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Performance Analysis of Steam Turbine Capacity of 35 MW at Geothermal Power Plant

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***Abstract* - Geothermal Power Plant has the main component, namely turbines. The decrease in turbine performance will affect the reliability of the plant and the generation power, The writing of this report aims to find out the main processes and components in the power plant. Then find out the performance of the turbine in the geothermal power plant to find out the performance of the turbine. After obtaining the turbine performance results, the authors identified parameters that affect turbine performance, and then to conclude the current performance conditions, the authors made a comparison between actual performance and performance by design. During operation, it is estimated that the efficiency of the turbine has decreased due to several factors such as frequent derating (decrease in load) or trip (unit shutdown), factors of length of maintenance, errors in operation and maintenance and other factors. Therefore, it is necessary to analyze the efficiency of the turbine whether the turbine is still within the limits of reliable conditions or not.**

The results of the analysis by taking samples for 16 days obtained the average efficiency of turbines at unit X plants is currently 74.40%. When compared to turbine efficiency by design of 75.28%, the turbine efficiency value is currently decreasing by ±0.88%.

Keywords: Turbines, Efficiency, Geothermal.

I. INTRODUCTION

Geothermal power plants are one of the environmentally friendly alternatives to power generation [1]. In general, geothermal is distributed and filtration is carried out to remove impurities contained in hot steam so that clean hot steam is used to drive turbines, then the steam can be converted into electrical energy using a generator [2]. Thus, one of the important components in geothermal power plants is the steam turbine. A steam turbine is a device that can convert hot steam into mechanical energy in the form of rotation of the turbine shaft which will then drive the generator so that it produces electrical energy [3]. There are things that need to be considered to keep the electricity generation process running normally is to look at the performance of each tool used, because when the performance of the tool decreases, it will affect the process that occurs and the electrical energy produced [4].

At this time, there was no research related to the efficiency of the steam turbine on the previous X unit. Therefore, this practical work is carried out as one of the author learning systems in order to be able to analyze and solve problems regarding the Performance Analysis of Steam Turbines with a Capacity of 35 MW Unit X at Geothermal Power Plant.

In conclusion later, the writer hopes the maximum value of turbine efficiency either for other parameters, and find a conclusion which lead to a way to improve the work of turbine to produce output at its best working condition [1] [2].

1.1 Method

This study is completed by calculating the performance of the steam turbine in actual conditions, design, and optimization that can be done. Performance is something that is achieved; demonstrated achievements; workability (equipment). Thus, the performance of a steam turbine is the working ability of a tool, namely a steam turbine. To interpret the performance of the steam turbine is to consider the efficiency of the steam turbine [1]. When the efficiency value is high, the performance of the steam turbine is still very good, but if the efficiency decreases, the working ability of the steam turbine decreases and loses energy [2].

- Calculating the Vapor Fraction

The vapor fraction or vapor quality is calculated by interpolating from the entropy value entering the turbine. Here is the formula used:

$$x = \frac{s_4 - s_{f5}}{s_{g5} - s_{f5}} \qquad (1)$$

Information:

x = Vapor fraction

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s_4 = Turbine inlet steam entropy (kJ/kg. K)

s_{f5}= Entropy of the turbine outgoing fluid (kJ/kg. K)

s_{f5} = Entropy of the turbine outgoing steam (kJ/kg. K)

- Calculating the Work of the Ideal Turbine

The work of an ideal turbine or the work of an isentropic turbine can be obtained from the following equation:

$$w_{ts} = h_4 - h_{s5} \qquad (2)$$

h_{s5} (Isentropic enthalpy) can be searched on the steam coming out of the turbine with using the formula:

$$h_{s5} = h_f + x\, h_{fg} \qquad (3)$$

Information:

h_{fg} = Enthalpy of the isentropic mixture out of the turbine (kJ/kg)
h_f=Enthalpy of isentropic fluid out of the turbine (kJ/kg)
h_{s5} = Turbine outgoing isentropic enthalpy (kJ/kg)
h_4=Turbine inlet steam enthalpy (kJ/kg)
w_{ts} = ideal/isentropic turbine work (kJ/kg)

- Calculating the Actual Turbine Work

The work of the turbine at the actual condition can be calculated by the following equation:

$$w_{ta} = h_4 - h_5 \qquad (4)$$

To be able to find the value of the turbine outgoing steam enthalpy (h5) at the actual condition can use the formula:

$$h_s = \frac{h_4 - A\left[1 - \left(\frac{h_{f5}}{h_{g5} - h_{f5}}\right)\right]}{1 + \frac{A}{h_{g5} - h_{f5}}} \qquad (5)$$

Where

$$A = 0{,}45 \times (h_4 - h_{s5}) \qquad (6)$$

The enthalpy value at the vapor condition can be searched by the equation:

$$h_{fg5} = h_{g5} - h_{f5} \qquad (7)$$

$$h_{g5} = h_{fg5} + h_{f5} \qquad (8)$$

Information:

h_5=Turbine outgoing steam enthalpy (kJ/kg)
h_{f5} = Enthalpy of turbine outgoing fluid (kJ/kg)
h_{g5}=Turbine outgoing steam enthalpy (kJ/kg)
w_{ta} =Actual turbine work (kJ/kg)

- Calculating Turbine Isentropic Efficiency

Turbine isentropic efficiency or thermodynamic efficiency of a steam turbine is a measured parameter of the magnitude of steam expansion in terms of actual decrease in enthalpy compared to ideal enthalpy. The isentropic efficiency of the turbine can be calculated by the standard CEI / IEC 60953-3 [5]:

$$\eta \text{ turbin isentropis} = \frac{\text{W turbin aktual}}{\text{W turbin ideal}} \times 100\% \quad (9)$$

- Calculating Isentropic Turbine Power

The calculation of the power of the isentropic turbine can use the equation:

$$\dot{W}_t = \dot{m}(h_4 - h_5) = \dot{m} \times w_{ts} \qquad (10)$$

Information:

$\dot{W}_t$ = Isentropical turbine power (kW)
$\dot{m}$ =Turbine inlet steam mass flow rate (kg/s)

- Calculating the Turbine Specific Steam Consumption Value

Turbine-specific steam consumption or turbine steam rate is the quantity of steam required to generate each kilowatt hour (kWh) of electricity by comparing the ratio of the mass flow rate of steam to the output power. The value of the turbine steam rate in units (kg/kWh) can be obtained from the following equation:

$$\text{Turbine Steam Rate} = \frac{\dot{m}}{\dot{w}} \qquad (11)$$

Information:

W= Output power/ generated power (kW)

- Calculating the Heat Rate

Turbine heat rate is the amount of heat needed to produce electricity of 1 (kWh) then expressed in units (kJ / kWh). The heat rate value can be calculated by the equation:

$$\text{Turbine Heat Rate} = \text{TSR} \times h_4 \qquad (12)$$

Information:

TSR= Turbine Steam Rate (kg/kWh)

- Calculating Turbine Thermal Efficiency

The thermal efficiency of the turbine shows how well the energy conversion is carried out on the steam turbine. The

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thermal efficiency of the turbine can be searched by the equation CEI/IEC 953-1 [5]:

$$\text{Thermal Efficiency } (\eta_{th}) = \frac{3600}{\text{Turbine Heat Rate}} \times 100\% \quad (13)$$

Turbine specifications that the author examined are shown in table 1 below.

Table 1: Turbine Specification

Categories	Value
Manufactured	Fuji Electric
Type	Single casing multi-stage condensing type
Rated Output	37260 kW
Inlet Steam Pressure	6.5 bar
Inlet Steam Temperature	166.8
Exhaust Pressure	0.10 bar
Rated Speed	3000 rpm
Direction of Rotation	Counter Clockwise (view from generator side)
Number of Blading Stage	Reaction stage 7

1.2 Theoretics

Maintenance of geothermal power plant uses a single flash steam system [6] [7]. The flow chart below is a flow chart of the power plant process that follows the process that occurs in the temperature-entropy diagram on the single flash steam system shown in Figure 1 below.

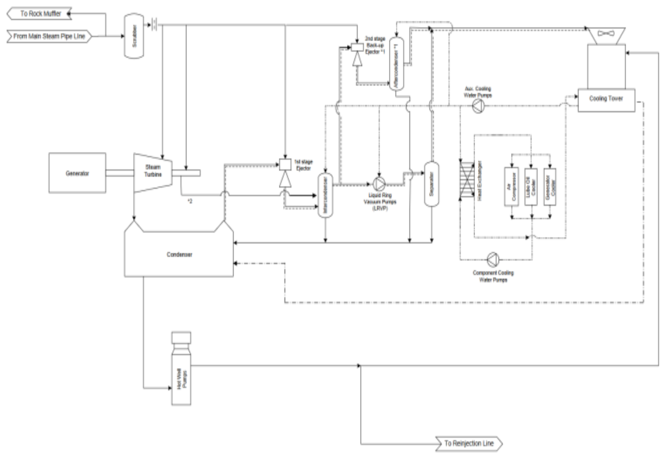

Figure 1: Process Flow Diagram of PLTP Unit X

The following is a temperature-entropy diagram shown in Figure 2 below as a depiction of the processes occurring in steam turbines.

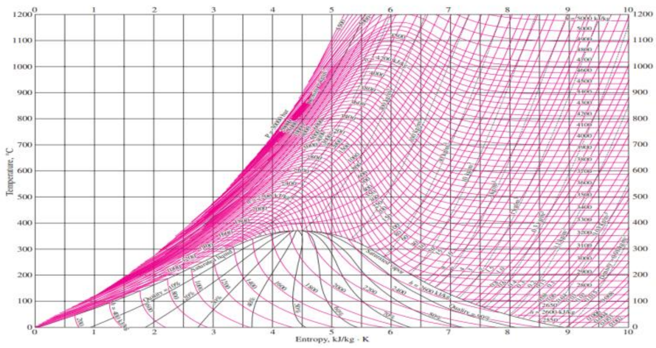

Figure 2: Diagram T-S [8]

The following is an energy balance scheme in a steam turbine by describing the incoming energy and outgoing energy that occurs in the turbine system shown in Figure 3 below.

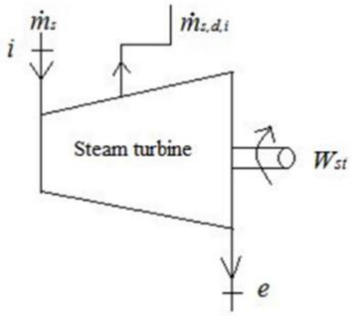

Figure 3: Steam Turbine Energy Balance [9]

In the illustration of the energy balance of a steam turbine, there are parameters that are measured when steam enters the turbine, namely inlet temperature, inlet pressure and steam mass flow rate which then steam thermal energy is converted into mechanical energy so that it can drive the generator to generate electricity, while the parameters measured when steam comes out of the turbine are outlet temperature and outlet pressure. However, according to law II of thermodynamics, not all thermal energy can be converted into mechanical energy so that there is heat or heat that is wasted into the environment.

II. STEAM TURBINE PERFORMANCE CALCULATION

In calculating the performance of the steam turbine, there are steps that must be taken to be able to find out the efficiency of the steam turbine. In addition, observation data is needed by measuring parameters such as: steam mass flow rate, inlet temperature, inlet pressure, and outlet temperature and outlet pressure to be elaborated in the calculation of steam turbine performance as follows.

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- Calculating the Vapor Fraction

To be able to calculate the fraction of steam or the quality of steam entering the turbine, data is needed in the form of an entropy value when it enters the turbine and an entropy value when it exits the turbine. To obtain the entropy value, interpolation is carried out in table A-3 (pressure table) thermodynamics [10]. Then, it can be known that

Using equation 1, the vapor fraction can be calculated as follows:

$$x = \frac{s_4 - s_{f5}}{s_{g5} - s_{f5}}$$

$$x = 0{,}77$$

- Calculating the Work of the Ideal/Isentropic Turbine

Isentropic turbine work is a mechanical effort produced when the turbine blades move now when steam enters. This occurs isentropic ally, namely at the entropy value that remains between the steam in and out of the turbine. The incoming vapor enthalpy value can be calculated using the thermodynamic A-3 (pressure table) table [10].

As for obtaining the isentropic enthalpy value out of the turbine, the process occurs isentropic ally (fixed entropy value) using table A-3 (pressure table) thermodynamics is carried out comparison and interpolation [10].

Using equation 3, the value of the turbine outgoing isentropic enthalpy can be calculated.

$$h_{s5} = h_f + x\, h_{fg}$$

$$h_{s5} = 2054{,}04 \text{ kJ/kg}$$

After obtaining the isentropic enthalpy value out of the turbine, it can be calculated the work of the turbine ideally / isentropic ally using the following equation 2.

$$w_{ts} = h_4 - h_{s5}$$

$$w_{ts} = 542{,}55 \text{ kJ/kg}$$

- Calculating the Turbine Work

The work of the turbine in actual conditions does not occur isentropic ally, because there is a change in the entropy value between the incoming steam and the steam out of the turbine. The enthalpy value can be calculated in the liquid phase and the steam phase when exiting the turbine using the thermodynamic A-3 (pressure table) table [10].

Using equations 5 and 6, it can be calculated the overall enthalpy value of steam coming out of the turbine.

$$h_s = \frac{h_4 - A\left[1 - \left(\frac{h_{f5}}{h_{g5} - h_{f5}}\right)\right]}{1 + \frac{A}{h_{g5} - h_{f5}}}$$

$$h_s = 2183{,}06 \text{ kJ/kg}$$

After obtaining the value of h5, the actual turbine work can be calculated using the following equation 4.

$$w_{ta} = h_4 - h_5$$

$$w_{ta} = 413{,}53 \text{ kJ/kg}$$

- Calculating Turbine Isentropic Efficiency

The performance of the steam turbine can be seen from the isentropic efficiency of the turbine, where the isentropic condition is the condition of the turbine to operate without friction causing power losses. Calculating the efficiency value using equation 9 which is a calculation formula based on the CEI/IEC 60953-3 [5] standard such as:

$$\eta \text{ turbine isentropic} = \frac{\text{W turbine actual}}{\text{W turbine ideal}} \times 100\%$$

$$\eta \text{ turbine isentropic} = 76{,}22\%$$

- Calculating Isentropic Turbine Power

To be able to calculate the power of an isentropic turbine, equation 10 is used as follows:

$$\dot{W}_t = \dot{m}(h_4 - h_5) = \dot{m} \times w_{ts}$$

$$\dot{W}_t = 105671136{,}2 \text{ kW}$$

- Calculating Turbine Specific Steam Consumption

To find out the quantity of steam needed to be able to generate electricity every hour (kWh) equation 11 is used as follows.

$$\text{Turbine Steam Rate} = \frac{\dot{m}}{\dot{W}}$$

$$\text{Turbine Steam Rate} = 7{,}7868 \text{ kg/kWh}$$

- Calculating the Heat Rate

Using equation 12, it can calculate the amount of heat required to produce electricity by 1 (kWh) below.

$$\text{Turbine Heat Rate} = \text{TSR} \times h_4$$

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$$\text{Turbine Heat Rate} = 20219{,}17 \text{ kJ/kWh}$$

- Calculating Turbine Thermal Efficiency

To find out the energy conversion carried out on the turbine thermally can use equation 13 which is a calculation of the thermal efficiency formula based on the CEI / IEC 953-1 standard [5]:

$$\text{Thermal Efficiency } (\eta_{th}) = \frac{3600}{\text{Turbine Heat Rate}} \times 100\%$$

$$\text{Thermal Efficiency } (\eta_{th}) = 17{,}80\%$$

III. RESULTS AND DISCUSSIONS

The maximum deviation of the parameter variables that the author examined based on the American Society of Mechanical Engineering is shown in Table 2 below.

Table 2: Variable Allowance [11]

Variable		Permissible Deviation From Design Condition
Main	Temperature	±30 °**F** from design
	Pressure	±3.0% of the absolute pressure
Initial Steam Quality		±0.5% points of quality for turbine
Exhaust Pressure		±2.5% of the absolute pressure
Primary Flow		Not specified

The profile of the inlet pressure to the isentropic efficiency of the turbine, is illustrated is show in Figure 4 below.

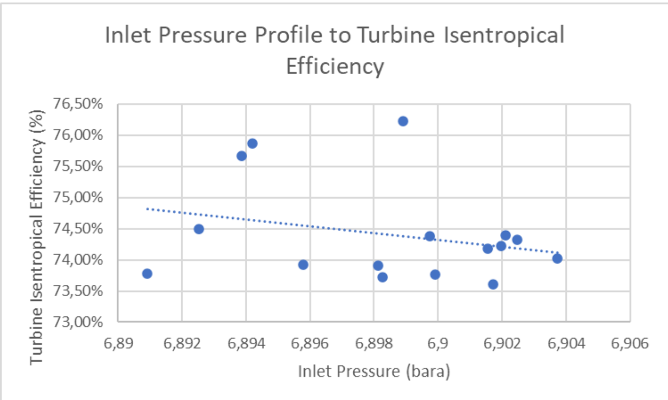

Figure 4: Inlet Pressure Profile to Turbine Isentropical Efficiency

In the profile of the inlet pressure to the isentropic efficiency of the turbine, it is illustrated that when the pressure enters the turbine about 6.894 to 6.899 absolute bar, the turbine isentropic efficiency ranges from 75.60% to 76.25% while when the inlet pressure is 6.901 to 6.904 bar absolutely produces a lower turbine isentropic efficiency ranging from 73.50% to 74.50%. This happens because the incoming steam with a pressure of 6,894 to 6,899 coals is a pressure that is more in line with the specifications of the turbine, namely the inlet pressure of 6.5 coals, but when the incoming steam pressure exceeds the turbine specification, it causes the efficiency of the turbine to decrease so that the performance of the turbine decreases. Pressure that exceeds specifications also results in the quality of steam entering the turbine decreases as well. This overpressure increases steam condensation at the final level of the turbine so that it can damage the turbine blades.

The profile of the outlet pressure to the isentropic efficiency of the turbine, is illustrated is show in Figure 5 below.

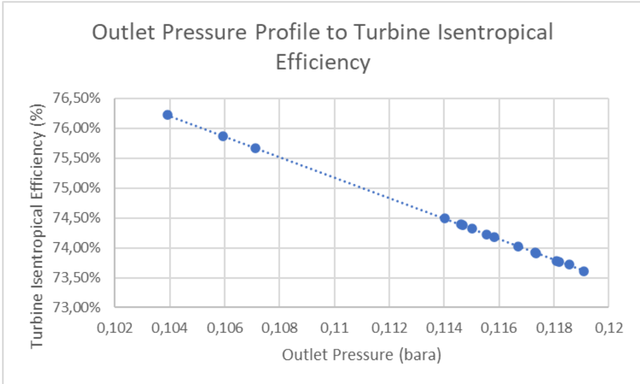

Figure 5: Outlet Pressure Profile to Turbine Isentropical Efficiency

In the above profile it is seen that the magnitude of the turbine's outgoing pressure value is inversely proportional to the turbine's isentropic efficiency value. When the turbine discharge pressure is of low value results in a high value of turbine efficiency. The value of the steam pressure when it exits the turbine is smaller than the pressure of the steam in the turbine because in the turbine, the steam is isentropic ally expanding and drives the turbine blades so that the kinetic energy of the steam produces work to drive the generator, then the pressure of the steam coming out of the turbine becomes lower. When the turbine exit pressure is more than 0.114 coals, the turbine isentropic efficiency decreases while when the pressure value is around 0.104 coals, it produces large turbine efficiency. This happens because when the steam enters the pressure is more pressure, it will produce a high-pressure value from the turbine due to a decrease in the vacuum pressure of the condenser so that the turbine performance decreases and requires steam consumption to generate power.

The profile of the steam rate to the steam rate applied vapor mass rate, is illustrated is show in Figure 6 below.

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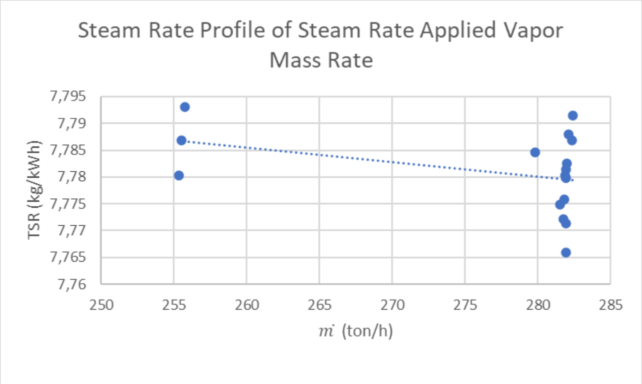

Figure 6: Steam Rate Profile of Steam Rate Applied Vapor Mass Rate

Turbine Steam Rate is the turbine-specific steam consumption required to generate electricity (kWh) [12]. In this case, the flow rate of steam mass is inversely proportional to the turbine steam rate which is proven in the profile above that when the flow rate of low steam mass is around 255 tons/h then the specific steam consumption to generate 1 kWh is higher up to 7,794 kg/kWh. This is due to the large pressure of incoming steam, when the incoming vapor pressure is low; it requires a high steam mass flow rate to produce a high steam rate turbine. However, it is said that it is good when the turbine steam rate is low to generate 1 kWh so that the required steam mass flow rate is also low with a higher pressure.

The profile of the inlet pressure to the thermal efficiency of the turbine, is illustrated is show in Figure 7 below.

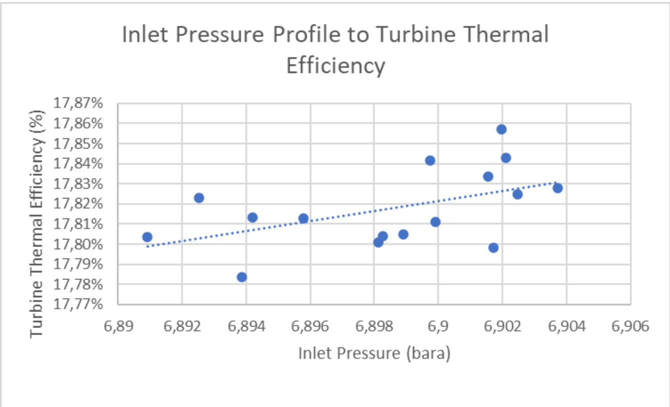

Figure 7: Inlet Pressure Profile to Turbine Thermal Efficiency

In the above profile can be seen that the low pressure of the incoming steam causes the thermal efficiency value of the turbine to also be low. Thermal efficiency is a good interpretation of whether energy conversion is carried out in steam turbines in terms of thermals. At an inlet steam pressure of about 6,894 bar produces a low thermal efficiency of the turbine while at an inlet steam pressure of 6,902 bara it produces a high thermal efficiency value of the turbine. This happens because the incoming steam pressure affects the turbine heat rate because the low incoming steam pressure requires a larger amount of heat to generate 1 kWh of electricity so that the thermal efficiency in the turbine becomes smaller. It is different when the steam turbine enters is already high, to generate electricity only requires a low amount of heat to produce a large thermal efficiency [13], because in its calculation the value of the turbine heat rate is inversely proportional to the thermal efficiency of the turbine.

The comparison profile of the actual efficiency and the design condition efficiency of the turbine, is illustrated is show in Figure 8 below.

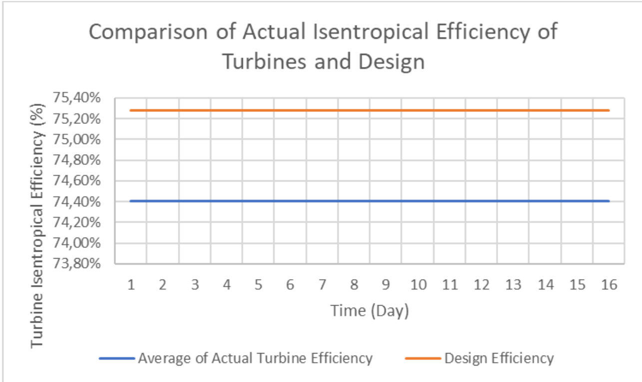

Figure 8: Comparison of Actual Isentropical Efficiency of Turbines and Design

The above profile provides an interpretation that there is a difference in the isentropic efficiency value of the turbine as well as by design [14]. In this case, the efficiency by design is the maximum efficiency or maximum performance that the turbine performs when operating so that the actual efficiency cannot exceed the efficiency by design, then the probability that what occurs is that the actual efficiency is lower than the efficiency by design. It is evident in the above profile that the isentropic efficiency of the turbine is lower than the isentropic efficiency of the turbine by design. The average actual efficiency for 16 days is 74.40%, while the turbine design efficiency is 75.28%, then the difference between the two is 0.88% which can be an opportunity for energy savings or an opportunity for increased efficiency [15].

IV. CONCLUSION

Based on the results of the research that has been done, some conclusions can be drawn as follows: the results of the calculation of the performance efficiency of the steam turbine with a capacity of 35 MW obtained an average actual efficiency of 74.40% with a turbine thermal efficiency of 17.82% while the efficiency of the steam turbine design performance was 75.28%. The difference in the efficiency of steam turbine performance by design condition with the actual

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condition 0.88% where turbine performance decreases with the age of equipment that has been used for a long time and energy loss occurs.

Lowering the turbine exhaust pressure (vacuum condenser pressure is getting better), because the turbine exit pressure obtained almost exceeds the allowable variable deviation, as evidenced by lowering the turbine exit pressure close to the turbine specifications, it can produce a turbine performance efficiency value of 76.22%. Exhaust pressure profile at design conditions, actual conditions and optimization conditions for turbine efficiency are 0.109 bar, 0.116 bar and 0.103 respectively.

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