

Time-dependent exergy analysis of a 120 MW steam turbine unit of sapele power plant

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Abstract: Time-dependent exergy model was used to assess the exergy losses that occurred in the major components of a 120 MW steam turbine unit of Sapele power station. Data used for the analysis were both base parameters and measured values recorded in the station operational logbook for the period of January 2007 to December 2011. Component's exergy destruction increments as compared with its base value were highlighted and possible causes of the increment were identified. The boiler section had the highest value. The economiser had a maximum of 4.26 % in 2009 and minimum of 1.25 % in 2007. While the evaporator had a maximum of 5.02 % in 2009 and minimum of 1.50 % in 2008. The superheater had maximum of 4.64 % in 2011 and minimum of 1.48 % in 2007. For the reheater, the maximum was 3.57 % in 2011 while the minimum was 1.71 % in 2007. Tube fouling, defective burners, steam traps and air heater fouling were adduced for the increment. Upgrading components with better designs, optimizing system performance and elimination of conditions that degrade efficiency between maintenance outages were suggested for improving the performance of the boiler section. The analysis showed that for the three turbine stages, HP turbine had the highest increment while the LP turbine had the lowest. The loss in the three turbine stages were attributed to throttling losses at the governor valves and silica deposits at the nozzles and blades. Retrofitting of rotors, diaphragms or complete stator/ rotor modules (inner block) were suggested for improving the situation. The results generally showed that exergy loss increased with increased operation time. It was observed that deterioration and obsolescence may be the major problems and that plant rehabilitation is a feasible solution. It was noted that the suggested modification and refurbishment of Sapele power plant units is an attractive solution to improve the plant economy and keep production cost competitive in a restructured Nigerian power system.

Keywords: Aging Effect, Exergy Destruction, Rehabilitation, Deregulated Market

1. Introduction

Electricity demands in Nigeria far outstrip its supply which is epileptic [1, 2]. Currently, electric energy output is very low, with present installed capacity for energy generation put at 6,200 MW, while actual output hovers between 2,500 MW and 3,200 MW [3]. By the year 2020, the Government's policy objective is that Nigeria should possess a generating capacity of at least 40,00 MW [4]. The investments required to finance an increase in total power station capacity from 12,000 MW to 40,000 MW is huge. Hence the need to incentivize the private sector to partner with government in this endeavour. The unbundling of the Power Holding Company of Nigeria (PHCN) has been an

important step

Restructured and liberalized power sectors promote increased competition through unbundling of generation, transmission and privatization of distribution or retailing function [5-8]. Decentralization requires the existing power plants to improve their performance in order to attain high thermal efficiency and reliability, so as to operate at low generation cost. To improve the performance of the plant, first it is necessary to find out the equipment/locations where losses are more [9-12].

Exergy analysis provides the tool for the clear distinction between energy losses to the environment and internal irreversibility of the process. Exergy is defined as the maximum theoretical useful work that can be obtained as a system interacts with an equilibrium state. Exergy is

generally not conserved like energy but is destroyed in the system. Exergy can be divided into four distinct classes, viz: physical, Chemical, potential and kinetic exergies. The two important ones are physical exergy and chemical exergy. In thermal power plant, the other two classes are assumed negligible as the elevation and speed have negligible changes. The physical exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium.

Exergy destruction 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 source of thermodynamic inefficiencies in a thermal system. Recent developments in exergy concept have allowed the definition of a new performance criterion which offers some advantages over the tradition ones [13-15]. Hence, exergy analysis can improve resource utilization by determining inefficient, wasteful processes within thermodynamic systems and the results obtained from such analysis can serve as a guide for reducing irreversibilities and performance monitoring giving room for performance improvement.

The objective of this study is to investigate the influence of aging on the exergy destruction in the main components of a 120 MW steam turbine unit of Sapele power station. Physical exergy was used in the analysis. The power plant is strategically located at Ogorode, close to sources of natural gas feedstock and a river for cooling its steam turbine generators. Sapele power plant has an installed capacity of 1020 MW which equates to approximately one-sixth of the nation's installed capacity [5]. It consists of 6 x 120 MW steam turbines and 4 x 75 MW gas turbines. The steam turbines were commissioned between December, 1978 and April, 1980 while the gas turbines were commissioned between June, 1981 and August, 1981. The steam turbine

designated ST02 used for this study was commissioned on February 2, 1979. The designed power output of the unit is 120 MW but due to operational inefficiencies and other losses, the daily output is about 80 MW. This study therefore seeks to investigate the causes of operational inefficiencies and losses resulting in decrease of expected output of the unit using exergy analysis. The study covers the period between January, 2007 and December, 2011.

Despite many publications on the exergy analysis of power plant [16-22], most of the them applied it to find optimum values for main cycle parameters. Although, these researches are useful to improve the design features of future power plants, they do not suggest any recommendation on how to improve an existing aged power plant. In this study, the calculated parameters based on operating data were compared with the "base" values (these are the values obtainable when the unit was newly installed) to determine the aging effects on the unit performance.

2. Materials and Method

The data used for this study were both base parameters for the steam turbine and measured values recorded in the station operational logbook for the period of January 2007 to December 2011 [23]. Parameters considered during the data collection were the pressures, temperatures and mass flowrates at various points. In the analysis of the data, mean values of daily parameters were computed using statistical methods. This was followed by monthly average and then the yearly average for the period of the research. Fig. 1 shows the schematic diagram of the power plant, demonstrating all its relevant components. The plant unit main thermodynamics data are shown in Table 1.

Using Mollier diagram and thermodynamic tables for steam and thermodynamic equations, the process parameters for the unit are obtained as given in Table 2.

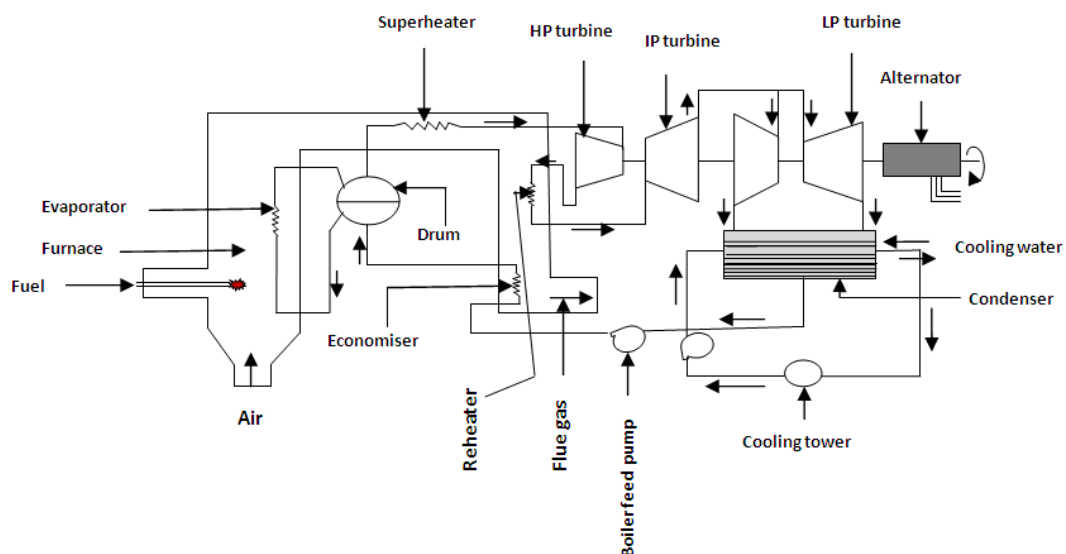


Fig 1. Schematic diagram of the plan

Table 1. Operating conditions of the 120 MW steam turbine unit

Steam flow	Base parameters			Operating parameters									
	Temp. (°C)	Press. (bar)	Steam flow rate (kg/s)	Average temperature (°C)					Average pressure (bar)				
				2007	2008	2009	2010	2011	2007	2008	2009	2010	2011
Boiler feed pump inlet	128	2.64	87	122	120	118	117	117	2.66	2.67	2.78	2.78	2.84
Boiler feed pump outlet	130	125	87	125	123	121	121	120	124.7	124.5	124	124	123
Economiser inlet	190	123	87	186	185	184	182	182	121.8	121.5	121	120	120
Economiser exhaust to Evaporator	210	122.2	87	207	205	203	201	201	121	120.7	120.1	119.2	119.2
Evaporator exhaust to Superheater	320	122.2	87	317	316	314	313	312	121	120.7	120.1	119.2	119.2
Superheater exhaust to HP turbine	510	120	87	505	502	501	500	498	118.3	118.2	117.6	117.1	117.1
HP turbine exhaust to Reheater	330	24	79	338	340	341	341	345	25.0	25.3	25.4	25.7	25.9
Reheater exhaust to IP turbine	510	24	72.7	505	502	501	500	498	23.8	23.7	23.5	23.4	23.4
IP turbine exhaust to LP turbine	240	2	65	245	247	249	253	252	2.2	2.2	2.4	2.4	2.4
LP turbine exhaust to Condenser	39	0.074	56.4	44	47	49	48	49	0.091	0.101	0.120	0.111	0.120
Condenser outlet	38	0.07	58.5	42	46	48	47	47	0.082	0.101	0.111	0.111	0.120

Table 2. Process data for the 120 MW steam turbine unit

Steam flow	Base parameters			Operating parameters									
	Enthalpy (kJ/kg)	Entropy (kJ/kgK)	Steam flow rate (kg/s)	Enthalpy (kJ/kg)					Entropy (kJ/kgK)				
				2007	2008	2009	2010	2011	2007	2008	2009	2010	2011
Boiler feed pump inlet	537.8	1.613	87	511.9	504.1	495.5	491.4	491.4	1.549	1.528	1.506	1.495	1.495
Boiler feed pump outlet	546	1.634	87	525.3	516.6	508	508	504.1	1.581	1.56	1.539	1.539	1.528
Economiser inlet	807.4	2.235	87	789.3	784.9	780.6	772	772	2.197	2.188	2.175	2.157	2.157
Economiser exhaust to Evaporator	897.9	2.425	87	884.5	875.3	866.2	851.3	851.3	2.397	2.379	2.361	2.34	2.34
Evaporator exhaust to Superheater	2798	3.449	87	2708	2711	2717	2719	2722	5.562	5.571	5.623	5.687	5.751
Superheater exhaust to HP turbine	3374	6.503	87	3431	3427	3410	3402	3402	6.807	6.791	6.719	6.681	6.681
HP turbine exhaust to Reheater	3103	6.969	79	3122	3127	3130	3131	3140	7.02	7.034	7.039	7.046	7.065
Reheater exhaust to IP turbine	3494	7.537	72.7	3456	3456	3473	3471	3466	7.52	7.51	7.503	7.498	7.492
IP turbine exhaust to LP turbine	2951	7.668	65	2962	2966	2970	2978	2876	7.726	7.734	7.78	7.795	7.792
LP turbine exhaust to Condenser	2383	7.668	56.4	2418	2439	2453	2446	2453	7.557	7.464	7.402	7.432	7.401
Condenser outlet	159.1	0.545	58.5	175.8	192.5	200.9	196.7	196.7	0.599	0.651	0.691	0.6645	0.6645

The mean daily temperature of the region hovers around 27 °C all the year round. The minimum and maximum temperatures are 20 °C and 40 °C respectively [21]. Hence, in this study, 30 °C was used as the mean ambient temperature and 1.013 bar as its pressure.

In analyzing the unit, the cycle was assumed to operate at steady state with no stray heat transfer from any component to its surroundings and negligible kinetic and potential energy effects. Certain components such as boiler stop valves, fuel and oil pumps, induced draught and forced

draught fans were neglected in the analysis. Pressure drops along pipelines were assumed to be negligible.

For a control volume, an exergy balance equation is expressed as

$$\sum \dot{W} = \sum \left(1 - \frac{T_o}{T}\right) \dot{Q} + \sum \dot{\Psi}_{in} - \sum \dot{\Psi}_{out} - \sum \dot{\Psi}_{des} \quad (1)$$

where

$\sum \dot{W}$ = sum of ideal work; T_o = reference temperature;
 T = temperature of system

ΣQ = sum of heat supplied; $\Sigma \dot{\Psi}_{in}$ = sum of exergy inflow; $\Sigma \dot{\Psi}_{out}$ = sum of exergy outflow

$\Sigma \dot{\Psi}_{des}$ = sum of exergy lost in the system due to irreversibilities
where

$$\dot{\Psi} = \dot{m} [h - h_o - T_o (s - s_o)] \quad (2)$$

and

\dot{m} is mass flowrate, h and s represent specific enthalpy and entropy respectively. The subscript o denotes reference condition.

For steam turbine

$$W = W_t = \dot{m}_s (h_{out,s} - h_{in,s}) \quad (3)$$

$$Q = \dot{m}_w (h_{out,w} - h_{in,w}) \quad (4)$$

where subscript s denotes steam phase and that for water is w .

Exergy of boiler feed pump is given by

$$\dot{\Psi}_{fw} = C_{pw} \left[(T_w - T_o) - T_o \ln \left(\frac{T_w}{T_o} \right) \right] \quad (5)$$

where C_{pw} is specific heat of water.

And the pump work, W_p is given by

$$W_p = \dot{m}_w v_w (P_{out,w} - P_{in,w}) \quad (6)$$

where v is specific volume P , pressure

The exergy efficiency, η_{ex} can be defined, according to Lozano and Valero [24] and Tsatsaronis and Winhold [25] by

$$\eta_{ex} = \frac{\text{product}}{\text{input}} \quad (7)$$

This equation establishes a relationship between the desired result (for instance, the heating of a steam flow, or the power in a turbine) and the input (the amount of exergy spent to obtain the result). In some systems there is no universal agreement as to what are an input and an output. Therefore their exergy efficiency must be defined by the expression proposed by Szargut *et al.* [26] as

$$\eta_{ex} = \frac{\text{outlet}}{\text{inlet}} \quad (8)$$

Table 3 summaries the equations used to compute the exergy destruction rate and exergy efficiency of the unit main components

Table 3. Formulae for the exergy destruction rate and exergy efficiency of the unit's main components

Component	Exergy destruction rate	Exergy efficiency
Boiler feed pump	$\dot{\Psi}_{des,p} = \dot{\Psi}_{in,p} - \dot{\Psi}_{out,p} + W_p$	$\eta_{ex,p} = 1 - \frac{\dot{\Psi}_{des,p}}{W_p}$
Economiser	$\dot{\Psi}_{des,ec} = \dot{\Psi}_{in,ec} - \dot{\Psi}_{out,ec}$	$\eta_{ex,ec} = \frac{\dot{\Psi}_{out,ec}}{\dot{\Psi}_{in,ec}}$
Evaporator	$\dot{\Psi}_{des,ev} = \dot{\Psi}_{in,ev} - \dot{\Psi}_{out,ev}$	$\eta_{ex,ev} = \frac{\dot{\Psi}_{out,ev}}{\dot{\Psi}_{in,ev}}$
Superheater	$\dot{\Psi}_{des,su} = \dot{\Psi}_{in,su} - \dot{\Psi}_{out,su}$	$\eta_{ex,su} = \frac{\dot{\Psi}_{out,su}}{\dot{\Psi}_{in,su}}$
Turbine	$\dot{\Psi}_{des,t} = \dot{\Psi}_{in,t} - \dot{\Psi}_{out,t} - W_t$	$\eta_{ex,t} = 1 - \frac{\dot{\Psi}_{des,t}}{\dot{\Psi}_{in,t} - \dot{\Psi}_{out,t}}$
Reheater	$\dot{\Psi}_{des,r} = \dot{\Psi}_{in,r} - \dot{\Psi}_{out,r}$	$\eta_{ex,r} = 1 - \frac{\dot{\Psi}_{des,r}}{\dot{\Psi}_{in,r}}$
Condenser	$\dot{\Psi}_{des,c} = \dot{\Psi}_{in,c} - \dot{\Psi}_{out,c}$	$\eta_{ex,c} = \frac{\dot{\Psi}_{out,c}}{\dot{\Psi}_{in,c}}$

3. Results and Discussion

When much of the 20 to 25 year old plants (that is, 160,000 to 200,000 operating hours) were originally designed, the plants were expected to run at base load. The only thermal limit applied in the design was creep; thermal fatigue resulting from frequent stops/starts was not anticipated [13]. Due to deterioration, steam power units of more than 200,000 operating hours are facing serious threats in view of their remaining lifetime. Even with proper operation and maintenance, the flow path section in the steam turbine plant will become fouled, eroded, corroded and covered with rust scale. The consequence is increased exergy destruction in their various components.

The base values of exergy destruction and exergy efficiency in boiler feed pump are 0.92 MW and 1.22 % respectively. The increment from the base values for the period under review is presented in Fig. 2.

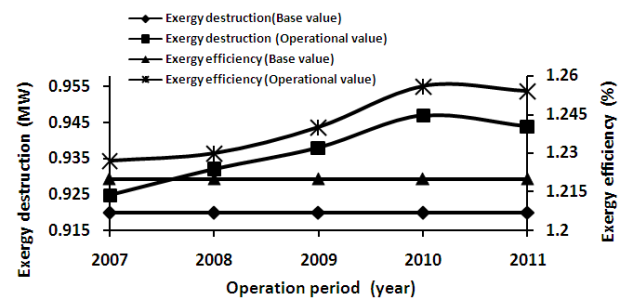


Fig 2. Exergy destruction and efficiency as a function of operation period in boiler feed pump

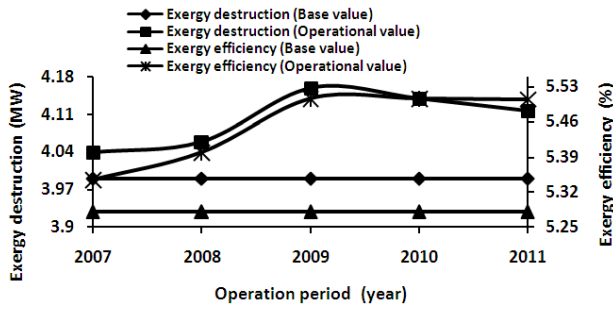


Fig 3. Variation of exergy destruction and efficiency with operation period in economiser

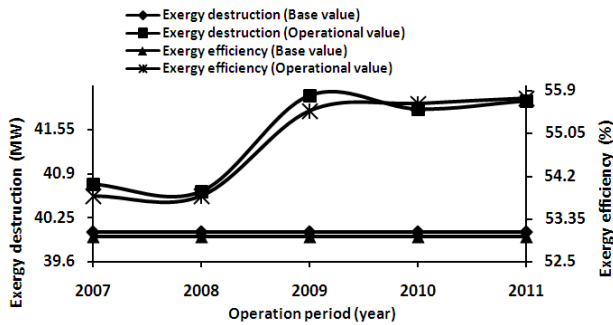


Fig 4. Exergy destruction and efficiency versus operation period in evaporator

Compared with the base values, the boiler feed pump has a minimum increment of 0.54 % in 2007 and a maximum of 2.93 % in 2010 for exergy destruction. While for exergy efficiency, a minimum increment of 0.57 % was obtained in 2007 and maximum of 2.95 % in 2010. These increments may be attributed to deterioration and obsolescence; improvement can be achieved by replacement of major portions or even the complete system.

The boiler section comprises the economiser, evaporator, superheater and reheater. The variation of exergy destruction and efficiency with operation period in the economiser is depicted in Fig. 3.

Its base value for exergy destruction is 3.99 MW while that for exergy efficiency is 5.28 %. Compared with the base value, the exergy destruction had been on the increase ranging from an increment of 1.25 % in 2007 to as high as 4.26 % in 2009. The exergy efficiency had its lowest value of 1.23 % in 2007 and it's highest of 4.31 % in 2009. Fig. 4 depicts the effect of operation period on exergy destruction and efficiency in the evaporator.

The base value of exergy destruction in the evaporator is 40.04 MW and that of exergy efficiency is 53 %. As can be observed, the minimum increment of exergy destruction is 1.50 % in 2008 and a maximum of 5.02 % in 2009. The exergy efficiency had a maximum increment of 5.19 % in 2009 and a minimum of 1.53 % in 2008. Fig. 5 presents the variation of exergy destruction and efficiency with operation period in the superheater.

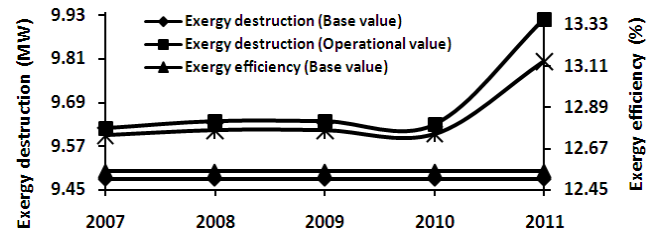


Fig 5. Exergy destruction and efficiency against operation period in superheater

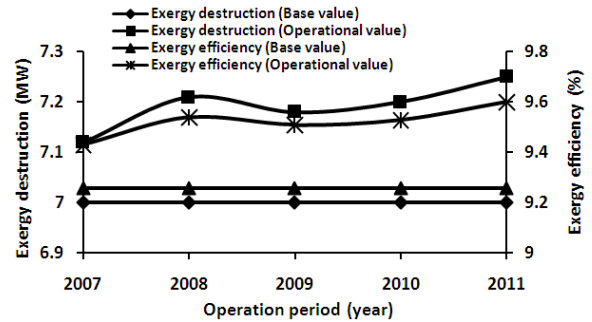


Fig 6. Exergy destruction and efficiency as a function of operation period in reheater

Exergy destruction and efficiency in the superheater had base values of 9.48 MW and 12.55 % respectively. The exergy destruction increment peaked at 4.64 % in 2011, with its lowest value being 1.48 % in 2007 while exergy efficiency attained its maximum increment of 4.66 % in 2011 and its minimum of 1.51 % in 2007. Effect of operation period on the exergy destruction and efficiency in the reheater is revealed in Fig. 6.

The exergy destruction had a base value of 7.00 MW in the reheater while that of the exergy efficiency is 9.26 %. It showed that exergy destruction had a maximum increment of 3.57 % in 2011 and maximum value of 1.71 % in 2007 while exergy efficiency had a maximum of 3.67 % in 2011 and minimum of 1.84 % in 2007.

The factors contributing to the higher irreversibilities in the boiler section are tube fouling, defective burners, steam traps and air heater fouling. Boiler section efficiency improvements can be realized through upgrading of components with better designs, optimizing system performance and eliminating conditions that degrade efficiency between maintenance outages. Primary areas to be considered are firing system design, furnace wall cleaning, convective heat transfer surface arrangement, air preheater heating element and seal design.

The turbine is a three stage turbine: the HP turbine, the intermediate pressure (IP) turbine and the low pressure (LP) turbine. Fig. 7 shows the plot of exergy destruction and efficiency against the operation period for HP turbine.

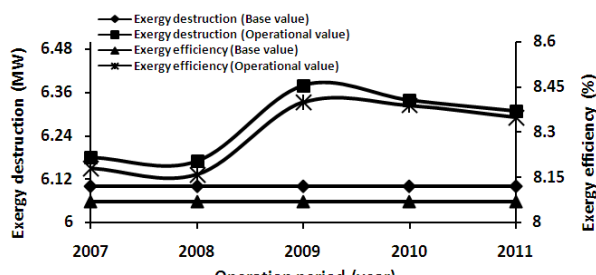


Fig 7. Exergy destruction and efficiency against operation period in HP turbine

The base value of exergy destruction in the HP turbine is 5.29 MW and that of exergy efficiency is 7.01 %. The maximum exergy destruction increment was 3.59 % in 2011 while the minimum was 1.04 % in 2007 and 2008. The exergy efficiency had a maximum of 3.42 % in 2011 and a minimum of 1.07 % in 2008. The variation of exergy destruction and efficiency in IP turbine with operation period is shown in Fig. 8.

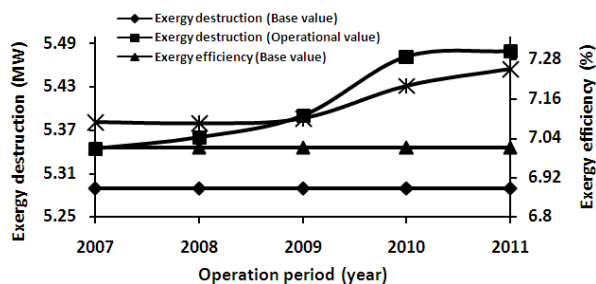


Fig 8. Exergy destruction and efficiency versus operation period in IP turbine

The exergy destruction base value in IP turbine is 6.1 MW and that of the exergy efficiency is 8.07 %. As can be seen, the exergy destruction increment had a maximum value of 4.59 % in 2009 and minimum of 1.15 % in 2008. The exergy efficiency had a maximum increment of 4.09 % in 2009 and minimum of 1.12 % in 2008. Fig. 9 depicts the effect of operation period on exergy destruction and efficiency in LP turbine. The base value of exergy destruction in LP turbine is 3.27 MW and that of the exergy efficiency is 4.33 %.

It was observed that exergy destruction had a maximum increment of 3.43 % in 2010 and minimum of 1.01 % in 2007. In the other hand, the exergy efficiency maximum value is 3.45 % in 2010 and minimum of 1.02 % in 2007.

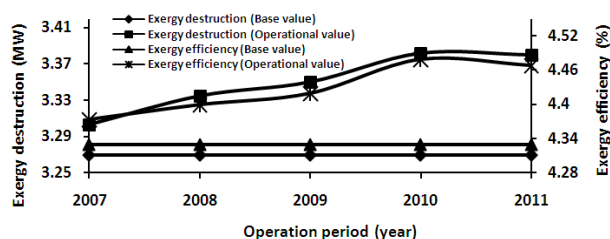


Fig 9. Variation of exergy destruction and efficiency with operation period in LP turbine

The factors that contribute to the irreversibilities in turbine are throttling losses at the turbine governor valves, silica deposits at the nozzles and blades. Amongst the three turbines, the HP turbine produces the highest irreversibility. Retrofitting of rotors, diaphragms or more commonly of complete stator/rotor modules (inner block) is a well proven way of significantly improving the heat rate of a steam turbine.

The variation of exergy destruction and efficiency with operation period in the condenser is shown in Fig. 10

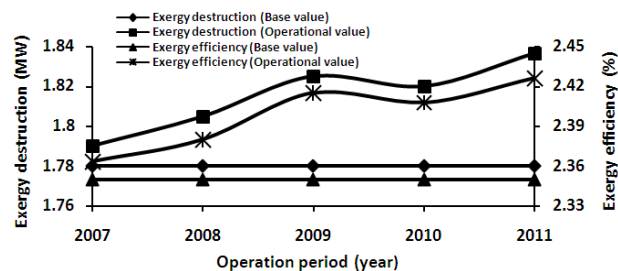


Fig 10. Exergy destruction and efficiency versus operation period in condenser

Exergy destruction and efficiency base values in the condenser are 1.78 MW and 2.35 % respectively. The exergy destruction increment peaked at 3.17 % in 2011 with its lowest value of 0.56 % in 2007 while exergy efficiency attained its maximum increment of 3.23 % in 2011 and its minimum of 0.58 % in 2007.

Sulphur deposits on water distribution plates were adduced for the increments. An effective means of improving the unit efficiency is to improve the vacuum or back pressure. Condenser tube bundle design 25 years ago was largely focused on packing as many tubes into the available volume as possible [22]. As a result some tubes condensed very little steam. A redesigned state-of-the-art tube bundle pattern will allow steam to access all the tubes and an improvement in condensing pressure is achieved. Cooling tower can also be retrofitted with modern packing to give an improvement in cooling water temperature and hence a lower condensing pressure and ultimately a higher power output.

From Figs 2 through 10, the exergy destruction of each component showed an approximately ascending trend with some oscillations. These oscillations might be related to the efforts of the maintenance crew in keeping the plant in good working conditions [10]. As observed in the figures, the exergy destruction and exergy efficiency for each component have similar trend. It is important to note that the civilian administration in Nigeria on its advent in 1999 made concerted efforts in rehabilitation of the plant [3]. This might be the reason why the plant's components had lower irreversibilities in 2007 and 2008. This suggests that steam power plant rehabilitation is a feasible solution for older units that have more than 200,000 operating hours. The results of a successful rehabilitation are reduced electricity production cost achieved by output increase, availability enhancement while at the same time extending

lifetime and complying with stricter environmental standards. Implementation of the rehabilitation project is also much shorter with taking typically 1-2 years as opposed to 3-4 years for the construction of a new plant. In addition, it is possible to operate part of the plant whilst one or two units are undergoing the rehabilitation process.

Power plant rehabilitation is a cost-effective method to regain competitive electricity production cost of older power plant units. The suggested necessary modifications and refurbishment of Sapele power plant units is an attractive solution to improve the plant economy and keep its production cost competitive in a restructured Nigerian power system.

4. Conclusion

The analysis revealed that the highest increment in exergy destruction as compared with its base value occurred in the boiler section. The economiser had a maximum of 4.26 % in 2009 and a minimum of 1.25 % in 2007. While for the evaporator, maximum of 5.02 % was obtained in 2009 and minimum of 1.50 % in 2008. The superheater had maximum of 4.64 % in 2011 and minimum of 1.48 % in 2007. For the reheater, the maximum was 3.57 % in 2011 and minimum of 1.71 % in 2007. Tube fouling, defective burners, steam traps and air heater fouling have been adduced for the increments. Upgrading components with better designs, optimizing system performance and elimination of conditions that degrade efficiency between maintenance outages are essential in improving the performance of the boiler section.

The analysis also showed that for the three turbine stages, HP turbine had the highest increment. HP turbine had a maximum of 4.59 % in 2011 and minimum of 1.15 % in 2007 and 2008; the IP turbine had a maximum of 3.59 % in 2009 and minimum of 1.04 % in 2008 while the LP turbine had a maximum of 3.43 % in 2010 and minimum of 1.01 % in 2007. Throttling losses at the governor valves and silica deposits at the nozzles and blades were the bane. Retrofitting of rotors, diaphragms or complete stator/rotor modules (inner block) can improve the situation.

The results of the analysis on boiler feed pump showed a maximum of 2.93 in 2010 and minimum of 0.54 % in 2007. The condenser had a maximum of 3.17 % in 2011 and lowest value of 0.56 % in 2007. Sulphur deposits on water distribution plates of the condenser was advanced for loss of vacuum and power. A redesigned state-of-art-tube bundle will allow steam to access all the tubes resulting in an improvement in condensing pressure. Cooling tower retrofitted with modern packing gives an improvement in cooling water temperature and hence a lower condensing pressure. The results showed that exergy loss increased with increased operation time. These suggest that deterioration and obsolescence may be the major problems; hence plant rehabilitation is a feasible solution. The results of a successful rehabilitation are reduced electricity production cost achieved by output increase, availability

enhancement while at the same time extending lifetime and complying with stricter environmental standards. The suggested necessary modifications and refurbishment of Sapele power plant units is an attractive solution to improve the plant economy and keep production cost competitive in a restructured Nigerian power system.

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