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FINAL YEAR PROJECT DISSERTATION

GAS TURBINE PERFORMANCE AT VARYING AIR INLET TEMPERATURE

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CERTIFICATION OF APPROVAL

GAS TURBINE PERFORMANCE AT VARYING AIR INLET TEMPERATURE

by

Mohammad Izzat B Mohd Saleh

A project dissertation submitted to the Mechanical Engineering Programme
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2013

CERTIFICATION OF ORIGINALITY

GAS TURBINE PERFORMANCE AT VARYING AIR INLET TEMPERATURE

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHAMMAD IZZAT B MOHD SALEH

ABSTRACT

Power generation systems in most locations are either being driven by a gas turbine or a steam turbine. Gas turbine, which drives the generators to produce electrical energy, are normally design to be operated based on the ISO standards which specifies the air temperature to be at 15ºC, air pressure to be at sea level of 101.325 kPa and a relative humidity of 60%. Ambient condition varies on different part of the world; therefore these conditions are seldom or never met by gas turbines especially those operating in the region of Middle East, where temperatures are usually high, and also area having tropical climate like Malaysia, where it is relatively much more humid.

This project is to study the effects of varying ambient air temperature towards the performance of a gas turbine. With reference from studies conducted in Dubai, Turkey and Iran, the pattern of declination of power output is known. The main concern is how the performance of gas turbine will be affected with respect to the humid Malaysian climate. Thus, this project will analyze the performance of gas turbine with varying inlet air temperature to demonstrate the effect of ambient air on a gas turbine. This is done by using dry ice to lower the air inlet temperature and also the temperature of the air after the first stage of compression. The findings of this project will hopefully be as guidance for researchers and engineers to roughly estimate the power output at 100% base loads and find a preliminary measures to curb underperforming gas turbines operating at an off-design condition.

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious, the Most Merciful. Praise be to Him the Almighty with his will and given strength, had I managed to my Final Year Project as a partial fulfillment to the University. Without the aid, guidance, blessings, knowledge and wisdom that He has bestowed, I would never have finished my final year report, yet alone stand against the challenges faced through the whole study period.

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND OF STUDY

In the field of power generations and also processing plants including in the Oil & Gas Industry, the turbines are a component in their daily operations [1]. A power generation plant uses either one of the two type of turbine or even a combination of both – gas turbine and steam turbine. These equipments are used to run the generator to generate AC current or electricity in a power generation system. In the case of processing plants, gas turbines are used to drive pumps or compressors and in some cases offshore, to generate electricity.

Gas turbine operates with the atmospheric air as the main medium. The air is first compressed – to increase the pressure, combusted – to increase the temperature and pressure, and then the high pressure air is used to drive the turbine before exiting via the exhaust. As gas turbine are been used in various locations, the atmospheric air conditions tends to varies thus affecting the performance of the turbine. Gas turbines are design by the Original Equipment Manufacturer (OEM) based on the International Standards Organization (ISO) condition of ambient air which is rarely being met. Studies have been done, amongst those in Iran and in Dubai, to determine how much does the performance of a gas turbine deviates or depreciates from the stated operating conditions as the temperature of the inlet air varies. The condition of the ambient air consists of three main factors that could affect the performance of the gas turbine.

i) Pressure	• The atmospheric pressure changes with the change in altitude. • At sea level, the atmospheric pressure is at 1atm or 101.325 kPa
ii) Humidity	• Humidity is the measure of the amount of moisture in the air.
iii) Temperature	• The temperature of the air causes the density of air to vary. • Hot air is much lighter while cooler air is much denser.

Using a small scale laboratory gas turbine, the performance of the gas turbine is monitored at by setting a constant speed for the motor and recording the torque output from the gas turbine as the inlet air temperature is being varied.

1.2. PROBLEM STATEMENT

In most cities, power plants are being driven by gas turbines to produce electricity. Unlike steam turbine which uses steam as its main medium, the quality of steam can be controlled by a boiler. Gas turbine on the other hand uses atmospheric air as the main medium; hence the change in the ambient air will affect the gas turbine as well. This causes amount of electricity produced in power plants varies due to the ambient conditions depending on the plant type and characteristics. M. Farzenah-Gord and M. Deymi-Dashtebayaz, stated “it is well known that ambient temperature, humidity and pressure are important factors in gas turbine performance. Thermodynamic analyses exposed that thermal efficiency and specific output decrease with an increase of humidity and ambient temperature” [2].

Gas turbines are designed for standard air condition, which under the International Standards Organization (ISO), specifies the inlet air condition to be at the sea level with pressure of 101.325 kPa, temperature of 15ºC and a humidity of 60% [3]. As gas turbines are being used all over the world, their operating condition deviates along with the ambient conditions. In places like Dubai, the ambient air temperature varies from the cold winter of approximately 11ºC to the summer temperatures of around 55ºC [4]. Therefore, gas turbines are operating in an off-design condition in these regions. If the operating periods at off-design conditions last for extended periods, measures should be taken for performance enhancement [5].

Malaysia has a typical tropical climate with temperature ranging between 23ºC and 34ºC, and the humidity level could reach as high as 90% (RH). Thus, gas turbines in Malaysia are operating at off-design condition when compared to the ISO standards. Previous studies had already depicted the effect of varying air inlet temperature with gas turbine performance. Hence, this study will be focused on the local climate and the performance of a gas turbine with respect to the inlet air temperature as Malaysia has a significant level of humidity compared to the studies done in Iran and Dubai, where the air humidity level are relatively dryer.

1.3. OBJECTIVES

This project is conducted to study the effects of varying inlet air temperature towards the performance of a gas turbine unit and relate it to the ISO standards as well as the previous findings around the world. The result will be used to compare how much the performance deviates from the normal operating condition which is being taken as the control. The degree of deviation and the percentage of difference will be compared with studies being done in other region of the world.

1.4. SCOPE OF STUDY

The project will evolve with the literature review which will guide the course of the project. The literature review will give a rough idea based on experiments and studies being done to study the performance of gas turbine in various locations. Based on the literature reviews done, the method of cooling the inlet air is chosen which will be based on the relevancy, ease of manufacturing, feasible cost, and the cooling effect towards the inlet air. The project will then enter it fabricating phase, where a model of a cooler system will be designed to be fitted at the air inlet of the gas turbine.

Once the cooler system is fitted well and the air inlet can be cooled down, the experimental phase will begin where the experiment will be conducted at various temperatures and recorded. Ranges of temperature to be tested are from as low as the ISO standards of 15ºC, up to the range of the local climate weather of 34ºC. These records will then be compared with the designed performance of a gas turbine under ISO standards and also the findings based on the other papers.

CHAPTER 2: LITERATURE REVIEW

2.1. GAS TURBINE / COMBUSTION TURBINE

Gas turbines are internal combustion engines that are mostly used in plants, refineries or as an engine for an airplane [2]. These types of turbine engines can generate a huge amount of powers which can be used in producing electricity in power plants or as a substitute to a motor to drive a compressor or a pump in a plant.

Gas turbine which is also called as a combustion turbine operates with 4 major parts of the equipment – compressor, combustion chamber, turbine, and exhaust. This rotating equipment works on the principal of Brayton-Cycle, which takes in air from the atmosphere via the compressor inlet, compresses it, to increase the pressure, before the air is being sent into the combustion chamber. The air is then mixed with injected gas for combustion, to further increase the temperature of the air. This air of high pressure and temperature is then used to run the turbine which rotates a shaft that is coupled to the driven equipment. Most of the air is then being channeled out to the exhaust, while some of it is used for reheating purposes [6].

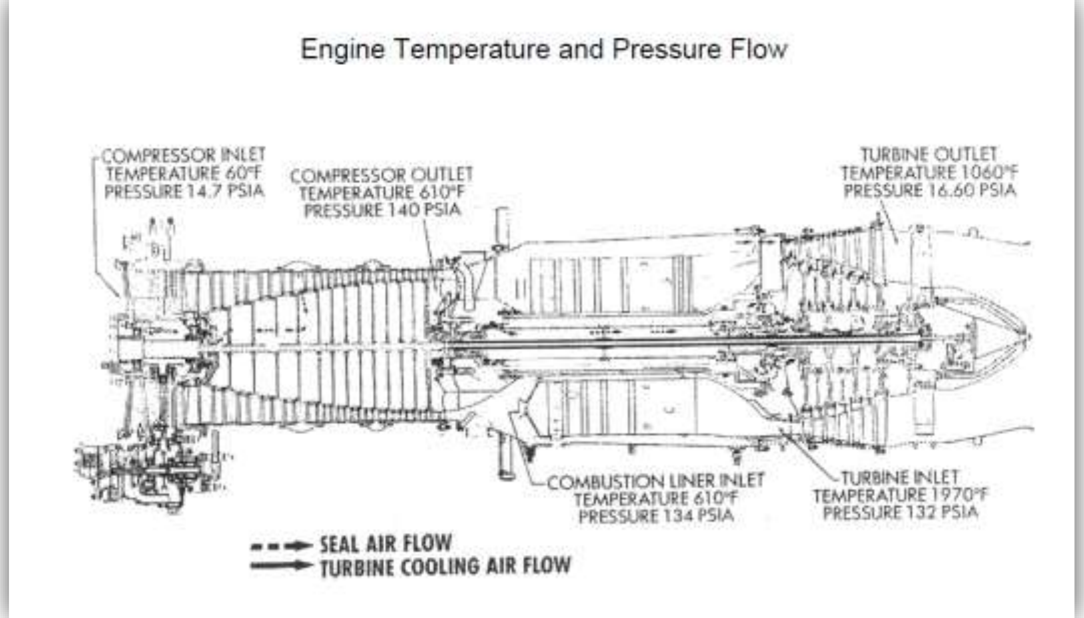


Figure 1: Parts / Section of a typical gas turbine

Gas turbines generally can be classified into two classes – the aero-derivative and the industrial / heavy-duty. These two types of turbines have different performance, operating envelope, cost, partial load behavior, and different performance variations with the ambient temperature [5]. Aero-derivative gas turbines are commonly used to power an airplane like the ones used on Airbus and Boeing aircrafts. While the industrial / heavy-duty combustion turbines are usually used in the industrial fields, including power generations and Oil & Gas Industry.

There are various configurations of gas turbines depending on its power out and its size. Small gas turbines are usually single shaft, while a bigger could have either two shafts or even three shafts. The size of the gas turbines also determines the number of compression stages and turbine stages the turbine has. Most gas turbine uses axial compressor but there are some turbines that uses the centrifugal compressor, depending on the OEM.

Around the world, gas turbines are a major source of power generation. Iran for instance has at least, 170 gas turbines to generate around 9500 MW of power.

2.2. AMBIENT AIR

Ambient is defined by *Dictionary.com* as the surrounding area or environment, or the complete surrounding or encompassing. Thus ambient air is the surrounding air, external to a building. Ambient air is actually a factor of temperature, pressure, altitude, and humidity.

As the Earth is relatively spherical in shape and the surface of the Earth is not flat due to existence of mountains, hills and valleys, temperatures and weathers deviate throughout the year depending on seasonal change, and it varies from one place to another around the globe, this was explained by the *British Geological Survey* [7], a natural environment research council in their website. Areas that are nearer to the equatorial line experience a higher temperature compared to areas further away from the equator, nearer to either the North Pole or the South Pole. This is due to the distance of the location from the Sun. The further away the location is from the Sun, the more direct radiation are diffused causing a lower radiation heat transfer to the particular surface of the compared to the locations nearer to the Sun. This is the reason why the poles are colder than the equator of the Earth.

Besides the solar radiation, the factor of altitudes also affects the ambient air, causing the alterations in the atmospheric pressure. Altitudes are commonly measured in relative to the sea level, taking it as the zero altitude. Points beneath the surface of the sea are altitudes below the sea level, while the above it is altitudes above sea level. The higher the point is above the sea level, the lower the ambient pressure it will experience. Consequently, the lower the point below the sea level the higher the pressure it will experience.

2.3. REVISITING THE BRAYTON CYCLE

Gas turbine operates with principles of open Brayton-cycle which is an open gas turbine cycle. This principle was derived from the reversible simple Brayton-cycle except the air is not being reused. Taking the initial the reversible Brayton cycle as reference, calculations are done based on the T-s diagram of an ideal Brayton cycle. As discussed by Ashley and Sarim [4], the concept of compressor polytrophic efficiency can be developed from considering small compression processes and by using the Gibbs equation for and ideal (isentropic) process. Using the definition of the isentropic compressor efficiency the expression (1) could be written, where γ is the ratio of specific heats and c_p is specific heat capacity at constant pressure. With the same thermodynamic principle the efficiency of the gas turbine expansion process could also be calculated as shown in equation (2).

$$\eta_c = \frac{\left[\frac{P_2}{P_1}\right]^{\left(\frac{\gamma-1}{\gamma}\right)}-1}{\left[\frac{P_2}{P_1}\right]^{\left[\frac{\gamma-1}{\gamma\eta pc}\right]}-1} \qquad (1)$$

Equation 1: Compressor Efficiency

$$\eta_{pt} = \frac{1-\left[\frac{P_3}{P_4}\right]^{\left[\eta_{pt}\left(\frac{\gamma-1}{\gamma}\right)\right]}}{1-\left[\frac{P_3}{P_4}\right]^{\left[\frac{\gamma-1}{\gamma}\right]}} \qquad (2)$$

Equation 2: Turbine Efficiency

Using the T-s diagram constructed for a gas turbine operating conditions based on the Brayton cycle (Figure 1), it is possible to calculate the cycle's efficiency by the following equation:

$$\eta = \frac{c_p\,(T_3-T_4)-c_p\,(T_2-T_1)}{c_p\,(T_3-T_2)}$$

By utilizing the isentropic relationship between pressure and temperature,

$$\frac{T_2}{T_1} = \frac{P_1}{P_2} = r = \frac{P_3}{P_4} = \frac{T_3}{T_4}$$

The simple cycle efficiency is shown as:

$$\eta = 1 - \left(\frac{1}{r}\right)^{\left[\frac{\gamma-1}{\gamma}\right]}$$

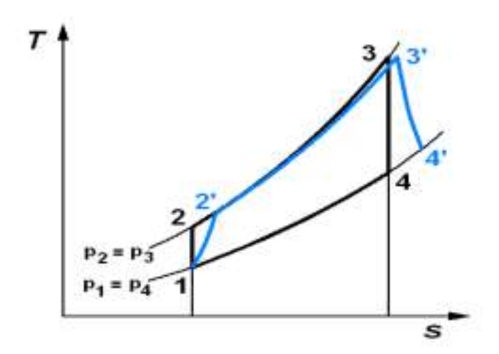


Figure 2: Brayton Cycle's T-s Diagram

Farzaneh-Gord and Deymi-Dashtebayaz [1], in their studies states the thermal efficiency, η_{th}, of the gas turbine can be calculated as:

$$\eta_{th} = \frac{\dot{w}_t - \dot{w}_c}{h_{3,air} - h_{2,air}}$$

Equation 3: Thermal Efficiency

Where the $\dot{w}_t$ and $\dot{w}_c$ are the work done by the turbine and the compressor and can be calculated by the following formula respectively:

$$\dot{\mathrm{W}}_t = \dot{\mathrm{m}}_{air}\dot{\mathrm{w}}_t = \dot{\mathrm{m}}_{air}\left(h_{3,air} - h_{4,air}\right) \qquad \dot{\mathrm{w}}_c = \frac{\dot{\mathrm{W}}_c}{\dot{\mathrm{m}}_{air}} = \left(h_{2,air} - h_{1,air}\right)$$

Equation 4: Turbine Work **Equation 5: Compressor Work**

Should the shaft speed of the turbine is known and the amount of torque it produces are also known, the following formula can be used to calculate the total power output.

$$P = \tau \times 2\pi \times \omega$$

Equation 6: Calculation of power given the torque and rotational speed

Where P is the power output, τ, is the torque produced and ω is the rotational speed

2.4. EFFECT OF AMBIENT AIR TO PERFORMANCE OF GAS TURBINE

Temperature plays a role in determining the efficiency of a gas turbine, therefore changes the inlet ambient temperature (T_1) will affect the efficiency and the power output of a gas turbine which can be seen as the amount of electricity produced in power plants.

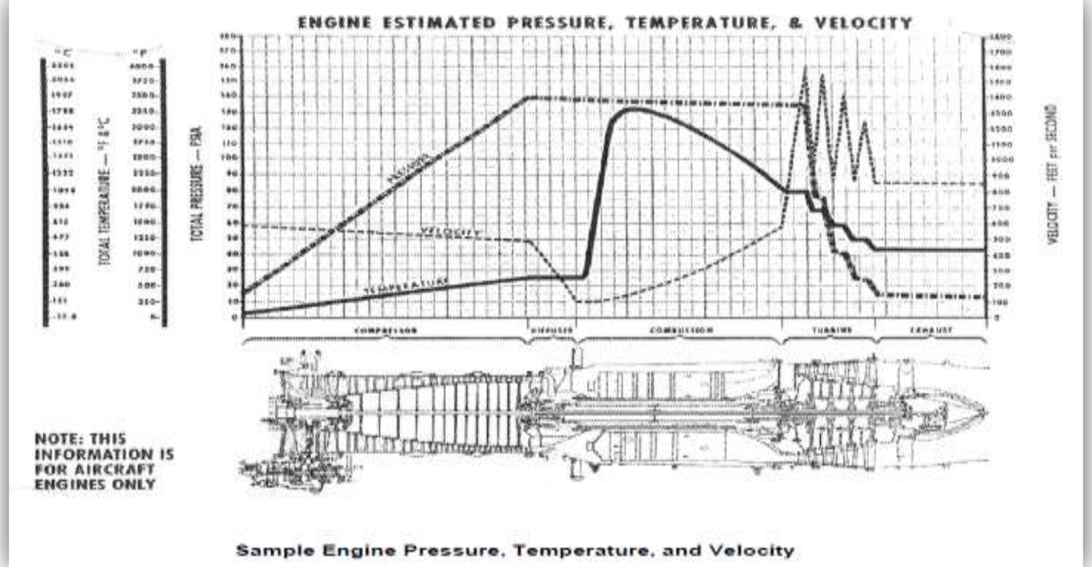


Figure 3: The temperature and pressure curves of the sections of a gas turbine

As stated by Early et al., “the ability of a gas turbine/electric generator to provide electric power is affected by the temperature of the air entering the gas turbine. Typically, the cooler the inlet air temperature the greater power that can be obtained from the turbine” [8]. This statement was proven by Hasan and Suleyman [5], as they studied on the effects of ambient air temperature resulting to the equation of monthly electricity production (E_m) below:

$$E_m = N \cdot LF_m \cdot G \cdot 24$$

Equation 7: Equation of monthly electricity production

Where N is the power, LF is the monthly load factor and G is the number of days in that particular month. The power, N, is calculated by the formula:

$$N = \frac{P_1}{R_a} V \left[\frac{W_t}{T_1} - \frac{c_{pa}}{\eta_{cis}} \left(P_{rc}^{\left(\frac{k_a - 1}{k_a}\right)} - 1 \right) \right]$$

Where P_1 is the inlet pressure and R_a is air ideal gas constant, V is the volumetric flow rate, W_t is the turbine work, T_1, compressor inlet temperature, η_{cis} is the compressor isentropic efficiency, k_a, is the air specific heat ratio and P_{rc} is the compressor pressure ratio.

From the study, it was shown that the electricity production, E_m, decreases on the months that have a relatively higher T_1 temperature (the summer season between May to September). The result of the study was plotted in a graph as which summarizes the effects of the ambient temperature towards the electricity produced in different regions in Turkey. Figure 2 shows the outcome of the study.

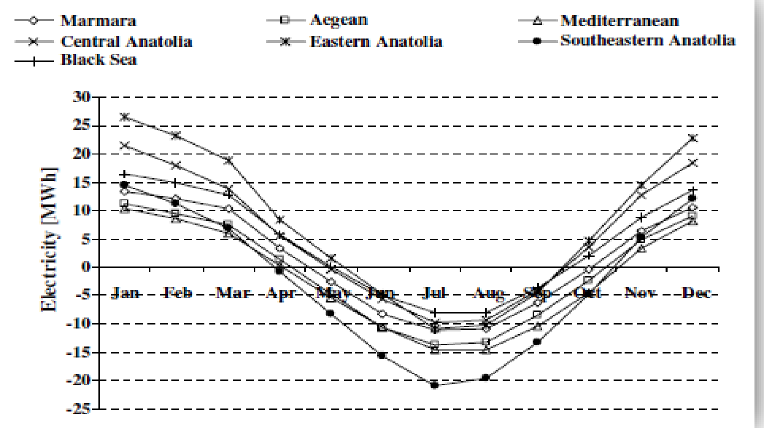


Figure 4: Electricity production losses and excess of regions with the ambient temperature (SOURCE: Hasan Huseyin & Suleyman)

The theory behind effects of temperature on the air is that temperature causes the change in air density. The density hot air is lighter, while cooled air is much denser. The dense air will give the turbine a higher mass flow rate, which requires more power to compress the air but on the other hand it also results to an increase in turbine output and efficiency [9]. Ameri and Hejazi stated in their study that the amount of increase in turbine power output is much more noticeable making the effect of the increase in power usage to compress the air less significant.

Previous studies have shown there are noticeable losses in terms of thermal efficiency and power output with the increase of ambient air temperature, where the latter's effect is much more substantial than the first. As documented by Hasan and Suleyman, depending on the temperature variations, the production loss ranges from 1.32% up to 7.85%. In locations where the ambient temperature is above 15^{o}C, especially in summer, the production loss ranges between 1.67-7.22%. The increase in ambient temperature in hot regions will cause the decrease in electricity production and also increases the fuel consumption rate per unit electricity produced. When the inlet air is cooled, the augmentation of power production is about 0.37-7.59% [5].

In a study conducted by Ameri and Hejazi in Chabahar [9], it was found that there is a relationship between air inlet temperature and the efficiency of a gas turbine. Due to the fact that cooler air is denser compared to hot air, cooler air will cause a higher mass flow rate and results to an increase in turbine output and its efficiency. Thus, it was found that each 1°C increase of ambient air temperature, the power output will decrease by 0.74%. While the average power output, can be increased up to 11.3% when the inlet air is cooled. The same pattern of deviation of performance was also recorded by Ashley and Sarim [4], in their study on the performance of gas turbine at varying ambient temperature, as shown in Figure 3 and Figure 4 respectively, stating "for every K rise in ambient temperature above the ISO condition, the thermal efficiency looses 0.1%, while the lost in power output is as high as 1.47MW".

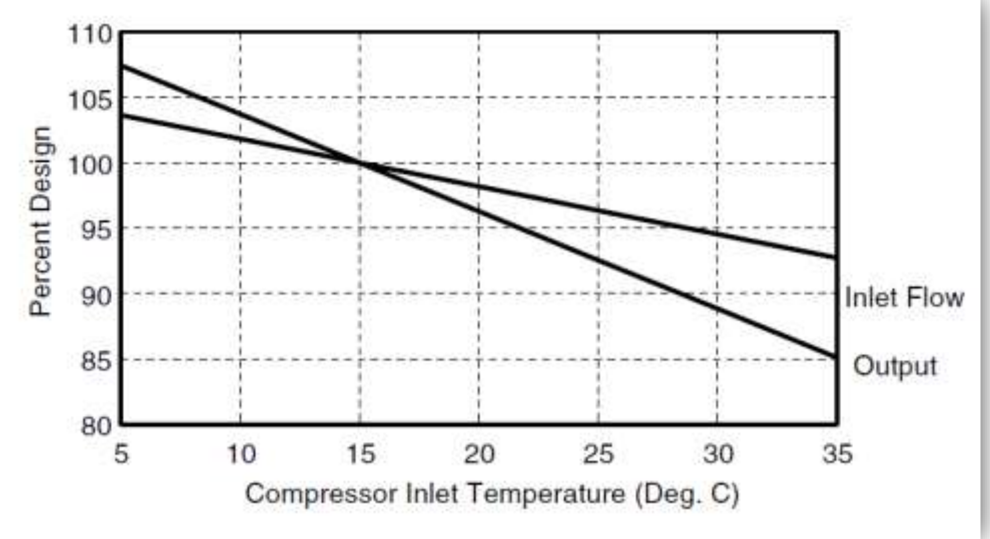


Figure 5: Gas turbine performance curve (*SOURCE: Ameri & Hejazi*)

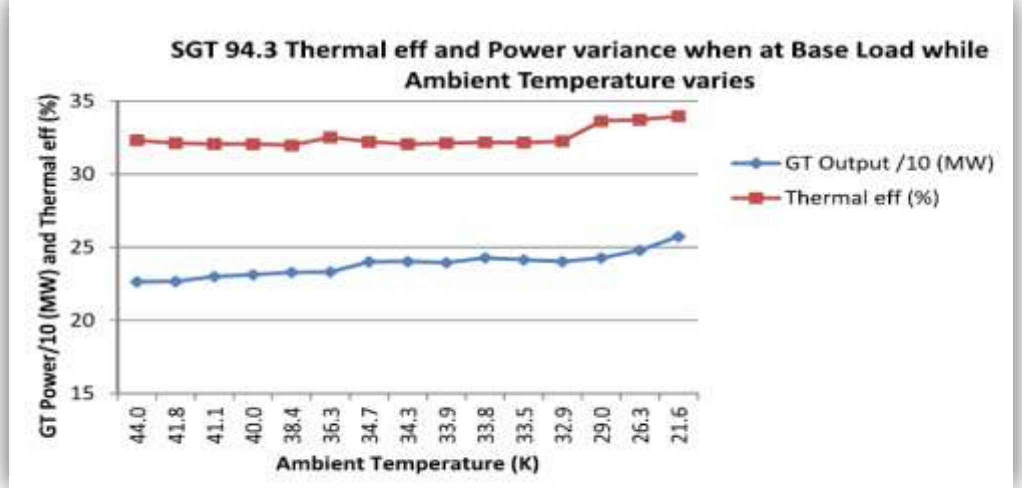


Figure 6: Behavior of gas turbine SGT 94.3 thermal efficiency and power variance when at base load at varying ambient temperature during the annual continuous monitored period. (*SOURCE: Ashley & Sarim*)

Hence, this project is to study and verify these findings, with respect to the Malaysian climate, to predict the power loses when a gas turbine operates in the tropical weather region. From the findings, preliminary measures to curb the drop in performance will be recommended.

2.5. GAS TURBINE INLET AIR COOLING METHODS

In most seasonal countries, gas turbine inlet air cooling technologies are being used during the hot season to augment the power output. While the methods used might be different from one gas turbine to another based on the location, the purpose is the same, to increase the performance during the hot seasons. Al-Ibrahim and Varnham, stated five known methods to decrease ambient air temperatures – 1) Wetted media evaporative cooling; 2) High-pressure fogging; 3) Absorption chiller cooling; 4) Refrigerative cooling; and 5) Thermal energy storage.

The wetted media evaporative cooling suits best in locations with hot and dry climates as it uses the latent heat of vaporization to cool ambient temperature from the dry-bulb to the wet bulb temperature. By using blowers and small water pumps in a typical system, this method of cooling could cool a large amount using the expenditure of a relatively small amount of energy. On the other hand, the approach of using fogging or high pressure fogging needs a proper calibration of the equipment. This method spray droplets of demineralized water about 5-20 microns in diameter causing the inlet air to be at 100% relative humidity as the fog droplets evaporates, making the air to cooled to the wet bulb temperature; lowest possible temperature obtainable without refrigeration. Precise calibration is required in this method as stated by Hill, that droplets of water >20 microns in diameter may strike the turbine blades and causes erosion.

A new approach of cooling the inlet air is by using turbo-expanders and throttling valves. This method is relatively cheap as there is no need for an installation of new mechanical equipment. It uses the concept of high pressure gas being expanded rapidly, causing the temperature to drop as well. This cooled gas is then used as coolant in the heat exchanger fitted before the compressor of the gas turbine. Farzaneh-Gord and Deymi-Dashtebayaz, in their study on effect of various inlet air cooling methods on gas turbine performance, shows that the best cooling method is by using the mechanical chiller system which could enhance the performance of gas turbines to about 5%, compared to the evaporative media system and turbo expanders of about 3% and 4% respectively.

The mechanical chiller system allows designers to reduce the inlet temperature as desired regardless of the ambient wet-bulb temperature making the system much more effective and reliable compared to the evaporative media system. The system consists of two basic components – 1) Mechanical chiller and 2) Compact heat exchanger. The drawback of this system is the cost which seems to be more expensive, Farzenah-Gurd and Deymi-Dashtebayaz, concluded in their study that the net increase of electricity production for the turbo-expander is the highest at 18,338 MWh/year as the system hardly consumes any energy. Whereas, the net increase in electricity production using mechanical chiller system and the evaporative media system are about 2501 MWh/year and 1132 MWh/year respectively.

Another method of cooling is by refrigerative cooling and thermal energy storage. This method have a relatively higher capital cost and could have a parasitic power requirements up to 50% compared to the absorption chillers methods. But this method do have the advantages of having a low maintenance cost. Refrigerative cooling method is been done by storing the thermal energy. The thermal energy storage stores cooling energy by either the sensible heat capacity of chilled water or the latent heat capacity of ice. Comparing the two methods of cooling, the chill water system is limited to 7oC when cooling the ambient air, while the ice thermal storage method can cool the air lower as it has the freezing temperature [3].

The result shows, by using an air inlet cooling system for gas turbines, the inlet air temperature could be reduce for a period of 9 months in a year, ranging from 4^{o}C to 35^{o}C. The most significant drop in inlet air temperature is during the hot/summer season creating augmentation of the gas turbine performance.

2.6. DRY ICE

Dry ice also known “card ice” is actually the carbon dioxide gas in the solid state of matter. Carbon dioxide which exists under the normal atmospheric condition in gaseous state has a very low temperature in the solid state. Due its physical properties and its triple point, dry ice undergoes phase change from solid to gas without going through the liquid phase, unless when it is pressurize above 5.13 atm of pressure. Then only the carbon dioxide will become liquid CO^2 at the temperature of -56.6^oC. Dry ice under normal atmospheric pressure (1 atm) has a sublimation and deposition point at -78.5^oC. This temperature much colder when compared to normal H_2O ice, hence dry ice provides a better cooling energy. The properties of dry ice can be summarized in the table below.

Table 1: Properties of Solid Carbon Dioxide (Dry Ice)

Name	**Solid Carbon dioxide (Dry ice)**
Chemical Formula	CO_2
Molecular Weight	44011 kg/kmol
Specific Gas Constant	0.1889 kJ/kg.K
Sublimation Point	-78.9 ^oC @ 1 Bar
Triple Point	-56.6 ^oC @ 5.18 Bar
Density	1977 kg/m^3
Critical Temperature	31°C
Critical Pressure	7383 Bar
Critical Density	466 kg/m^3

The physical properties of dry ice allow it to sublimates and not melt. This allow the dry ice to not leave any residues except for moistures from the atmosphere which condensate, unlike the normal ice which melts and leave a puddle of water on the surface. Dry ice is actually widely been used especially in the industry of frozen foods and its transportation. The advantage of using dry ice over mechanical chiller is that, it is cheaper and does not need any maintenance cost. In this region of Ipoh, Malaysia, dry ice can be purchased at the price of RM 7 per kilogram of dry ice.

CHAPTER 3: METHODOLOGY

3.1. PROJECT FLOW CHART

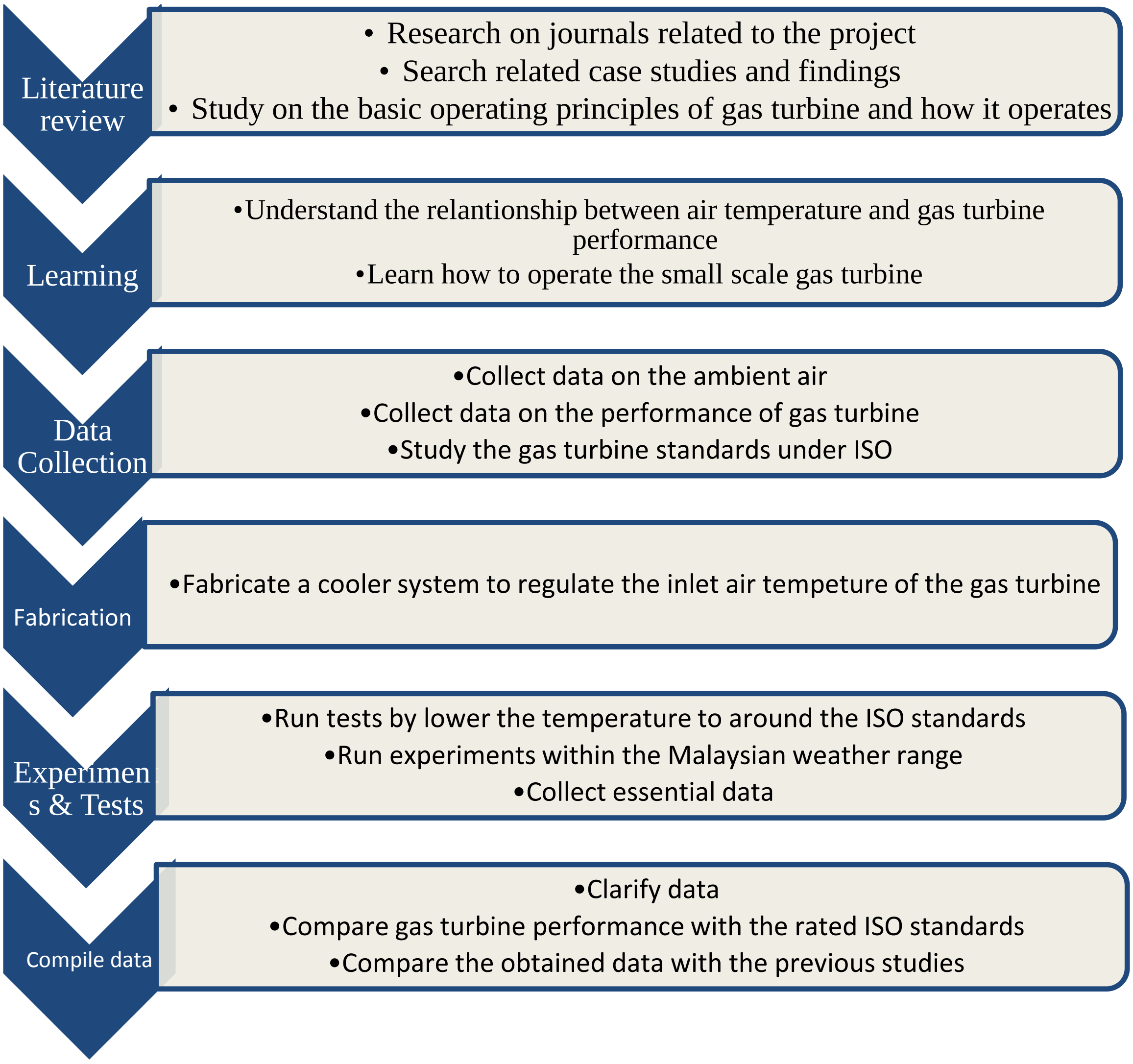
The project commences with the study of gas turbines and its governing principle. It is then followed by the study of how the change in the ambient air temperature affects the performance of a gas turbine, and how significant is the impact of the varying air temperature.

As project will be in a laboratory scale experiment, a two shaft gas turbine unit, TGT 1.5 kW, placed at the laboratory in Block 15 in Universiti Teknologi PETRONAS, will be used to carry out the experiment. The experiment will evolve by first, collecting the data for the normal operating condition of the gas turbine. This data will be used as a control before the modification of an air cooling unit is made. Next, the sizes of the inlet filters and air inlet will be measure for fabricating purposes.

To test the effects of cooling towards the system, net-like holder will be mounted to the air filter of the compressor during the fabrication stage. This net-like holder will be used to hold dry ice while allowing air to pass through, hence allowing the process of heat transfer, making the air entering the gas turbine via the air inlet of the compressor to be cooled down. Another cooling mechanism will be attached at the piping of the gas turbine, right after the first stage of compression. The test will be conducted by first using only one point of cooling – either the inlet or the piping cooling method – and it then both the points will be used to evaluate the cooling effects. In order to control the cooling load, the amount of dry ice used will vary in terms of mass for each run of experiment. This eases the process of finding the relation between the air temperature and the power output of the gas turbine. Hence, making it possible to observe the effect of decreased in air temperature on the performance of the gas turbine.

The data will be tabulated and compared with the control data, to observe the deviation in performance before the air is cooled and after the cooling system is installed. The amount of deviation and the data collected will also be compared to the ISO standards and the results from previous studies that have been conducted on the performance of gas turbine with varying air inlet temperature.

3.2. PROJECT FLOW CHART



Literature review

- Research on journals related to the project
- Search related case studies and findings
- Study on the basic operating principles of gas turbine and how it operates

Learning

- Understand the relantionship between air temperature and gas turbine performance
- Learn how to operate the small scale gas turbine

Data Collection

- Collect data on the ambient air
- Collect data on the performance of gas turbine
- Study the gas turbine standards under ISO

Fabrication

- Fabricate a cooler system to regulate the inlet air tempeture of the gas turbine

Experimens & Tests

- Run tests by lower the temperature to around the ISO standards
- Run experiments within the Malaysian weather range
- Collect essential data

Compile data

- Clarify data
- Compare gas turbine performance with the rated ISO standards
- Compare the obtained data with the previous studies

Figure 7: Overall Flowchart of the Project

3.3. TOOLS AND EQUIPMENT

- Two Shaft Gas Turbine TGT 1.5 kW

Figure 8: TGT 1.5 kW Unit

The TGT 1.5 kW is the main equipment to conduct the experiment in a laboratory scale. The gas turbine is equipped with temperature probes, pressure gauges and speedometer. The data for the gas turbine can be gathered by taking the readings on the panel.

- Microsoft Office - Data collection, analysis and report compilation

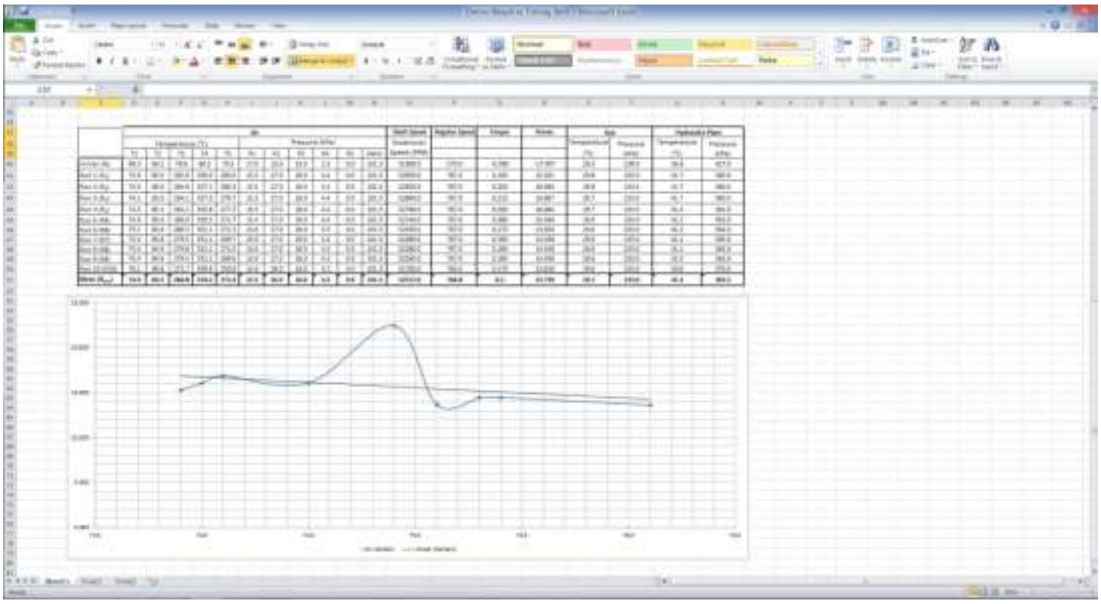


Figure 9: Preliminary result collected and tabulated in Microsoft Excel

Microsoft Office, mainly Microsoft Excel, is the main medium to tabulate the data and plot the graph. While the Microsoft Word, will be used to compile the data into a report and technical paper.

CHAPTER 4: PROJECT ACTIVITIES

The experiments of the projects are being done at a few conditions. This is to determine i) the performance at control condition; ii) the effect of cooling at different area; iii) the performance of the gas turbine when the inlet air is cooled down.

4.1. EQUIPMENT TESTING WITHOUT BELT

In order to conduct the experiment and to observe the effect of cooling towards the performance of gas turbine, the normal operating condition and its power output should be recorded as a control. Theoretically, the power output and operating condition can be known by the Brayton cycle's T-s diagram. But, theoretical data differs from the actual, due to the existence of enthalpy which makes things irreversible and causes the deviation from the ideal condition.

Therefore, an experiment was conducted to test the functionality of the gas turbine as well as the reliability. The gas turbine was found to be functioning except for a few components, which can then be override by controlling the opening of valves directly. The reliability on the other hand can be determined by taking a number of readings of the gas turbine running performance and comparing it. Should the data be in close range the readings and the performance of the gas turbine is considered as reliable. The results of the experiment are as follows*.

Table 2: Tabulated data obtained from the demonstration experiment.

	Air											**Shaft Speed**	**Gas**		**Hydraulics Plant**	
	Temperature (^{o}C)					Pressure (kPa)						Rotational Speed (RPM)	Temperature (^{o}C)	Pressure (kPa)	Temperature (^{o}C)	Pressure (kPa)
	T1	T2	T3	T4	T5	P1	P2	P3	P4	P5	Patm					
Initial (R$_i$)	28.8	30.4	41.8	43.1	29.2	-0.2	0.0	0.0	0.0	0.0	101.3	0.0	25.1	140.0	30.4	461.0
Run 1 (R$_1$)	76.0	86.5	288.0	341.2	281.0	15.5	29.0	29.0	4.8	0.0	101.3	56520.0	25.8	235.0	37.7	400.0
Run 2 (R$_2$)	65.5	74.6	245.0	301.8	250.0	16.4	26.0	26.0	4.6	0.0	101.3	50430.0	25.6	236.0	38.2	399.0
Run 3 (R$_3$)	67.2	76.7	286.9	332.5	282.6	16.4	27.0	26.0	4.9	0.0	101.3	56550.0	26.0	235.0	42.3	375.0
Run 4 (R$_4$)	70.4	79.7	265.8	324.9	269.0	16.2	26.0	25.0	4.4	0.0	101.3	49990.0	28.0	234.0	41.2	388.0
Mean (R$_{ave}$)	69.8	79.4	271.4	325.1	270.7	16.1	27.0	26.5	4.7	0.0	101.3	53372.5	26.4	235.0	39.9	390.5

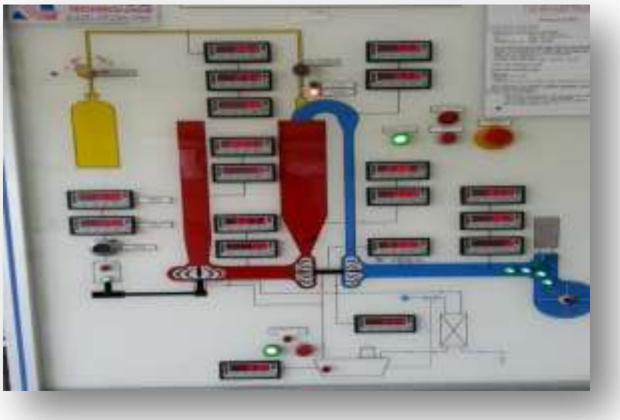


Figure 10: Indicator panel of TGT 1.5 kW

The Figure shows the panel indicating the reading of the conditions at point 1 until point 5. Where point 1, is after the first stage of compressor, followed by point 2 which is after the second compressor stage. Point 3 is the point in the combustion chamber and where the combustion takes place. While point 4 and point 5, are at the after the first turbine stage and at the exhaust of the gas turbine respectively.

The experiment conducted was with the objectives of:

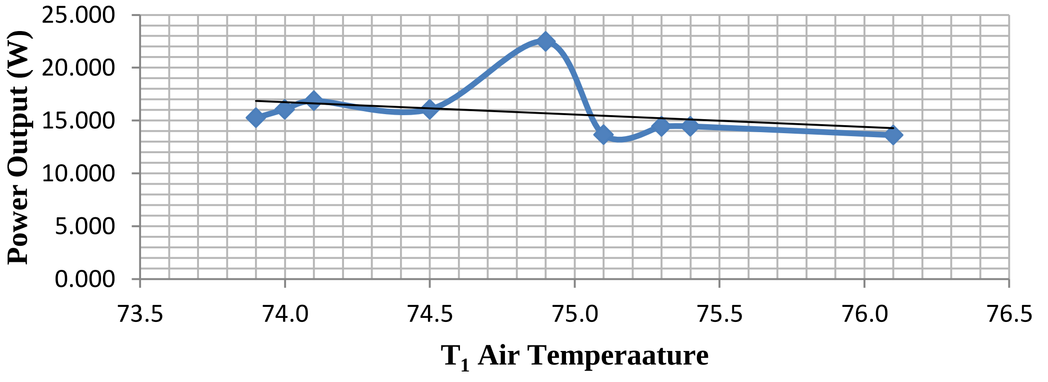
- Identify the normal operating range for the Two Shaft Gas Turbine Unit TGT 1.5 KW
- Study the procedure to operate the gas turbine unit.
- Learn the precautious steps in operating the gas turbine.

From the experiment the normal operating air condition at position 1 until position 5 can be known. But the power output reading was not available, due to the missing belt connecting the turbine to the electrical motor. Therefore the experiment was inconclusive, because the power output is not known, making it not possible to calculate the normal efficiency of the gas turbine. Despite the missing data, the data obtained shown in Table 1, can be used to observe the operating air temperature and pressure at each point. Taking the mean, the inlet air is about 69.8 oC and the pressure is at 16.1 kPag after the first compression stage. The full report of the procedures and result of the experiment can be seen in Appendix A section.

4.2. EQUIPMENT NORMAL OPERATING CONDITION EXPERIMENT

An experiment was conducted to study the normal operating condition of the gas turbine to complement on the previous test which was inconclusive. As the belt connecting the turbine to the motor was already available, this test was done mainly to know the power output of the gas turbine. A few factors were set as a controlled, to study the relationship between air temperature and the power output. Power output can be determined using Equation 6.

The angular speed of the motor was set as constant and also the other parameters of the gas inlet temperature and pressure. The result of the experiment is taken to be the controlled parameter, taken the mean readings of the ten runs done. Due to the fact that the equipment's temperature increases as it operates in longer periods. The ten readings taken from the experiment when plotted individually shows the slight effect of increase of air temperature with the power output, thus yielding the following graph.



Graph 1: T1 Temperature vs. Power Output

This graph indicates that the air temperature does effects the performance of the gas turbine. The effect can be seen from the graph that is declining with the increase in temperature. This effect is expected to be more obvious once the cooling system is installed. The full report of the experiment can be seen in Appendix B section

4.3. STUDY ON THE COOLING EFFECTS OF DRY ICE

As dry ice is to be used to cool the inlet air and also the piping, the cooling effects of dry ice was studied. In the aim of predicting how much will the inlet air temperature will be decreased after the cooling from the dry ice, the cooling energy of the dry ice was being studied. The test was done by doing a small experiment of placing a known mass and of dry ice into a beaker of a known mass of boiling water. The temperature of the mixture is then observed and the final temperature is recorded.

Figure 11: Mixture of hot water and dry ice

Figure 12: Temperature of Hot water

The result from the experiment was inconclusive as it yielded a result that was non logical. By using the equation of:

$$m_{ice}l_{ice} + m_{ice}c_{p,ice}\Delta T_{ice} = m_{water}c_{p,water}\Delta T_{water}$$

Where: m = mass (kg)
L = latent heat of fusion
c = specific heat
$\Delta T = Temperature_{final} - Temperature_{initial}$

From the experiment, the heat value of the decrease in the water temperature was found to be at -144200 J which was not equal to the cooling energy from the dry ice. The faulty in the result was expected due to the equation or error in reading and the control parameters of the experiment. In order to obtain a viable result, the experiment is to be repeated in the coming weeks to study the cooling load of the dry ice.

4.4. T1 COOLING EXPERIMENT

This experiment was conducted to determine the effective cooling area on the gas turbine. There were two areas that were proposed for cooling – i) at the air inlet; ii) at the passageway of the air (T1).

Figure 13: T1 Cooling Method

The procedures for this experiment are:

a) Weight a certain amount of dry ice
b) Wrap it around the area of T1, after the first stage of compression
c) Ensure that parameters like the speed of the motor are kept constant.
d) Observe the changes in temperatures, especially at T1, T2 and also the torque output of the gas turbine.

4.5. INLET AIR COOLING EXPERIMENT

With theory of the compression side of the gas turbine, sucks in air, for it to compress before the combustion and the turbine stage, the motion of air that is being sucked is being used as a medium for heat transfer.

Using dry ice as a cooling energy, the holder of the dry ice was made and mounted at the air inlet of the compressor. The dry ice holder must have the properties of

a) Able to hold at least 5 kg of dry ice
b) Able to allow air to pass through
c) Able to be stretched due to the fact that dry ice does not have a uniform shape.

Figure 14: Dry Ice Holder

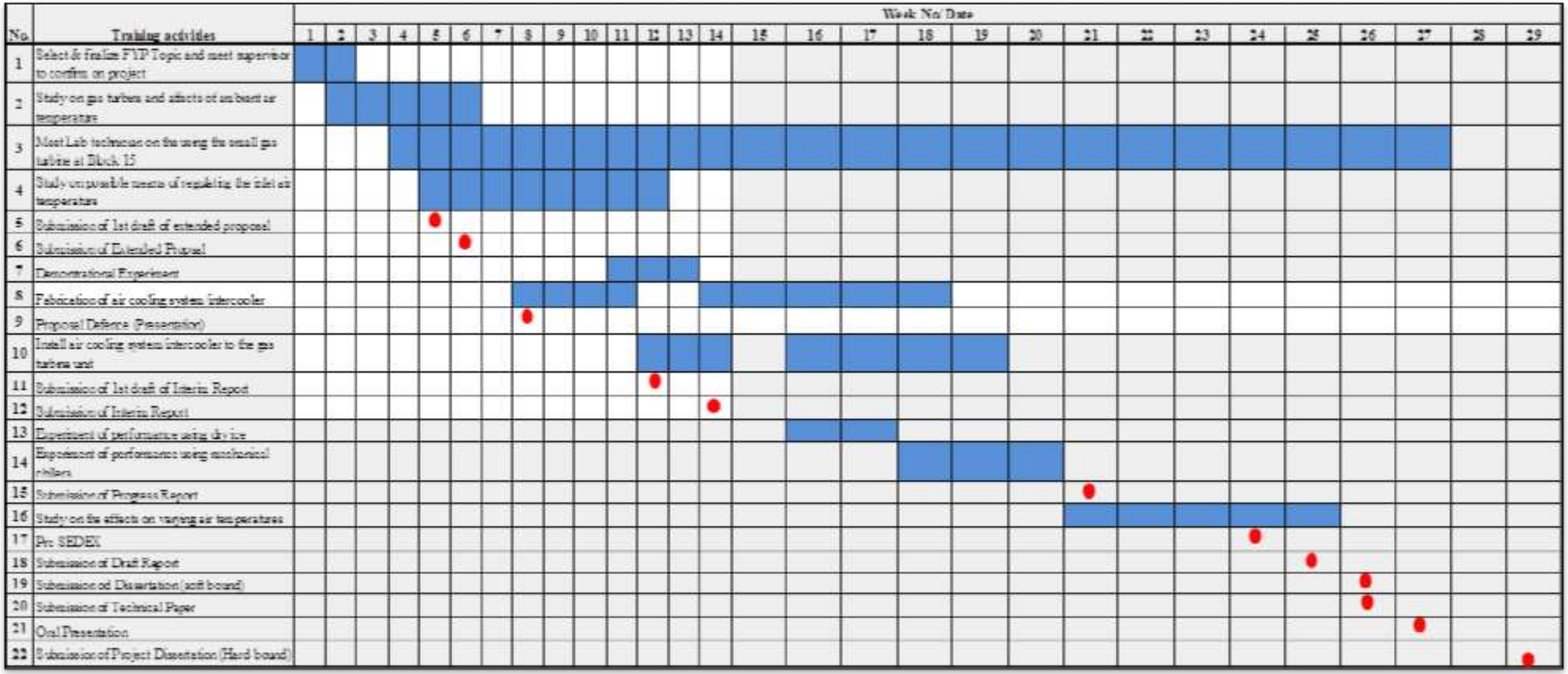
The experiment was conducted by using 3 kg of dry ice to cool the ambient air before it enters the first stage of compression. The experimental procedures for this experiment are as follows:

a) Weight a certain amount of dry ice
b) Place it inside the holder, before the first stage of compression.
c) Ensure that parameters like the speed of the motor are kept constant.
d) Observe the changes in temperatures, especially at T1, T2 and also the torque output of the gas turbine.

As this is the main experiment for the project, the results and discussions are discussed in Chapter 6.

CHAPTER 5: GANTT CHART & MILESTONES

Table 3: Final Year Project I & II Gant Chart and Milestones



No.	Training activities	Week No/ Date																												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	Select & finalize FYP Topic and meet supervisor to confirm on project	🟦	🟦																											
2	Study on gas turbine and affects of ambient air temperature		🟦	🟦	🟦	🟦	🟦																							
3	Meet Lab technician on the using the small gas turbine at Block 15				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
4	Study on possible means of regulating the inlet air temperature					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																	
5	Submission of 1st draft of extended proposal					●																								
6	Submission of Extended Proposal						●																							
7	Demonstrational Experiment											🟦	🟦	🟦																
8	Fabrication of air cooling system intercooler								🟦	🟦	🟦	🟦			🟦	🟦	🟦	🟦	🟦											
9	Proposal Defence (Presentation)								●																					
10	Install air cooling system intercooler to the gas turbine unit												🟦	🟦	🟦		🟦	🟦	🟦	🟦										
11	Submission of 1st draft of Interim Report												●																	
12	Submission of Interim Report														●															
13	Experiment of performance using dry ice																🟦	🟦												
14	Experiment of performance using mechanical chillers																		🟦	🟦	🟦									
15	Submission of Progress Report																					●								
16	Study on the effects on varying air temperatures																					🟦	🟦	🟦	🟦	🟦				
17	Pre SEDEX																								●					
18	Submission of Draft Report																									●				
19	Submission od Dissertation (soft bound)																										●			
20	Submission of Technical Paper																										●			
21	Oral Presentation																											●		
22	Submission of Project Dissertation (Hard bound)																													●

● Milestone

🟦 Progress

CHAPTER 6: RESULTS

The project yielded a few results as a method to compare the possibilities of cooling method. The result of cooling at T1 can be seen as discussed in Chapter 4. Like most Gas Turbine Inlet Air Cooler (GTIAC) in the market – except the high pressure fogging method, the cooling method is done by the means of heat transfer. As the air goes across a cooler medium or body, the air losses its heat by transferring it to the medium with a lower temperature. The high pressure fogging method on the other hand uses water particles that are sprayed toward the inlet of the gas turbine [3].

Using dry ice, the same method of heat transfer principle is being used, as discussed in Chapter 4.5. The figures below show the method of using dry ice as a cooling medium for the gas turbine. Notice the temperature could reach down until 12.1°C which is about 13°C difference from the ambient temperature.

Figure 15: Inlet Air Cooling Method

Figure 16: Inlet Air Temperature

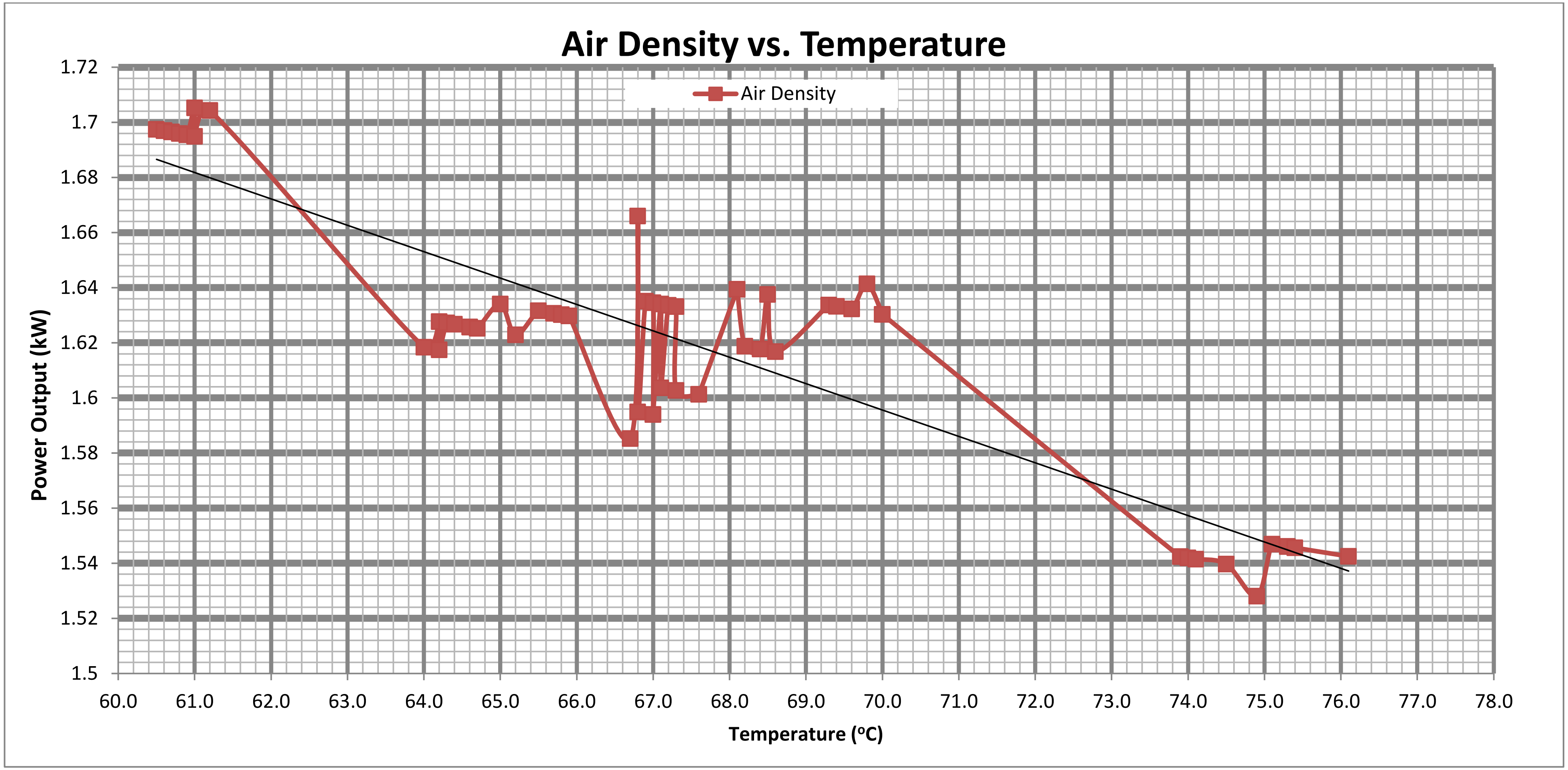
From the experiment done in Chapter 4.5, the following tables and graphs we obtained.

Table 4: Experimental Results of Air Inlet Cooling Method

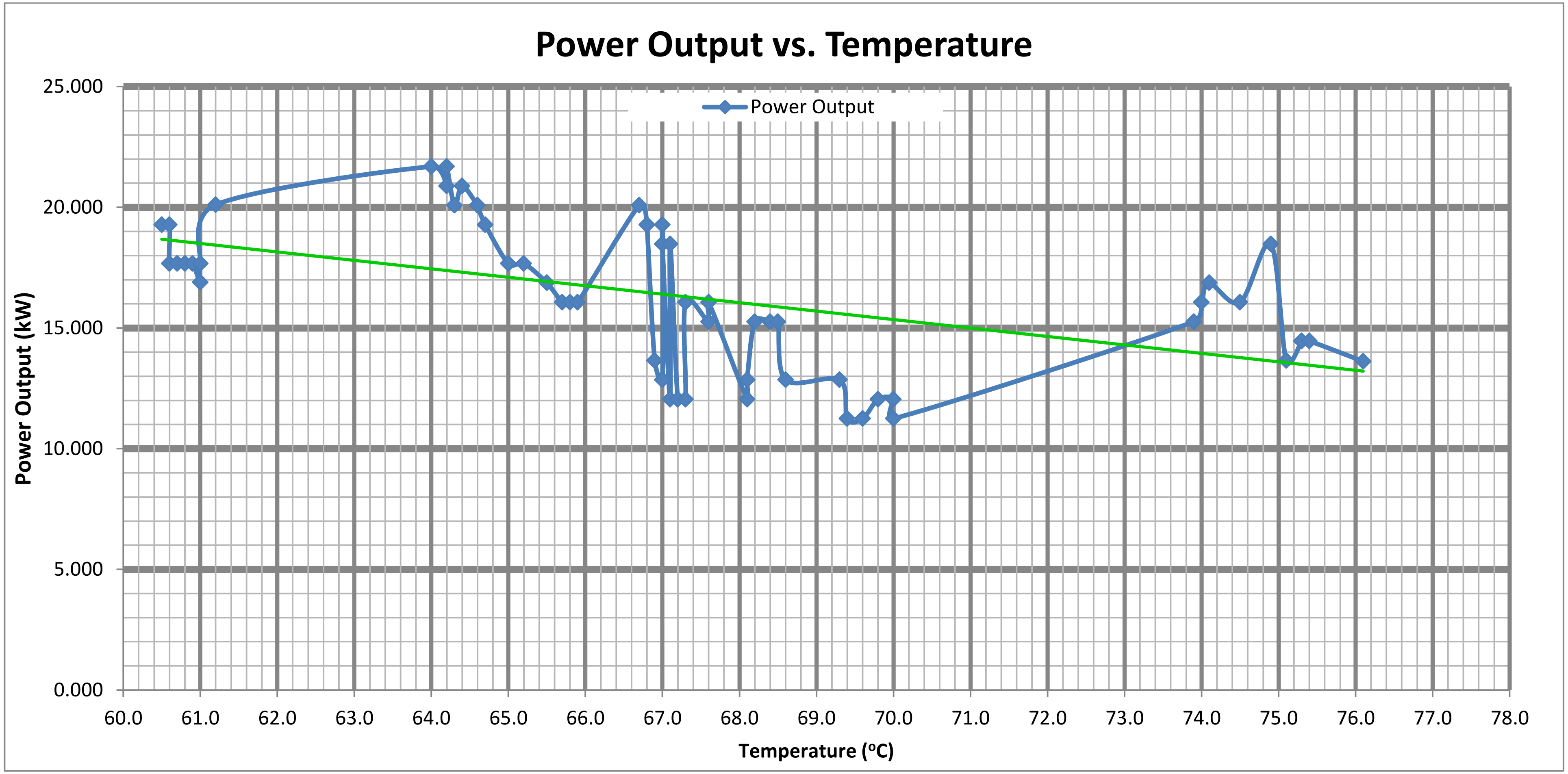
Air											Shaft Speed	Angular Speed	Torque	Power	Gas		Hydraulics Plant		Air Density
Temperature (^oC)					Pressure (kPa)						Rotational Speed (RPM)				Temp. (^oC)	Press. (kPa)	Temp. (^oC)	Press. (kPa)	kg/m3
T1	T2	T3	T4	T5	P1	P2	P3	P4	P5	Patm									
60.5	72.8	287.4	317.2	281.6	16.4	28.0	27.0	4.6	0.0	101.3	51730.0	767.0	0.240	19.277	28.2	235.0	42.8	347.0	1.69746
60.6	72.6	288.0	317.2	282.5	16.4	28.0	27.0	4.6	0.0	101.3	51820.0	767.0	0.240	19.277	28.4	235.0	43.1	344.0	1.696951
60.6	72.5	285.9	316.6	279.8	16.4	28.0	27.0	4.6	0.0	101.3	51650.0	767.0	0.220	17.670	28.1	235.0	42.3	34.9	1.696951
60.7	72.6	284.9	316.7	278.9	16.4	28.0	27.0	4.6	0.0	101.3	51620.0	767.0	0.220	17.670	28.1	234.0	41.9	351.0	1.696443
60.8	72.7	284.0	316.6	278.5	16.4	28.0	27.0	4.6	0.0	101.3	51590.0	767.0	0.220	17.670	28.2	235.0	41.7	352.0	1.695934
60.9	72.7	283.9	316.5	278.4	16.4	28.0	27.0	4.6	0.0	101.3	51590.0	767.0	0.220	17.670	28.1	235.0	41.7	352.0	1.695426
61.0	72.8	281.9	316.1	276.2	16.5	28.0	27.0	4.6	0.0	101.3	51520.0	768.0	0.210	16.889	28.1	234.0	41.3	354.0	1.705254
61.0	72.7	282.9	316.5	277.8	16.4	28.0	27.0	4.6	0.0	101.3	51590.0	767.0	0.220	17.670	28.1	235.0	41.6	353.0	1.694919
61.2	72.9	279.6	315.6	274.0	16.5	28.0	27.0	4.5	0.0	101.3	51440.0	768.0	0.250	20.106	27.9	234.0	40.9	35.9	1.704233
64.0	77.1	309.0	339.9	302.5	15.8	28.0	28.0	4.7	0.0	101.3	53360.0	767.0	0.270	21.686	30.2	234.0	45.1	329.0	1.618373
64.2	77.2	305.4	339.8	299.1	15.9	28.0	28.0	4.7	0.0	101.3	53310.0	767.0	0.260	20.883	30.2	234.0	44.1	335.0	1.62765
64.2	77.1	307.1	339.6	301.9	15.8	28.0	28.0	4.7	0.0	101.3	53310.0	767.0	0.270	21.686	30.2	234.0	44.6	331.0	1.617413
64.3	77.2	306.1	339.3	300.8	15.9	28.0	28.0	4.7	0.0	101.3	53360.0	767.0	0.250	20.080	30.3	234.0	44.5	333.0	1.627168
64.4	77.0	304.6	339.5	298.0	15.9	28.0	28.0	4.7	0.0	101.3	53250.0	767.0	0.260	20.883	30.2	234.0	43.5	337.0	1.626685
64.6	77.3	300.9	339.6	294.6	15.9	28.0	27.0	4.7	0.0	101.3	53140.0	767.0	0.250	20.080	29.9	234.0	43.1	342.0	1.625722
64.6	77.2	303.3	339.8	296.8	15.9	28.0	28.0	4.7	0.0	101.3	53230.0	767.0	0.250	20.080	30.1	234.0	43.5	33.8	1.625722
64.7	77.3	299.6	339.4	293.9	15.9	28.0	27.0	4.7	0.0	101.3	53110.0	767.0	0.240	19.277	29.0	234.0	42.9	343.0	1.62524
65.0	77.3	283.4	333.0	286.6	16.0	28.0	27.0	4.6	0.0	101.3	52620.0	767.0	0.220	17.670	29.8	234.0	42.0	34.8	1.63401
65.2	77.3	282.4	332.4	284.0	15.9	28.0	27.0	4.6	0.0	101.3	52560.0	767.0	0.220	17.670	29.8	234.0	41.7	351.0	1.622837
65.5	77.6	278.0	331.9	279.9	16.0	28.0	27.0	4.6	0.0	101.3	52410.0	767.0	0.210	16.867	29.8	234.0	40.9	356.0	1.631597

65.7	77.4	277.1	331.9	276.9	16.0	28.0	27.0	4.5	0.0	101.3	52380.0	767.0	0.200	16.064	29.8	234.0	40.6	359.0	1.630633
65.8	77.4	276.5	331.2	275.2	16.0	28.0	27.0	4.5	0.0	101.3	52320.0	767.0	0.200	16.064	29.8	234.0	40.4	361.0	1.630152
65.9	77.5	276.4	330.9	273.9	16.0	28.0	27.0	4.5	0.0	101.3	52300.0	767.0	0.200	16.064	29.8	234.0	40.3	362.0	1.629671
66.7	78.7	304.0	340.1	291.1	15.6	28.0	27.0	4.6	0.0	101.3	53280.0	767.0	0.250	20.080	31.1	233.0	44.6	339.0	1.585187
66.8	77.1	286.4	328.6	281.7	16.4	27.0	26.0	4.4	0.0	101.3	50950.0	767.0	0.240	19.277	24.4	237.0	39.0	368.0	1.665988
66.8	78.7	299.8	338.8	286.6	15.7	28.0	27.0	4.6	0.0	101.3	53150.0	767.0	0.240	19.277	31.1	233.0	43.9	343.0	1.594879
66.9	77.7	268.0	327.3	257.0	16.1	28.0	27.0	4.4	0.0	101.3	51880.0	767.0	0.170	13.654	29.9	234.0	39.0	375.0	1.635032
67.0	77.7	267.1	327.2	255.0	16.1	27.0	27.0	4.4	0.0	101.3	51840.0	767.0	0.160	12.851	29.8	234.0	38.9	376.0	1.634551
67.0	78.6	291.3	335.0	281.6	15.7	28.0	27.0	4.6	0.0	101.3	53070.0	767.0	0.240	19.277	31.1	233.0	43.7	344.0	1.593941
67.0	78.6	294.9	336.7	282.1	15.7	28.0	27.0	4.6	0.0	101.3	53100.0	767.0	0.230	18.474	31.1	233.0	43.8	344.0	1.593941
67.1	77.8	264.2	325.3	252.4	16.1	27.0	27.0	4.4	0.0	101.3	51780.0	767.0	0.150	12.048	29.7	233.0	38.8	378.0	1.63407
67.1	78.6	286.2	330.8	278.2	15.8	28.0	27.0	4.5	0.0	101.3	52690.0	767.0	0.230	18.474	31.1	233.0	43.1	346.0	1.603622
67.2	77.8	262.9	323.4	249.0	16.1	27.0	27.0	4.4	0.0	101.3	51710.0	767.0	0.150	12.048	29.8	233.0	38.6	380.0	1.63359
67.3	77.9	262.5	322.8	248.3	16.1	27.0	27.0	4.4	0.0	101.3	51720.0	767.0	0.150	12.048	29.8	233.0	38.6	380.0	1.63311
67.3	78.1	281.5	327.3	263.9	15.8	28.0	27.0	4.5	0.0	101.3	52450.0	767.0	0.200	16.064	31.0	232.0	43.3	353.0	1.602679
67.6	77.8	279.4	323.9	253.8	15.8	27.0	27.0	4.4	0.0	101.3	52300.0	767.0	0.190	15.261	31.0	232.0	43.4	356.0	1.601268
67.6	77.8	279.8	325.2	257.6	15.8	28.0	27.0	4.5	0.0	101.3	52350.0	767.0	0.200	16.064	31.0	232.0	43.3	354.0	1.601268
68.1	76.9	277.6	317.7	270.2	16.2	26.0	25.0	4.3	0.0	101.3	50340.0	767.0	0.150	12.048	26.9	235.0	39.8	365.0	1.6394
68.1	76.9	278.3	317.8	270.2	16.2	26.0	25.0	4.3	0.0	101.3	50350.0	767.0	0.160	12.851	26.9	235.0	39.9	364.0	1.6394
68.2	77.8	256.1	315.3	233.2	16.0	27.0	27.0	4.3	0.0	101.3	51970.0	767.0	0.190	15.261	29.7	233.0	38.3	391.0	1.618685
68.4	77.7	254.8	314.2	227.8	16.0	27.0	27.0	4.3	0.0	101.3	51910.0	767.0	0.190	15.261	29.7	233.0	38.2	392.0	1.617737
68.5	76.7	253.4	301.9	252.5	16.2	26.0	25.0	4.2	0.0	101.3	50110.0	767.0	0.190	15.261	26.7	235.0	38.6	378.0	1.637479
68.6	77.6	254.3	313.3	224.0	16.0	27.0	26.0	4.3	0.0	101.3	51860.0	767.0	0.160	12.851	29.7	233.0	38.2	393.0	1.61679
69.3	76.2	246.6	299.1	235.9	16.2	26.0	25.0	4.1	0.0	101.3	49720.0	767.0	0.160	12.851	26.6	235.0	37.2	394.0	1.633652
69.4	76.0	243.1	296.9	229.1	16.2	26.0	25.0	4.1	0.0	101.3	49570.0	767.0	0.140	11.245	26.6	235.0	36.5	399.0	1.633175
69.6	75.8	240.5	295.3	223.2	16.2	26.0	25.0	4.1	0.0	101.3	49440.0	767.0	0.140	11.245	26.6	235.0	36.1	402.0	1.632222

69.8	75.6	238.3	293.4	216.1	16.3	26.0	25.0	4.1	0.0	101.3	49300.0	767.0	0.150	12.048	26.6	235.0	35.8	406.0	1.641339
70.0	75.3	235.2	291.0	207.7	16.2	25.0	25.0	4.0	0.0	101.3	49150.0	767.0	0.150	12.048	26.5	235.0	35.5	410.0	1.630318
70.0	75.4	235.8	291.9	209.9	16.2	26.0	25.0	4.0	0.0	101.3	49200.0	767.0	0.140	11.245	26.5	235.0	35.6	408.0	1.630318
73.9	85.0	295.0	336.9	280.9	15.5	27.0	26.0	4.4	0.0	101.3	52950.0	767.0	0.190	15.261	29.8	233.0	41.7	360.0	1.542336
74.0	85.0	294.6	337.1	280.3	15.5	27.0	26.0	4.4	0.0	101.3	52920.0	767.0	0.200	16.064	29.8	233.0	41.7	360.0	1.541891
74.1	85.0	294.1	337.0	279.7	15.5	27.0	26.0	4.4	0.0	101.3	52890.0	767.0	0.210	16.867	29.7	233.0	41.7	360.0	1.541447
74.5	85.1	292.1	335.8	277.3	15.5	27.0	26.0	4.4	0.0	101.3	52790.0	767.0	0.200	16.064	29.7	233.0	41.4	361.0	1.539673
74.9	85.0	280.9	330.5	272.7	15.4	27.0	26.0	4.4	0.0	101.3	52740.0	767.0	0.230	18.474	29.6	233.0	41.2	365.0	1.52798
75.1	84.9	280.5	331.1	271.5	15.6	27.0	26.0	4.3	0.0	101.3	52330.0	767.0	0.170	13.654	29.6	233.0	41.2	364.0	1.546935
75.3	84.8	279.5	331.1	269.7	15.6	27.0	26.0	4.3	0.0	101.3	52280.0	767.0	0.180	14.458	29.6	233.0	41.1	365.0	1.546047
75.3	84.9	279.6	331.1	271.0	15.6	27.0	26.0	4.3	0.0	101.3	52280.0	767.0	0.180	14.458	29.6	233.0	41.1	365.0	1.546047
75.4	84.8	279.4	331.1	269.6	15.6	27.0	26.0	4.3	0.0	101.3	52290.0	767.0	0.180	14.458	29.6	233.0	41.0	365.0	1.545603
76.1	80.8	272.7	339.8	250.8	15.6	26.0	26.0	4.2	0.0	101.3	51700.0	765.0	0.170	13.619	29.6	233.0	40.6	370.0	1.542504



Graph 2: Air Density vs. Temperature



Graph 3: Power Output vs. Temperature

Graph 4: Inlet Air Cooling Method - Power Output vs. Temperature

From the data obtained and the graph plotted, it can be seen that by using dry ice to cool the inlet air the air temperature can be cooled down up to 60.5°C. Studying graph obtained, by taking the linear line, the author can calculate the drop in performance in term of power output of the gas turbine. It can also be seen that with the increase in air temperature the density of air tends to drop. This causes the cooler air to be denser and hotter air to be lighter. From the graph it is shown that at the temperature of 76.1°C, the air density is at 1.54 kg/m^3. While at the temperature of 60.5°C, the air density is at 1.68 kg/m^3. Relating this to the natural phenomena, the occurrence of the sea and land breeze happen due to the same principle. Cooler air which is denser, have a higher mass causing the increase in mass flow rate of the system. The author however was not able to verify this data as the instruments measuring the flow of air is not functioning well.

The graph also shows the augmentation of the power output of the gas turbine as the temperature decreases. From the graph, the power output can reach up until 21.6W when cooled. But at high temperature of about 75°C, the power output is only about 13.6W. This shows a difference in power output, hence verifying the fact that temperature does effects the performance of a gas turbine. The difference of 8W of power plays shows a huge improvement in performance. This is because different gas turbines operates at different ranges and have their own stated power output. If a small laboratory gas turbine shows an improvement of 8W, a normal gas turbine would simply amplify the amount of power augmented. This is in line with the findings from the study done by Ashley and Sarim, which states that an increase in the ambient temperature the decrease in power output is about 1.47MW, which is a substantial amount.

Studying the linear line of power output, the improvement with the decrease in temperature shows an augmentation of 2.41% of power output. Comparing this percentage increment of the power output with the study being done in Turkey by Hasan and Suleyman, it is in the range of power improvement percentage stated by them. Hasan and Suleyman states, the drop of power output per increase in degrees of temperature is about 0.37-7.59%. This shows the data obtain in this experiment is valid, and the method of using dry ice as a cooling medium is possible.

As discussed, the drop in power out as the temperature increases as mainly due to the drop of air density. This is because as the hot air is lighter, the lower the mass of air are passing through, causing the impact on the turbine to be less. On a contrary, should the air is cooler it becomes much denser. With the same amount of volume, the air is simply heavier compare to the hot air. This allows it to have larger impact when the colliding with the turbine face, causing a higher power output.

T1 Cooling vs Air Inlet Cooling

The option of cooling at T1 or at the air inlet was studied. Comparing the results in Chapter 4.4 and 4.5, the method used in Chapter 4.5 which is the air inlet cooling clearly shows that the range of temperature it can cause the ambient air to drop is much more wider, with a lower minimum temperature. When calculating the average at different points of the air filter, it is found that the air temperature drop until about 12.6°C. This symbolizes the ambient air temperature. The normal ambient temperature is the lab is about 24.8°C and when operating, the gas turbine T1 temperature at this condition is about 76°C. By cooling the air at the inlet, T1 temperature was reduced to 60.5°C, which shows a drop of about 15.5°C. This however was not able by using the method of cooling at T1, as seen in the graph in Chapter 4.4, the lowest temperature is at 68.1°C. Looking into the data obtained from that particular experiment, it can be said that the data might have some errors. This is because as the dry ice is being placed; T1 and T2 temperature reading should be decreasing as the cooling occurs after the first compression stage. But what the data shows is that the temperature at both point are almost constant, with the change in power output. This show there might be other factors causing the power to drop.

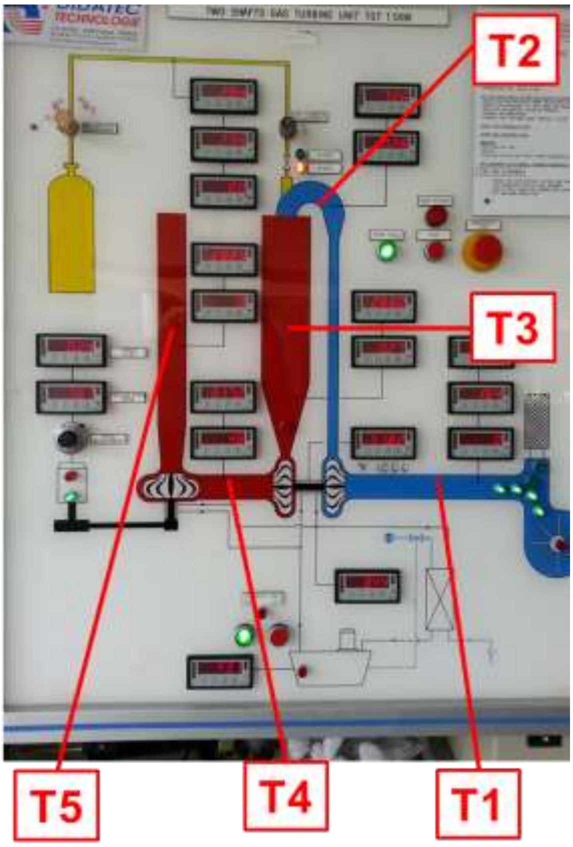


Figure 17: Position of Temperature Probes

Using Dry Ice

There is various method of cooling, and some of the methods are already available in the market known as Gas Turbine Inlet Air Cooling (GTIAC). As discussed in the literature review, some of these methods are more efficient at certain terrain, while the some are much cheaper relatively.

The use of dry ice as method of cooling has a few strong points that it should be considered as a real option of cooling method. Among the advantages of using dry ice are:

a) **Relatively cheap and easy to purchase**

   Comparing to other complicated and complex method of cooling, this method is relatively cheaper as it does not requires any mechanical equipment such as chillers that need to be purchase. CO_2 is abundant in the atmosphere, therefore to search for places that sells dry ice is as easy as searching the shops that supplies dry ice to ice-cream trucks.

b) **Have a high cooling energy**

Comparing to the normal ice or chillers, the cooling energy provided by a dry ice is higher, as it sublimates at the temperature of -78.9°C, while chillers can only supply chill water at most is above freezing temperatures.

c) **Does not leave any residues / water droplets on the gas turbine.**

Methods like high pressure fogging have a high risk of leaving water droplets in the compressor. This could cause a liquid carry over in the compressor, which could lead to faulty of the gas turbine or in long term, corrosion due to rust.

It is undeniable that dry ices are consumables as it sublimates. This means that over a period of time the dry ice will run out and need to be replaced. This actually is the main disadvantage of this cooling method compared to others. On the other hand, the fact that dry ice is consumable, it can be deploy and used when necessary only. Take absorption chiller for instance. The equipment producing chilled water need to run all day round to produce a certain amount of cooling energy. Dry ice has the advantage of instant cooling.

Consider the case of Univeristi Teknologi PETRONAS power usage and cooling load. The figure below shows the load profile for the university.

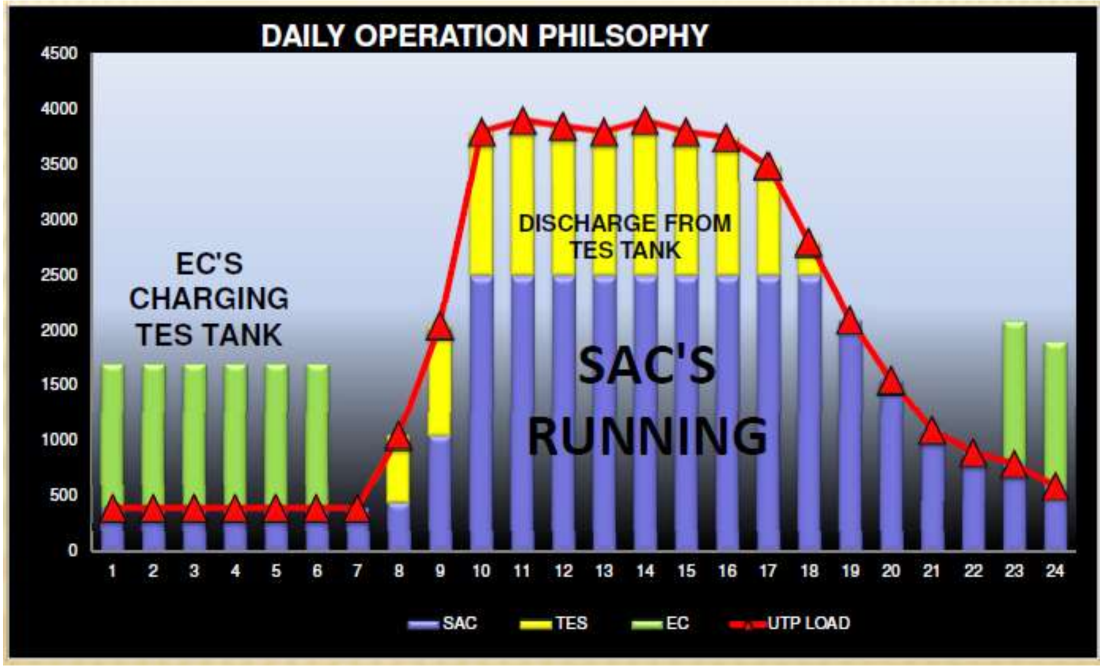


Figure 18: UTP Load Profile

From the figure, it can be said that the peak load is during the mid-day period of around 1200 hours until 1700 hours. Taking the fact, 3 kilograms of dry ice can last for about two hours; this requires about 12 kilograms of dry ice per day to cater the peak period. The cost of dry ice per kilogram is about RM 7, which means per day the operational cost to improve the gas turbine performance is only RM 84. This is much cheaper than operating a chiller system.

If the gas turbines can operate at its optimum performance in times of peak load, the power output would increase, yielding a better power efficiency and wasting less energy per fuel consumed.

CHAPTER 7: CONCLUSION

The project of studying the performance of gas turbine at various inlet air temperatures was a success as the finding of the project yields similar patterns of the studies being done at other locations around the world. When compared to the studies done in Turkey, Dubai and Iran, the finding of this project is within the range of power augmentation percentage of 0.37-7.59%, as the power increase obtained by this project was found to be at 2.41%, despite using another method of cooling.

There are possibilities of using dry ice as a mean of cooling, especially to cater for a certain period, like those peak periods during the mid-day. Methods of cooling that is cheap, safe and leaves no residues to the gas turbine should be explored; perhaps there are possibilities of using them in a larger scale. Gas turbines are very sensitive, especially towards foreign objects and liquids. These could cause faulty on the gas turbine and in some cases damaging it instantly. The use of dry ice which is solid carbon dioxide is relatively safe as it does not cause any water droplets to form which could lead to rusting and corrosion.

Among the recommendation the author has put forward is the study of cooling the inlet air by spraying liquid nitrogen. Liquid nitrogen has a much lower temperature compared to solid carbon dioxide. Spraying it, will only boils the liquid at a temperature below zero, causing it to cool down the air and particles around it. The technology of spraying liquid nitrogen has been use in the field of medicine, making the fact that it is not a new invention.

As fuel prices are rising and the electricity tariffs are getting more expensive, methods of enhancing the performance of gas turbine to produce electricity need to be looked into, to help save costs, whether the person is producing electricity which allows a larger margin of profit or even the purchasing electricity, which will help save cost.

CHAPTER 8: REFERENCE

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APPENDIX

EXPERIMENT REPORT

APPENDIX

1. INTRODUCTION

1.1. Abstract

The gas turbine TGT 1.5 kW unit is an experimental unit to study the operation of a gas turbine in a small, laboratory scale. This experiment was done to study the normal operating condition of the gas turbine, prior to making any modifications needed to bring the inlet air to a much lower temperature. As there are some limitations due to the condition of the equipment, the condition of air is the only conclusive result of this demonstrational experiment. To know the power output and the amount of torque output by the TGT 1.5 kW, the experiment need to be repeated with a belt connecting the turbine to the motor shaft.

1.2. Objectives

This experiment was done to meet the objectives below:

a) Identify the normal operating range for the Two Shaft Gas Turbine Unit TGT 1.5 KW
b) Study the procedure to operate the gas turbine unit.
c) Learn the precautious steps in operating the gas turbine.

1.3. Introduction to Gas Turbine

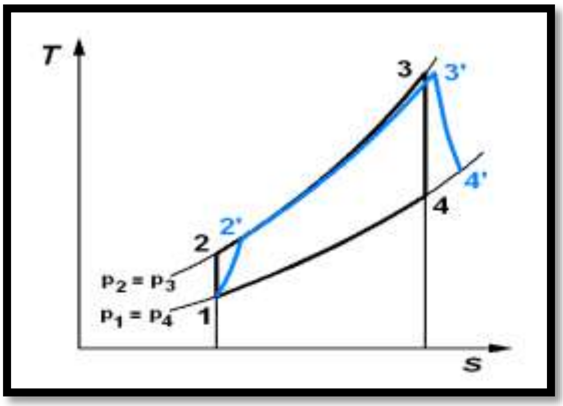
Gas turbines also known as a combustion turbine is a type a of internal combustion engine. It has an upstream compressor and a downstream compressor with ta combustion chamber In between. Powered by fuel of natural gas (or of the same gas composition), these type of internal combustion engine can produce a huge amount of power normally between 1.5 kW up to 50 MW. Gas turbines are often being used as a driver to run a generator set, compressor and also a pump.

The basic principle of a gas turbine as almost similar to the operation of a steam turbine except the medium is not steam but air. Fresh atmospheric air are filtered and enters the compressor of the gas turbine where is compressed to increase the pressure before entering the combustion chamber. In the combustion chamber, the air is heated to further increase the temperature and pressure. This high temperature and high pressure air is then used to drive the turbine part of the gas turbine.

2. THEORY

2.1. Basics of Gas Turbine

Engines are governed by the principles of thermodynamics and fluid mechanics. Just like the diesel engine which uses the principles of the Diesel-Cycle and the steam turbine with the principles of Rankine-Cycle, gas turbines are also being govern by a basic principle of the Brayton-Cycle.



Referring to the above T-s diagram of the Brayton-Cycle, the numbering shows the condition of the air at the point of on the gas turbine unit.

- Point 1, is the atmospheric temperature and pressure of the ambient air.
- Point 2, is the point after the compression stage.
- Point 3, is the point at the combustion chamber where the air is being heated.
- Point 4, is the point at the exhaust of the gas turbine.

The work being done is between 1 and 2, where work is needed to compress the atmospheric air. Heat is then being added by the combustion process in the combustion chamber which takes place between point 2 and 3. At constant pressure the air is heated to a higher temperature before entering the turbine. Between point 3 and 4, work is given out by the system as the hot and high pressure air drivers the turbine causing the shaft to rotate. The rotation of the turbine shaft is the output work by the gas turbine; hence a measuring point of power output is by measuring the rotation of the turbine.

2.2. Gas Turbine Components

Gas turbine has four basic components excluding the subsystem of the turbine – (1) compressor, (2) combustion chamber, (3) turbine and (4) exhaust. There are 2 type of energy being given out by a gas turbine; work and heat.

The compressor in a gas turbine is usually a multi-stage compressor, either axial or centrifugal. Every stage the blades of the compressor increase the pressure of the air creating a higher pressure output at point 2. The combustion chamber heats up the air, increasing the temperature to point 3, by the combustion of natural gas and air. By doing so it increases the amount of energy content in the air before it is used to run the turbines.

The turbines are attached to the shaft. Air at high temperature and high pressure, drives the turbine end of the gas turbine producing work. The hot air is then being directed to the exhaust of the gas turbine. In some cases of co-generation, the exhaust air of the gas turbine also known as flue gas, are re-used either for cooling purposes or even to generate steam like those used in the heat recovery steam generator (HRSG).

3. EXPERIMENTAL PROCEDURE

In order to test the normal operating condition and to the test the equipment functionality the follow procedures were done.

Start-up and Operating Procedures.

1. Make sure the Two Shaft Gas Turbine TGT 1.5 kW unit is in good condition.
2. Make sure there is ventilation and airflow by opening the door of the lab. Standby a fire extinguisher next to the gas turbine or the operator of the system as a precaution step.
3. Switch on the main power supply, open the tap water and switch on the compressor.
4. The TGT 1.5 kW unit needs a continuous supply of water to keep the hydraulics plant cool. The compressor is used to kick-start the compressor to run.
5. Attach the LPG tank using the hose and make sure it is fitted snugly.
6. Switch on the switch of the unit and make sure all the panels are lighted up with the initial reading.
7. Adjust the air inlet from the compressor and the amount of gas that enters the gas turbine.
8. Make sure the pressure of the gas inlet is about 1 Bar, and the hydraulic plant is flowing.
9. Press the manual restart button. The gas turbine will starts itself once the condition is right and start operating.
10. Adjust the air inlet and the amount of gas, to obtain a steady combustion in the combustion chamber by observing the type of fire.
11. Once the combustion is stable, record all the readings on the panel.
12. Make sure the gas turbine does not operate for more than 15 minutes, to avoid overheating or and problem to the gas turbine unit.
13. Shutdown the unit by following the shutdown procedures.
14. Repeat steps 6 to 12, three times minimum to obtain the average operating condition for the TGT 1.5 kW unit.

Shutdown Procedures

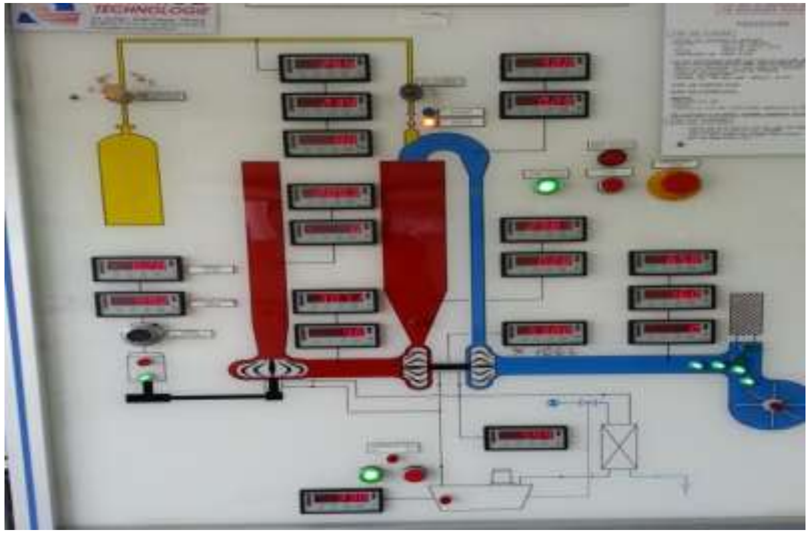
1. Make sure the unit does not run for more than 15 minutes.

2. Shutdown by increasing the amount of air intake to the gas turbine, which will put off the flame and starts to cools down the unit. (Notice the “manual restart” button is lighted up again)
3. Make sure the shaft speed of the centre reaches zero.
4. Leave the hydraulic plant to run for about 10 minutes to cool down the compressor and turbine of the gas turbine.
5. Once the temperature has reached a normal range switch off the TGT 1.5 kW unit by pressing the “STOP” button.
6. Switch off the air compressor followed by the main power supply. Then close the water tap.

Close the doors of the lab and do housekeeping; make sure the area is clean.

4. DATA COLLECTION & RESULTS

	Air											Shaft Speed	Gas		Hydraulics Plant	
	Temperature (^{o}C)					Pressure (kPa)						Rotational Speed (RPM)	Temperature (^{o}C)	Pressure (kPa)	Temperature (^{o}C)	Pressure (kPa)
	T1	T2	T3	T4	T5	P1	P2	P3	P4	P5	Patm					
Initial (R$_i$)	28.8	30.4	41.8	43.1	29.2	-0.2	0.0	0.0	0.0	0.0	101.3	0.0	25.1	140.0	30.4	461.0
Run 1 (R$_1$)	76.0	86.5	288.0	341.2	281.0	15.5	29.0	29.0	4.8	0.0	101.3	56520.0	25.8	235.0	37.7	400.0
Run 2 (R$_2$)	65.5	74.6	245.0	301.8	250.0	16.4	26.0	26.0	4.6	0.0	101.3	50430.0	25.6	236.0	38.2	399.0
Run 3 (R$_3$)	67.2	76.7	286.9	332.5	282.6	16.4	27.0	26.0	4.9	0.0	101.3	56550.0	26.0	235.0	42.3	375.0
Run 4 (R$_4$)	70.4	79.7	265.8	324.9	269.0	16.2	26.0	25.0	4.4	0.0	101.3	49990.0	28.0	234.0	41.2	388.0
Mean (R$_{ave}$)	69.8	79.4	271.4	325.1	270.7	16.1	27.0	26.5	4.7	0.0	101.3	53372.5	26.4	235.0	39.9	390.5



5. DISCUSSION

5.1. Safety Precautions

The result in section 4 shows the operating point of the gas turbine TGT 1.5 kW unit. The procedures taken include the precautious steps for any hazards. Ventilation and a continuous air flow is required to ensure the exhaust gas is being released outside and not trapping which might have any health side effects to personnel inside the lab, as the exhaust gas releases carbon dioxide and carbon monoxide due to combustion.

Gas turbine is a combustion engine, which means there is the usage of fire. For safety purposes a fire extinguisher is needed to be on standby should anything happens. This is because the gas turbine unit is using fire and two LPG tanks which are flammable. Other precautious steps include checking the fitting of the gas hose and also the supply of continuous water.

5.2. Experimental Discussion

This particular unit of TGT 1.5 kW gas turbine has a slight problem with the controls of the gas inlet and the air inlet. The gas turbine supposed to disengage from the compressor and should be using the direct air from the atmosphere via the top filter. Hence the speed of the turbine should determine amount of air inlet. Unfortunately for this unit the amount of air entering is being regulated by adjusting the opening on the outlet of the compressor. The opening should not be open fully nor shut fully. The gas control on the panel is experiencing some problem, so the method of regulating the gas flow is by adjusting the amount of gas via the knob at the back of the panel.

The amount of gas and air should be controlled and adjusted to make sure the stoichiometric value is met. Should the amount of either gas be more, there will be a waste of gas, and there will be incomplete combustion, causing the flame to be unstable or even change to become more reddish. If the amount of air is more the flame will be put out. Thus the right amount should be set by observing the condition of the flame.

The experiment was repeated at least thrice and the average of all the readings was taken. This was done as there are fluctuations throughout the readings of all the parameters – temperature, pressure, and shaft speed. The measurement of the torque output and the output rotational speed cannot be measured due the broken belt that is attached to the motor.

In the experiment the numbers indicate the point at where the temperature probe and pressure gauge are placed.

- Point 1 – T1, P1 – The air temperature and pressure after first stage of compression.
- Point 2 – T2, P2 – The air condition after the compression stage.
- Point 3 – T3, P3 – The condition at the combustion chamber
- Point 4 – T4, P4 – The air condition after the turbine
- Point 5 – T5, P5 –Air condition at the exhaust.

As the reading of the flowrate of the air intake cannot be taken due to instrumentation problem, and the air inlet is via the compressor, the gas turbine is to be considered as having a two stage compressor. Thus, at point 1, the condition of air is after the first stage of compression. The gas turbine also has two stages of turbine, which the first stage is used to run the second stage compressor. While the second stage turbine is used to run the motor for the power output.

6. CONCLUSION

The experiment was done as a demonstration to test the TGT 1.5 kW unit operability and to test the normal operating condition to be compared before any modifications are done to the gas turbine unit. The normal operating condition taken the inlet air is the lab temperature of 25^{o}C and at the atmospheric pressure of 1 atm (101.325 kPa), the compressor shaft and the first stage turbine speed is at an average of 53372.5 RPM.

This experiment can only show the average operating conditions of the air at each point, but the amount of power output is inconclusive. The experiment will need to be repeated once the belt attaching the turbine to the motor is available. From there, we can calculate the power output as the torque and speed at the motor will be knows by the indicating panel.

GAS TURBINE CONTROL CONDITION TEST
30 MAY 2013
MOHAMMAD IZZAT B MOHD SALEH

Problem Statement

- Temperature affects the density of air, ergo affects the performance of a gas turbine. What is the normal operating condition of the gas turbine before being affected by air temperature?

Objectives

- The experiment was conducted with the objectives of
    - To study normal operating condition of the gas turbine to be used as a control

Theory / Background

GAS TURBINE

Gas turbine which is considered as one of the forms of internal combustion engines (ICE) operates with the principles of Brayton Cycle. It consists of 4 main parts – compressor, combustion chamber, turbine and exhaust. Gas turbine uses the atmospheric air as a medium to generate energy. The atmospheric air is being compressed to increase the pressure, before undergoing combustion to further increase the pressure. This high pressure air will then cause the turbine to turn, producing energy as the shaft spins. The hot air will then be channelled out through the exhaust and in some cases the hot air is being reused to create a cogeneration system.

The performance of gas turbines are usually being tested and monitored in two methods – thermal efficiency and gas turbine power output. Depending on the operating conditions and the design parameters of a gas turbine, different size of gas turbines has different range of power output.

Controlled Parameters

- Angular Speed of motor = 767 rpm
- Atmospheric conditions
    - Temperature = 25^{o}C
    - Pressure = 101.325 kPa

GAS TURBINE CONTROL CONDITION TEST
30 MAY 2013
MOHAMMAD IZZAT B MOHD SALEH

Procedure

1. Prepare the following apparatus:
    - TGT 1.5 kW Gas turbine
2. Switch on the main power supply, the assisting compressor and open the tap to make sure there is a running water for the hydraulics plant
3. Make sure the gas piping is fitted snugly, and check for any leakages.
4. The opening for the compressor and the gas inlet is set to the third level and the sixth level respectively.
5. Press the “Manual Start” button, and wait for the gas turbine to run and ignite.
6. The flame ignition is observed and the air inlet opening for the compressor is adjusted to obtain a stable ignition.
7. Record the temperature, pressure, shaft rpm and the torque readings on the digital readings.
8. Steps 4 to 7 are repeated thrice to obtain an average reading of each position.
9. All the readings are being recorded into an excel sheet and the average is being calculated. The rough plot for the temperature rise is being plot in a graph.

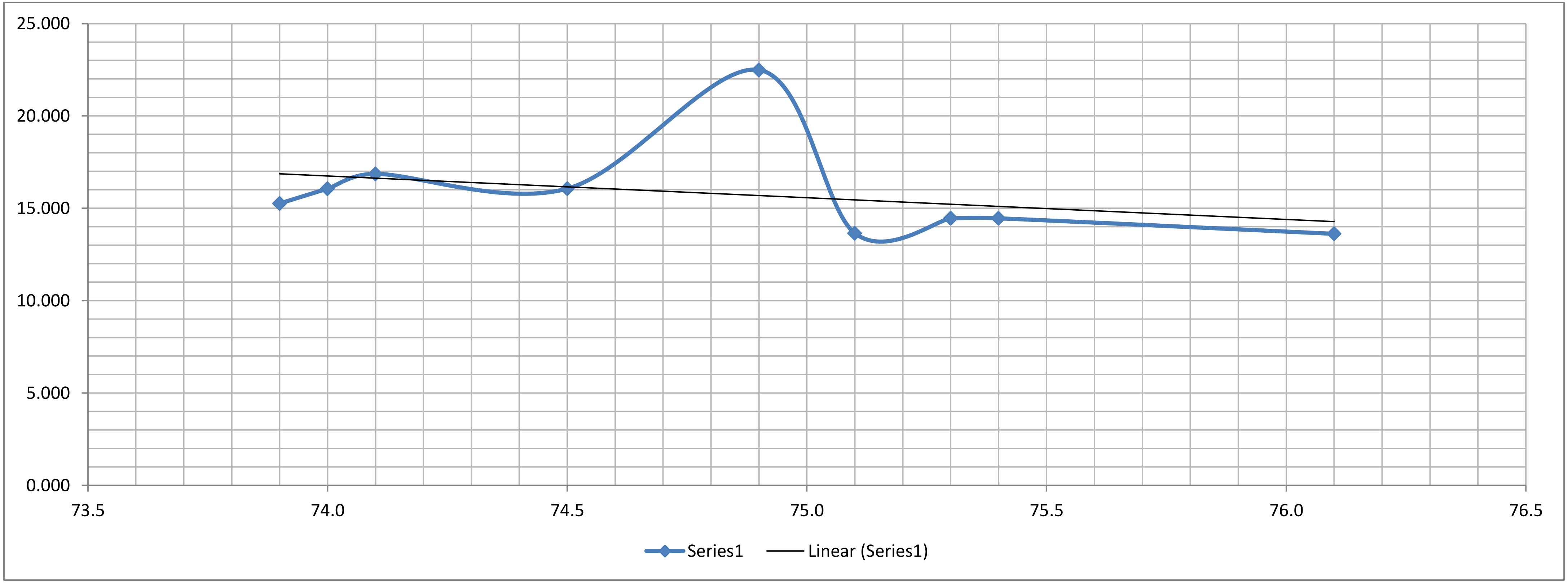
Results

From the experiment, the follow results we obtained:

	Air											Shaft Speed	Angular Speed	Torque	Power	Gas		Hydraulics Plant	
	Temperature (^{o}C)					Pressure (kPa)						Rotational Speed (RPM)	Rotational Speed (RPM)	(Nm)	Watts (W)	Temp. (^{o}C)	Press. (kPa)	Temp. (^{o}C)	Press. (kPa)
	T1	T2	T3	T4	T5	P1	P2	P3	P4	P5	Patm								
Initial (R_i)	69.3	69.2	78.6	66.5	70.5	17.0	15.0	16.0	2.3	0.0	101.3	31900.0	570.0	-0.300	-17.907	26.5	238.0	36.8	427.0
Run 1 (R_1)	73.9	85.0	295.0	336.9	280.9	15.5	27.0	26.0	4.4	0.0	101.3	52950.0	767.0	0.190	15.261	29.8	233.0	41.7	360.0
Run 2 (R_2)	74.0	85.0	294.6	337.1	280.3	15.5	27.0	26.0	4.4	0.0	101.3	52920.0	767.0	0.200	16.064	29.8	233.0	41.7	360.0
Run 3 (R_3)	74.1	85.0	294.1	337.0	279.7	15.5	27.0	26.0	4.4	0.0	101.3	52890.0	767.0	0.210	16.867	29.7	233.0	41.7	360.0
Run 4 (R_4)	74.5	85.1	292.1	335.8	277.3	15.5	27.0	26.0	4.4	0.0	101.3	52790.0	767.0	0.200	16.064	29.7	233.0	41.4	361.0
Run 5 (R5)	74.9	85.0	280.9	330.5	272.7	15.4	27.0	26.0	4.4	0.0	101.3	52740.0	767.0	0.280	22.490	29.6	233.0	41.2	365.0
Run 6 (R6)	75.1	84.9	280.5	331.1	271.5	15.6	27.0	26.0	4.3	0.0	101.3	52330.0	767.0	0.170	13.654	29.6	233.0	41.2	364.0
Run 7 (R7)	75.3	84.8	279.5	331.1	269.7	15.6	27.0	26.0	4.3	0.0	101.3	52280.0	767.0	0.180	14.458	29.6	233.0	41.1	365.0
Run 8 (R8)	75.3	84.9	279.6	331.1	271.0	15.6	27.0	26.0	4.3	0.0	101.3	52280.0	767.0	0.180	14.458	29.6	233.0	41.1	365.0
Run 9 (R9)	75.4	84.8	279.4	331.1	269.6	15.6	27.0	26.0	4.3	0.0	101.3	52290.0	767.0	0.180	14.458	29.6	233.0	41.0	365.0
Run 10 (R10)	76.1	80.8	272.7	339.8	250.8	15.6	26.0	26.0	4.2	0.0	101.3	51700.0	765.0	0.170	13.619	29.6	233.0	40.6	370.0
Mean (R_{ave})	**74.9**	**84.5**	**284.8**	**334.2**	**272.4**	**15.5**	**26.9**	**26.0**	**4.3**	**0.0**	**101.3**	**52517.0**	**766.8**	**0.2**	**15.739**	**29.7**	**233.0**	**41.3**	**363.5**

	GAS TURBINE CONTROL CONDITION TEST **30 MAY 2013** *MOHAMMAD IZZAT B MOHD SALEH*	

Graph



Discussion

From the result of the experiment, it is found that the power output of the gas turbine varies and is increasing with the number of times the experiment is being run. One of the main factors, is the fact that, the compressor is running longer causes the compressor to heat up, although the rise is only about 1°C at P1. Hence to get a better consistent reading the experiment need to be done repeated times and the average of the temperature and the pressure at each point is calculated.

As the gas turbine is placed in the lab, the environment is controlled, making our initial air inlet temperature and pressure to be at 25°C and 101.32 kPa respectively. With the atmospheric condition being controlled and the shaft speed of the motor is being set as a constant at around 52500 rpm, the torque that the gas turbine produces is directly proportional to the air temperature. Using the ideal gas law which states:

$$PV = \frac{m}{M}RT$$

Where: P = *Pressure (Pa)*

V = *Volume (m^3)*

m = *mass (grams)*

M = *Molar mass (grams per mole)*

T = *Temperature (Kelvin)*

Assuming a fixed volume within the piping internals, the volume and mass will be a fixed through P1 and P2 section. Taking the average of the reading of P1 and P2 as a base for the ideal gas equation, we will get the following equation.

$P_{1,ave} = 15500\ Pa$ $P_{2,ave} = 26900\ Pa$ $P_{ave} = \frac{15500+26900}{2} = 21200\ Pa$

$$T_{1,ave} = 347.9\ K \qquad T_{2,ave} = 357.5\ K \qquad T_{ave} = \frac{347.9 + 357.5}{2} = 352.7\ K$$

$$V = Ah = \pi r^2 h = \pi(0.11)^2(0.2) = 7.6027\ e^{-3}\ m^3$$

$$PV = \frac{m}{M} RT$$

$$(21200)(7.6027\ e^{-3}) = \frac{m}{28.97}(8.314)(352.7)$$

$$\boldsymbol{m = 1.592\ e^{-3} kg}$$

Thus the mass of air is known to be at 1.592 e^{-3} kg, which can be a basis to calculate the mass and volume of air at a certain point in the pipe. This value of mass will allow us to calculate the density of air.

Temperature affects air density, as the temperature rises the less dense the air will be. At a lower temperature where the air is much denser, the gas turbine is said to be performing better. This is due to the fact that more energy is being transferred to the turbine, hence producing more power output.

Conclusion

The experiment met its objective, as we were able to obtain the normal operating condition of the gas turbine. Taken the average from 10 readings allows us to get a precise reading of the normal operating condition of the gas turbine at the shaft speed of 52500 rpm. An added value from conducting this experiment is the fact that we can see the preliminary results from the effects of air temperature towards the performance of the gas turbine, as plotted in the graph.