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Energy and Exergy Analysis of Steam Generation Unit of a Petrochemical Plant

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ABSTRACT

This study presents the energy and exergy analysis of the steam generation unit of a 120 tonnes per hour capacity Petrochemical Olefins Plant located in the Niger Delta area of Nigeria. Operational data for a period of one year collected from logbook and direct measurements from the plant and used for analysis included pressure, temperature and mass flow rate at entries and exits of the major components, namely combustion chamber, superheater, economizer, air preheater, feed water pump and deaerator. Using energy and exergy equations, the components were analyzed separately and energy efficiency, exergy efficiency and losses were determined. The results indicate that the highest energy loss and exergy destruction occurring in the combustion chamber were 10.734MW and 17.256MW, which represent 60.40% and 63.52% of total energy loss and exergy destruction in the plant respectively. The energy and exergy efficiencies of the combustion chamber were found to be 89.64% and 66.77% respectively. The highest exergy destruction that happened in the combustion chamber is an indication of irreversibility within the combustion process. The findings of this study would enable the plant management to identify components that require priority focus to reduce exergy destruction for plant improvement.

KEYWORDS: energy efficiency, Mass flow rate, Irreversibility, exergy efficiency, exergy destruction.

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1.0 INTRODUCTION

Steam is a vital mode of energy carrier utilized for power generation and for industrial processing such as fertilizer, refineries, chemical, fiber, and textiles. Coal and natural gas are known sources of steam production. Energy conversion of fuel to steam takes place in boilers and the steam produced is used to generate electricity and for process plant. Evaluation of steam generation systems is essential in industries for effective energy usage (Pilankar & Kale, 2016). Energy is very important to life and its conservation has become essential to human development. The quest for energy in the world is increasing astronomically especially in industrial sectors, therefore it becomes necessary to properly utilize available energy resources. The need for energy improvement in the industrial sector is essential for increasing productivity and efficiency. The first law of thermodynamics is adopted to analyse energy utilization, but it does not distinguish between the quality and quantity of energy, which is why exergy analysis is important. Exergy analysis is based on the second law of thermodynamics, and it is the property that helps us to figure out the useful work potential of a given amount of energy at some specified state (Saidur *et al.*, 2010).

Exergy analysis is very important in engineering, especially in systems evaluation to ascertain the processes that need improvement. Systems and processes that do not perform optimally could be identified and improved through in-depth evaluation of the entire system. Exergy is used to measure system performance by analyzing the exergy destructed in each component of a process. It could be used to draw performance comparison

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of systems and processes to help make informed operational decisions (Kumar *et al.*, 2015).

Energy and exergy analysis of industrial steam generation plants have been done by researchers in various systems applications. Akubue *et al.* (2014) performed exergy analysis of 10,000TPH capacity of a brewery operated with an oil-fired steam boiler unit located in Nigeria. It was found that the combustion chamber experienced the greatest exergy loss of 36 percent in real time, while the mixing region recorded a minimum of 3.5 percent and heat exchanger at 33.6 percent. The average efficiencies of energy and exergy were 95.34 percent and 24.45 percent respectively.

By adjusting the various parameters in the boiler section of a plant, Babu *et al.* (2015) investigated the efficiency of economizer, super heater & air preheater. By utilising the boiler accessories, the plant productivity improved. Economizer, for example, raises the temperature of the input water, whereas superheater raises the temperature of the steam produced in the boiler. The air preheater raises the temperature of input air before it reaches the furnace.

Jamali *et al.* (2017) used the engineering equation solver to calculate the energy and exergy analyses of boiler of 50MW unit of Lakhra coal power plant. It was observed that the combustor was where uncontrolled chemical reactions and maximum loss and destruction due to heat loss and radiation losses occur was the most destructive part of the boiler with energy loss of 90 percent and exergy destruction was 55 percent, followed by super heater with 5 percent energy loss and 36 percent exergy destruction. According to their analysis, the air preheater was the most efficient portion of the boiler with energy and exergy efficiency of 78 percent and 79 percent respectively.

Mali and Mehta (2012) carried out energy and exergy analysis on 125MW coal base thermal power plant. Exergy loss in the combustor was discovered to be 47.43 percent. Exergy efficiency was noticed to be lower at all points of the unit equipment. The work also revealed that the combustor, superheater, economizer, and air preheater sections all have significant losses of available energy. There were comparison charts where energy and exergy efficiency, exergy destruction and energy losses were shown.

At Benso Oil Palm Plantation, Mborah and Gbadam (2010) conducted energy and exergy analysis on a 500KW steam power plant. Mass, energy, and exergy balance equations were used to calculate the required outputs of work, heat, and irreversibility of the various components. According to the finding, nearly half of the heat energy generated in the combustor is lost. In summary, it was advised that the combustor be improved further to enhance plant performance and they also demonstrated from the output gotten how energy and exergy were used to identify areas of inefficiencies in the plant.

The DCM Shriram power plant was studied by Hitendra and Jambu (2015) using energy and exergy analysis. The work revealed that exergy efficiency is less when compared to energy efficiency at every point of the power plant component and showed significant loss of energy in the combustor, superheater, economizer, and air preheater sections. Charts for energy efficiency, exergy efficiency, exergy destruction and energy losses were presented in the article.

The focus of this work is to analyze a steam generation unit of a Petrochemical Olefins Plant using energy and exergy methods. The boiler in the steam generation unit was leaking and the furnace used to be filled with water during start up. The leakage rate increased to about 30 tonnes per hour. Pneumatic and hydro-tests were conducted, and some tubes were found to be leaking. The failed tubes were plugged and welded using 309L filler wire and the boiler was successfully pressure tested. As a result of the foregoing, it becomes imperative to analyze the energy and exergy of the steam generation unit to identify components that

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have major energy loss and exergy destruction for improvement.

2.0 MATERIALS AND METHODS

The steam generation unit is located at Eleme area of Rivers State, Nigeria and was constructed with three steam generation units; identify as SG-1A, SG-1B and SG-1C, each of 120TPH capacity. The operating condition of the plant is presented in Table 1. The plant uses natural gas as fuel which is supplied through AGIP gas plant. The properties of natural gas are shown in Table 2. In this study, steam generation unit SG-1C, was analyzed because of tube leakage maintenance performed on the unit. The steam generated in the plant are stepped down to various types, using pressure valves and are exported to fertilizer plant, polyethylene plant, feed conditioning unit and part of which are used to drive prime movers such as turbofans and turbo-pumps at olefins plant.

The schematic diagram of one 120 tonnes per hour steam generation unit with its major components considered for analysis is shown in Figure 1. The continuous supply of feed water from demineralizer unit at a temperature of 56°C and pressure of 10bar goes to the deaerators where dissolved oxygen and gases are removed to the atmosphere from a value of 10ppb to 0.0001ppb by raising the temperature of feed water from 56°C to 110°C. The deaerated water is pumped to the economizer at inlet temperature of 110^0C and undergoes heating process where the temperature is raised to 150^0C by flue gases before flowing to the boiler. The saturated steam exit boiler into the superheater where heat from flue gases raised the temperature to superheated steam with negligible moisture content. The superheated steam produced in the superheater is distributed via headers to processing plants.

2.1 Thermodynamic analysis

The mass, energy, and exergy balances at steady state with infinitesimal changes in potential and kinetic energy of a control volume can be represented as given by Pilankar and Kale (2016):

$$\sum \dot{m}_i = \sum \dot{m}_e \qquad (1)$$

where m is mass flow rate (kg/s)

$$Q - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \qquad (2)$$

where Q = heat transfer (kJ/s), $\dot{W}$= work done (kJ/s), h = specific enthalpy (kJ/kg)

$$I_{heat} - \dot{W} = \sum \dot{m}_e \varepsilon_e - \sum \dot{m}_i \varepsilon_i + I_d \qquad (3)$$

where I_{heat} is the net exergy transfer by heat at temperature T, ε = specific exergy (kJ/kg) and I_d is exergy destruction.

$$I_{heat} = \sum\left(1 - \frac{T_0}{T}\right) Q \qquad (4)$$

where T_0 = reference state temperature (K)

The specific exergy flow is made up of the physical and chemical terms given by

$$\varepsilon = \varepsilon^{ph} + \varepsilon^{ch} \qquad (5)$$

where ε^{ph} = specific physical exergy flow (kJ/kg), ε^{ch} = specific chemical exergy flow (kJ/kg).

The specific physical exergy flow is given by.

$$\varepsilon^{ph} = h - h_0 - T_0(S - S_0) \qquad (6)$$

where S = specific entropy (kJ/kgK)

Total exergy flow is expressed as:

$$I = \dot{m} \times \varepsilon \qquad (7)$$

where I = total exergy flow (kJ/s)

The complete combustion equation is expressed as:

$$0.9817CH_4 + 0.016C_2H_6 + 0.001C_3H_8 + 0.0002C_4H_{10} + 0.0011N_2 + 2.0257(O_2 + 3.76\,N_2) \rightarrow 1.0175CO_2 + 2.0164\,H_2O + 7.617732N_2 \qquad (8)$$

From the formula, the air fuel ratio by mass is 17.

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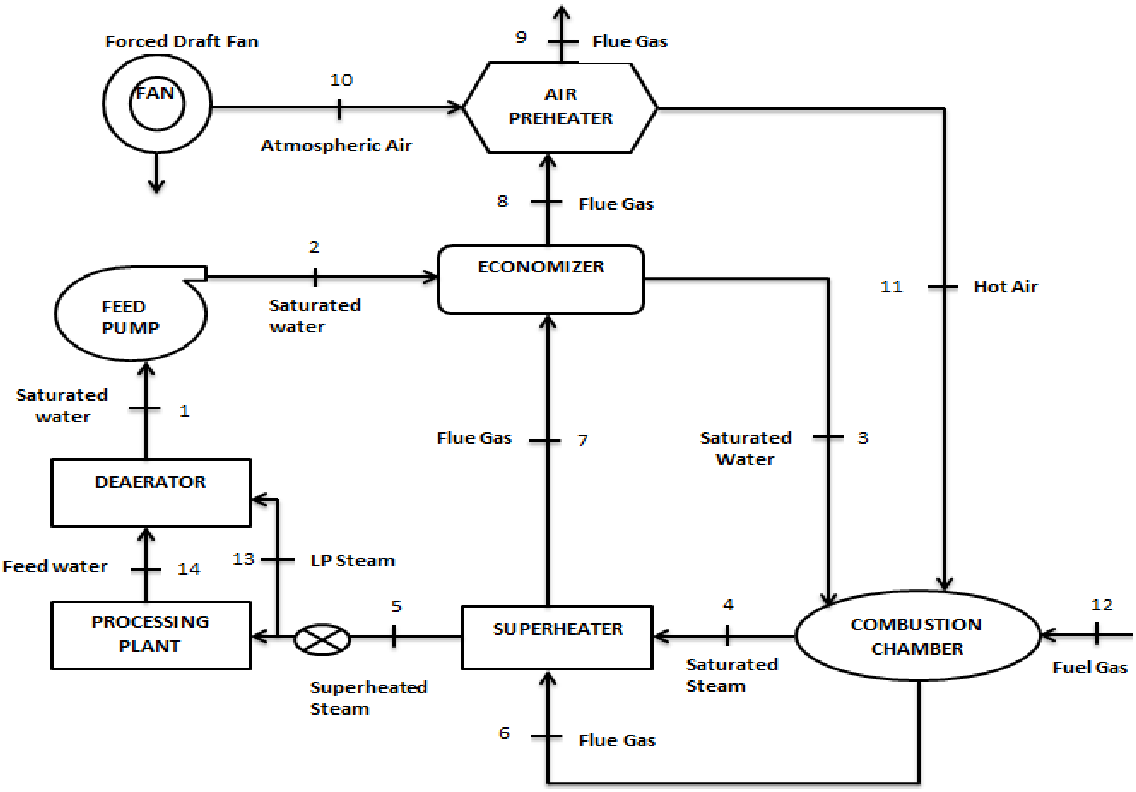

Figure 1: Schematic Representation of the Steam Generation Unit

Table 1: Operating Conditions of the Steam Generation Unit, 2020

Operating condition	Value
Fuel gas volumetric flow rate at MCR per boiler	9900 Nm^3/hr.
Mass flow rate of fuel (Natural gas)	1.704 kg/s
Lower Calorific Value of fuel	44965 kJ/kg
Steam flow rate	19.53 kg/s
High Pressure Steam (pressure)	47 bar
High Pressure Steam (temperature)	400ºC
Water temperature to boiler	150 ºC
Stack gas temperature	145 ºC

Source: Operational manual at Olefins plant of Indorama PCL

After combustion, the flue gas compositions are 9.55% CO_2, 18.93% H_2O, 71.52%N_2 and molar mass of the mixture is 27.6481kg/kmol.

For gaseous fuel the standard molar specific chemical exergy is expressed as given by Moran *et al*. (2011):

$$\varepsilon_f^{-ch} = -\Delta G^0 + \sum_{PD} n_{PD}\, \varepsilon_{PD}^{-ch} - \sum_R n_R\, \varepsilon_R^{-ch} \quad (9)$$

were ΔG^0 = change in standard Gibbs function (kJ/kmol), n = number of mole (kmol), R = co-reactants and PD = products.

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Table 2: Composition of natural gas

Composition	Volume (%)
CH_4	98.17
C_2H_6	1.60
C_3H_8	0.10
C_4H_{10}	0.02
N_2	0.11
Total	100.00

Source: Operational manual at Olefins plant of Indorama PCL

The molar chemical exergy of flue gases is obtained as expressed by Moran *et al.* (2011):

$$\varepsilon_g^{-ch} = \sum y_i \ \varepsilon_i^{-ch} + \bar{R}T_0 \sum y_i \ln y_i \quad (10)$$

where y_i = mole fraction of component i

ε_i^{-ch} = standard chemical exergy of component i

$\bar{R}$ = 8.3144 kJ/kmolK (molar or universal gas constant).

The chemical exergy of air is obtained as given by Ohijeabon *et al.* (2015):

$$\varepsilon_a^{-ch} = \sum (y_i \ \varepsilon_i^{-ch})_a \quad (11)$$

The mole fractions of the constituents of air in a standard environment and various standard chemical exergies of substances are shown in Table 3.

The specific chemical exergy is obtained by the expression:

$$\varepsilon^{ch} = \frac{\varepsilon^{-ch}}{M} \quad (12)$$

where M = molar mass of chemical substance (kg/kmol). The specific chemical exergy of hydrocarbon fuel, flue gases, air, water, and steam as applied in the combustor are shown in Table 4.

2.1.1 Energy loss, Exergy destruction, Energy and Exergy Efficiencies

The expression for energy loss (E_{loss}), exergy destruction (I_d), energy (ŋ) and exergy (Ψ) efficiencies for the processes are based on the following definitions (Jamali *et al.*, 2017; Saidur *et al.*, 2010):

$$E_{loss} = Energy_{in} - Energy_{out} \quad (13)$$

$$I_d = Exergy_{in} - Exergy_{out} \quad (14)$$

$$\eta = \frac{\text{energy in products}}{\text{total energy input}} \quad (15)$$

$$\Psi = \frac{\text{exergy in products}}{\text{total exergy input}} \quad (16)$$

Table 3: Chemical exergies of substances and mole fraction of constituents of atmospheric air at reference conditions of 25°C and 1 atmosphere

Substance	Formula	Mole fraction	Chemical exergies (kJ/kmol)
Nitrogen	$N_{2(g)}$	0.7565	720
Oxygen	$O_{2(g)}$	0.2035	3,970
Carbon(iv) oxide	$CO_{2(g)}$	0.0003	19,870
Argon	$Ar_{(g)}$	0.0091	11,640
Water	$H_2O_{(g)}$	0.0303	9,500
Water	$H_2O(liq)$	-	900
Hydrogen	$H_{2(g)}$	0.0001	236,100
Carbon(ii) oxide	$CO_{(g)}$	-	275,100
Methane	$CH_{4(g)}$	-	831,650
Ethane	$C_2H_{6(g)}$	-	1,495,840
Propane	$C_3H_{8(g)}$	-	2,154,000
Butane	$C_4H_{10(g)}$	-	2,805,800

Source: (Ohijeagbon *et al.*, 2014; Moran *et al.*, 2011)

Table 4: Specific chemical exergy of material flows in the combustion chamber

Substance	Specific chemical exergy (kJ/kg)
Air	61.32
Water	49.12
Steam	526.33
Flue gases	82.48
Fuel (natural gas)	51809.64

2.1.2 Energy and exergy analysis of Combustion chamber

Figure 2 shows the schematics of the combustion chamber.

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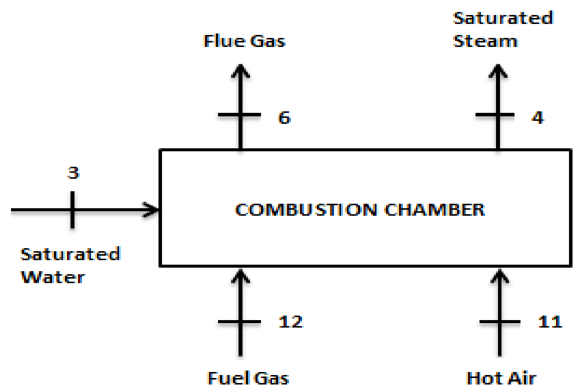

Figure 2: Schematic diagram of combustion chamber

Mass balance is expressed as:

$$\dot{m}_{12} + \dot{m}_{11} + \dot{m}_3 = \dot{m}_6 + \dot{m}_4 \quad (17)$$

Energy input to combustion chamber (E_{icc}):

$$E_{icc} = \dot{m}_{11} \times h_{11} + \dot{m}_3 \times h_3 \times \dot{m}_{12} \times h_{12} \quad (18)$$

where h_{11} = specific enthalpy of air at combustor inlet (kJ/kg), h_3 = specific enthalpy of saturated water at combustor inlet (kJ/kg), h_{12} = specific enthalpy of fuel (kJ/kg) and is equal to the lower heating value of the fuel (Elfeituri & Almotalip, 2017; Rastogi *et al.*, 2018).

Energy output of combustion chamber (E_{occ}):

$$E_{occ} = \dot{m}_6 \times h_6 + \dot{m}_4 \times h_4 \quad (19)$$

The enthalpy of flue gases was obtained using Table A-18, A-20, and A-23 (Cengel & Boles, 2006).

Exergy input to combustion chamber (I_{icc}):

$$I_{icc} = \varepsilon_{11}^{ph} + \varepsilon_{11}^{ch} + \varepsilon_3^{ph} + \varepsilon_3^{ch} + \varepsilon_{12}^{ph} + \varepsilon_{12}^{ch} \quad (20)$$

where ε_{11}^{ph} , ε_3^{ph} and ε_{12}^{ph} are the specific physical exergies of air, saturated water and fuel at combustor inlet while ε_{11}^{ch}, ε_3^{ch} and ε_{12}^{ch} are the specific chemical exergies of air, saturated water and fuel at inlet of combustor.

At near ambient conditions, the specific physical exergy of hydrocarbon fuels is close to zero and the specific exergy is approximately the specific chemical exergy of the fuel (Dincer & Rosen, 2007).

Exergy output of combustion chamber (I_{occ}):

$$I_{occ} = \varepsilon_6^{ph} + \varepsilon_6^{ch} + \varepsilon_4^{ph} + \varepsilon_4^{ch} \quad (21)$$

where ε_6^{ph} and ε_4^{ph} are the specific physical exergies of flue gas and saturated steam at outlet of combustor and ε_6^{ch} and ε_4^{ch} are the specific chemical exergies of flue gas and saturated steam at outlet of combustor.

The specific exergies of water and steam are taken as 49.12kJ/kg and 526.33kJ/kg respectively (Ohijeagbon *et al.*, 2014).

The specific entropy of flue gases is obtained as given by Ohijeagbon *et al.* (2015):

$$S_g = S_a + C_p \ln \frac{T_g}{T_a} \quad (22)$$

where, S_g = specific entropy of flue gases (kJ/kgK), S_a = reference state entropy of air (kJ/kgK), $C_p = C_{pg} \cong C_{pa} \cong$ 1kJ/kg K (C_{pg} and C_{pa} are the specific heat of flue gas and air), T_g = flue gas temperature (K), T_a = reference state temperature of air (K).

2.1.3 Energy and exergy analysis of Superheater

Figure 3 shows the schematics of the superheater.

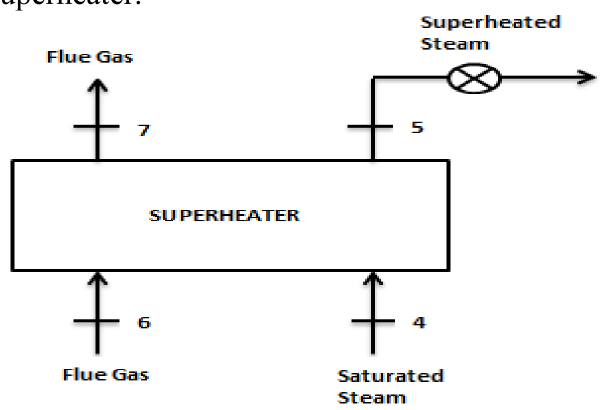

Figure 3: Schematic diagram of superheater

Mass balance: $\dot{m}_6 + \dot{m}_4 = \dot{m}_7 + \dot{m}_5$ (23)

Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

Energy input to superheater (E_{isp}):

$$E_{isp} = \dot{m}_6(h_6 - h_7) \quad (24)$$

Energy output of superheater (E_{osp}):

$$E_{osp} = \dot{m}_4(h_5 - h_4) \quad (25)$$

The Exergy input to superheater (I_{isp}):

$$I_{isp} = \dot{m}_6(h_6 - T_oS_6) - \dot{m}_6(h_7 - T_os_7) \quad (26)$$

Exergy output of superheater (I_{osp}):

$$I_{osp} = \dot{m}_4(h_5 - T_oS_5) - \dot{m}_4(h_4 - T_os_4) \quad (27)$$

2.1.4 Energy and exergy analysis of Economizer

The economizer component is illustrated in Figure 4.

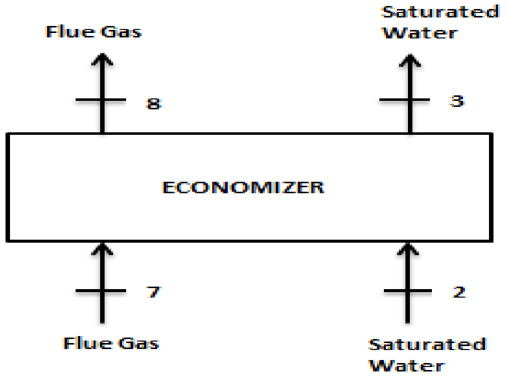

Figure 4: Schematic diagram of economizer

Mass balance: $\dot{m}_7 + \dot{m}_2 = \dot{m}_8 + \dot{m}_3$ (28)

The energy input to economizer (E_{iec}):

$$E_{iec} = \dot{m}_7(h_7 - h_8) \quad (29)$$

Energy output of economizer (E_{oec}):

$$E_{oec} = \dot{m}_2(h_3 - h_2) \quad (30)$$

The Exergy input to Economizer (I_{iec}):

$$I_{iec} = \dot{m}_7(h_7 - T_oS_7) - \dot{m}_7(h_8 - T_oS_8) \quad (31)$$

Exergy output of Economizer (I_{oec}):

$$I_{oec} = \dot{m}_2 (h_3 - T_oS_3) - \dot{m}_2(h_2 - T_oS_2) \quad (32)$$

2.1.5 Energy and exergy analysis of Air preheater

Figure 5 shows the schematics of the preheater.

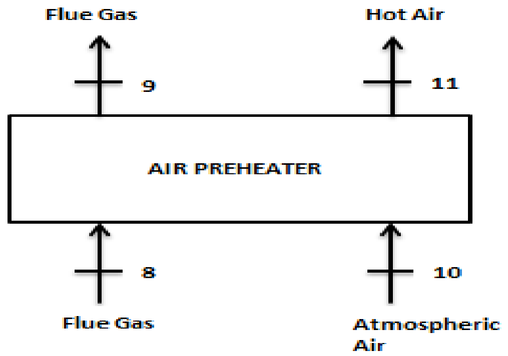

Figure 5: Schematic diagram of air preheater

Mass balance: $\dot{m}_8 + \dot{m}_{10} = \dot{m}_9 + \dot{m}_{11}$ (33)

Energy input to air preheater (E_{iap}):

$$E_{iap} = \dot{m}_8(h_8 - h_9) \quad (34)$$

Energy output of air preheater (E_{oap}):

$$E_{oap} = \dot{m}_{10}(h_{11} - h_{10}) \quad (35)$$

The Exergy input to air preheater (I_{iap}):

$$I_{iap} = \dot{m}_8(h_8 - T_oS_8) - \dot{m}_8(h_9 - T_oS_9) \quad (36)$$

Exergy output of air preheater (I_{oap}):

$$I_{oap} = \dot{m}_{10}(h_{11} - T_oS_{11}) - \dot{m}_{10}(h_{10} - T_oS_{10}) \quad (37)$$

2.2.6 Energy and exergy analysis of Feed Water Pump

Figure 6 shows the schematics of the feed water pump.

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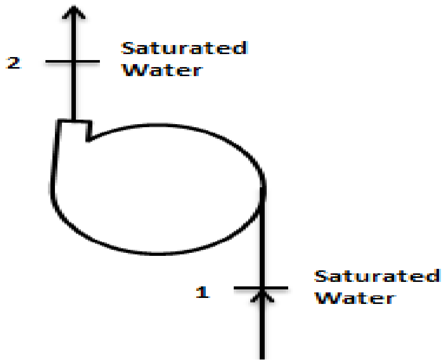

Figure 6: Schematic diagram of feed water pump

Mass balance $\dot{m}_1 = \dot{m}_2$ (38)
The energy loss by the feed water pump is expressed as given by Kaushik *et al*. (2011):

$$E_{lp} = \dot{m}_1(h_1 - h_2) + \dot{W}_P \quad (39)$$

where $\dot{W}_P$ = work transfer in feed water pump (kJ/s).
The energy efficiency of feed water pump is expressed as given by Kaushik *et al*. (2011):

$$\eta_P = 1 - \frac{E_{lp}}{\dot{W}_P} = \frac{\dot{m}_1(h_2 - h_1)}{\dot{W}_P} \quad (40)$$

The exergy destruction in feed water pump (I_{dp}):

$$I_{dp} = \dot{m}_1(\varepsilon_1 - \varepsilon_2) + \dot{W}_P \quad (41)$$

where ε_1 and ε_2 are the specific exergies of saturated water at inlet and outlet of feed water pump.

The exergy efficiency of feed water pump is given by

$$\Psi_P = 1 - \frac{I_{dp}}{\dot{W}_P} = \frac{\dot{m}_1(\varepsilon_2 - \varepsilon_1)}{\dot{W}_P} \quad (42)$$

(Kaushik *et al*., 2011).

2.2.7 Energy and exergy analysis of Deaerator

Figure 7 shows the schematics of the deaerator.

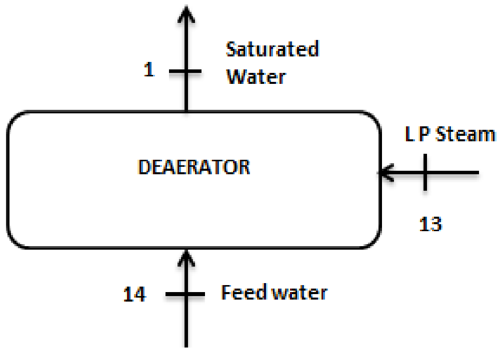

Figure 7: Schematic diagram of deaerator

The mass balance is expressed as:

$$\dot{m}_{14} + \dot{m}_{13} = \dot{m}_1 \quad (43)$$

The energy loss at deaerator (E_{lde}):

$$\dot{m}_{14}h_{14} + \dot{m}_{13}h_{13} = \dot{m}_1 h_1 + E_{lde} \quad (44)$$

The energy efficiency of deaerator is given as:

$$\eta_{de} = \frac{\dot{m}_1 h_1}{\dot{m}_{14}h_{14} + \dot{m}_{13}h_{13}} \quad (45)$$

(Pilankar & Kale, 2016).

Exergy destruction in deaerator (I_{de}):

$$\dot{m}_{14}\varepsilon_{14} + \dot{m}_{13}\varepsilon_{13} = \dot{m}_1\varepsilon_1 + I_{de} \quad (46)$$

where ε_{14} = specific exergy of feed water (kJ/kg), ε_{13}= specific exergy of low-pressure steam (kJ/kg), ε_1= specific exergy of saturated water (kJ/kg).
The exergy efficiency of deaerator (Ψ_{de}):

$$\Psi_{de} = \frac{\dot{m}_1\varepsilon_1}{\dot{m}_{14}\varepsilon_{14} + \dot{m}_{13}\varepsilon_{13}} \quad (47)$$

(Pilankar & Kale, 2016).

2.3 Assumptions

The following assumptions were made and used for analysis:

i. The processes are at steady-state and steady flow with infinitesimal variations in kinetic and potential energies.
ii. Condition for dead state is taken at 101.32 kPa and 25°C.
iii. The mass flow rate is the same for saturated water, steam, and superheated steam.
iv. Ideal gases are assumed for flue gases and air.
v. Combustion is complete.
vi. Air fuel ratio is taken as 17:1.

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3.0 RESULTS AND DISCUSSION

The thermodynamic data of the steam generation unit of a petrochemical olefins plant at specified points in Figure 1 are shown in Table 5, while the results of the energy losses and exergy destruction are tabulated in Table 6. It can be seen from Table 6 that the total exergy destroyed in the system is 27.165MW and the combustion chamber has the largest exergy destruction with a percentage loss of 63.52%, this is in comparison with the work of Jamali et al, (2017) where the combustor accounts for about 55% of the plant loss which could be due to inadequate lagging of the combustor, incomplete combustion and poor preheating of combustion air. Figure 6 shows that exergy destruction is higher than energy loss in each of the components, and from Figure 8; it was noted that energy efficiency is higher than exergy efficiency for each component in the steam generation unit. Exergy destruction in each component of the steam generation unit was presented in Figure 9 and it was observed that the combustion chamber has the largest exergy destruction whereas the feed water pump has the lowest exergy destructed.

Table 5(a): Thermodynamic Data of the Steam Generation Unit at various Points

State	Stream flow	Temperature (°C)	Pressure (bar)
1	Water	109.03	1.40
2	Water	110.12	55.10
3	Water	150.04	52.45
4	Steam	266.24	51.07
5	Steam	400.03	47.00
6	Flue gas	785	1.0130
7	Flue gas	510	1.0125
8	Flue gas	340	1.0123
9	Flue gas	145	1.0118
10	Air	25	1.0132
11	Hot air	229	1.0132
12	Fuel	25	1.0132
13	LPSteam	180.00	0.75
14	Water	56.00	10.00

Table 5(b): Thermodynamic Data of the Steam Generation Unit at various Points

State	Mass flow rate (kg/s)	Specific Volume (m^3/kg)	Specific Enthalpy (kJ/kg)	Specific Entropy (kJ/kgK)
1	19.53	0.00105	458.00	1.4110
2	19.53	0.00130	461.64	1.4119
3	19.53	0.00129	632.15	1.8415
4	19.53	0.03795	2792.44	5.9567
5	19.53	0.06245	3201.40	6.6829
6	30.672		1249.57	2.9623
7	30.672		894.24	2.6613
8	30.672		686.46	2.4166
9	30.672		459.18	2.0334
10	28.968		298.18	1.6953
11	28.968		505.08	2.2236
12	1.704		44965	
13	1.70		2837.80	7.8814
14	17.83		234.84	0.7811

Table 6: Results of Energy losses and Exergy destruction

Component	Energy Loss (kJ/s)	Exergy Destruction (kJ/s)	Energy Loss (%)
Combustor	10734.25	17256.40	60.40
Superheater	2911.69	4386.91	16.38
Economizer	3042.97	3306.60	17.12
Air preheater	977.65	2035.64	5.51
Feed water pump	39.03	44.27	0.21
Deaerator	66.72	135.69	0.38
Total	17772.31	27165.51	

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Volume 5, Issue 2, June 2023
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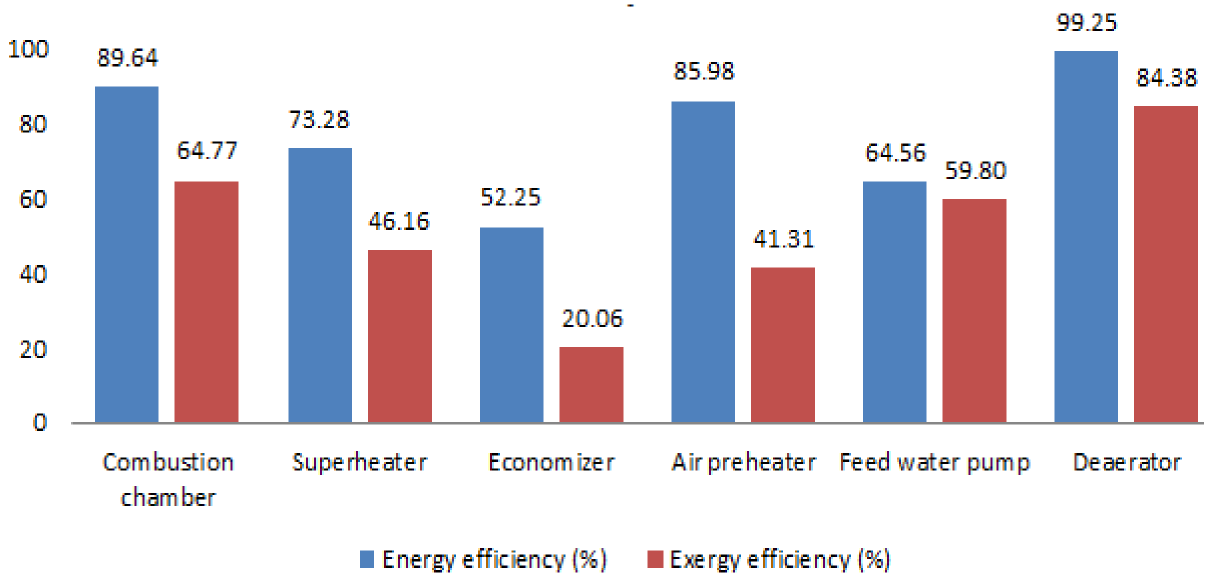

Figure 8: Energy and Exergy efficiencies of the steam generation unit components

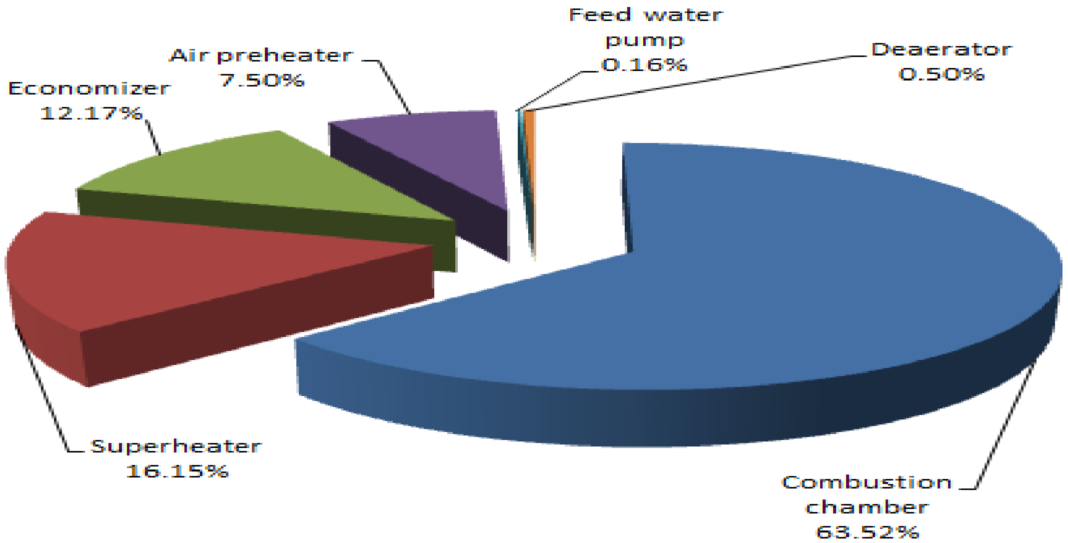

Figure 9: Exergy Destruction of the Steam Generation Unit Components

4.0 CONCLUSION

In this study, an energy and exergy analysis were performed on a steam generation unit of a Petrochemical Olefins Plant on individual components, namely combustion chamber, superheater, economizer, air preheater, feed water pump and deaerator. In the considered unit, it was found as follows:

i. The combustion chamber is the primary component that contributed to the largest energy and exergy losses in comparison to the other components. The energy loss and exergy destruction in the combustion chamber were 10.734MW and 17.256MW, representing 60.40% and 63.52% respectively of the total losses in the steam generation unit.

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ii. Exergy destruction was higher than energy loss across the components.
iii. Exergy efficiency analysis done for each of the components considered was less than corresponding energy efficiency.
iv. The feed pump and deaerator are the most efficient components, indicating effective energy transfer.

From the analysis, it is recommended that the combustion air should be properly preheated and the combustion chamber, adequately lagged with refractory materials to enhance efficient combustion and prevent energy loss thereby improving plant performance. Energy and exergy analysis should be performed periodically to provide plant operators and designers useful information required to improve the performance of the plant. The effect of varying loads on the steam generation unit is recommended for study.

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NOMENCLATURE:
E Energy flow (kJ/s)
I Exergy flow (kJ/s)
H Specific enthalpy (kJ/kg)
$\dot{m}$ Mass flow rate (kg/s)
S Specific entropy (kJ/kgK)
T_o Reference temperature (K)
$\dot{W}$ Work transfer (kJ/s)
T Temperature (°C)
$\bar{R}$ Molar gas constant (kJ/kmol)
ΔG^0 Change in Gibbs function (kJ/kmol)
Q Heat transfer (kJ/s)
y_i Mole fraction of component i
M Molar mass of substance (kg/kmol)
C_p Specific heat at constant pressure (kJ/kgK)

Subscripts
g Flue gas
PD Product
R Reactant
a Air
i Inlet
e Exit
f Fuel
d Destruction
icc Inlet to combustor
occ Outlet of combustor
isp Inlet of superheater
osp Outlet of superheater
iec Inlet of economizer
oec Outlet of economizer
iap Inlet of air preheater
oap Outlet of air preheater
p Feed water pump
lp Losses in feed pump
dp Destruction in feed pump
lde Losses in deaerator

Superscripts
ch Chemical
ph Physical

Abbreviations
LPS Low Pressure Steam
MCR Maximum Circulating Rating
ppb Parts per billion

Chemical Symbols
CH_4 Methane
C_2H_6 Ethane
C_3H_8 Propane
C_4H_{10} Butane
O Oxygen
A_r Argon
C Carbon
H Hydrogen
CO_2 Carbon (IV) oxide
N_2 Nitrogen
H_2O Water vapor (gas)

Greek Symbols
ŋ Energy efficiency (%)
Ψ Exergy efficiency (%)
ε Specific exergy (kJ/kg)
ε^{-ch} Molar chemical exergy (kJ/kmol)

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