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THE EXERGY ANALYSIS AND OPTIMIZATION ON 815 MW SUPERCRITICAL STEAM POWER PLANT PAITON, INDONESIA

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Abstract

The exergy analysis of supercritical steam power plant system at unit 3 Paitoon was carried out based on the first and second thermodynamic laws. The exergy flow and exergetic efficiency are calculated for each generator component including boiler, HTP, IPT, LPT, deaerator, condenser, HPH, LPH, CEP and FWP. The steam exergy flowing into the system is 970288 kW which is used to produce 815 MW of electricity with the overall exergy efficiency of the plant is 26.32%. Sankey diagram shows the loss of exergy in each component of the power plant. Irreversibilities in boilers, condensers, turbines, LPH, HPH, pumps and daerators are 1041068.79 kW (18.87%), 400619.99 kW (7.28%), 891940.73 kW (16.17%), 41511.13 kW (0.75%), 59977.63 kW (7.28%) (1.09%), 10815.02 kW (0.20%) and 4745.18 kW (0.09%) and the total exergy that can be converted into electrical energy is 3097083.84 kW (55.96%) of the total exergy that enters the system. The greatest irreversibility was found in boilers in the amount of 1677003 kW (17.28%). Based on the results of optimization carried out by varying the output pressure, the boiler obtained the highest efficiency value of 61.20% at an output pressure of 24.53 bar.

Keywords: *Steam power plant, exergy, irreversibiliy, optimization*

1. Introduction

Electricity is one of the important factors that supports the development of any country. Currently the use of electricity is increasing rapidly as it is in line with the increase on economic growth. To meet the needs of electricity, the availability of energy resources and the use of appropriate technology need to be considered. We also need clean energy (low emissions), efficient and sustainable energy that do not have impact on environmental pollution, climate change and interfere country's energy reserves. Electricity supply must be endeavored to meet all the needs of the community and industry at a reasonable price and high reliability. In addition to meeting the needs of electricity for remote areas, it is also continuely developed. This relates to the efforts in improving people's living standards.

The Indonesian government is currently planning to achieve an electrification ratio of 95% by 2025 [1]. Meanwhile, the capacity of the national electricity system is now in critical condition as indicated by the existence of supply deficits in several regions. This problem requires an increase in supply so that development needs to be done in stages. One of the efforts that is being carried out is to implement a program to accelerate the construction of 35 coal-fired power plants with an overall capacity of 10000 MW.

Steam power plant is a type of thermal power plant that is widely used in Indonesia. Its practical use and easiness to obtain fuel make this type of power plant becoming the first choice. Indonesia has ratified the Paris Agreement through Law No.16 / 2016 concerning the ratification of the Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC). This ratification shows that Indonesia has committed to contribute to the world community to prevent the worsening climate crisis. Therefore, supercritical technology has emerged in coal-fired steam power plants which improve the efficiency, reduce the raw material costs and emissions [2], [3].

Energy and exergy analyses based on the first and second laws of thermodynamics are needed to analyze the thermal system of a plant. These analyses are needed to identify the source of

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inefficiency, determine the location and magnitude of exergy loss that occur [4], [5], [6], [7]. In addition, thing that needs to be considered is determining the optimal working conditions of the plant to get the most optimal conditions in order to achieve the highest efficiency values.

Bayu Rudiyanto et al., Conducted an exergy analysis at PT. YTL East Java unit 5 where the greatest irreversibility is found in boilers (sub critical) in the amount of 1677003 kW (17.28%). While the optimization carried out by varying the output pressure on the boiler obtained the highest efficiency value of 94.04% at an output pressure of 41 bar [8]. Bayu Rudiyanto et al., conducted an exergy analysis of the steam cycle geothermal power plant system resulting from the separation at PT. Indonesia Power UPJP Kamojang or PLTP Kamojang unit 2 through the Engineering Equation Solver (EES) software, where the greatest irreversibility occured in the main condenser, which was 180,783.2 kW (58.3%) [9]. The energy and exergy analyses of dry-steam geothermal power plant case study in Kamojang geothermal power plant unit 2 showed the amount of energy efficiency of 19.03% and exergy efficiency of 40.31% [10].

Ningning Si et al., evaluated the performance of a 1000 MW double reheat ultra-supercritical power plant. An exergy analysis was performed to direct the energy loss distribution of this system [12]. Study of providing a detailed guidance for the selection of the optimal regulating measures when considering the enhancement of exergy efficiency and flexibility comprehensively under different conditions and periods [13]. S.C. Kaushik et al., reviewed in depth the use of energy and the exergy analyses of the thermal powerplant system, to understand the performance of the system with the use of coal and concluded that the main energy loss occurred in the boiler, this happened irreversibly because the coal fuel in the combustion chamber had been combined according to the cycle. In was also explained in the study that the exergy method is useful for increasing the efficiency of steam power plant [14].

Based on the above problems, it is necessary to have an exergy analysis on 815 MW supercritical steam power plant in Paiton, East Java to identify the exergy losses that occur. In addition, it can be a reference for management to prioritize improvements and optimizations in the future. This as an effort to reduce losses that occur and improve the efficiency of thermodynamics in the system.

Description of 815 MW Supercritical Steam Power Plant System

1. The Principles of Paiton Unit 3 Supercritical Steam Power Plant System

The Paiton Unit 3 Steam Power Plant Project officially started operating on 18 March 2012 using an independent power producer / IPP (Private Power Plant) scheme. This unit 3 Paiton power plant uses sub-bituminous coal in its operation. This Steam Power Plant was built by Mistrubishi Heavy Industry. Boilers used are supercritical vertical furnace waterwall with sliding pressure. Steam parameters are 2,695 tons per hour, pressure 25.8 MPa (g) and temperature 542ºC. Fuels use sub-bituminous coal. Total water content of 30%, calorific value 4,500 kcal / kg a.r., maximum ash content of 3% and minimum ash melting temperature of 1,150oC. The condenser cooling system is seawater with an open cycle which is pumped into the condenser and released through an open channel.

The process at Paiton Unit 3 supercritical steam power plant uses the same feed water heating process as sub-critical. The difference is that the CEP and BFP raise the boiler feed pressure above the critical pressure. When the boiler water is raised at the high pressure, two gas and liquid phases are not found, so there is no need for separating the boiler drum and also recirculating the liquid phase to the evaporation stage. In the Figure 1 we can see the process line in the T-s diagram does not touch the saturation line as in the sub-critical. Steam becomes a superheat condition after reaching critical temperatures. Steam at the final temperature is expanded into the HP turbine as in the sub-critical power plant process. The output of the turbine HP, the steam will be reheated into the boiler to increase the pressure and temperature. This cycle process with reheat can increase the efficiency of the steam cycle. In high pressure process such supercritical reheat, it uses one to two stages.

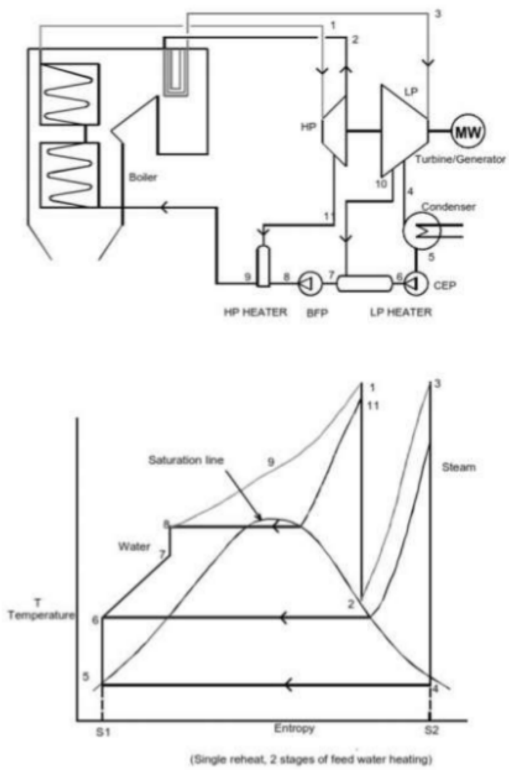

Figure 1. The Super-critical steam cycle and supercritical steam power plant T-s diagram

2. 2. The Operation Process of Unit 3 Paiton Steam Power Plant

The steam power system in Paiton unit 3 uses a closed loop control system with 8 main components namely Boilers, High Pressure Turbine / HPT, Intermediate Pressure Turbines / IPT, and Low Pressure Turbines / LPT), Condensers, Condensate Pumps (CP), Low Pressure Heater (LPH), Daerator, Boiler Feed Pump (BFP), and High Pressure Heater (HPH).

The working fluid of each state is different for each component consisting of the vapor and water phases so it is assumed to be the ideal gas for air to facilitate analysis. The diagram of the Unit 3 Paiton steam power plant is illustrated in the Rankine Cycle to give an overview of the location of each state and component as a whole, as well as the direction of the working fluid flow used to conduct energy and exergy analysis shown in the Figure 2.

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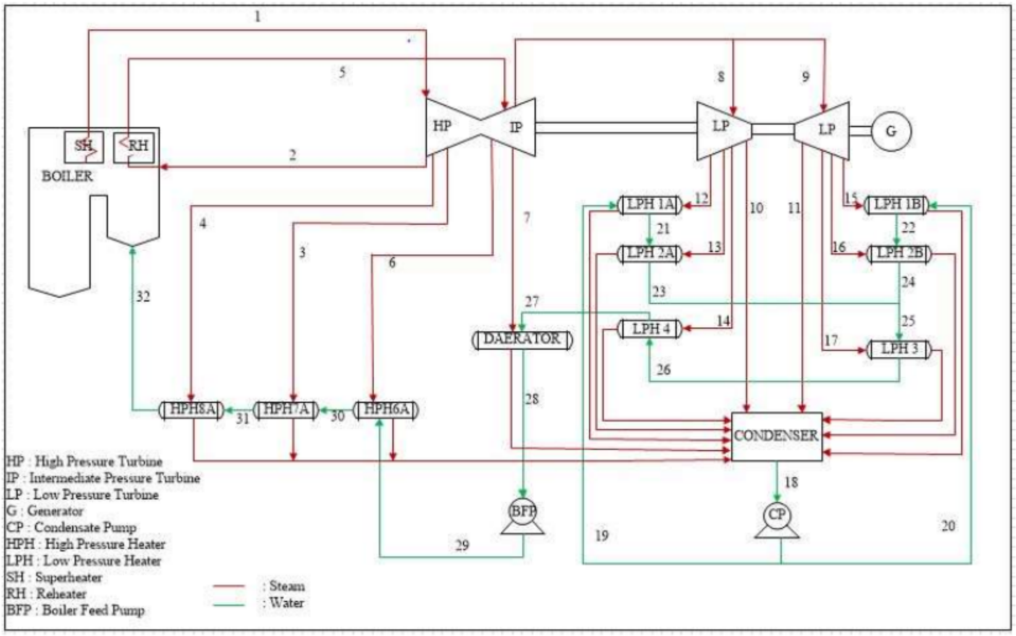

Figure 1. The Work Cycle of Unit 3 Paiton Steam Power Plant

Based on The Figure 2, the total state used for analysis is 32 with number symbols to facilitate analysis. The working fluid state in each state, called state 0, is the environmental condition of the Paiton steam power plant which is used as a dead state system when conducting an exergy analysis. Then the working state 1 fluid is pure dry steam with high pressure, where the steam is preheated by the superheater which utilizes the fluid (exhaust gas) from the boiler. High pressure dry steam from superheater components is used as a source for producing electricity, which is channeled to the high pressure turbine (HPT) to turn the turbine. State 2 of its working fluid is steam as the output of high pressure turbine (HPT) which is flowed into the reheater (RH) to be reupgraded by the reheater utilizing the exhaust gas from the boiler before entering into the intermediate pressure turbine (IPT). State 3 working fluid is the steam output from the high pressure turbine (HPT) which is supplied to the 7A high pressure heater (HPH 7A), where the heat is used to heat water before entering the boiler. State 4 working fluid is the steam output from the high pressure turbine (HPT) which is flowed to the high pressure heater 8A (HPH 8A), where the heat is used to heat water before entering the boiler. State 5 is the working fluid, which is the steam from the reheater to the intermediate pressure turbine (IPT), which in this condition the medium pressure steam and the temperature is high because the steam has been reheated by the reheater. The State 6 working fluid is the steam output from the intermediate pressure turbine which is used to heat the water in the 6A high pressure heater. State 7 working fluid is the steam output from the intermediate pressure turbine that flows into the daerator, where the heat is used to heat the water in the daerator.

State 8 and 9 working fluid, pressurized vapor output from intermediate pressure turbine (IPT) which is used to rotate low pressure turbine A and B. State 10 and 11 working fluid are the remaining vapor output from low pressure turbine (IPT) which is flowed to the condenser to condensing the vapor fluid to water fluid. State 12, 13 and 14 of its working fluid are hot steam output from low pressure turbine A (LPT A) to low pressure heater A (LPH A), where the remaining heat is used to increase the temperature of the water before it is delivered to the boiler. State 15, 16, and 17 working fluid, namely the hot steam output from low pressure turbine B (LPT B) which is flowed to the low pressure heater B (LPH B), where the remaining heat from the turbine output steam is utilized before condensation by the condenser. State 18 working fluid is water that results from condensation of hot steam from the turbine by the condenser, where the water is reused as input for boiler products. State

19 and 20 working fluid, ie condensed water will be pumped by a Condensate pump (CP) to a low pressure heater (LPH). State 21-26 is the initial water heating process by a low pressure heater (LPH) where the water which initially has a low temperature will be raised in temperature. Low pressure heater (LPH) is one of the low pressure heat exchangers where the heat is obtained from a low pressure turbine (LPT) output.

State 27, the working fluid, water that has been increased in temperature which will be passed to the daerator, the function of the daerator itself is to remove the oxygen and gas dissolved in water. The xxygen dissolved in water will cause corrosion in the boiler. State 28 works fluid, the output water from the daerator will be pumped by the boiler feed pump (BFP) to the boiler. State 29, 30, 31, and 32, the working fluid, which is water that is pumped by the boiler feed pump (BFP) will be raised by the high pressure heater (HPH) before entering the boiler. High pressure heater (HPH) itself functions as a high pressure heat exchanger where the heat from the High pressure heater (HPH) is obtained from the high pressure turbine (HPT) and intermediate pressure turbine (IPT).

2. Thermodynamic Method

The exergy analysis was carried out using primary data in the form of daily operational data of Unit 3 Steam Power Plant, Paiton, East Java at 100% load (Full Load). The data taken are: Actual operating data include: Steam Power Plant daily operating data and production data with parameters of temperature, pressure, and steam mass flow rate during the production process, The Manual book of Unit 3 Steam Power Plant Paiton, East Java, data on Paiton area conditions include: atmospheric temperature, atmospheric pressure, altitude and humidity, thermodynamic property tables and relevant scientific journals and text books as universal parameters. These data then become raw data for calculating energy equilibrium and exergy equilibrium. The analysis was performed using the Engineering Equation Solver (EES) application to facilitate calculations.

The exergy analysis will evaluate the exergy balance in each fluid flow condition. In the exergy calculation, there are 4 main components, namely the physical exergy rate, the chemical exergy rate, the kinetic exergy rate and the potential exergy rate where the total exergy rate formula is:

$$\dot{E}_{TOT} = \dot{E}_{PH} + \dot{E}_{KN} + \dot{E}_{PT} + \dot{E}_{CH} \tag{1}$$

Explanation:

$\dot{E}$ = rate of total exergy (kW)
$\dot{E}_{PH}$ = rate of physical exergy (kW)
$\dot{E}_{KN}$ = 8empera exergy rate (kW)
$\dot{E}_{PT}$ = potential exergy rate (kW)
$\dot{E}_{CH}$ = the rate of chemical exergy (kW)

In this study, the exergy analysis will ignore the rate of chemical exergy, the rate of kinetic exergy and the rate of potential exergy as well as changes in the exergy rate due to the effects of nuclear, magnetic, electricity and interparsial so that the total exergy in the flow will only consist of 1 main component, namely the rate of physical exergy. Then the calculation for the total exergy rate is

$$\dot{E}_{TOT} = \dot{E}_{PH} \tag{2}$$

Where:

$\dot{E}_{TOT}$ = rate of total exergy (kW)
$\dot{E}_{PH}$ = rate of physical exergy (kW)

The rate of physical exergy is always related to the temperature, enthalpy and entropy of the material. In a closed system, the rate of physical exergy in a particular state is expressed by the following equation:

$$\dot{E}_{PH} = \dot{m}.[(h - h_0) - T_0(s - s_0)] \tag{3}$$

where:

$\dot{E}_{PH}$ = rate of physical exergy (kW)

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$\dot{m}$ = mass flow rate (kg/s)
h = Fluid enthalpy (kJ/kg)
h_0 = environmental enthalpy (kJ/kg)
T_0 = Environmental temperature(°C)
s = fluid entropy (kJ/kg.K)
s_0 = environmental entropy (kJ/kg.K)

Then the value of exergy loss or irreversibility can be determined in each subsystem using the following equation:

$$\dot{E}_{Loss} = I = \dot{E}_{In} - \dot{E}_{Out} \quad (4)$$

where:

$\dot{E}_{Loss}$ /I = the exergy loss rate or irreversibility (kW)
$\dot{E}_{In}$ = exergy input rate (kW)
$\dot{E}_{Out}$ = exergy output rate (kW)

Table 1. The Exergy Rate of Each Component

Component	Equivalent Exergy Rate	Irreversibility	
Boiler	$Qin + \dot{E}n_2 + \dot{E}n_{32} = \dot{E}n_1 + \dot{E}n_5$	$(Qin + \dot{E}n_2 + \dot{E}n_{32}) - (\dot{E}n_1 + \dot{E}n_5)$	(6)
HPT	$\dot{E}n_1 = \dot{E}n_2 + \dot{E}n_3 + \dot{E}n_4$	$\dot{E}n_1 - (\dot{E}n_2 + \dot{E}n_3 + \dot{E}n_4)$	(7)
IPT	$\dot{E}n_5 = \dot{E}n_6 + \dot{E}n_7 + \dot{E}n_8 + \dot{E}n_9$	$\dot{E}n_5 - (\dot{E}n_6 + \dot{E}n_7 + \dot{E}n_8 + \dot{E}n_9)$	(8)
LPT A	$\dot{E}n_8 = \dot{E}n_{10} + \dot{E}n_{12} + \dot{E}n_{13} + \dot{E}n_{14}$	$\dot{E}n_8 - (\dot{E}n_{10} + \dot{E}n_{12} + \dot{E}n_{13} + \dot{E}n_{14})$	(9)
LPT B	$\dot{E}n_9 = \dot{E}n_{11} + \dot{E}n_{15} + \dot{E}n_{16} + \dot{E}n_{17}$	$\dot{E}n_9 - (\dot{E}n_{11} + \dot{E}n_{15} + \dot{E}n_{16} + \dot{E}n_{17})$	(10)
Kondensor	$\dot{E}n_{10} + \dot{E}n_{11} = \dot{E}n_{18}$	$(\dot{E}n_{10} + \dot{E}n_{11}) - \dot{E}n_{18}$	(11)
CP	$\dot{E}n_{18} = \dot{E}n_{19} + \dot{E}n_{20}$	$\dot{E}n_{18} - (\dot{E}n_{19} + \dot{E}n_{20})$	(12)
LPH 1A	$\dot{E}n_{12} + \dot{E}n_{19} = \dot{E}n_{21}$	$(\dot{E}n_{12} + \dot{E}n_{19}) - \dot{E}n_{21}$	(13)
LPH 2A	$\dot{E}n_{13} + \dot{E}n_{21} = \dot{E}n_{23}$	$(\dot{E}n_{13} + \dot{E}n_{21}) - \dot{E}n_{23}$	(14)
LPH 4	$\dot{E}n_{14} + \dot{E}n_{23} = \dot{E}n_{26}$	$(\dot{E}n_{14} + \dot{E}n_{23}) - \dot{E}n_{26}$	(15)
LPH 1 B	$\dot{E}n_{15} + \dot{E}n_{20} = \dot{E}n_{22}$	$(\dot{E}n_{15} + \dot{E}n_{20}) - \dot{E}n_{22}$	(16)
LPH 2B	$\dot{E}n_{16} + \dot{E}n_{22} = \dot{E}n_{24}$	$(\dot{E}n_{16} + \dot{E}n_{22}) - \dot{E}n_{24}$	(17)
LPH 3	$\dot{E}n_{17} + \dot{E}n_{25} = \dot{E}n_{26}$	$(\dot{E}n_{17} + \dot{E}n_{25}) - \dot{E}n_{26}$	(18)
Daerator	$\dot{E}n_7 + \dot{E}n_{17} = \dot{E}n_{28}$	$(\dot{E}n_7 + \dot{E}n_{17}) - \dot{E}n_{28}$	(19)
BFP	$\dot{E}n_{28} = \dot{E}n_{29}$	$\dot{E}n_{28} - \dot{E}n_{29}$	(20)
HPH 6A	$\dot{E}n_6 + \dot{E}n_{29} = \dot{E}n_{30}$	$(\dot{E}n_6 + \dot{E}n_{29}) - \dot{E}n_{30}$	(21)
HPH 7A	$\dot{E}n_3 + \dot{E}n_{30} = \dot{E}n_{31}$	$(\dot{E}n_3 + \dot{E}n_{30}) - \dot{E}n_{31}$	(22)
HPH 8A	$\dot{E}n_4 + \dot{E}n_{31} = \dot{E}n_{32}$	$(\dot{E}n_4 + \dot{E}n_{31}) - \dot{E}n_{32}$	(23)

The exergetic efficiencies of components and systems are determined using equations 24 and 25.

$$\eta_{exergy} = \left[1 - \left(\frac{I}{\dot{E}_{in}}\right)\right] x100\% \quad (24)$$

$$\eta_{System} = \frac{\dot{W}_{output}}{\dot{E}_{in}} x100\%$$

(25)

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To get a clearer picture, the steps of the research methodology can be seen in The Figure 3 below:

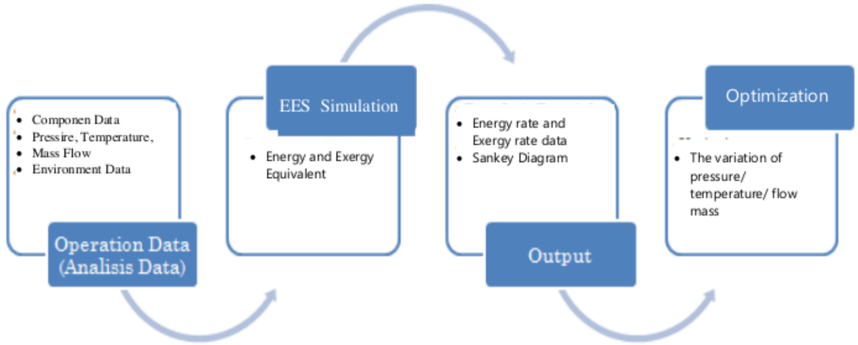

Figure 3. Algorithm Methodology

3. Based on the Table 2, it is known the value of energy rate that entered each component. The energy rate in the boiler of 4106558,959 kW came from the combustion of fuel to heat water to dry steam. Then the rate of energy entering the High Pressure Turbine was 2121369 kW, Intermediate Pressure Turbine was 1923426.12 kW, and Low Pressure Turbine A and B were 685703.37 kW and 684964.2 kW, this energy comes from steam boiler output. The incoming energy was used to turn turbines and generators to produce electricity. Turbine itself is a vital component in generator. The next component, the condenser, based on the Table 2, had an energy rate of 425266,945 kW. This energy came from turbine output steam which was condensed with the help of small pipes containing cooling water to become condensate (water). Then the rate of energy entering the pump was 325688.08 kW, this energy came from water to be pumped to several components. Low Pressure Heater and High Pressure Heater had energy rates of 1144900.60 kW and 1563362.18 kW, respectively, the energy came from water that was preheated before entering the boiler so that the water temperature was higher. The next component was daerator with an energy rate of 281767,807 kW derived from water which would be removed by gases or oxygen dissolved in water so that it is completely clean and ready before entering the boiler.

4. Result and Discussion

The exergy analysis was carried out at a generator load of 815 MW. The data related to thermodynamics in each fluid phase are presented in the table 1 below:

Table 1 The Operational Data of Each State

Stream		state	ṁ	P	T	h	s	e	Energy	Exergy
from	to		kg/s	Mpa	°C	KJ/kg	KJ/kg.K	KJ/kg	KW	KW
Environment		0		0.1	30	125.8	0.4365			
Superheater	High Pressure Turbine	1	631.36	21.58	544.79	3360	6.264	1469	2121369.6	919287
High Pressure Turbine	Reheater	2	532.51	4.03	309.98	2986	6.403	1053	1590074.86	561242
High Pressure Turbine	High Pressure Heater 7A	3	37.42	4.03	309.98	2986	6.403	1053	111736.12	39398
High Pressure Turbine	High Pressure Heater 8A	4	61.43	6.06	360.67	3071	6.374	1146	188651.53	70404
Reheater	Intermediate Pressure Turbine	5	532.51	3.73	571.77	3612	7.328	1398	1923426.12	742973
Intermediate Pressure Turbine	High Pressure Heater 6A	6	19.63	1.84	465.04	3393	7.37	1166	66604.59	22887
Intermediate Pressure Turbine	Daerator	7	20	0.95	373.93	3209	7.405	971.8	64180	19436
Intermediate Pressure Turbine	Low Pressure Turbine A	8	246.39	0.03	150.84	2783	8.182	310.2	685703.37	76430
Intermediate Pressure Turbine	Low Pressure Turbine B	9	246.39	0.03	149.43	2780	8.175	309.4	684964.2	76239
Low Pressure Turbine A	Condenser	10	73.95	0.07	44.72	187.3	0.6348	1.448	13850.835	107
Low Pressure Turbine B	Condenser	11	56.6	0.07	45.39	190.1	0.6436	1.581	10759.66	89.51
Low Pressure Turbine A	Low Pressure Heater 1A	12	202.16	0.3	65.72	275.3	0.9022	8.436	55654.648	912.6
Low Pressure Turbine A	Low Pressure Heater 2A	13	108.18	0.3	109.84	460.8	1.417	38.03	49849.344	4114
Low Pressure Turbine A	Low Pressure Heater 4	14	20.03	0.3	281.46	3031	7.635	724.3	60710.93	14508
Low Pressure Turbine B	Low Pressure Heater 1B	15	7.25	0.02	66.43	2621	7.943	220.9	19002.25	1601
Low Pressure Turbine B	Low Pressure Heater 2B	16	122.1	0.02	105.4	2696	8.152	232.5	329181.6	28389
Low Pressure Turbine B	Low Pressure Heater 3	17	60.44	0.02	185.43	2850	8.522	274.7	172254	16606
Condenser	Condensate Pump	18	355.71	0.08	39.85	166.9	0.5702	0.6551	59367.999	233
Condensate Pump	Low Pressure Heater 1A	19	177.86	3.2	40.09	170.7	0.5722	3.818	30360.702	679
Condensate Pump	Low Pressure Heater 1B	20	177.86	3.2	40.33	171.7	0.5754	3.851	30538.562	684.9

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Low Pressure Heater 1A	Low Pressure Heater 2A	21	177.86	3.2	63.99	270.5	0.8792	10.58	48111.13	1883
Low Pressure Heater 1B	Low Pressure Heater 2B	22	177.86	3.2	64.16	271.2	0.8813	10.66	48235.632	1895
Low Pressure Heater 2A	Low Pressure Heater 3	23	177.86	3.2	89.58	377.6	1.185	24.91	67159.936	4431
Low Pressure Heater 2B	Low Pressure Heater 3	24	177.86	3.2	89.51	377.3	1.185	24.86	67106.578	4422
Low Pressure Heater 2A dan 2B	Low Pressure Heater 3	25	355.71	3.2	89.59	377.6	1.186	24.92	134316.096	8864
Low Pressure Heater 3	Low Pressure Heater 4	26	355.71	3.2	111.18	468.6	1.429	42.07	166685.706	14964
Low Pressure Heater 4	Daerator	27	355.71	0.97	145.15	611.7	1.792	75.3	217587.807	26785
Daerator	Boiler Feed Pump	28	355.71	0.97	176.69	748.7	2.107	116.6	266320.077	41482
Boiler Feed Pump	High Pressure Heater 6A	29	426.97	24.79	184.36	794.7	2.15	149.7	339313.059	63910
High Pressure Heater 6A	High Pressure Heater 7A	30	426.97	24.23	211.58	913.3	2.403	191.6	389951.701	81805
High Pressure Heater 7A	High Pressure Heater 8A	31	426.97	24.23	251.62	1094	2.762	264	467105.18	112705
High Pressure Heater 8A	Boiler	32	426.97	24.23	278.55	1223	3.001	320	522184.31	147787

Based on the Table 1, the enthalpy, entropy, energy, and exergy values in each state were used to analyze the energy rate and exergy rate in each main component of the Paiton steam power plant, namely Boilers, High Pressure Turbines / HPT, Intermediate Pressure Turbines / IPT , and Low Pressure Turbine / LPT), Condenser, Condensate Pump (CP), Low Pressure Heater (LPH), Daerator, Boiler Feed Pump (BFP), and High Pressure Heater (HPH) using Engineering Equation Solver (EES) software.

The Energy and Exergy Analysis

The Table 2 shows the results of the energy and exergy analysis of a supercritical steam power plant with a generating load of 815 MW. Based on the table, the efficiency variation of a component was obtained as follows.

Table 2. Calculation Results of Energy and Exergy Analysis

Component Name	Input Energy	Output Energy	Loss Energy	Input Exergy	Output Exergy	Ireversibility	Exergy Efficiency
	KW	KW	KW	KW	KW	KW	%
Boiler	4106558.959	4044795.72	61763.2388	2703328.789	1662260	1041068.789	61.48937587
High Pressure Turbine	2121369.6	1890462.51	230907.09	927274	671044	256230	72.36739087
Intermediate Pressure Turbine	1923426.12	1501452.16	421973.96	744531	194992	549539	26.18991016
Low Pressure Turbine A	685703.37	180065.757	505637.613	76430	19641.6	56788.4	25.69880937
Low Pressure Turbine B	684964.2	531197.51	153766.69	76239	46685.51	29553.49	61.23573237

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Condenser	425266.945	59367.999	365898.946	400852.96	233	400619.96	0.058126052
Condensate Pump	59367.999	60899.264	1531.265	1632	1363.9	268.1	83.57230392
Low Pressure Heater 1A	86015.35	48111.13	37904.22	2384	1883	501	78.98489933
Low Pressure Heater 2A	97960.474	67159.936	30800.538	5997	4431	1566	73.88694347
Low Pressure Heater 4	227396.636	217587.807	9808.829	29472	26785	2687	90.88287188
Low Pressure Heater 1B	49540.812	48235.632	1305.18	2285.9	1895	390.9	82.89951441
Low Pressure Heater 2B	377417.232	67106.578	310310.654	30284	4422	25862	14.60176991
Low Pressure Heater 3	306570.096	166685.706	139884.39	25470	14964	10506	58.75147232
Daerator	281767.807	266320.077	15447.73	46221	41482	4739	89.74708466
Boiler Feed Pump	266320.077	339313.059	72992.982	41482	63910	-22428	154.0668242
High Pressure Heater 6A	405917.649	389951.701	15965.948	86797	81805	4992	94.24864915
High Pressure Heater 7A	501687.821	467105.18	34582.641	121203	112705	8498	92.98862239
High Pressure Heater 8A	655756.71	522184.31	133572.4	183109	136648	46461	74.62658853

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In general, the energy analysis of the Unit 3 Paiton Steam Power Plant supercritical system only shows the magnitude of the incoming and changing energy rate during the process due to the decrease in enthalpy during the process for each component. Of course, not all of these values can be converted into work due to the environmental influences. For this reason, this research also discusses the exergy analysis in the steam power plant cycle to determine the cause of the decrease in enthalpy during the process that takes place in each state and to consider the value of entropy growth, in accordance with the second law of thermodynamics where in a system it will always lead to equilibrium with the environment. The results of this analysis can be used as a reference for optimization and to improve efficiency.

Unit 3 Paiton Supercritical Steam Power Plant System Exergy Analysis

The Exergy analysis was carried out to determine the magnitude, location and the cause of irreversibility or loss of exergy on the Unit 3 Paiton Supecritical Steam Power Plant Cycle consisting of Boilers, Steam Turbines (High Pressure Turbine / HPT, Intermediate Pressure Turbines / IPT, and Low Pressure Turbines / LPT), Condenser, Condensate Pump (CP), Low Pressure Heater (LPH), Daerator, Boiler Feed Pump (BFP), and High Pressure Heater (HPH). The Figure 4, shows the amount of exergy for each component.

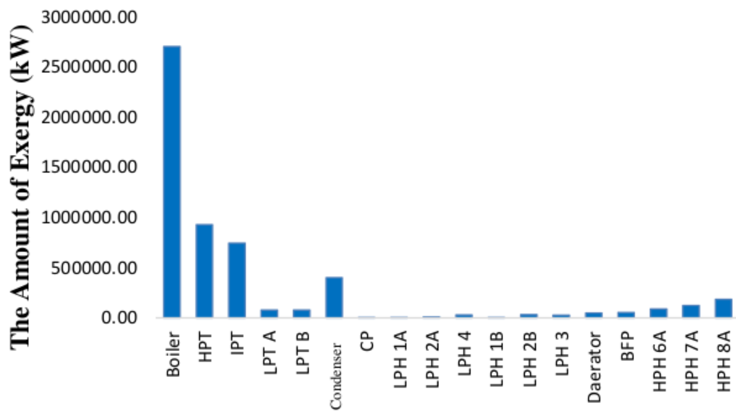

Figure 4. The Exergy for each component

The exergy rate is the availability of energy that can be used in a process per unit time. In the Figure 4, the smallest exergy rate was in the Condensate Pump component which was 1631.39 kW and the biggest exergy rate was in the boiler component, where the exergy value of 2691663.22 kW originating from the combustion process would enter the system to generate the power of 711570 kW. Then after going through the boiler, the steam would go to High Pressure Turbine (HPT) with an available exergy rate of 927467.84 kW. The exergy rate that would enter the HPT showed a decrease which mean the exergy rate that exited the boiler was destroyed as a result of the irreversibility of the boiler itself, regarding the amount of irreversibility of each component that would be presented in the next graph which showed the magnitude of the exergy rate that entered and exited at each component. Likewise, the available exergy rate that would enter the Intermediate Pressure Turbine (IPT) with a total of 744448.98 kW, the number had also decreased compared to the total exergy rate that would enter the HPT. This certainly shows that in HPT also experienced exergy destruction as a result of irreversibility of the HPT itself, the causes of exergy destruction would be discussed in the discussion of each component after this.

Exergy rates that would enter the Low Pressure Turbine A and B (LPT) amounted to 76430.18 and 76233.07 kW which would produce a power generation of 711570 kW. Compared to the exergy rate that would enter IPT at 744448.98 kW, the exergy to the turbine was far reduced, terms, besides being influenced by the irreversibility of the turbine itself, it was also affected by the portion division of the steam out of the turbine towards auxiliary components, namely Low Pressure Heater 1 (AB), 2 (AB), 3, and 4 and High Pressure Heater A6 - A8. The next component is the condenser which according to the table having a value of 400853.01 kW, the exergy is the turbine output to the condenser which has undergone expansion in the turbine to produce mechanical energy transmitted to the generator to produce a power generation of 711570 kW. The last component is Condensate Pump (CP), daerator, and Boiler Feed Pump (BFP), which based on the table 4.4 had exergy values of 1631.39 kW, 46220.96 kW and 53369.78 kW. The location and magnitude of irreversibility can be determined by calculating the irreversibility of each component of the Paiton steam power plant, which can be seen in The Figure 5.

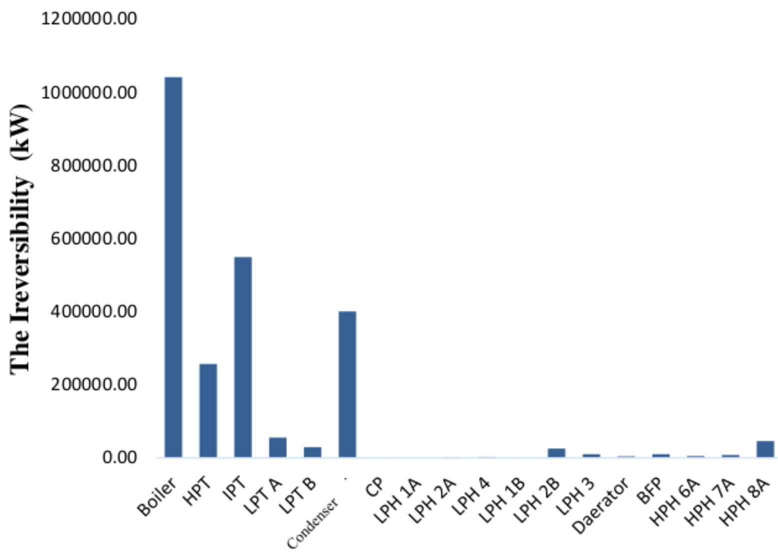

Figure 5. The Irreversibility of each component

A description of the exergetic efficiency of each component is presented using the graph in The Figure 6.

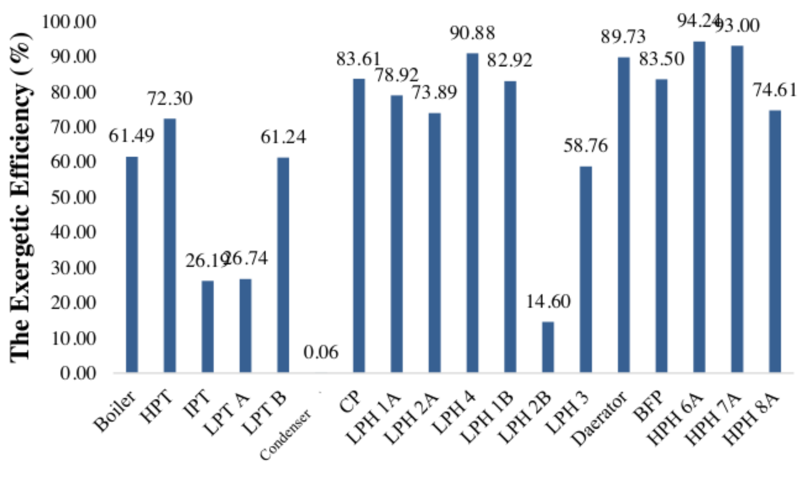

Figure 6. The Exergetic Efficiency of Each Component

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Based on The Figure 6, it can be seen that HPH 6A, HPH 7A, and LPH 4 have exergetic efficiency above 90% which means there was not much loss of exergy in the component. The average exergetic efficiency of the four turbines according to The Figure 4.5 showed a figure of 46.62% where in some of the irreversibility or loss of exergy occured during the expansion process. The condenser had an exergetic efficiency of 0.06%. Then in CP and BFP, each had exergetic efficiency of 83.61% and 83.50%. The exergetic efficiency of boilers and daerators were 61.49% and 89.73%, respectively. LPH and HPH had an average exergetic efficiency of 66.66% and 87.28%. In addition to the exergetic efficiency of each component, it can also be known that the overall exergetic efficiency of the power plant system by comparing the exergy of the product in this case was the power generated by the exergy that entered the system. The results of the calculation can be seen that the overall system exergy efficiency was 26.32%.

The Sankey diagram in the Figure 7 can provide the information about the amount of exergy that entered the system as well as the amount of exergy that is lost in each component of the Unit 3 Paiton Supercritical Steam Power plant.

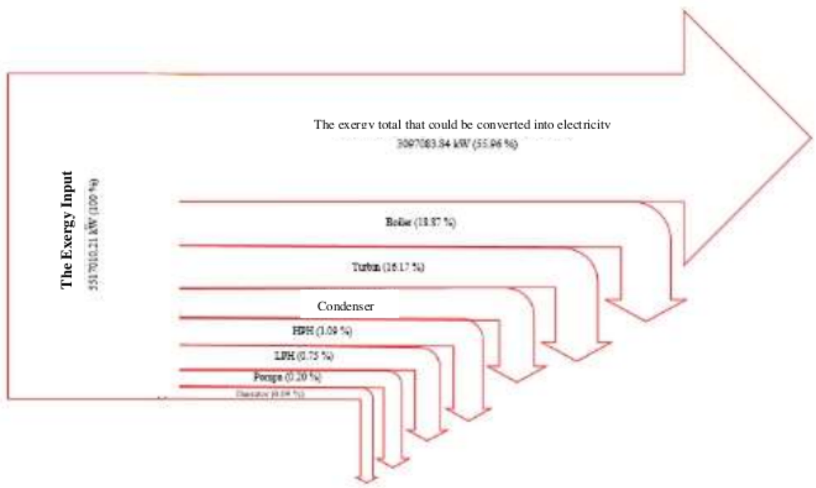

Figure 7. The Sankey Diagram of Unit 3 Paiton Supercritical Steam Power plant Exergy Flow

The exergy flow as well as the extermination rate for each component have been described previously, the Sankey diagram is used to provide a clearer picture of the exergy flow at the Unit 3 Paito supercritical steam power plant. Based on The Figure 6, it shows that the total exergy that entered the system was 5517010.21 kW . Not all of the flow of exergy could be converted into electrical energy because of the exergy that was lost as a result of the irreversibility of components in the steam power plant system. The Figure 5 shows the amount of exergy lost in Boilers, Turbines, Condensers, High Pressure Heaters, Low Pressure Heaters, Pumps and Daerators respectively 1041068.79 kW or 18.87%, 891940.73 kW or 16.17%, 400619.99 kW or 7.28%, 59977.63 kW or 1.09%, 41511.13 kW or 0.75%, 10815.02 kW or 0.20% and 4745.18 kW or 0.09%. The total exergy that could be converted into electrical energy was 3097083.84 kW or 55.96% of the total exergy that entered the system.

The Exergy Optimization on Unit 3 Paiton Supercritical Steam Power plant

This section explains the optimization efforts on the boiler as a component that has the greatest exergy losses in a steam power plant system. In this section, the optimization method that the researcher was done would be explained as an effort to reduce irreversibility and increase the exergetic efficiency of the boiler. The exergy optimization was carried out by varying the boiler output pressure. Pressure variations used were adjusted to the specifications of the boiler and set point set by the company, namely 24.53 MPa, 23.53 MPa, 22.53 MPa, 21.53 MPa, 20.53 MPa, 19.53 MPa, and 18.53 MPa. The optimization was done by simulations using EES software with the applied loading of 711570 kW. Simulation results are shown in the Figure 8.

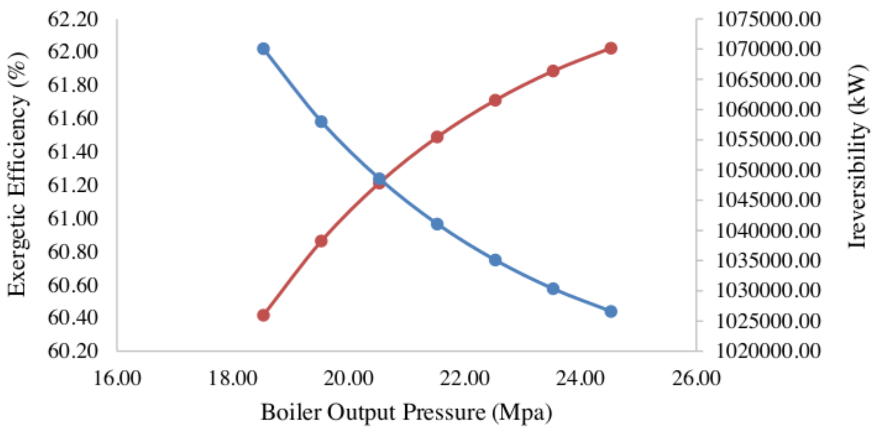

Figure 8. The Influence of pressure on exergetic irreversibility and efficiency

Based on The Figure 8, it can be explained that the higher the boiler output pressure causes the exergetic efficiency to increase and the irreversibility decreases, so as to get the optimal exergetic efficiency value, the steam output pressure produced by the boiler should be higher but still within the range of the component values then the quality Steam turbine input is getting better so that the energy produced by the turbine will increase which then can increase the thermal efficiency of the cycle.

5. Conclusion

The energy analysis provides information about the rate of energy in each component of the steam power plant without considering entropy growth and environmental conditions. Whereas the exergy analysis that has been done can provide information that the greatest irreversibility lies in boilers at 1041068.79 kW, followed by turbines at 891940.73 kW, and condensers at 400619.99 kW, while on other components such as High Pressure Heater, Low Pressure Heater, Pumps, and daerators respectively, each has 59977.63 kW, 41511.13 kW, 10815.02 kW, and 4745.18 kW.

The exergy optimization was carried out on the boiler as the component that has the highest irreversibility in the steam power plant system. The optimization can be done by varying the boiler output pressure. The optimization results show that the higher the boiler output pressure causes the exergetic efficiency to increase and irreversibility to decrease. The Optimal boiler output pressure was obtained at a pressure of 24.53 MPa in the range of component values.

Nomenclature

$\dot{E}_k$	Exergy rate (kW)
h	Enthalpy (KJ/Kg)
$\dot{m}$	Mass flow (kg/s)
s	Entropy (KJ/Kg.K)
e	Exergy flow rate (kW/s)
η_k	Exergy efficiency (%)
I	Irreversibility (kW)

Subscript

CH	Chemical
KN	Kinetic
PH	Physic
PT	Potensial
II	Second Law
I	Input
Out	Output

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