Full Paper

RELEVANCE OF EXERGY ANALYSIS IN THE ASSESSMENT OF THERMAL POWER PLANT PERFORMANCE

A.N. Anozie
Applied Thermodynamics and Process Design Research Laboratory
Department of Chemical Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria

O.J. Odejobi
Applied Thermodynamics and Process Design Research Laboratory
Department of Chemical Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria
oludareodejobi@yahoo.co.uk

O.P. Ayoola
Applied Thermodynamics and Process Design Research Laboratory
Department of Chemical Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria

ABSTRACT:

Exergy analysis of a natural gas based thermal power plant at Egbin, Ikorodu, Lagos State, was done to: evaluate the exergy and energy efficiencies and irreversibilities of units, subsystems and overall system; identify the units with large thermodynamic irreversibilities and investigate the causes of irreversibilities in the units and how they can be minimized; study the effect of interaction of units on the performance of subsystems and overall system. Process simulation was done using HYSYS, commercial process simulator software, and exergy analysis was done using Microsoft Excel Spreadsheet. It was found that the condenser unit has the lowest exergetic efficiency and the highest energetic efficiency of 22.6% and 99.9%, respectively. The furnace/boiler unit was found to have the highest irreversibility of 1484.3 MW and the regenerative unit has the lowest irreversibility of 9.7 MW. The study of the units interaction revealed that the furnace/boiler unit made the highest contribution of about 67% to the overall process irreversibility while the least contribution of 9.7% came from the turbines/generator unit. It was found that the optimum natural gas mass flow rate which optimized the flue gas temperature and CO2 emission was 40,000 kg/h rather than the operating rate of 45,570 kg/h.

Keywords: Exergy, energy, thermal power plant, efficiency, irreversibility, units and subsystems.

1. INTRODUCTION

The rate of depletion of fossil fuel reserves and environmental impact of combustion of fossil fuel has necessitated the operation of power plants in the most efficient manner. Thermodynamic analysis, such as energy and exergy analysis, has increasingly attracted the interest to achieve this goal. Energy is always conserved in every device or process. Unlike energy, exergy is not always conserved but is destroyed. The major causes of thermodynamic imperfection of the thermal processes are not accounted for by energy or first law analysis. It is the exergy or second law analysis that accounts for the irreversibilities like the heat transfer through a finite temperature difference, chemical reactions, friction, mixing and unrestrained expansion (Cengel and Boles, 2004).

A number of studies on exergy analysis have been carried out by researchers (Bejan, 1988; Moran, 1982 and Mohamad and Bandpy, 2005) to evaluate the performance of thermal power plants at different operating conditions. Caton, 2000 examined analytically the exergy destruction during combustion processes in an internal combustion engine. The rates of exergy destruction in a spray combustion process for gas turbine application and in a fundamental laminar diffusion flame, respectively, were evaluated using computational fluid dynamic models (Datta, 2000). Sciubba and Su, 1986 had earlier done a second law analysis of the steam turbine power cycle to analyse the influence of reheat temperature and pressure on regenerative cycle performance. Nag and De (1997) also performed the second law analysis on gas and steam turbine combined cycles to study the effects of different operating parameters on the cycle performance. The comparison of coal-fired and nuclear steam power plants using energy and exergy analyses to identify areas with potential for performance improvement had also been investigated (Rosen, 2001). Dincer and Al-Muslim (2001) carried out analysis of a Rankine cycle reheat steam power plant to study the energy and exergy efficiencies at different operating conditions with varying boiler temperature, boiler pressure, mass fraction ratio and work output from the cycle. The generalized exergy balance and cost balance equations had been utilized to study the effects of the annualized cost of a component on the production cost in 1000 KW gas-turbine cogeneration system (Kwon, *et al.*, 2001). Rosen and Dincer (2003) had performed a thermoeconomic analysis of power plants and applied it on a coal fired electricity generating station. Alasfour and Alajmi (2000) investigated the exergetic destructions of a steam generation system. Three irreversible processes investigated were combustion, heat transfer and streams mixing processes and the results showed that at stoichiometric condition, the exergy was destroyed mainly by two irreversibilities, associated with heat transfer and combustion processes, and to a much lesser extent by streams mixing process.

The literature on exergy analysis reveals a lack of clear information on the exergy balance in practical natural gas based thermal power plants. And up till now there has not been any work done on the thermodynamic analysis of Egbin thermal power plant, one of the present major sources of electricity to the national grid, located in Ikorodu, Lagos State, Nigeria. The objectives of this study are to: evaluate the energy and exergy efficiencies and irreversibilities of units, subsystems and overall system; identify the areas with large thermodynamic irreversibilities and investigate the causes of irreversibilities in the units and how they can be minimized; study the effect of units interaction on the performance of subsystems and overall system.

2. PLANT DESCRIPTION

Egbin thermal power plant comprises of six independent 220 MW boiler-turbine sets. The sets are dual firing using either natural gas and/or high pour fuel oil (HPFO). Figure 1 shows the flow diagram of a complete set. Each set has three turbines, namely: high pressure turbine (T_1), intermediate pressure turbine (T_2) and low pressure turbine (T_3). The turbines are mounted on a single shaft and a generator is coupled directly with them. Single stage reheating is employed between T_1 and T_2. The super heated steam from the boiler (E_b) drives T_1, and the exhaust from T_1 goes through the reheater (E_r) and then enters T_2. Both the boiler (E_b) and reheater (E_r) are in the furnace (E_1). The exhaust from T_2 goes directly to T_3. The T_3 exhaust gets condensed in the condenser (E_3). The condensed steam in the condenser is pumped by the condensate extraction pump (CEP) into the steam air ejector (E_4) which removes air trapped in the process steam. The water is further pumped through the gland condenser (E_5), drain cooler (E_6) into the low pressure feed water heaters E_7, E_8 and E_9. The low pressure heaters (LPHs) utilize the extraction steam bled from different stages of T_3 to heat the process water. The drains from the LPHs are cascaded backward as a way of waste heat recovery to further heat up the process water. The drip from the drain cooler is fed back into the condenser. The water from E_9 enters the deaerator (E_{10}) which also removes air trapped in the process water. The pegging steam for deaerator comes from T_2 exhaust. The feed water from the deaerator is pumped into the furnace and high pressure heaters (HPHs), E_{11} and E_{12}, through the boiler feed pump (BFP). The extraction steam for the HPHs is coming from T_2 and the exhaust from T_1 cascaded backward into the reheater. Superheated steam from the boiler enters directly into T_1 where it provides shaft work that drives the turbine blade. Exhaust steam from T_1 goes back into the reheater before it passes on to T_2. The exhaust from T_2 enters directly into T_3 to provide shaft work that drives the generator to generate electricity. The exhaust steam from T_3 is condensed in the condenser using lagoon water as coolant.

3. THEORY

The specific exergy of a stream of material consists of the physical exergy and the chemical exergy terms.

$$E_j = E_j^{ph} + E_j^{ch} \quad \text{.................... (1)}$$

The specific physical exergy (excluding kinetic and potential energy) was evaluated from the following equation:

$$E_j^{ph} = (h_j - h_o) - T_o(s_j - s_o) = \Delta h - T_o \Delta s \quad \text{.................. (2)}$$

The standard molar chemical exergy, $\bar{e}^{CH}$ of substances considered in this study are given in Table 1 (Moran, 1999).

The molar chemical exergy of a gas mixture is given as (Moran, 1999):

$$\bar{e}^{CH} = \sum_{i=1}^{j} y_i \bar{e}_i^{CH} + \bar{R} T_o \sum_{i=1}^{j} y_i \ln y_i \quad \text{.......... (3)}$$

Table 1: Standard Molar Chemical Exergy, $\bar{e}^{CH}$ (kJ/kmol) of Various Substances at 298K and p_o.

Substance	Formula	Exergy(kJ/kmol)
Methane	CH_4(g)	831,650
Oxygen	O_2(g)	3,950
Carbon(IV) Oxide	CO_2(g)	19,870
Water	H_2O(g)	9,500
Nitrogen	N_2(g)	720

The exergy rate of a stream *j* was obtained from its specific value as:

$$\dot{E}x_j = \dot{m}_j E_j \quad \text{................................ (4)}$$

The energy rate of a stream *j* was obtained from its specific value as:

$$\dot{E}_j = \dot{m}_j (h_j - h_o) \quad \text{.......................... (5)}$$

In the analysis of a plant unit where there is no power production the exergetic efficiency and the energetic efficiency are given by equations (6) and (7), respectively, as:

$$\psi = \frac{\sum \dot{E}x_{out}}{\sum \dot{E}x_{in}} \quad \text{.................................. (6)}$$

$$\eta = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad \text{.................................... (7)}$$

The exergy efficiency in a unit or subsystem with power generation was evaluated as (Sengupta, *et al.*, 2007):

$$\psi = \frac{P_{net}}{\sum \dot{E}x_{in} - \sum \dot{E}x_{out}} \quad \text{.................. (8)}$$

and the energy efficiency was estimated as:

$$\eta = \frac{P_{net}}{\sum \dot{E}_{in} - \sum \dot{E}_{out}} \quad \text{........................ (9)}$$

$$\eta = \frac{Power\ produced}{Heat\ Supplied\ From\ Fuel} \quad \text{............ (10)}$$

The irreversibility, also called exergy destruction or exergy loss is calculated by setting up the exergy balance and taking the difference between all incoming or outgoing exergy flows. It has the formula given as (Cornelissen, 1997):

$$I = \sum_{in} \dot{E}x_i - \sum_{out} \dot{E}x_j \quad \text{........................ (11)}$$

4. METHODOLOGY

In this work, process data were extracted from the process flow diagram prepared by the plant designers. The extracted data were used as input to the HYSYS (2003) process simulator to provide a heat and mass balnce for the plant. The mass balance was based on mass flow rates. The heat balance was based on temperature, pressure, heat loads and the mass flow rates. HYSYS (2003) was used to validate the data in the existing process flow diagram to ensure that a reliable balance was obtained at different points shown in Figure 1. In this simulation, the following assumptions were made: the natural gas burnt in the combustor was assumed to be 100% methane; the compressed air used in the combustor was standard air; unaccounted heat loss from the system due to radiation and convection was neglected; fuel was assumed to enter the combustor at room temperature; fuel undergoes complete combustion, hence the flue gas composition included oxygen, nitrogen, water vapour and carbon (IV) oxide only.

EXCEL spreadsheet was used for exergy and energy analysis. The exergetic and energetic efficiencies of the four major units that make up the complete plant, namely: the turbine and generator unit, the condenser unit, the regenerative unit and the furnace and boiler unit, were evaluated. The thermal power plant units were grouped into subsystems and overall system, as clearly marked out in Figure 1, for the purpose of studying the effect of interaction of the units on the energetic and exergetic efficiencies of the plant.

4.1. Analysis Of The Plant Units

4.1.1 The turbines/ generator unit

Only physical exergy was considered for the streams that cross the boundary of this unit. The exergy rate entering the boundary is:

$$\dot{E}x_{in} = \dot{E}x_1 + \dot{E}x_{12} \quad \ldots\ldots (12)$$

The exergy rate leaving the unit is:

$$\dot{E}x_{out} = \dot{E}x_5 + \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_{13} + \dot{E}x_{14} + \dot{E}x_{15} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{21} + \dot{E}x_{24} \quad \ldots\ldots (13)$$

The exergetic and energetic efficiencies of the turbines /generator unit were evaluated using equations (8) and (9), where P_{net} is the generator power output.

4.1.2. The condenser unit

Like the turbines/generator, only the physical exergy was considered for the condenser unit. The streams entering the condenser were regarded as the cold streams, while the hot stream was the one leaving. The exergy rate entering the condenser is:

$$\dot{E}x_{hot} = \dot{E}x_{27} - \dot{E}x_{27i} \quad \ldots\ldots (14)$$

and the exergy rate leaving the condenser is:

$$\dot{E}x_{cold} = \dot{E}x_{29} - \dot{E}x_{28} \quad \ldots\ldots (15)$$

The energetic and exergetic efficiencies of the condenser were evaluated using equations (6) and (7), respectively.

4.1.3 The regenerative unit

The regenerative unit comprises the air ejector, gland condenser, deaerator, low pressure and high pressure heaters. Only the physical exergy was considered for the regenerative unit. The exergy rate of the inlet streams and power entering the regenerative unit is:

$$\dot{E}x_{in} = \dot{E}x_9 + \dot{E}x_{10} + \dot{E}x_{15} + \dot{E}x_{16} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{23} + \dot{E}x_{26} + \dot{E}x_{30} + P^{CEP} + P^{BFW} \quad \ldots (16)$$

and the exergy rate leaving the regenerative unit is:

$$\dot{E}x_{out} = \dot{E}x_{33} + \dot{E}x_{34} + \dot{E}x_{39} + \dot{E}x_{46} + \dot{E}x_{51} \quad \ldots\ldots (17)$$

The energetic and exergetic efficiencies of the regenerative unit were evaluated using equations (6) and (7), respectively.

4.1.4. The furnace/boiler unit

Both the physical and chemical exergy associated with fuel input, air for combustion of fuel and flue gas, as well as the heat exergy released from combustion of fuel in the furnace were accounted for in this unit.

4.2. Analysis Of Subsystems And Overall System

4.2.1 Reference unit for subsystem analysis or Subsystem I

The reference unit for subsystem analysis is the turbines/generator unit which is also denoted as Subsystem 1. The physical exergy for streams entering and leaving the subsystem I are given by equations (12) and (13) and the efficiencies were evaluated by equations (8) and (9).

4.2.2. Subsystem II

Subsystem II comprises the turbines/generator and condenser units. The exergy rate entering and leaving the subsystem are:

$$\dot{E}x_{in} = \dot{E}x_1 + \dot{E}x_{12} + \dot{E}x_{25} + \dot{E}x_{28} + \dot{E}x_{39} \quad .. (18)$$

and

$$\dot{E}x_{out} = \dot{E}x_5 + \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_{13} + \dot{E}x_{14} + \dot{E}x_{15} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{21} + \dot{E}x_{29} + \dot{E}x_{30} \quad \ldots\ldots (19)$$

The net power output from the subsystem is:

$$P_{net} = G - P^{CCW} \quad \ldots\ldots (20)$$

where P^{ccw} is the power consumed by the condenser cooling water pump which was unknown and assumed to be zero in this analysis. The energy and exergy efficiencies of subsystem II were calculated using equations (8) and (9).

4.2.3. Subsystem III

Subsystem III comprises the turbines/generator, condenser and the regenerative units. The exergy rates entering and leaving the subsystem are:

$$\dot{E}x_{in} = \dot{E}x_1 + \dot{E}x_{12} + \dot{E}x_{28} \quad \ldots\ldots (21)$$

and

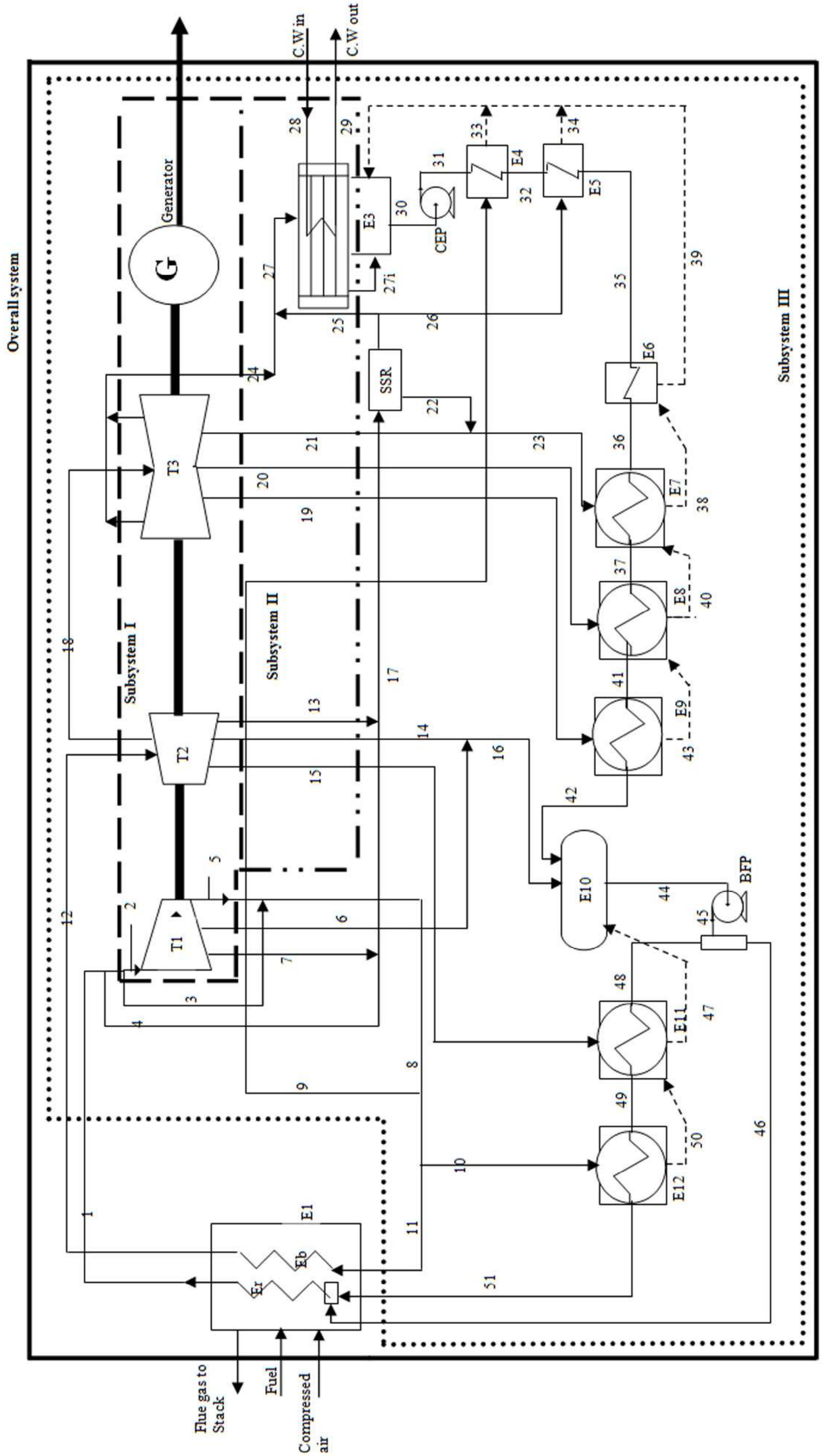

Figure 1. Process flow diagram of the plant showing the subsystems and overall system. Subsystem I: ; Subsystem II: ;Subsystem III ; Overall system ;

$$\dot{E}x_{out} = \dot{E}x_{11} + \dot{E}x_{29} + \dot{E}x_{46} + \dot{E}x_{51} \quad \text{.......... (22)}$$

The boiler feed water pump (BFP) and the condensate extraction pump (CEP) power input were accounted for in the net power output from this subsytem and the net power output from the subsystem is:

$$P_{net} = G - P^{CEP} - P^{BFP} \quad \text{................ (23)}$$

The values of P^{CEP} and P^{BFP} were 543.04kJ/h and 40173.21kJ/h, respectively. The energy and exergy efficiencies of subsystem III were calculated using equations (8) and (9).

4.2.4. Overall System

The overall system comprises the entire cycle with the turbines/generator, condenser, regenerative and furnace/boiler units. In the analysis of overall system, the exergy due to reaction, that is, the chemical exergy due to combustion of fuel was taken into consideration in addition to the physical exergy due to the streams of material entering and leaving the overall system. In the overall system analysis it was assumed that the total auxiliary power consumption (P_{aux}) in the plant was 5% of the generated power.

The stoichiometric equation representing the complete combustion of methane in oxygen is

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \quad \text{... (24)}$$

The specific exergy of reaction can be written as (Som, *et al*., 2005):

$$\bar{e}_{in}^{fuel} = (((\bar{h}_{CO_2} + 2\bar{h}_{H_2O}) - (2\bar{h}_{O_2} + \bar{h}_{CH_4})) - T_o((\bar{s}_{CO_2} + 2\bar{s}_{H_2O}) - (2\bar{s}_{O_2} + \bar{s}_{CH_4}))) \quad (25)$$

The molar enthalpies and entropies for the components taking part in the reaction are given in Table 2 (Perry and Green, 1997; Smith and Van Ness, 2004).

Considering the exergy input with fuel, air and circulating water, the total exergy flow rate entering the overall system is

$$\dot{E}x_{in} = \dot{E}x_{fuel} + \dot{E}x_{fuel}^{ch} + \dot{E}x_{air} + \dot{E}x_{air}^{ch} + \dot{E}x_{28} + \dot{E}x_{Q} \quad \text{.......... (26)}$$

Table 2: Molar enthalpy and molar entropy values

Species	Molar enthalpy ($\bar{h}$)	Molar entropy ($\bar{s}$)
CH4	$-74520 kJ/kmol$	$186.16 kJ/kmol^oC$
O2	0	$205.03 kJ/kmol^oC$
CO2	$-393509 kJ/kmol$	$213.69 kJ/kmol^oC$
H2O	$-241818 kJ/kmol$	$188.72 kJ/kmol^oC$

where $\dot{E}x_{Q}$ is the exergy rate of reaction.

The exergy flow rate leaving the overall system is:

$$\dot{E}x_{out} = \dot{E}x_{flue\,gas\,to\,stack} + \dot{E}x_{29} + \dot{E}x_{flue\,gas}^{ch} \quad \text{........... (27)}$$

where $\dot{E}x^{ch}$ is the chemical exergy rate associated with the stream of material in question. The energy and exergy efficiencies of the overall system were calculated using equations (8) and (9).

5. Results and Discussion

5.1. Physical and Thermodynamic Properties Of Streams

The parameters of the process streams and their calculated exergetic and energetic values at full load of 220 MW are presented in Table 3.

5.2. Components Exergy and Energy Efficiencies

The exergetic and energetic efficiencies of the four units in the plant are presented in Figure 2.

From Figure 2, it was observed that the regenerative unit has the highest exergetic efficiency of 93.6% and its energetic efficiency was 94.8%. The high exergetic efficiency in the regenerative unit could be due to low exergy loss resulting from heat recovery from turbines bleeds. The cascaded heat was used within the system thereby reducing energy losses to the environment. The consequence is high energy efficiency

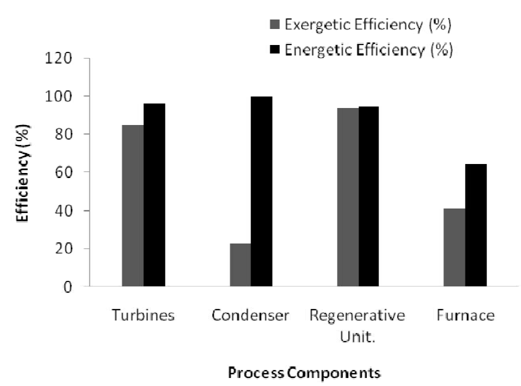

Figure 2: Exergetic and Energetic Efficiencies of the Plant Units

recorded in the regenerative unit. The condenser unit has the highest energy efficiency of 99.9%. The high energy efficiency in the condenser unit could be due to high performance of the water recirculating system in place. The lowest exergetic efficiency of 22.6% in the system occured in the condenser unit. The low exergetic efficiency in this unit could be due to high exergy destruction resulting from heat ejection from the process through the condenser. Condensation of steam coming out of low pressure turbine at about 106oC to about 42oC also invovled high exergy destruction. The furnace/boiler unit has exergetic efficiency and energetic efficiencies of 41.3% and 64.3%, respectively. The low energetic efficiency in the

Table 3: Parameters of the streams and their exergetic and energetic values

Stream	Flow (kg/h)	T°C	PkPa	ΔH (kJ/kg)	ΔS (kJ/kg-K)	E (kJ/kg)	ex (kJ/kg)	Total Ex(kJ/kg)	$\dot{E}_{xj}$ (kJ/h)	$\dot{E}_j$ (kJ/h)
1	647504	538	12500	3540	6.281	1667.6339	527.77778	2195.4117	1421537843	2292164160
2	645869	538	12500	3440	6.281	1567.6339	527.77778	2095.4117	1353361445	2221789360
5	629325	500.4	9779	3120	6.307	1239.8833	527.77778	1767.6611	1112433308	1963494000
6	3675	336.8	2689	3110	6.468	1181.8892	527.77778	1709.667	6283026.14	11429250
7	1762	336.8	2689	3110	6.468	1181.8892	527.77778	1709.667	3012433.21	5479820
8	634762	337.1	2689	3120	6.469	1191.5911	527.77778	1719.3689	1091390028	1980457440
9	540	337.1	2689	3023	6.469	1094.2264	527.77778	1622.0041	875882.238	1632223.044
10	50308	337.1	2689	3023	6.469	1094.2264	527.77778	1622.0041	81599784.5	152062735
11	579724	337.1	2689	3023	6.469	1094.2264	527.77778	1622.0041	940314730	1752294207
12	579724	538	3076	3453	7.029	1357.2904	527.77778	1885.0681	1092819245	2001575527
13	1081	328.3	495.1	3043	7.269	875.74637	527.77778	1403.5241	1517209.6	3289088.723
14	22593	326.6	495.1	3043	7.259	878.72737	527.77778	1406.5051	31777170.7	68742258.57
15	29942	434.6	1371	3253	7.129	1127.4804	527.77778	1655.2581	49561739.3	97390405.14
16	26268	326.6	495.1	3043	7.259	878.72737	527.77778	1406.5051	36946077.1	79923943.17
17	560900	328.3	495.1	3043	7.269	875.74637	527.77778	1403.5241	787236692	1706614121
18	537215	328.3	495.1	3043	7.269	875.74637	527.77778	1403.5241	753994223	1634549305
19	22332	252.8	227.1	2980	7.369	783.3011	527.77778	1311.0789	29279013.5	66549360
20	20953	175.4	86.45	2831	7.499	595.5481	527.77778	1123.3259	23537047.1	59317943
21	34739	100.7	27.29	2690	7.689	397.9091	527.77778	925.68688	32157436.4	93447910
22	1241	339.3	495.1	3063	7.309	883.82237	527.77778	1411.6001	1751795.78	3800730.365
23	35980	109	27.29	2623	7.729	318.62037	527.77778	846.39814	30453405.2	94362416.88
24	459191	105.7	1.353	2398	7.679	108.8901	527.77778	636.66788	292352159	1101140018
25	1040	339.3	495.1	3158	7.309	942.6421	527.77778	1470.4199	1529236.67	3284320
26	950	339.3	495.1	3063	7.309	883.82237	527.77778	1411.6001	1341020.14	2909503.503
27	460231	106.2	29.64	2613	7.679	323.52537	527.77778	851.30314	391796097	1202415741
27i	460231	42.1	29.64	74	0.241	1.873244	527.77778	529.65102	243761819.4	33926086.49
28	32590000	30	4.241	22	0.072	0.0796649	527.77778	527.85744	1.7203E+10	702081967.9
29	32590000	38.32	6.661	57	0.189	1.1055023	527.77778	528.88328	1.7236E+10	1872178250
30	541000	42	8.252	76	0.239	4.7314694	527.77778	532.50925	288087503	41103756.82
31	541000	42	9	76	0.239	4.7314694	527.77778	532.50925	288087503	41103756.82
32	541000	42.62	9	76	0.248	2.0485694	527.77778	529.82635	286636054	41103756.82
33	540	99.1	2689	323	0.96	36.459266	527.77778	564.23704	304688.004	174223.0438
34	950	99.1	495.1	323	0.962	35.863066	527.77778	563.64084	535458.802	306503.503
36	541000	69.18	30	363	1.089	38.004366	527.77778	565.78214	306088140	196185679.1
39	79265	99.07	98.14	683	1.943	103.42697	527.77778	631.20474	50032444	54109084.38
46	20000	163	709.5	613	1.674	113.61587	527.77778	641.39364	12827872.9	12252705.33
47	627504	163	709.5	613	1.674	113.61587	527.77778	641.39364	402477077	384431080.1
51	627504	200.4	3151	793	2.06	178.54927	527.77778	706.32704	443223045	497381800.1
52	647504	165.6	709.5	780	2.07	163.22857	527.77778	691.00635	447429375	505108674.4
Compressed Air	572760	30	865	3.0256	-0.607	183.9723	4.4939885	188.46629	107945951.4	1732942.656
Flue gas to Stack	618324	333.1	241	780	-0.261	857.8041	1154.8598	2012.6639	1244478393	482292720
Fuel	45570	27	243	3	-0.45	137.145	51978.125	52115.27	2374892854	136710

furnace/boiler unit when compared with other process components could be an indication of high heat loss from the combustion reaction of fuel with air in the furnace/boiler unit. The low exeregetic efficiency could equally be as a result of high exergy destruction in the combution reaction in the furnace. The turbines/ generator unit has exergetic efficiency of 85% and energetic efficiency of 96.3%. Unlike in the furnace/boiler unit, which served the function of the heat engine where process heat is being raised thereby subjected to high exergy and energy losses. The available work in the turbine/generator was useful for power generation. High energetic efficiency in the turbine/generator indicated low heat loss since there was no reaction taking place in the turbine/generator, only conversion of heat to power was involved. This was an indication that heat loss as a result of combustion of fuel could significantly effect process unit efficiency.

5.3. Components Irreversibilities

The irreversibilities associated with each of the four components in the plant are shown in Figures 3. It was observed that the furnace/boiler unit has the highest irreversibility (1484.3 MW) followed by the turbines/generator unit (259 MW). The irreversibility of the condenser unit was 31.8 MW, and that of the regenerative unit was 9.7 MW, which was the lowest.

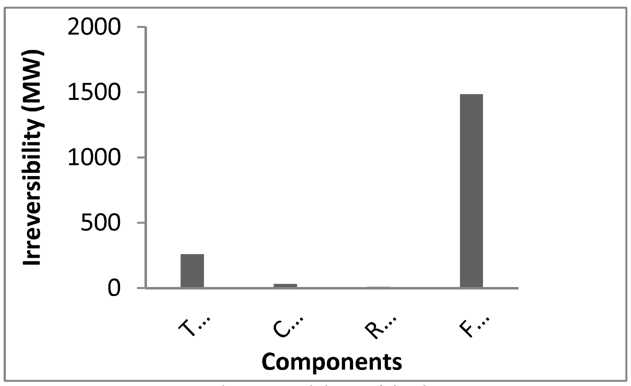

Figure 3: The irreversibilities of the plant units

The high irreversibilty in the furnace/boiler unit was an indication of significant exergy loss due to high entropy generation at conditions at which the unit operates to raise process steam. The furnace/boiler unit operates at high temperature and pressure, the available work at these conditions was used to produce heat to raise process steam. The combustion reaction in the unit was also highly exothemic hence, exergy destuction in these units was so high as reflected in the high irreversibility exhibited. The condenser and the regenerative units operate at low tempeartures and pressures, hence their entropy generations are low as reflected in their irrversibilities.

Examination of Figures 2 and 3 showed that condenser unit has low exergy efficiency and relatively low thermodynamic irreversibility. Also, the regenerative unit has high exergy efficiency and relatively low irreversibility. These situations arise because exergy efficiency values are quantitative measurements derived as the ratio of two numbers with the constraint that the ratio is not greater than 1, whereas irreversibilities are quantitative measurements derived as the difference between two numbers. In fact, four possible combinations of exergy efficiencies and irreversibilities can exist as shown below:

High exergy efficiency- Large irreversibility
High exergy efficiency- Small irreversibility
Low exergy efficiency- Large irreversibility
Low exergy efficiency- Small irreversibility

Thus, it is possible for the ratio of two large numbers to be high and the difference to be large as well, and the ratio of two small numbers to be high and the difference to be small.

Exergy analysis generates ideas about how improvements can be made in process components. Specifically, the furnace/boiler component was investigated further in order to find ways of improving its performance. It must be pointed out that the magnitude of losses in a unit does not always imply the greatest potential for improvement. To recover the losses in the furnace reactor, a reversible reactor which would be capable of extracting work directly from the reaction itself, similar to a fuel cell type of device, would be required. In practice, such a reactor cannot be built and the best that can be done is to extract heat from the reaction. It becomes justifiable to base the assessment of performance of reactors on the maximum practical target which is achieveable with current technology. It therefore becomes necessary to divide the total irreversibilities in reactors into inherent/unavoidable and non-inherent/avoidable irreversibilities (Debbigh, 1956). Linnhoff (1979) formulated a simple equation for evaluating the non-inherent/avoidable irreversibilities in chemical reactors as:

$$\dot{I}_{non-inherent} = \dot{I}_{actual} - \dot{I}_{best\ practice} \quad ....(29)$$

and further defined the most efficient operating conditions for identifying the "best practical" reactor, given the constraints of current technology. For an exothermic reaction, it was recommended that the strategy should be to use the reaction to boost as much heat as possible to as high a level as possible. The required operating conditions to achieve this strategy are: preheat to, or as close as possible to, reaction temperature; recover as much heat as possible directly from the reaction; run the reaction at, or as close to, the maximum feasible tempearture throughout; and optimize the mass flow rate. These conditions were applied to the furnace reactor. The temperature of the flue gas from the furnace is a function of the gas mass flow rate and this variation was derived by simulation and is shown in Figure 4. From Figure 4 it was observed that the optimum gas mass flowrate, at the point of inflexion, is 40,000kg/h giving an optimum flue gas temperature of 104.6oC. It was found from Figure 4 that operating the plant below the gas flow rate of 38,000kg/h is not realistic and that feasible operation lies between gas flow rate of 38,000 kg/h and 45,570 kg/h. It was found from simulation that operation

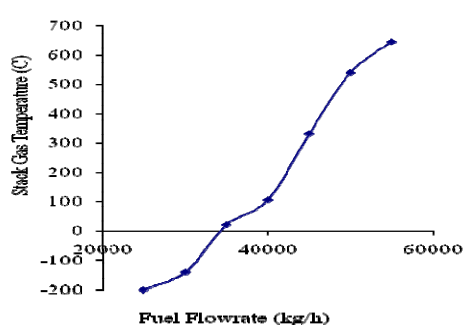

Figure 4: Variation of flue gas temperature with gas mass flow rate.

within this range of gas flow rate did not have any significant effect on the exergy efficiency of the thermal power plant. The variation of CO_2 emission with gas mass flow rate is shown in Figure 5.

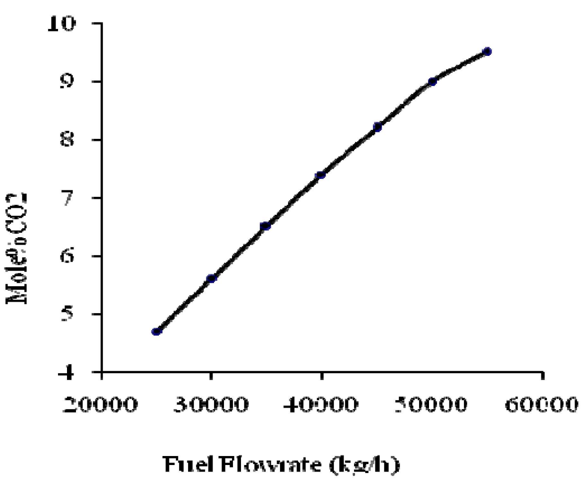

Figure 5: Variation of CO_2 emission with gas flow rate.

It was found that increasing the gas mass flow rate increased the CO_2 emission. Therefore, it is better to operate the plant at optimum gas flow rate of 40,000kg/h than at 45,570kg/h prevailing in the plant. The only improvement that can be made in the furnace/boiler unit to further enhance heat recovery from the flue gas is to use the flue gas to preheat the inlet air and gas streams to the furnace.

Boilers generally are known to have large thermodynamics heat loss due to combustion of fuel. The question now is: are there alternative technologies for energy recovery from the furnace heat which can be used in place of the bolier? Can work or power be recovered from the furnace hot gas? Gas turbines can not be used for work recovery in the present situation because the furnace gas is at low pressure. Also the use of heat engines to recover power from the furnace gas is not practicable in this case because of the high temperature of the gas. Therefore, heat recovery will remain, for the moment, the practical approach to energy recovery from the furnace hot gas, and the boiler is the practical technology to be used in the present situation. From all indications it is unlikely that much improvement can be made in the design and operating specifications of the furnace/boiler unit. This showed that high thermodynamic heat loss in units do not always imply the greatest potential for improvement and that high heat loss may be due to limitations of current technology.

5.4. Subsystems and Overall System Performances

The results of subsystems and overall system analyses are shown in Figures 6 and 7.

In subsystem I, which is also the reference turbines/generator unit for system analysis, the exergy and energy efficiencies were 85% and 96.3%, respectively, and the irreversibility was 259 MW, as previously determined.

In subsystem II, the exergy efficiency dropped slightly to 83% and energy efficiency also increased slightly to 99.8%. The subsystem irrversibility also increased to 312 MW. The increase

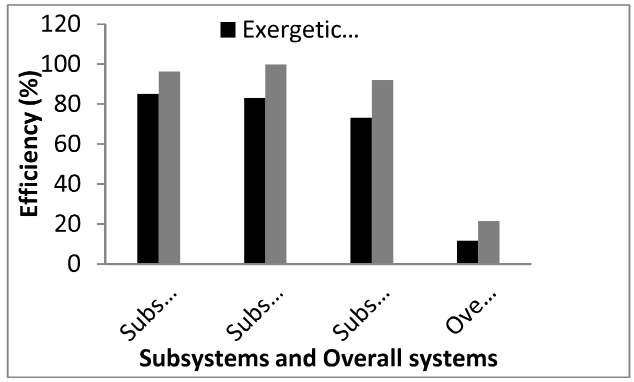

Figure 6: Exergetic and Energetic Efficiencies of Subsystems and Overall system

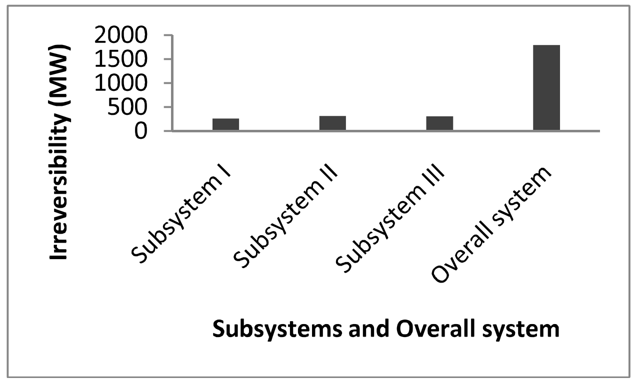

Figure 7: The irreversibility associated with subsystems interaction

in subsystem irreversibility indicated that inclusion of condenser in the process could result in increase in the exergy loss as a result of heat expulsion from the system through the condenser unit.

In subsystem III, the exergy and energy efficiencies dropped to 73.1% and 92%, respectively. The subsystem irrversibility reduced to 301 MW. The reduction in subsystem irreversibility indicated that inclusion of regenerative unit in the process could result in reduction in the exergy loss as heat is being recovered from the turbine thereby reducing heat ejection into the environment and consequently reducing exergy destruction in the process. The regenerative unit had the lowest unit irreversibility and made significant contribution to redction in irreversibility due to system interaction.

In the overall system, the exergy and energy efficiencies were further lowered to 11.7% and 21.4%, respectively, by the introduction of the furnace/boiler unit. Also, the overall irreversibility was further increased to 1790 MW. The high energetic efficiency of the overall process over the exergetic efficiency was due to high exergy destruction originated from combustion of fuel with the air in the furnace/boiler unit. The study of the system interaction effects helped to identify the furnace/boiler unit as making the most significant contribution to increasing overall process irreversibility. The unit made 67.2% contribution to the overall process irrversibility of 2662 MW. The turbines/generator unit made the least contribution of 9.7%. The condenser and the regenerative units contibuted 11.7% and 11.3%, respectively, to the overall process irreveresibility. The highest contribution came from the furnace/boiler unit because of the entropy generation at high temperature and pressure at which the process steam was supplied from the furnace/boiler unit.

6. Conclusions

In this work, energy and exergy analyses were performed on 220 MW Egbin thermal power plant to study units, subsystems and overall system performances using HYSYS (2003) process simulator and Microsoft Excel Spreadsheet. It was found that the regenerative unit has the highest exergy efficiency; the furnace/boiler unit has the lowest energy efficiency; and the condenser unit has the highest energy efficiency. It was also discovered that process units interaction infleuenced the overall thermodynamic irreversibility of the process. The causes of thermodynamic irreversibilities in the units were identified. The study revealed that the optimum fuel flow rate of 40,000kg/h will reduce the flue gas temperature and CO_2 emission to the atmosphere. The overall system exergetic and energetic efficiencies were 11.7% and 21.4%, respectively. The subsystems and overall system study revealed that the furnace/boiler unit made the greatest contribution to the system irreversibility and the consequence was drop in both exergetic and energetic efficiencies of the overall system.

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