

ANALYSIS OF STEAM POWER PLANT AT KADUNA REFINING AND PETROCHEMICAL COMPANY FROM EXERGETIC PERSPECTIVE

ABSTRACT

This study presents the exergetic analysis of steam power plant at kaduna refining and petrochemical company limited. The aim of this research is to analyze the system components separately, and to identify and quantify the sites having the largest exergy losses. The performance of the plant was established and detailed break-up of exergy destruction of the considered plant has been presented. Computer softwares (ASPEN HYSYS, AUTOCAD and MICROSOFT EXCEL) were used for the simulation and calculation of properties that include stream enthalpy and entropy using the flow rate, working temperature and pressure of each equipment gotten from the company, at an assumed dead state temperature of 25°C at pressure of 101KPa. The analysis shows that The total exergy destroyed in the system is 209000kW, which makes about 18% of the total exergy entering the system The site having the largest exergy destruction was found to be in the boiler, having a 20000KW destroyed with a percentage performance loss of 36%, followed by the condenser, with 5880KW destroyed and percentage performance loss of 6%.Where as other equipments have total exergy efficiency of 2%. At end of this study, it can be suggested that the air for combustion should be properly preheated and the boilers should be properly lagged to avoid work loss. Analysis should be done periodically for each unit of the plant as a performance test; this will be helpful for maintenance and replacement decisions.

Key Words – Steam power plant; Exergy; exergy destruction; temperature; pressure; enthalpy; entropy; energy.

Nomenclature

h Specific enthalpy (J/kg)	s Specific entropy (J/kgK)
I Exergy destruction rate (W)	T Temperature (K)
$\dot{m}$ Mass flow rate (kg/s)	$\dot{W}$ Work done rate or power done by the system (W)
P Pressure (Pa)	$\dot{X}$ Total energy rate (W)
Q Heat transfer rate to the system (W)	
ψ Specific exergy (J/kg)	

Subscripts

e exit

i inlet

o Dead state condition

1. INTRODUCTION

Energy availability and optimization is paramount in determining the level of civilization of any generation. Energy, being the ability or capacity to do work is a property of objects, transferable among them via fundamental interactions, which can be transformed but not created or destroyed. The utilization of energy is one of the most important signs showing the development stages of countries and living standards of communities. Population increment, urbanization, industrializing, and technological development result directly in increasing energy consumption. This rapidly growing trend brings about the crucial environmental problems such as contamination and greenhouse effect. (Suryvanshee and Chaube, 2013). Energy can be electrical, mechanical, chemical, thermal solar or nuclear. The most used form of energy is the electrical energy which is a clean form of energy.

Steam power plant is one of the major sources of electricity and most industries use it to generate electricity needed to run their equipment. To assist in improving the efficiencies of power plants, their thermodynamic characteristics and performances are usually investigated. Power plants are normally examined using energy analysis which 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.

Exergy is the minimum theoretical useful work required to form a quantity of matter from substances present in the environment and to bring the matter to a specified state (Bejan et al, 1996). Exergy is different from energy in the sense that the former is destroyed rather conserved in the system however, it is conceptualized as a universal standard of energy quality. The second law (Exergy analysis) deals with the quality of energy and is concerned with the degradation of energy during a process, the entropy generation, and the lost opportunities to do work and it offers plenty of room for improvement. The second law of thermodynamics has proved to be a powerful tool in the optimization of complex thermodynamic systems (Ganapathy *et al.*, 2009; Makinde, 2008; Cengel and Boles, 2008) cited by Mborah and Gbadam (2010).

Exergy investigations of the energy use were first introduced in USA (Reistad, 1975) cited by Saidur et al., (2009). A lot of work has been carried out on exergy analysis of a system and steam power plant, notable among them are the works of the following researchers: Mborah and Gbadam (2010), performed an energy and exergy analysis on steam plant of 500KW at Ghana and found out that 50% of the total heat energy generated in the combustion chamber is not available for doing any useful work. Hamidi (2012), investigated the Energetic and Exergetic feasibility of a Direct Steam generation Solar thermal plant, and at the end of the investigation, author found out that the boiler of the plant has the

highest irreversibility rate. Saidur et al (2009) studied the energy, exergy and economic analysis of industrial boilers. They found that 72.46% and 24.89% were the energy and exergy efficiencies respectively and the combustion chamber was found to be the major contributor for exergy destruction. Rashad and El Maihy (2009) did an energy and exergy analysis of Shobra El-khima power plant in Cairo. Their aim was to study the components separately and to identify and quantify the sites having largest energy and exergy losses at different load. Their study revealed that the percentage ratio of exergy destruction to the total exergy destruction was found to be maximum in the turbine system. Nuhu et al(2012) carried out energy and exergy analysis of a Fluid Catalytic Cracking Unit of Kaduna Refining and Petrochemical Company Limited. Their study revealed computed ideal work of 74.169MW which characterized the system as work producing, loss of 0.68MW from the condenser, 61.20 and 24.77 % as percentage exergy and second law efficiencies of the system respectively. Ahmadi and Dincer(2011), thermodynamically analysed a combined cycle power plant with supplementary firing system through energy and exergy. They studied the influences of changes in demanded power and fuel cost by considering three different output powers, that is, 160, 180 and 200MW. They developed and validated their model by comparing the results of their simulation code with actual data. Their results revealed that the average difference between the model results and the actual data was about 1.41%. They however stated that various cases are investigated to determine how to decrease the objective function(cost, mass flowrate etc) for the optimized design and operating parameters(fuel, cost, power output etc) Ganjehkaviri et al(2014) carried out a comprehensive thermodynamic modeling of a combined cycle power plant, moreso, the effects of economic strategies and parameters on the plant optimization. They evaluated the optimum design points for corresponding economic variables like fuel cost and interest rate, using exergy economic assessment and optimization with algorithm genetic. The effects of economic parameters variations on the sustainability, carbon dioxide emission and fuel consumption of the plant were investigated and presented for a combined cycle power plant by the researchers. They stated in their result that by using the optimum values, the exergy efficiency increased to around 6% while CO₂ emission was reduced by 5.63%, the variation in the cost was less than 1% because of the implementation of cost constraint.. Ganjehkaviri et al(2015) presented a comprehensive thermodynamic modeling of a combined cycle power plant with dual pressure heat recovery steam generator. They conducted and discussed three cases of steam turbine outlet quality. In other hand, estimated and compared energy and exergy analysis of each components for the three different cases. They stated that the obtained results showed that it is really important to keep the quality of the vapour at turbine outlet constant in 88% for the result to be more realistic and also optimization and data are more technically feasible and applicable.

The main originality of this research emanates from the fact that, from available literature, little or no concerted effort has been made by any researcher to carry out exergy analysis of steam power plant at Kaduna Refining and Petrochemical Company(KPRC). So this research work is the first attempt with a view to enhancing the maintenance and performance of the steam power plant.

1.1 Background of study

The Power Plant and Utility Department (PPUD) complex of Kaduna Refining and Petrochemical Company(KRPC) is saddled with the responsibility of providing safe, reliable and secured electric power, steam, water (cooling, drinking, service, and boiler feed), Air (instrument, plant), nitrogen etc. required for continuous operation of the Process Plants and other facilities in the Refineries and Petrochemical Plants.

The aim of this research is to analyze the system components separately, identify and quantify the sites having the largest exergy losses and suggest solution to the problem.

2. MATERIAL AND METHODS

2.1 Plant Analysis

The steam power plant and its main units that are described here, are in line with the descriptions given by CHIYODA Chemical Engineering and Construction Co. Ltd (1981)

The plant has a total installed capacity of (56) MW, designated in unit No. 70 in Kaduna Refining and petrochemical Company Limited (KRPC) located at 16km, Kachia road Kaduna, Nigeria. It is housed with Power Plant and Utility Main Control Room. The power house consists of (2) deaerators, feed water pumps, (5) boilers, (4) steam turbines units (4x14) MW at 100% load and condensers. The power plant uses fuel oil.

Feed water from the demineralizer unit goes to the deaerators where dissolved oxygen is being separated to the atmosphere from a value of 1.00ppm to 0.007ppm thereby increasing the temperature from 45 °C at 1atm pressure to 125 °C. The deaerated water goes to the heater through the pumps, undergoing another heating process where the temperature is further raised to 140°C which flows to the boilers. The boilers heat up the water to steam at 412°C temperature and a pressure of 4.18MPa. This steam is used to drive the prime mover of the turbo generators and other turbine pumps and exhausts to a water cooled condenser where the low pressure section steam is condensed to condensate under vacuum at a pressure of 88kPa and the condensate flows back to the demineralizer unit and the process is recycled.

2.1.1 Main units of the steam power plant

The main units of the steam power plant consists of the following:

1 Feed water unit:

This comprises of :

(a) deaerators, where dissolved oxygen and other gases are removed to prevent corrosion damage in the steam system and increase the feed water temperature as well.

The design parameters of the deaerator are listed below:

Capacity	: Total 640 t/h
Dissolved Oxygen content	: Inlet 1.0 ppm
	: Outlet 0.007 ppm
Feed water temperature	: Inlet 45°C
	: Outlet 125°C

(b) feed water pumps, which transport feed water to the boiler. The system consist of three High Pressure (HP) boiler feed water pumps, two Low Pressure (LP) boiler feed water pumps and one start up boiler feed water pump

Below is the list of design parameters of boiler feed water pump:

For high pressured feed water

Capacity	:(480 t/h for boilers and 120 t/h for process water)
Suction pressure	: 0.24MPa
Discharge pressure	: 5.93MPa

167 Feed water (FW) temperature : 125°C

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169 (c) Water heater

170 The deaerated water is pumped to the heater (70E01A,B) which acts as a preheater of the feed
171 water. It has the following design conditions:

172

173 Capacity : Total 480 t/h

174 Feed water temperature : Inlet 125°C

175 Outlet 140°C

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177 (2) **Boiler unit**

178 All boilers are designed to be operated in parallel with equal load distribution and with fuel gas, fuel oil or
179 both fuels firing.

180

181 Design Conditions

182 Types of Boilers : IHI-FW SD, two drums and natural circulation type

183 The steam generators serve to produce the steam needed for the functioning of the process plant of the
184 refinery and of the turbo-alternators; they burn a fuel (gas or fuel oil) which develops the heat necessary
185 for vapourize the water.

186 The fundamental parts of steam generator are:

187 The Combustion Chamber: where the fuel is burnt

188 The Boiler: where the heat produced by the combustion is transmitted to the water,
189 vapourizing it.

190 The Economizer: where the feed water is preheated and brought to the conditions close to vapourization.

191 The Superheater: where the steam produced by the boiler, exposed to the action of the heat, is dried and
192 superheated

193 The Air-Preheated: where by exploiting the heat still possessed by flue gases which leave the boiler to
194 preheat the air needed for combustion.

195 Boiler, economizer, superheater and preheater have a tubular structure i.e. are made up of a bank of
196 tubes with the aim of increasing the extension of the metal surface through which the heat is transmitted
197 by the hot gases.

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199 Design conditions

200 Type of boiler : IHI-FWSD, two drums and natural circulation type.

201 Number : Five sets

202 Evaporation of each boiler at MCR : 120,000Kg/hr

203 Two hour peak load : 138,000Kg/hr

204 Maximum allowable working pressure : 4.21MPa

205 Maximum steam pressure at superheater outlet at MCR: 4.18MPa

206 Working steam temperature at superheater outlet : 412°C

207 Feed water temperature at economizer inlet : 140°C

208 Air temperature at forced draft fan inlet : 35°C

209 Draft system : Forced draft system

210 Firing system : Gas and or oil firing system.

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212 (3) **Turbine unit** (condensing type)

213 The unit is made up of four turbine generators which can each generate 14MW at an output voltage of
214 11KiloVolts (AV), AC, 50Hz. The turbines are impulse, extraction and condensing type driven by steam of
215 pressure 4.11MPa, 412°C at a speed of 6362 revolution per
216 minute (rpm).

217 Design conditions:

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219 Type : Three phase and synchronous type

220 The turbine speed : 6,362rpm

221 The generator shaft speed : 1,500rpm

Steam temperature / pressure : 412°C /4.16MPa

2.2 Thermodynamic Analysis

Schematic representation of the cycle of the power plant is depicted in figure 1. This consists of five main components namely boiler, superheater turbine, condenser and pump. Additional components were added to enhance cycle performance and to improve efficiency.

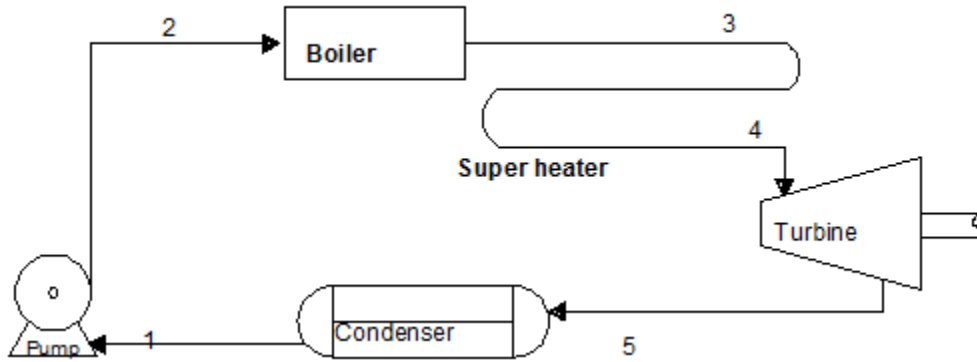


Figure 1: Schematic representation of the cycle

Exergy (also known as Work Potential) is defined as the maximum useful work that can be obtained from a system at a given state in a given environment; in other words, the most work you can get out of a system. Exergy destruction (I) is the measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system. (Rashad and El Maihy, 2009). This can be represented mathematically as :

$$\Psi = (h - h_0) - T_0(S - S_0) \quad (2.1)$$

$$\dot{X} = \dot{m}\Psi_i = \dot{m} (h - h_0) - T_0(S - S_0) \quad (2.2)$$

$$I = \dot{X}_r - \dot{X}_o \quad (2.3)$$

The performance loss can be calculated as:

$$P_{\text{loss}} = \frac{I}{\dot{X}_{\text{in}}} \quad (2.4)$$

Mass and energy balance should be performed prior to exergy balance. This can ensure that all flows included are balance (Khalifa, 2009). Mass balance for steady state, steady flow process can be written as:

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (2.5)$$

Therefore, energy balance can be written based on the first law of thermodynamics, as:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \quad (2.6)$$

According to Rashad and El Maihy(2009), the exergy destruction rate and the exergy efficiency for a steady state operation, and choosing each component as a control volume, are defined as shown in Table 1.

Table 1.Definitions of the exergy destruction rate and the exergy efficiency of the plant

	Exergy Destruction Rate
Pumps	$I_{\text{pump}} = \dot{X}_{\text{in}} - \dot{X}_{\text{out}} + \dot{W}_{\text{pump}}$
Heaters	$I_{\text{heater}} = \dot{X}_{\text{in}} - \dot{X}_{\text{out}}$
Turbine	$I_{\text{turbine}} = \dot{X}_{\text{in}} - \dot{X}_{\text{out}} - \dot{W}_{\text{el}}$
Condenser	$I_{\text{condenser}} = \dot{X}_{\text{in}} - \dot{X}_{\text{out}}$

2.3 Assumptions

The following assumptions in line with works of Adams(2014) and Acir et al(2012) were adopted for the analysis:

1. The reference state for the steam and feed water is the water at a temperature of 25°C , pressure of 101KPa, enthalpy of -890000 kJ/kg and entropy of 894.6 kJ/kg-C.
2. All processes are steady-state and steady-flow with negligible potential and kinetic energy effect.

2.4 Modeling of the plant

Power plant consists mainly of deaeration section, pre-heating section (heat exchanger networks), boiler feed water pumps, boiler, superheaters, turbine, and condenser. The plant can be represented in block diagram as shown in Figure 2. The model is based on a standard cycle shown in figure 1 to which are added various components for improvement, as in figure 2.

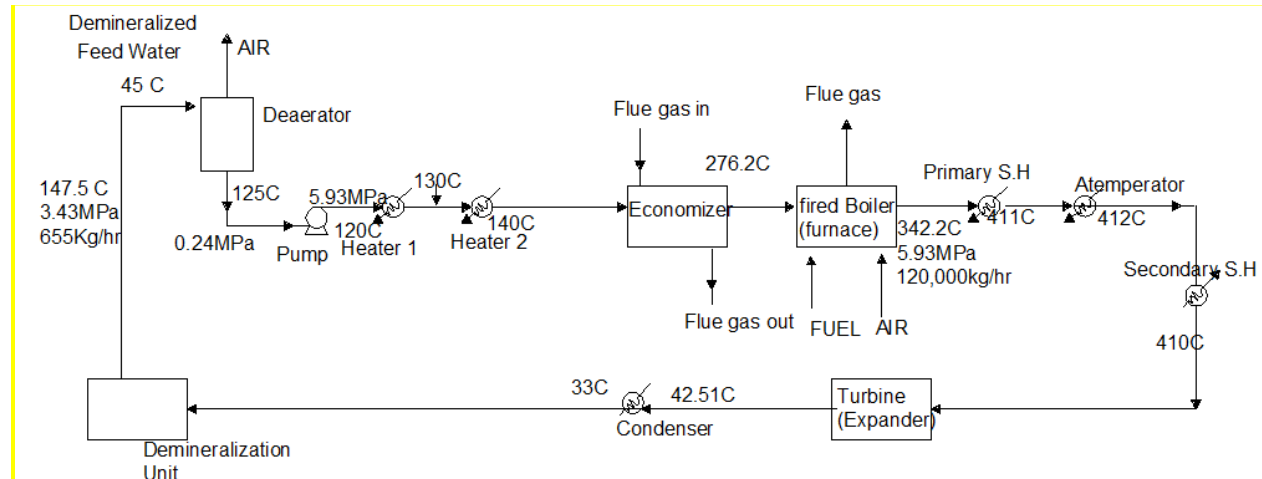


Figure 2 Block diagram of steam power plant

The simulation of the steam power plant was done using Aspen Hysis software version 8.0, with KRPC, PPU data log sheet (mass flow, temperature, and pressure readings) in line with the supervised work of Adam(2014). The temperature, pressure, flow rates, enthalpy, and entropy used for the exergy analysis were obtained from the simulation results..

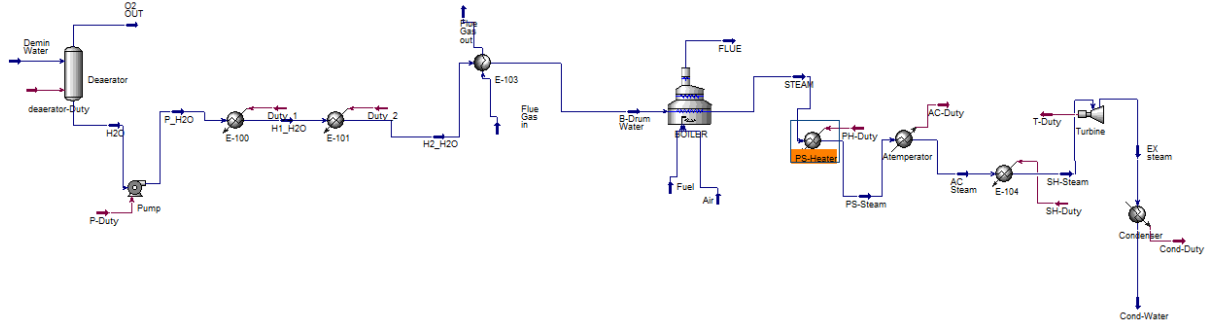


Figure 3 Aspen HYSYS V 8.0 Simulation of the steam power plant

3.0 RESULT AND DISCUSSION

3.1 RESULT.

The results of the analysis of the units are tabulated in table 2, showing the stream exergy of each equipment. The exergy analysis of major equipment are shown in figure 4, exergy destructed and percentage performance losses are depicted in table 3.

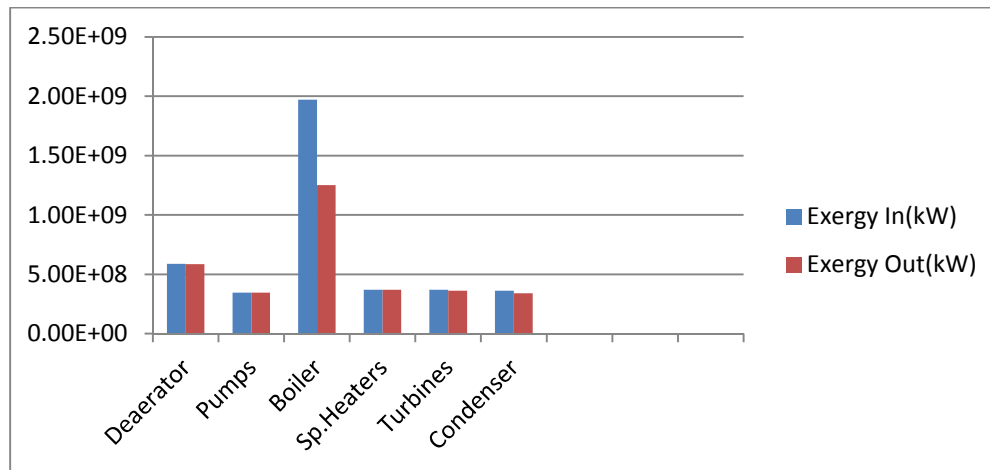
Table 2 Analysis result of the units.

Temperature: 25°C, Pressure: 101.3Kpa.

Components	Inlet streams KJ/h	Outlet streams KJ/h	Exergy(in) KJ/h	Exergy(out) KJ/h
Deaerator	5.69E+08	2.42E+08	5.88E+08	5.87E+08
Pump	3.45E+08	3.45E+08	3.46E+08	3.45E+08
Heater 1	3.45E+08	3.45E+08	3.451E+08	3.45E+08
Heater 2	3.45E+08	3.45E+08	3.453E+08	3.45E+08
Economizer	3.45E+08	3.62E+08	1.231E+09	1.23E+09
Boiler	3.62E+08	3.68E+08	1.97E+09	1.25E+09
Pri-S.H	3.68E+08	3.70E+08	3.72E+08	3.70E+08
Atemp.	3.70E+08	3.70E+08	3.73E+08	3.70E+08
Sec-S.H	3.70E+08	3.70E+08	3.71E+08	3.70E+08
Turbine	3.70E+08	3.62E+08	3.70E+08	3.62E+08

Condenser	3.62E+08	3.41E+08	3.62E+08	3.41E+08
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Figure 4 Exergy analysis of major equipment.

Table 3 Exergy destructed and percentage performance losses

Equipment	Exergy In KW	Exergy Out KW	Irreversibility. KW	Percentage Loss %
Deaerator	1.65E+05	1.64E+05	2.72E+02	0.164848
Pump	9.68E+04	9.66E+04	1.76E+02	0.181818
Boiler	5.51E+05	3.51E+05	2.00E+05	36.29764
Pri-S.H	1.04E+05	1.39E+05	9.79E+01	0.094135

Turbine	1.39E+05	1.02E+05	2.24E+03	1.611511
Condenser	1.02E+05	9.55E+04	5.88E+03	5.770363
Total	1.16E+06	9.48E+05	2.10E+05	44.120315

3.2 DISCUSSION

From figure 4, where the inlet and outlet exergies were presented, it can be seen that the boiler has the largest inlet as well as outlet exergy, where as the heaters have the lowest exergy both inlet and outlet giving rise to low exergy destructed.

It can be seen from table 3 that the total exergy destroyed in the system is 209MW and the boiler has the largest exergy destruction with a percentage performance loss of 36.3% , it counts alone for about 95% of the plant loss ,this is in comparison with work of Hamidi (2012) where the boiler was found to have the highest percentage irreversibility of 84%. This could be due to improper lagging of the boiler as well as improper pre heating of the combustion air, **tubes fouling and faulty burners**. The primary super heater has the least percentage performance loss of 0.09%. The turbine and the condenser have exergy destruction of 2240KW and 5880KW respectively. **The exergy loss in the turbine could be as result of drop in pressure across the blades of the turbine and heat loss to the surroundings.** **The heat transfer from the turbine outlet steam to the environment through cooling medium, water in this case, could be responsible for the remarkable exergy loss in the condenser.**

4.0 CONCLUSIONS AND RECOMMENDATION

In this study, an exergy analysis of PPU of KRPC has been presented. In the considered PPU, the maximum exergy destructed was found in the boilers where 36.3% of the input exergy was destructed to the environment. Next to it was the exergy destructed in the condensers where 5880KW of exergy was destructed which represent 5.77% of the input exergy, followed by the turbine having 1.61% and less than 1% for all other components.

From the research it is recommended that the boilers should be properly lagged to avoid energy leak and the combustion air should be properly pre-heated as this enhances rapid combustion of air- fuel mixture in the combustion chamber of the boiler.

The exergy analysis should be done periodically for each unit of the plant as a performance test; this will be helpful for maintenance and replacement decisions. The effect of varying the reference environment state on the exergy analysis is highly recommended for the next phase of study.

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