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Thermodynamic Evaluation of a Gas-Fired Steam Turbine Power Plant

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ABSTRACT

This research work seeks to conduct thermodynamic evaluation of a gas-fired steam turbine power plant. The energy and exergy efficiencies of the plant equipment were evaluated respectively; the exergy destruction and costing of the plant were determined. The data for this research work was obtained through direct observation and interviews from operational records of the plant. MATLAB software was used to analyze the collected data. Energy and exergy methods based on first and second laws of thermodynamics were applied to analyze the data of the plant. Results revealed that the condenser had the highest energy efficiency of 93.07%, the boiler had the lowest energy efficiency at 44.99%, while the turbine had an energy efficiency of 57.59%. The overall efficiency of the plant was 24.11%. The results of exergy efficiency of the boiler, turbine and condenser were also obtained as 69.44%, 89.70% and 15.76% respectively. The energy losses in boiler, turbine and condenser equipment of the plant were analyzed and the following results such as 33.62 MW, 11.66MW and 1.62MW were obtained. Similarly, the exergy losses and the cost rate of exergy destruction of the plant were also achieved. The research work also helps in investigating the areas in the power plant with high energy losses as a means to improve production output, and consequently enhancing the performance of the steam power plant.

Keywords: Thermodynamic, Gas-Fired Steam Turbine, Power Plant, Evaluation

INTRODUCTION

A power plant is an industrial facility used to generate electric power. Most power plants contain one or more generators, a rotating machine that converts mechanical power into electrical power (Oyegoke *et al.* 2020). A plant includes several units such as turbine, generator, etc., and the building or buildings necessary for the generation of power, as an electric or nuclear power. Some of the available types of power plant are Wind Power, Thermal Power, Solar Power, Hydro-power, Steam Power, and Gas Power Plant. A steam turbine power plant is a system in which thermal energy of the steam is transformed into kinetic energy, and later, in its turn is transformed into the mechanical energy rotation of the turbine shaft and finally to electrical energy in the turbo-generator (Khalil, 2004). The main feature of a gas-fired steam turbine plant that distinguishes it from other power plant is its operation logic that has its boiler fired with natural gas. The gas-fired steam power plant operation obeys the laws of thermodynamics. These laws provide ground or basis for evaluating several processes, including compression, combustion, heat recovery, pumping, and expansion processes (Adeoye & Bamisaye, 2016). The thermodynamic evaluation aims to identify the magnitude and locations of energy losses to improve existing systems or processes or to develop new processes by applying mass and energy balances (Ofodu & Abam, 2002; Adegboyega & Odeyemi, 2011).

The thermodynamic performance of the gas-fired steam turbine power plant can be assessed in terms of turbine work, heat input and output, thermal efficiency, heat rate and the overall efficiency of the plant. Without an adequate supply of energy, the stability of the economic order, as well as the political structure of a society is in

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jeopardy (Ogieva *et al.*, 2015). Thermal power generating units' accounts 68.14% compared with other sources of power units in Nigeria (Adegboyega & Odeyemi, 2011). Steam turbines are known to have high energy losses from heat loss, vibration losses and from other causes at each turbine section along the steam path which causes a reduction in the overall efficiency of the steam power plant (Ibrahim &Marwah, 2015). Also, the natural hot gases, if allowed expelled in to the environment, can contribute to global warming causing environmental harm. In order to save our environment from pollution, the natural hot gases are used or converted to a heat source for a steam turbine power plant for electricity generation. As result of high energy losses from heat loss and vibration losses in the plant operations that lead to several problems such as reduced plant efficiency, low electricity or power production output, etc are a major concern of this study as it affects the overall efficiency performance of the power plant. Therefore, this study aims at assessing thermodynamic evaluation of a gas-fired steam turbine power plant.

MATERIALS AND METHODS

The materials used for this study are the gas-fired steam turbine power plant's operational data collected from Sapele power plant managed by Ogorode Generating Company Ltd, Delta State, Nigeria. Data were obtained through direct observation, interviews and from operational logbook of the plant. The data include the mass flow rates, pressures and temperatures at various points. The energy and exergy efficiencies of the boiler, turbine, and condenser equipment were evaluated. MATLAB computer program was employed to analyse the data. Also, energy and exergy analytical methods were applied for the performance evaluation of the plant.

The steam turbine power plant operates on the principle of Rankine cycle; which is discussed extensively by (Ighodaro & Osikhuemhe, 2019).

Figure 1 is a schematic representation of the steam cycle.

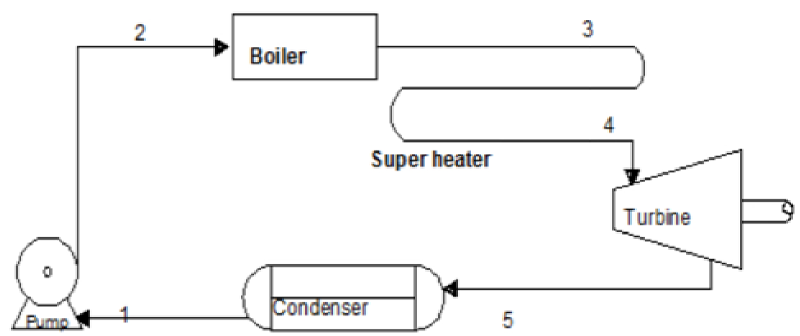

Fig. 1 Schematic representation of the Steam Cycle

The ideal Rankine cycle consists of four processes; 1 -2-3-4-1 is illustrated as shown in the T-s diagram in Fig. 2

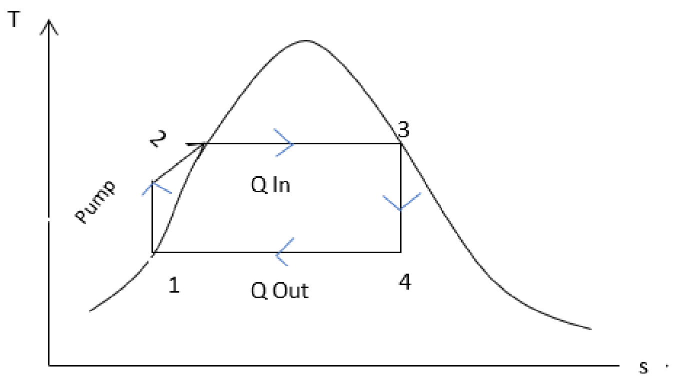

Figure 2: Temperature-Entropy (T-s) Diagram of Ideal Rankine Cycle (Ighodaro & Osikhuemhe, 2019)

The four thermodynamic processes in the Rankine Cycle are detailed as follows:

1 to 2: Isentropic compression (Pump): During the isentropic compression process, external work is done on the working fluid by means of pumping operation.

2 to 3: Isobaric heat supply (Steam Generator or Boiler): During this p the heat from the high temperature source is added to the working fluid to convert it into superheated steam.

3 to 4: Isentropic expansion (Steam turbine): An isentropic process, in which the entropy of working fluid remains constant.

4 to 1: Isobaric heat rejection (Condenser): An isobaric process, in which the pressure of working fluid remains constant.

2.1 Energy Efficiency Analysis

Energy analysis is done on the boiler through the first law of thermodynamics. Figure 3 is a schematic diagram of energy transfer used to determine the energy transfer in the boiler from the energy source into steam and energy efficiency of the boiler.

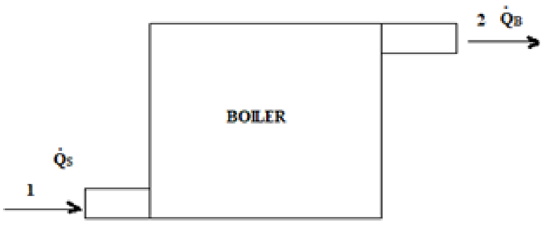

Fig. 3 Schematic diagram of Energy Transfer

2.1.1 Boiler Efficiency

Energy efficiency of the boiler (η_B) is the percentage of heat input that is effectively utilized to generate steam. From Figure 2 it is given as (Yunus & Michael, 2018)

$$\eta_B = \frac{\dot{Q}_B}{\dot{Q}_S} \tag{1}$$

where $\dot{Q}_B$ and $\dot{Q}_S$ are the energy transfer from the boiler and energy source to the boiler, respectively.

The efficiency of the boiler can also be given as

$$Boiler\ Efficiency = \frac{Heat\ Output}{Heat\ Input} \tag{2}$$

$$Enegry\ loss\ in\ Boiler = Heat\ Input - Heat\ Output \tag{3}$$

2.1.2 Turbine Efficiency

Figure 4 shows a steam turbine system in which the heat energy supplied by the steam is converted into mechanical energy by expanding at high pressure and temperature. After passing through the turbine, pressure and temperature are lowered. The turbine efficiency is given as the ratio of the work output of turbine to the heat input to the turbine (output heat generated by boiler).

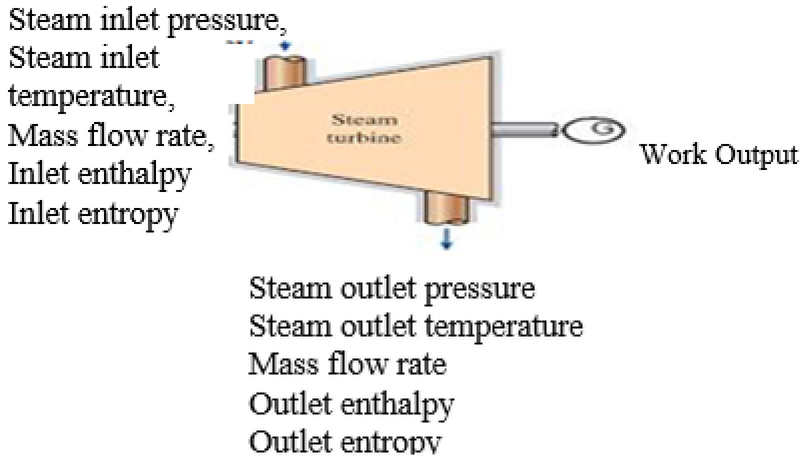

Fig. 4 Turbine Efficiency and Relevant Parameter

The turbine efficiency can be evaluated using the formula (Ighodaro & Osikhuemhe, 2019)

$$Turbine\ Efficiency = \frac{Work\ Output\ \ of\ \ Turbine}{Work\ \ Input\ to\ \ turbine\,(Heat\ Output\ of\ \ Boiler)} \tag{4}$$

$$Enegry\ \ loss\ \ in\ Turbine = Work\ \ Input\ \ - Work\ \ Output \tag{5}$$

2.1.3 Condenser Efficiency

Figure 5 is a condenser system which accepts a vapour stream and converts it to a liquid. The condenser efficiency is calculated as the ratio of the mass flow rate of the condenser cooling water, the caloric value of the condenser cooling water, and the temperature difference between the outlet and inlet cooling water to the product of the mass flow rate of the turbine's steam output and the enthalpy difference between the inlet and outlet steam to the condenser.

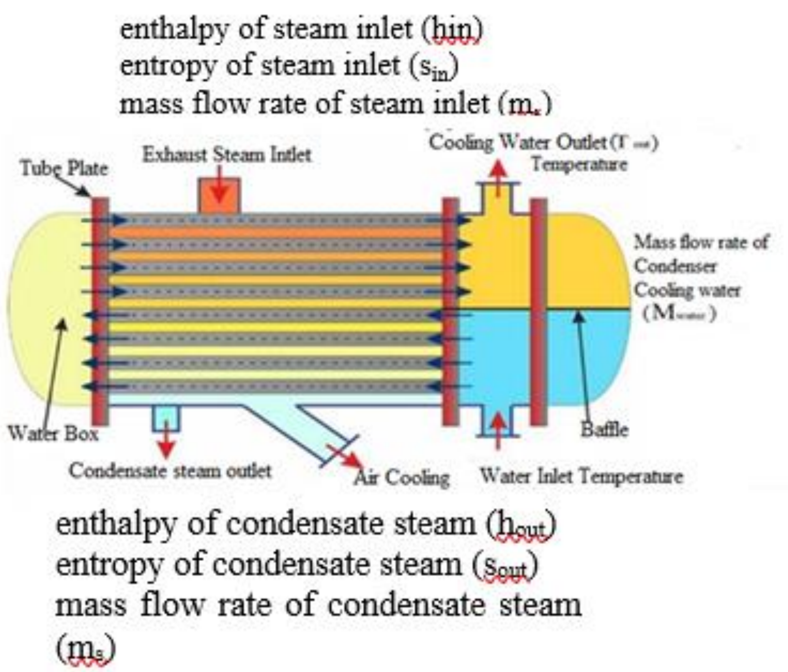

Fig. 5 Condenser Efficiency and Relevant Parameters

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The condenser efficiency can be evaluated using the formula (Ighodaro & Osikhuemhe, 2019)

$$Condenser\ Efficiency = \frac{\dot{m}_W\ Cp_W(T_{Out} - T_{In})}{\dot{m}_S\ (h_{in} - h_{Out})} \tag{6}$$

where $\dot{m}_W$,Cp_W, T_{Out}, T_{In}, $\dot{m}_S$, h_{In} and h_{Out} are the mass flow rate of the condenser cooling water , calorific value of the condenser cooling water, temperature of output condenser cooling water, temperature of input condenser cooling water , mass flow rate of steam output of turbine into the condenser, enthalpy of the steam inlet to the condenser and enthalpy of the steam outlet to the condenser, respectively.

$$Energy\ loss\ in\ Condenser = [\dot{m}_S\ (h_{In} - h_{Out})] - [\dot{m}_W\ Cp_W(T_{Out} - T_{In})] \tag{7}$$

2.1.4 Overall Efficiency

The following equation expresses the overall efficiency of the plant (Ighodaro & Osikhuemhe, 2019)

$$\eta_O = \eta_b\ x\ \eta_t\ x\ \eta_C \tag{8}$$

where η_b, η_t and η_c are the boiler efficiency, turbine efficiency and condenser efficiency, respectively.

2.2 Exergy Analysis of Gas-Fired Steam Turbine Power Plant

The exergy efficiency and exergy destruction of the gas-fired steam turbine power plant are analyzed based on the second law of thermodynamics.

2.2.1 Exergy Efficiency of the Boiler

Exergy efficiency is the ratio of the total exergy leaving the boiler to the total exergy entering (Yunus & Michael, 2018) and it is given as

$$\zeta_B = 1 - \frac{\dot{E}_{DB}}{\dot{E}_2 + \dot{E}_S} \tag{9}$$

where $\dot{E}_{DB}$, $\dot{E}_2$ and $\dot{E}_s$ are the exergy destruction in boiler, the outlet heat from the boiler and the heat supply into the system.

The exergy efficiency of the boiler is also given as

$$Boiler\ Exergy\ Efficiency\ (\psi_{Boiler}) = \frac{Exergy\ increase\ of\ steam}{Exergy\ of\ heat\ input} \tag{10}$$

(Ighodaro & Osikhuemhe, 2019)

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$$Exergy\ destruction\ in\ the\ boiler = Q_{IN}\left[2 - \frac{T_0}{T_1}\right.$$
$$\left. - m(h - h_0) - T_0(S_1 - S_0)\right] \qquad (11)$$

where Q_{IN}, T_0, T_1, $\dot{m}$, h_I, h_o, S_1 and S_0 are the amount of heat input into the system, temperature of fluid outlet, temperature of fluid inlet, mass flow rate of water per unit time, enthalpy of the fluid inlet, enthalpy of the fluid outlet, entropy of fluid inlet of the boiler and entropy of fluid outlet.

2.2.2 Exergy Efficiency of the Turbine

The exergy efficiency of the turbine is given as (Ighodaro & Osikhuemhe, 2019)

$$TurbineExergy\ Efficiency\ (\psi_{turbine}) = \frac{Wt}{Wt + Ed} \qquad (12)$$

where Wt and Ed are the work done by turbine and exergy destruction in the turbine.

$$Exergy\ destruction\ in\ the\ Turbine = T_0\sigma \qquad (13)$$

and

$$\sigma = m(S_2 - S_1) \qquad (14)$$

where m, S_2 and S_1 are the unit mass of turbine, entropy at point 2 and point1 respectively.

2.2.3 Exergy Efficiency of the Condenser

The exergy efficiency of the condenser is given as (Ighodaro & Osikhuemhe, 2019)

$$Condenser\ Exergy\ Efficiency\ (\psi_{condenser}) = \frac{\dot{M}_W(\varepsilon_{W0} - \varepsilon_{W1})}{\dot{M}_{St}(\varepsilon_2 - \varepsilon_3)} \qquad (15)$$

where M_W, ε_{wo}, ε_{wi}, M_{St}, ε_2 and ε_3 are mass flow rate of water, exergy of water outlet, exergy flow rate of water inlet, mass flow rate of steam and exergy at point 2 and point 3 respectively.

$$Exergy\ destruction\ in\ the\ Condenser = \dot{M}_{stream}(\varepsilon_3 - \varepsilon_4)$$
$$- \dot{M}_{water}(\varepsilon_{w0} - \varepsilon_{w1}) \qquad (16)$$

where M_{steam}, ε_3, ε_4, M_{water}, ε_{wo}, and ε_{wi}, are mass flow rate of steam, exergy at point 3 and point 4, mass flow rate of water, exergy of water outlet and water inlet.

RESULTS AND DISSCUSSION

From the data obtained, the results of the thermodynamic evaluation of a gas-fired steam turbine power plant are shown in table 1 and discussed using the various graphs (bar charts).

Table 1: Results for the Thermodynamic Evaluation of Ogorode Gas Fired-Steam Turbine Power Plant

Component	**Energy Efficiency (%)**	**Exergy Efficiency (%)**	**Energy Loss MW**	**Exergy Loss MW**
Boiler	44.99	69.44	33.62	12.10
Turbine	57.59	89.70	11.66	1.817
Condenser	93.07	15.76	1.62	2.189

From Table 1, the energy efficiency of the boiler, turbine and condenser equipment in the plant as analyzed is presented in Figure 6. The illustration revealed that the condenser had the highest energy efficiency at 93.07% and the boiler had the lowest energy efficiency at 44.99% amongst the equipment in the plant, as the turbine equipment had an energy efficiency of 57.59%.

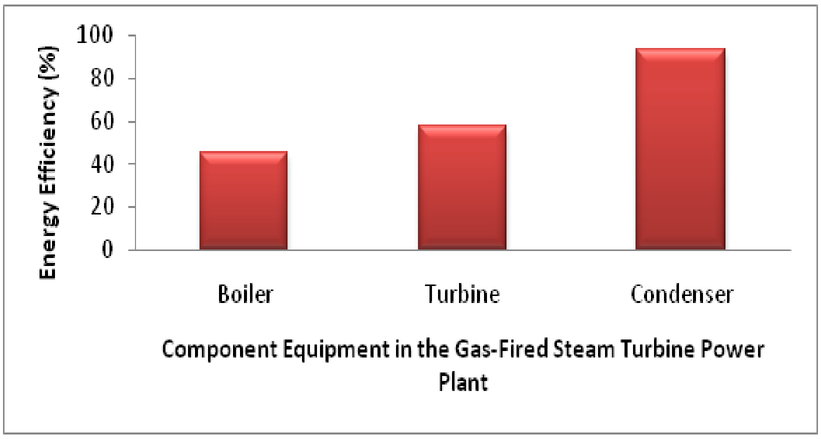

Fig. 6 Energy Efficiency of the Plant

The exergy efficiency of the boiler, turbine and condenser equipment as analyzed is presented in Figure 7. The illustration revealed that the turbine had the highest exergy efficiency at 89.70% and the condenser had the lowest exergy efficiency at 15.76%. The boiler equipment had an exergy efficiency of 69.44%.

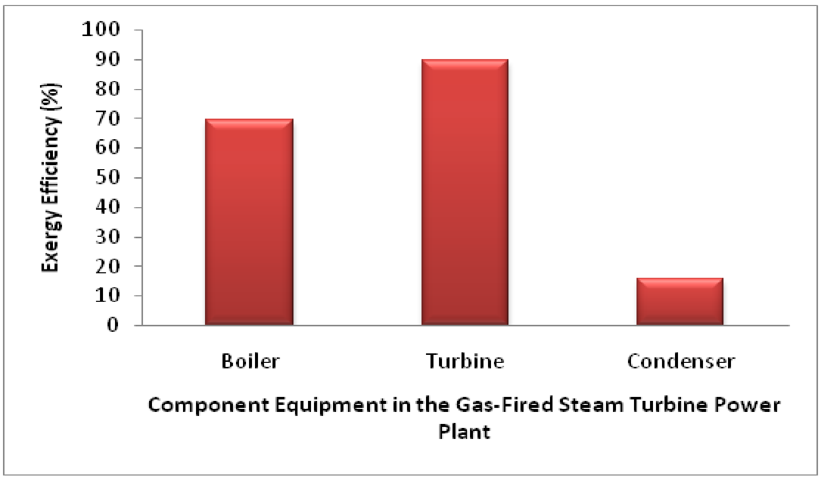

Fig. 7 Exergy Efficiency of the Plant

The loss in energy of the boiler, turbine and condenser equipment in the gas-fired steam turbine power plant is presented in Figure 8. It revealed that the boiler had the highest loss in energy at 33.62 MW and the condenser had the lowest loss in energy at 1.62 MW. The turbine equipment had an energy loss of 11.66 MW.

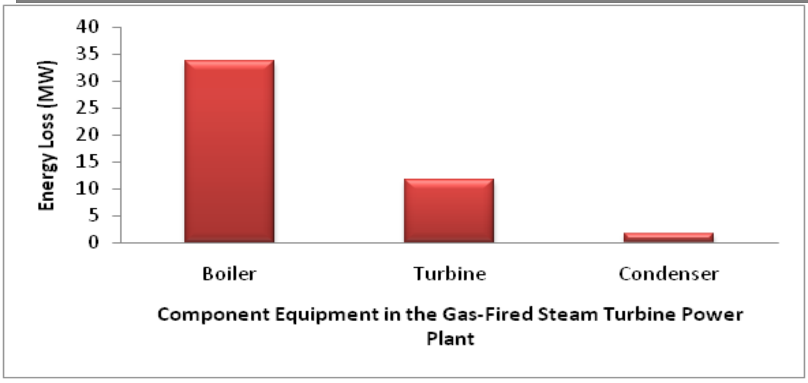

Fig. 8 Energy Loss of the Plant

The loss in exergy of the boiler, turbine and condenser equipment is presented in Figure 9, which revealed that the boiler had the highest loss in exergy at 12.10 MW and the turbine had the lowest loss in exergy at 1.817 MW. The condenser equipment had an exergy loss of 2.189 MW.

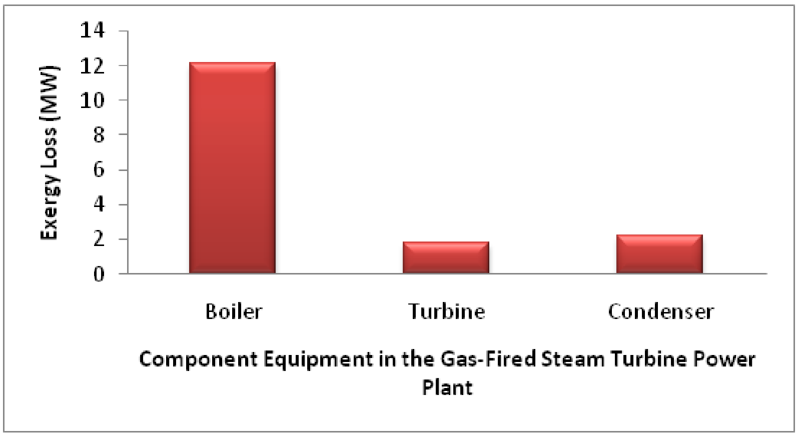

Fig. 9 Exergy Loss of the Plant

CONCLUSION

This research was conducted for the thermodynamic evaluation of a gas-fired steam turbine power plant located in Sapele, managed by Ogorode generating Company Ltd, Delta State. The work was to evaluate energy and exergy efficiency, energy and exergy losses and also to determine exergy destruction of the plant. The analysis revealed that the condenser had the highest energy efficiency of 93.07% and the boiler had the lowest energy efficiency of 44.99%, while turbine had energy efficiency of 57.59%. The overall efficiency of the plant was 24.11%.

The exergy efficiency results revealed that the turbine had the highest exergy efficiency of 89.70%, the condenser had the lowest exergy efficiency of 15.76%, while boiler equipment had exergy efficiency of 69.44%.

The exergy destruction of the plant was determined. Results also revealed that the boiler had the highest energy loss of 33.62 MW, the condenser had the lowest loss of energy at 1.62 MW, while the turbine equipment had energy loss of 11.66 MW. Finally, the exergy losses of the boiler, turbine and condenser equipment in the plant were also achieved.

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