Analysis and Determination of Optimum Performance Parameters for a Ten Megawatt Steam Turbine

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Abstract: In order to contribute to the development of a steam turbine locally, optimum performance parameters for a ten (10) megawatt steam turbine were analyzed for power generation in Iesus Hominum Salvator (IHS) community. Total power consumption of electrical appliances was estimated, from which future capacity projection was done for the design. A two-stage turbine with re-heater and regenerator Rankine cycle was adopted for the analysis. MATLAB code which is based on certain governing equations for estimating performance parameters based on the operating temperatures and pressures was developed. The effects of operating pressures on performance parameters were simulated and used to determine the optimum operating parameters for efficiency, steam quality and flow rate respectively using Response Surface Methodology (RSM). Results from investigation shows that efficiency and steam quality tend to increase as re-heat pressure increases, while the volume of steam required to generate 10MW decreases. Efficiency of steam tends to increase with feed water pressures while the steam quality is unaffected. Efficiency of steam tends to decrease with the steam pressure at the turbine exit while the quality of steam tends to increase. Operating pressures for optimum efficiency, flow rate and steam quality obtained using RSM are 0.82MPa, 0.85MPa and 0.47MPa while efficiency, flow rate and steam quality are 42.2%, 2.8m^3/s and 90% respectively. Optimum operating parameters for efficiency and economy were successfully determined for the design of 10MW steam turbine.

Keywords: Megawatt Steam Turbine; Iesus Hominum Salvator (IHS) community; Two-Stage Turbine; Re-heater; Regenerator; Rankine Cycle; MATLAB code; Response Surface Methodology (RSM).

1.0 Introduction

Electricity is not freely available in nature, so it must be "produced" (that is, transforming other forms of energy to electricity). Production is carried out in power stations (also called "power plants"). Electricity is most often generated at a power plant by electromechanical generators, primarily driven by not only heat engines fueled by combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind.

Steam is the working fluid in the operation of steam turbine. Steam has been a popular mode of conveying energy since the industrial revolution. (Ramananth., 2013). A steam turbine is a heat engine in which the energy of the steam is transformed into work. Firstly, the steam from the boiler expands through a nozzle and is converted into kinetic energy in the turbine. The kinetic energy is then converted into work on rotating blades (Church, 1950). In a typical condensing turbine high pressure and high temperature steam is allowed to expand progressively in stages through the various rows of blades until it is exhausted to the condenser. As the steam progresses through the turbine, the pressure reduces and the volume of the steam increases. To compensate for this volume, increase the blade passages of the turbine take the shape of an expanding cone, with the largest diameter blades located at the low pressure end of the turbine. The amount of heat that is converted into kinetic energy by the fixed blades (or nozzles) is dependent on the design shape of these blades. Steam turbines are used for power generation due to the following: low initial cost, low expense for maintenance, exhaust steam is free of oil contamination as no internal lubrication is needed, ability to utilize high pressure and high temperature steam, high rotational speed, high capacity, weight ratio, smooth, nearly vibration free operation, can be built in small or very large units (up to 1200MW) and high efficiency over a wide range of load conditions., (Bullard., 1981).

A steam turbine can be considered as a rotary heat engine constructed of a number of cylinders (each cylinder comprises a cylinder casing that contains a rotor). Individual rotors are supported within their respective cylinder casing by journal bearings. The cylinder casing is the stationary component of the turbine while the rotating section of the turbine is referred to as the rotor. The cylinder casing contains rows of stationary or fixed blades with rotating blades connected to the rotor. These rotating blades are installed between the fixed blades. The stationary blades are fitted into the cylinder casing in such a fashion as to direct or redirect the steam onto the next row of rotating blades. The cylinder rotors are coupled together and connected to the alternator rotor. Steam governor valves control the turbine output. A condenser installed at the exhaust or low-pressure end of the turbine receives and condenses the steam prior to it being pumped back to the boiler. Steam turbines operation is based on the Rankine cycle. They are designed to operate on certain operating conditions like steam inlet pressure and temperature and turbine exhaust pressure, which affects the performance of the turbines significantly. Therefore, analyzing and determining the best performance parameters of a steam turbine for efficiency, mass flow-rate and steam quality will contribute to the development of a steam turbine locally which will help to reduce local electricity problems. The research and pragmatic efforts aimed at analyzing and determining the optimum performance parameters of a ten (10) megawatts steam turbine in Iesus Hominum Salvator (IHS) community in delta state. However, the demand of power has been increasing extensively over the years in Iesus Hominum Salvator (IHS) community in delta state due to expansion and rapid rate of development. The presence of 11KVA industrial plant to address the local electricity problem is no longer sufficient. It however seems that no matter how much effort put into it, the problem lingers simply because electricity demand keep rising while power supply remains stagnant and or declining. To solve this problem, a Ten (10) megawatts steam turbine was modeled based on operating parameters in order to determine the best optimum parameters for efficiency and economy. Implementing this project will create the platform into development of steam turbine in Iesus Hominum Salvator (IHS) community that can address electrical power problems. Although, the project is limited to the determination of optimum design parameters for best performance of a ten (10) megawatts steam turbine suitable for power generation in Iesus Hominum Salvator (IHS) community in Delta State, Nigeria. The specific objectives of this research study are:

(1) To estimate the power consumption rate in Iesus Hominum Salvator (IHS) community using a developed MATLAB code configuration system equations;
(2) To model and simulate a Two-Stage Turbine Power generation plant with re-heater and regenerator Rankine cycle using a MATLAB Programming Engineering Tool;
(3) To determine the optimum design and operating parameters for best performance, efficiency, steam quality and flow rate using a Response Surface Methodology (RSM).

Hence, section 2, 3 and 4 of this paper elucidated on the methods adopted in the study, main results and their interpretation. Hence, the summary of the whole finding presented in form of conclusion respectively.

2.0 Methodology

2.1 Determination of Power Consumption Rate in IHS

The total consumption rate of the electrical appliances used in IHS community was calculated by summing up the respective consumption rate of the various departments in IHS. The calculation was based on the formula below.

$$C.R = \frac{\sum P.R \times T_{av}}{1000} \qquad (1)$$

Where

C.R= Consumption rate in kW /hr
P.R= Power rating electrical appliances in Watts
T_{av}= Average time of use in hours

Table 3.1 depicts the results obtained from energy consumption rate of the appliances in IHS community used for power estimation

2.2 Model and simulate a Two-Stage Turbine Power generation plant

2.2.1 Turbine Cycle Design

Modern two stage Re- heater turbines with respective feed waters system in each turbine stage was used for this work. It is the design used in steam turbine power generation plants. Schematic diagram and T-s diagram for the steam turbine cycle are shown in the figures 2.1 and 2.2 respectively.

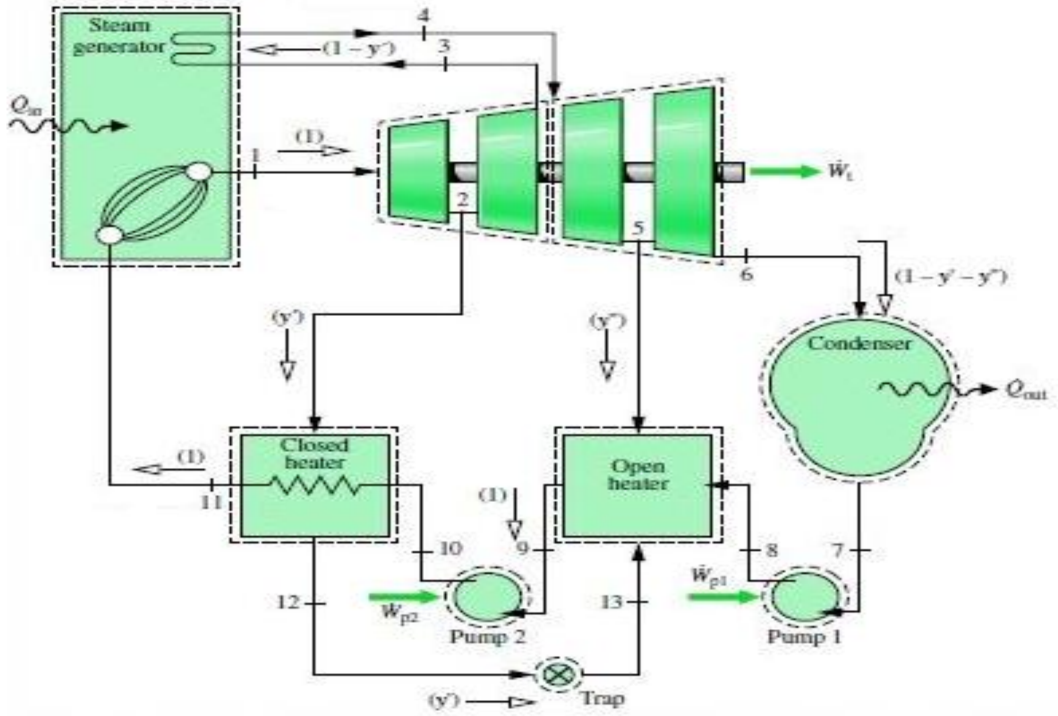

Figure 2.1 Schematic Diagram of a Steam Turbine (Source: Michael and Howard, 2006)

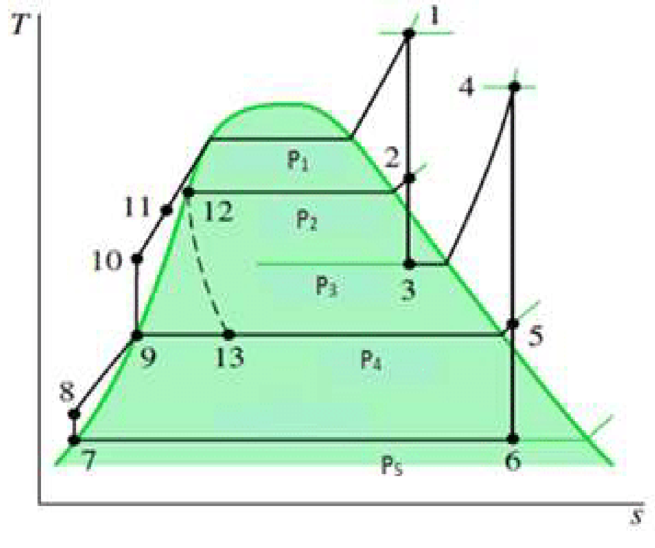

Figure 2.2 T-S diagram (Source: Michael and Howard, 2006)

2.2.2 MATLAB Programming algorithm for Simulation Experiment

MATLAB Version 2015 was used to develop a program to calculate for the performance parameters. These include Efficiency, work output of the turbine, mass flow rate, Steam fraction and Steam quality using operating parameters such as inlet pressure, different stages of pressures, exit pressure in order to determine the data for optimization using Response Surface Methodology (RSM). Figure 2.3 shows the flowchart of the program.

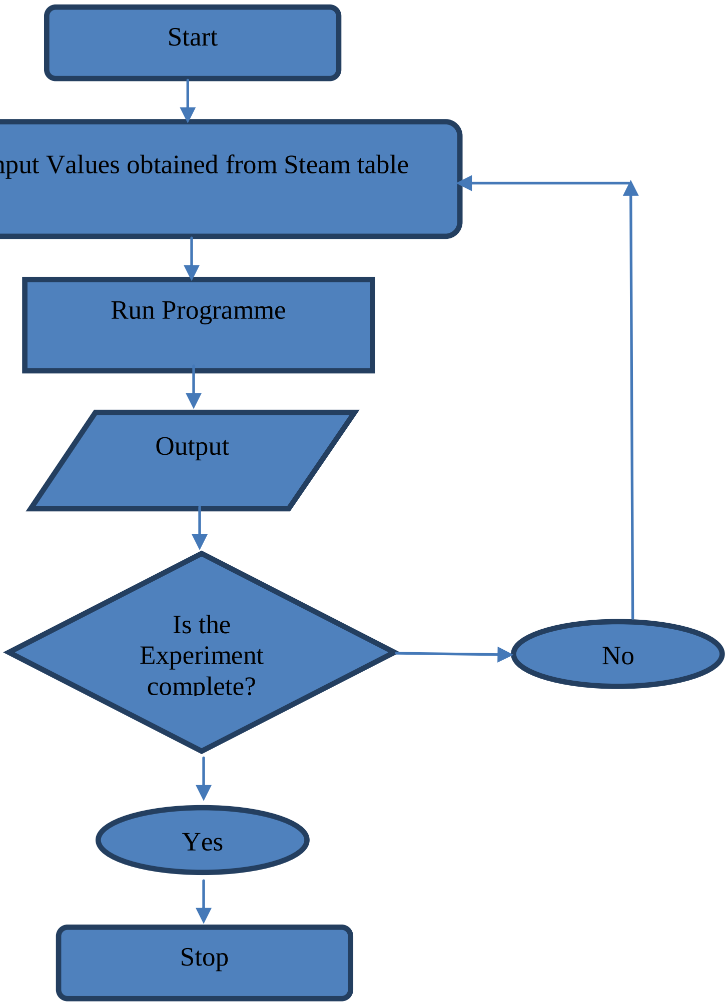

Figure 2.3: Flow Chart of the MATLAB program (See Appendix 1 for the MATLAB codes)

However, the experiment was carried out on the below assumptions:

(1) Each component in the cycle is analyzed as a control volume at steady state. The control volumes are shown on the accompanying sketch by broken line in steam turbine schematic diagram;
(2) There is no steady heat transfer from any component to its surroundings;
(3) The working fluid undergoes internally reversible processes as it passes through the turbines, pumps, steam generator, re- heater and condenser;
(4) The expansion through the trap is a throttling process;
(5) Kinetic and potential energy effects are negligible;
(6) Condensate exits the closed heater as a saturated liquid at 2MPa. Feed-water exits the open heater as a saturated liquid at 0.3MPa. Condensate exits the condenser as a saturated liquid.

In the turbine, various operating parameters affect condensation and back pressure, steam consumption and efficiency. Turbines are designed for particular operating conditions like steam inlet pressure and temperature and turbine exhaust pressure which affects the performance of the turbines significantly. Using the MATLAB version 2015, a total of 87rum (see Appendix 4) were implemented for the different pressure values. This was done to investigate the effect of pressure on the performance parameters which include Efficiency, Mass Flow Rate, Steam Quality and Steam Fraction. Microsoft excel was used to represent the effects graphically. A variation in these parameters affects the steam consumption in the turbines and also affects the turbine efficiency. The operating parameters imputed in the turbine will affect the turbine performance in terms of mass flow rate, steam quality and efficiency. All turbines are designed for a specific steam inlet pressure. To obtain the design, efficiency, steam inlet pressure was maintained at design level. Similarly, at a higher steam inlet pressure, the energy available to run the turbine was high, which in turn reduced the steam consumption in the turbine. For the experiments, steam entry pressure was 8.0MPa, at 480°c. The steam re-heated temperature was 440°c and re-heat pressure was varied between 1.5 and 4MPa respectively before entering the second turbine. It expands to the condenser pressure varied between 0.007MPa and 0.10MPa experimental pressure. Steam is extracted from the first turbine at different pressures ranging from 1MPa to 4MPa and fed to the closed feed water heater. Feed water leaves the closed heater at 205°c and 8.0MPa for all experiments, and the condensate exits as saturated liquid at 0.007MPa to 0.10MPa range of pressures. The condensate is tapped into the open feed water heater. Steam extracted from the second turbine at 0.2 to 0.5MPa is also fed into the open feed water heater, which operates at 0.2 to 0.5MPa. The steam exiting the open feed water heater is saturated liquid at 0.2MPa to 0.5MPa. The net power output of the cycle is 10MW as estimated power for the analysis.

2.3 Operating Parameters

The operating parameters are the pressures and temperatures of the turbine at different stages. This is depicted in figure 3.2. Considering figure 3.2, P_1& T_1 are the inlet pressure and the inlet temperature, P_2 is the first feed heater pressure, P_3& T_4 are the Re-heat pressure and re-heat temperature, P_4 is the super- heated pressure, P_5 is the second feed heater pressure and P_6 is the condenser pressure.

2.3.1 Performance Parameters

The performance parameters are the efficiency, Steam quality and Mass flow rate. The efficiency of the turbine is a function of the pressure and temperature at the inlet, regenerators and feed waters and exit of the turbine. The mass flow rate is a function of the quantity of steam flowing to the turbine.

2.3.2 Mass and energy rate balance correlation

From figure 2.1 and 2.2: y' and y''can be determined by application of mass and energy rate balance. The energy balance in figure 2.2 referring to the closed feed heater can however be deduce as:

$$y'h_2 + h_{10} = y'h_{12} + h_{11}$$

$$y' = \frac{h_{11} - h_{10}}{h_{2-h_{12}}} \tag{2}$$

The steam fractiony' is the steam that was blended from the turbine.

The fraction y'' can be determined by application of mass and energy rate balances to a control volume enclosing the open heater in figure 3.1, resulting in:

$$(y'' \text{x} h_5) + (1 - y' - y'')\, h_8 + (y' \text{x} h_{13}) = h_9$$

$$0 = (\text{y x} h_5) + (1 - y' - y'')\, h_8 + (y' \text{x} h_{13}) - h_9$$

$$y'' = \frac{[\,(1 - y')\, h_8 + (y' \text{ x } h_{13}) - h_9\,]}{(h_8 - h_5)} \tag{3}$$

The following work and heat transfer values are expressed on the basis of a unit mass entering the first turbine.

The work developed by the first turbine per unit of mass entering in figure 2.1 is given as:

$$\frac{w_{t1}}{m_1} = h_1 - h_2 + (1 - y')\,(h_2 - h_3) \tag{4}$$

Similarly, for the second turbine in figure 3.1:

$$\frac{w_{t2}}{m_2} = (1 - y^1)\,(h_4 - h_5)\,(1 - y' - y'')\,(h_5 - h_6) \tag{5}$$

For the first Feed pump in figure 3.1:

$$\frac{w_{p1}}{m} = (1 - y' - y'')\,(h_8 - h_7) \tag{6}$$

For the secondFeed pump in figure 3.1:

$$\frac{w_{p2}}{m} = (h_{10} - h_9) \tag{7}$$

The total heat added is the sum of the energy added by heat transfer during boiling/superheating and re-heating. When expressed on the basis of unit of mass entering the first turbine, this is:

$$\frac{Q_{in}}{m} = (h_1 - h_{11}) \tag{8}$$

The thermal efficiency is:

$$\eta = \frac{w_{t1}}{m} + \frac{w_{t2}}{m} - \frac{w_{p1}}{m} - \frac{w_{p2}}{m} \div \frac{Q_{in}}{m} \tag{9}$$

2.3.3 Design Optimization

Turbine design attempts to obtain operating parameters for the best efficiency. To obtain the optimum operating parameters, Response Surface Methodology (RSM) was used to design for the five different pressure stages as it affects efficiency, flow rate and feed-waters which is cost implicative. Appendix 3 contains details of rum data. A total of 17rv/m was designed for the different ranges of pressure values.

2.4 Use of Response Surface Methodology (RSM)

The main purpose of RSM is the determination of the optimum settings of the control variables that results in a maximum or minimum response over a certain region of interest. This requires having a good fitting model that provides an adequate representation of the mean response because such a model is to be utilized to determine the value of the optimum (Andre et al., 2010). Some variables which influences the steam turbine were observed, the limits of these parameters were analyzed prior to the analysis of the steam turbine. Three key variables with their values that affect the response were mainly observed. The steam turbine operating parameters were observed to vary with these combinations of variables. The constraint function is shown in Table 2.2**.** Therefore, the parameters of steam turbines can be represented by the function of three parameters as:
Steam turbine operating parameters = f (X_1, X_2, X_3)

Where: X_1 = Re-heat pressure (MPa), X_2= First feed heater pressure (MPa) and X_3= Second feed heater pressure (MPa)

Table 2.1 Constraint Function Table

S/N	Operating Parameters Variables	Constraints
1	Re-heat Pressure (MPa)	$0.50 \le X_1 \le 3.0$
2	First feed heater Pressure (MPa)	$0.70 \le X_2 \le 1.20$
3	Second feed heater pressure (MPa)	$0.10 \le X_3 \le 0.50$

2.4.1 Factors Design Using RSM

The steam turbine tests were conducted using the MATLAB simulation code developed. The codes are contained in Appendix 1. The process parameters in coded and actual values are shown in Table 3.3. The experimental layout plan and the measured values of responses are shown in Appendix 2.

Table 2.2: Process parameters in coded and actual values

Factors	Symbol	X_1	X_2	X_3
		-1	**0**	**1**
Re-heat Pressure (MPa)	X_1	0.50	1.75	3.00
First feed water Pressure (MPa)	X_2	0.70	0.95	1.20
Second feed water pressure (MPa)	X_3	0.10	0.30	0.50

3.0 RESULTS AND DISCUSSIONS

3.1 Discussion of Experiment

Shown in Table 3.1 is the total energy consumption of 760.84kWh from 474 Compact Fluorescent (CFL) bulbs of 36W each, 59 Air conditioning units of 1492W each and 40 fans of 90W each. The consumption of the appliances in the other structures such as Science Laboratory, Administrative Building, etc. was also shown and was used to obtain the consumption estimate used for the simulation.

3.1.1 Effect of Pressure on the Performance Parameters Using MATLAB

The results from the investigation of the effect of pressure on the performance parameters using MATLAB (Version 2015) are presented in figures respectively.

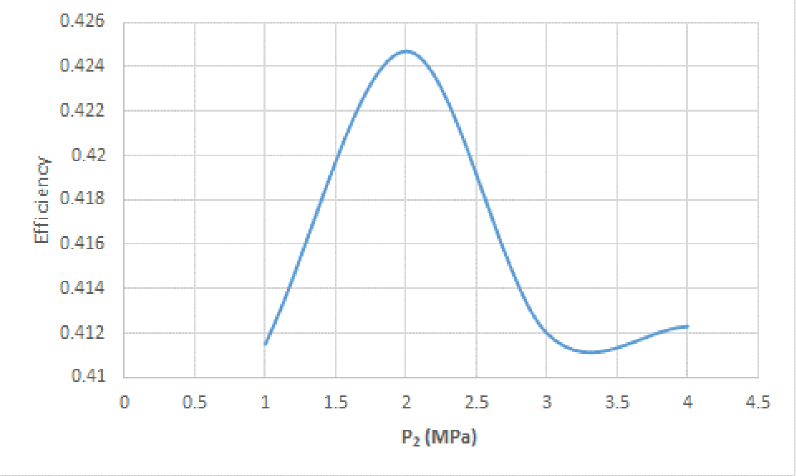

Figure 3.1 Graph of Efficiency against First Feed Water Pressure, P_2 (MPa)

Figure 3.1 shows that the efficiency of the steam turbine first increased with increase in the first feed water pressure from 1 to about 2.0 MPa, a gradual decrease with further increase in pressure beyond 2.0MPa was observed. The maximum efficiency was recorded to be about 0.427.

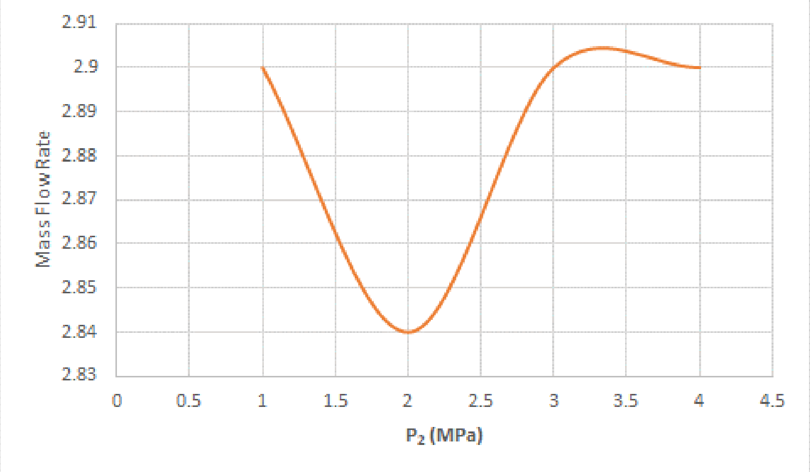

Figure 3.2 Graph of Mass Flow Rate against First Feed Water Pressure, P_2 (MPa)

Figure 3.2 shows that the mass flow rate of the steam turbine first decreased with increase in the first feed water pressure then it began to increase after a pressure of 2.0MPa. It remained fairly constant at 3.0MPa.

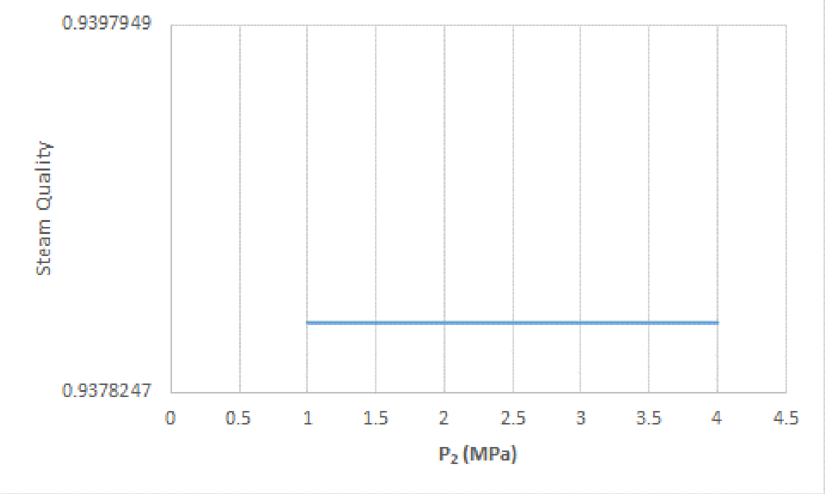

Figure 3.3 Graph of Steam Quality against First Feed Water Pressure, P_2 (MPa)

In Figure 3.3, the steam quality was constant despite an increase in the first feed water pressure.

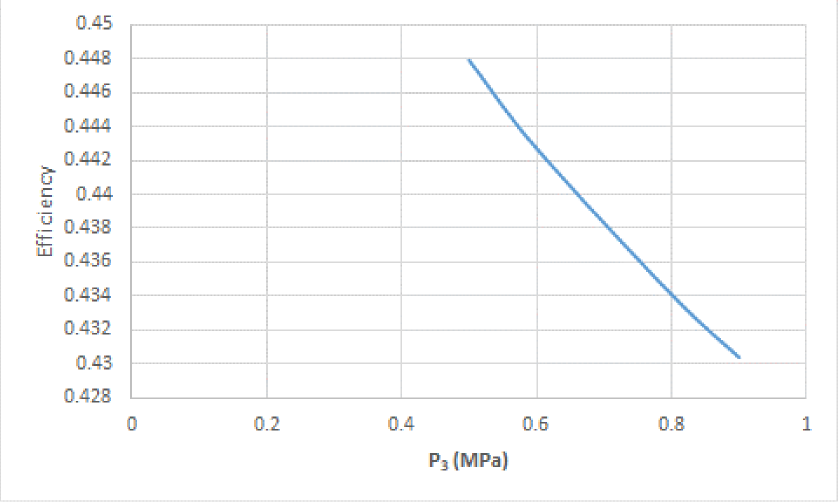

Figure 3.4 Graph of Efficiency against Reheat Pressure, P_3 (MPa)

In Figure 3.4, an increase in the pressure caused the efficiency of the steam turbine to decrease.

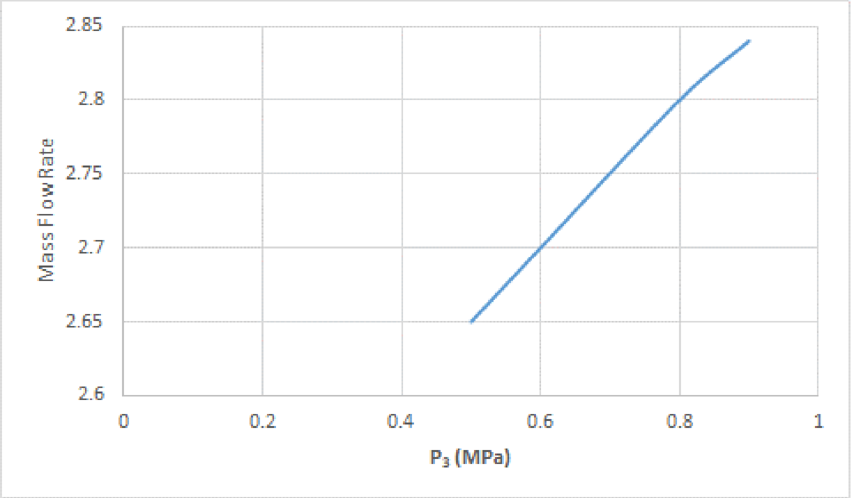

Figure 3.5 Graph of Mass Flow Rate against Reheat Pressure, P_3 (MPa)

Figure 3.5 reveals that the mass flow rate increased with increase in reheat pressure.

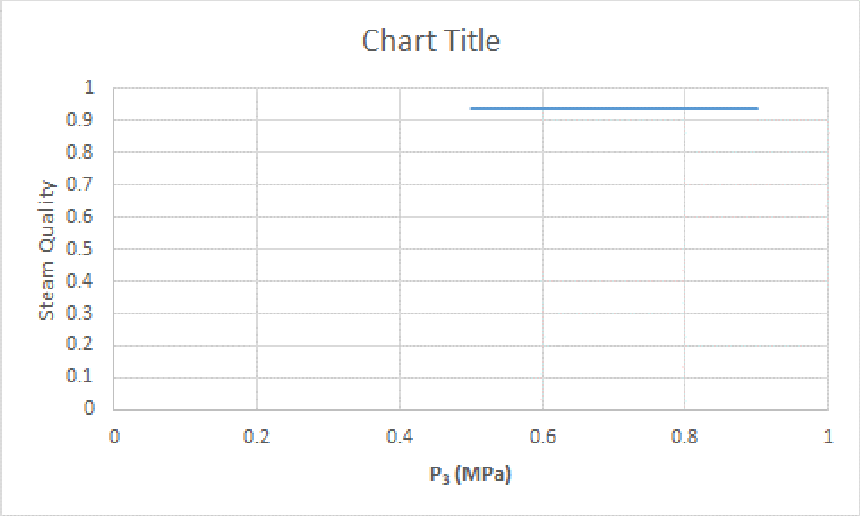

Figure 3.6 Graph of Steam Quality against Reheat Pressure, P_3 (MPa)

Figure 3.6 shows that an increase in reheat pressure had little effect on the steam quality.

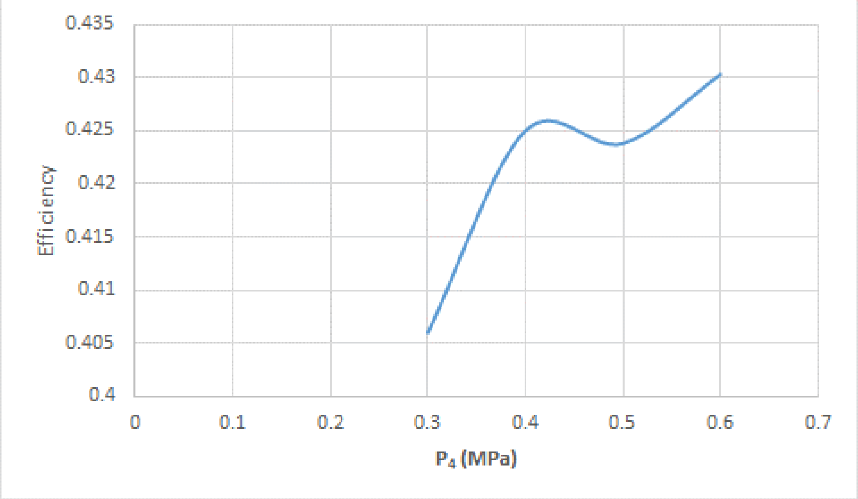

Figure 3.7 Graph of Efficiency against Superheated Pressure, P_4 (MPa)

Figure 3.7 reveals that the efficiency of the steam turbine increased with increase in superheated pressure.

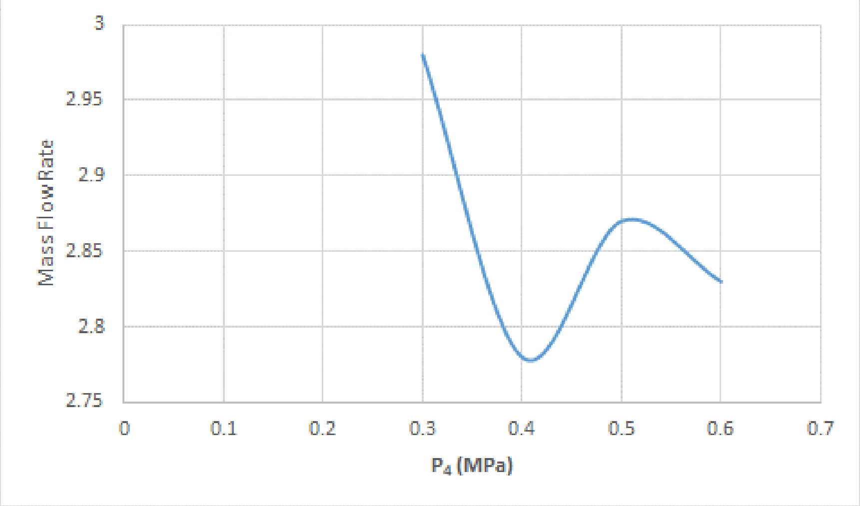

Figure 3.8 Graph of Mass Flow Rate against Superheated Pressure, P_4 (MPa)

In Figure 3.8, the mass flow rate of the steam turbine decreased as the superheated pressure increased. Then increased from 0.4MPa of the second feed water pressure.

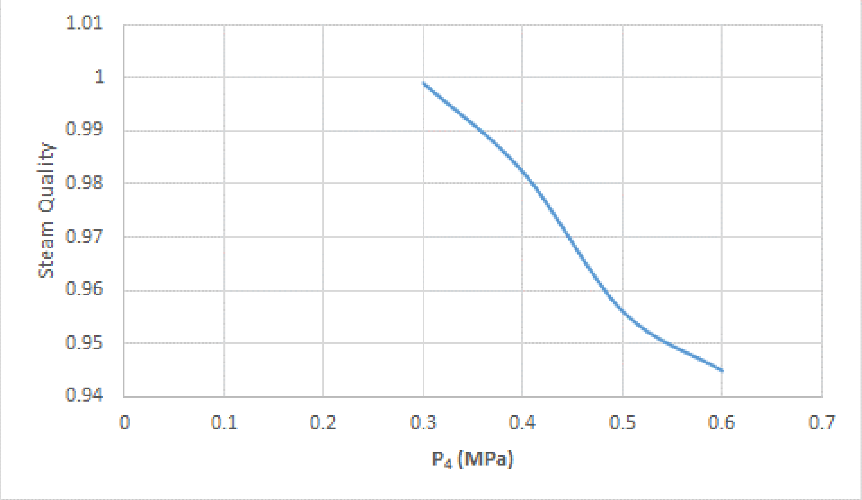

Figure 3.9 Graph of Steam Quality against Superheated Pressure, P_4 (MPa)

Figure 3.9 reveals a rather steady decrease in steam quality with increase in superheated pressure of the turbine.

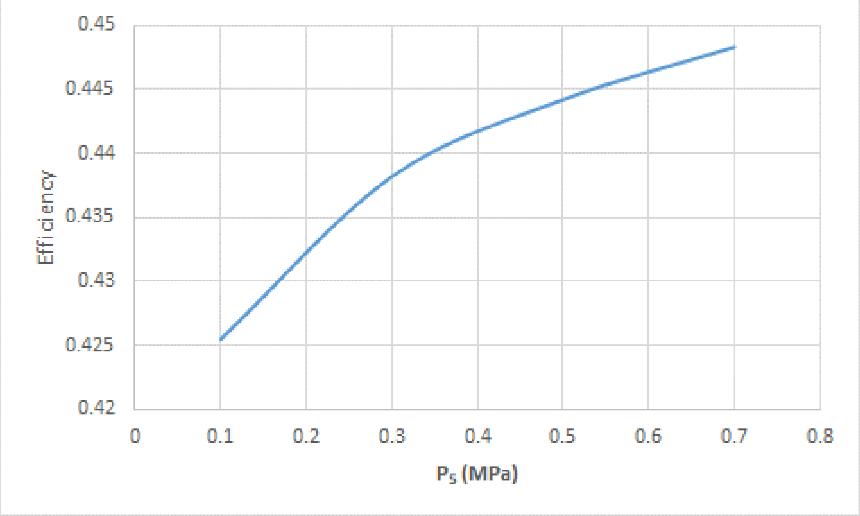

Figure 3.10 Graph of Efficiency against Second Feed Water Pressure, P_5 (MPa)

In Figure 3.10, the turbine efficiency increased with increase in the second feed water pressure.

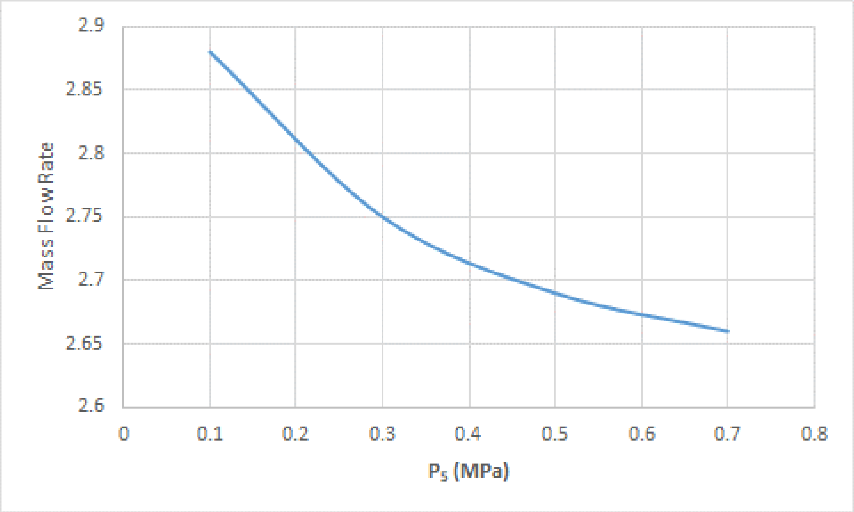

Figure 3.11 Graph of Mass Flow Rate against Second Feed Water Pressure, P_5 (MPa)

Figure 3.11 shows that the mass flow rate decreased with increase in the second feed water pressure.

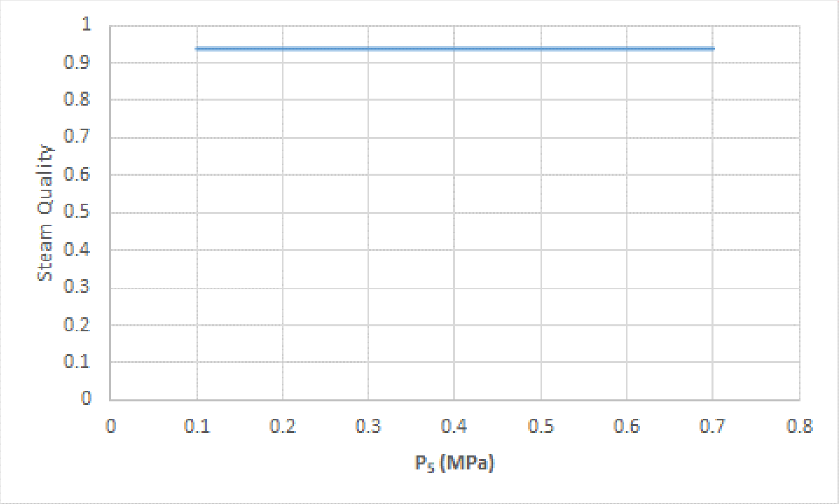

Figure 3.12 Graph of Steam Quality against Second Feed Water Pressure, P_5 (MPa)

Figure 3.12 shows that steam quality remained constant with increase in the second feed water pressure.

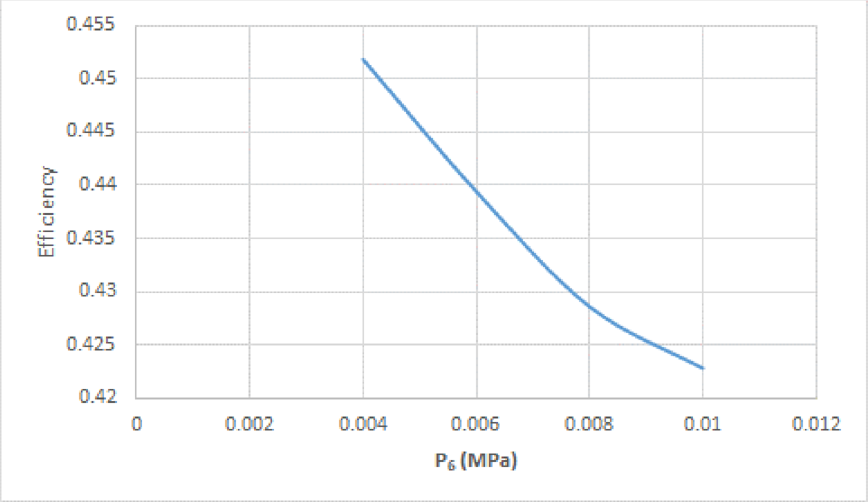

Figure 3.13 Graph of Efficiency against Condenser Pressure, P_6 (MPa)

Figure 3.13 shows that the turbine efficiency decreased with increase in condenser pressure.

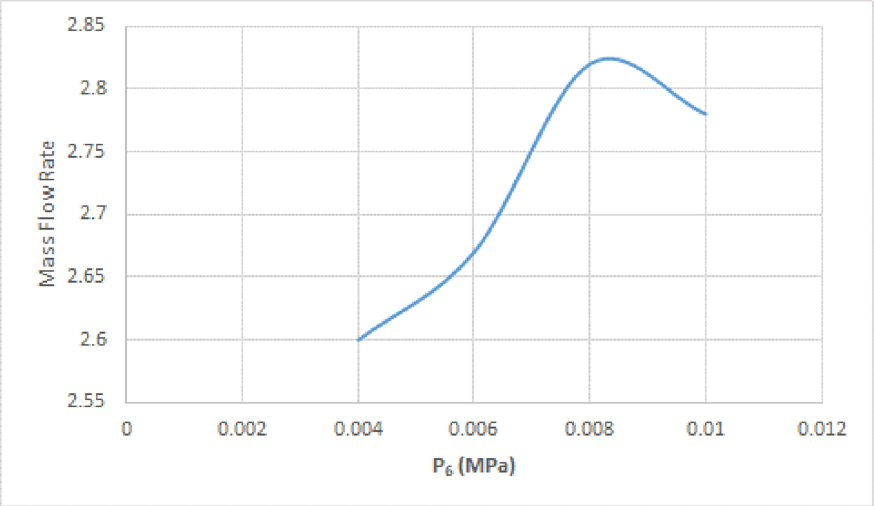

Figure 3.14 Graph of Mass Flow Rate against Condenser Pressure, P_6 (MPa)

In Figure 3.14, the mass flow rate first increased, then began to decrease at about 0.08MPa with further increase of the condenser pressure.

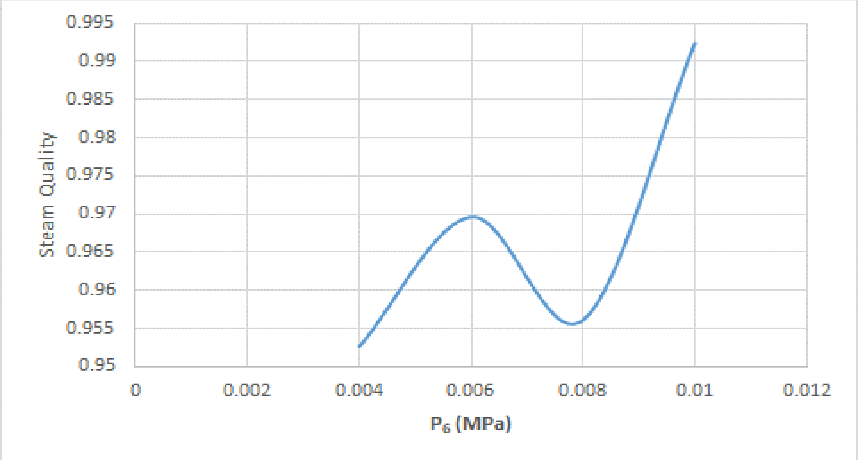

Figure 3.15 Graph of Steam Quality against Condenser Pressure, P_6 (MPa)

Figure 3.15 shows that the steam quality was increasing before a sudden drop.Then, increased with increase in the condenser pressure beyond 0.08MPa.

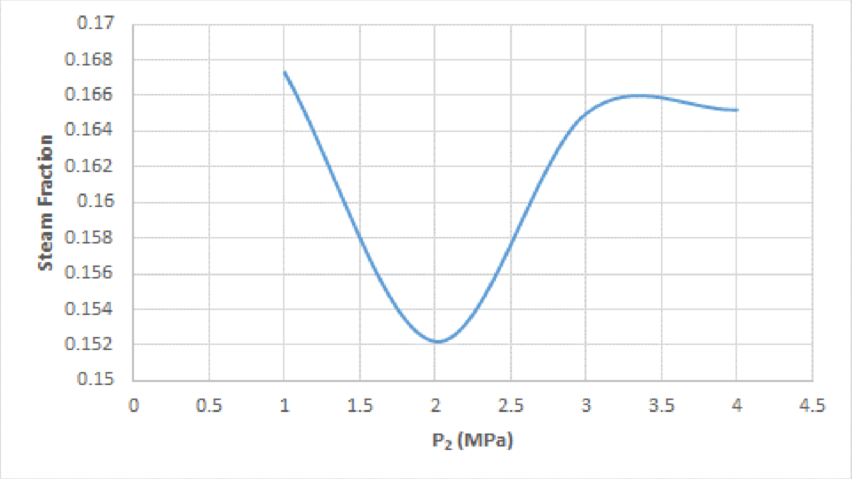

Figure 3.16 Graph of Steam Fraction against First Feed Water Pressure, P_2 (MPa)

Figure 3.16 shows that the steam fraction first decreased and then began to increase from about 2MPa of the first feed water pressure

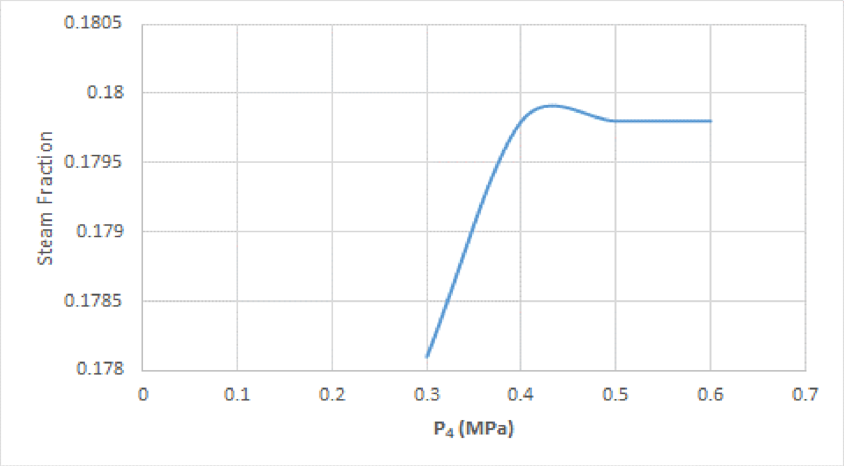

Figure 3.17 Graph of Steam Fraction against Superheated Pressure, P_4 (MPa)

Figure 3.17 shows that the steam fraction increased with increase in superheated pressure but was constant beyond 0.45MPa.

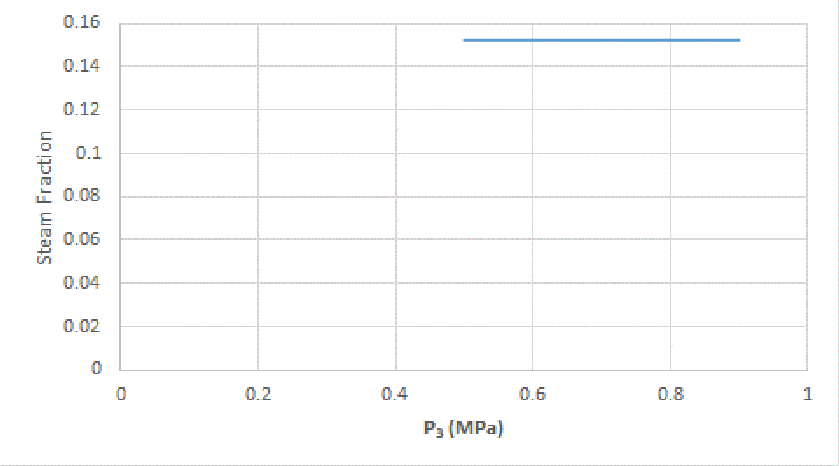

Figure 3.18 Graph of Steam Fraction against Reheat Pressure, P_3 (MPa)

Figure 3.18 show that the steam fraction was constant with increase in the reheat pressure and condenser pressure respectively.

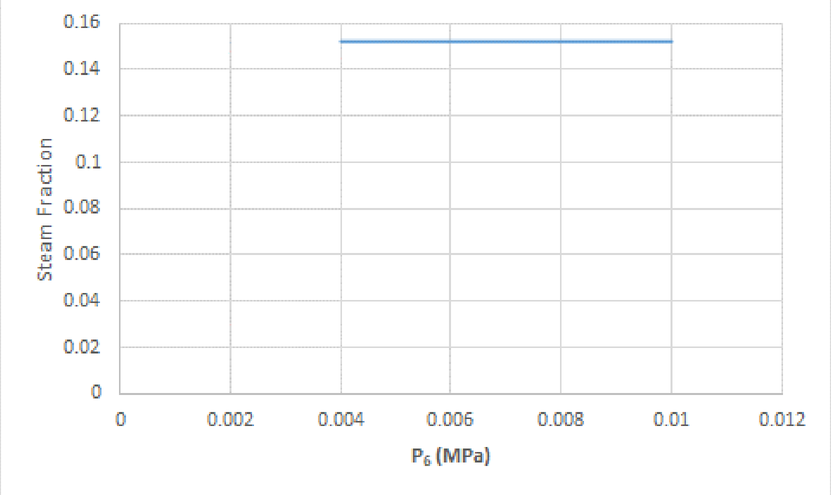

Figure 3.19 Graph of Steam Fraction against Condenser Pressure, P_6 (MPa)

Figure 3.19 show that the steam fraction was constant with increase in the reheat pressure and condenser pressure respectively.

Table 3.1: Constraints for modified performance characteristic response model

Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
Re-heat Pressure	is in range	0.5	3	1	1	3
First Feed Water Pressure	is in range	0.7	1.2	1	1	3
Second feed Water Pressure	is in range	0.1	0.5	1	1	3
Efficiency	Maximize	0.33262	0.4221	1	1	3
Flow Rate	is in range	2.7	4	1	1	3
Steam Quality	Maximize	0.8408	0.9895	1	1	3

Table 3.2: Estimated optimization values of experimental variables X_1, X_2, and X_3

Actual Variables	Estimate	Unit
Re-heat Pressure	0.500	Mpa
First Feed Water Pressure	0.700	Mpa
Second Feed Water Pressure	0.417	Mpa

Re-heat pressure of 0.500MPa, first feed water pressure of 0.700MPa and Second feed water pressure of 0.417MPa optimum values were obtained and the mass flow rate and steam quality of the steam turbine were 2.819m^3/s and 0.956 respectively with a desirability of 0.880.

Table 3.3: Validation of Test Results

Performance Parameters	**Predicted Value**	**Experimental Value**	**Error (%)**
Efficiency	0.422	0.418	0.96
Mass Flow Rate	2.819	2.841	0.77
Steam Quality	0.956	0.953	0.31

4.0 Conclusion

MATLAB Version 2015 was used to develop a program to calculate for the performance parameters. These include Efficiency, work output of the turbine, mass flow rate, Steam fraction and Steam quality using operating parameters such as inlet pressure, different stages of pressures, exit pressure in order to determine the data for optimization using Response Surface Methodology (RSM). MATLAB version 2015, were implemented for the different pressure values. This was done to investigate the effect of pressure on the performance parameters .Microsoft Excel was used to represent the effects graphically. From the analysis, it was deduced that the effects of steam turbine operating parameters on its performance parameters, as well as to determine the optimum performance parameters of a steam turbine which would be needed to design a 10MW steam turbine in Iesus Hominum Salvator community (IHS) was carried out. The main results obtained from the study are:

- The optimal value of the efficiency of the steam turbine is 42%, with mass flow rate and steam quality of the steam turbine as 2.819m^3/s and 0.956 respectively;
- At reheat pressure of 0.50MPa, first feed water pressure of 0.70MPa and second feed water pressure of 0.417MPa. Prior to the analysis of a steam turbine, some operating parameters which affect the steam turbine were and the limit of these parameters were observed;
- The key variables with their constraint values that affect the response were mainly observed. However, the steam turbine operating parameters were observed to vary with these combinations of variables;
- The optimization procedure of Design Experts for efficiency and flow rate ranging from 0.3326 - 0.4221% and 2.7 - 4.0 m^3/s are obtained. And the optimized values from the optimization values are presented and were deduced with the predicted efficiency, flow rate and steam quality of 0.422%, 2.819m^3/s and 0.956% respectively with a desirability value of 0.880. Hence, preferred option amongst the options compared in the reviewed literatures taking Nigeria as a case study.

In summary, introducing a steam turbine power plant with an optimal value using a developed optimization procedure will enhance energy efficiency in Nigeria and of course increases energy availability. For future study, change in the values of the operating parameters should be closely monitored, given that any slight change in these values can significantly affect the values of the performance parameters. This will help to reduce error. Moreover, the use of combined cycle, which involves using gas and steam turbine can be implemented to obtain higher efficiency. At same time extended to see the effect of temperature on performance parameters when varied.

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