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Energy and Exergy Analysis of Steam Power Plant in Paiton, Indonesia

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Abstract. The exergy analysis of steam power plant system in PT. Jawa Power-YTL, East Java unit 5 was performed based on the first and second law of thermodynamics. Exergy flow and exergy efficiency were calculated for each component of the plant i.e. the boiler, HTP, IPT, LPT, deaerator, condenser, HPH, LPH, CEP and FWP. The exergy steam-flow of 970288 kW produced 610.000 kW of electricity with an exergy efficiency of 26.36%. Sankey diagram showed the exergy loss on each component of the steam power plant. The irreversibility of the boiler, condenser, turbine, LPH, HPH, pump and daerator were 1677003 kW (17,28 %), 738122 kW (7,61 %), 152894 kW (1,58 %), 111881 kW (1,15 %), 470520 kW (4,85 %), 193494 kW (1,99 %) and 1081771 kW (11,15 %), respectively. The total exergy that could be converted into electrical energy in the system was 5276259 kW (54,39%). The highest irreversibility was in the boiler with 1677003 kW (17,28%). The optimization result showed that the highest efficiency was 94.04% at an output pressure of 41 bar.

1. Introduction

Energy plays a very crucial role in everyday life. Over the years, there has been a continuous increase in the world's energy needs. Based on the observation of the International Energy Agency (IEA), the world energy demand in the year 2030 will increase by 45% while the average energy demand in Indonesia will increase by 1.6% per year [1]. Indonesia Energy Outlook about Energy Development in Supporting the Green Industry shows that at an average population growth rate of 6.9% per year, the energy demand in the year 2050 will increase by 7.7-fold against the energy demand in the year 2014 [2]. Energy needs will continue to increase as the economic growth of a nation increases. Steam power plants such as thermal power plants are some of the inventions developed to meet increasing energy needs. An estimate of 74% of the total capacity of national power plant is located in Java-Bali, 16% in Sumatra, 3% in Kalimantan, while the rest are located in other islands (such as Sulawesi, Maluku, West Nusa Tenggara-East Nusa Tenggara, Papua). This is in line with the population distribution and other economic activities in these locations. In terms of fuel input, coal-fired and gas-fired plants have the highest share of 50% (26 GW) and 23% (12 GW) respectively, followed by an oil-fueled plant with a share of 14% (7.5 GW) [2]. Steam power plant is a type of thermal power plant that is often used in Indonesia cost effectiveness and ease of use [3]. The use of fossil fuels to power thermal plants has become a major challenge for power plant industries. The increase in the price of fossil fuels has resulted in an increase in the costs of operating power plants [4].

The occurrence of energy losses in the system results in a decrease in efficiency. According to the second law of thermodynamic, there is no efficient energy conversion process. Thus, there is an inevitable decrease in the quality of energy [5], [6],[7],[8]. Considering the fact that the energy source used in the power plant is mostly coal which is classified as a non-renewable energy with an estimated availability of 59 years ahead, there is a need to improve the efficiency of the system [9]. Therefore, there is a need to conduct an analysis which involves the calculation of the exergy of each component and determination of the magnitude of exergy loss on each component. Exergy analysis is an effective procedure that can be used to optimize the steam turbine cycle. It is a method of thermal system analysis that combines the first and second laws of thermodynamic. This method can detect the real condition, causes and location of system loss in order to formulate an effective improvement for certain components or overall system performance [10], [11].

A research study on exergy analysis conducted by Gurturk and Oztop carried out exergy analysis on a congen fluidized bed boiler used for salt production [12]. Another study on exergy analysis in a steam power plant reported that the greatest amount of energy was lost in in the boilers and turbine. Furthermore, the also identified the effects of environmental conditions on the efficacy of the plant [13]. Rudiyanto, *et al*. conducted a preliminary analysis of a dry-steam geothermal power plant by employing an exergy assessment method in Kamojang geothermal power plant [14]. Similarly, a study conducted by Pambudi, *et al*. involved an exergy analysis and optimization of a single-flash geothermal power plant [15]. Kaushik *et al.* described this methodology in detail and concluded that the highest amount of exergy loss was recorded in the boiler [16]. Khan *et al.* performed an energy and exergy analysis on the rankine cycle [17]. In addition, research studies on exergy and energy illustration in a steam power plant was done by Rosen and Scott. The authors reported that the boiler experienced a higher energy efficiency of 95% compared to the exergy efficiency of 50%, respectively. Based on this result, the authors suggested that the exergy efficiency can be increased by reducing the source of exergy from the provided resources (by matching the provision of exergy on demand), using tools to increase exergy efficiency, increasing the temperature of the delivered heat product, and the utilization of waste heat for process requirements [18]. The research study is conducted by Aljundi aimed to analyze the components of each system to obtain the location of the highest energy and exergy loss. The result of the study showed that the highest exergy destruction of 77% occurred at the combustion chamber in the boiler when its energy efficiency was 43.8% [19]. Other researchers have used exergy analysis to identify the exergy lossin steam power plants, especially in boilers [20]-[21].

This study aimed to conduct an exergy analysis on the steam power plant in Paiton YTL East Java in order to identify the occurrence of exergy loss. The findings generated in this study could be a reference point for the management, formulation of an improvement priority scale and optimization of processes in order to reduce the losses and improve the thermodynamic efficiency of the system.

2. System Description

2.1. Steam-Water Cycle at Steam Power Plant

Paiton-steam power plant uses a closed loop system that uses water repeatedly. Water is added if the quantity is below the set point. This water is converted into steam during certain processes. The water in the boiler comes from the sea through various processes in the Water Treatment Plant (WTP), thereby forming demineralized water from the water from the WTP was supplied to the condenser and pumped into the Condenser Poliser Plant (CPP) to remove corrosion and precipitation.

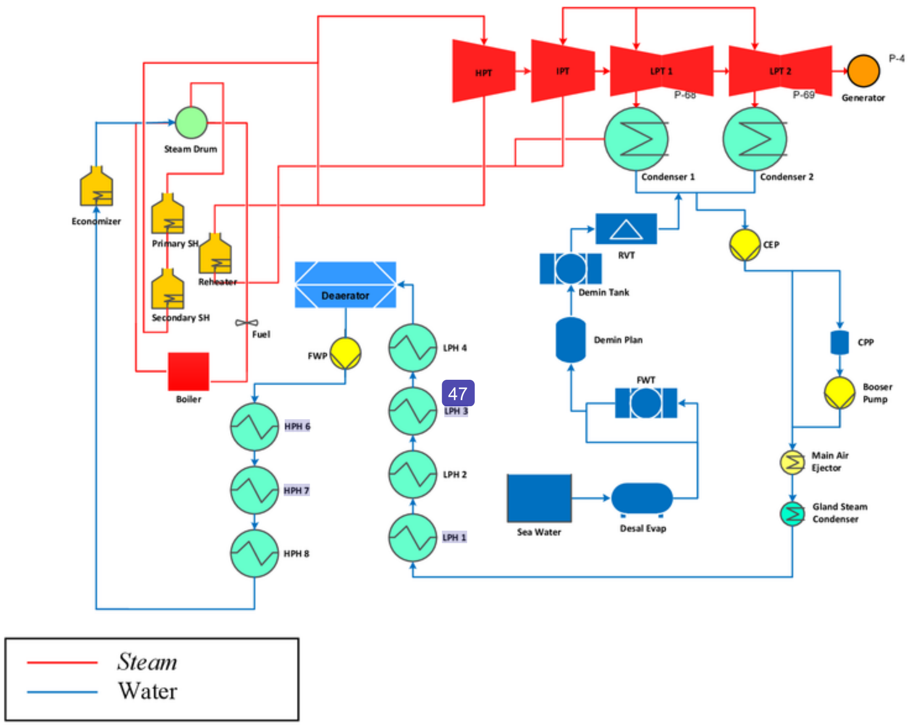

Figure 1. Steam-Water Cycle in PT. YTL Steam Power Plant, East Java.

After this process, the water was passed through the Low Pressure Heater (LPH) A1, A2, A3 and A4 and a deaerator to remove O_2 and CO_2 gases. In the deaerator, the oxygen content is reduced to prevent excess oxidation. The occurrence of oxidation in the pipe results in corrosion and leakage. The water and oxygen content in the pipe was reduced and stored in a Feedwater Storage Pump. Two active pumps were driven by a baby turbine and one standby pump and the water was heated using A6, A7 and A8 High Pressure Heater (HPH). The heated water was pumped into the economizer and reheated to reach higher temperature. The water was then passed into the steam drum to separate steam from water. The water and steam will be reheated by the evaporator and superheater. The boiler pipes in the superheaterare always in direct contact with the fire; this increases the steam temperature to about 500 °C.

The steam generated from the steam drum will be passed through the first and secondary superheater to form the superheated steam (main steam). This is used to rotate the High Pressure Turbine (HPT) in order to reduce the pressure and temperature, and reheat the steam in the reheater. This steam is used to rotate the Intermediate Pressure Turbine (IPT) and the Low Pressure Turbine (LPT). The roration of the turbine rotor is caused by the conversion of thermal energy to mechanical rotation energy. This drives the generator and converts its mechanical energy to electrical energy.

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2.2. Working Process of Steam Power Plant

The general working principle of PT. YTL Steam Power Plant East Java Unit 5 involves the burning of coal in the boiler to heat and convert the water to a very hot steam, which is used to drive the turbine and generate electricity from the magnetic field coil in the generator. The heated feed water in the boiler is obtained from the demineralized water in the Water Treatment Plant (WTP). This water enters the Condensate Extraction Pump (CEP) and mixes with the condensate water from condenser 1 (K1) and condenser 2 (K2).

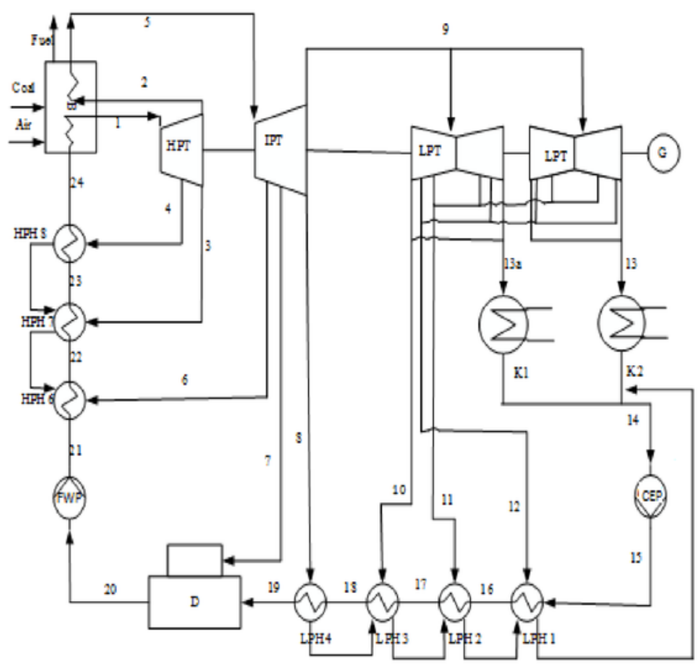


Figure 2. System Diagram of PT. YTL Steam Power Plant East Java Unit 5.

Furthermore, the demineralized and condensate water was passed through the CEP into the A1, A2, A3 and A4 Low Pressure Heater (LPH) for preheating. Feed water was also passed through the deaerator to remove non-condensable gases and Oxygen gas (to prevent oxidation in the pipe) which can cause corrosion and leakage of the pipe. The water was then passed through the High Pressure Heater (HPH) A6, A7 and A8 by Feedwater Pump (FWP) for reheating. The water then enters the water feeds into the superheater. The main steam produced from the superheater was supplied to the High Pressure Turbine (HPT). The steam produced from HPT with a low pressure and temperature was reheated and supplied to the turbine i.e. Intermediate Pressure Turbine (IPT) and Low Pressure Turbine (LPT). The rotor in the rotating turbine was used to convert the thermal energy from steam to mechanical rotation energy. This drives the generator and converts its mechanical energy to electrical energy.

3. Thermodynamic Method

Exergy analysis was conducted by using the primary data i.e. daily operational data of PT. YTL Steam Power Plant East Java at 100% load (Full Load) for 1 month in March 2017. The data included an actual operating data (i.e. daily operating data of the steam power plant), production data, temperature, pressure, and steam flow rate during the production process, the manual book for PT. YTL Steam Power Plant East Java Paiton, documented the Paiton area condition data. These include atmospheric temperature, atmospheric pressure, altitude and humidity, thermodynamic properties tables and relevant scientific journals and textbooks as universal parameters. The raw data was used to calculate energy and exergy balance. This analysis was done by using the Engineering Equation Solver (EES) application.

Exergy analysis involved the evaluation of the exergy balance at each fluid flow condition. The 4 main components of the exergy equation [19] i.e. physical exergy rate, chemical exergy rate, kinetic exergy rate and potensial exergy rate were used to calculate the total exergy flow:

$$\dot{E} = \dot{E}_{PH} + \dot{E}_{KN} + \dot{E}_{PT} + \dot{E}_{CH} \qquad (1)$$

In this research, exergy analysis neglected chemical exergy rate, kinetic exergy rate, potensial exergy rate as well as exergy rate due to nuclear, magnetic, electrical and interpartial effects. Thus, the total exergy flow consisted of 1 main component i.e. physical exergy rate. Therefore, the total exergy rate [19] was determined using the equation:

$$\dot{E} = \dot{E}_{PH} \qquad (2)$$

where:

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

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

Physical exergy rate is always associated with temperature, enthalpy and enthropy of the material. In a closed system, the physical exergy rate at a certain state was calculated using the following equation [19]:

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

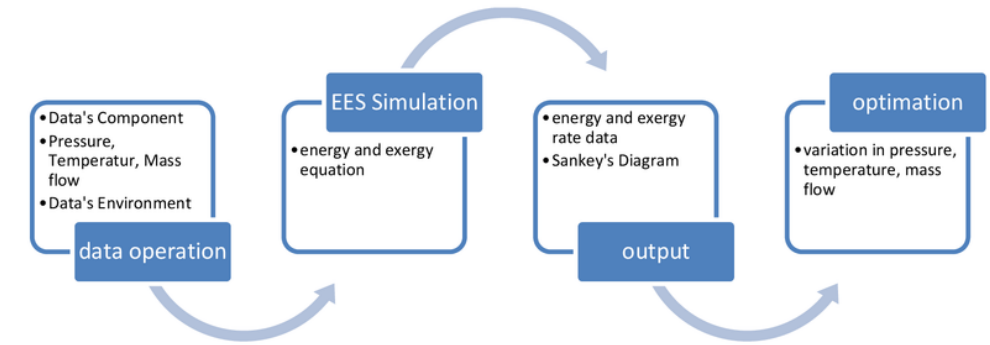
Exergy loss or irreversibility at each subsystem was calculated as follows:

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

The general equation for the determination of exergetic efficiency is:

$$\eta_{eksergi} = \frac{\dot{E}_{In}}{\dot{E}_{Out}} \times 100\% \qquad (5)$$

The basic components of the methodology is shown in Figure 3.



Box 1= Component data, pressure, temperature, mass flow, ambient temperature. Data Operation (Data Analysis)
Box 2 = EES Simulation, Energy and Exergy Equation
Box 3 = Data on energy rate and exergy rate
Box 4 = Optimization, Varying pressure/temperature/mass flow

Figure 3. Algorithm Methodology.

4. Results and Discussions

Exergy analysis was conducted with a generator load of 610 MW. The thermodynamic properties at each fluid phase is shown in Table 1.

4.1. Energy and Exergy Analysis

Table 2 shows the result of the energy and exergy analysis in the steam power plant with a total generator load of 610 MW.

The energy balance analysis shows the difference between the incoming energy and the outgoing energy of the system. This difference is equivalent to the losses or energy wasted from this steam turbine cycle. This may be due to the low isentropic efficiency of the component or actual efficiency when compared to the design component efficiency. A low efficiency is affected by the lifespan of the component, which results in the degradation of its performance. Another factor that cause losses in the cycle is the loss of energy to the environment due to leakage and isolation of the steam turbine system.

Table 3 shows the exergy efficiency of each component in the generator unit at 100% load. The exergy efficiency of a boiler (48.06%) had a total exergy loss (Irreversibility) of about 1677003 kW. Irreversibility is caused by friction between hot combustion gases and working fluid that flows through boiler pipes, thereby, leading to a decrease in pressure. Such pressure drops can result in a lower pressure state compared to the ideal condition. In addition, the exergy loss in a boiler is due to the presence of a slag on the boiler pipes that decrease the thermal conductivity of the pipe and inhibit heat transfer.The exergetic efficiency of each component is shown in Figure 4.

Table 1. Operational data at each state

Name Component	State	Phase	Pressure (Bar)	Temperature (°C)	$\dot{m}$ (Kg/s)	Enthalpy (kJ/kg)	Enthropy (kJ/kgK)
Superheater Out	1	Steam	165	520	564	3348	6,356
Reheater In	2	Steam	40,23	515	484,5	3479	7,131
HPT Out	3	Steam	50,02	253	42,39	1100	2,784
HPT Out	4	Steam	78,03	275	35,44	1209	3,015
IPT In	5	Steam	24,52	515	484,5	3496	7,376
IPT Out	6	Steam	23,29	219	455,2	938,9	2,508
IPT Out	7	Steam	6,72	189	455,2	2821	6,854
IPT Out	8	Steam	2,45	123	19,8	516,6	1,56
LPT In	9	Steam	1,09	178	20,8	2831	7,699
LPT Out	10	Steam	1,71	128	24,33	2726	7,246
LPT Out	11	Steam	0,68	94	23,52	2668	7,515
LPT Out	12	Steam	0,26	58	11,93	242,8	0,806
Cond In	13a	Steam	0,07	46	163	2585	8,316
Cond In	13	Steam	0,07	46	174,7	2585	8,316
Cond Out	14	Water	22,86	45	410	190,4	0,6376
CEP Out	15	Water	29,5	39	410	165,9	0,5578
LPH A1 Out	16	Water	49,43	58	11,93	246,9	0,8035
LPH A2 Out	17	Water	48,23	94	23,5	397,4	1,235
LPH A3 Out	18	Water	42,69	128	24,33	540,6	1,61
LPH A4 Out	19	Water	37,05	151	455,2	638,6	0,2812
Deaerator Out	20	Water	27,56	189	455,2	803,9	2,224
FWP Out	21	Water	35,67	167	176,5	707,7	0,3097
HPH A6 Out	22	Water	197	219	156,7	944,5	2,478
HPH A7 Out	23	Water	197	253	42,4	1100	2,784
HPH A8 Out	24	Water	197	275	35,4	1206	2,981

Table 2. Calculation Result of Energy and Exergy Analysis in the Steam Power Plant

Nama Komponen	En In (kW)	En Out (kW)	Ek In (kW)	Ek Out (kW)	ΔE Sistem (kW)	I (kW)	ηEn (%)	ηEk (%)
Boiler	3602388	1728268	3228831	1551828	1874120	1677003	47,98	48,06
HPT	1888272	1596138	1706213	1590354	292134	115859	84,53	93,23
IPT	1693843	925902	1522618	1521469	767941	1149	54,66	99,92
LPT	872313	58885	51333	15100	813428	36233	6,75	29,42
Condenser	872988	78064	744047	5925	794924	738122	8,94	0,796
CEP	78064	68091	16056	7003	9973	9053	87,13	43,62
LPH A1	70916	2946	8035	1082	67970	6953	4,15	13,47
LPH A2	65697	9346	55422	5363	56351	50059	14,13	9,68
LPH A3	75670	13153	63176	8764	62517	54412	17,38	13,87
LPH A4	290710	23381	15449	14993	267329	456	8,04	97,05
Daerator	1574914	365959	1357173	275402	1208955	1081771	23,24	20,29
FWP	365959	124909	275402	90961	241050	184441	34,13	33,03
HPH A6	552324	148003	432958	115655	404321	317303	26,80	26,71
HPH A7	194629	46626	153095	37509	148003	115586	23,96	24,5
HPH A8	89469	42737	72481	34851	46732	37630	47,77	48,08
Total	12288156	5232408	9702289	5276259	7055748	4426030		

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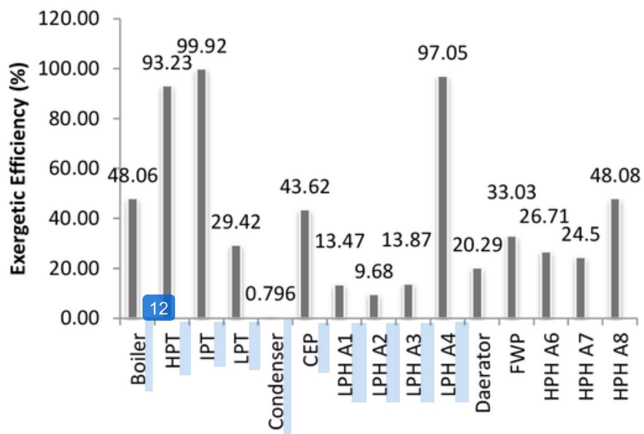

Figure 4. Exergetic Efficiency of Each Component.

Figure 4 shows that the exergetic efficiency of HPT, IPT and LPH A4 are above 90%. This means that there was not much loss of exergy in these components. The average exergetic efficiency of these three turbines was 74.2% in which some part of irreversibility of the 610000 kW turbine was converted to electrical energy. The exergetic efficiency of the condenser was 0.796%. The exergetic efficiency of CEP and FWP was 43.62% and 33.03% respectively while the exergetic efficiency of the boiler and daerator was 48.06% and 20.29%. Furtermore, the exergetic efficiency of HPH and LPH was 33.10% and 33.52%, respectively. The overall exergetic efficiency of the steam power plant system can be determined by comparing the desired product exergy with the exergy that entered into the system. The result of the calculation showed that the overall exergetic efficiency of the system was 26.36%.

4.2. Sankey diagram

Sankey diagram (Figure 5) provides a clear picture of the exergy flow in the system and the loss of exergy in each component of the power plant.

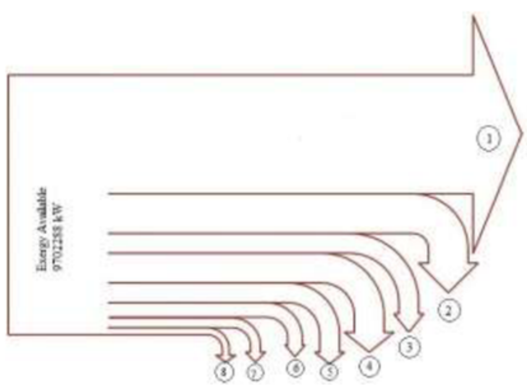

Figure 5. Sankey Diagram.

Key: 1. Electricity 5276259 kW, 54,39%. 2. Boiler 1677003 kW, 17,28%, 3. Condensor 738122 kW, 7,61%, 4. Deaerator 1081771 kW, 11,15%, 5. High Pressure Heater 470520 kW, 4,85% 6. Pump 193494 kW, 1,99%, 7. Turbine 152894 kW, 1,58%, 8. Low Pressure Heater 111881 kW, 1,15%.

The exergy flow in PT. YTL Steam Power Plant East Java unit 5 is shown in Figure 5. This shows that the total exergy entering the system was 9702288 kW. All exergy flow can be converted into electrical energy due to exergy loss and the irreversibility of components in the steam power plant system. The sankey diagram also shows the amount of exergy loss in the boiler, condenser, turbine, low pressure heater, high pressure heater, pump and deaerator (i.e. 1677003 kW or 17.28%, 738122 kW or 7.61%, 152894 kW or 1.58%, 111881 kW or 1.15%, 470520 kW or 4.85%, 193494 kW or 1.99% and 1081771 kW or 11.15%, respectively). In addition, the total exergy that could be converted into electrical energy was 5276259 kW (which is equivalent to 54.39% of the total exergy that enters the system).

4.3. Boiler Optimization

The result of the exergy analysis shows that the boiler had the highest exergy destruction. Therefore, the system was optimized by varying the output pressure of the boiler (main steam) on boiler exergetic efficiency. The optimization result obtained from the Engineering Equation Solver (EES) software is shown in Figure 6:

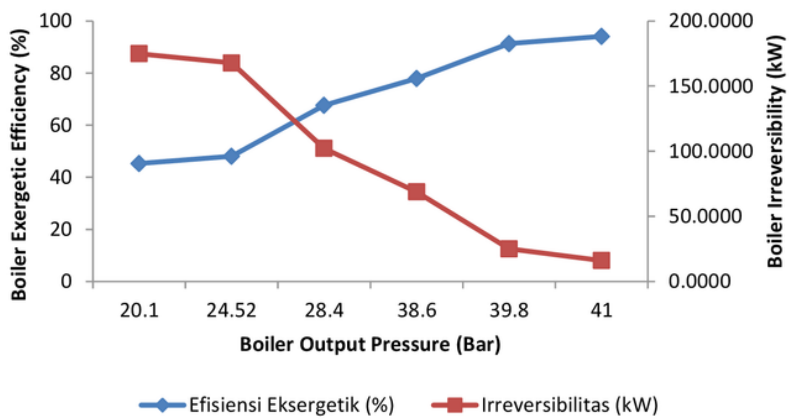

Figure 6. The Effect of Varying Boiler Output Pressure on Efficiency.

Figure 6 shows that there was an increase in exergetic efficiency at 28.4 bar pressure with 610 MW load, which resulted in a boiler's exergetic efficiency of 67.58%. Meanwhile, the simulation resulted in the highest exergetic efficiency of 94.04% at a pressure 41 bar. It also showed that increasing the boiler's output pressure resulted in a decrease in exergy destruction. This led to an increase in exergetic efficiency. When the steam output pressure generated by the boiler was increased within the range of the component values, there was better steam input quality, which resulted in an increase in the energy generated from the turbine and increase in the thermal efficiency of the cycle.

5. Conclusion

The exergy analysis carried out in this study provided information about the location, amount of exergy loss and the process inefficiency level in the steam power plant system. The highest exergy destruction occurred in a boiler with 1677003 kW, followed by a deaerator and condenser with 1081771 kW and 738122 kW. Meanwhile, the exergy destruction at the HPH, LPH, pump and turbine were 470520 kW, 111881 kW, 193494 kW and 152894 kW respectively.

Exergy optimization was conducted in theboiler (which experienced the highest energy loss and exergy destruction) by varying output pressure. The simulation result showed that the high output

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pressure resulted in reduced exergy destruction and increased exergetic efficiency. The simulation at a pressure of 41 bar resulted in an exergetic efficiency of 94.04%. When the steam output pressure generated by the boiler was increased within the range of the component values, there was a better steam input quality, which resulted in an increase in the energy generated from the turbine and increase in the thermal efficiency of the cycle.

Nomenclature

$\dot{E}$	Exergy rate (kW)
h	Enthalpy (KJ/Kg)
ṁ	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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