EFFECTS OF PRESSURE ON STEAM TURBINE PERFORMANCE IN A SMALL SCALE POWER PLANT

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EFFECTS OF PRESSURE ON STEAM TURBINE PERFORMANCE IN A SMALL SCALE POWER PLANT

ABSTRACT

Power plant consists of 4 main components that determine the efficiency of the whole system. Each component has its own function and there are always room for improvements to increase the efficiency. Advancing the procedure of working condition of power plant impressively enhanced the turbine power output, in which simultaneously reduce the energy consumption. The industrial sector being the biggest player in power plant usage, constantly seeking improvisation and effectiveness of the power plant operation. With the present market trend of continuous rising of fuel and energy prices, reducing the energy requirement has become a top objective. Every minor or major changes in power plant system greatly affect the output. The main objective of this study was to vary the boiler pressure plus turbine pressure and study the efficiency of the steam turbine power output. Therefore, modification and changes were done for the operating conditions of boiler pressure and turbine pressure which influenced the power plant turbine performance significantly. Energy balance of the plant was analysed in the experiment by varying aforesaid parameters. Detailed calculation and analysis had been done for each sets of experiment outcome. Increasing these parameters value influences the steam utilization in the turbines and further increased the turbine effectiveness. The examination done shows that increasing boiler pressure and turbine pressure enhance the power yield of the turbine, efficiency and effectiveness in regular steam control plants. In the end of thesis, the experiment had been conducted successfully and some recommendation had been identified for future research and development.

Keywords: Steam Turbine Power Plant, Boiler, Turbine, Pressure, Power Output.

KESAN TEKANAN TERHADAP PRESTASI TURBIN STIM DALAM LOJI JANAKUASA SKALA KECIL

ABSTRAK

Loji janakuasa terdiri daripada 4 komponen utama yang menentukan kecekapan seluruh sistem. Setiap komponen mempunyai fungsi tersendiri dan sentiasa ada ruang untuk penambahbaikan bagi meningkatkan kecekapan. Memajukan prosedur keadaan kerja loji janakuasa mampu meningkatkan pengeluaran kuasa turbin dan pada masa yang sama mengurangkan penggunaan tenaga. Sektor industri sentiasa mencari cara penambahbaikan dan keberkesanan operasi loji janakuasa disebabkan mereka merupakan pengguna utama loji janakuasa. Tambahan pula dengan trend pasaran semasa bagi bahan api dan tenaga yang sentiasa meningkat, mengurangkan penggunaan tenaga menjadi objektif utama. Setiap perubahan sama ada yang kecil atau besar memberi impak yang besar terhadap penghasilan tenaga. Objektif utama kajian ini adalah untuk mengkaji pengubahan tekanan dandang dan tekanan turbin terhadap kecekapan penghasilan kuasa turbin stim. Oleh itu, pengubahan dilakukan pada keadaan operasi tekanan dandang dan tekanan turbin yang mempengaruhi prestasi turbin loji janakuasa. Imbangan tenaga dikaji dengan mengubah faktor manipulasi tersebut. Pengiraan dan analisis terperinci dilakukan pada setiap set hasil eksperimen. Peningkatan nilai kedua-dua tekanan mempengaruhi penggunaan stim di turbin dan seterusnya meningkatkan keberkesanan turbin. Hasil eksperimen ini menunjukkan bahawa tekanan dandang dan tekanan turbin yang semakin menaik akan meningkatkan tenaga turbin, kecekapan dan keberkesanan loji janakuasa stim. Akhirnya, eksperimen telah dijalankan dengan jayanya serta beberapa cadangan telah dikenal pasti untuk penyelidikan dan pembangunan pada masa hadapan.

Kata kunci: Loji Janakuasa Turbin Stim, Dandang, Turbin, Tekanan, Hasil Tenaga.

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LIST OF SYMBOLS AND ABBREVIATIONS

P	:	Pressure
T	:	Temperature
η	:	Efficiency
P	:	Power output rate
h	:	Mass specific enthalpy
m	:	Mass
W	:	Work done
s	:	Entropy
Q	:	Heat absorbed or released
W	:	Watt
J	:	Joule
kg	:	kilogram
ρ	:	Density
TNB	:	Tenaga Nasional Berhad
Int.rev	:	Internally reversible
CCGT	:	Combined Cycle Gas Turbine
HRSG	:	Heat Recovery Steam Generator
RPM	:	Rotation per minute

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CHAPTER 1: INTRODUCTION

1.1 Project Background

Candles would be the only item fast selling in a grocery shop if electric utility company in Peninsular Malaysia known as Tenaga Nasional Malaysia (TNB) announce there would be power supply cut-off on any particular area be it for maintenance or any other reason. Electricity/power and water has become such an important element in our daily lives and a day being without either one of it would make our life so unbearable. Our younger generation especially, have been used to having electricity and water without any disruption and even 1 hour disruption would cause a major haywire in our daily live routines. Dating back to 1800s, our ancestors used to pump the water from well and light up lamp only during the required time to avoid wastage of oil. Then there's a period where water and power being supplied by the authority on daily basis but with time restriction whereby they would only supply on specific time. Focusing on electricity and precisely, without electricity our life would be a total mess and hassle.

Electricity is produced in the electricity generating stations called the power plant. It is mainly working on turbine and since ages steam has been the medium as conveying energy. To name it, there are many type of power plant such as thermal, nuclear, hydraulic, gas and fossil fuel. Among everything that available, steam power plant use to be the one commonly used as it is much more conventional and electricity production can be expected in large scale. Being the most sought after, studies for steam power plant has never stopped to improvise the power output and reduce the cost consumption. Dating the existence of power plant goes back to 1880s where a fossil fueled power plant been started using for supplying electricity. It was a very simple mechanism at that period which only able to be delivered over short distance and been used for street lighting. Until today, new invention in the development of power plant being continually researched to improve the unit performance. Comparing from those days to today, power plant have advanced beyond our imagination. It has been easy to be operated and more importantly analyzing the energy of a power plant have made everyone's life easy.

1.2 Problem Statement

The work is related to energy analyses and therefore utilizing the steam power plant would be the best option in using it as an experiment apparatus and tools. Power output of a steam power plant have never achieved efficiency of more than 80%. The research to improve the efficiency have been continually carried out from time to time and its enhancement can be achieved by analyzing every components and manipulating the parameter to achieve a desired power output. A steam power plant has 4 main components; the boiler, turbine, condenser and pump. These components have variable parameter and analyse of the energy balance on the system will result the best performance of a particular plant. In order to do that, it is very important to explore the first and second law of thermodynamics and translate them into practicality.

1.3 Project Objective

Theoretically, the optimum performance on energy balance of a steam power plant can be easily carried out by manipulating the pressure value on both boiler. Precisely, the efficiency of the steam power plant can be analyzed with the following main objective;

1. Investigation on the effect of pressure variation on the performance of a steam turbine power plant.

2. Measurement and analyses of pressure during the power plant operation.

3. Validation of the factors that affecting the steam turbine performance.

1.4 Project Scope

Utilizing the STEM ISI IMPIANTI 3-kW experimental power plant at Thermal-hydraulic laboratory, Faculty of Engineering, University of Malaya experiments were performed to study the effects of pressure on steam power plant. Therefore a complete studies have been carried out on the energy balance of the system and the functionality of steam power plant. A complete and thorough studies have been conducted on Rankine cycle and other basic principle of working system of the steam power plant. Components of a steam power plants were also analyzed in detail in order to avoid any error and unnecessary factors that may compromise the results. Every parameter involves with the components and the power plant were operated correctly using the 'manual operating book'. The first law of thermodynamic has been studied in detail to analyse the equation for the energy balance and to conduct analyses for energy relationships involved in each components.(Balmer, 2011a) Data were collected completely and analyses on energy balance were carried out analytically to obtain the relationship of energy balance of this steam power plant.

Figure 1.1: STEM ISI IMPIANTI 3-kW

CHAPTER 2: LITERATURE REVIEW

Power station or in another word referred to as power generating station are the industrial facility made use of for the purpose of electric power generation. The electric power normally generated and distributed in both small scale range of 100MW to 500MW and mass scale of more than 500MW as well. The usual targeted location are the sub-urban regions or the place far from main town due to the requisites like huge land and water demand. Usually huge power stations would have one or more generators which converts the mechanical power to electrical power. As it is known, the relative motion between conductor and magnetic field creates the electrical source. Looking from a bigger scope, power plants could be in different forms as follows: (a) Geo-thermal, (b) Hydraulic, (c) Gas turbine, (d) Thermal and (e) Nuclear. Furthermore, Power plants of Thermal, geo-thermal, and nuclear sources uses steam as their fluid for working and those plants have a lot of likeliness with respect to their structure as well as cycle. Gas turbine plants are often used as peaking units and combine cycle as well.(Kehlhofer, Hannemann, Rukes, & Stirnimann, 2009) This is because they run just for limited time-periods of the day in order to satisfy the demand of the peak load. However, they are being increasingly used in conjunction with a bottoming steam plant in the mode of combined cycle power generation. Other than that, we too have hydraulic power plant which has multipurpose such cater for irrigation, afforestation, flood control, fisheries, navigation, etc. on the downside note, they are expensive and take long time to build. In other hand, geothermal power plant can only be built in certain geographical locations.

Among other power plant, thermal-based power plant generates beyond 80% of the overall electricity produced globally. Some of the energy source for the thermal power plant are coal, fuel oil, fossil fuel and natural gas while steam are the working fluid. Besides that, steam is also required in many industries for the purpose of heat processing. For the purpose of meeting the combined necessities for heat processing as well as power, cogeneration plants are mostly installed. (16.1 Sasaki & Hisa, 2003)

2.1 History of Power Plant

The supply of electricity by the fueled fossil power-plants for the purpose of industrial usage can be backdated from the 1870s whereby initially easy-to-use D.C. generators were coupled together into piston steam engines that were reciprocating and coal-fired. Primarily, electricity was used for essence of providing light in the districts and relatively delivered over short distances. However, the initial ever-existent central stations for generation was pioneered in September 1880 at Pearl Street, Manhattan, New York City by Thomas Edison. Due to the usage of electricity only for lighting alone, it couldn't offer a market that was economical for the successive generations, which hence led to the necessity of discovering new electricity applications. As more popularity began to arise for the electric tramways at urban areas, this led to the subway system's electric traction adoption which was in coincidence with the extensive spread in latter parts of 1880s and 1890s, of the generating equipment's construction.(Casella & Leva, 2003)

In early stage, power plant boiler designs using the coal or coal gas supply led to the generation of steam in an easy-to-use tube for boiling water which typically operated at 0.9MPa (9 bar) and 150 ˚C (300 ˚F) and could have been in connection with a generator of 30kW. Since that period, there have been evolvement of into a system of more complexity by the typical power plant's topography. In contemporary times, boiler designs as well as turbine designs makes use of newly-made metallic alloys that has the capability of operating at super-crucial conditions of 28.5 MPa (285bar) at a temperature of 600˚C (1112˚F), thereby leading to an electricity generation of 1300MW.

However, in order to reduce the operating costs, there have been advances in the design of plants from units generation based on Rankine Cycle wherein it normally could achieve a 30-40% range of thermal efficiency. Nowadays, combined cycle gas turbine (CCGT) units making use of the latest heat recovery steam generator (HRSG) plant can achieve efficiency up to 50-70%. Locally, about 67% of efficiency is achieved by TNB's Tunku Jaafar Power Plant in Port Dickson. Other than that, the exclusion of the limitations of the European Community with regards to the burning of gas to generate power, coupled with other factors, has led to the units of the CCGT being deployed increasingly. Besides that, different current plant may now appear in which the core principles for distributing and generating have been put into mastery as of the end of the 19th century. In the new era, the evolution of the design of power-plants has been largely incremental mainly driven by the new technology.(Achilli, Cath, & Childress, 2009)

In the previous thirty years, we have seen the equipment used for micro-processing being integrated into every facet for both distributing and generating whereas in the coming 20 years we should see the technology develop further whereby bringing in applications that are of pseudo-intelligence and which can definitely lead to the harnessing of the rapid expansion of the power for computation. Other than that, computer-based systems that are newly developed will as well lead to the increase in the automation of the plant, enhance control of units, and allow additional flexibility in the operation of plants as well as concurrently aid in maximizing unit efficiency and reducing harmful emissions. In order to improve the unit emissions, better means of developing designs of plants are continuously sought off until now.(Tschoegl, 2000b)

2.2 Thermal Power Station

It is important to state that a thermal-based power plant that is coal-fired or a thermal-based power station, to a large extent, is the mostly used conventional approach of generating power in electricity with a high efficiency that is reasonable. For example, coal is being used by it as the essential supply of fuel for purpose of boiling the available water to s stream that is super-heated in order to drive the turbine of the stream. Other than coal as fuel supply, fuel oil, natural gas and fossil fuel are also widely being used to boil the water. Then, there is a mechanical coupling of the turbine steam to a rotor alternator whereas this will lead the rotation into generating electric power. India in general, makes use of brown or bituminous coal in replacement of the fuel boiler which consists of a content that is volatile with ranges from 8-13% as well as a 5-16% content of ash. However, for purpose of the plant's thermal efficiency enhancement, coal is therefore made use of in the powdered or pulverized form.(Flynn, 2003)

Furthermore, steam is gotten inside the boiler of the steam at quite a high pressure, with regards to a thermal power-plant that is coal fired through the pulverized coal been burnt. Next, in order to attain a temperature that is highly extreme, there is need for the super-heater to super heat the steam. Permission is then given to the steam that has been super-heated to have entrance to the turbine wherein the blade of the turbine will undergo rotation through the steam's pressure.(Ersayin & Ozgener, 2015) As stated earlier, mechanically coupled turbine with alternator is done in order to ensure that the rotor rotates with the blades of the turbine's rotation. Subsequently after the turbine has gone through, there is a sudden fall by the pressure of the steam which eventually leads to the steam's volume decreased correspondingly. Also, after energy has been transferred to the rotors of the turbine, it allows the steam to pass through the blades of the turbine into turbines' condenser steam. However, there is a circulation, with the aid of the pump of cold water at the ambient temperature which eventually results to the wet steam's low pressure being condensed.

There were an additional supply of the condensed water into a water heater of lower pressure wherein an increase in the feed water temperature occurs due to the lower pressure steam, and the high pressure is heated again. This therefore gives an outline of a thermal-based power-plant's fundamental working methodology.(Gyftopoulos, 1997)

2.2.1 Advantages of Thermal Power Plants

a) Cheaper price of fuel for the power plant usage.

b) Less initial modal required compared to other power plant.

c) Requires less space as compared to hydro-electric power stations.

2.2.2 Disadvantages of Thermal Power Plants

a) The smoke and fumes produced by the power plant during operation pollute the atmosphere.

b) Higher cost required for the operation of the power plant compared to hydroelectric plant

2.3 Thermal Power Plant System

Most of the electricity generating power-plants are the variation of thermal power-plant wherein the working fluid is water. The essential segments of the plant are demonstrated in Figure 2.1 to get a better understanding and facilitate the analysis. Separating the general plant into four subsystems marking from A to D on the diagram. The main focus would be on the subsystem A whereby thermal power plant plays an important role. Subsystem A consists of Boiler, Turbine, Condenser, and Pump parts. Each analysis were made considering certain principles to verify the results. Energy principles conservation, thermodynamics 2^{nd} law, and Mass principles conservation, are some of the factors that high priority were given.(Balmer, 2011c)

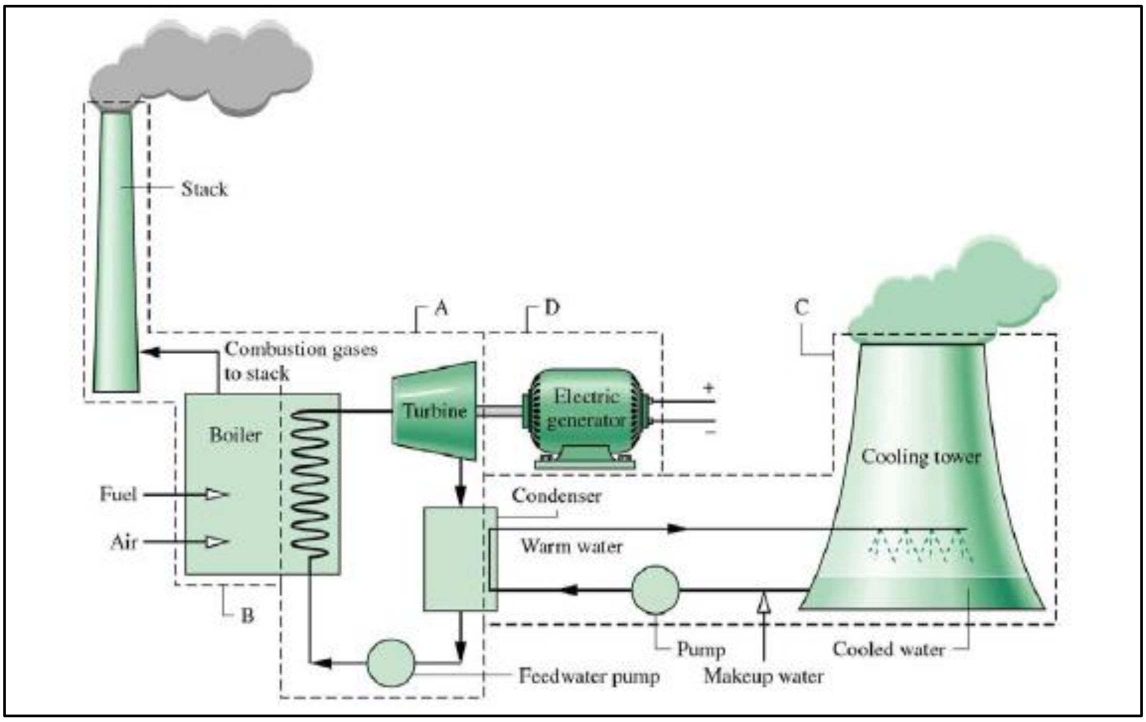


Figure 2.1: Components of thermal power plant (Michael J. Moran, 2014)

2.3.1 Analyzing Power System

The work and heat principal from the subsystem part A is shown clearly in in Figure 2.2. Constraint factors are taken into consideration such as stray heat transfer, kinetic and potential energy changes that takes place will be neglected for accurate analysis. System is considered operating in steady state. Let us examine how energy transfers take place in each state under subsystem A. (Balmer, 2011b)

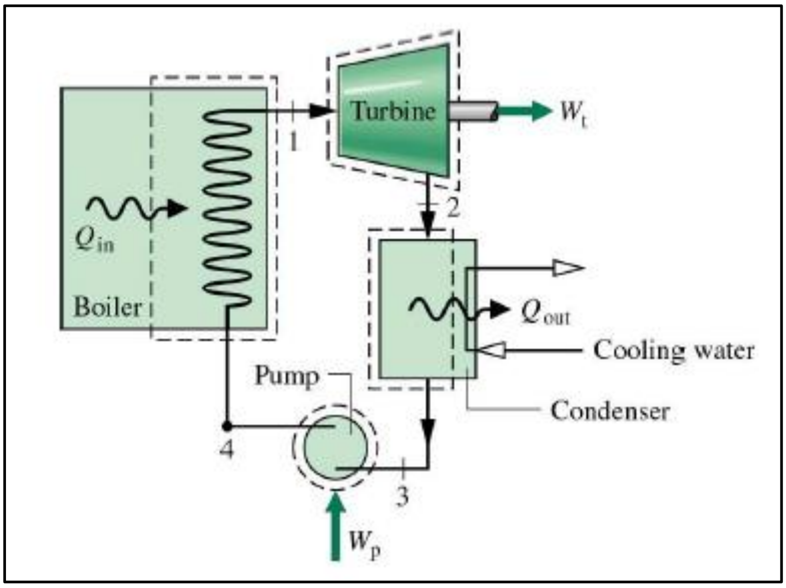


Figure 2.2: Work and heat transfer principal of subsystem A(Michael J. Moran, 2014)

2.3.1.1 Turbine

(Michael J. Moran, 2014)Steam at the 1st state from the boiler having a pressure and temperature of a high degree expands via the turbine and leads to the production of W (work) which later flows at the 2nd state to the Condenser with a pressure of very low degree. Analyzing the work produced by turbine would be:

$$\frac{\dot{W}t}{\dot{m}} = h1 - h2$$

where; $\dot{m}$ = mass flow rate

$\frac{\dot{W}t}{\dot{m}}$ = work rate developed per unit mass of steam

2.3.1.2 Condenser

Condenser operates in a way that the transfer of heat occurs to the cooling water from the steam which flows in a stream that is separated inside the condenser part itself. This causes the steam to condense. Analyzing the steady condition of the rate of energy and mass gives out;

$$\frac{\dot{Q}out}{\dot{m}} = h_2 - h_3$$

where; $\dot{m}$ = mass flow rate

$\frac{\dot{Q}out}{\dot{m}}$ = heat rate transferred by energy from the working fluid to cooling water per unit mass of working fluid flowing through the condenser

2.3.1.3 Pump

The liquid which has been condensed after flowing through condenser will be pumped back into the boiler to continue the working fluid cycle. Analyzing the heat transfer, energy rate and mass balances gives:

$$\frac{\dot{W}p}{\dot{m}} = \mathrm{h}_4 - \mathrm{h}_3$$

where; $\dot{m}$ = mass flow rate

$\frac{\dot{W}p}{\dot{m}}$ = Power rate per unit of mass that pass through the pump

2.3.1.4 Boiler

The working fluid that leaves the pump will enter back the boiler to complete the cycle which will be again heated up to the point of saturation as well as evaporated in the boiler. Analyzing the rate of balance between the energy and mass of a boiler gives:

$$\frac{\dot{Q}in}{\dot{m}} = h_1 - h_4$$

where; $\dot{m}$ = mass flow rate

$\frac{\dot{Q}in}{\dot{m}}$ = heat rate transferred by energy into the working fluid per unit mass that pass through the boiler

2.3.1.5 Performance Analysis

The thermal-efficiency measures the level to which energy that is inputted into the working-fluid and passes alongside the boiler is again converted into the output of the network.(Ersayin & Ozgener, 2015) Therefore, the outputted network is of equivalence to the inputted net-heat. In other ways, the expression of the thermal-efficiency can be;

$$\eta = \frac{\frac{\dot{W}t}{\dot{m}} - \frac{\dot{W}p}{\dot{m}}}{\frac{\dot{Q}in}{\dot{m}}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 \dot{-} h_4)}$$

Since the net work output equals the net heat input, therefore it is equivalently

$$\eta = \frac{\frac{\dot{Q}in}{\dot{m}} - \frac{\dot{Q}out}{\dot{m}}}{\frac{\dot{Q}in}{\dot{m}}} = 1 - \frac{\frac{\dot{Q}out}{\dot{m}}}{\frac{\dot{Q}in}{\dot{m}}} = 1 - \frac{(h_2 - h_3)}{(h_1 \dot{-} h_4)}$$

2.3.2 Ideal Rankine Cycle

When a working-fluid pass across many constituents of a power-plant cycle that is easy without irreversibility, there will be a flow by the working fluid at a fixed pressure across all those components as frictional pressure loss is considered absent from the condenser and boiler. Whereas for the turbine and pump, the processes would be isentropic in the absence of irreversibility and heat loss to surroundings. A clear figure idealizing the Ideal Rankine Cycle shown in Figure 2.3 (1' - 2' – 3 – 4 - 1') when including the possibility of superheating the vapor is given below:(Tschoegl, 2000a)

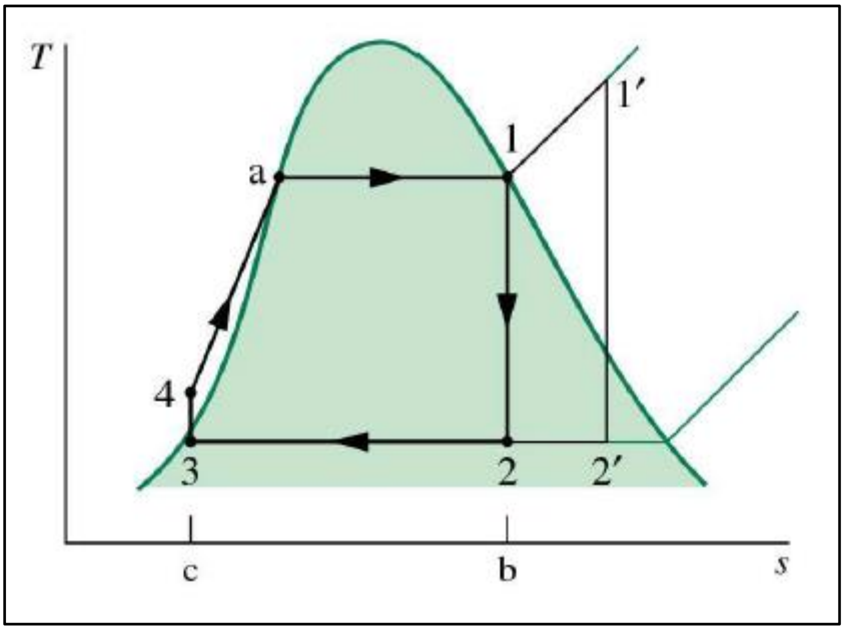


Figure 2.3: Temperature-entropy of the ideal Rankine Cycle

Table 2.1: Process orders

Process 1-2	Isentropic expansion. Happens to the working fluid that pass through the turbine to condenser pressure from saturated vapor at state 1.
Process 2-3	Heat transfer from the working fluid when it flows at fix pressure through the condenser with saturated liquid at state 3.
Process 3-4	Isentropic compression in the pump to state 4
Process 4-1	Heat transfer to the working fluid when it flows at fix pressure through the boiler.

(Gyftopoulos, 1997)However since an ideal Rankine cycle consists of internally reversible process, we could analyze the areas under the process lines as heat transfers per unit of mass. Considering the area "1 – b – c – 4 – a – 1", representing the transferring heat to the working-fluid as it pass across the boiler whereas area "2 – b – c – 3 – 2" represents the transferred heat from the working-fluid that passes across the condenser, both considered per unit of the flowing mass. As the pump idealized as operating without irreversibility's, earlier equation of pump work would be;

$$\left(\frac{\dot{W}p}{\dot{m}}\right)int.rev = \int_{3}^{4} vdp$$

2.3.3 Effects of Boiler and Condenser Pressure on the Rankine Cycle

Thermodynamically, the cycle's thermal efficiency would be increased if the energy's temperature is added averagely via the mean of increased transfer of heat. Study shown above were the effects on performance when there are changes in the condenser pressure and boiler pressure in an ideal Rankine Cycle. Figure 2.4 shown two ideal cycles varies when the boiler pressure and condenser pressure were manipulated. Figure 2.4(a) refers to the cycle which have the same condenser pressure but the boiler pressure were manipulated. Maintaining a higher pressure cycle of (1' – 2' – 3' – 4' – 1') results in the average temperature of heat addition to be high as well. Therefore, raising up the pressure of the boiler of a very good Rankine Cycle results into a higher thermal efficiency. Figure 2.4(b) shown the cycles with the same boiler pressure but different condenser pressure (1 – 2' – 3' – 4' – 1) results into a lower temperature of heat rejection. Therefore, this shows that the decrease in the pressure of the condenser will result into a thermal efficiency that is higher. Furthermore, the lowest achievable pressure for condenser is the pressure that saturates and which corresponds to the temperature that is ambient as it could be the least probable temperature needed for rejection of the heat to the surrounding/environment. However, the main reason for including the condenser in a power-plant is for the maintenance of the least achievable pressure of the condenser in order to ensure that there is an impactful up-rise in the thermal efficiency as well as network. Having a condenser will as well ensure that the flow of the working fluid will be in a loop that is closed. (Regulagadda, Dincer, & Naterer, 2010)

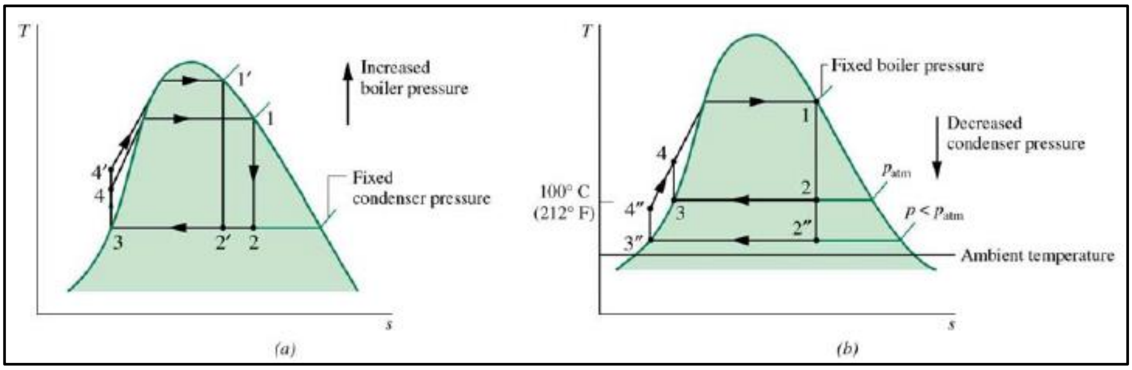


Figure 2.4: Effects of varying operating pressure on the ideal Rankine cycle

2.4 Effects of Condenser Pressure on the Rankine Cycle

Condenser is considered as one of the main component that affect the steam power plant performance even though thermal power plant consists of pump, steam generator, turbine and condenser. (Demirel, 2014) Condenser functions as a means of creating a turbine's pressure of vacuum so as to ensure increase in the output of power and in generating low-steam and this is an important factor as well for the creation of a given output of power. Secondly, its importance is by declining feed-water heat in water circulation and recovering the condensate. Other than that, many other efforts have being made continuously to improve the condenser's performance or heat exchanger in other words. Operating the plant at an optimum condition is important for the extraction of the maximum power output. In order to achieve the desired thermal efficiency, parameters that affect the performance were studied by detailing the lower end of the pressure's condenser condition on the outcome of the power-plant. For the purpose of this study, following aspects were assumed;

a) Exchanger of heat of the tube and shell type is to prevent any leakage of air to the condenser.
b) Steady-state condition by thermodynamic law.

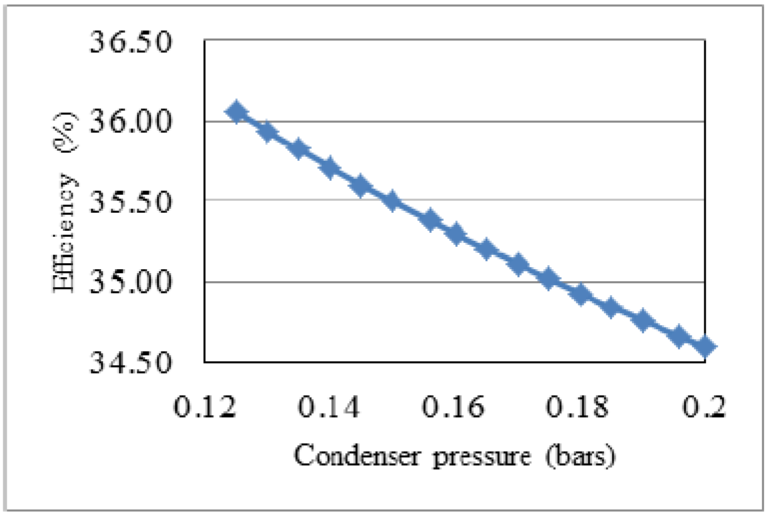


Figure 2.5: Variation of thermal efficiency with respect to condenser pressure

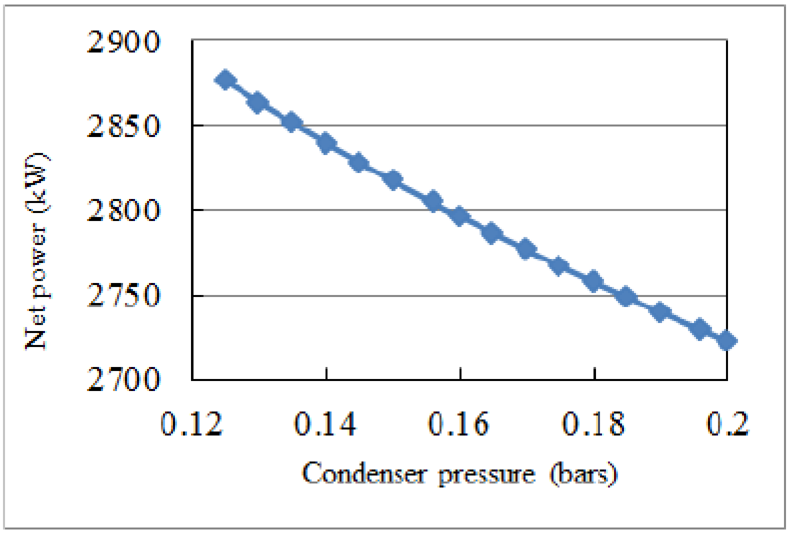


Figure 2.6: Variation of net power with respect to condenser pressure

(Ali, Baheta, & Hassan, 2014) stated that Figure 2.5 and Figure 2.6 shows the impact made by the pressure in the condenser with regards to the efficiency of the plant as well as its output of the net-power accordingly. Both the efficiency of the cycle thermal as well as the output of the net-power decreases as there is an increase in the pressure of the condenser. This is because the steam that leaves where the turbine is has an enthalphy that is high and the rejected energy from the medium of cooling is in a waste form. Other than that, the mass rate flow of the cooling water, its leakage in air and temperature also affects the pressure of the condenser. Other simulation's has shown the impact of the temperature of the cooling water with regards to the pressure of the condenser. Analyzing the Figure 2.7, it shows that the condenser pressure rises up as there occurs an increase in the temperature of the cooling water inlet. Usually cooling water could be from the natural water or in a loop system that is closed after it has been cooled down. Therefore, an increase should occur in the rate flow of the mass if there is an increase also in the temperature of the cooling water for the purpose of ensuring maintenance of the pressure of the condenser. (Ali et al., 2014)

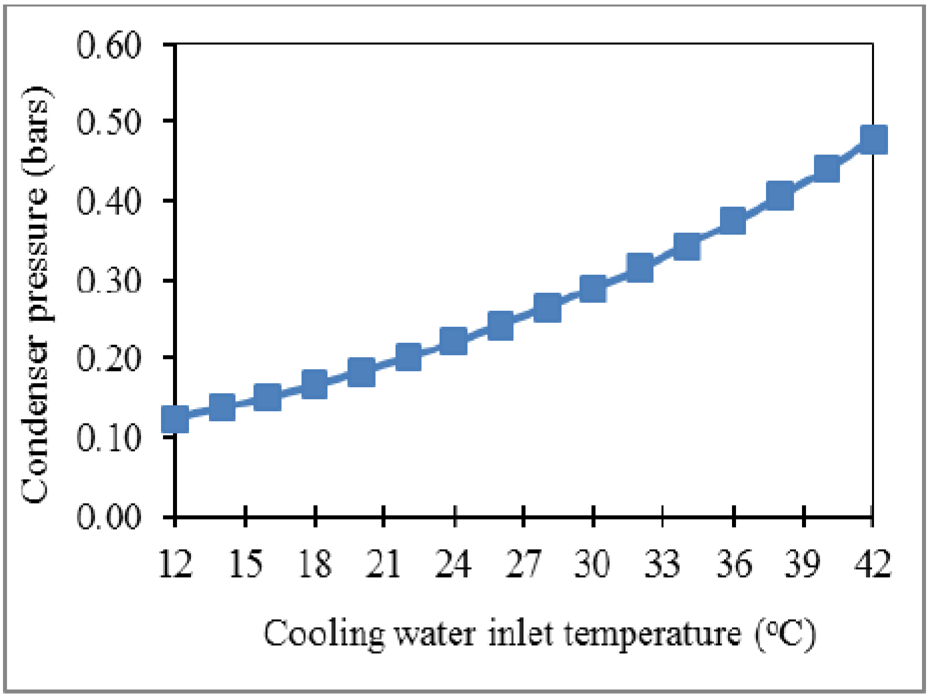


Figure 2.7: Condenser pressure vs cooling water inlet temperature

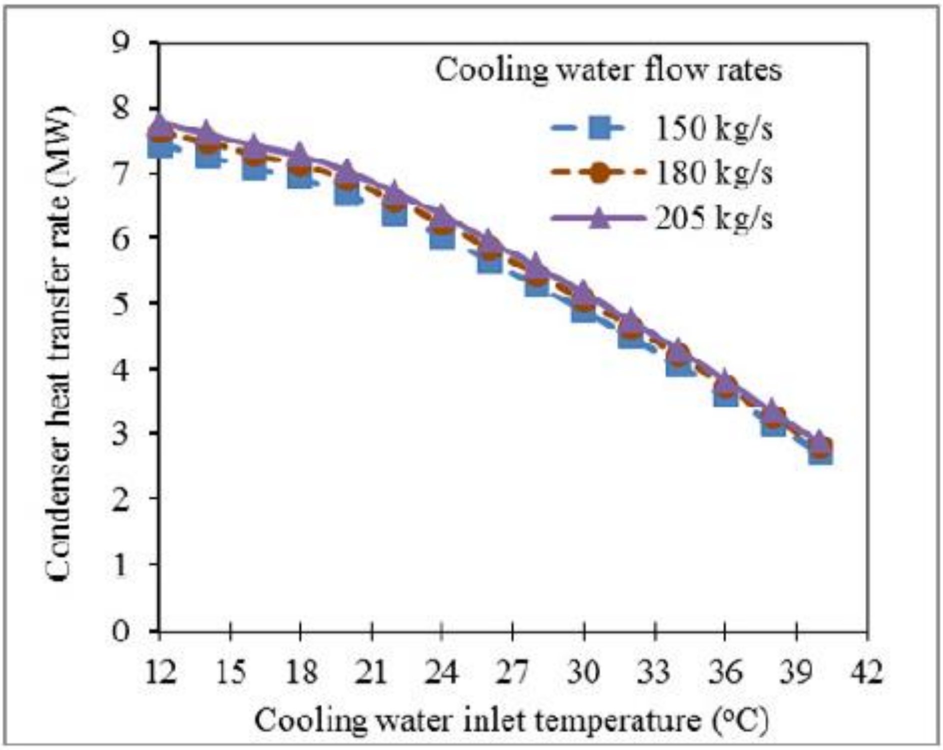


Figure 2.8: Variation of condenser heat transfer rate vs cooling water inlet temperature

Whereas the Figure 2.8 shows the differences in the transfer of heat rate by the condenser in accordance with the different flow-rate of the cooling water. As can be seen in Figure 2.8, the rate in transferring heat reduces as an increase occurs in the temperature of the inlet water. This is so due to the fact that for every given steam temperature of a condenser, there is a decrease in the gradient of the temperature amidst two streams once there is an increase in the temperature of the inlet cooling water, which results to reduced transfer of heat between the two streams. Besides that, the more the increase in flow, the greater the transfer of heat as the flow-rate of the mass is in direct proportion to the transfer of heat.(Ali et al., 2014)

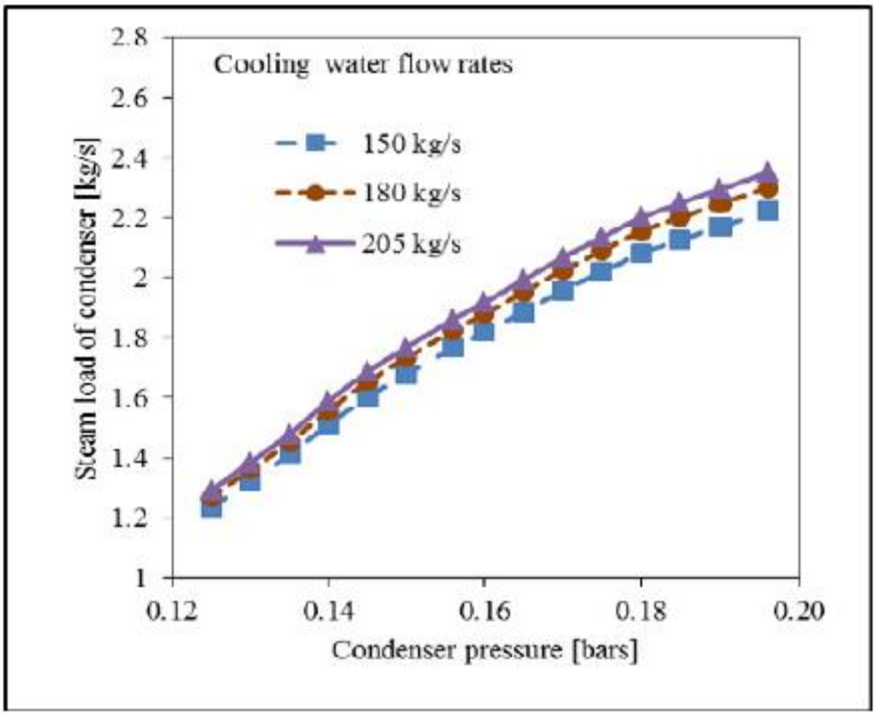


Figure 2.9: Condenser steam load vs condenser pressure

Referring to Figure 2.9, the increasing pressure of the condenser causes an increase in the steam that enters into the condenser as well. This happens because when there is a high pressure in the condenser, the exit-enthalpy of the turbine would be higher as well and the precise output of the power of the turbine would be low. The desired output would be using flow-rate of steam that is higher and therefore there will be an increase in the steam load of the condenser as well.(Ali et al., 2014) If the cooling water flow-rate of mass is reduced, then there would be an increase in a condenser's steam load for its given pressure. The power-plant is firmly dependent on lesser conditions in operating pressure because the condenser is one of the important element for the exchange of heat. If an increase occurs in the pressure of the condenser, both the efficiency of the thermal as well as the output of the net-power would decrease while an up-rise would occur in the consumption of steam. On the other side, the pressure of the condenser is determined via the flor-rate of mass and temperature of the cooling water. In that way, the condenser pressure is higher as the flow-rate of cooling water is smaller for a given temperature of a cooling water inlet.

2.5 Improving Performance

Power plant sector have never stopped on working out to improve its efficiency. This also entails the improving of efficiency in power plants by means that can generate more work output compared to less heat input. Profitability of a power plant always play an important role considering other factors of a power plant such the lifespan, maintenance and wear-tear of its component.(Hussain, Sebzali, & Ameer, 2014) Many modifications were incorporated over the years but two cycle modification we would see in depth are superheat and reheat which could much more assist in the increase of the pressure in boilers and in the reduction of the pressure in condensers. It is mentioned earlier in the discussion that the increase in the pressure of the boiler or the pressure of the condenser would increase the thermal efficiency overall but at the same time it’s important to note that it might end up in reducing the quality of the steam at the turbine’s end-point which would cause to erode the turbine blade. In other word, it would decrease the turbine efficiency and increase the expenses for maintenance. These two cycle modification, superheat and reheat could also offshore the challenge of low duality of the exhaust of the turbine.

2.5.1 Superheat

Superheat assist in further transferring heat to the saturated vapor at the turbine inlet therefore producing super-heated state of the vapor at the inlet of the turbine. Superheat is done in a distinct exchanger of heat referred to as super-heater. Having a mixture of super-heater and boiler brings out a complete steam generator. Figure 2.10 gives a description of an actual Rankine cycle complete with a superheated vapor at the turbine inlet; 1' –> 2' –> 3 –> 4 –> 1'. This shows that a super-heater included cycle has a higher average heat addition temperature compared to cycle without a superheating and therefore the thermal efficiency becomes higher as well. Besides that, superheating do eliminate the challenge of low quality in steam at the exhaust of a turbine as regarding a super-heating that is adequate, the state of exhausting the turbine would be in the vapor region that has been super-heated.(Haseli, 2018)

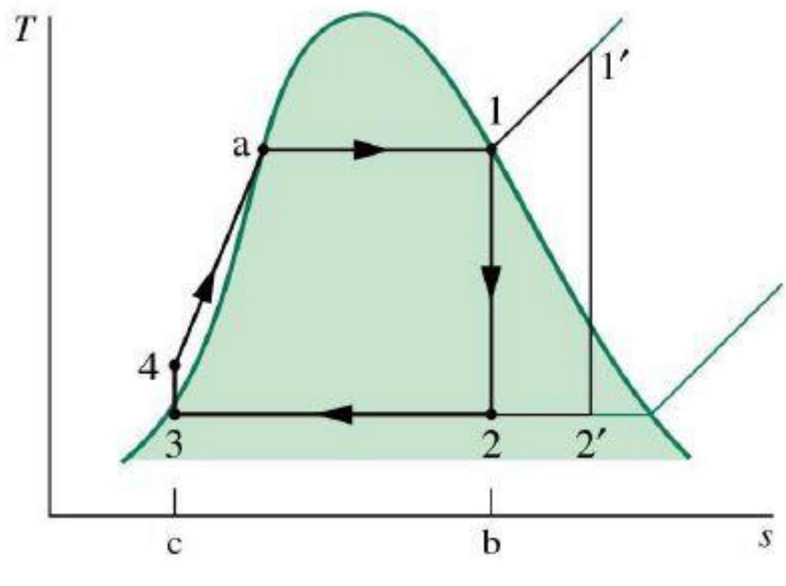


Figure 2.10: Rankine cycle with superheater

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Experiment Set Up

As mentioned earlier in Chapter 1 and Chapter 2 complete power plant set up consists of 4 components which are boiler, turbine, pump and condenser as shown in Figure 3.1. The Rankine cycle starts by having water flows from pump to turbine through high pressure boiler whereby the work done by the pump known as $W_{out.}$ The heat that transferred into the working fluid at boiler known as $Q_{in.}$ Next, the working fluid flows through turbine whereby work produced by the turbine, known as W_t. At the turbine, the work produced through the rotation of turbine as a results of the steam hitting the turbine blade in which the turbine shaft connected with the rotary of generator. As the working fluid flows through the condenser, the heat is transferred out, Q_{out} to cooling water which is in separate stream line. Afterwards, the working fluid channeled back to high pressure boiler through the pump and keeping the working fluid in continuous cycle.(Alobaid et al., 2017)

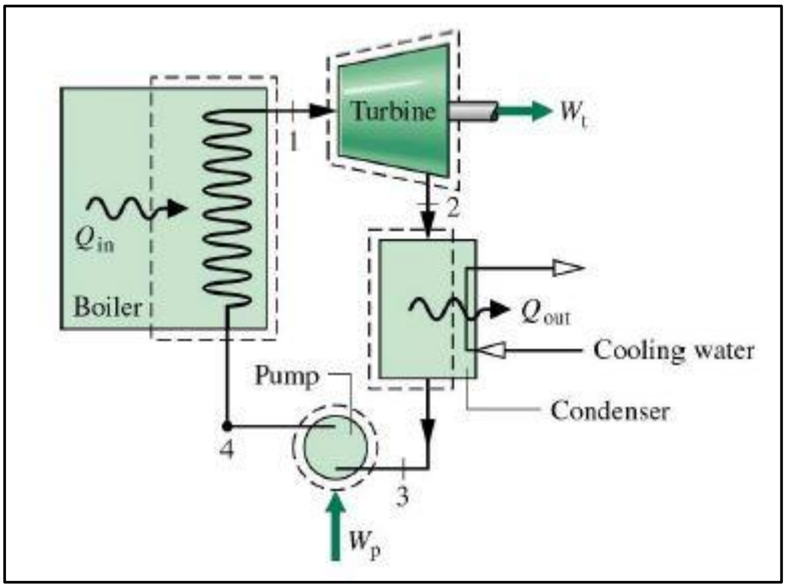


Figure 3.1: Basic components of steam turbine power plant

Figure 3.2 below shows the diagram components arrangement and order for the methodology of the research of steam power plant in the STEM ISI IMPIANTI 3-kW experimental power plant at Thermal-hydraulic laboratory, Faculty of Engineering, University of Malaya.

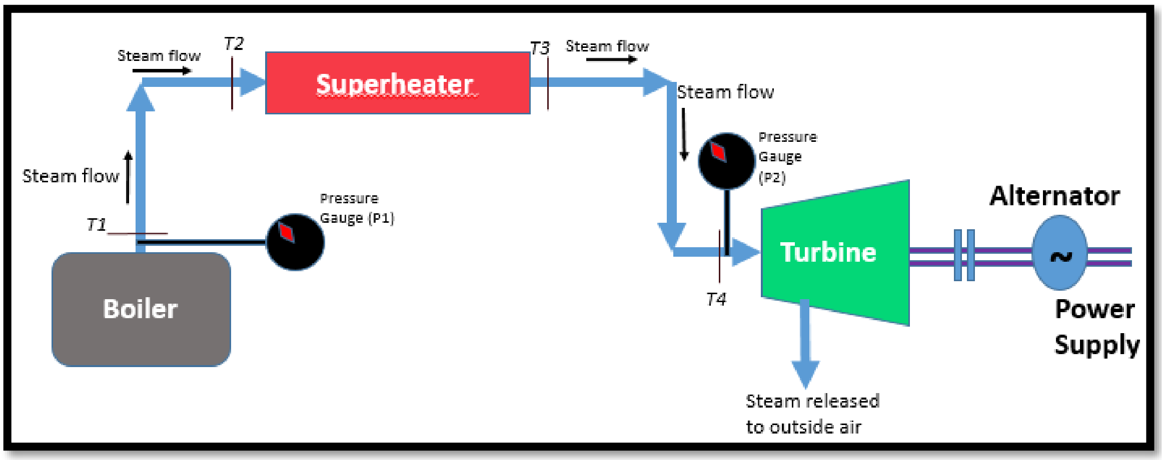


Figure 3.2: Component set-up in lab

The small scale power plant lab consists of boiler and turbine were sufficient for us to research on the effects of pressure on the steam turbine output. Additionally, superheater were installed between boiler and turbine along the pipeline which is between T_2 and T_3. Diesel fuel were used to power up the boiler and heat the water and the working fluid was from the water treatment facility. The total fuel consumption for the whole experiment reflected in the table below with its calorific value and density.

Table 3.1 Diesel fuel properties

Total experiment time	90	min
Diesel consumption	25	L
Diesel calorific value	45.5	MJ/kg
Diesel density, ρ	0.832	kg/L
Mass Used	20.8	kg

3.2 Steam Cycle

The Rankine cycle starts with water being pumped by the pump to the high-pressure boiler. The work being done by the pump considered as W_p. The high-pressure boiler being feed with diesel fuel to assist in creating working fluid in the form of steam. There was pressure gauge, P_1 connected with the boiler to control the pressure of steam at the boiler stage before allowing steam to enter the working fluid pipeline.

Figure 3.3: Pressure gauge, P_1 connected at boiler

Pressure gauge, P_1 considered as the first manipulating variable parameter whereby the whole experiment conducted using two value of this boiler pressure, at 7bar and 8bar. Once the steam flows out from the boiler, the temperature 1, T_1 is recorded as the steam flows into the pipeline. It's installed right after the steam flows into the steam pipeline to measure the energy that the steam carries when it enters the pipeline. A component known as superheater installed along the pipeline approximately in the middle of whole steam pipeline.

Figure 3.4: Superheater installed along the steam pipeline

Superheater assisted in making the steam to a state superheated vapor condition before it reaches turbine inlet. Another temperature sensor, T_2 installed right before the steam enters the superheater and another temperature sensor, T_3 right after the steams exits the superheater. This is to monitor the temperature increment happens inside the superheater. Steam flows through the pipeline in a very high temperature and in another word, having a high kinetic energy. The fourth temperature sensor, T_4 were installed right before the steam enters the turbine.

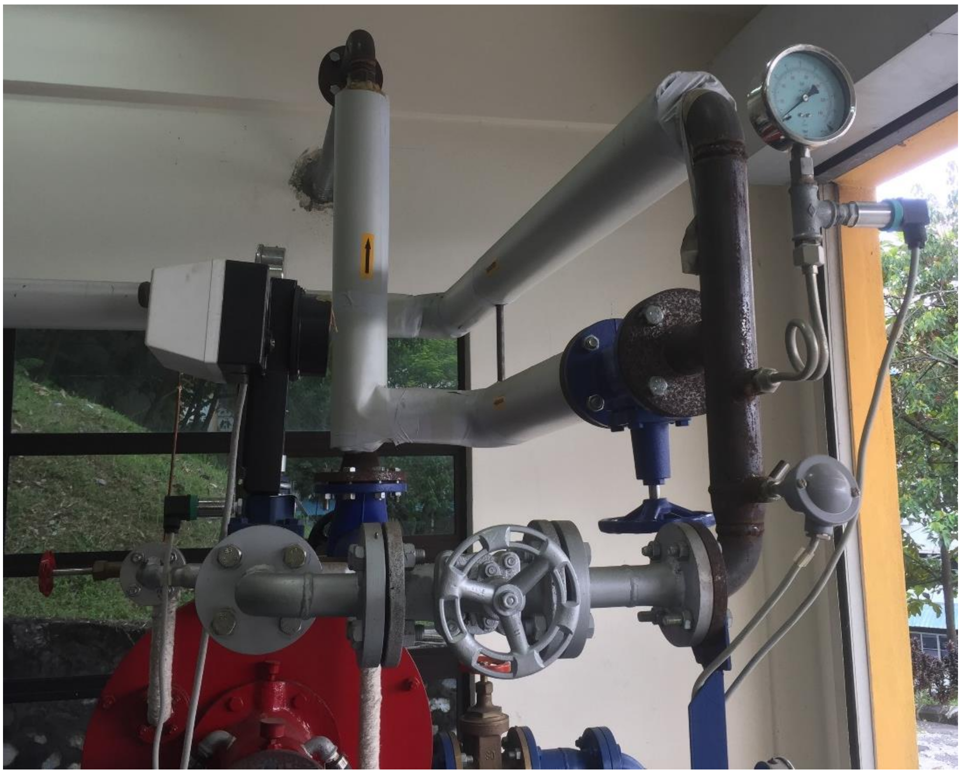


Figure 3.5: Pressure gauge, P_2 connected at turbine

In total, we had 4 temperature sensor installed along the steam pipeline. The second manipulating variable were the turbine pressure whereby a pressure gauge, P_2 installed right before the steam enters the turbine. In that way, the pressure of the steam that enters the turbine can be controlled. The experiment were conducted in a way that boiler pressure set at 7 bar and turbine pressure set at 2, 3 and 4 bar. Then the experiment repeated using those turbine pressure value for boiler pressure of 8 bar. The boiler pressure, P_1 and turbine pressure, P_2 are the two parameter that were used as the manipulating variable to study the turbine power output. The high pressure and high temperature from the steam enters the turbine through the pipeline and hit the surface of the turbine blade connected to the rotary generator whereby it produce mechanical energy and later this energy converted into electrical energy.

Figure 3.6: Turbine connected through shaft with generator

Based on the temperature values recorded at 4 different point, we can get the value of enthalpy and entropy by referring to property table and charts from the Thermodynamic reference book. Therefore, the amount of energy carried by the steam at each point were identified and compared when the pressure value manipulated. Other than that, the main objective of studying the power output when the boiler pressure and turbine pressure manipulated were recorded and analysed accordingly.(Yunus A. Cengel, 2015b)

Figure 3.7: Complete experiment set-up

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Experimental Condition

Experiment conducted by manipulating boiler pressure, P_1 and turbine pressure, P_2 and the value of the turbine power output recorded. The maximum rotation of the generator in the lab stands at 8600 rotation per minute. The maximum power of the generator is 3kW and the power factor is 2.5. Based on the lab experiment size, the maximum efficiency that achieved using this generator is 2.567625.

Table 4.1 Diesel fuel heat input value

Total experiment time	90	min
Diesel consumption	25	L
Diesel calorific value	45.5	MJ/kg
Diesel density, ρ	0.832	kg/L
Mass Used	20.8	kg
Total Heat (MJ)	946.4	MJ
Total Heat (kJ)	946400	kJ
Total Heat Input	175.259259	kW
Rate of Heat Input	116.839506	kW-h

Table 4.1 above shows the experimental condition of this work for the rate of heat input using the calorific value of diesel gas properties. The rate of heat input from the burning of diesel gas to the working fluid inside the high pressure boiler is 117 kWh. Point to note is that the steam flow rate for all the experiment above fixed at 420 kg/h which is constant value throughout the whole experiment. Table 4.2 below shows the complete result of the experiment when the boiler pressure and turbine pressure manipulated.(Regulagadda et al., 2010) Readings of temperature at 4 different location and the turbine rotational speed stated in the table below at respective pressure values.

4.2 Results

Table 4.2 below shows the experimented data obtained on this work. Based on the result, it shows that as the turbine pressure increases for each value of boiler pressure, the rotational speed increases too up to 3100 RPM. The turbine pressure of 4 bar for each 7 and 8 bar of boiler pressure shows the highest turbine inlet temperature. This could be due to the buildup pressure that occurs at turbine inlet as a result of controlling the turbine pressure at high value of 4 bar. Therefore the temperature also shows a high value at turbine inlet. When the temperature value is high, relatively the amount of kinetic energy in the steam is high as well. The high turbine rotational speed were the result of the steam hitting the turbine blade at a very high speed. As a result, high turbine rotational speed created high electricity. The efficiency of the generator at these turbine pressure also would be higher which is cost saving as well.

Table 4.2 Experimental Results

Test No	Pressure (bar)		Temperature (°C)				Turbine Rotational Speed (RPM)	Average Rotation (RPM)
	Boiler P_1	Turbine P_2	Boiler Outlet T_1	Superheater Inlet T_2	Superheater Outlet T_3	Turbine Inlet T_4		
1	7	2	122	120	125	135	1100 - 1300	1200
2	7	3	137	134	136	140	2100 - 2500	2300
3	7	4	141	139	142	148	2600 - 3100	2850
4	8	2	130	128	132	135	1200 - 1400	1300
5	8	3	136	135	138	143	2100 - 2700	2400
6	8	4	145	140	146	150	2700 - 3100	2800

4.3 Ideal Cycle vs Experimental Result

Other important element to note is the deviation of the temperature from point T_1 to T_2. (Yunus A. Cengel, 2015a) stated that in an idealized cycle, the temperature from point T_1 to T_2 should be constant to achieve the maximum efficiency but based on the results of the experiment, we noticed a slight decrease as the steam flows from T_1 to T_2 and increased back when it reaches T_3 which is mainly due to the superheater installed. The temperature drop as the steam flows from T_1 to T_2 is due to the reversibilities. Two main factors which might have contributed to this are the heat loss to the surroundings and fluid friction. Heat loss might have occurred as the steam flow in the pipeline from T_1 to T_2. The length of pipeline in which the steam flows and the internal features of the pipeline have contributed to this factor. Eventually temperature increase occurred when the steam reaches T_3; thanks to the superheater contribution. In addition, this results was proven in the figure below, Figure 4.1 stated that deviation occurs compared to the idealized Rankine cycle.

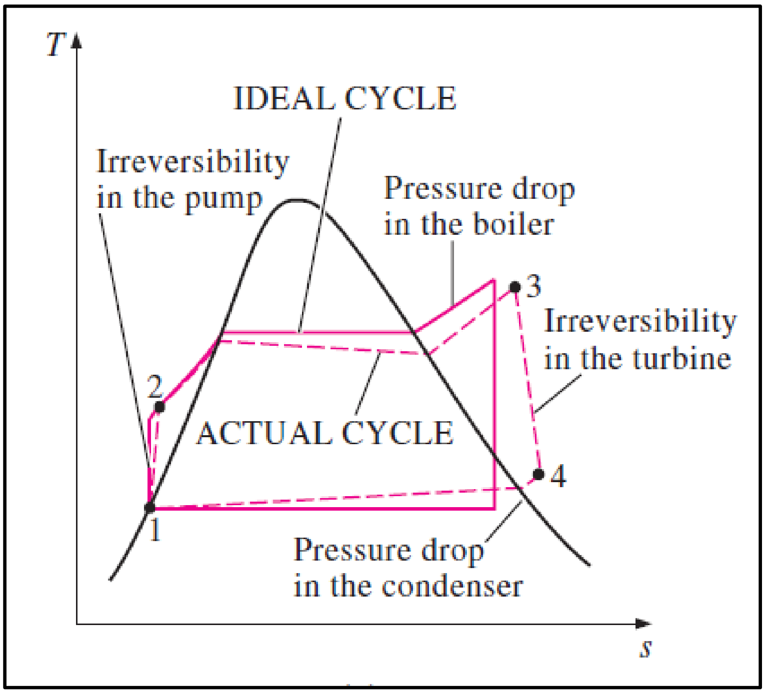
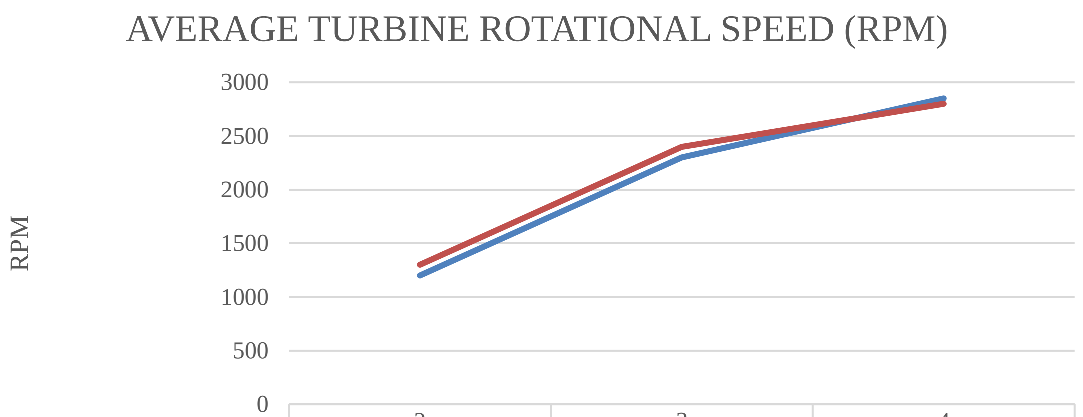


Figure 4.1 Deviation of Actual Vapor Power Cycle from the Ideal Rankine Cycle (Yunus A. Cengel, 2015a)

4.4 Discussion



	2	3	4
Boiler Pressure 7 bar	1200	2300	2850
Boiler Pressure 8 bar	1300	2400	2800

Figure 4.2 Average Turbine Rotational Speed (RPM)

Figure 4.2 above shows the average turbine rotational speed for each turbine pressure on respective boiler pressure value. It shows that boiler pressure at 7 bar with turbine pressure 4 bar recorded the highest turbine rotational speed. Recalling the objective of the studies which is to study the boiler and turbine pressure that gives out the highest value of turbine rotational speed, boiler pressure of 7 bar and turbine pressure 4 bar have the highest generation of electricity from the power plant located in the lab. The boiler pressure of the current plant can only achieve maximum up to 8 bar. Respectively, the boiler pressure of 8 bar have lesser turbine rotational compared to boiler pressure of 7 bar due to straining the system to achieve maximum boiler pressure and therefore less efficiency resulted. This shows that the power output increases as the turbine pressure increase regardless of the boiler pressure. This is shown in the Table 4.3 below.

Table 4.3 Power Output for Different Boiler and Turbine Pressure Value

Test No	Pressure (bar)		Temperature (°C)				Average Rotation (RPM)	Power Output (kW-h)
	Boiler P_1	Turbine P_2	Boiler Outlet T_1	Superheater Inlet T_2	Superheater Outlet T_3	Turbine Inlet T_4		
1	7	2	122	120	125	135	1200	1.04651
2	7	3	137	134	136	140	2300	2.00581
3	7	4	141	139	142	148	2850	2.48547
4	8	2	130	128	132	135	1300	1.13372
5	8	3	136	135	138	143	2400	2.09302
6	8	4	145	140	146	150	2800	2.44186

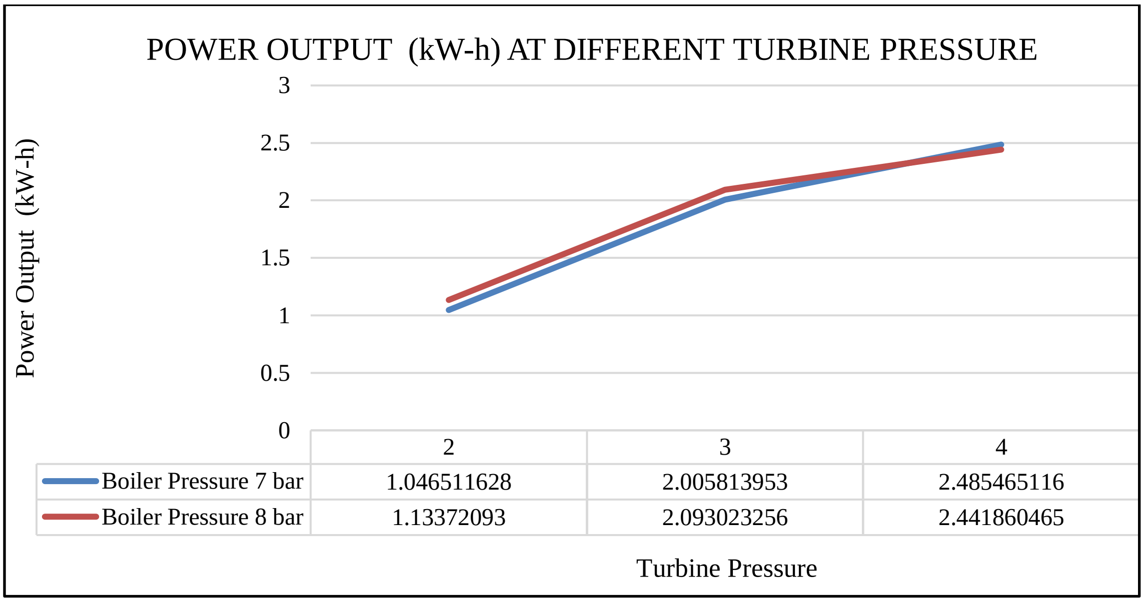


Figure 4.3 Power Output (Kw-H) for Different Boiler and Turbine Pressure Value

Table 4.3 shows that the power output for boiler pressure of 7 (turbine pressure 4 bar) bar shows 2.48547 kW-h while boiler pressure of 8 bar (turbine pressure 4 bar) shows 2.44186 kW-h. The value of power output at each boiler pressure and turbine pressure represented in the Figure 4.3 above.

Respectively mechanical work of the power plant has been incorporated as per table below

Table 4.4 Mechanical Work for Different Boiler and Turbine Pressure Value

Test No	Pressure (bar)		Temperature (ºC)				Average Rotation (RPM)	Mechanical
	Boiler P_1	Turbine P_2	Boiler Outlet T_1	Superheater Inlet T_2	Superheater Outlet T_3	Turbine Inlet T_4		
1	7	2	122	120	125	135	1200	34.89552
2	7	3	137	134	136	140	2300	66.88307
3	7	4	141	139	142	148	2850	82.87685
4	8	2	130	128	132	135	1300	37.80348
5	8	3	136	135	138	143	2400	69.79103
6	8	4	145	140	146	150	2800	81.42287

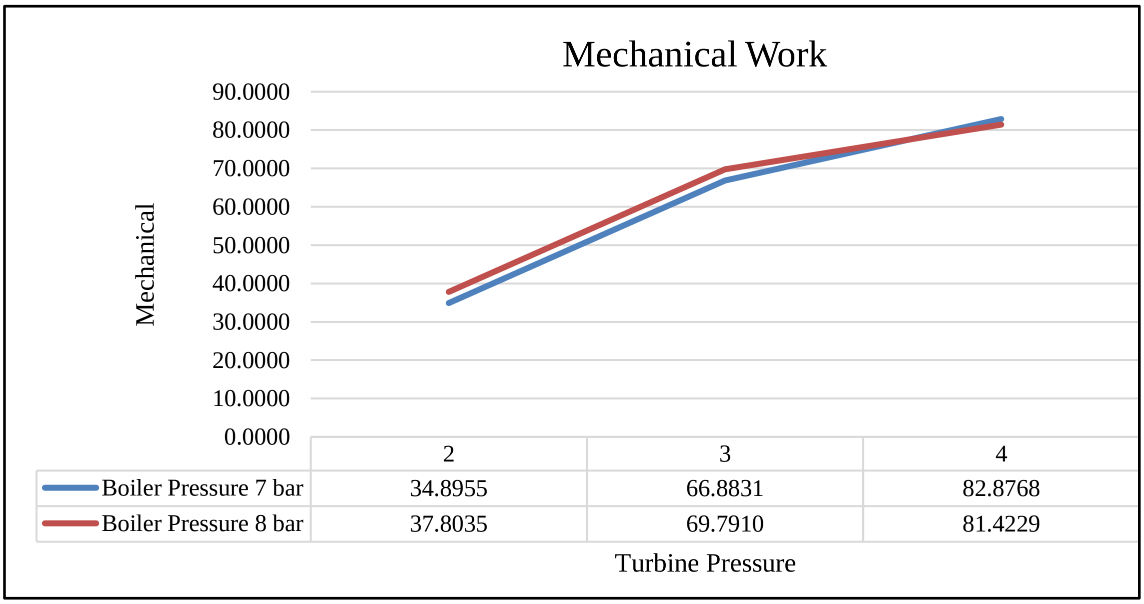


Figure 4.4 Mechanical Work for Different Boiler and Turbine Pressure Value

Relatively, enthalpy shows high value as the recorded temperature is high as well. Higher enthalpy shows that the working fluid having higher kinetic energy.

Table 4.5 Enthalpy Value at Different Temperature

Boiler Pressure: 7 bar			
Turbine Pressure (bar)	**Temperature (˚C)**		**Enthalpy, h (kJ/kg)**
2	T_1	122	2708.8
	T_2	120	2706.0
	T_3	125	2713.1
	T_4	135	2726.9
3	T_1	137	2729.5
	T_2	134	2725.5
	T_3	136	2728.2
	T_4	140	2733.5
4	T_1	141	2734.8
	T_2	139	2732.2
	T_3	142	2736.0
	T_4	148	2743.5

Boiler Pressure: 8 bar			
Turbine Pressure (bar)	**Temperature (˚C)**		**Enthalpy, h (kJ/kg)**
2	T_1	130	2720.1
	T_2	128	2717.3
	T_3	132	2722.8
	T_4	135	2726.9
3	T_1	136	2728.2
	T_2	135	2726.9
	T_3	138	2730.9
	T_4	143	2737.3
4	T_1	145	2739.8
	T_2	140	2733.5
	T_3	146	2741
	T_4	150	2745.9

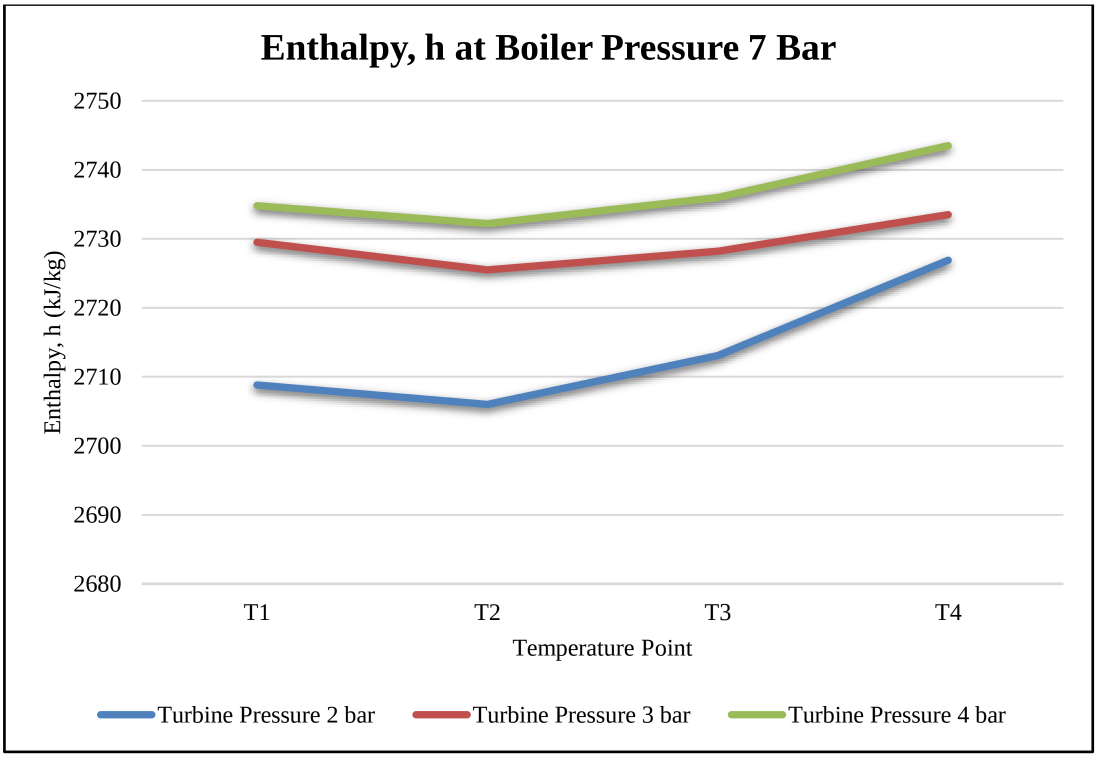


Figure 4.5: Enthalpy value at boiler pressure 7 bar

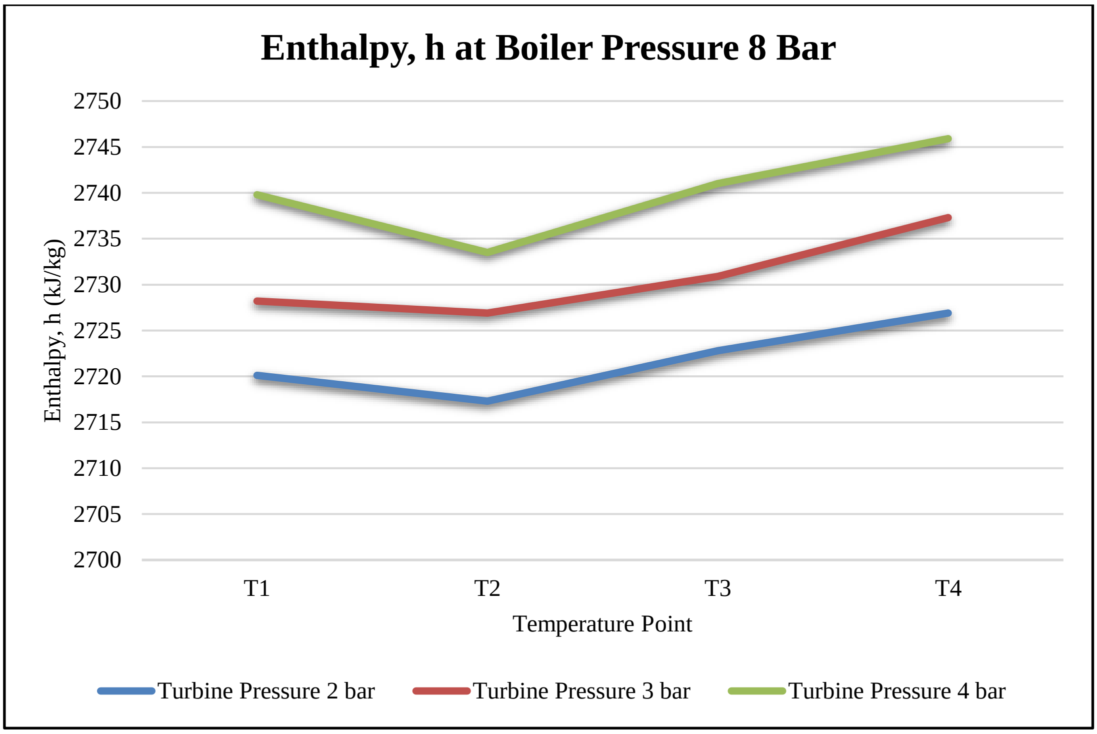


Figure 4.6: Enthalpy value at boiler pressure 8 bar

Other important factor in comparison is analyzing the entropy of the working fluid at respective particular temperature.

Table 4.6 Entropy Value at Different Temperature

Boiler Pressure: 7 bar			
Turbine Pressure (bar)	**Temperature (˚C)**		**Entropy, s (kJ/kg.K)**
2	T_1	122	7.1084
	T_2	120	7.1292
	T_3	125	7.0771
	T_4	135	6.9773
3	T_1	137	6.9581
	T_2	134	6.9871
	T_3	136	6.9677
	T_4	140	6.9294
4	T_1	141	6.9201
	T_2	139	6.9390
	T_3	142	6.9107
	T_4	148	6.8553

Boiler Pressure: 8 bar			
Turbine Pressure (bar)	**Temperature (˚C)**		**Entropy, s (kJ/kg.K)**
2	T_1	130	7.0265
	T_2	128	7.0467
	T_3	132	7.0068
	T_4	135	6.9773
3	T_1	136	6.9677
	T_2	135	6.9773
	T_3	138	6.9486
	T_4	143	6.9014
4	T_1	145	6.8827
	T_2	140	6.9294
	T_3	146	6.8736
	T_4	150	6.8371

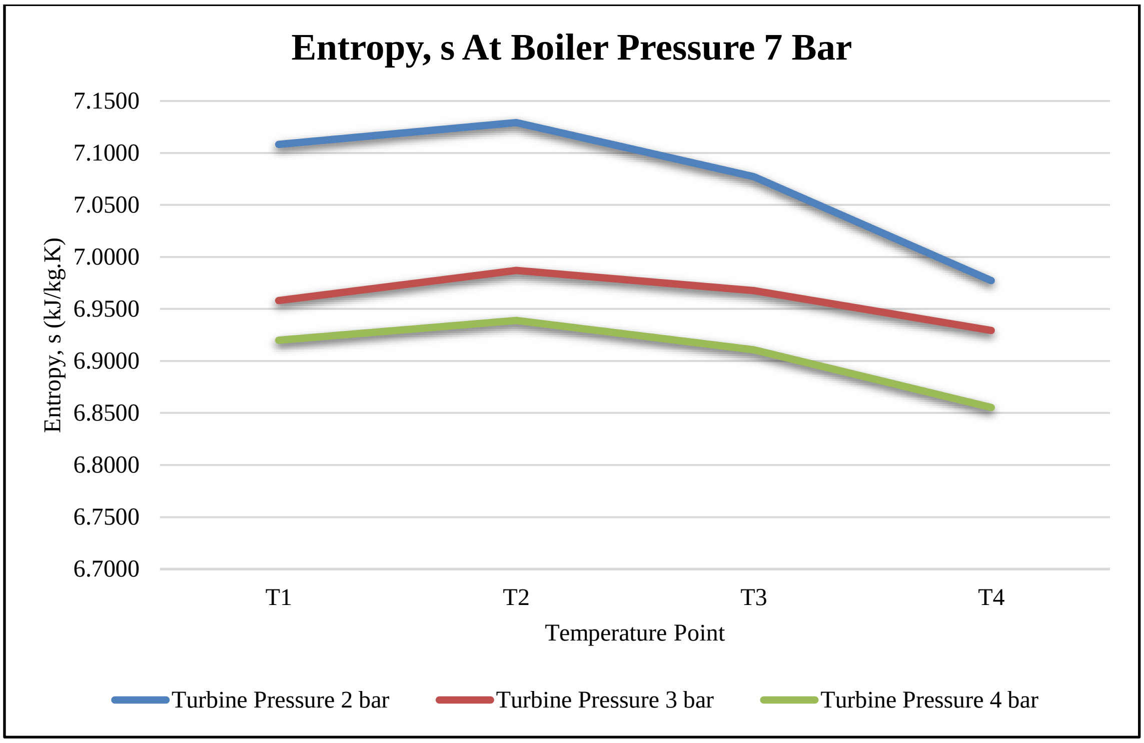


Figure 4.7: Entropy value at boiler pressure 7 bar

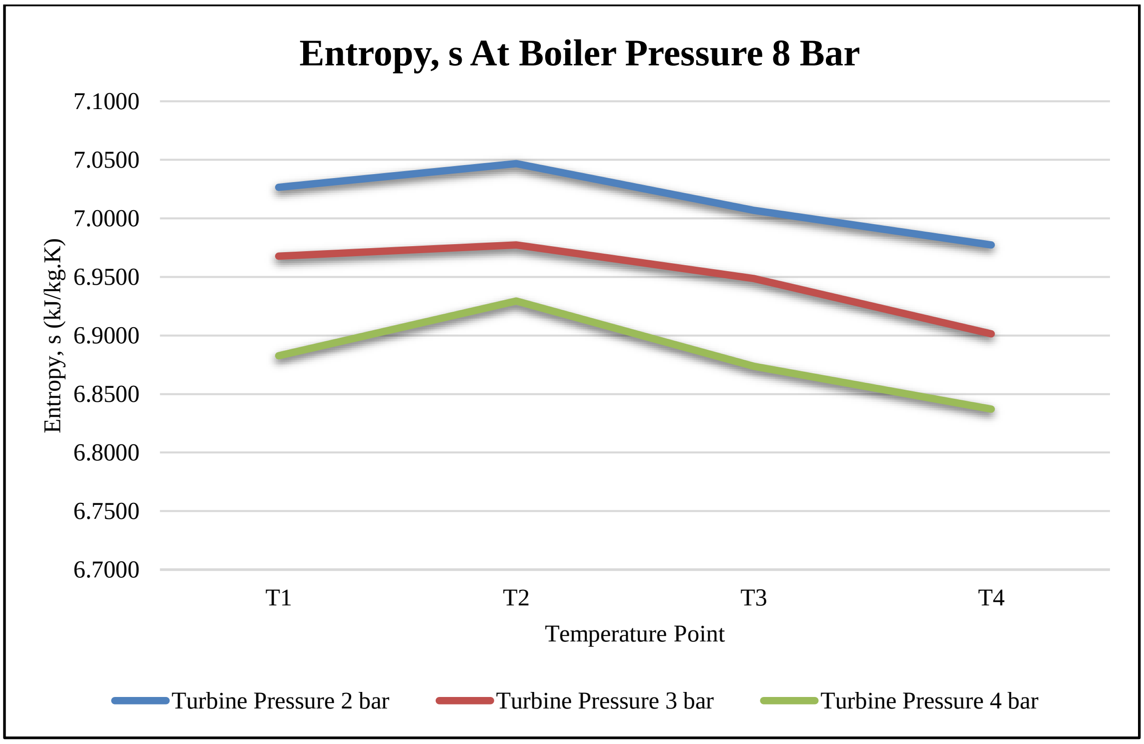


Figure 4.8: Entropy value at boiler pressure 8 bar

Table 4.7 Efficiency for Different Boiler and Turbine Pressure Value

Test No	Pressure (bar)		Temperature (°C)				Average Rotation (RPM)	Efficiency
	Boiler P_1	Turbine P_2	Boiler Outlet T_1	Superheater Inlet T_2	Superheater Outlet T_3	Turbine Inlet T_4		
1	7	2	122	120	125	135	1200	0.895986
2	7	3	137	134	136	140	2300	1.717306
3	7	4	141	139	142	148	2850	2.127967
4	8	2	130	128	132	135	1300	0.970651
5	8	3	136	135	138	143	2400	1.791972
6	8	4	145	140	146	150	2800	2.090634

Relatively to the power output produced by each manipulated variable, efficiency table constructed as above and represented in the graph below as well.

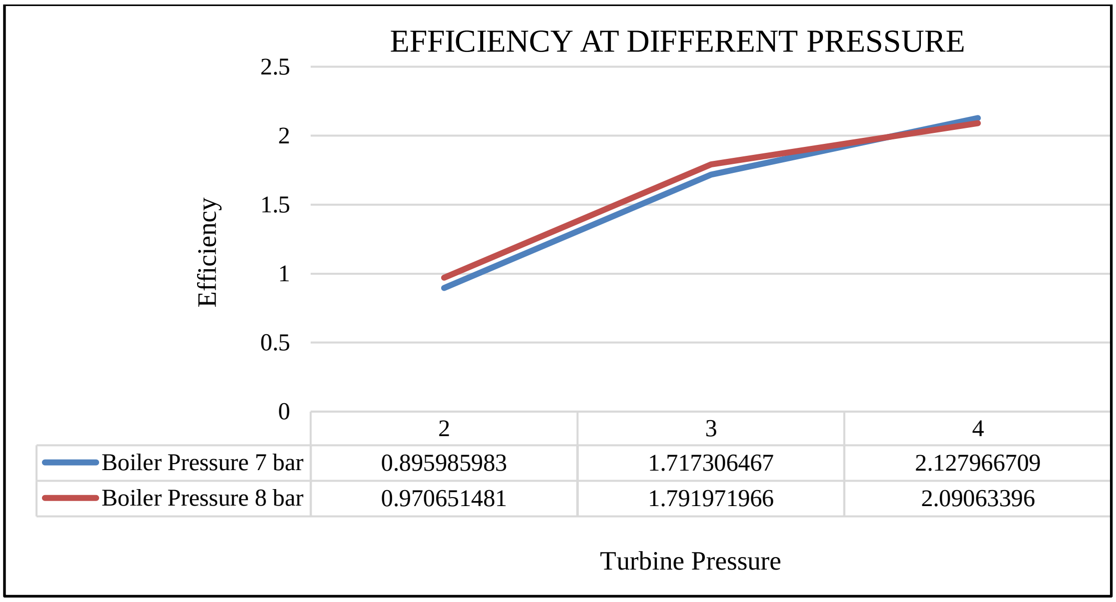


Figure 4.9 Efficiency for Different Boiler and Turbine Pressure Value

In the end, it shows that operating the lab power plant system with 7 bar of boiler pressure and 4 bar of turbine pressure produce the most effective and efficient output. Even though operating the boiler pressure at 8 bar produce almost the same power output and efficiency level as 7 bar, but 8 bar of pressure would strain the system. Other than that, the drawback of using 8 bar boiler pressure is that it would consume more fuel to burn in order to achieve the 8 bar. Therefore, using 7 bar of boiler pressure would be the best choice suiting the 4 bar of turbine pressure to produce the most power output.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Referring to the objective of the work which is to study the effects of pressure variation on the performance of a steam turbine power plant, the experiment was conducted properly and any error that could jeopardize the results was avoided completely to achieve the accurate outcome. Therefore, it can be concluded that increasing the turbine pressure would increase the efficiency of the steam turbine power plant regardless of the boiler pressure value. Manipulating the boiler pressure value and turbine pressure value to study the power output of steam turbine, the whole experiment was modeled thermodynamically and accordingly. Furthermore, the factors affecting the steam turbine performance were validated and found out that operating this power plant with the boiler pressure of 7 bar and 4 bar of turbine pressure would be the most efficient for generating electricity. Controlling the turbine pressure value at 4 bar produce the highest rotation of turbine and directly proven to be the most efficient value. Meanwhile for the boiler pressure value, after repeated experiment it shows that 7 bar is the most suitable pressure compare to 8 bar. This is because 8 bar is the maximum capacity that boiler can operate and operating the boiler at that pressure could strain the system and consequently the efficiency drops. Therefore, increasing the pressure at the inlet of turbine have increased the temperature of the steam at the inlet of turbine and subsequently enhance the performance of the power plant. When higher efficiency achieved, it contributes for the cost saving in power plant industry. As discussed in Chapter 1, cost saving is an important factor in power plant industry because poor management of power plant system could lead to loss in the power plant electricity generation and therefore it wouldn't be a profitable venture.

5.1 Recommendation

1. Improvement can be made to the power plant to increase the efficiency such as including irreversibilities into the analysis to improve significant influence on the cycle performance.
2. Other than that, conducting thermodynamic analysis to equipment such as condenser and feedwater pump too can improve the performance of the power plant.

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APPENDIX

EXPERIMENTAL DATA

Test No	Pressure (bar)		Temperature (^oC)				Turbine Rotational Speed (RPM)	Average Rotation	Steam Flow Rate (kg/h)	Water droplet weight (g)	Droplet collection duration (min)
	Boiler P1	Turbine P2	Boiler Outlet T1	Superheater Inlet T2	Superheater Outlet T3	Turbine Inlet T4					
1	5	2	133	118	124	120	530 - 700	615	420	7.2	10
2	7	2	122	120	125	135	1100 - 1300	1200	420	11.8	10
3	7	3	137	134	136	140	2100 - 2500	2300	420	28.0	10
4	7	4	141	139	142	148	2600 - 3100	2850	420	101.6	10
5	8	2	130	128	132	135	1200 - 1400	1300	420	11.1	5
6	8	3	136	135	138	143	2100 - 2700	2400	420	30.0	5
7	8	4	145	140	146	150	2700 - 3100	2800	420	111.0	5

CALCULATED RESULTS

Power Output	Efficiency	Mechanical	Defficiency
0.536337209	0.459192816	17.88395175	82.11587412
1.046511628	0.895985983	34.89551561	65.10414462
2.005813953	1.717306467	66.88307159	33.11627718
2.485465116	2.127966709	82.87684958	17.12234347
1.13372093	0.970651481	37.80347525	62.19615667
2.093023256	1.791971966	69.79103123	30.20828924
2.441860465	2.09063396	81.42286977	18.57633744

STEAM PROPERTIES

Specific Volume on T4	Mass of vapor at T4	Volume of vapor at T4	Mass of collected water(w)	Quality
0.8919	70	62.433	0.0072	0.999897
0.5887	70	41.209	0.0118	0.999831
0.5089	70	35.623	0.028	0.9996
0.416	70	29.12	0.1016	0.998551
0.5887	35	20.6045	0.0111	0.999683
0.474	35	16.59	0.03	0.999144
0.3928	35	13.748	0.111	0.996839