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Analysis of Thermal Efficiency in Star Energy Geothermal Darajat

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Abstract— ***After years of operation, the plant will no longer operate optimally according to its design. The practice of the work cycle shows that the original value of thermal efficiency will always be below 100%, this is because during the cycle process of creating work, the energy received by the system by heat transfer will not be fully received and will be absorbed by the environment. In this research, thermal efficiency analysis was carried out in accordance with the first and second laws of thermodynamic efficiency and thermoeconomic calculations to calculate losses. Based on calculations that have been carried out, the thermal efficiency of the Star Energy Geothermal Darajat unit-3 geothermal power plant system is 21.72% with the largest exergy loss being in the condenser component of 62,219,418 kW with an exergy loss cost of 252,766,682.24 Rp/ days and the smallest is in the cooling tower of 599,362 kW with exergy loss costs of 23,655,907.11. Rp/day from the following results it can be seen that this efficiency value depends on the performance of each component.***

IndexTerms—Efficiency, Exergy, Thermal, Thermoeconomic.

I. INTRODUCTION

Every power plant loses efficiency due to continuous operation, age, and many other reasons. Everything gets older as time goes by. After years of operation, the plant will no longer operate optimally according to its design. Efficiency will worsen, this reduction in efficiency leads to increased carbon emissions. Optimization of power generation systems is one of the most important subjects in the energy field.[1]

In geothermal power plants, steam is obtained from the earth's reservoir layer by utilizing the heat contained within the earth, such as in the earth’s crust, mantle and core.[2] In the production process of this geothermal power plant, the steam used is dry steam or steam that has a high level dryness produced directly from the production well is directly channeled into the turbine or is often known as the direct dry steam system method.[3] In this production process there is a lot of heat loss, which can be explained by the fact that the thermal value found in the production process steam will always decrease as the production process progresses. [4]

In this research will using not only the first law of thermodynamics efficiency to calculate the thermal efficiency but also using the exergy analysis to calculate the theoritics maximum energy that can be use from steam to power turbine, and thermoecononomics to calculate the losses.

II. RESEARCH METHODS

A. Research Flow Diagram

This section is an overview of the steps in the thermal efficiency analysis at the Star Energy Darajat geothermal power plant shown in Figure. 1. The flow diagram aims to depict the process of implementing geothermal power plant analysis so that it is easy to understand and complete based on the specified sequence.

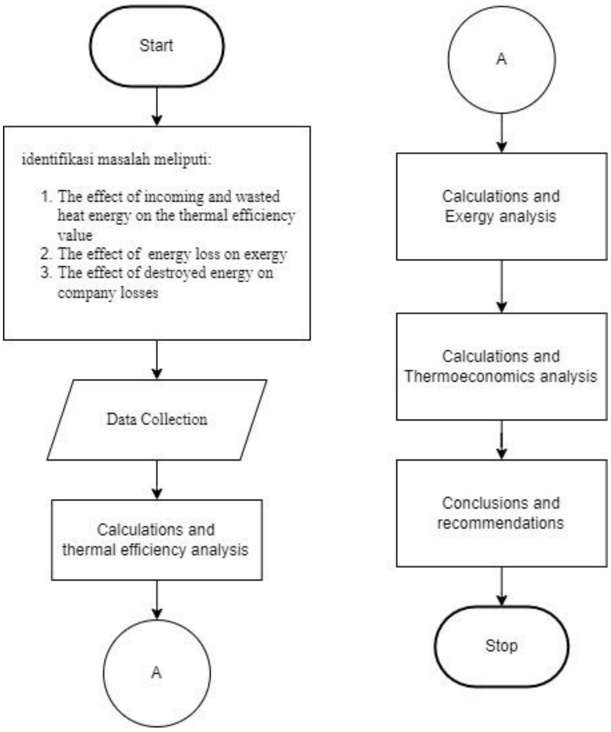

Fig. 1. Research Flowchart

B. Problems Identification

Problem identification is an effort to define the problem and make it more measurable to make it easier to answer the problem.

C. Data Collection

The method in this research uses direct data collection to obtain the data needed in this research. Taking thermal efficiency data requires data on generation capacity, entropy, enthalpy, pressure, mass rate, steam quality and temperature which are taken 24 times a day for 1 week. Thermal efficiency is the net distribution of electricity generation divided by the heat input. After collecting the data directly, the data is processed to obtain an analysis of the data.

D. Calculation and Analysis of Thermal Efficiency

Efficiency is a term generally used to indicate some measure of how well resources are used.[5] Efficiency will always below 100% because in work cycle the energy received by system will always be less than given to the system.[6] This calculation is carried out using data that has been taken for a week with a generation operating time of 24 hours per day. The data taken is data originating from the company's DCS (Distributed Control System) and PI-Data. The data obtained will be used to calculate the overall entropy and enthalpy for each component and continue to find thermal efficiency. In this calculations the effects of kinetic energy will be ignored.[7] The stages for carrying out thermal efficiency calculations at the Darajat geothermal power plant are as follows: [8]

1. Find the value of Enthalpy (h1) and entropy (s1) at the steam pressure entering the turbine (P1) using interpolation and the superheated steam table.

$$H=\left(1-\frac{P-P_1}{P_2-P_1}\right)\left(H_1+\frac{T-T_1}{T_2-T_1}(H_2-H_1)\right)+\frac{P-P_1}{P_2-P_1}\left(H_3+\frac{T-T_1}{T_2-T_1}(H_4-H_3)\right) \tag{1}$$

P = The pressure sought (BarG)
P_1 = Lower limit pressure (BarG)
P_2 = Upper limit pressure (BarG)
T = The temperature sought (°C)
T_1 = Lower limit temperature (°C)
T_2 = Upper limit temperature (°C)
H = The entalphy sought (kj/kg)
H_1 = enthalpy at T1 and P1 (kj/kg)
H_2 = enthalpy at T1 and P2 (kj/kg)
H_3 = enthalpy at T2 and P1 (kj/kg)
H_4 = enthalpy at T2 and P2 (kj/kg)

2. Find the values of fluid enthalpy (hf), steam enthalpy (hg), and mixture enthalpy (hfg) at the turbine exit pressure (P2). (sfg) at the turbine exit pressure (P2).

3. Calculate the steam output enthalpy from the turbine (h2) using the equation:

$$(h_1-h_2)\,.\,\dot{m}=\frac{generator\ output\ (MW)}{generator\ efficiency} \tag{2}$$

h_1 = state 1 enthalpy (kJ/kg)
h_2 = state 2 enthalpy (kJ/kg)
$\dot{m}$ =steam flow rate (kg/s)

4. Calculate the steam fraction (x) at turbine using the equation:

$$s_1=s_{f2}+x\,.\,s_{fg2} \tag{3}$$

s_1 = state 1 spesific enthropy (kJ/kg)
s_{f2} = state 2 enthropy of saturated water (kJ/kg)
x = steam fraction
s_{fg2} = difference between saturated vapor and saturated liquid enthropy (kJ/kg)

5. Calculate the ideal enthalpy (h2s) at turbine output using the equation:

$$h_{2s}=h_{f2}+x.\,h_{fg2} \tag{4}$$

h_{2s} = state 2 ideal enthalpy (kJ/kg)
h_{f2} = state 2 saturated vapor enthalpy (kJ/kg)
x = steam fraction
h_{fg2} = difference between saturated vapor and saturated liquid enthalpy (kJ/kg)

7. calculate turbine efficiency using the equation :

$$\eta_t=\frac{W}{W_S}=\frac{h_1-h_2}{h_1-h_{2s}} \tag{5}$$

η_t = turbine efficiency (%)
h_{2s} = state 2 ideal enthalpy (kJ/kg)
h_2 = state 2 enthalpy (kJ/kg)
h_1 = state 1 enthalpy (kJ/kg)

8. calculate power work generation by turbine with the equation:

$$W_T=\dot{m}\,.\,\eta_t\,(h_1-h_{2s}) \tag{6}$$

W_T = turbine work generation (MW)
$\dot{m}$ = steam flow rate (kg/s)
η_t = turbine efficiency(%)
h_1 = state 1 enthalpy (kJ/kg)
h_{2s} = state 2 ideal enthalpy (kJ/kg)

9. Calculate thermal efficiency of power plant system using equation:

$$\eta\text{sistem}=\frac{\sum W}{Qin}=\frac{W_{turbine}-W_{total\,pump}}{Qin} \tag{7}$$

ηsystem = system thermal efficiency (kJ/kg)
W_{turbin} = power generation (MW)
$W_{total\ pum}$ = power that used by pump (MW)
Qin = amount of heat input (kJ/kg)

E. Calculation and analysis of exergy

Because first law analysis from an energy performance perspective is considered insufficient, the evaluation of exergy components has received considerable attention in the thermodynamic analysis of thermal processes and plant systems. There are three types of energy transmission across surfaces which include work transfer, heat transfer and the relationship of energy to mass or fluid transfer. Heat source temperature and system function are also used to evaluate open flow systems and to test plant efficiency when kinetic and potential energy changes are neglected. It can be decided which processes should be taken into account. The basic energy balance is not enough to find system deficiencies. In such cases, exergy evaluation is considered essential to determine imperfections in the process.[9]

The stages for carrying out exergy analysis calculations at the Darajat geothermal power plant are as follows:

1. Calculate exergy at *state* 1, 2, and 3 using the equation:

$$E_n = m[(h_n - h_0) - T_0(S_n - S_0)] \qquad (8)$$

E_k = exergy at n state (kW)
h_k = enthalpy at n state (kJ/kg)
h_0 = exergy in the environment (kJ/kg)
T_0 = environment temperature (K)
S_k = enthropy at n state (kJ/kg.K)
S_0 = exergy in the environment (kJ/kg.K)

2. Calculate exergy loss in production process components using the equation:

$$E_{kloss} = E_{kin} - E_{kout} \qquad (9)$$

E_{kloss} = Exergy loss (kW)
E_{kin} = Exergy input (kW)
E_{kout} = Exergy output (kW)

3. Calculate the exergy efficiency of production process components using the equation:

$$\eta_{ek} = 1 - \frac{Eksergi\ Out}{Eksergi\ in}\ x\ 100\% \qquad (10)$$

Keterangan:
η_{ek} = exergy efficiency (%)
Eksergi *out* = Exergy output (kW)
Eksergi *in* = Exergy input(kW)

F. *Calculation and analysis of thermoeconomic*

Thermoeconomics is a branch of engineering science that combines exergy analysis with economic principles.[10] The reference used in calculating the cost of exergy losses is the Basic Electricity Tariff (TDL) per kWh. The basic electricity tariff in Indonesia per month, March 2023 for class I-4/TT with a power limit of more than 30,000 kVa is IDR. 1.644.- so that to calculate the cost of exergy losses from each component, the thermoeconomic calculation is obtained using the following equation:

$$C \ = \ E\ x\ TDL\ x \ \ hour \qquad (11)$$

C = cost (Rp)
E = Eksergi loss (kW)
TDL = basic electricity tariff (Rp)

G. *Conclusion and Recommendations*

If the results of the calculations for thermal efficiency, exergy and losses have been obtained, the remaining conclusions will be drawn and suggestions for further research will be given.

III. RESULTS AND DISCUSSION

A. *Calculation and Analysis of Thermal Efficiency*

Based on data obtained from the control room operator, 1 month of data was taken in March 2023 to represent the thermal efficiency calculation of PLTP Star Energy Geothermal Darajat unit 3, where this 1 month's data has been averaged on an Excel spread sheet. In calculating the parameters used (pressure, temperature, flow rate, enthalpy and entropy) the average values are taken per day for 24 hours.

TABLE I
THERMAL EFFICIENCY CALCULATION PARAMETERS

State	Flow Rate (kg/s)	Temp (^{0}C)	Pressure (BarG)	Entropy (kJ/kg.K)	Entalphy (kJ/kg)	Note
1	201,40	205	15,94	6,404	2796,39	Turbine
2s	152,94	162	5,43	6,404	2725,76	Ideal
2	152,94	162	5,43	6,684	2203,31	Actual
3	3,56	20	-	0,2966	83,96	Cooling Tower

So, after calculating the Thermal Plant Efficiency Calculation stages, the thermal efficiency of the Darajat Star Energy geothermal powerplant system is obtained as follows :

$$\eta system \ = \frac{Wt - Wpump}{Qin}$$

$$= \frac{124{,}7 - 2{,}439}{562{,}8}$$

$$= 21{,}72\%$$

The Star Energy Geothermal Darajat Unit-3 geothermal power plant has a thermal efficiency of 21.72%. The low thermal efficiency value of the geothermal power plant compared to other types of power plants is because in this plant the geothermal fluid tends to be at lower temperatures compared to power plants that use fuels such as coal, gas and nuclear.[10] Poor heat insulators and the low temperature of this fluid reduce the efficiency of converting heat energy into electrical energy, so that a lot of heat energy is wasted into the environment. Several things can be done to maintain and increase the thermal efficiency value, such using the remaining heat energy directly using cogeneration where the remaining heat can be used directly to heating water, and create new turbines that can utilize the remaining steam that comes out of the main turbine.

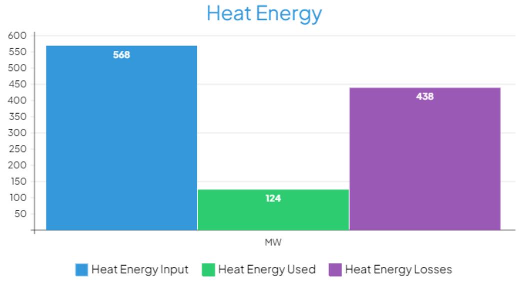

Fig. 2. Heat Usage graph

With a thermal efficiency value of 21.72%, it can be found that this plant loses around 438 MW in the form of heat energy which can be used to produce electrical energy. This calculation is based on the heat energy entering the plant and minus the turbine work rate value according to the previous calculation. . The low ability of the system to absorb heat energy is also caused by the steam coming out of the reservoir which has a fairly low temperature, thereby reducing the enthalpy value and causing the vapor phase to be very close to the saturated vapor phase value.

B. Calculation and Analysis of Exergy

This calculation is carried out using data that has been taken for a week with a generation operating time of 24 hours per day. The data taken is data originating from the company's DCS (Distributed Control System) and PI-Data. The data obtained will be used to calculate the overall entropy and enthalpy for each component and continue to find thermal efficiency. In reviewing the plant, based on the Piping Instrument Diagram (P&Id) obtained from Star Energy Geothermal Darajat which can be simplified into a Process Flow Diagram (PFD), the type of PLTP at Star Energy Geothermal Darajat is a dry steam power plant. Then the state is determined to calculate the exergy value. In calculating the exergy value for each state, temperature, pressure and flow rate data for each state are used.

TABLE II
EXERGY CALCULATION PARAMETER

State	Flow Rate (kg/s)	Entropy (kJ/kg.K)		Entalphy (kJ/kg)	
		in	out	in	out
1	201,40	6,404	6,684	2796,39	2203,31
2	152,94	6,684	2,379	2203,31	690,16
3	35,61	2,379	0,297	690,16	83,96

By using equation 7, the exergy calculation results obtained with the data in Table II for each state, it is also known that the environmental temperature used is 18 (◦C) so that the enthalpy from the environmental temperature (*h*0) is 290.46 kJ/kg and the entropy from the environmental temperature (0) is 1.668 kJ/kg.K which is obtained from the Thermodynamic Table of Ideal Gas Properties of Air. After calculating the exergy of the entire state, the calculation results in Table 3 are obtained as follows:

TABLE III
EXERGY AT DIFFERENT STATE

State	Exergy (kW)	Components
1	226.805,60	Turbine
2	69.060,67	Condenser
3	6.841,25	Cooling tower

After obtaining the exergy calculation results in Table III, exergy loss and exergy efficiency can be obtained using equation 8 and equation 9, following are the calculations of exergy loss and exergy efficiency for each component:

TABLE IV
EXERGY CALCULATION PARAMETER

Components	Exergy (kW)	Exergy loss (kW)	Exergy efficiency (%)
Turbine	226.805,60	25.106,12	88,93
Condenser	69.060,67	62.219,42	90,10
Cooling tower	6.841,25	599,36	91,23

In accordance with the data contained in the exergy table, the largest loss of exergy was in the condenser at 62.219,42 kW. This is because the function of the condenser itself is as a coolant for the remaining steam from the turbine, which means that it deliberately removes the remaining heat contained in the steam which causes the steam to return. again becomes water to be put back into the earth. Meanwhile, the lowest exergy is found in the cooling tower at 599,362 kW, this is because the cooling tower works to cool the water from the condenser so that it has the same temperature as the environment. And it can be seen that the exergy value lost from the turbine is relatively large, namely 25.106,12 kW. This can occur due to many things such as the choice of material on the turbine blade and also corrosion occurring on the turbine blades. Apart from that, it can also be seen that the incoming temperature and coming out of the turbine is quite different so that the entropy value will be different too. Due to exergy destruction and losses, the performance of real world utilization processes will always be less than ideal. How close they come to the ideal depends on various factors, such as technical possibilities, economic considerations, and societal requirements, and is evaluated through the concept of efficiency[11]

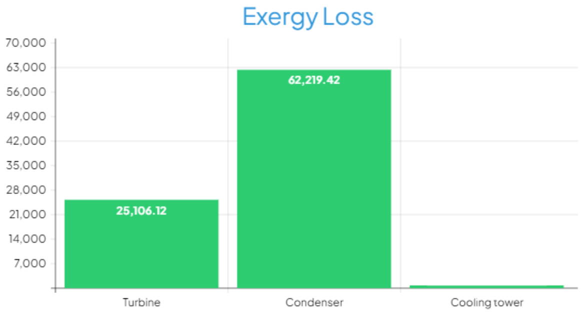

Fig. 3. Exergy loss Graph

From this calculation it can be seen that the value of the exergy loss in each component is quite large, especially in the condenser. In the condenser there is the largest exergy loss due to a drastic change in the fluid phase, namely from steam to liquid so that the heat contained in the steam will disappear and cause a large exergy loss too. Because exergy is the theoretical maximum limit of a thermal engine to absorb heat and convert it into other forms of energy, the large exergy loss reduces the thermal engine's ability to convert heat into other forms of work so that the large exergy loss also explains that the system will not be able to convert heat energy to the maximum and will affect the thermal efficiency value of the generator itself

C. Calculation and Analysis of thermoeconomics

In calculating the cost of exergy losses, use the Indonesian Basic Electricity Tariff per kWh for March 2023 as a reference. To determine the cost of exergy losses per unit, thermoeconomic calculations can be carried out using the equation. The assumption used in the Indonesian Basic Electricity Tariff for March 2023 for industries that do not receive subsidies is IDR 1,644.52 per kWh which is included in group I-4/TT with a power limit of more than 30,000 kVA. So the result of calculation is as follows:

TABLE V
THERMOECONOMIC CALCULATION

Components	Exergy loss (kW)	Loss (Rp/day)
Turbine	25.106,12	990.900.395,10
Condenser	62.219,42	2.455.705.854,94
Cooling tower	599,36	23.655.907,11
	Total	3.470.262.157,15

From the calculation results, it can be seen that the cost of exergy losses for the largest component is in the condenser, amounting to 2.455.705.854,94 Rp/day. Meanwhile, loss costs for turbine are 990.900.395,1 Rp/day. If you look at Table 4.4, the largest exergy loss is also found in the condenser component, while the lowest exergy loss is in the cooling tower component, so the cost of exergy loss in the cooling tower is small at 23.655.907,11 Rp./day. So it can be concluded that the cost of exergy loss will be directly proportional to the exergy loss. Several factors can influence the exergy value and exergy loss costs, one of which is the amount of process input and output which can impact the efficiency and exergy loss costs of the component. The greater the value of exergy loss or lost exergy loss, the greater the costs required. In contrast to the comparison between exergy loss and exergy efficiency, the greater the exergy loss, the smaller the exergy efficiency of the component. Exergy loss costs based on thermoeconomics begin with carrying out an exergy analysis so that the exergy loss value is known, after that from an economic perspective the loss value is obtained in the form of the cost of each component.

IV. CONCLUSIONS

The thermal efficiency of the Star Energy Geothermal Darajat unit-3 geothermal power generation system is 21.72%. With a lost energy value of 438 MW. This low efficiency value is caused by the low temperature and enthalpy of the steam entering the plant, thereby limiting the efficiency of the system in receiving heat energy. So the incoming energy will affect the thermal efficiency value. The greater the temperature, the greater the thermal efficiency value. By obtaining the thermal efficiency of this power plant, it can be seen that the efficiency is very good for geothermal power plants.

The amount of exergy loss in the turbine component is 226,805.60 kW, the condenser is 62,219.42 kW, and the cooling tower is 599.36 kW. This exergy loss value does not affect the value of thermal efficiency, this is because thermal efficiency does not use a comparison with the environment or dead state.

The total loss value from exergy loss is IDR 3,470,262,157.15/day. The greater the exergy loss value for each component, the greater the loss value experienced according to thermoeconomic calculations, so that the exergy loss value and the loss value are directly proportional.

Companies can use the remaining heat from steam directly in accordance with cogeneration to increase thermal efficiency values such as for heating rooms and water.

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