and cold temperature of 32C. The overall performance of the engine using heat regenerator has improved over the performance of the engine without heat regenerator. At no load test condition, the brake power from Beale formula has improved by 1%, brake thermal efficiency (BTE) has improved by 0.9% at the higher temperature difference between hot source and cold temperature of 1% as compared to the engine performance without heat regenerator

Chapter 1

1. INTRODUCTION

1.1 Overview

A Stirling engine is a heat engine that operates by cyclic compression and expansion of air or other gas at different temperatures, such that there is a net conversion of heat energy to mechanical work. More specifically, the Stirling engine is a closed-cycle regenerative heat engine with a permanently working fluid. This working principle shows that a thermodynamics system in which the working fluid is permanently contained in the system.

The Stirling engine has higher efficiency compared to steam engines, quite operation and able to use any heat source for operation. The heat energy source is generated external to the Stirling engine. Because Stirling engine is compatible with alternative and renewable energy sources it could become increasingly significant as the price of conventional fuels rises.

The Stirling engine can be classified into three types. The Alpha type engine relies on interconnecting the power pistons of multiple cylinders to move the working gas, with the cylinders held at different temperatures. The Beta and Gamma type Stirling engines use a displacer piston to move the working gas back and forth between hot and cold heat exchangers in the same cylinder.

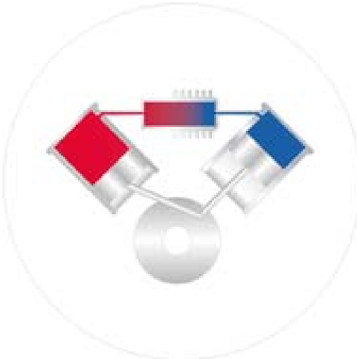


Figure 1.1 Alpha-type Stirling Engine

Figure 1.2 Beta-type Stirling Engine

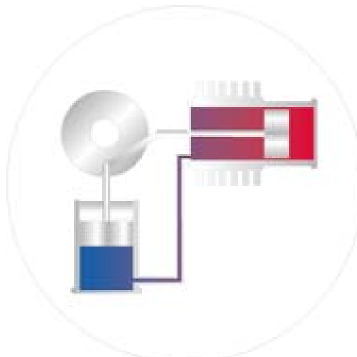


Figure 1.3 Gamma-type Stirling Engine

1.2 Problem statement

The gamma-type Stirling engine available in the School Of Mechanical Engineering, USM laboratory suffers heat and pressure loss that leads to low thermal efficiency and low power output.

Based on previous study, there is a probability of heat loss at the heater section which is in between the heat source and the base plate of the Stirling engine that affect the heater temperature. The differential temperature for Stirling engine is the most crucial parameter to ensure that the working gas (Air) can be transferred well between the hot and cold section of the engine.

The power piston temperature is between 60□C to 70□C due to the material characteristic of the power piston. The power piston is made of Teflon and the thermal expansion of the material can affect the performance of the engine. Top plate temperature of the displacer must be controlled to avoid thermal expansion of the moving parts such as piston induce an excess friction between the moving parts and the cylinder wall that can affect the engine performance.

Another problem that leads to low power output of the Stirling engine is that the temperature of Air is still high when it reach the cold section of the engine. This will result in low compression at the cold section. It also resulting in small temperature different between the hot and cold section of the engine. Theoretically, the temperature different between the hot and cold section must be huge for the engine to perform effectively. [1][2]

Heat loss and power loss during the gamma STE operation are the main problems that leads to low output performance of the engine. Based on the previous study, the brake power at no load condition (Beale formula) was 0Watt at the heater temperature of 370C and cold temperature of 20C. At load test condition, the brake power of the engine was only 0.013619Watt at the heater temperature of xxC and cold temperature of xxC. The possible root causes of the heat loss and pressure loss problems are as per following:-

1. Pressure loss due to the lacking of heat regeneration during engine operation. Elaborate on improper compression and expansion processes if the working fluid is not at the desired state of condition.

2. The incapability of increasing and controlling the heat source or heater temperature to avoid heat loss.

1.3. Objective

This study is to achieve the following objectives:

1. To design, fabricate and test heat regenerator for gamma-type Stirling engine operation in order to improve the performance of the engine.
2. To improve the heat source system temperature control for gamma-type Stirling engine.
3. To test the gamma-type Stirling engine performance with the use of heat regenerator and to compare the results with the engine performance without heat regenerator

1.4. Scope

In this project, three design of heat re-generator were selected to choose the most suitable heat regeneration system for the gamma-type Stirling engine. After the best design was selected, fabrication process took place. To improve the heat source, a stove was designed and fabricated. Experimental testing on measuring the thermal efficiency, static and dynamic test was conducted in the laboratory and the result was taken. The three design of the heat re-generator was created using SOLIDWORK software to see if the design can fit with the actual dimension of the Stirling engine.

1.5. Outline of report

This thesis is divided into five main chapters. The first chapter discusses on overview of Stirling engine, problem statement regarding the experimental problem is also reviewed in this chapter. The project scopes, objectives and the outline of the report also reviewed in this chapter.

In chapter 2, the literature review based on the definition of Gamma-type Stirling engine, heat regenerator, Stirling engine efficiency, and Teflon and aluminium characteristic against temperature will be presented.

In chapter 3, the methodologies in term of preparation of Stirling engine, Prony brake test and experimental procedure will be presented. This chapter will describe about the materials and equipment used in this experimenting procedure.

In chapter 4, results obtained from the experiments will be tabulated, discussed and verified. After that, the optimization of the engine will be discussed to ensure that the result from the experiment are acceptable.

Finally, the conclusion of the project will be discussed in chapter 5. Some suggestion and recommendations are given to improve the performance of the gamma-type Stirling engine in future research.

Chapter 2

2. LITERATURE REVIEW

2.1 Gamma-type Stirling Engine

The gamma type Stirling Engine, is a two cylinder Stirling Engine which has a cylinder for the power piston and another cylinder for expansion and contraction of the working gas. This design was developed to take advantage of small differential temperature between the hot and cold sides of the engine. A gamma-type Stirling engine is simply a beta Stirling engine which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, one containing a displacer, with a hot and a cold end. Both of it still connected to the same flywheel and the pistons are typically in parallel. The gas in the two cylinders can flow freely between them and remains in a single body. This composition produces a lower compression ratio because the volume of the connection between the two but is mechanically simpler and often used in multi-cylinder Stirling engines.[3]

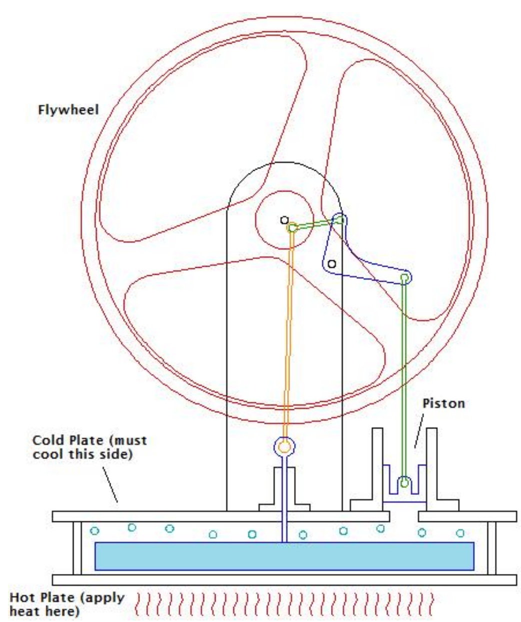


Figure 2.1 Gamma-type Stirling Engine

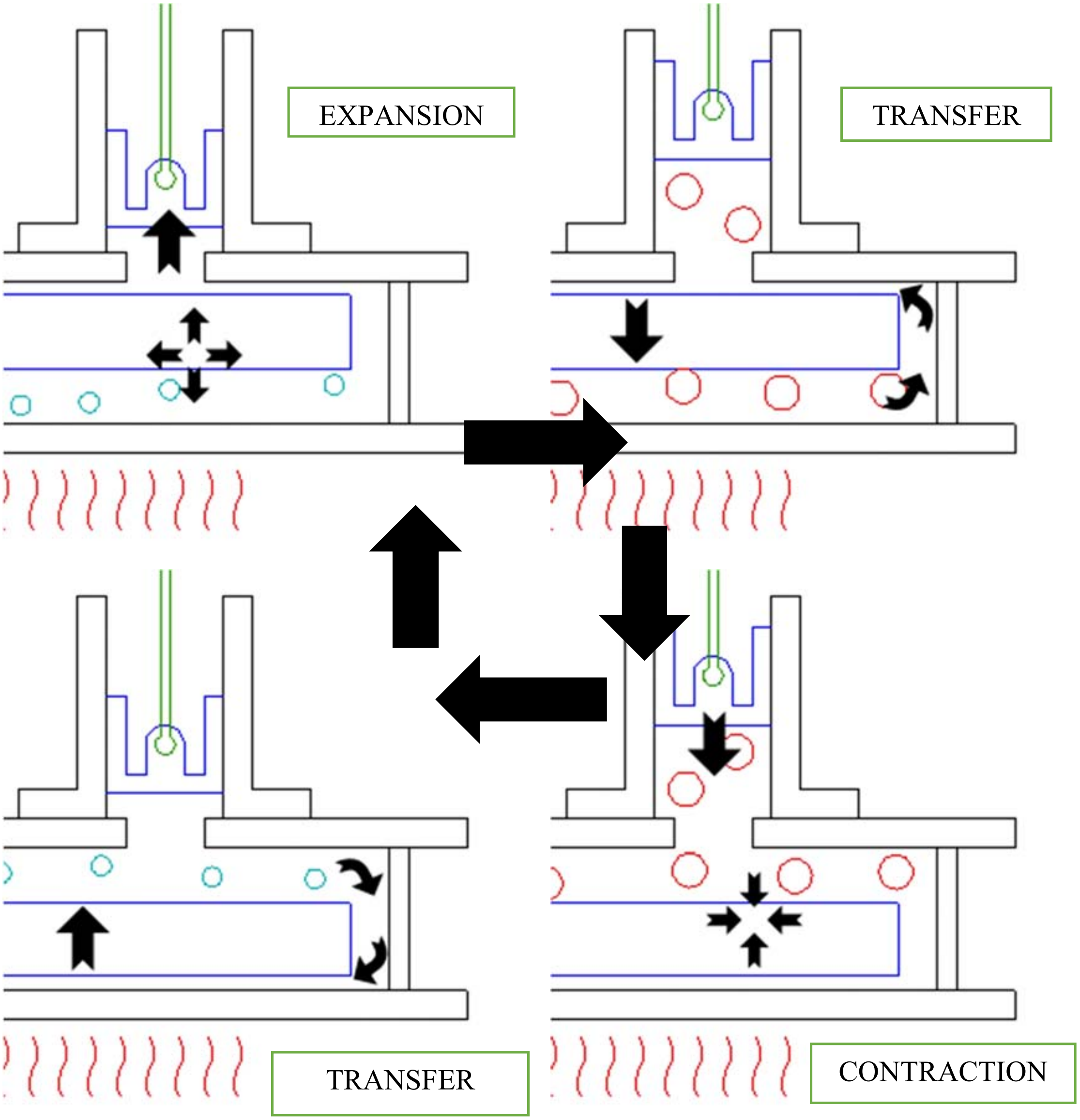


Figure 2.2 Gamma-type Stirling Engine cycle

From the figure above, the process starts from expansion phase where the heat source heats up the air inside the cylinder. The air is then expand and push the displacer up until it reach cold end of the cylinder. The transfer is when the displacer moves up to the cold end of the cylinder. At the cold end, the air contract and the power piston moves downward. The final phase is transfer phase where the displacer moving downwards. All the process keeps on rotating until the engine stop. [4]

The upscaled Gamma type Stirling engine consist of some mechanical component such as flywheel, displacer piston, and power piston. But, the key component of the Stirling engine is heat source. The heat source may be provided by the combustion of a fuel and, since the combustion products do not mix with the working fluid and hence do not come into contact with the internal parts of the engine, a Stirling engine can run on fuels that would damage other types of engines' internals, such as landfill gas which contains siloxane.

2.2 Stirling Engine efficiency

The gases used inside a Stirling engine never leave the engine. There are no exhaust valves that vent high-pressure gasses, as in a gasoline or diesel engine, and there are no explosions taking place. Because of this, Stirling engines are very quiet. The Stirling cycle uses an external heat source, which could be anything from gasoline to solar energy to the heat produced by decaying plants. Today, Stirling engines are used in some very specialized applications, like in submarines or auxiliary power generators, where quiet operation is important. The Stirling engine contains a fixed amount of gas which is transferred back and forth between a "cold" and a "hot" end of a long cylinder. The "displacer piston" moves the gas between the two ends and the "power piston" changes the internal volume as the gas expands and contracts. [5]

This efficiency correspond to the one of the theoretical ideal Stirlng cycle, which considers two isothermic (expansion and compression) and two isochoric (heating and cooling) processes. However, real engines present many difficulties on the design and these isothermic and isochoric processes are impossible to reproduce.

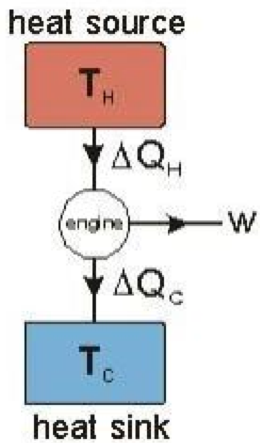


Figure 2.3 Heat flow in stirling engine

During each cycle :

W is the net work done by the engine

ΔQ_h Is the energy taken from the hot source

ΔQ_c Is the energy given to the cold sink

General known formula for calculating efficiency is obtained from dividing input power by output power of a system. This gives more accurate result, if it is possible to calculate power directly. [6]

One of the most efficient Stirling engines ever made was the MOD II automotive engine, produced in the 1980′s. It reached a peak thermal efficiency of 38.5%. Compare this to a modern spark-ignition (gasoline) engine, which has a peak efficiency of 20-25%.

2.3 Moving parts

2.3.1. Teflon (Polytetrafluoethylene PTFE) Characteristic against temperature

PolyTetraFluoroEthylene is a fluorocarbon-based polymer and is commonly abbreviated PTFE. The Teflon® brand of PTFE is manufactured only by DuPont.Several other manufacturers make their own brands of PTFE which can often be used as substitute materials. This fluoroplastic family offers high chemical resistance, low and high temperature capability, resistance to weathering, low friction, electrical and thermal insulation, and "slipperiness". PTFE's mechanical properties are low compared to other plastics, but its properties remain at a useful level over a wide temperature range of -100°F to +400°F (-73°C to 204°C). Mechanical properties are often enhanced by adding fillers (see paragraph below). It has excellent thermal and electrical insulation properties and a low coefficient of friction. PTFE is very dense and cannot be melt processed, it must be compressed and sintered to form useful shapes

PTFE's mechanical properties can be enhanced by adding fillers such as glass fibers, carbon, graphite, molybdenum disulphide, and bronze. Generally, filled PTFE's maintain their excellent chemical and high temperature characteristics, while fillers improve mechanical strength, stability, and wear resistance. The properties of 25% glass-filled and 25% carbon-filled PTFE grades are shown below for comparison purposes. [7]

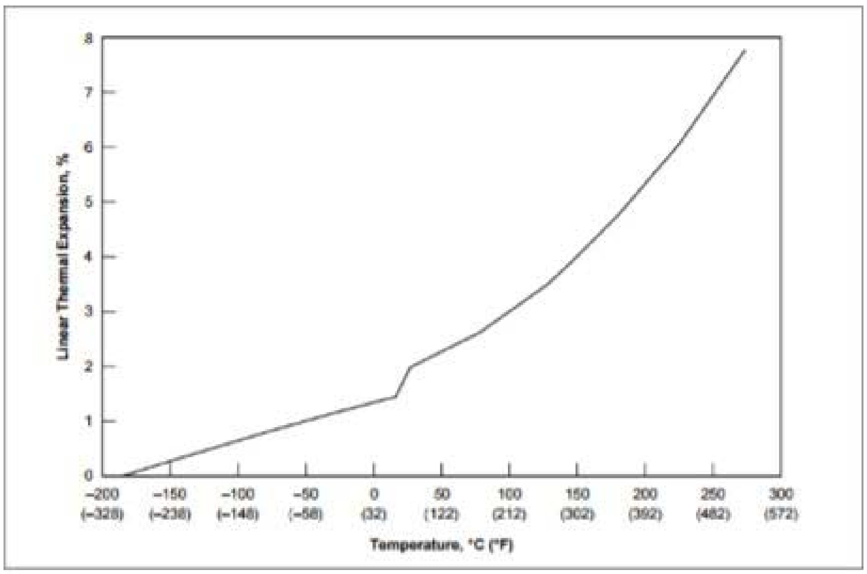


Figure 2.4 Linear expansion of Teflon

Temperature Range, °C (°F)	Linear Coefficient of Expansion, 10^{-6} mm/mm·°C	10^{-6} in/in·°F
25 to −190 (77 to −310)	8.6	4.8
25 to −150 (77 to −238)	9.6	5.3
25 to −100 (77 to −148)	11.2	6.2
25 to −50 (77 to −58)	13.5	7.5
25 to 0 (77 to 32)	20	11.1
10 to 20 (50 to 68)	16	8.9
20 to 25 (68 to 77)	79	43.9
25 to 30 (77 to 86)	16	8.9
25 to 50 (77 to 122)	12.4	6.9
25 to 100 (77 to 212)	12.4	6.9
25 to 150 (77 to 302)	13.5	7.5
25 to 200 (77 to 392)	15.1	8.4
25 to 250 (77 to 482)	17.5	9.7
25 to 300 (77 to 572)	22	12.1

Table 2.1 Linear coefficient of Aluminium

2.3.2. Aluminium characteristic against temperature

The thermal conductivity of aluminium is about three times greater than that of steel. This makes aluminium an important material for both cooling and heating applications such as heat-exchangers. Combined with it being non-toxic this property means aluminium is used extensively in cooking utensils and kitchenware.

Property	Value
Atomic Number	13
Atomic Weight (g/mol)	26.98
Valency	3
Crystal Structure	FCC
Melting Point (°C)	660.2
Boiling Point (°C)	2480
Mean Specific Heat (0-100°C) (cal/g.°C)	0.219
Thermal Conductivity (0-100°C) (cal/cms. °C)	0.57
Co-Efficient of Linear Expansion (0-100°C) ($x10^{-6}$/°C)	23.5
Electrical Resistivity at 20°C (Ω.cm)	2.69
Density (g/cm^3)	2.6898
Modulus of Elasticity (GPa)	68.3
Poissons Ratio	0.34

Table 2.2 Properties of Aluminium

2.4. LPG gas (Liquefied Petroleum Gas)

LPG (Liquefied Petroleum Gas) is a mixture of gaseous hydrocarbons, produced from natural gas and oil extraction (66%) and from oil refining (34%). As an associated gas, it is automatically generated during the production of methane and during the refining process itself. If LPG wasn't captured at this point, it would have to be destroyed through flaring or venting, an unacceptable waste of an immediately available and exceptional energy source.

One of LPG's greatest strengths is its versatility, with over 1000 different uses: in the home for heating and real flame cooking; in the garden for barbecues; in your vehicle to lower your transport costs; commercially in forklift trucks, farming, industrial heating, catering and caravan parks to name but a few.

LPG exist in two forms which is Propane and Butane. The difference in their properties means that they are particularly suited to specific uses. Propane's lower boiling point suits outdoor storage and is primarily uses for central heating, cooking and numerous commercial applications. Butane, which doesn't work in cooler conditions, is best used indoors and is perfect for powering indoor portable heaters.

Commercially available LPG is currently derived from mainly from fossil fuels. Burning LPG releases carbon dioxide, a greenhouse gas. The reaction also produces some carbon monoxide. LPG does, however, release less CO2 per unit of energy than does coal or oil. It emits 81% of the CO2 per kWh produced by oil, 70% of that of coal, and less than 50% of that emitted by coal-generated electricity distributed via the grid. Being a mix of propane and butane, LPG emits less carbon per joule than butane but more carbon per joule than propane. LPG burns more cleanly than higher molecular weight hydrocarbons because it releases less particulates. [8][9]

Figure 2.5 LPG Tank

2.5. Cooler bed as an auxiliary cooler

Stirling engine works when there is a temperature different between the hot and cold end of the Stirling engine. If the temperature different are higher, more speed can be obtained. Thus, cooler bed has been fabricated in order to increase the temperature different and avoid heat loss from the heat source due to the melting ice.

Copper is a good conductor of heat. This means that if one end is heated, the other end will reach the same temperature is short period of time. Most metals are pretty good conductors however, apart from silver, copper is the best.

Based on table, copper and aluminium have the highest thermal conductivity while steel and bronze have the lowest. Heat conductivity is a very important property when deciding which metal to use for a specific application. As copper is an excellent conductor of heat, it’s good for heat exchangers, heat sinks, and even saucepan bottoms. Because steel is a poor conductor of heat, it’s good for high-temperature environments like airplane engines.

Metal	Thermal Conductivity (W/mK)
Silver	429
Copper	399
Gold	316
Aluminium	235
Yellow Brass	120
Cast iron	80.1
Stainless steel	14.0

Table 2.3 Metals thermal conductivity

Figure 2.6 Copper cooler bed

2.6. Heat re-generator in gamma-type Stirling engine

In the gamma-type Stirling engine, the heat regenerator is to make sure the air is at low temperature when it reach the cold end of the Stirling engine. The air need to be at low temperature so that the temperature different is high in order to produce greater power of the Stirling engine. The cold air is to compress so that the power piston will able to moves down during the compression process.

In thermal regenerator operation the hot fluid passes through the channels of the packing for a length of time called the "hot period," at the end of which, the hot fluid is switched off. A reversal now takes place when the cold fluid is admitted into the channels of the packing, initially driving out any hot fluid still resident in these channels, thereby purging the regenerator. The cold fluid then flows through the regenerator for a length of time called the "cold period," at the end of which the cold fluid is switched off and another reversal occurs in which, this time, the hot fluid purges the channels of the packing of any remaining cold fluid. A fresh hot period then begins. During the hot period, heat is transferred from the hot fluid and is stored in the packing of the regenerator. In the subsequent cold period, this heat is regenerated and is transferred to the cold fluid passing through the exchanger. [10][11]

Figure 2.7 Heat Regenerator using steel wool

Propertis	Stainless steel	Copper	Aluminium	Monel 400
Density ($kg.m^{-3}$)	7.850	8.920	2.700	8.800
Thermal capacity ($J.kg^{-1}.K^{-1}$)	477	385	902	430
Thermal conductivity ($W.m^{-1}.k^{-1}$)	26	390	237	22

Figure 2.8 Properties of material with 90% porosity

The use f copper as heat regenerator is not recommended because of its ability to oxidize as the working fluid is water. The oxidation process will change the physical properties of copper. Due to its high heat capacity and thermal exchange rate, the stainless steel regenerator is shown to be the best Stirling engine regenerator material.

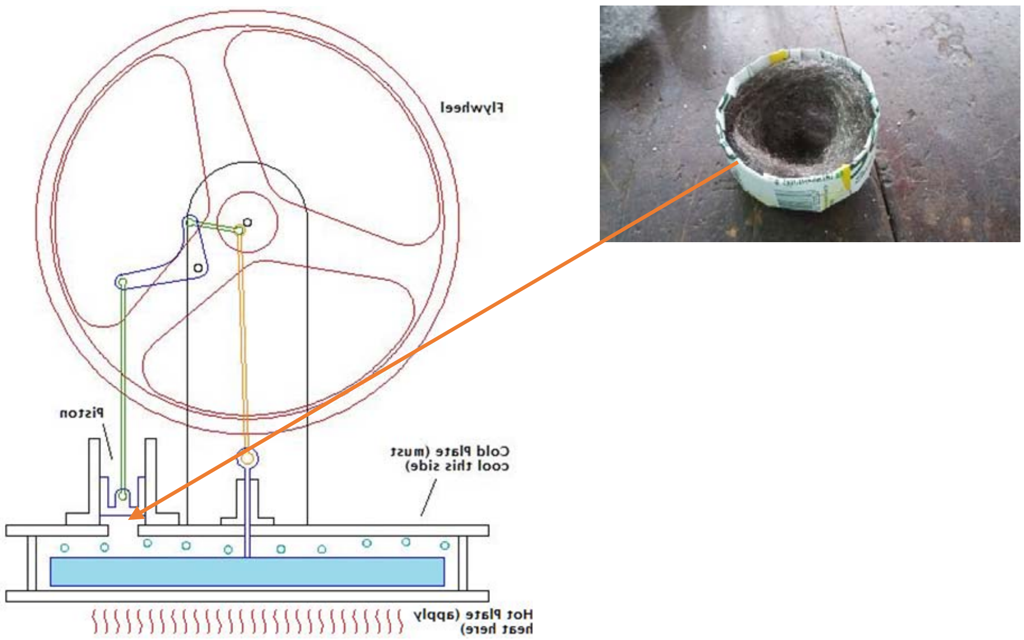


Figure 2.9 Heat regenerator istallation

Chapter 3

3. METHODOLOGY

3.1. Overview

Different in temperature is the main factors that affects the performance and efficiency of the Stirling engine. Thus, a set of experiment will be conducted to study the efficiency and performance of the Stirling engine when a hear re-generator is installed. The experimental procedure will be explained in this chapter in order to obtain the optimum range of different temperature and power output of the Stirling engine.

3.2. Engine specification

Engine Specification	**Value with unit**
Power piston bore	5.99 cm
Power piston stroke	3.00 cm
Power piston swept volume	84.55 cc
Power piston dead volume	1.01 cc
Displacer bore	47.30 cm
Displacer stroke	3.00 cm
Displacer swept volume	5271.49 cc
Displacer dead volume	10684.15 cc
Compression ratio	1.5

Table 3.1 engine specification for High temperature (HTD) Differential gamma type Stirling engine

3.3. Experimental setup

All the parts of the engine has to be assemble. For this upscaled configuration, some of the parts has to be assemble by extra person due to its weight.

1. All of the parts has to be clean from any types of contaminants especially rust.

2. All the gap of the engine has to be covered by gasket. The gasket was treated with silicon (for gasket) to ensure there is no air leaking from the engine.

3. The stove was put under the engine to heat it and was attached to the gas tank.

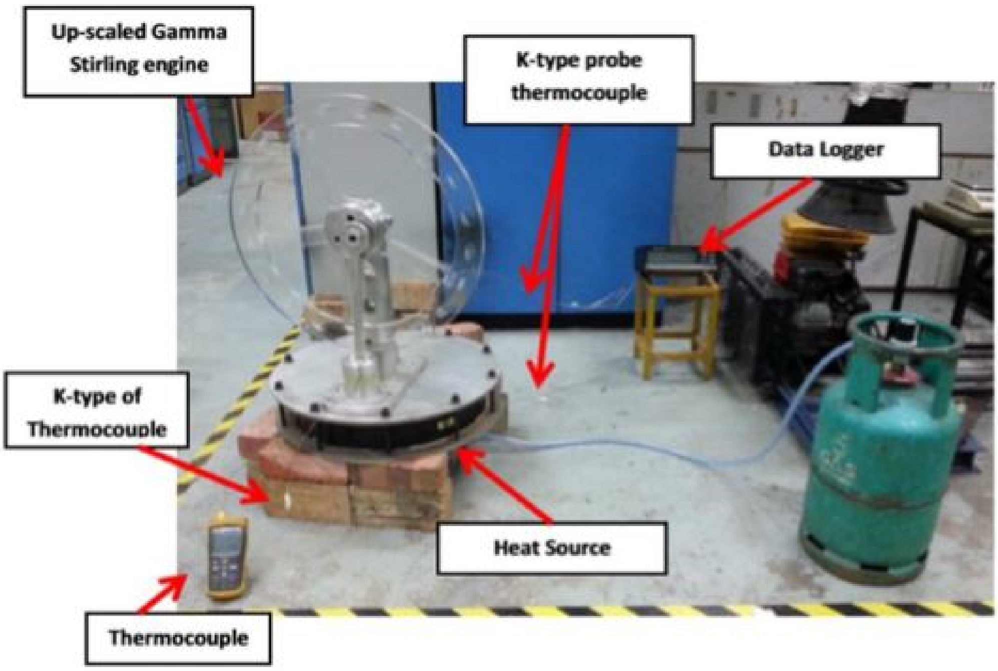


Figure 3.1 Experimental setup

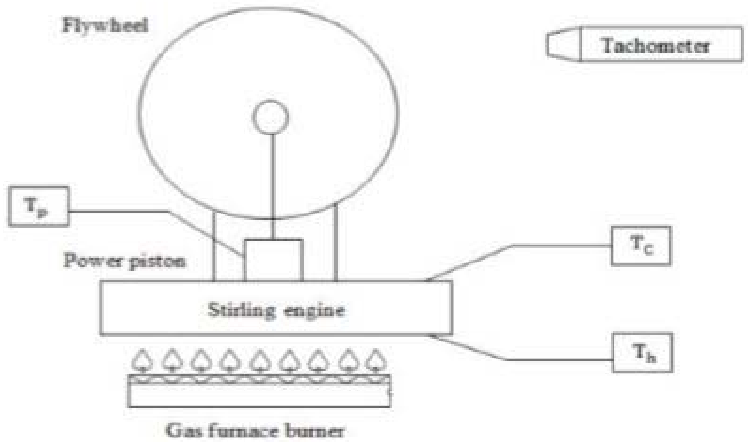


Figure 3.2 Schematic diagram of setup

3.4. Materials and equipment

The materials and equipment used in this experiment are as follow:

Material:

1. LPG Tank
2. Gasket
3. High temperature silicon
4. Plastic straw
5. String and hooks
6. Beads

Equipment:

1.1 Tachometer

1.2 Infrared thermometer

1.3 K-type thermocouple

3.5. Experimental procedure

1. Setup the equipment.
2. Heat was supplied under the engine.
3. Wait for a while to warm up the air inside the engine then trigger manually the flywheel to rotate.

4. The speed of flywheel will be taken by using tachometer every 1 minute.

5. The temperature of bottom plate, top plate, power piston, and displacer piston also has to be taken every 1 minute.

6. After 15- 20 minutes, the heat was removed from the engine.

7. All of the data was tabulated

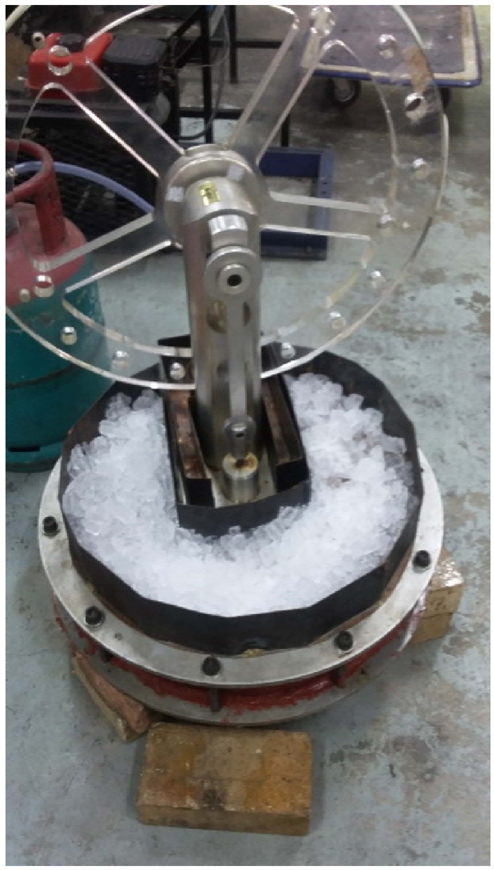


Figure 3.3 Experimental setup with auxiliary cooler

the figure above, it is just shows for no load engine operation. For engine operation at load condition, dynamic load testing was done by referring Pony brake test. At first, the upscaled gamma Stirling engine was run at no load condition. When the rotation of speed of flywheel is in steady state, a string was attached to the flywheel while on the other end of string a tiny bag was tied to it. The other end of string was connected with a spring. A spring that used in this testing was elastic rubber. The load weight was added into tiny plastic bag one by one until the flywheel stop rotating. The rotational speed is determined by using Tachometer

The steps are shown in the following chart :

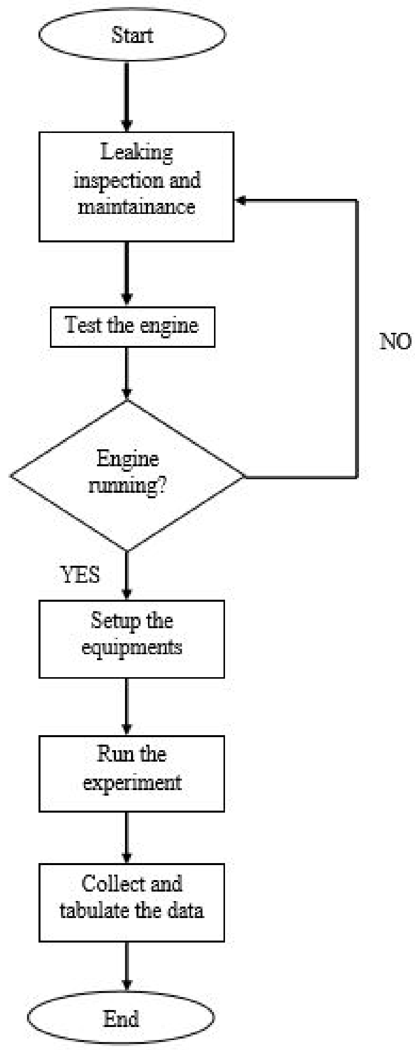


Figure 3.4 Experimental flowchart

3.6. Dynamic load test

It measures the torque produced by an engine. In fact, the term “brake horsepower” derives from this method of torque measurement. Measurement is made by wrapping a belt around the engine's output shaft and measuring the force transferred to the belt through friction. Friction is increased by tightening the belt until the shaft's rotation frequency is reduced. Additional engine power can be applied until the engine's limit is reached. For the belt method it is common to use a pair of spring balances and apply a pretension to the belt. When the shaft rotates, one balance will demonstrate an increased tension while the other shows reduced tension. Factor in the shaft diameter, and the difference is a measure of the torque. In another approach, clamp a lever to the shaft and measure using a single balance. The torque is then related to the lever length, shaft diameter and measured force. [7]

Power is calculated by multiplying torque by rotational speed:

$$T=(S-W)r=(S-mg)r$$

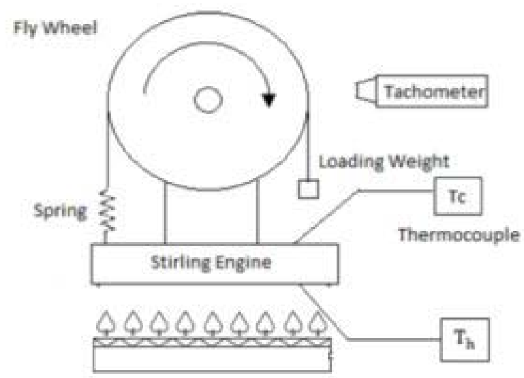
Where ,

T=touque
S=spring load
W=weight
R=flywheel radius

$$P=\frac{2\pi NT}{60}$$

Where ,

P=brake power
T=touque



Brake thermal efficiency was calculated by formula :

BTE=Brake power/q

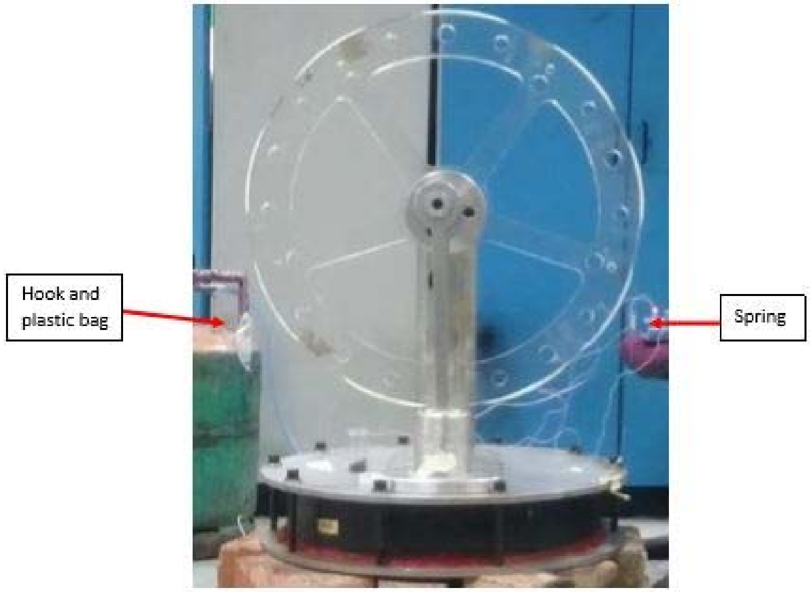


Figure 3.5Dynamic load test setup