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Exergy Audit of Thermodynamic Parameters and Performance Analysis of Ogorode Thermal Power Plant in Delta State, Nigeria.

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ABSTRACT

The exergy analysis of the Ogorode steam plant is presented. The aim was to determine and identify the magnitudes and locations of real exergy losses in order to improve plant efficiency. The exergy losses occurred in the various components of the steam plant, such as the boiler, economizer, turbine, super heater, condenser, pump, feed water heater, reheater, and air pre-heater, and these have been calculated using the concepts of availability or available exergy and irreversibility. The temperature and pressure of the plant's running conditions were combined to determine the process irreversibility (exergy losses) and the exergy efficiency of the plant. The exergy losses of the individual components of the plant show that the maximum exergy losses are in steam turbine operation one (STO_1) and steam turbine operation two (STO_2). STO_1 and STO_2 are 813 kJ/kg, 820 kJ/kg, 822 kJ/kg, and 815 kJ/kg that occurred in the turbine between 2019 and 2021, while the minimum exergy losses in STO_1 and STO_2 are 68 kJ/kg, 150 kJ/kg, 280 kJ/kg, and 276 kJ/kg that occurred in the boiler system between 2019 and 2021. There was a high energy efficiency of 82% and 80% in the superheater between 2019 and 2021, while 89% in the feed water heater and 73% in the superheater had the same duration. The efficiency of 15% and 21% were the minimum in the pump system between 2019 and 2021, while the turbine had a minimum of 20% and 27% from 2019 to 2021. The highest losses of exergy occurred in the turbine as a result of the irreversibility inherent in the turbine process, corroded turbine blades as a result of wet steam, and low energy delivered to the superheater tubes. It was concluded that the turbine inlet temperature should be increased, more energy delivered to the superheater should be increased, boiler pressure should be increased, and weak feed water heaters should be replaced for better performance of the thermal plant.

Keywords: Exergy; thermodynamics; Energy; Audit; Power Plant

1.0 INTRODUCTION

The exergy method of analysis is based on the second law of thermodynamics and the concept of irreversible production of entropy. Energy-related engineering systems are designed, and their performance is evaluated primarily by using the energy balance deduced from the first law of thermodynamics. Engineers and scientists have been conventionally applying the first law to calculate the enthalpy balance for more than a century to quantify the loss of efficiency in a process due to a loss of energy. However, in recent years, the exergy analysis of energy systems has more and more drawn the interest of engineers and scientific communities (Robert, 1986). The exergy concept has gained considerable interest in the thermodynamic analysis of thermal processes and plant systems (Ganapathy et al., 2009). Based on the second law of thermodynamics, the exergy analysis presents the third step in the plant system analysis, following the mass and the enthalpy balances. The aim of the exergy analysis is to identify the magnitudes and locations of exergy losses in order to improve the existing systems, processes, or systems. Researchers have shown that exergy analysis has become a key aspect in providing a better understanding of the analysis of power system processes, the quantification of sources of inefficiencies, and distinguishing the quality of energy (or heat) used (Jin et al., 1997).

Nowadays, there are few methods to measure the performance of a power plant. The first law of thermodynamics (energy analysis) deals with the quantity of energy and asserts that energy cannot be created or destroyed. The law merely serves as a necessary tool for the bookkeeping of energy during a process and offers no challenges to the engineer. The second law (exergy analysis), however, deals with the quality of energy. It is concerned with the degradation of energy during a process, the generation of entropy, and the loss of opportunities to do work, and it offers plenty of room for improvement. Although the method of exergy is often considered to be a new method for analyzing energy systems (Hussain et al., 2005),

However, system analysis based on the energy law alone is deceptive because the exergy law shows that energy has quantity as well as quality. Based on the underlying facts, exergy analysis was performed on the Ogorode thermal plant in order to provide a quantitative measure of the quality of the energy in terms of its ability to perform work, which leads to a more rational use of energy. A lot of energy is being used to run the Ogorode power plant in Sapele, Delta State. If a large proportion of this energy is not put to use, then it will be uneconomical to run such a power plant. So, there is a need to quantify the amount of loss in each process of the power plant with a view to determining which of the processes gives a lower amount of energy loss or the highest loss. This evaluation would assist in determining a means of reducing, to a minimum, the processes that yield the highest degradation with the attendant reduction in the cost of energy generation.

The aim of this research work is to predict the imperfection of the Ogorode thermal power plant in Sapele Delta State with a view to minimizing its losses. This will be achieved by assessing the exergy distribution in several plant components and also determining the component with the maximum exergy loss. This is done to ensure that all available work is put to use, i.e., maximize the available work potential. It is evidence that not all energy is available to do work in any thermal power plant. So, to improve the plant's output, there should be a way to reduce its huge energy losses. And the reduction in energy losses means that there is more to benefit from the energy input in the power plant.

Since a lot of energy is being used to run a power plant, if a large proportion of this energy is allowed to go to waste, it means that the design capacity will not be met and the overall efficiency will be equally affected. Furthermore, cost reduction will be an economic benefit. This implies that if a huge proportion of energy that is generated at a very high cost is not efficiently put to use, then it will not be economical to run such a plant. Therefore, there is a need to reduce energy waste, which will definitely reduce the generation cost of energy for economic reasons.

Lastly, energy waste always results in pollution and climate change, which are not environmentally friendly. Exergy analysis will be performed on the various components of the Orogode steam plant: the boiler with its fittings and accessories, the condenser, preheater, super heater, economizer, desuperheater, turbine, feed water heater, and reheater. Finally, focus will be on the process with the highest exergy losses, with a view to improving the existing processes.

Recently, a lot of studies based on exergy analysis have been carried out by many researchers all over the world in various systems applications (Ganapathy et al., 2009). The continued quest for higher thermal efficiencies has resulted in some innovations, modifications to the basic vapour power cycle (Yunus and Michael, 2007). Jin et al. (1997) analyzed two operating advanced power plants using a methodology of graphical exergy analysis and pointed out the inefficient segments in the combined cycle plant. They stated that the low performance of the combined cycle plant was due to the higher energy loss caused by mixing in the combustor, the higher energy waste from the heat recovery steam generator, and the higher energy loss in the bottoming cycle. Ganapathy et al. (2009) performed exergy analysis on the 50 MW power generation capacity of Unit 1 of the Thermal Power Station 1 of Neyveli Lignite Corporation Limited, Neyveli. It was aimed at identifying the magnitudes and locations of real energy losses so as to improve the existing systems, processes, or components.

The works of Rosen and Dincer (1997) applied exergy analyses to a wide range of processes, including the production of hydrogen and hydrogen-derived fuels, electrical and thermal power generation, thermal energy storage, and the energy utilization of countries. He also examined the several significant implications of exergy analyses in the fields of environmental impact assessment and economics. Suresh et al. (2006) compared the energy and exergy analyses of thermal power plants based on advanced steam parameters in Indian climatic conditions.

The study involves coal-based thermal power plants using sub-critical, super-critical, and ultra-supercritical steam conditions. The design consideration of a 500 MW unit size was considered. The study encompasses the effect of condenser pressure on plant and exergy efficiency. The effect of high-grade coal on performance parameters as compared to typical low-grade coal in India was also studied. The major exergy loss took place in coal combustion, followed by steam generators (Eastop and McConkey, 1993). Due to condenser pressure limitations, the maximum possible plant efficiency was found to be about 41% for super-critical steam power plants and 44.4% for ultra-supercritical steam power plants (Mborah and Gbadam, 2010).

2.0 MATERIALS AND METHODS

2.1 Ogorode Thermal Power Plants

The conception and construction of the Sapele power station in Orogode, Delta State, was the outcome of a series of studies conducted in the 1970s. In fact, the necessity to construct the power plant was to enable Nigeria to meet as much as possible the rising demand for electricity, a peculiar characteristic of a growing and developing economy. The station consists of a 6 x 120 megawatt steam turbine capable of producing 720 megawatts at full firing. The steam turbines have facilities for either firing the boiler on natural gas or high-pour fuel oil; the boiler type is water in a tube. The gas turbine combustion chamber is fired on natural gas only. At the moment, only two of the six installed steam turbine units are available for operation, while none of the four gas turbine units are operational. The available ones are steam turbine operation one (STO1) and steam turbine operation two (STO2). The present average available capabilities are as follows: STO1 is now 80 megawatts, STO2 has 90 megawatts, and the total is 170 megawatts. However, efforts are being made to bring back more units on stream.

2.1.1 Steam turbine specifications

Boiler

Manufacturer: Deutsche Babcock
Designer pressure: 115 bar
Average year of manufacturer: 1976
Evaporation: 455,000 kilogram per hour
Steam pressure (super heater outlet): 94 bar
Steam temperature (super heater outlet):201^{o}C
Gas firing (100%)
Air consumption: 467,900 kilogram per hour
Gas consumption: 30, 586 kilogram per hour

Turbine

Manufacturer: Brown Boveri (BCC)
Rated terminal output: 120megawatts
Live steam pressure: 87.3 bar
Live steam temperature: 510^{o}C
Generator: 0.9 power factor
Rate speed: 3000 revolution per minute

2.1.2 Gas turbine specifications

Manufacturer: Brown Boveri (BCC)
Type: TA14005
Number of stages: 5
Output: 75 megawatts
Speed: 3000 revolution per minute
Gas inlet pressure (absolute) approximate: 9.5 bar
Gas inlet temperature (mixed temperature) approximate: 945^{o}C
Exhaust gas temperature approximate: 485^{o}C
Exhaust gas mass flow approximate: 365kg/sec
Exhaust gas pressure (absolute) at diffuser outlet: 1.0813

2.2 Collection of data

Data collection for the studies was obtained from the PHCN (formerly NEPA) Sapele thermal power station log sheet for the available steam turbines (STO 1) and (STO 2). The collected data covered the period 2019–2021, excluding 2020 due to interference from COVID-19. The specific items in the data collected include the steam temperature at the inlet and exit states of each component and the steam pressure at the inlet and exit states of each component, while entropy and enthalpy were taken from the steam table.

Tables 1 and 2 show the average data collected from the period under study (2019 and 2021) for turbine units of ST01 and ST02.

Table 1: Average Temperature and Pressure of components for 2019 and 2021 from STO1 turbine unit

	Steam Turbine Unit One (ST01) 2019				Steam Turbine Unit One (ST01) 2021			
Components	Average Inlet Temp. .(°C)	Average Exit Temp. (°C)	Average Inlet Pressure (bar)	Average Exit Pressure (bar)	Average Inlet Temp. .(°C)	Average Exit Temp. (°C)	Average Inlet Pressure (bar)	Aver Exit Press (bar)
Boiler	213	511	98	86	213	511	97	87
Economizer	92	210	92	28	192	208	92	28.3
Turbine	512	254	94	5	512	254	94	5
Super heater	430	510	90	84	428	507	88	83
Condenser	153	46	87	9.8	154	44	91	9.5
Pump	158	172	5.5	7.9	159	170	5.3	7.9
Feed Water Heater	133	290	4.7	97	132	291	4.7	94
Reheater	118	258	0.6	2.14	117	258	0.6	2.14
Air Preheater	211.4	225	20.1	28.5	212	225	20	28.5

Table 2: Average Temperature and Pressure of components for 2019 and 2021 from STO2 turbine unit

	Steam Turbine Unit Two (ST02) 2019				Steam Turbine Unit Two (ST02) 2021			
Components	Average Inlet Temp. .(°C)	Average Exit Temp. (°C)	Average Inlet Pressure (bar)	Average Exit Pressure (bar)	Average Inlet Temp. .(°C)	Average Exit Temp. (°C)	Average Inlet Pressure (bar)	Aver Exit Press (bar)
Boiler	212	512	94	91	213	512	92	89
Economizer	191	207	90	27.5	189	209	93	28
Turbine	511	246	87	4.3	514	248	90	4.4
Super heater	422	501	92	85	427	498	87	85
Condenser	160	45	89	10.4	160	43	92	11
Pump	158	168	5.30	7.7	157	166	5.51	7.8
Feed Water Heater	132	294	4.7	92	131	292	4.62	95
Reheater	119	258	0.6	2.07	120	258	0.7	2.21
Air Preheater	210	223	20	29.1	215	225	20.5	29.1

2.3 Exergy Analysis approach for each component

Boiler Availability $(Ava_b) = b_{1b} - b_{2b} = (h_1 - T_0 s_1) - (h_0 - T_0 s_0)$ (1)

Boiler irreversibility/exergy dest. $(e_{xb}) = (h_1 - h_2) - (h_1 - T_0 s_1) - (h_0 - T_0 s_0)$ (2)

Exergy efficiency of the boiler $(€_b) = 1 - \underline{T_0 S_{gen}}\, h_2 - h_1$ (3)

Where, $S_{gen} = S_2 - S_1$

Availability in steam turbine $(Ava_t) = T_0 (s_2 - s_1)$ (4)

Irreversibilty/exergy dest. In steam turbine $(e_{xt}) = (h_2 - h_1) - T_0 (s_2 - s_1)$ (5)

Availability in feed water heater (Ava_{fwh}), $= b_{1fwh} - b_{2fwh} + b_{1c} - b_{2c}$ (6)

Irreversibility in the feed water heater $= (h_2 - h_1) - (b_{1fwh} - b_{2fwh} + b_{1c} - b_{2c})$ (7)

3.0 RESULTS AND DISCUSSION

The availabilities, irreversibility, and exergy efficiency were calculated at different state points from the operating data of Sapele steam plant components such as the boiler, economizer, turbine, super heater, condenser, pump, feed water heater, reheater, and air pre-heater. The results of the calculations are presented in Tables 3 to 6.

Table 3: Calculated values of Availability, Irreversibility and Exergy Efficiency of plant components (STO1) for 2019

Components	Availability (kJ/kg)	Irreversibility (kJ/kg)	Exergy Efficiency (%)
Boiler	602	68	35
Economizer	584	765	74
Turbine	919	813	19
Super heater	830	295	82
Condenser	1155	462	37
Pump	623	677	15
Feed Water Heater	823	573	84
Re-heater	109	452	76
Air Pre-heater	560	763	20

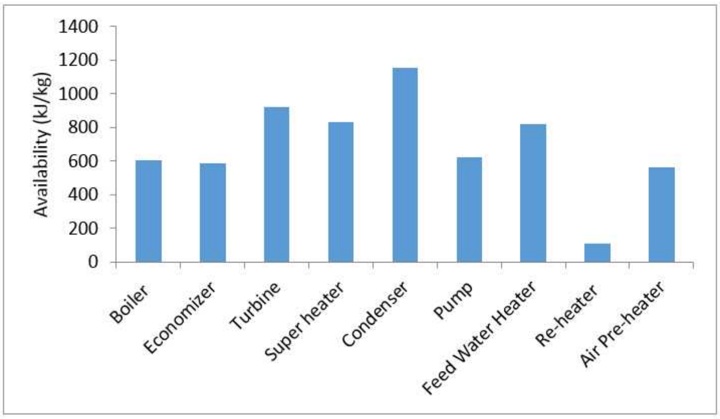

Figure 1: Availability of different components for(STO1) in year 2019

From Table 3 and Figure 1, it was observed that the condenser has the highest availability of 1155 kJ/kg, followed by the turbine with 919 kJ/kg in STO1 in 2019. This shows that some of the fuel gases were not fully utilized by the economizer. As the turbine temperature and pressure increased, the steam expanded along the turbine, but the temperature dropped towards the end of the turbine. It was observed that the maximum loss (irreversibility) of 813 kJ/kg occurred in the turbine. This may be due to less heat energy delivered to the super heater tubes and the wetness of steam at the exhaust. The exergy efficiency was seen to be highest on the feed water component.

Table 4: Calculated Values of Availability, Irreversibility and Exergy Efficiency of Plant Components (STO1) for 2021.

Components	Availability (kJ/kg)	Irreversibility (kJ/kg)	Exergy Efficiency (%)
Boiler	606.7	280	46
Economizer	583.6	789	70
Turbine	903	822	20
Super heater	900	285	76
Condenser	1255	400	34
Pump	626	676.2	20
Feed Water Heater	825	571	80
Re-heater	236	460	61
Air Pre-heater	552	760	23

Table 5: Calculated Values of Availability, Irreversibility and Exergy Efficiency of Plant Components (STO2) for 2019.

Components	Availability (kJ/kg)	Irreversibility (kJ/kg)	Exergy Efficiency (%)
Boiler	605.4	150	40
Economizer	601.2	808	73
Turbine	912	820	22
Super heater	850	342	80
Condenser	1050	420	32
Pump	630	684.3	21
Feed Water Heater	750	585	89
Re-heater	629	470	66
Air Pre-heater	614	754	25

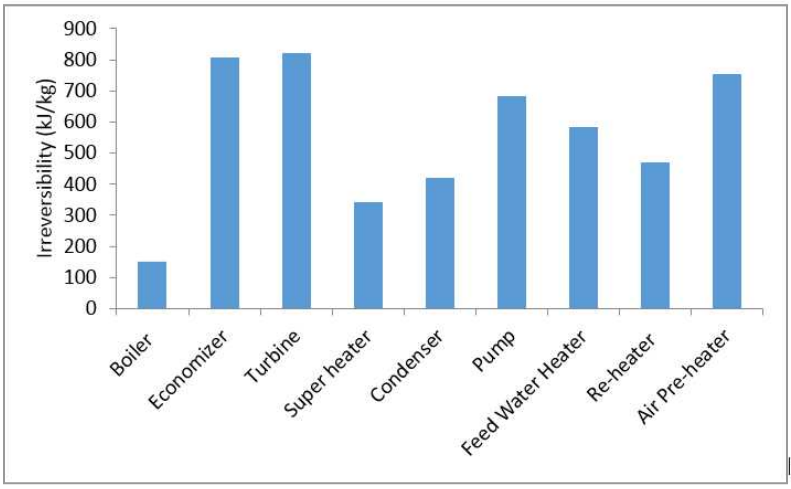

Figure 2: Availability of different components(STO2) in year 2019

Table 6:Calculated Values of Availability, Irreversibility and Exergy Efficiency of Plant Components (ST02) for 2021.

Components	Availability (kJ/kg)	Irreversibility (kJ/kg)	Exergy Efficiency (%)
Boiler	612	276	51
Economizer	560.4	645	72
Turbine	855	815	27
Super heater	905	276	73
Condenser	1122	385	40
Pump	570	630	33
Feed Water Heater	865	554	64
Re-heater	260	465	58
Air Pre-heater	540	743	32

Table 4 showed that the exergy loss of 822 kJ/kg occurred in the turbine section. This could be due to the effect of decreased steam turbine discharge pressure and increased steam temperature. But if the turbine inlet pressure and temperature increase, then efficiency will increase. Table 5 and Figure 2 show that the highest irreversibility occurred in the turbine. This may be due to the decrease in mass flow rate in the turbine as a result of a decrease in temperature and pressure. Therefore, with an increase in the energy supplied, the work output increased, and the irreversibility may have decreased. In Table 6, it was observed that the highest exergy losses occurred in the turbine again. Thus, the exergy analysis diverts our attention towards the turbine for plant performance improvement. The analysis of the plant based on exergy principles has proven that the chance of improving the plant output is greater in the turbine by reducing its huge exergy losses. From the discussion above, it was observed that the exergy analysis pinpoints the system where attention has to be paid to maximize plant performance. From the comparison of exergy losses between different components in steam turbine plant 1 (STO1), it can be observed that the maximum loss (irreversibility) of 813 kJ/kg was calculated in 2019, but the losses were increased to 822 kJ/kg in 2021. The STO2 was calculated to record a loss of 820 kJ/kg in 2019 in the turbine section but was reduced to 815 kJ/kg in 2021. This problem might have occurred in the turbine due to less heat energy delivered to the super heater tubes, wet steam, and a corroded blade in the turbine. Hence, with an increase in the heat energy supplied, the work output of the turbine will be higher, and the irreversibility will be minimal. With maximum work output from the turbine, plant performance will increase. This is because the smaller the irreversibility associated with a process (the turbine), the greater the power that is produced or the less power consumed. Therefore, the performance of the system can be improved by minimizing the irreversibility associated with it. From the discussion above, it is observed that the exergy analysis pinpoints the system where attention has to be paid to maximize plant performance.

4.0 CONCLUSION

The exergy analysis was performed on the Ogorode Steam Power Plant, Sapele, with about 120.248 KW of output energy. The exergy distribution of the steam power plant components has been calculated. The exergy analysis results showed that in STO1 and STO2 for 2019 and 2021, the highest exergy losses of 813 kJ/kg, 820 kJ/kg, 822 kJ/kg, and 815 kJ/kg took place within the turbine system, while the minimum exergy losses of 68 kJ/kg, 150 kJ/kg, 280 kJ/kg, and 276 kJ/kg occurred in the boiler system in STO1 and STO2 for 2019 and 2021. There was a high exergy efficiency of 82% and 89% in the super heater between 2019 and 2021, and 80% and 64% in the feed water heater between 2019 and 2021. The efficiency of 11%, 15%, and 21% was the minimum in the pump system in 2019, while the turbine had a minimum of 20% and 27% in 2019 and 2021. These losses may have occurred in the turbine due to less heat energy delivered to the super heater tubes, wet steam, a corroded blade, and the irreversibility inherent in the turbine. This analysis shows that the chance of improving plant output is greater in the turbine system. This analysis shows that the chance of improving plant output is greater in the turbine system.

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