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Energy and Exergy Investigations of a 972mw Based Steam Parameters Thermal Power Plant in Nigeria

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Abstract: The generation of electricity is critical to the expansion of the economy and the improvement of people's standard of living. Scientists from all over the world find themselves increasingly aware of the impact of power plants as a result of the expanding human population and the ever-increasing demand for dependable sources of energy. The construction of about 95% of power plants is carried out in accordance with energy performance requirements, which take into account only the first law of thermodynamics. It is not possible to use the first equation of thermodynamics to compute the actual effective energy loss since it does not differentiate between the quantity and quality of energy.

Calculating energy and exergy based on the properties of the steam was at the focus of the investigation into the energy and exergy efficiency of the plant. According to the findings, an increase in the parameters governing the scalding steam caused an increase in both the system's efficiency and its enthalpy. The boiler has the highest exergy efficiency (59.66%), whereas the condenser has the highest energy efficiency (48.10%). The investigation proved beyond a shadow of a doubt that the boiler was the principal cause of the system's irreversibility.

Keywords: Energy, exergy, mass flowrate, thermal power plant, efficiency, irreversibility

1. Introduction

Energy consumption is one of the most crucial markers of a country's level of development and its citizens' standard of life. Urbanization, industrialization, technical progress, and population expansion all contribute to a rise in energy consumption [1]. It is common knowledge that energy is an essential resource for any country. It is often assumed that the quantity and quality of a nation's energy resources are directly proportionate to its degree of modernity. Nigeria, for instance, contains huge fossil fuel resources (such as oil, gas, and coal) as well as renewable power generating options (such as solar, wind, and biogas). Improving the energy supply is necessary for more efficient utilization of energy sources [2]. Due to the growing complexity of contemporary energy production systems, more exact thermodynamic calculations are necessary. Therefore, the study of energy and exergy has grown in popularity. Frequently, thermal power plant efficiency are assessed using energy analysis criteria [3] derived from the First Law of Thermodynamics.

Exergy analysis based on the Second Law of Thermodynamics, on the other hand, has proven to be an indispensable tool for the design, assessment, optimization, and modernisation of thermal power plants. By studying the power plant's exergetic performance, it is possible to obtain a more comprehensive understanding of the plant's overall component efficiency, as well as its magnitudes, locations, and causes of irreversibility. The integration of exergetic and energetic analysis will allow for a thorough investigation of the power plant's infrastructure. Electrical power and thermal efficiency, two energy performance measures derived from the first law of thermodynamics, are commonly

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*Corresponding author: silasoseme@gmail.com,silas.okuma@nmu.edu.ng used to assess the success of thermal power plants. Recent design, assessment, optimization, and improvement of thermal power plants [4] have benefited from the energy performance resulting from the second law of thermodynamics. Historically, the energy balance derived from the first law of thermodynamics was used to design and assess the performance of energy-related engineering systems [5-6]. The first law of thermodynamics [7] stipulates that energy cannot be created or destroyed. Exergy analysis may assist in designing, evaluating, and optimizing the efficiency of thermal systems [8-10]. Sahil Suryvanshee et al. [11] found that boiler system losses accounted for 57% of total power plant exergy losses, whereas turbine losses accounted for 33% and condenser losses accounted for 5%, and the overall power plant exergy efficiency was 31.12%. Kiran Bala Sachdeva and Karun [12] used energy and exergy analysis to determine the root causes of thermodynamic inefficiency in thermal power plants. An examination indicated that the boiler was responsible for 68 percent of the total exergy loss at the facility. Ligang Wang et al. [13] postulated and designed a novel exergy research to evaluate energy conversion systems by decomposing exergy degradation into endogenous and exogenous components. This gave them with the data necessary to formulate a plan for enhancing the system's functionality.

Experimental analysis of exergy annihilation in boilers by Ghazikhani et al. [14] found that the combustor is the location of maximal irreversibility. Jyoti Naik et al. [15] estimated the exergy of a 120MW coal-fired thermal power station, whereas Exergy of a 500-kilowatt steam power plant at a benso oil palm industry was evaluated by Mborah and Gbadam [16], and they found that fifty percent of the system's total exergy is wasted in the combustor. Reddy et al. [17] analyzed the thermodynamics of a coal-burning thermal power plant and a natural gas-burning cogeneration power station. Moreover, an investigation of a 250 MW steam power plant by Karim Maghsoudi et al[18] revealed that 341.1 MW of energy was lost in the condenser and 58.88 MW was lost in the boiler, with the boiler exhibiting the highest exergy loss at 87.91% and the turbine and condenser experiencing the lowest losses at 6.69% and 2.23%, respectively. Exergy was the subject of an investigation by Rashidi et al. [19] on the development of a steam cycle with two reheaters, a three-stage turbine, and six extraction sites. They analyzed the effects of turbine intake pressure, steam temperature at the boiler's exit, and condenser pressure on the first and second law efficiencies, exergy, and irreversibility.The boiler system (77%) and turbine (13% of total exergy destruction) had the largest percentage ratios of exergy destruction, and the energy and exergy efficiency based on reduced heating value of fuel were 26% and 25%, respectively. In the past, energy studies have assessed the operations of power plants to enhance turbine efficiency and output.

Tsatsaronis and Moung-Ho [21] developed the categories of avoidable and irreversible exergy degradation, which are used to evaluate the likelihood of improving the thermodynamic performance and cost-effectiveness of a system

Rosen [22] compares the performance of nuclear and coal-fired power stations using exergy analysis. Habib and Zubair[23] examined reheated Rankine cycle power plants using the second law. Dincer and Muslim [24] analyzed the thermodynamics of reheat cycles in power plants. Sengupta et al. [25] investigated the exergy of a 210-megawatt thermal power plant. Rosen and Dincer [26] did an exergoeconomic study of power plants that use various fuel sources. They contrasted the amount spent on capital to the amount lost due to heat and cold. Kwak et al. [27] addressed both exergetic and thermoeconomic aspects in their analysis of power plants. Rosen[22] examined both energy and exergy in his studies of coal-burning and nuclear power plants. Energy and exergy efficiency is 37% for both coal-fired and nuclear operations. Both plants wrought comparable harm. Naterer et al. [28] evaluated the coal-fired thermal power plant using data on boiler and turbine losses. Morosuk and Tsatsaronis [29] employed sophisticated exergy analysis to evaluate the performance of a basic gas turbine cycle,their approach was presented in detail. Khaliq and Kaushik [30] investigated the efficiency of a gas turbine cogeneration system with reheated combustion.Koroneos et al.[31] In relation to the pressure and temperature of the process steam employed in the design of the heat recovery steam generator and reheat, research has been conducted on energy and exergetic efficiency. Ertesvag et al. [32] analyzed the exergy of a gas-fired power plant with carbon dioxide collection. During the steam production and fuel combustion stages, more than 80% of the system's exergy is wasted as heat, indicating that these two steps are inefficient.

Petrakopoulou et al. [33] have demonstrated that, when comparing a combined power plant, exergy research is preferable to traditional research. Extensive study on exergy has shown several development and enhancement possibilities. Therefore, it makes logical that integrating energetic and exergetic analysis might disclose more about the system's overall composition. This research will give a more accurate method for measuring performance and finding opportunities for improvement. It is intended to use exergy to discover, categorize, and measure energy loss. This may be valuable for both the planned development of thermal power facilities and the provision of usage recommendations for existing plants. Due to its foundation in the first rule of thermodynamics, energy analysis is subject to a variety of constraints, such as the necessity to account for the general loss in energy quality caused by dissipative processes [34-36]. This research analyses the exergetic and energetic performance of each component of a thermal power plant to determine the system's performance improvement requirements. This is vital because it is necessary to monitor the plant's efficiency, comprehend the factors that affect it, and then remove energy losses from the system.

2. Methods

2.1 Description of Experimental Site

The thermal power plant at Sapele, Delta State, has a 1020 MW installed capacity. Using this fuel, six 120 MW steam turbines can generate an average of 86.72 MWH/H per day and about 2,500 GWH annually. 972 MW of the sapele power plant's 1,050 MW capacity are now in use. The location of the Sapele power station in the Niger Delta enables it to use nearby natural gas sources and a river for cooling its steam turbine engines. Fig. 1 depicts a schematic illustration of the power generators at the facility.

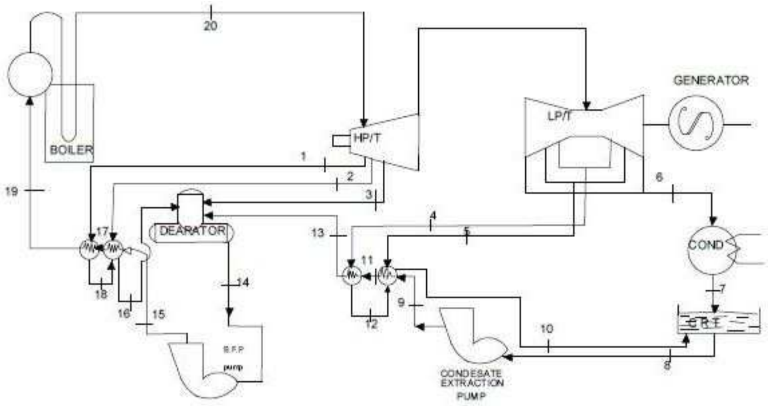

Fig.1 - Schematic diagram of the power plant, [37]

Fig.1 displays the plant's three primary subsystems: the cooling tower, steam cycle/thermal cycle, and boiler. Combustion chamber and heat exchanger are subsystem components of the boiler. The steam cycle subsystem is comprised of pumps, feed water heaters, condensers, turbines, and other equipment. The cooling tower subsystem comprises of cooling towers and fans.

2.2 Energy and Exergy Analysis

Using a study of energy and exergy, we determined the exergy lost by each subsystem component. Each subsystem's energy and exergy values have been examined to determine the overall plant system's losses. Combining the first and second principles of thermodynamics, exergy analysis offers a numerical evaluation of the quality of the energy in terms of its ability to do work. Exact energy notation appears as follows:

$$\varepsilon = \varepsilon_{k.e} + \varepsilon_{p.e} + \varepsilon_{ph} + \varepsilon_{ch} \qquad (1)$$

Where $\varepsilon_{k.e}$ and $\varepsilon_{p.e}$ denote energy owing to velocity or kinetic energy and exergy due to potential energy, respectively. ε_{ph} is physical exergy, or exergy owing to temperature and pressure differences with regard to the reference point, while ch represents chemical energy (i.e due to reaction).

2.2.1 Boiler Subsystem

The energy balance equations of the first law are used to determine the energy losses of the subsystem's components, while the exergy balance equations of the second law are used to determine the exergy losses. **2.2.2 Combustor**

The mass, exergy and energy balances of a combustion system;

$$\dot{m}_f + \dot{m}_a = \dot{m}_g \qquad (2)$$

$$\dot{m}_f(h_f - h_g) + \dot{m}_a(h_a - h_g) = Q_c \qquad (3)$$

$$\dot{m}_f(\varepsilon_f - \varepsilon_g) + \dot{m}_a(\varepsilon_a - \varepsilon_g) - E_{QC} = I_c \qquad (4)$$

Where the fuel (Natural gas) enters the combustor at ambient temperature and pressure and heat energy losses occurs.

2.2.3 Super Heaters

The super heaters of the plant include convective super heaters, screen super heaters and roof superheaters. An energy and exergy balances of the analysis of the super heaters are;

Energy balance;

$$\dot{m}_g(h_{giSH} - h_{goSH}) + \dot{m}_S(h_{is} - h_{so}) = Q_{SH} \qquad (5)$$

Exergy balance;

$$\dot{m}_g(\varepsilon_{giSH} - \varepsilon_{goSH}) + \dot{m}_S(\varepsilon_{is} - \varepsilon_{so}) - E_{QSH} = I_{SH} \qquad (6)$$

2.2.4 Condensate Extraction pump

The following equations represent the mass, energy and exergy balances for the condensate extraction pump.

$ɱ_3 = ɱ_4$ (7)

$ɱ_3(h_3-h_4) + W_{CEP} = Q_{CEP}$ (8)

$ɱ_3(h_3-Ɛ_4) + W_{CEP} = I_{CEP}$ (9)

2.2.5 Heat Recovery System

For air:

$ɱ_{ai} = ɱ_{ao} = ɱ_a$ (10)

For water:

$ɱ_{wi} = ɱ_{wo} = ɱ_w$ (11)

For hot gases:

$ɱ_{gi} = ɱ_{go} = ɱ_g$ (12)

$ɱ_g(h_{gi}-h_{go}) + ɱ_w(h_{wi}-h_{wo}) + ɱ_a(h_{ai}-h_{ao}) = Q$ (13)

3. Results and Discussion

Table 1 provides the data that was obtained from the system at the power plant. We compared the mass, energy, and exergy of each component in the system in order to arrive at an accurate calculation of the exergy losses. The findings of this investigation are shown in Table 1 for the steam power plant operating with a turbine load of 80 MW. It has been shown that an increase in enthalpy results in an improvement in the efficiency of the system by adjusting the mass flow rate, the temperature, and the pressure.

Table 1 - Parametric value of energy and exergy analysis of power plant

Section	Mass flow rate(kg/s)	Temperature (C^0)	Pressure (bar)	Enthalpy (kj/kg)	Entropy (Kj/kgk)
		Steam Generator			
Feedwater in	124.436	211.6	20	908.54	2.447
Main steam out	124.436	510	89	3454.11	6.657
Reheat steam in	124.436	157.9	5.98	666.287	6.761
Reheat steam out	124.436	211.6	20	908.54	6.34
		Steam Turbine (Inlet flow)			
High-pressure turbine	124.436	510	89	3454.11	6.657
Low-pressure turbine	90.07	41.7	0.083	2271.34	8.227
		Extraction Steam flows			
Feedwater 1	103.34	42.9	0.85	180.54	7.5
Feedwater 2	103.34	67.2	0.28	284.66	6.86
Feedwater 3	103.34	111.5	1.5	468.92	5.7
Feedwater 4	124.44	183.5	13.68	784.69	6.55
Feedwater 5	124.44	211.6	20	908.54	6.34
		Condenser			
Condenser out	124.44	211.6	20	908.54	6.547
Cooling water in	103.44	41.7	0.083	2271.34	8.225
Cooling water out	103.34	111.5	1.5	468.92	5.739

The energy efficiency of the system's components is depicted as shown in Fig.2. The condenser is responsible for fifty percent of the system's overall energy efficiency, as seen.In addition, the plot illustrates that the condenser is responsible for fifty percent of the plant's total energy losses, the most of which are lost during power production. Consequently, appraising a power plant only on the basis of the first law concept might lead to the erroneous conclusion that the condenser is more capable of increasing the plant's electric power output by lowering its large energy losses. Therefore, an energy analysis based on the first law of thermodynamics cannot be utilized to discover chances to improve the power plant's efficiency. Nonetheless, the second law analysis is useful for identifying the actual power-generating losses that occur across the whole power plant.

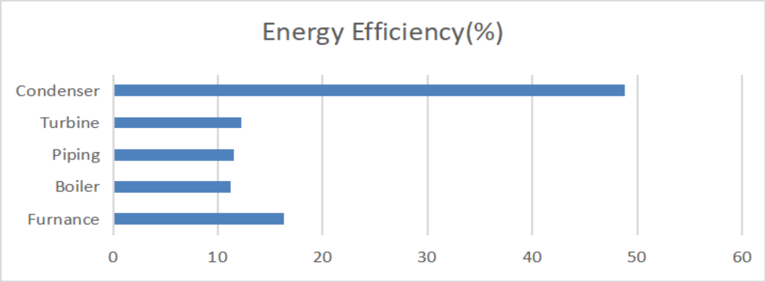

Fig. 2 - Energy efficiency for the system components

Fig. 3 depicts the study of the energy efficiency of plant portions. The data indicate that 59.66% of total exergy loss occurs in the boiler section. This significant exergy loss is entirely caused by the combustion process in the combustor and the huge temperature differential between the combustion gas and steam during heat transfer. This actually reduces the overall output of the plant compared to its energy intake. In addition to tube fouling, faulty burners, poor fuel quality, ineffective soot blowers, valve steam traps, and air heater fouling, other factors may contribute to the high prevalence of irreversibility. Consequently, equipment inspections must be done with the boiler turned off.

The frictional effect, pressure drops across the turbine blades, and pressure and heat losses to the environment all contribute to turbines' exergy losses. Due to the fact that the higher pressure (HP), intermediate pressure (IP), and low pressure (LP) turbines account for 2.43 percent of the total energy destruction, the irreversibility of energy destruction must be decreased. Other potential causes of irreversibility include silica deposit on nozzles and blades, operating steam below the allowed temperature, and throttling losses at the governor valve of the turbine. The HP and IP turbines use the most amount of exergy among the three stages.

The results of these research [1,38-40] are congruent with those of our investigation. This suggests that the boiler is the largest cause of energy loss. This is a serious issue that must be remedied as soon as possible by converting all current gas turbine-based power plants to combined cycles.

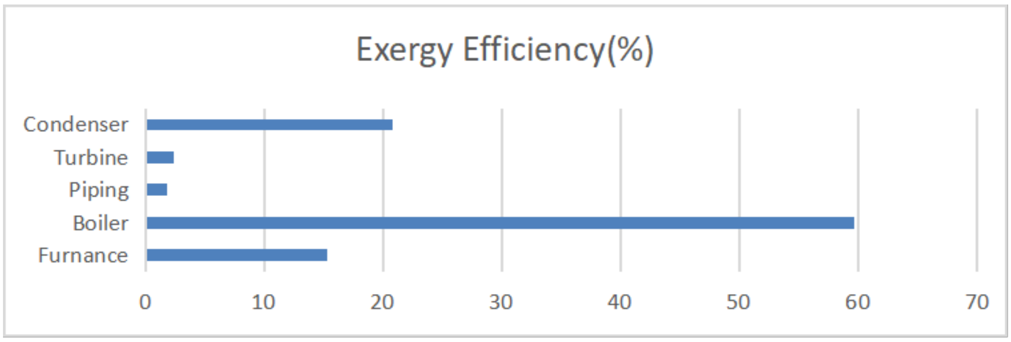

Fig. 3 - Exergy efficiency for the system components

Fig. 4 shows a comparison of the energy and exergy efficiency of the plant system. The boiler exhibited the highest exergy loss (59.66%) . This occur as a result of the combustor's combustion process becomes irreversible. However, the condenser loses the highest amount of energy (48.8%). Exergy analysis is a valuable tool for making maintenance and operating decisions. In light of the energy analysis, it is nearly impossible to make judgments that would increase the performance of the plant. Consequently, plant output as a whole decreases. This is due to the fact that the first law analysis often fails when measuring the rate of performance degradation of a single component. Analysis of exergy processes might be aided by locating the places in a power cycle when irreversibility occurs.

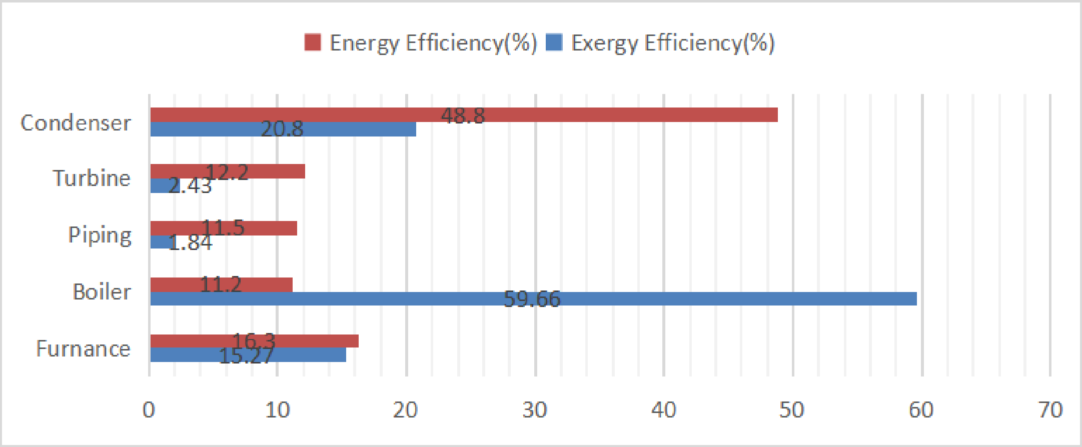

Fig. 4 - Comparative plot of energy and exergy efficiency for the system components

4. Conclusion

This article contains an assessment of a thermal power plant station located in Sapele, which is located in Delta State, Nigeria. Even though the exergetic analysis demonstrated that the boiler had the highest exergetic efficiency, the condenser in the power plant system had the highest energetic efficiency. This disparity is entirely attributable to the heat that was lost during the process of heat transfer between the combustion gas and the steam that took place during the combustion reaction in the combustor.Altering the mass flow rate, temperature, and pressure in the thermal power plant are all things that have been well investigated. It has been demonstrated that there is a correlation between an increase in the enthalpy of the system and an increase in the efficiency of the system in conjunction with the parameters of the superheated steam.

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