THE DEVELOPMENT OF GAS TURBINE ENGINE USING TURBOCHARGER

by

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ENDORSEMENT

I, Mohd Norhafidan bin Isa hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

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Date: 12 June 2018

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ABSTRACT

Gas turbine engine using turbocharger (also known as micro gas turbine engine) is a small-scale gas turbine engine that can be used to drive a portable power generator and has a potential to produce low emission. In this project, a small gas turbine engine is developed using a turbocharger from a car engine.

This thesis is focused in designing and fabricating required components and supporting/auxiliary systems for the operational of the gas turbine engine which are ignition system, fuel injection system, lubrication system, air ducting and combustion chamber. In this report, the designing and fabricating method for all auxiliary systems and combustion chamber are presented. The ignition system used conventional spark plug system to ignite the fuel-air mixture in the combustion chamber. The fuel used is butane gas which is a type of fuel that used in cooking purpose. Lubrication system is required since the rotating shaft inside the turbocharger which is directly connected with compressor wheel and turbine wheel will rotate at several thousand revolutions per minute during the operation. A simple lubrication system is designed and fabricated to deliver an amount of lubricating oil on the rotating shaft to reduce wear and for longer lifespan.

The combustion chamber is the most crucial part. It consists of two main parts which are flame housing and flame tube. These parts are carefully designed to get the perfect combustion for the engine to self-sustaining the combustion process. In this report, the method in designing the combustion chamber also presented. The designed combustion chamber is studied to determine whether it is suitable for this project or not. After all systems and combustion chamber are completely fabricated, the system is assembled with the turbocharger and the engine is tested for several times. The operational performance of all system and the gas turbine engine also are observed during the engine operation. All problems encountered in each system and its solutions are presented.

PEMBANGUNAN BAGI ENJIN TURBIN GAS MENGGUNAKAN PENGECAJ TURBO

ABSTRAK

Enjin turbin gas menggunakan pengecas turbo (atau juga dikenali sebagai enjin turbin gas mikro) merupakan enjin turbin gas berskala kecil yang menjadi penjana juasa mudah alih dan mampu mengasilkan tahap pelepasan yang rendah. Dalam projek ini, satu enjin turbin gas yang kecil dibina menggunakan pengecas turbo daripada sebuah kereta.

Laporan ini memberi tumpuan kepada rekabentuk dan febrikasi sistem-sistem yang diperlukan oleh enjin turbo gas untuk beroperasi iaitu sistem pencucuhan, sistem pembekal bahan api, sistem pelinciran dan kebuk pembakaran. Dalam laporan ini, kaedah reka bentuk dan febrikasi semua pembantu sistem dan kebuk pembakaran dibentangkan. Sistem pencucuhan palam pencucuh yang konvensional digunakan untuk menyalakan campuran bahan api dan udara di dalam kebuk pembakaran. Bahan api yang digunakan di dalam projek ini ialah gas butana yang merupakan bahan api yang digunakan untuk tujuan memasak. Sistem pelinciran diperlukan di dalam projek ini oleh sebab aci berputar didalam pengecas turbo yang disambungkan secara terus dengan bilah jejari pemampat dan bilah jejari turbin akan berputar pada beberapa ribu revolusi per minit semasa beroperasi. Satu sistem pelinciran yang ringkas direka bentuk dan difabrikasi untuk menyalurkan minyak pelincir pada aci berputar untuk mengurangkan kadar haus dan untuk jangka hayat yang lebih lama.

Kebuk pembakaran adalah bahagian yang penting dalam projek ini. Ia terdiri daripada dua bahagian utama iaitu selongsong api dan tiub api. Bahagian-bahagian ini direka bentuk dengan teliti untuk mendapatkan pembakaran yang sempurna supaya enjin ini dapat mengekalkan proses pembakaran sendiri. Laporan ini juga membentangkan kaedah kebuk pembakaran direka bentuk. Kebuk pembakaran yang siap direka bentuk kemudiannya dikaji untuk mengetahui sama ada ianya sesuai digunakan untuk projek ini atau tidak. Selepas semua sistem dan kebuk pembakaran siap sepenuhnya, sistem-sistem tersebut dipasang dengan pengecaj turbo dan enjin diuji untuk beberapa kali. Prestasi kesemua sistem dan enjin turbin gas diperhatikan semasa enjin tersebut sedang beroperasi. Kesemua masalah yang hadir dalam setiap sistem dan cara untuk mnyelesaikannya juga dibentangkan.

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T1	: Temperature of air intake [K]
T2	: Temperature of compressed air [K]
T3	: Turbine entry temperature [K]
P1	: Pressure of air intake [kPa]
P2	: Pressure of compressed air [kPa]
P3	: Turbine entry pressure [kPa]
γ	: Heat capacity ratio of air, γ = 1.4
n_c	: Compressor efficiency, n_c = 0.73
P2/P1	: Pressure ratio, P2/P1 = 1.7
R	: Gas constant, R = 278 J/kg.K
A_{reff}	: Reference area or cross-sectional area of flame housing [mm]
m_a	: Mass flow rate of air intake [kg/s]
$\frac{\Delta P_{2-3}}{q_{reff}}$	: Combustor pressure drop factor, $\frac{\Delta P_{2-3}}{q_{reff}}$ = 40
$\frac{\Delta P_{2-3}}{P2}$	: Combustor pressure loss, $\frac{\Delta P_{2-3}}{P2}$ = 0.053
r_{reff}	: Reference radius [mm]
D_{reff}	: Reference diameter [mm]

π : Pi, π = 3.142

A_{ft} : Cross-sectional area of flame tube [mm]

r_{ft} : Radius of flame tube [mm]

D_{ft} : Diameter of flame tube [mm]

PF : Pattern factor

T_{max} : Melting point temperature for the turbine wheel [K]

L_{ft} : Length of flame tube [mm]

$\frac{\Delta P_L}{q_{reff}}$: Liner pressure loss factor

L_{PZ} : Length of primary zone [mm]

L_{SZ} : Length of secondary zone [mm]

L_{DZ} : Length of dilution or cooling zone [mm]

m_a : Air mass flow rates in inlet [kg/s]

m_{an} : Air mass flow rates in annulus [kg/s]

m_{RZ} : Air mass flow rates in recirculation zone [kg/s]

m_{PZ} : Air mass flow rates in primary zone [kg/s]

m_{SZ} : Air mass flow rates in secondary zone [kg/s]

m_{DZ} : Air mass flow rates in dilution zone [kg/s]

B : Bleed ratio

$C_{d,h}$: Hole discharged coefficient

A_h : Hole area [mm^2]

α : Orifice area ratio

A_{an} : Annulus area [mm]

K : Pressure loss factor

δ : Momentum loss factor, δ = between 0.75 - 0.9

μ : Ratio between bleed ratio and orifice area ratio

D_h : Diameter hole [mm]

N_h : Number of hole

σ_1 : Hoop stress [MPa]

σ_2 : Longitudinal stress [MPa]

σ_3 : Normal stress acting on combustion chamber lid [MPa]

P : Pressure in the vessels [MPa]

r : Inner radius of the vessel [mm]

t : Thickness of the wall [mm]

F : Force exerted [N]

A : Surface area [mm]

$\dot{m}_f$: Mass flow rate of butane [kg/s]

ρ_f : Fuel density [kg/m^3]

V_f : Fuel velocity [m/s]

A_f : Cross sectional area of fuel injector at nozzle [mm^2]

CHAPTER 1

INTRODUCTION

The first chapter is to understand the project itself from the basic. Since this project is used a turbocharger from a car, a better understanding required about the turbocharger’s components and how it is works. A turbocharger is used in a car to increase the engine efficiency since it increase the air flow inside the combustion chamber by compressed the air using a compressor. In this chapter, the mission statement, objectives, scope of works and the problem statements are explained.

1.1 Introduction.

Gas turbine engine is mainly used for two purposes which are for power production and for generating thrust force in an aircraft. Even though these functions are different, the working principle behind each case is the same. For generating thrust force, in order to make the aircraft move forward, the gas turbine engine should produce a force in forward direction. This force is produced by jet affect to the exit fluid. When a high velocity fluid is ejected the engine, it will produce a reaction force which will powered the aircraft. This force known as jet forces which will make the aircraft move forward.

Figure 1.1: Gas turbine engines as aircraft propulsion system and power generation. (windies-online.com, 2014)

Gas turbine engine has a few sections. The first section is the inlet section where the air is taken from an opening in front of the engine. The second section is compressor section where the function is to suck the air and pressurized by a compressor. The third section is combustion section where the fuel is added into the compressed air and burned in a combustion chamber to produce hot gases and leave the combustion chamber to the turbine section and produce very high energy level. The last section is the turbine section where it is converts the hot gases out of the combustion chamber into mechanical energy by expanding the hot high-pressure gases to a lower temperature and pressures to drive the compressor, shaft and other mechanical part. Thus the process of producing high velocity jet and outlet has become self-sustainable (Soares, 1998).

The concept of a turbocharger used in a car is the same as gas turbine engine. A turbocharger is used in a car to increase the engine efficiency since it increase the air flow inside the combustion chamber by compressed it using a compressor (Kech *et al.*, 2011). Turbocharging is a common technique to increase the power density of internal combustion engine which help to reduce the fuel consumption and pollutant emission (Enagi *et al.*, 2017). It is consists of three basic parts which are a compressor, a turbine and center housing. Turbocharger compressors generally consist of three parts which are compressor wheel, diffuser and compressor housing. During the rotation of the compressor wheel, air is entering towards the turbocharger inlet in axial direction with high velocity and after that it will spread in radial direction as shown in Figure 1.2. The function of the diffuser is to collect the air and slow it down before the air reaching the compressor exit. As the result, it will rise the temperature and pressure before it is channeled to car engine for combustion process. The compressor wheel is connected directly to the exhaust gas turbine through a common shaft. Thus, it will rotate same rotational speed as the turbine. Generally, the exhaust gas turbine consists of turbine wheel and turbine casing. The exhaust gas generated from combustion process inside of car engine is then channeled to the turbine inlet, and then it will flow to the exhaust manifold for ejection. In this case, the pressure of the exhaust gasses is converted into kinetic energy inside the turbine casing and supplied to the turbine rotor. Since the compressor wheel and the turbine wheel are directly connected through a shaft, the kinetic energy of the exhaust gasses is convert into mechanical energy to drive the compressor wheel through a shaft (Colin Cutler, 2017).

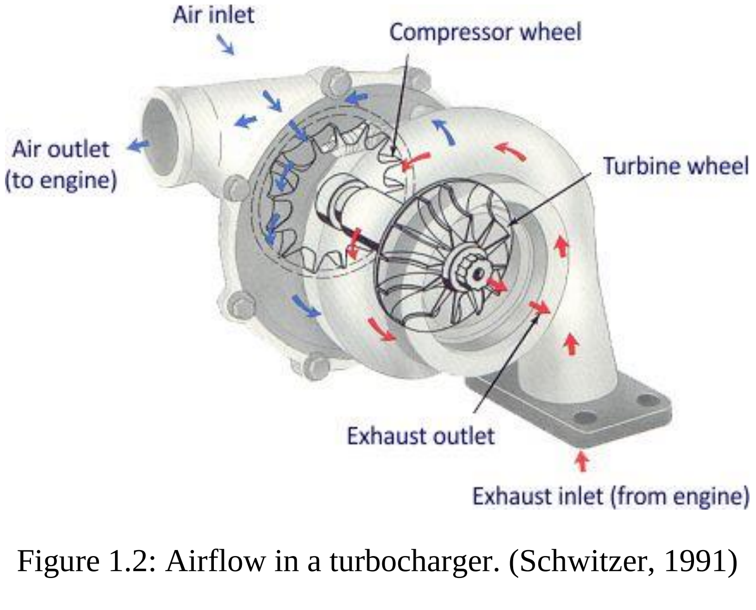

Figure 1.2: Airflow in a turbocharger. (Schwitzer, 1991)

Since the process and mechanical works inside gas turbine engine is same as turbocharger, a small gas turbine engine can be develop by using turbocharger by adding a combustion chamber and other systems. It is found that, the development and the study on small gas turbine engine or known as micro gas turbine engine has been expanded for several benefits such as electrical generator (Nascimento *et al.*, 2013). The development of micro gas turbine also offers potential for saving energy and reducing Carbon Monoxide (CO) emission (Enagi *et al*, 2017).

1.2 Mission Statement.

Design, fabricate and assemble all auxiliary system and combustion chamber with a turbocharger to make it as gas turbine engine.

1.3 Objective.

There are a few objectives in this project. The objectives can be listed according to its priority as below:

1. To design, fabricate and test auxiliary system of gas turbine; combustion chamber, ignition system, fuel injection system, lubrication system.
2. To assemble all systems in developing the gas turbine engine using turbocharger and testing the gas turbine engine.

1.4 Scope of work.

1. Study the basic concept of turbocharger and its components.
2. Study the basic concept of gas turbine engine.
3. Design and fabricate the combustion chamber.
4. Design and fabricate the auxiliary systems; fuel system, lubrication system and ignition system.
5. Assembly all systems to make it as gas turbine engine and test the engine.

1.5 Problem Statement.

The development of gas turbine engine using turbocharger is good platform to understand the concept of gas turbine engine. Currently in Malaysia, the used of this kind technology still not yet expanded. There are several problems in developing of gas turbine using turbocharger from a car.

The main problem in developing a small gas turbine is the design of the combustion chamber. Extensive study is required in designing the combustion chamber to get a perfect combustion. The combustion chamber consists of flame tube and flame housing. One of the requirements in designing a combustion chamber is the material selection must have very high melting point so that it can withstand with high temperature (Rodgers, 2015). Thus, it will not melt during combustion process. The fuel injection system also plays important role in producing a perfect combustion. Air must be completely mixed with the fuel before it burns to avoid incomplete combustion (Yu. M. Pchelkin, 1967). There are two types of fuel which is gas fuel and liquid fuel. A type of fuel which can be easily mixed with air and easy to ignite is required.

Second is the flame tube. Flame tube also is an important part need to be designed since the combustion will take place inside of it. Flame tube consists of three zones of hole which are primary zone, intermediate zone and dilution or cooling zone with different size of hole from small, medium and larger respectively and these zones will affected the flame stability. These zones must be designed based on the amount of air that can be sucked by the turbocharger (Thoma *et al.*, 2010). Since we need perfect combustion, the correct size and number of hole are required.

Third is about the ignition system. Ignition system in car is quiet complex and expensive since we need a lot of components such as 12V battery, ignition coil, distributor, breaker, condenser and spark plug. The conventional spark plug system that has been developed by Moktar, 2011 does not produce the spark continuously. Thus, a simple ignition system should be designed to ignite the spark plug and perfectly burn the mixture of air and fuel. A spark plug which having different core and type such as platinum spark plug and iridium spark plug should also be selected correctly.

The fourth is the lubrication system. Lubrication system is important in every single mechanical part in turbocharger especially for the shaft since it will rotate for several thousand revolutions per minute. Thus, lubrication system is required to improve its efficiency and to reduce wear since it will rotate at several thousand revolution per minute (Rodgers, 2015). A systematic lubrication system is required to circulate the lubrication oil through its path to make sure the shaft and the bearing inside the turbocharger is lubricated continuously during the engine is on operating. From all these problems, this study is proposed.

CHAPTER 2

LITERATURE REVIEW

At the beginning on this chapter, it describes the concept of Brayton Cycle or also known as constant pressure cycle. To build a gas turbine engine from a turbocharger, the combustion chamber and the auxiliary system such as ignition system, fuel injection system and the lubrications system is required. Thus, extensive study research is done for these systems to get the idea on how to develop these systems for this project.

2.1 Reviews on Brayton Cycle.

Brayton Cycle describes the workings of a constant-pressure heat in engine (Giampaolo, 2003). Figure 2.1 shows the graph of temperature against entropy for open loop Brayton cycle. At process 1 to 2, the air is sucked and compressed by a compressor (isentropic compression). For process 2 to 3, the compressed air is then mixed with fuel and burned in combustion chamber at constant pressure which the temperature raises to a very high level. For process 3 to 4, the exhaust gases after combustion are release to the environment (isentropic expansion).

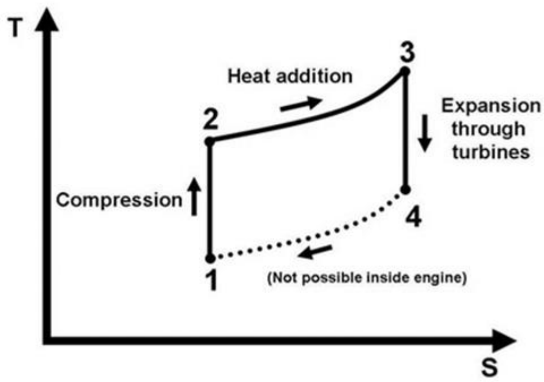

Figure 2.1: Graph of Temperature against Entropy for open loop Brayton cycle.

2.2 Reviews on Combustion Chamber.

The combustion chamber is the most crucial component in gas turbine engine. It is a place where the combustion of the air-fuel mixture takes place. The main parts of combustion chamber are flame tube and flame housing as labeled in Figure 2.2. Flame tube contains the combustion process and introduces the various airflows (intermediate, dilution, and cooling). Flame housing is larger in diameter compared to the flame tube. The flame housing is protected from thermal loads by the air flowing in it. The flame housing serves as a pressure vessel that must withstand the difference between the high pressures inside the combustor and the lower pressure outside. The combustion chamber fed very high air pressure which was channeled by the compressor. An amount of compressed air is then enters in the flame tube through primary zone hole and mixed with fuel and the others will flow through the gap between the casing and flame tube and will enter to the intermediate zone and dilution zone which act as cooling air to cool down the flame tube wall. The combustion process is then occurs when heat is supply to the fuel-air mixture and produced the hot gases. The hot gases which have high energy will leave the combustion chamber through combustion chamber outlet to the turbine section to turn the turbine.

The fuel-air ratio that will be used in combustion process is important to be considered. The air-fuel mixture must be completely burnt to avoid the creating unwanted emission such as CO from unburnt fuel. Stoichiometry measure the quantitative relationship between reactants and product in chemical reaction. Stoichiometry can be obtained by balancing the chemical equation between the reaction of fuel and air. It provides the exact number of molecule of each reactant to get the complete combustion. Thus, a stoichiometry or the ideal mixture of fuel and air must be achieved to produce a perfect combustion (Thoma *et al.*, 2010). Below are the examples of stoichiometry chemical reaction of combustion process by using propane and butane as fuel (Ouellette *et al*, 2015):

$$C_3H_8\ (g) + \ 5O_2\ (g) + 18.8N_2\ (g) \rightarrow 3CO_2\ (g) + 4H_20\ (g) + 18.8N_2\ (g)$$

Combustion process by using propane as fuel

$$C_4H_{10}\ (g) + \ 6.5O_2\ (g) + 24.5N_2\ (g) \rightarrow 4CO_2\ (g) + 5H_20\ (g) + 24.5N_2\ (g)$$

Combustion process by using butane as fuel

Flame tube consists of three zones of holes for flame stabilization. These zones are known as primary zone, intermediate zone and dilution or cooling zone with different size of hole from small, medium and larger respectively. The primary zone is the section where the main combustion of air occurs. The intermediate zone is the section where air enters to the flame tube through the second layer of hole on the flame tube to complete the combustion reaction process and diluting the high concentrations of Carbon Monoxide, CO and Hydrogen, H_2. Dilution zone is the section where air enters into the flame tube through the last layer of hole at the end of the flame tube to produce uniform temperature profile. The construction of these zones is important for stoichiometry the combustion process to control the temperature produce in combustion chamber and stable the flame to keep the flame self-sustaining. Another thing is the combustion process must only take place around the combustion chamber only before it exit at the chamber outlet. If the combustion process is reach at the back of the engine, it will have possibility to damage the turbine (Thoma *et al.*, 2010).

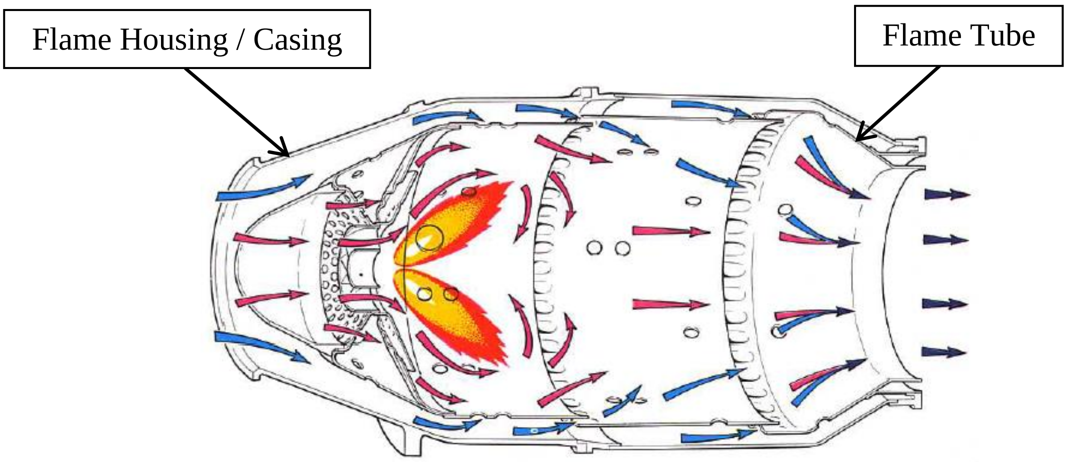

Figure 2.2: General airflow pattern and flame stabilizing (Emerson Nascimento, 1996).

The material used in gas turbine engine also play important role. We all know that the combustion process will produced about several thousand degree celsius of hot gases, thus the material used to build the combustion chamber must be able to withstand with very high temperature service. Titanium is a unique material which is strong, light, excellent resistance to corrosion and very high melting point usually is recommended in constructions of aircraft gas turbine engine's parts (Glenny *et al.*, 1975). However, we still need to consider the material's cost and the availability of the material in constructions of the combustion chamber for this project.

2.3 Reviews on Ignition System.

Ignition system is the systems that use to generate heat to ignite the mixture of air and fuel in combustion chamber. The ignition system must be able to produce about 30kV and above to force electrical current across the spark plug gap to ignite the highly compressed air in the combustion chamber (Williams, 2005). Basic ignition system in a car consists of the battery, ignition coil, distributor, cable, breaker, condenser or capacitor and spark plug. The main component in a car's ignition system is ignition coil. Ignition coil consists of two coils of wire that wrapped around the same iron core which are primary coil and secondary coil. The primary coil is connected to the primary circuit and secondary coil is connected to the secondary circuit. The secondary coil has more turns of wire compared to primary coil. It is a kind of transformer that used to step up the voltage supply in primary circuit to a higher voltage of electricity in the secondary circuit.

When the ignition system switch is turned on, current will flow from the battery through the primary coil and it will create magnetic field around it as well as around the secondary coil. If the current is suddenly stopped, it will cause the magnetic field to suddenly collapse. Based on principle of electromagnetic induction, the induced current that created in the secondary coil due to the sudden change of magnetic field will jumped to a very high voltage and bridges the gap across the spark plug electrodes to ignite the mixture of fuel and air. A condenser is used to absorb the back Electromotive Force (EMF) from the magnetic field to increase the life of breaker points (Williams, 2005). So, that is how the simple ignition system works. Breaker point is commonly used in conventional ignition system to interrupt the current flow from the battery to the primary coil. However, the rapid technology advancement now days have introduced the electronic on-off switch such as relay to interrupt the current flow.

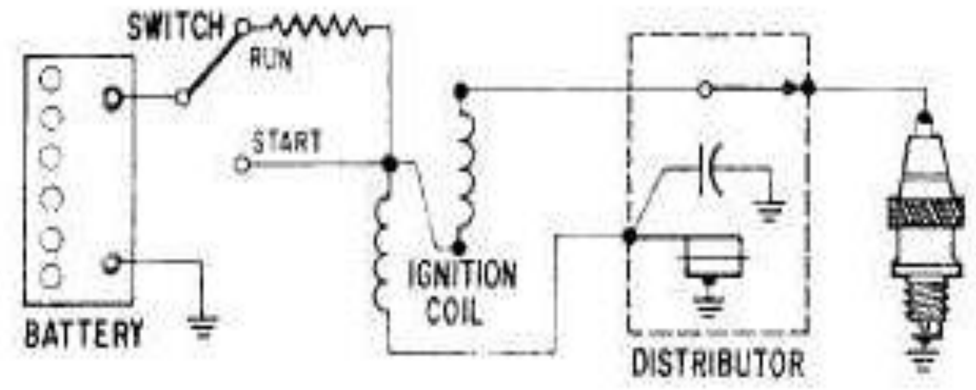

Figure 2.3: Simple Ignition Systems Circuit

Spark plug systems are commonly used in cars ignition system or in an internal combustion engine. There are a few types of spark plug available now days have been used in internal combustion engine. The spark plug can be distinguished based on what type of material they used to build its core such as copper core, platinum core and iridium core. Each core they used has their own advantages. For copper core or also known as standard spark plugs, it is providing good heat dissipation, lower emissions and durable. For platinum core spark plugs, it is quicker starts, faster acceleration, cleaner firing, durable and longer life. While for iridium core spark plugs, it is providing better power, smooth-running engines, longer lifespan compared to the previous spark plugs (Handerson, 2013). No wonder why the cost is different since they used different type of material as its core.

2.4 Reviews on Fuel Injection System.

Fuel is a substance that used in combustion process. Carbon (C) and Hydrogen (H_2) are the basic elements that used for combustion. However, fuel also can be form with various compounds such as the composition of carbon, hydrogen and oxygen, nitrogen and other elements (Yu. M. Pchelkin, 1967). There are several types of fuel that can be used in internal combustion engines such as gasoline, diesel oil and kerosene. Fuel can be form in solid, liquid and gas. Examples of fuel gas are methane, propane, butane and hydrogen. Since fuel gas are in gaseous form, a little supplied heat or spark can cause it to burn compared to fuel in solid and liquid form. Thus, to ease the mechanism of fuel injection system, fuel gas has been chosen as a fuel in this project since fuel gas is easier to ignite compared to liquid and solid fuel. Alkane is saturated hydrocarbon that can react with oxygen in a combustion reaction. It has general chemical formula C_nH_{2n+2}. Examples of alkanes are methane, ethane, propane, butane and pentane which have chemical formula of CH_4, C_3H_6, C_3H_8, C_4H_{10} and C_5H_{12} respectively. Under standard a condition which is at 0^oC, methane, ethane propane and butane are in gaseous form. Generally, the ability of alkane to react with oxygen is increases as the number of carbon decreases.

Propane and butane which has chemical formula C_3H_8 and C_4H_{10} respectively are commonly used for cooking purpose and easily to get since they are sold in stores. Both of them have maximum flame temperature in air of 3595 ^oF (1979.4 ^oC) and 3615 ^oF (1990.6 ^oC) respectively. One aspect we need to consider in the choosing of fuel in this project is the autoignition temperature of the fuel. Autoignition temperature is the lowest temperature of the substance which can spontaneously ignite without supplied any external heat. This is mean, at that particular temperature, the substance will combust itself and it is good to know since the gas turbine must be achieve self-running state and sustain the combustion process. Autoignition for propane and butane is 878 ^{o}F (470 ^{o}C) and 761 °F (405 °C) (Hamor, 2012). The comparisons of the chemical properties between them are required to get the best fuel from aspect of availability of it, the ability to reach the idle state of combustion and the price of it.

Fuel injection system is systems which introduce or supplying fuel in the combustion chamber for combustion process. During the operation, the fuel is supplied from a fuel tank into the combustion chamber. There are several requirements in designing fuel injection system for gas turbine engine. Fuel injection system not only delivers fuel into the combustion chamber with the sufficient quantity, but it also need to make proper spray pattern so that the fuel can mixed very well with air. Another critical condition is the flow of fuel must be control during the engine is started, accelerated and achieve its self-running speed. If the fuel is overflow, it will over mixed with air and have tendency to blowout the combustion chamber. Stoichiometry measure the quantitative relationship between reactants and product in chemical reaction. Stoichiometry can be obtained by balancing the chemical equation between the reaction of fuel and air. It provides the exact number of molecules of each reactant to get the complete combustion. Since ideal combustion is required during combustion process, stoichiometry of fuel and air must be achieved.

2.5 Reviews on Lubrication System.

During the operation, the rotating shaft which is connected with the compressor wheel and turbine wheel will rotate at several thousand revolutions per minute. As the result, it created friction between the moving parts which is it will increase the temperature of the rotating shaft and bearing, thus it will cause it to wear. A systematic lubrication system must be design for this gas turbine engine for the health of the turbocharger, so it can run with its best performance. Lubrication system is systems that deliver an amount of lubricant to moving parts. Lubricant that has been delivers will creating a clearance between the moving parts, which is the part is float on the lubricant thin film to reduce the contact between them. This phenomenon is called as hydrodynamic. As the result, its help to reduce wears and friction between them. In a car's engine system, the lubricant which is circulates around it also act as cleaner where it is clean the engine from dust and metal particle and bring them back to the lubricant container. The lubricant that has been delivered also act as a coolant to cool down the rotating shaft since it is producing amount of heat while it is rotating with several thousand revolutions per minute (Julian Brough, 2005).

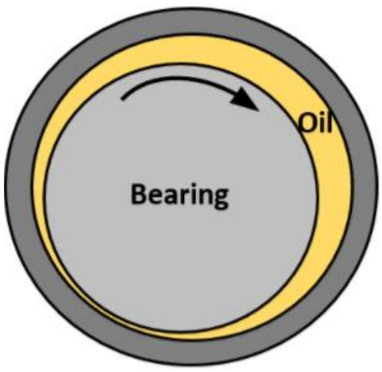

Figure 2.4: Clearance between the moving parts (hydrodynamic phenomenon).

Oil is a substance that can be used as a lubricant. Generally, turbine engine used synthetic lubricant oil since the lubricant can retain their lubricating properties, have better thermal stability and viscosity. Synthetic oil has high viscosity index. Viscosity index is the relationship between the changes in viscosity due to the change of temperature. The higher the viscosity index, the lower the changes of its viscosity. Thus, this will allow the lubricant to maintain its viscosity at any working temperature. Another point why synthetic oil is chosen as lubricant oil in gas turbine engine is because it has high flash point. Flash point is the lowest temperature for the fluid to form an ignitable mixture in air. Thus, synthetic oil is recommended as lubricant oil in gas turbine engine due to high temperature in its operation. Viscosity is measure the resistance of a fluid to flow. The lower the viscosity, the faster the fluid will flow. Thus, compatible lubricant oil must be chosen wisely, so the lubricant oil can go through to the whole rotating shaft during the engine is on operating and easier to pump the oil circulating the turbocharger’s part (Polichronis *et al.*, 2013).

CHAPTER 3

METHODOLOGY

This chapter requires to design every single system involve in developing a small gas turbine using turbocharge. The systems involved are combustion chamber, fuel injection system, lubrication system and ignition system. At the beginning on this chapter, it describes the type of turbocharger that will be used in this project. The critical part in designing is to design the combustion chamber since we need to consider the material selection, flame tube design and the hole for flame stabilization to get the perfect combustion. Other systems are not too critical since we can use available part such as spark plug, battery, pump, ignition coil in market and do some modification on it to make that particular system. The fabrication and assembly process on these systems are also explained on this chapter.

3.1 Turbocharger.

There are many automotive turbochargers that can be used to convert into a self-sustaining gas turbine engine. The turbocharger that will be used in this project is GT2554R which is previously used by a student for his final year project as shown in Figure 3.1 (Moktar, 2011). This turbocharger basically used in a Nissan 240sx, one of Nissan's cars that used for racing development. It has power of 151kW (202 hp) at 6000 rpm and torque of 202 lb.ft (274 N.m) at 4000 rpm. Since this turbocharger is used by a sports car, I believe that this turbocharger can perform very well in my project. Below show the turbocharger that I will use in my final year project.

Figure 3.1: GT2554R (Moktar, 2011)

First of all, the features of the turbocharger used must be known. It is important to know the features because there are some parameters required in the process of designing the combustion chamber. The turbocharger that will be used in this project is GT2554R. The turbocharger is manufactured by Garret. "GT" means Garret Turbo. "25" is signified of the frame size of the turbo based on the turbine wheel inducer measurement (the larger the number, the larger the turbine wheel). "54" represent the diameter of the compressor exducer in millimeter. While "R" tells the turbocharger is provided with ball bearing unit.

Figure 3.2 shows the illustration of the inducer and exducer diameter of compressor and turbine wheels. The diameter of the compressor wheel and turbine wheel is tabulated as below.

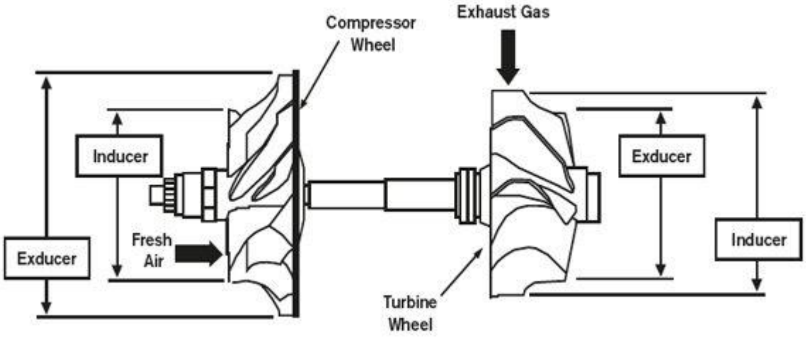

Figure 3.2: Illustration of the inducer and exducer diameter of compressor and turbine wheels (Machone, 2010).

Table 3.1: Diameter of the compressor and turbine wheel

	Inducer diameter (mm)	Exducer diameter (mm)
Compressor	42	54
Turbine	53	42

Figure 3.3 shows the compressor maps for GT2554R where it is describes a particular compressor's performance characteristics, including efficiency, mass flow range, boost pressure capability, and turbo speed. Compressor maps describe the pressure ratio and the mass of air flow through the compressor at particular condition with its efficiency. Efficiency Island on the maps represents the compressor efficiency at any point on the maps. The maximum efficiency of GT2554R is 73% where this efficiency can be achieved at 17.5 lbs/min (0.13 kg/s) and pressure ratio at 1.7. Thus, this condition will be used as the assumption at the beginning design process of the combustion chamber that will be explained on the next chapter.

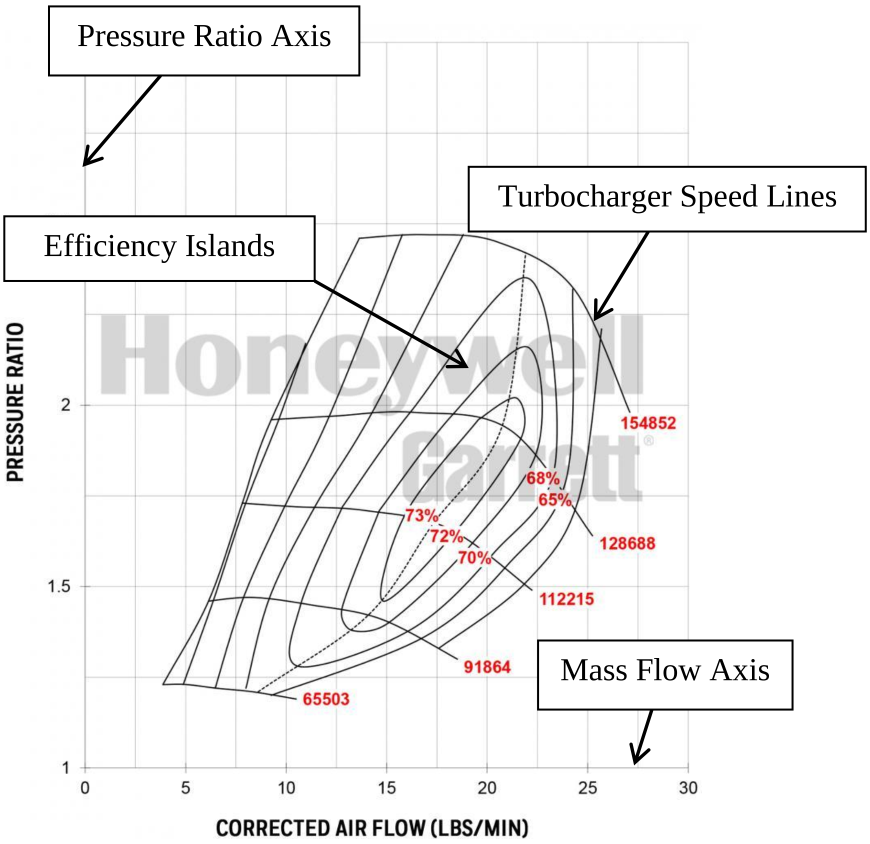

Figure 3.3: Compressor maps for GT2554R (Honeyywell Garret, 2009).

3.2 Combustion Chamber.

Combustion chamber is very important part in developing this gas turbine engine in this project. It is a place where the combustion of the air-fuel mixture takes place. Combustion chamber consists of two main parts which are flame tube and flame housing. These main parts must be design carefully since it will affects the performance of the combustion chamber. Flame tube consists of three zones of hole which are the primary zone, intermediate zone and dilution or cooling zone with different size of hole from small, medium and larger respectively.

By referring to Arthur H. Lefebvre and Dilip R. Ballal: Gas Turbine Combustion "*Alternative Fuels and Emissions*" (Lefebvre and Ballal, 2010), and other related journals, the combustion chamber can be built based on the turbocharger that we used and all parameters that we have. Below are the parameters that we have and will be used in the combustion chamber design process:

Table 3.2: Available parameter (Honeyywell Garret, 2009).

Parameter	**Value**
Temperature of air during intake, T1	298 K
Pressure of air during intake, P1	101.325 kPa
Heat capacity ratio of air, γ	1.4
Compressor efficiency, n_c	0.73
Pressure ratio, P2/P1	1.7
Compressor diameter (exducer)	54 mm
Gas constant, R	278 J/kg.K

At the beginning phase of the combustion chamber design process, the air temperature and pressure in process 1, 2, and 3 as shown in Figure 2.1 must be estimated. Since the pressure ratio is known, the pressure of air after it is being sucked and compressed by the compressor, P2 can be found as below:

$$Pressure\ ratio = \frac{P2}{P1} \tag{3.1}$$

And its temperature can be simply found by using thermodynamic analysis as equation below:

$$\frac{T2}{T1} = \left[1 + \frac{(\frac{P2}{P1})^{\frac{\gamma-1}{\gamma}}}{n_c} \right] \tag{3.2}$$

To get the air turbine entry temperature (TET), T3, the assumption method is made based on the combustion chamber design for turbocharger which has been developed by Silva and Lacava (Eduardo and Silva, 2013). Their project is about the research on the combustion chamber for turbocharger. Thus, the temperature profile from their test is then compared with temperature profile for this project to get the approximate of T3.

$$\frac{T3}{T2} = \frac{T3_j}{T2_j} \tag{3.3}$$

Where $T2_j$ is the air temperature after compressed and $T3_j$ is the turbine entry temperature from Silva and Lacava (Eduardo and Silva, 2013). After the air properties are defined as above, the cross-sectional area of the flame housing or also known as the reference area, A_{reff} can be calculated as equation below (Lefebvre and Ballal, 2010).

$$A_{reff} = \left[\frac{R}{2}\left(\frac{m_a T2^{0.5}}{P2}\right)\left(\frac{\Delta P_{2-3}}{q_{reff}}\right)\left(\frac{\Delta P_{2-3}}{P2}\right)^{-1}\right]^{0.5} \tag{3.4}$$

where m_a is the air mass flow rate intake in kg/s is, $\frac{\Delta P_{2-3}}{q_{reff}}$ is the combustor pressure drop factor and $\frac{\Delta P_{2-3}}{P2}$ is the combustor pressure loss. The values for both of this parameter are suggested by Melconian and Modak (1985) which the value for multi-can type is 40 and 0.053 respectively (Carlos and Filho, 2004). By using simple mathematical formula or circular area, the radius, r_{reff} and diameter, D_{reff} for the reference area can be calculated as below.

$$A_{reff} = \pi r_{reff}^2 \tag{3.5}$$

$$r_{reff} = \sqrt{\frac{A_{reff}}{\pi}} \tag{3.6}$$

$$D_{reff} = 2\, r_{reff} \tag{3.7}$$

Since the combustor pressure loss is known, the pressure of the hot gas entry to the turbine wheel can be calculated as below:

$$\frac{\Delta P_{2-3}}{P2} = 0.053 \tag{3.8}$$

Where ΔP_{2-3} is equal to P2 – P3 and P3 is the turbine entry pressure. As show below are the variety of combustion chamber types and its illustration of the reference dimension. The multi-can type is selected as combustion chamber type for this project since the flame tube and the flame housing is separated from the other compared to the other as shown in figure below and it is meets the requirement for this project which is required to design for single flame tube and flame housing.

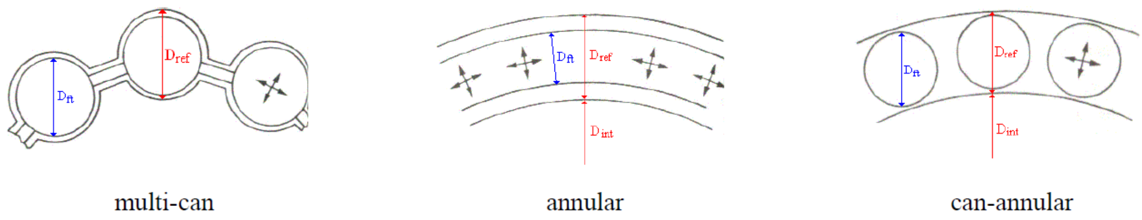

Figure 3.4: Combustion chamber types

The calculation for the cross-sectional area for the flame tube, A_{ft} is suggested by Melconian and Modak (1985) as equation below (Carlos and Filho, 2004).

$$A_{ft} = 0.7\, A_{reff} \tag{3.9}$$

This relationship is satisfactory for multi-can and can-annular only. For annular type, the value is about 0.65-0.67 is more appropriated (Carlos and Filho, 2004). Again, by using simple mathematical formula or circular area, the radius, r_{ft} and diameter, D_{ft} for the flame tube area can be calculated as below.

$$r_{ft} = \sqrt{\frac{A_{ft}}{\pi}} \tag{3.10}$$

$$D_{ft} = 2\, r_{ft} \tag{3.11}$$

Pattern factor is important parameters that affect the output of the engine and durability of the combustion chamber to withstand the hot gases. The turbine wheel is fixed relative to the combustion chamber, the combustion chamber must be design to