STEAM TURBINE PERFORMANCE UNDER VARIATION OF INLET TEMPERATURE IN A STEAM POWER PLANT

AZWIN KAMARULZAMAN

FACULTY OF ENGINEERING UNIVERSITY OF MALAYA KUALA LUMPUR

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AZWIN KAMARULZAMAN

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Matric No: KQK170014

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ABSTRACT

Steam turbine is one of the most important equipment in a power generation plant. With greater demand of power around the globe for domestic and industrial applications, the need on enhancing the power plant performance is substantially emerging. Many researchers scrutinize several parameters such as inlet temperature and pressure, outlet pressure, steam/gas flow rate, geometry, material and economics in efforts to improve the turbine performance. Numerous studies on steam turbines, gas turbines, combined cycle and wind turbines are conducted through simulation, modelling, numerical analysis, theoretical analysis and comparative study. The present work is basically the investigation into the effects of inlet temperature variations on the performance of a steam turbine in a power generation plant through experimental works. The study also intended to measure and analyze the thermodynamics parameters during steam turbine operation and finally validate the factors contributing to the steam turbine performance. The experiment was conducted in a small steam power generation plant of 3 kW capacity. The close cycle system consists of boiler, superheater, steam turbine, condenser, electric generator and pump. Seven different sets of operating parameters are designed and used in this experiment. Other variables namely boiler and turbine pressures, steam flow rate and fuel characteristics are kept as constant to simplify the analysis. The analysis includes determining the thermodynamics and performance parameters involving total heat input, rate of heat input, power output, steam quality, thermal and mechanical efficiencies for the system. Experimental results confirm that high turbine inlet temperature significantly enhances the steam turbine performance in terms of power output, thermal and mechanical efficiencies. Highest mechanical efficiency of 82.85% and power output of 2.485 kWh are obtained when the turbine inlet temperature and pressure are at 148°C and 4 bar respectively with steam quality of 0.9968. Steam quality slightly declines by 0.001% to 0.3% as the turbine inlet temperature escalates. Recommendations for future study are also discussed in this report.

Keywords: Power plant, steam turbine performance, inlet temperature, power output, mechanical efficiency

PRESTASI TURBIN STIM DI BAWAH VARIASI SUHU MASUK DI LOJI JANAKUASA STIM

ABSTRAK

Turbin stim adalah salah satu peralatan terpenting di loji janakuasa elektrik. Dengan permintaan terhadap kuasa elektrik yang semakin meningkat di seluruh dunia untuk aplikasi domestik dan perindustrian, keperluan untuk meningkatkan prestasi loji janakuasa dilihat semakin penting. Ramai penyelidik meneliti beberapa parameter seperti suhu dan tekanan masuk, tekanan keluar, kadar aliran stim / gas, geometri, bahan dan ekonomi dalam usaha meningkatkan prestasi turbin. Pelbagai kajian mengenai turbin stim, turbin gas, gabungan kitaran kuasa dan turbin angin dijalankan melalui simulasi, pemodelan, analisis berangka, analisis teoritis dan kajian perbandingan. Penyelidikan ini dijalankan melalui kerja-kerja eksperimen bagi meyiasat kesan variasi suhu masuk terhadap prestasi turbin stim di sebuah loji janakuasa. Kajian ini juga bertujuan untuk mengukur dan menganalisis parameter termodinamik semasa operasi turbin stim dan seterusnya mengesahkan faktor yang menyumbang kepada prestasi turbin stim. Eksperimen ini dijalankan di loji janakuasa stim kecil dengan kapasiti 3 kW. Sistem janakuasa ini adalah kitaran tertutup yang terdiri daripada dandang, pemanas lampau, turbin stim, pemeluwap, penjana elektrik dan pam. Tujuh set parameter operasi yang berbeza direka dan digunakan dalam eksperimen ini. Pembolehubah lain seperti tekanan dandang dan turbin, kadar aliran stim dan ciri-ciri bahan api disimpan sebagai pemalar untuk memudahkan analisis. Analisis ini termasuk menentukan termodinamik dan parameter prestasi yang melibatkan input haba, kadar input haba, jumlah kuasa eletrik yang terhasil, kualiti stim, kecekapan haba dan kecekapan mekanikal untuk system janakuasa. Hasil eksperimen mengesahkan bahawa suhu masuk turbin yang tinggi telah meningkatkan prestasi turbin stim dari segi jumlah kuasa elektrik yang terhasil, kecekapan haba dan kecekapan mekanikal dengan ketara. Kecekapan mekanikal tertinggi sebanyak 82.85% dan 2.485 kWh kuasa elektrik diperoleh apabila suhu masuk dan tekanan turbin masing-masing berada di paras 148°C dan 4 bar dan kualiti wap sebanyak 0.9968. Kualiti wap sedikit menurun sebanyak 0.001% hingga 0.3% apabila suhu masuk turbin meningkat. Cadangan untuk kajian pada masa depan juga dibincangkan dalam laporan ini.

Kata kunci: Loji janakuasa, prestasi turbin wap, suhu masuk, output kuasa, kecekapan mekanikal

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LIST OF SYMBOLS AND ABBREVIATIONS

GCV	:	gross calorific value (MJ/kg)
h	:	specific enthalpy (kJ/kg)
m	:	mass (kg)
ṁ	:	mass flow rate
Р	:	power (kW)
p_1	:	boiler pressure (bar)
p_2	:	turbine pressure (bar)
Q_{in}	:	total heat supplied (MJ)
Ż	:	rate of heat input (kJ/s or kW)
Q _{total}	:	total heat energy in specified time (kW.h)
N	:	turbine rotational speed (rpm)
$N_{ m avg}$:	average turbine rotational speed (rpm)
N_{\max}	:	maximum turbine rotational speed (rpm)
Т	:	temperature (°C)
T_1	:	boiler outlet temperature (°C)
T_2	:	superheater inlet temperature (°C)
T ₃	:	superheater outlet temperature (°C)
T_4	:	turbine inlet temperature (°C)
t	:	time (hr)
toe	:	tonne of oil equivalent
TWh	:	terra watt hours
V	÷	volume (L)
W	÷	work
x	:	quality
η	:	efficiency (%)
η_t	:	thermal efficiency (%)
$\eta_{turbine}$:	turbine mechanical efficiency (%)
ρ	:	density

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CHAPTER 1: INTRODUCTION

1.1 Background

The world today is currently facing a tremendous energy evolution. Growth in global energy demand is forecasted to intensify for over the next 25 years (**Figure 1.1**). Approximately 70% of the increase in primary energy goes to the power sector. Energy growth in the buildings sector also develops robustly, driven by an increase in demand for space cooling, lighting and electrical appliance. A slow but steady increase in energy demand is sighted in the transport sector as the demand is offset by the growing technologies on energy efficiency.



Figure 1.1: Primary energy consumption by sector (BP, 2018)

Consequently, this scenario has stimulated the growth of power generation. More sources of energy are required to generate electricity to support the demand. Based on **Figure 1.2**, it can be seen that the power generation is no longer depending on conventional fuel, but have shifted towards other alternative sources that are more environment friendly, or simply termed as the green energy.



Figure 1.2: Growth of power generation in 2016-2040 (BP, 2018)

On the other hand, many concerns arise from this energy evolution particularly on global warming and other environmental impacts. Environmental impact has always been the issue that is deliberated together with the economic growth and energy sources depletion since the last three decades. The goal is to balance or minimize the impact as the industrial revolution progresses. Various initiatives have been taken such as controlling the usage and limiting the dependency on conventional fuel sources, shifting towards renewable energy and introducing the energy efficiency scheme especially in the

major industries and buildings. The initiatives are divided into two major categories that are approaches when generating power and approaches to energy use. In power generation sector, many experts and professionals have taken initiatives to increase the thermal efficiency and power output with the intention to meet the energy demand and environment conservation objectives. High thermal efficiency denotes more thermal energy from the fuel source is converted into electrical energy effectively. Therefore, less usage of fuel and lower carbon dioxide (CO2) emissions. The simple representation of thermal efficiency and fuel input correlations is shown in **Figure 1.3**.



Figure 1.3 : Thermal efficiency and fuel input correlation (TEPCO, 2010)

Several methods can be applied to increase the power output and thermal efficiency of a power generation plant. One of the methods is by increasing the efficiency of turbine used in the power plant. According to Steam and Gas Turbine Report 2018, nearly half of turbine population is used in power generation and another half in oil and gas, manufacturing, marine and aviation sectors. Turbine is a device that converts thermal energy from high pressure and temperature working fluid into kinetic energy or mechanical work on a rotating output shaft. The shaft drives the electric generator to produce electricity. More electricity can be generated when turbine produces more work

as its efficiency getting improved. Further reduction on fuel is also attainable. Therefore, it is very significant to improve the turbine efficiency to achieve the earlier mentioned targets.

1.2 Problem Statement

Rigorous efforts are made by researchers and equipment manufacturers to improve the performance of the steam turbines today in order to increase overall power plant efficiency. This can be achieved by increasing the temperature of the steam entering the turbine as reported in studies by others. However, these studies are conducted using simulation, numerical, comparative or theoretical analysis, not on actual turbine. Hence, it is necessary to study the effect of inlet temperature on a physical steam turbine under operating conditions and measure the related parameters.

1.3 **Objectives of Study**

The purposes of this study are:

- To investigate the effect of inlet temperature variations on the performance of a steam turbine in a laboratory-scale steam power generation plant of 3 kW capacity.
- 2. To measure and analyze the thermodynamics parameters during steam turbine operation.
- 3. To validate the factors contributing to the steam turbine performance.

1.4 Scope

In achieving such objectives, experimental works were conducted in a laboratory-scale steam power generation plant of 3 kW capacity. All thermal and thermodynamics parameters were recorded and further analyzed in order to investigate the effect of inlet temperature variations on the steam turbine performance. The value of some variables in this experiment were fixed as constant such as steam flow rate, power factor and fuel characteristics to simplify the analysis.

Several assumptions were made for the present study as follows:

- i. Steam turbine is analyzed as a control volume at steady state.
- ii. Steam passes through boiler, superheater, turbine and condenser at constant pressure. Superheated vapor enters the turbine.
- iii. All processes of the steam as working fluid are internally reversible.
- iv. Boiler efficiency is not considered in this study. Heat energy generated from fuel is conserved and fully converted to the turbine works.
- v. The turbine and pump operated adiabatically.
- vi. All losses are negligible.
- vii. Kinetic and potential energy effects are negligible.

1.5 Structure of the Research Project Report

The first part of this report reviews on the available literature and studies by other scholars on steam turbine performance analysis and the effect of temperature on turbine and power plant performance. It continues with the methodology section that describes the details about the method, experiment setup, parameters and criteria used in this study. The next section presents the result from the experiment that has been performed. It follows by the discussion section that deliberates on assessment on the effect of turbine inlet temperatures against the power output, mechanical efficiency and steam quality. The report ends with conclusion of the study and recommendation for future studies in the area of steam turbine.

CHAPTER 2: LITERATURE REVIEW

Various studies have been carried out globally with the objective to improve the performance of power plant in terms of efficiency and economic.

In a study on performance analysis of steam turbine at partial load conditions, A. Sinan Karakurt (2017) evaluated the effects of different flow rate on steam turbine isentropic efficiency and power plant performance. The author stated that the isentropic and thermal efficiency are influenced by variations in pressure, temperature and flow rates at the inlet and outlet of turbine. Performance calculations were made for 100%, 80% and 60% loads and the results showed the declining performance of steam turbine and power plant as a whole, when operating at partial load conditions. The study also emphasized on a comprehensive measurement system and standard for obtaining more accurate results.

Rout et al. (2013) had performed thermal analysis of steam turbine power plants with three different cycles namely regenerative cycle, superheater cycle and cogeneration cycle. The numerical analysis results for all three cycles showed that power output and thermal efficiency increases steadily as the turbine inlet temperature rises. The study also indicated that cogeneration cycle has generated more power output than the superheater and cogeneration cycles with the increase in turbine inlet temperature. The effect of turbine inlet temperature on thermal efficiency was highest on the superheater cycle.

The turbine industry has taken the same approach in considering the effect of turbine inlet temperature in design of steam turbine. The high steam condition has been one of the major criteria to be considered in designing impulse turbines. Some turbine manufacturers designed standard inlet conditions up to 513°C with pressure range of 59 to 100 bar (A. Manaf & Marzuki, 2004). Mitsubishi Heavy Industries, Ltd. (MHI), a major player in turbine industry, has manufactured a high efficiency and large capacity

commercial steam turbine that can operate at 600°C temperature and developed a new material for high temperature application (Eiichiro et al., 2003).

Shams et al. (2017) have reported on the effect of inlet temperature of gas turbine to power output and thermal efficiency. Contrary to the steam turbine, gas turbine thermal efficiency increases as the inlet air temperature decreases. This was due to denser air and increase in mass flow rate of the air entering the gas turbine. Hence most studies related to the effect of gas turbine inlet temperature are on the analysis and comparative studies of using different air-cooling method. This study showed that an increase of 0.53% in power output and 0.22% in thermal efficiency as the inlet air temperature drops by 1°C.

The result of the performance analysis is often presented comprehensively, showing the effect of inlet temperature on different performance parameters of gas/steam turbine. Power output, thermal efficiency, heat rate, specific fuel consumption, consumed fuel mass flow rate and economics were among the performance parameters observed and reported by El-Shazly et al. (2016) when investigating on different turbine inlet cooling techniques on gas turbine performance. The study revealed that gas turbine performance decreases when the air ambient temperature rises. 16.94% and 4.85% reductions in power output and thermal efficiency respectively were observed when the temperature of inlet air increase by 22°C.

Haseli (2018) conducted a study on enhancement of thermal power plants efficiency through specific entropy generation. The study showed higher turbine inlet temperature has improved the thermal efficiency and reduced the specific entropy generation. Nonetheless, the main constraint was the durability of turbine blades in a high temperature condition. Another option to boost the overall thermal efficiency can be made by improving the isentropic efficiencies of the compressor and the gas turbine. The results revealed that 85% of the inefficiencies of the combined cycle studied takes place in the gas turbine cycle.

Geete and Khandwawala (2013) worked on thermodynamic analysis of 120MW power plant with combined effect of constant inlet pressure (124.61 bar) and different inlet temperatures (507.78 °C, 517.78 °C, 527.78 °C, 537.78 °C, 547.78 °C, 557.78 °C and 567.78 °C). Instead of focusing on steam turbine alone, the analysis also include boiler, condenser, feed water pump and heater. The study concluded that power output and heat rate increase with constant inlet pressure and different inlet temperatures. Correction curves for power output and heat rate with the combined effects of constant inlet pressure and different temperatures are established.

In a high temperature pressurized fluidized bed combined gas/steam power cycle, the power output by the gas turbine has increased by 20% out of total power generated and overall efficiency increase by 8% as the inlet temperature increases to 870 °C from 538 °C (Graves, 1980).

Ganjehkaviri et al. (2015) performed a comprehensive thermodynamic modeling and optimization of a combined cycle power plant, focusing on the effect of steam quality at the turbine outlet on power output. A mathematical model is used to analyze the energy, exergoeconomic and exergoenviromental of a combined cycle power plant. The optimizations considered the exergy efficiency of power plant, total cost including estimated environmental damage costs due to pollution and CO₂ emission. The result showed that the steam turbine inlet pressure and temperature are increased by increasing the outlet vapor steam quality. The study suggested a system with 88% quality at steam turbine outlet as the most efficient, economical and has less damaging impact to the environment.

There are two main methods used to analyze and measure the efficiency of thermal power plant. The methods are by energy analysis and exergy analysis. Energy analysis is performed based on the First Law of Thermodynamics, which is also known as Law of Conservation of Energy. This means that energy can neither be created nor destroyed, but it can only be transferred (Moran & Shapiro, 2004). In the case of power generation plant, the energy contained in the fuel is transferred to the working fluid and continuously transmitted through the power plant components and finally generate electrical power or electricity. The law also stated that all energy is transferred throughout the internal system in the form of heat or work. The energy analysis has some limitations due to the properties of surrounding environment, degradation of energy quality and irreversibility are not considered in the analysis (Regulagadda et al., 2010).

Exergy analysis measures the work potential or quality of different forms of energy in relative to its surrounding environment. Exergy is the maximum useful work that is obtained by the system when it reaches the equilibrium state with a heat reservoir. Based on Second Law of Thermodynamics, exergy is destroyed when a process is irreversible and this increases the total entropy of the system. Exergy analysis considers losses and irreversibility, which provides a quantitative measure of the system inefficiency. (Kotas, 1985)

Despite of many studies conducted on performance of steam or gas turbines under variations of operating parameters, the open literature shows that:

- Only some are concentrating on steam turbine while others are on gas turbines, combined cycle or wind turbines. (Arrieta & Lora, 2005; Chiesa et al., 1993; Kilani et al., 2017; Mohapatra & Sanjay, 2015; Poullikkas, 2005).
- As mentioned previously, many researchers address their studies on certain parameters such as inlet pressure and temperature, outlet pressure, flow rate and

geometry. These parameters are manipulated to optimize power, efficiency, specific fuel consumption and cost.

 Most studies conducted are based on modelling, simulation, comparative analysis, numerical analysis or theoretical analysis. Investigation on the effect of temperature, pressure or other operating parameters on turbine performance through experiment has not been discussed so far.

 Table 2.1 summarizes the methods used in turbine performance studies.

Author (Year)	Cycle	Method
A. Sinan Karakurt (2017)	Steam	Numerical analysis
A.Manaf & Marzuki (2004)	Steam	N/A (book reference)
Chaibakhsh and Ghaffari (2008)	Steam	Mathematical modelling & simulation
Chiesa et al. (1993)	Gas, combined	Numerical analysis
Eiichiro et al., (2003)	Steam	N/A (manufacturer's data)
El-Shazly et al. (2016)	Gas	Mathematical modelling
Ganjehkaviri et al. (2015)	Combined	Mathematical Modelling
Geete & Khandwawala (2013)	Combined	Numerical analysis
Graves (1980)	Combined	Numerical analysis
Haseli (2018)	Combined, gas	Numerical analysis
Kilani et al (2017)	Combined	Comparative analysis
Mohapatra & Sanjay (2015)	Gas	Comparative analysis
Poullikkas (2005)	Gas	Comparative analysis
Rout et al. (2013)	Steam	Numerical analysis
Shams et al. (2017)	Gas	Software simulation

Table 2.1: Summary of methods used in turbine performance studies

CHAPTER 3: METHODOLOGY

This section explains the details regarding the experiment, parameters and criteria used to evaluate and analyze the effect of inlet temperatures on the performance of steam turbine.

3.1 Experimental Setup

3.1.1 Description of test facility

Figure 3.1 shows the schematic diagram of the test facility, STEM ISI Impianti 3-kW experimental plant, used in the present study, located at the Thermal-hydraulic laboratory, Faculty of Engineering, University of Malaya. The close system of this test facility consists of a boiler, superheater, turbine, condenser, pump, electric generator with complete measurement apparatus.



Figure 3.1: Schematic diagram of test facility

The boiler uses diesel as its fuel to heat water that is supplied from a treated water tank, as shown in **Figure 3.2**. As the temperature and pressure increase inside the boiler, the wet steam is produced and channeled to a superheater through a 100-mm piping system. **Figure 3.3** shows the photo of the superheater used in this experiment. The superheater reheats the wet steam, converting them into superheated steam or dry steam.



Figure 3.2: Treated water tank



Figure 3.3: Superheater and superheater control panel

Turbine receives the superheated steam and converts the thermal energy from the steam to mechanical work or rotary motion. The rotary motion of the turbine shaft drives the electrical generator to produce electricity. At the turbine exhaust, condenser cools and condense the steam at pressure lower than the atmosphere, to become condensate. The condensate is then returned to the boiler or released to the drain. **Figure 3.4** shows the other equipment configuration consisting of turbine, electric generator and condenser at the laboratory.



Figure 3.4: Equipment configuration

3.1.2 Experimental parameters

Table 3.1 shows the operating conditions and variables used in this experiment to recognize the effect of varying the operating parameters on the performance of a steam turbine. There are seven (7) sets of operating parameters designed for the experiment. The boiler and turbine pressures and steam flow rate for each test are set as constant.

Test no	Boiler pressure, p1 (bar)	Turbine pressure, p2 (bar)	Steam flow rate, m _{steam} (kg/h)
1	5	2	420
2	7	2	420
3	7	3	420
4	7	4	420
5	8	2	420
6	8	3	420
7	8	4	420

Table 3.1: Operating conditions and variables

Other experiment parameters measured and used for analysis are described in Table 3.2.

Table 3.2: Other experiment parameters and system setting

Parameter	Value
Experiment duration, t	90 min
Diesel consumption, V _{diesel}	25 liter
Diesel gross calorific value, GCV _{diesel}	45.5 MJ/kg ¹
Diesel density, ρ_{diesel}	0.832 kg/L
System power factor	2.5
Turbine maximum rotation, N	8600 rpm
Maximum power, P_{max}	3 kW-h

1 (European Association, 2016)

Steam temperature is measured at four (4) different points as indicated in **Figure 3.5**, by using K-type thermocouple with digital display. The example of the temperature measurement point in the laboratory is displayed in **Figure 3.6**.



Figure 3.5: Steam temperature measurement points



Figure 3.6: Temperature, T₃ measurement point in the laboratory (in circle)

3.1.3 Experimental Procedure

Procedures described in this section are implemented during the experiment for the work. Boiler is started up and operated until the pressure has achieved 5 bar. When the steam is produced at a stable boiler pressure, the turbine pressure is monitored by using pressure gauge and set at the desired operating condition as per **Table 3.1** by adjusting the inlet and exhaust valve. Once the boiler and turbine pressures have stabilized, the steam temperature is measured by using K-type thermocouple, at four (4) different points; i) boiler outlet, T_1 , ii) superheater inlet, T_2 , iii) superheater outlet, T_3 and iv) turbine inlet, T_4 . Precautions shall be taken when measuring the steam temperatures at height and near the hot surfaces.

At turbine control panel, the system power factor is set at 2.5. This is necessary to lower down the turbine rotational speed in order to reduce the noise and disturbance from the turbine. The turbine rotational speed reading is obtained and recorded from the control panel. Due to fluctuation of the turbine rotational speed, the reading is taken in a range of minimum and maximum speed that occurred at the specified turbine pressure and temperature. The average of the speed is then calculated and used for analysis.

Water droplets from turbine sampling point is collected by using a beaker for 10 minutes duration. An empty beaker must be weighed before collecting the water droplets. After 10 minutes, the beaker containing water droplets are then weighed by using weighing machine. The weight of water is obtained by deducting the weight of the empty beaker.

The experiment is repeated by setting the boiler and turbine pressures to different conditions as per **Table 3.1**.

3.1.4 Data collection and acquisition

Appropriate data collection and record are very important in order to ensure the accuracy of the results and analysis. Several devices used for data collection purpose are specified in this section.

For steam temperature measurement, K-type thermocouple with digital display (**Figure 3.7**) is used. This thermocouple has a large measurement range of -200 to 1370°C and is able to show the temperature in 0.1° C steps. The accuracy of this device is $0.1\%+1^{\circ}$ C.



Figure 3.7: K-type thermocouple with digital display

Pressure gauge used in this experiment is a Bourdon type pressure gauge with analogue display (**Figure 3.8**) that have been installed at boiler and turbine. The pressure gauge uses a curved tube or called as Bourdon tube and is connected to a fixed pipe containing the fluid to be measured. The accuracy of the gauge is $\pm 1\%$.



Figure 3.8: Pressure gauge with analogue display

Figure **3.9** and **3.10** shows the turbine control panel that is used to set and retrieve data on some parameters such as torque and rotational speed during the experimental works.



Figure 3.9: Turbine control panel



Figure 3.10: Turbine parameters setting and display

Weighing machine and glass beaker (**Figure 3.11**) are utilized to collect and weigh the water droplets from the turbine sampling point.



Figure 3.11: Weighing machine and glass beaker

3.2 Data Analysis

3.2.1 Heat input

 Q_{in} is the total amount of heat or thermal energy supplied to the system from burning the fuel. In this case, diesel is used as boiler fuel with GCV of 45.5 MJ/kg. Q_{in} is calculated by using the following formula:

$$Q_{in} = V_{diesel} \times GCV_{diesel} \times \rho_{diesel}$$
(1)
$$\dot{Q} = \frac{Q_{in} \times \left(\frac{1000kJ}{1\,MJ}\right)}{t \times \left(\frac{3600s}{1\,hr}\right)}$$
(2)

Q_{total} is the total amount of heat energy generated or transmitted to the system at a constant rate within a given time period. It is derived from the following formula:

$$Q_{total} = \dot{Q} \times t \tag{3}$$

3.2.2 Maximum efficiency of the system

 η_{max} is the minimum specific heat required to produce power. P_{max} is given as 3-kW as per system setting. η_{max} of the system is determined by the following formula:

$$\eta_{max} = \frac{P_{max}}{Q_{total}} \times 100\% \tag{4}$$

3.2.3 **Power output**

N determines the amount of power, P that can be generated from the system. Different rate of operating pressures and temperatures vary *N*. For each test of different operating parameters, the N_{avg} is recorded and calculated. P_{out} is computed based on the N_{avg} and system specifications such as N_{max} , system power factor of 2.5 and P_{max}.

$$P_{out} = \frac{N_{avg}}{N_{max}} \times 2.5 \times P_{max}$$
(5)

3.2.4 Thermal efficiency

Steam turbine thermal efficiency, η_t relates P_{out} with Q_{total} as follows:

$$\eta_t = \frac{P_{out}}{Q_{total}} \times 100\% \tag{6}$$

3.2.5 Mechanical efficiency

Mechanical efficiency measures the effectiveness of steam turbine in converting the energy and power received into mechanical works. It is calculated as a ratio of measured performance to the performance of an ideal machine. In this case, mechanical efficiency of turbine is calculated by η_t as a ratio to the η_{max} of the system:

$$\eta_{turbine} = \frac{\eta_t}{\eta_{max}} \times 100\% \tag{7}$$

3.2.6 Steam quality

Steam quality, x is defined as the mass fraction of saturated steam in a mixture of steam vapor and liquid. In this experiment, x can be easily evaluated by collecting water droplets (liquid) from the steam turbine. The m_{steam} can be obtained from \dot{m}_{steam} and specific volume at the particular temperature. By knowing the m_{steam} and m_{water} , x can be quantified as follow:

$$\chi = \frac{m_{steam}}{(m_{steam} + m_{water})}$$
(8)

CHAPTER 4: RESULTS & DISCUSSION

4.1 Experimental results

The results obtained from the experiment are presented in **Table 4.1**. It is observed that the turbine inlet temperature fluctuates as the turbine pressure changes. The increase in turbine pressure and inlet temperature also demonstrates an increase in average turbine rotation. This validates that more heat or higher thermal energy contained in the steam produces more mechanical works. It is also observed that the boiler pressure does not give any significant impact on the turbine rotation. The average turbine rotation generated at boiler pressure of 7 bar does not have any major difference with turbine rotation generated at 8 bar.

Test no	Boiler pressure, p1 (bar)	Turbine pressure, p ₂ (bar)	Steam flow rate, ṁ _{steam} (kg/h)	Turbine inlet temperature, T4 (°C)	Average turbine rotational speed, N _{avg} (rpm)
1	5	2	420	120	615
2	7	2	420	135	1200
3	7	3	420	140	2300
4	7	4	420	148	2850
5	8	2	420	135	1300
6	8	3	420	143	2400
7	8	4	420	150	2800

Table 4.1: Experimental Results

Based on calculation, the system has converted 946.4 MJ of heat supplied from 25 liter of diesel to produce 262.889 kWh of electrical energy.

$$Q_{in} = 25L \times 45.5 \frac{MJ}{kg} \times 0.832 \frac{kg}{L} = 946.4 MJ$$

$$\dot{Q} = \frac{946.4 \, MJ \, \times \, (\frac{1000 \, kJ}{1 \, MJ})}{1.5 \, hr \, \times \, (\frac{3600s}{1 \, hr})} = 175.259 \, \text{kW}$$

$$Q_{total} = 175.259 \, kW \times 1.5 \, hr = 262.889 \, kW-h$$

Maximum efficiency that the power generation system can achieve is as below:

$$\eta_{max} = \frac{3 \, kW - h}{262.889 \, kW - h} \times 100\% = 1.14\%$$

Mass of steam calculated:

$$m_{steam} = 420 \frac{kg}{h} \times 10 \min \times \left(\frac{1 hr}{60 \min}\right) = 70 kg$$

Mass of water is obtained from the collected water droplet weight.

The effect of turbine inlet temperature and pressures on the calculated on the performance parameters is discussed in the following sections.

4.2 Effect of turbine inlet temperature on power output

Power output were calculated by using Eq. (5) and presented in Table 4.2. Further analysis is carried out to examine the effect of turbine inlet temperature on the power output.

Test no	T4 (°C)	Pout (kWh)
1	120	0.536
2	135	1.047
3	140	2.006
4	148	2.485
5	135	1.134
6	143	2.093
7	150	2.442

 Table 4.2 : Power output under different turbine inlet temperatures

As depicted in **Figure 4.1**, power output produced increases as the turbine inlet temperature rises.



Figure 4.1: Power output versus turbine inlet temperature

At higher temperature and pressure, the steam has higher specific enthalpy or more energy per unit of mass. This explains the additional power generated at high temperature as compared to lower temperatures. The result agrees with the studies by Rout et al. (2013), Geete and Khandwawala (2013) and Graves (1980) that stated power output increased as the turbine inlet temperature increases.

4.3 Effect of turbine and boiler pressures on power output

Table 4.3 shows the power output produced at different turbine and boiler pressures. The same characteristic as the turbine inlet temperature is displayed by turbine pressure, as depicted in **Figure 4.2**. The power output produced is highest at 4 bar as compared to other lower turbine pressures.

Test no	<i>p</i> ₁ (bar)	<i>p</i> ₂ (bar)	Pout (kWh)
1	5	2	0.536
2	7	2	1.047
3	7	3	2.006
4	7	4	2.485
5	8	2	1.134
6	8	3	2.093
7	8	4	2.442

Table 4.3: Power output under different boiler and turbine pressures



Figure 4.2: Power output versus turbine pressure

Recalling the basic of vapor power system that is the ideal Rankine cycle. By looking at **Figure 4.3(a)**, the average temperature of heat addition is greater for 1'-2'-3-4'-1' than from the initial cycle 1-2-3-4-1. This shows that the thermal efficiency increases as the boiler pressure increases. The same condition happens when lowering the condenser pressure while keeping boiler at a fixed pressure as shown in **Figure 4.3(b)**. The greater thermal efficiency is obtained by decreasing the condenser pressure. By having a condenser operating at pressure lower than the atmospheric, the steam turbine has a lower-pressure region at its discharge, resulting in significant increase in net work and thermal efficiency.



Figure 4.3: Effects of varying operating pressure on ideal Rankine cycle (a) Effect of boiler pressure (b) Effect of condenser pressure (Moran & Shapiro, 2004)

4.4 Effect of turbine inlet temperature on mechanical efficiency

Analysis on mechanical efficiency demonstrates that higher efficiency is obtained when the turbine inlet temperature is higher. This agrees with the previous findings as more turbine efficiency and effectiveness creates more power output. The result is also consistent with the study by Graves (1980). **Table 4.4** and **Figure 4.4** shows the mechanical efficiency of the turbine under variations of turbine inlet temperatures.

Table 4.4: Mechanical efficiency under different turbine inlet temperatures

Test no	T4 (°C)	ηturbine (%)
1	120	17.88
2	135	34.88
3	140	66.86
4	148	82.85
5	135	37.80
6	143	69.77
7	150	81.40



Figure 4.4: Mechanical efficiency versus turbine inlet temperature

4.5 Effect of turbine inlet temperature on steam quality

The experimental results also suggests a minor reduction of 0.001% to 0.3% in the steam quality as the temperature of the turbine inlet escalates, as illustrated in **Table 4.5** and **Figure 4.5**. This implies that more liquid is produced at the elevated temperature.

Test no	T ₄ (°C)	x
1	120	0.9999
2	135	0.9998
3	140	0.9996
4	148	0.9986
5	135	0.9997
6	143	0.9991
7	150	0.9968

Table 4.5 : Steam quality for different turbine inlet temperatures



Figure 4.5: Steam quality versus turbine inlet temperature

CHAPTER 5: CONCLUSION

Experimental work has been carried out on a laboratory-scale steam power plant of 3 kW capacity. Based on the experimental results and analysis, the following conclusions have been achieved:

- 1. The steam turbine exhibits a significant increase in performance in terms of power output, thermal efficiency and mechanical efficiency with the increasing turbine inlet temperature.
- 2. Highest mechanical efficiency of 82.85% and power output of 2.485 kWh were attained at the turbine inlet temperature and turbine pressure of 148°C and 4 bar respectively.
- 3. Steam quality slightly declines by 0.001% to 0.3% as the turbine inlet temperature escalates. The highest mechanical efficiency and power output were achieved with the steam quality of 0.9968.
- 4. All thermodynamics and performance parameters during the operation of steam turbine are measured and analyzed. The result is validated and consistent with the existing theories in open literature.
- 5. High turbine inlet temperature contributes to the improved performance of the turbine and overall power plant. Further performance optimization can be achieved by considering other parameters such as turbine inlet and outlet pressure, steam flow rate and boiler pressure.

Recommendations for future work are listed below:

- 1. Perform exergy or thermodynamics analysis for overall cycle by including all equipment namely boiler, superheater, condenser and feedwater pump.
- 2. Include losses and irreversibility into the analysis to improve the analysis accuracy as these have distinct influence on the cycle performance.

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REFERENCES

- A. Manaf, A. R., & Marzuki, M. N. (2004). *An Introduction to Steam Machinery* (Second edition ed.). Kuala Lumpur: Penerbit Universiti Malaya.
- A. Sinan Karakurt, U. G. (2017). Performance analysis of a steam turbine power plant at part load conditions. *Journal of Thermal Engineering*, 3(2), 1121-1128.
- Arrieta, F. R. P., & Lora, E. E. S. (2005). Influence of ambient temperature on combined-cycle power-plant performance. *Applied Energy*, 80(3), 261-272. doi:10.1016/j.apenergy.2004.04.007
- Association, E. A. M. (2016). Differences Between Diesel and Petrol. Retrieved from <u>https://www.acea.be/news/article/differences-between-diesel-and-petrol</u>
- BP. (2018). BP Energy Outlook 2018. Retrieved from https://www.bp.com:
- Chaibakhsh, A., & Ghaffari, A. (2008). Steam turbine model. *Simulation Modelling Practice and Theory*, *16*(9), 1145-1162. doi:10.1016/j.simpat.2008.05.017
- Chiesa, P., Consonni, S., Lozza, G., & Macchi, E. (1993). Predicting the ultimate performance of advanced power cycles based on very high temperature gas turbine engines. *ASME Journals, 93-GT-223*.
- Eiichiro, W., Yoshinori, T., Takashi, N., Hiroharu, O., Keizo, T., Toshihiro, M., . . . Tanehiro, S. (2003). *Development of NewHigh Efficiency Steam Turbine*. Retrieved from
- El-Shazly, A. A., Elhelw, M., Sorour, M. M., & El-Maghlany, W. M. (2016). Gas turbine performance enhancement via utilizing different integrated turbine inlet cooling techniques. *Alexandria Engineering Journal*, 55(3), 1903-1914. doi:10.1016/j.aej.2016.07.036
- Ganjehkaviri, A., Mohd Jaafar, M. N., & Hosseini, S. E. (2015). Optimization and the effect of steam turbine outlet quality on the output power of a combined cycle power plant. *Energy Conversion and Management*, 89, 231-243. doi:10.1016/j.enconman.2014.09.042
- Geete, A., & Khandwawala, A. I. (2013). Thermodynamic analysis of 120MW thermal power plant with combined effect of constant inlet pressure (124.61bar) and different inlet temperatures. *Case Studies in Thermal Engineering*, *1*(1), 17-25. doi:https://doi.org/10.1016/j.csite.2013.08.001

- Graves, R. L. (1980). Effect of Pressure and Turbine Inlet Temperature on the Efficiency of Pressurized Fluidized Bed Power Plants. *ASME Journals, 80-GT-102*.
- Haseli, Y. (2018). Efficiency improvement of thermal power plants through specific entropy generation. *Energy Conversion and Management, 159*, 109-120. doi:10.1016/j.enconman.2018.01.001
- Kilani, N., Khir, T., & Ben Brahim, A. (2017). Performance analysis of two combined cycle power plants with different steam injection system design. *International Journal of Hydrogen Energy*, 42(17), 12856-12864. doi:10.1016/j.ijhydene.2017.01.233
- Kotas, T. J. (1985). *The exergy method of thermal plant analysis*. Butterworths: Anchor Brendon Ltd.
- Mohapatra, A. K., & Sanjay. (2015). Comparative analysis of inlet air cooling techniques integrated to cooled gas turbine plant. *Journal of the Energy Institute*, 88(3), 344-358. doi:10.1016/j.joei.2014.07.006
- Moran, M. J., & Shapiro, H. N. (2004). *Fundamentals of Engineering Thermodynamics* (5th ed.): John Wiley & Sons, Inc.
- Poullikkas, A. (2005). An overview of current and future sustainable gas turbine technologies. *Renewable and Sustainable Energy Reviews*, 9(5), 409-443. doi:10.1016/j.rser.2004.05.009
- Regulagadda, P., Dincer, I., & Naterer, G. F. (2010). Exergy analysis of a thermal power plant with measured boiler and turbine losses. *Applied Thermal Engineering*, *30*(8-9), 970-976. doi:10.1016/j.applthermaleng.2010.01.008
- Rout, I. S., Gaikwad, A., Verma, V. K., & Tariq, M. (2013). Thermal analysis of steam turbine power plants. *IOSR Journal of Mechanical and Civil Engineering* (*IOSR-JMCE*), 7(2), 28-36.
- Shams, B. M., Elkanzi, E. M., Ramadhan, Z., Rahma, S., & Khamis, M. (2017). Gas turbine inlet air cooling system for enhancing propane recovery in a gas plant: Theoretical and cost analyses. *Journal of Natural Gas Science and Engineering*, 43, 22-32. doi:10.1016/j.jngse.2017.03.031
- TEPCO, J. (2010). Protecting the Earth from global warming Increase thermal power efficiency.