PERFORMANCE CHARACTERISTIC OF SINGLE STAGE MICRO GAS TURBINE (MGT) RUNNING ON LIQUID BIOFUELS

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DECLARATION

I hereby declare that this thesis is composed by myself, that the work contained herein is my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. In addition, this thesis has not previously been accepted in substance for any degree and is not being concurrently in candidature for any degree.

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LIST OF ABBREVIATIONS

MGT	Micro Gas Turbine
CO	Carbon Monoxide
NOx	Nitrogen Oxide
SFC	Specific Fuel Consumption
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
COT	Compressor Outlet Temperature

ABSTRAK

Biofuel amat dipentingkan pada masa depan sebagai bahan api hijau yang boleh diperbaharui, terutamanya, di kawasan luar bandar yang menghadapi kesulitan pengangkutan diesel untuk menjana set penjana diesel. Walaubagaimanpun, terdapat banyak biomass di kwasan luar bandar yang boleh mengganti diesel. Turbin gas mikro dengan biofuel cecair dapat menyelesaikan isu harga tinggi diesel dan isu gabungan kuasa haba dalam set penjana diesel. Turbin gas mikro merupakan penjana tenaga yang dikembangkan daripada sistem pembakaran turbin gas. Di samping itu, turbin gas mikro yang dijalan dengan biofuel cecair semakin menarik perhatian di peringkat global oleh sebab mesra alam dan keupayaan untuk megitar semula biomass terbuang.

Prestasi turbin gas mikro yang dijalan dengan biofuel perlu dinilai dan dikaji untuk membangunkan sistem ini. Dalam projek ini, prestasi turbin gas mikro dicirikan dengan pembakaran diesel sebagai penanda aras kepada sistem. Biofuel yang digunakan dalam projek ini adalah campuran diesel dan minyak sayuran dalam nisbah tertentu, sebagai contoh, B10 bermakna 10 peratus minyak sayuran dicampur dengan 90 peratus diesel. Nisbah campuran yang paling optimum akan didapati dan dibandingkan dengan diesel. Tumpuan utama adalah pada kuasa dijana, penggunaan bahan api tertentu, pelepasan karbon monoxide (CO) dan nitrogen oksida (NO_x).

Dalam projek ini, kuasa turbin tertinggi adalah 10.365 kW untuk turbin gas mikro yang dijalankan dengan diesel dan penggunaan bahan api tertentu yang paling rendah untuk turbin gas mikro yang dijalankan pada diesel adalah 0.1215 kg / kWh. Hasilnya menunjukkan bahawa biofuel boleh menghasilkan kuasa turbin hampir sama dengan diesel, walaubagaimanapun, dengan pengorbanan prestasi penggunaan bahan api tertentu. Selain itu, biofuel mempunyai pelepasan CO dan pelepasan NOx yang lebih tinggi berbanding diesel, sementara itu, penurunan pelepasan CO adalah berkaitan dengan suhu yang lebih tinggi dan nisbah kesetaraan yang lebih tinggi, kontrasnya, peningkatan pelepasan NO_x adalah berkaitan dengan suhu yang lebih tinggi dan nisbah kesetaraan yang lebih tinggi. Biofuel paling optimum ialah B80 yang mempunyai pelepasan CO yang lebih rendah dan pelepasan NO_x pada suhu yang lebih tinggi.

ABSTRACT

Biofuels are the future interest on renewable green fuels, especially in rural areas which the difficulties in diesel transportation for the running of the diesel generator set. Nevertheless, there are plenty of biomass which can be make use of, to replace diesel in rural areas. The liquid biofuel micro gas turbine can solve the problem of the diesel high price issue and combined heat power problem in diesel generator set. A micro gas turbine is an energy generator which is developed from gas turbine combustion system. In addition, micro gas turbine running on liquid biofuels is getting attraction globally due to the environmentally friendly and the ability to recirculate the wasted biomass.

The performance of the micro gas turbine running with biofuels have to be evaluate and study to further develop the system. In this project, the performance of the micro gas turbine is characterised with diesel combustion which acts as the benchmark to the system. The biofuels used in the project is the blending of diesel and vegetable oil in certain ratio, for example, B10 means 10 percent of vegetable oil and 90 percent of diesel. The most optimum blending ratio is found out and compare with the diesel. The main focus is on the power output, specific fuel consumption and emission of carbon monoxide (CO) and nitrogen oxide (NO_x).

In this project, the highest turbine power is 10.365 kW for micro gas turbine running on diesel and the lowest specific fuel consumption for micro gas turbine running on diesel is 0.1215 kg/kWh. The result indicate that the biofuel can produce almost similar turbine power as the diesel, however, with the sacrifice of the specific fuel consumption performance. Furthermore, the biofuels have much higher CO emission and NO_x emission compare to diesel, in the meanwhile, the CO emission decrease with higher temperature and higher equivalence ratio, contrarily, NO_x emission increase with higher temperature and higher equivalence ratio. The most optimum biofuel is B80 which has a lower CO emission and NO_x emission at higher temperature.

CHAPTER ONE INTRODUCTION

1.1 Introduction

A gas turbine is an internal combustion engine which convert the chemical energy of natural gas or other liquid fuels to mechanical energy for driving a generator that produces electrical energy. The gas turbine heats a mixture of air and fuel at a very high temperature, causing the turbine blades to spin at high speed and generate electricity. There are three main components in a gas turbine which comprise of a compressor, a combustor and a power turbine. The gas turbine is suitable as the high power engine such as engine for airplane.

The micro gas turbine has been developed from the gas turbine system which offer some advantages over other small scale power generation system. Micro gas turbines are small-scale independent and reliable distributed generation systems that offer potential for saving energy and reducing carbon monoxide emissions [1]. Micro gas turbines are a promising technology for distributed power generation because of their compact size, low emissions, minimal maintenance, low noise, high reliability and multi-fuel capability [2]. Micro gas turbine engines which produce extremely low emissions have the prospect to be used for hybrid vehicles, continuous power generation and distributed power source [2]. For most of the simple cycle micro gas turbines, where no heat recovery from the exhaust for preheating of the combustion gas or known as recuperated, are single stage, single shaft and low pressure gas turbine [3]. Recuperation typically doubles the electrical efficiency of the unit whilst reducing the amount of recoverable heat from the combustion chamber, however, this may not be desirable depending on the application [3]. A simple micro gas turbine compresses the incoming air, then passes through the recuperator where heat is gained before entering combustor, hence, the hot high pressure gas or fuel is exhausted through the turbine which extracts energy and uses to drive the compressor and shaft-mounted alternator. The alternator is a high-speed device producing a high frequency output which is converted to the desired mains frequency and voltage in the power conditioner [4].

The main benefit of using micro gas turbine is the application of biomass or biofuels can be utilised for low greenhouse gasses emission. Biomass such as agricultural and urban wastes is an important type of renewable energy fuel sources especially in Malaysia with agriculture as her main economy [5]. Biofuel is a type of fuel which obtainable from biological material and can be existed in the form of solid, liquid or gas. Unlike fossil fuel which is derived from fossils of biological material, biofuels are more environmental friendly and renewable. Normally, biofuel can be derived from agricultural crop, food waste and other by-product from industry. Biofuel is considered greener and cleaner than conventional fossil fuel due to the balance of the emission and consumption of the greenhouse gas in the growth of the plantation. Besides, there are some crucial advantages over the usage of biofuels in energy generation in term of environment, socio-economic and technology concerns. A further advantage of the use of biofuels is the possibility to use various technologies that allow small scale production, according to the spirit of decentralization and medium scale plants [6]. Nevertheless, some typical problems arise with the application of the biofuels on micro gas turbines, including, possible contamination of the lubricating oil with the biofuel, formation of deposits in the injector, implementation of high frequency injector for achieving fast ignition in combustion chamber and much more [7,8]. Hence, difference composition of diesel and biofuel blends should be further research to test the performance of the micro gas turbine.

Recently, substantial attention is given to the micro gas turbine and biofuel due to their capability and potential applications on the energy regeneration with environment friendly. The fuel properties and engine performances have been studied since few years back and available in the literatures [7,8,9]. The micro gas turbine running on diesel have been proven to be effective in lots of research and study, in fact, offering several advantages compared to other ignition engines [7,8,9]. The advantages of the using of micro gas turbine running on biofuels gains interest especially in rural area due to the effortless availability [9].

The existing fuels today are mostly extracted from fossil fuels which is not renewable. The problem arises with the common believe that the world oil reserve to be decline and the negatively impact on the environment. Nevertheless, the implementation of the biofuel is believed to be more environmental friendly and most crucial part is the renewable of biofuel. Unlike fossil fuel, biofuel is easily obtained from biological material such as agricultural and urban wastes which is a vital fuel source for country like Malaysia with agriculture as main economy [7,8]. Nonetheless, the main concern on the biofuel is the possibility of the contamination deposit in the injector and combustion chamber since biofuel are basically a lower quality renewable fuels which related to the unfavourable physical and chemical characteristics, for instance, high viscosity and corrosive [5]. In addition, liquid biofuels suffer in general from the higher viscosity that is directly associated with injection and atomization deficiencies, lower heating value and higher ash content that greatly affect combustion stability [9].

The application of the biofuels on micro gas turbine is favourable for the benefits to the economy and environmental. However, the performance of the micro gas turbine running on biofuel is still lack of information. Hence, the performance of the micro gas turbine running on the biofuels have to study further on the optimisation of energy conversion and efficiency.

1.2 Problem Statement

Biofuels are the future interest on renewable green fuels. The biofuel that gain interest for research in the project is the vegetable oil and diesel blending. The main concern of the usage of biofuels over other fossil fuels is the higher viscosity, the lower heating value and other properties which will affect the combustion and performance on emission effect of the micro gas turbine. However, there are still lack of information of the performance of existing single stage micro gas turbine running on liquid biofuels, hence, the experimental analysis is required to clarify the performance characteristic of the micro gas turbine running with the diesel, vegetable oil and the mixing of the biofuels.

1.3 Objective

The project is aimed:

1) To characterise the combustion and performance of the micro gas turbine (MST) with diesel as the benchmark
2) To evaluate the combustion and performance of the micro gas turbine (MST) with difference ratio of vegetable oil with diesel blending
3) To analyse the combustion and performance of the micro gas turbine (MST) with 100% of vegetable oil with preheating

1.4 Scope of Work

The performance characterisation of micro gas turbine is mainly focus on combustion, temperature profile and emission. The performance of the 100% of diesel will be the benchmark of the whole experiment. The blending of vegetable oil with diesel will be premixed with different ratio from B10 up to B100. With different ratio of vegetable oil and diesel blending, the performance characteristics will be compared to the micro gas turbine running on 100% diesel which act as the benchmark. B100 which is vegetable oil is preheated to overcome its high viscosity at difference temperature level.

CHAPTER TWO LITERATURE REVIEW

2.1 Overview

The performance of the MST has been investigated in some publish papers and journals which can the reference for the current project. The focus of the publish papers and journals are more on the combustion and the emission effect. The relationship between the effect of the combustion and acoustic also being related in some study.

2.2 Literature Review

In a study by Al-Attab et al. [5], the performance of the two stage MGT was characterized experimentally with liquefied petroleum gas and producer gas fuels in dual-fuel mode and then with pressurized producer gas in single-fuel mode. The producer gas are the gas derived from biomass by using pressurised gasification process. There are some similarities with the current project which both consist of the blending of fuels to test the performance of the MST. Nevertheless, this study was not covered the combustion performance of the MST running on liquefied biofuels and diesel. The current project also does not involve the pressurize gasification process.

Another study by Chiaramonti et al. [8], this study was focussed on the exhaust emissions of the MST running on biofuels and compared the experimental result with the diesel. The result from this study was aimed to serve as a basis standard for modifying the micro gas turbine to be operated with biofuels from fast pyrolysis. The biofuels being used in this journal was preheated with different temperature and different blending ratio of the vegetable oil and diesel oil. The outcome of this study is very similar with the current project and can be referred in many aspects especially the operating parameters such as hourly consumption of fuel, fuel injection pressure, exhaust temperature and the exhaust emissions. However, this study was tested the performance of the MST with biodiesel at different fuel pre-heating temperature, which is the gap of study between the current project which is tested with different blending ratio of the vegetable oil and diesel.

Furthermore, the design of the combustion chamber is also being related to the combustion performance of the fuel in the MST. In a study by Enagi et al. [1], the design of a combustion chamber and the performance of MST was investigated. The design of the single state MST using in current project is mainly based on the design recommendation of this study with some minor modification. The modification includes adding a water injector to cool down the combustion chamber and others. From this study, the design and development of the combustion chamber for MST was performed by SolidWorks and Ansys-Fluent simulation software. The experimental test for the performance characteristic of MST was by using liquefied petroleum gas. However, the design consideration of the MST in this study was based on two stage turbines with a by-pass valve to release some of the pressure inside the turbine to prevent over speeding of shaft. In addition, the performance of the biofuels and vegetable oil was not being tested in this study. Hence, there are some gap between this study and current project.

In the other hand, the current project is also utilised the acoustic analysis. The main purpose of involve acoustic analysis in the current project is to check the stability of the combustion inside combustion chamber. Modern gas turbines for power generation are often affected by combustion instabilities generated by mutual interactions between the heat oscillations produced by the flame and pressure fluctuations. These very strong pressure oscillations are due to propagations and reflections of acoustic waves in the combustion chamber [10]. The challenges for modern advanced combustors are to be significantly more efficient with reduced pollutant emissions. In addition, chemical composition, pressures, thermal signatures, flows as well as their interactions are expected to be more complex for obtaining optimum performances [11]. In general, a particular injector or combustion system usually varies significantly with respect to the driving mechanisms of any combustion stability. The unsteady heat release rates from swirl injectors and turbulent flames have been simulated using CFD numerical tools [12,13]. Other simulation studies also investigated the vibration and acoustic pressure non-instructive measurements for internal combustion engines [14,15,16].

This current project investigates the combustion and performance of the turbocharger based MGT running on liquid biofuel. The fuels being tested is diesel, vegetable oil and biofuel blending by vegetable oil and diesel. The performance of the diesel will be the benchmark to compare with the performance of biofuel. The consideration for the performance of the biofuel in priority are the renewable, emission, turbine power and SFC. The vegetable oil is preheated at difference temperature level to overwhelm with the high viscosity.

CHAPTER THREE METHODOLOGY

3.1 Overview

This study includes both the modification and experimental work, to investigate the combustion and performance of the MST with diesel, biofuel blending and vegetable oil. The temperature profile, flow rate and emission result are getting from the experimental, then the power, SFC, equivalence ratio and efficiency are getting from calculation. The result is further analyse and plot in graph.

3.2 Activity Chart

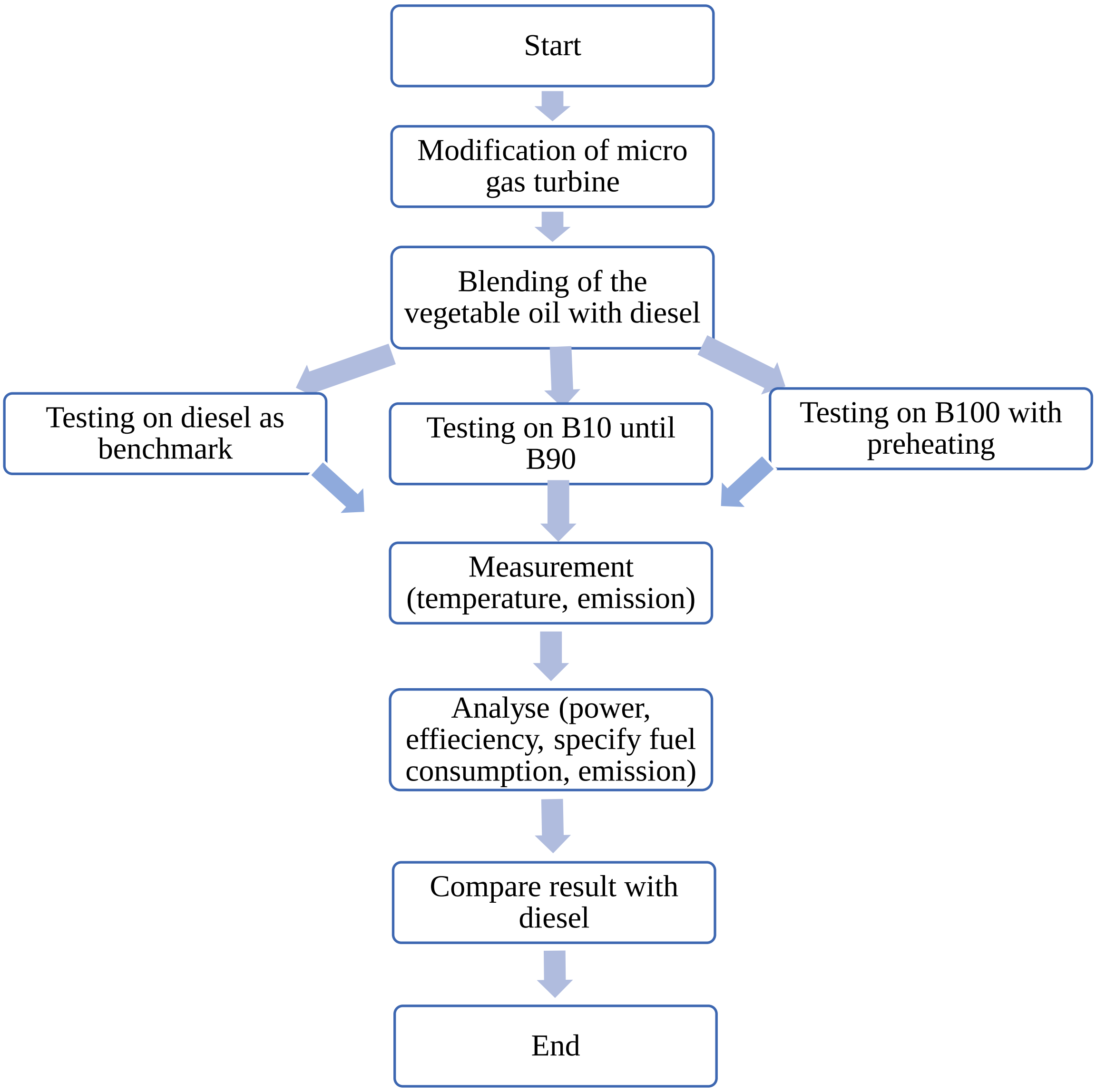

Figure 3.1: Activity Flow Chart for the Project

3.3 Methodology Activity

First of all, the current available MST in Biomass Lab is modified to have better performance. The main modification includes the addition of water injection at the combustion chamber to reduce the temperature of turbine inlet in combustion chamber. The water injector is inserted to the wall of combustion chamber and distilled water is being used in the system with constant flow rate at 1.0 g/s to 2.0g/s. It is very important to have suitable flow rate to maintain the combustion chamber temperature at range without affected the combustion process inside combustion chamber. Then, the damage thermocouples are replaced with new one and some leakage is also fixed. The heat recovering unit is sealed with some cement at the entry and being covered with the aluminium foil. This is to ensure the heat loss from the heat recovering unit is minimum and hence increase the efficiency of the MST. Furthermore, three microphones are inserted to the combustion chamber to record the combustion sound. The microphones are being named as static in, static out and dynamic in for which static in is the sound at the combustion chamber inlet, static out is the sound at combustion chamber outlet and dynamic in is the sound at combustion inlet through the pitot tube. After that, the vegetable oil and diesel are mixed at different ratio from B10 up to B100 where B10 means there are 10% of vegetable oil and 90% of diesel blending.

The performance characteristic of the single state MST running on liquid biofuel is carried out by experiment to get the measurable data and analyse the data acquired to calculate the performance of the MST. The biofuel being used in this project is the blending of vegetable oil and diesel. Diesel will be the benchmark for the performance of the MST, and the performance of the biofuels from B10 until B100 will be tested and to be compared with the performance of the diesel. There are 4 injectors being tested and injector 2 is chosen due to better performance.

After all the preparation work, the performance of the MST is tested with the diesel as the benchmark. Then, the experiment continues with the biofuel from B10 until B100. After that, B100 which is 100% of vegetable oil is repeated with difference preheating temperature at 100ºC, 150ºC and 200ºC. The preheating process is to overcome the high viscosity of vegetable oil. One of the variable that should be controlled is the diesel or biofuels flow rate. The flow rate of diesel and biofuel can be controlled by the compressor pressure, start from 0.1 bar to 0.5 bar. The measurement from the experiments are the temperature of the combustion chamber, turbine and compressor at inlet and outlet, the emission gas such as carbon monoxide (CO) and nitrogen oxide (NO_x) in addition the flow rate of air and fuel. From the measurement result, the MGT performance can be analysed through the calculation. The output includes the power of the MGT, the efficiency of the MGT, the equivalence ratio and the SFC. The result will be compared with the diesel which is the benchmark in the project and the best blending ratio of biofuel is found. The set up of the micro gas turbine is as shown in the Figure 3.2 and the detail process will be discuss in the below.

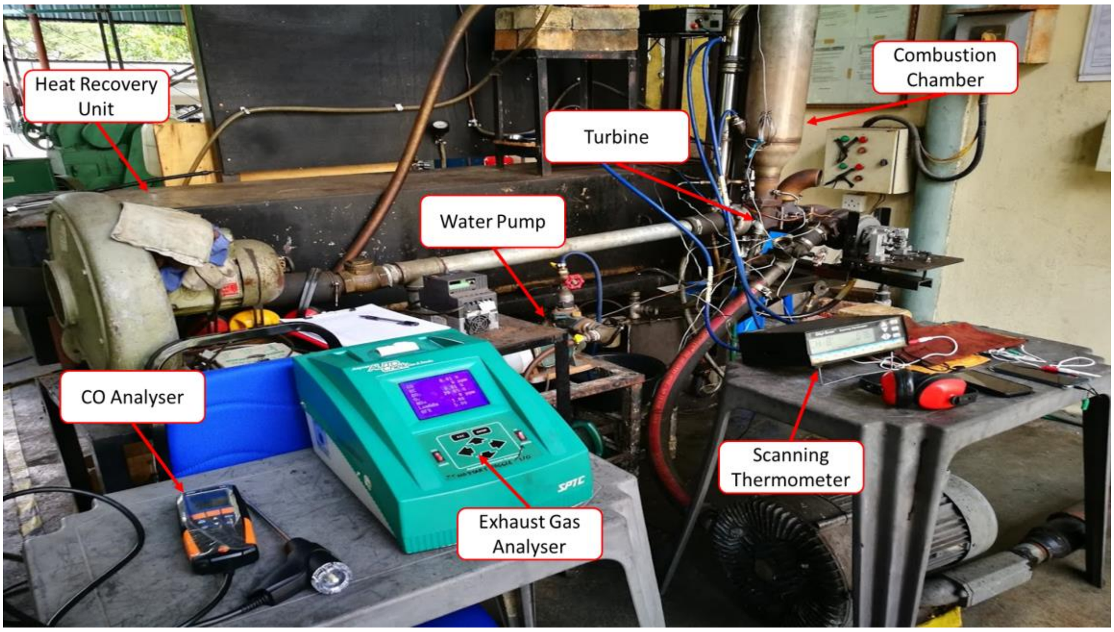

Figure 3.2: MGT in the Biomass Lab

3.4 Measuring Equipment

The measuring equipment being used in the project include scanning thermometer, CO analyser, exhaust gas analyser, stopwatch and hot wire anemometer.

The Digi-Sense scanning thermometer (as shown in Figure 3.3) is a 12 channel data logger for temperature which can store up to 4680 sets of readings with time and date. The data can transfer to computer easily. The scanning thermometer is used to record down the temperature profile of the temperature at turbine inlet, turbine outlet, compressor outlet and fuel inlet.

The Testo 310 CO analyser (as shown in Figure 3.4) is a measuring tool for direct O_2, CO, flue gas and ambient temperature measurements. The CO analyser is to check the CO emission of the MGT at the outlet of heat recovery unit.

The AutoChek exhaust gas analyser (as shown in Figure 3.5) is a multifunction exhaust gas analyser for CO, NO_x and other emission gas. The emission interested are only CO and NO_x.

The stopwatch is used to check the flow rate of fuel for which the time taken for 100 ml of fuel injected is measured by stopwatch. While the hot wire anemometer is used to check the flow rate of air intake.

Figure 3.3: Scanning thermometer

Figure 3.4: CO analyser

Figure 3.5: Exhaust gas analyser

3.5 Experimental Procedure

In the experiment, MGT is started with liquefied petroleum gas for warming the combustion chamber before liquid fuel is injector. After 10 minutes, the diesel fuel is injected into the combustion chamber through the injector. The flow rate of the diesel injection is controlled by the compressor pressure. The compressor pressure is increase every 0.1 bar until 0.5 bar to take measurement. The measurement to be recorded include the temperature at the turbine inlet, turbine outlet, compressor outlet and fuel inlet, the emission of CO and NO_x, the flow rate of the air intake and the time taken of 100 ml diesel fuel injection. Nevertheless, the water injection system should be connected and operated if the temperature of the turbine inlet is too high (around 900 ºC) to avoid overheat of the turbine which will affect the performance of the micro gas turbine and also damage the turbine blade. After that, MGT is allowed to run at low pressure and low temperature to cool down before running the second experiment. The experiment for all fuels are running for two times to get the average. The data obtained from the experiment will be used to calculate and analyse the combustion and performance characteristic include the power output of the MGT, the efficiency of the MGT, SFC of fuels and the equivalence ratio. The experiment is repeated with biofuel, start from B0 until B100 and also the vegetable oil with preheated at temperature of 100ºC, 150 ºC and 200 ºC.

In addition, the acoustic sound at the combustion chamber are also recorded during the experiment for static in, static out and dynamic in. The acoustic sound is used for analysing the pressure inside the combustion chamber during the combustion process is taken place by the aids of software, for instance, the Adobe Audition and MATLAB. The acoustic file will be analysed by using the Adobe Audition first to separate the combustion process at difference pressure. Then, the acoustic file will be analysed by using MATLAB to plot out the graph of decibels ratio against frequency to compare the spectral response of the acoustic sound.

3.6 MGT Characterisation

The manipulative variable in this project is the compressor pressure which control the injection pressure of fuel. While the responding variables in this project is many, however, the focus is on the turbine power, SFC at exhaust and the emission of CO and NO_x.

The calculation is as shown below:

(Take diesel with compressor pressure at 0.1 bar as example)

Mass Flow Rate of Air, $\dot{m}_{air} = \rho vA$

$= 1.16 \times 10.30 \times 0.003632$

$= 0.04339$ kg/s

Mass Flow Rate of Diesel, $\dot{m}_{diesel} = \rho V$

$= 787 \times (((100/66) \times 60)/(60 \times 106))$

$= 0.00119$ kg/s

Total Mass Flow Rate, $\dot{m}_{total} = \dot{m}_{air} + \dot{m}_{diesel}$

$= 0.04339 + 0.00119$

$= 0.04458$ kg/s

Turbine Power = $Cp_{total} \times \dot{m}_{total} \times (TIT-TOT)$

$= 1.12 \times 0.04458 \times (759-677)$

$= 4.095$ kW --- (1)

Compressor Work = $Cp_{air} \times \dot{m}_{air} \times (COT-30)$

$= 1.009 \times 0.04339 \times (80-30)$

$= 2.189$ kW

Turbine Efficiency = (Compressor Work/Turbine Power) x 100%

$= 2.189/4.095 \times 100\%$

$= 53.463$ % ---(2)

Rate of Heat Change in Diesel Combustion, $Q_{diesel} = \dot{m}_{diesel} \times HV$

$= 0.00119 \times 45000$

$= 53.659$ kW

Rate of Heat Change in Exhaust Gas, $Q_{exhaust} = Cp_{total} \times \dot{m}_{total} \times (TOT-30)$

$= 1.12 \times 0.04458 \times (677-30)$

$= 31.730$ kW

Fuel efficiency $= Q_{exhaust}/Q_{diesel} \times 100\%$

$= 31.730/53.659 \times 100\%$

$= 59.133$ %

Specific Fuel Consumption, SFC $= (\dot{m}_{diesel} \times 3600)/Q_{exhaust}$

$= (0.00119 \times 3600)/31.730$

$= 0.1353$ kg/kWh ---(3)

Actual Air Fuel Ratio, $AFR_{actual} = \dot{m}_{air} / \dot{m}_{diesel}$

$= 0.04339 / 0.00119$

$= 36.389$

Equivalence Ratio $= AFR_{stoichiometric} / AFR_{actual}$

$= 14.7 / 36.389$

$= 0.404$ ---(4)

CHAPTER FOUR RESULT AND DISCUSSION

4.1 Overview

The temperature profile, flow rate and emission result are getting directly from the experimental, while the power, SFC, equivalence ratio and efficiency are getting from calculation.

4.2 MGT Characterisation with Diesel

Table 4.1 shows the performance of the MGT running on diesel. The results are plotted in figure below. From the Figure 4.1, the turbine power output in the micro gas turbine is increase with the increase of the turbine inlet temperature. The turbine power has a difference of 6.27 kW over the increase of 139 ºC. The turbine power increase due to the richer combustion condition at high compressor pressure and also high turbine inlet temperature. Furthermore, the SFC has a slight increase of 0.0108 kg/kWh in general but with a sudden drop at temperature of 864 ºC, which means the optimum SFC is at 864 ºC. From Figure 4.2, the combustion process is in lean combustion region. The diesel combustion in MGT is allowed to have equivalence ratio at 0.4 to 0.5, which is very lean, due to the lean operation limit of diesel is very low. The turbine power is increased as the combustion process more toward the bigger equivalence ratio or more richer part. In the other hand, SFC also increase as the increase in equivalence ratio. From both Figure 4.1 and Figure 4.2, the turbine power rise significantly with just a slight increment in the specific fuel consumption. Thus, the performance of the diesel in micro gas turbine is increase with the increase in the turbine inlet temperature and the increase in the equivalence ratio in overall.

Table 4.1: MGT performance analysis for diesel

MGT Pressure (bar)	TIT (ºC)	TOT (ºC)	Turbine power (kW)	Compressor power (kW)	Turbine efficiency (%)	SFC Exhaust (kg/kWh)	Equivalence Ratio
0.1	759	677	4.095	2.189	53.463	0.1353	0.404
0.2	813	708	5.835	2.872	49.213	0.1343	0.421
0.3	848	728	7.847	4.074	51.921	0.1215	0.391
0.4	864	739	8.425	4.769	56.602	0.1404	0.461
0.5	898	760	10.365	5.499	53.049	0.1461	0.495

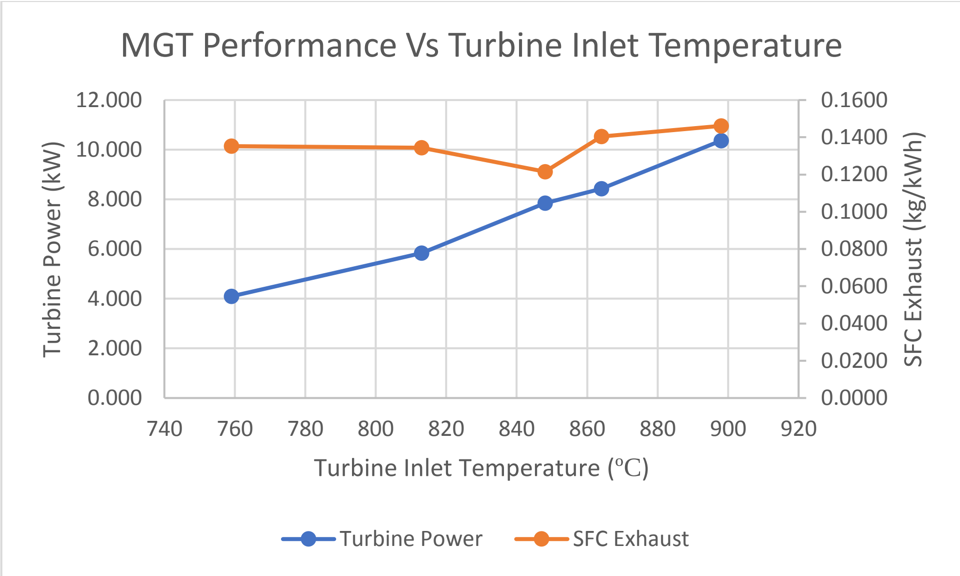

Figure 4.1: The graph of MGT performance versus TIT for diesel

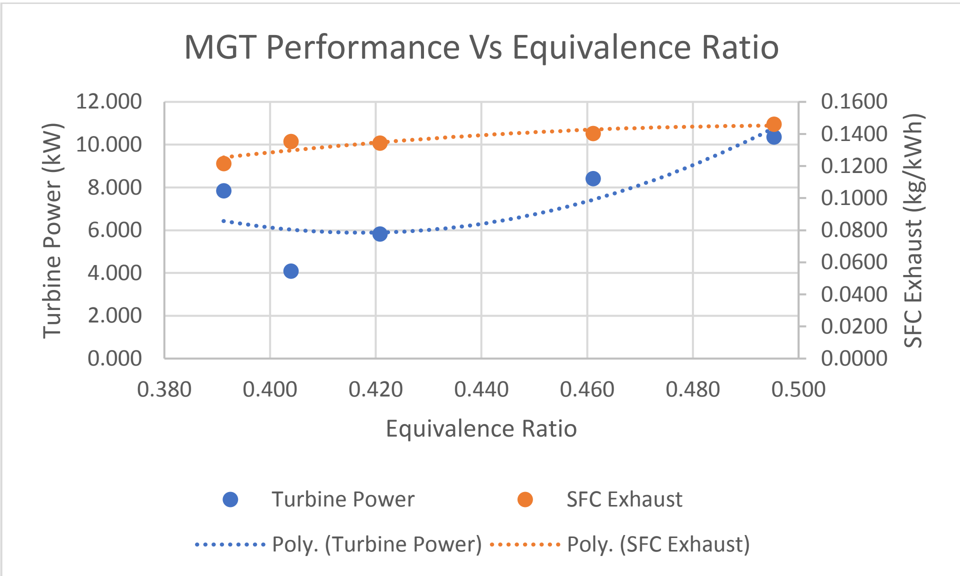

Figure 4.2: The graph of MGT performance versus equivalence ratio for diesel