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Exergy Analysis of a Steam Boiler Plant in a brewery in Nigeria

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Abstract - In this study, the exergy method was used to evaluate the performance of a 10,000 tonnes/hr oil fired steam boiler plant in a brewery in Nigeria. The exergy losses in the various subsystems of the plant: combustion chamber, mixing region and heat exchanger were calculated based on energy and exergy balance equations. The distribution of the exergy losses in the plant subsystems during the real time plant running conditions has been assessed to locate process irreversibilities. The First and the Second law efficiencies of the plant have also be calculated. Comparison between exergy losses of the subsystems based on the calculated values shows that the maximum exergy losses of 36% occur in the combustion chamber in real time whereas a minimum of 3.51% occur in the mixing region and 33.60% was in the heat exchanger. The average energy and exergy efficiencies recorded were 95.34% and 24.45% respectively. Therefore, exergy losses are particularly high in the subsystems; plant manufacturers must give considerations to measures for enhanced heat transfer, and waste energy recovery.

Keywords: energy efficiency, exergy efficiency, LPFO, irreversibility, steam boiler plant,

1 INTRODUCTION

In the Sub Sahara Africa, Nigeria ranks as the foremost fossil energy producer. The energy mix in the country is dominated by oil which account for about 57%, followed by natural gas (36%) and hydroelectricity (7%) while other sources such as coal, nuclear and renewable energies plays no significant role in the country's energy consumption mix [1]. Sambo [2] reported that the industrial energy consumption in Nigeria is about 12% of the total energy. This position the industrial sectors as a prime target for energy efficiency measures [3], given the fact that energy consumption in the industries, with the associated emissions, is causing local, regional and global environmental problems such as ozone depletion and global warming [4].

In boiler operations, the heat losses that occur through the three major modes of heat transfer is a promising area of increasing boiler efficiency. The various ways by which heat is lost in a boiler include the flue gas losses, radiation, and blow-down [5]. To optimize the operation of a boiler plant, it is necessary to identify inherent areas of energy wastages and find ways to minimize it.

A large number of studies based on exergy analysis have been carried out by many researchers all over the world in various systems applications. Horlock and Young [6] estimated the rational efficiencies of three modern fossil fuel power plants using the exergy method. Rosen, et al [7, 8, and 9] applied exergy analysis to a wide range of processes involved in the production of hydrogen and hydrogen-driven fuels, electrical and thermal power generation, thermal energy storage, and exergy utilization of countries. They also examined the several significant implications of exergy analysis in the fields of environmental impact and economics and found out the merit of exergy analysis over energy analysis. Again, Jin et al [10] analyzed two operating advanced power plants using a methodology of graphical exergy analysis otherwise called 'Grassman diagram'.

In this study, exergy and energy analysis are undertaken in order to quantify the losses inherent in a typical boiler plant operating in tropical conditions of the sub sahara Africa. The work also, in the light of the findings, makes recommendations for design improvement, and waste energy recovery, as a way of influencing energy policies decision, and environmental impact project

2 ANALYSES

2.1 Combustion Analysis

The primary source of thermal energy for combustion in the case-study brewery boiler plant is low Pour Fuel Oil (LPFO). It consists of long carbon chain of order 9-70 [11]. In this context, the composition by mass given by [12] is used for the combustion analysis and the ultimate result analysis is as shown in Table 1.

Table 1: Ultimate Analysis of LPFO.

Constituents	C	H_2	S	O_2	N_2
Mass fraction.	0.86	0.12	0.003	0.012	0.005

Assuming complete combustion, and no dissociation, the ultimate analysis result was used to determine the masses/moles of the reactants and products using the stoichiometric equation (1) below:

$$\frac{0.86}{12}C+\frac{0.12}{1}H+\frac{0.003}{32}S+\frac{0.012}{16}O+\frac{0.005}{14}N+a\left(0.21O_2+0.79N_2\right)\rightarrow$$

$$bCO_2+dH_2O+eSO_2+\left(\frac{0.005}{28}+0.79a\right)N_2 \qquad (1)$$

For real operating systems, achieving complete combustion is never possible; then letting " x " represents excess air (in fractions), the actual combustion equation becomes:

$$\frac{0.86}{12}C+0.12H+\frac{0.003}{32}S+\left[\left(0.21a(1+x)+\frac{0.012}{32}\right)\right]O_2$$

$$+\left[0.79a(1+x)+\frac{0.005}{28}\right)N_2\rightarrow bCO_2+dH_2O+eSO_2$$

$$+0.21axO_2+\left[\frac{0.005}{28}+0.79a(1+x)\right]N_2 \qquad (2)$$

2.2 Exergy Analysis

The boiler plant was divided into three (3) subsystems: The combustion chamber, heat exchanger and the mixing region as in Figure 4 below. The following assumptions were made to ease computation:

- No heat and pressure losses in the system.
- Excess air of 19% over stoichiometric requirement is provided. The choice of 19% excess air follows the recommendation of [13] for an oil-fired boiler.
- Both air and fuel are delivered at atmospheric condition.
- Constant pressure process

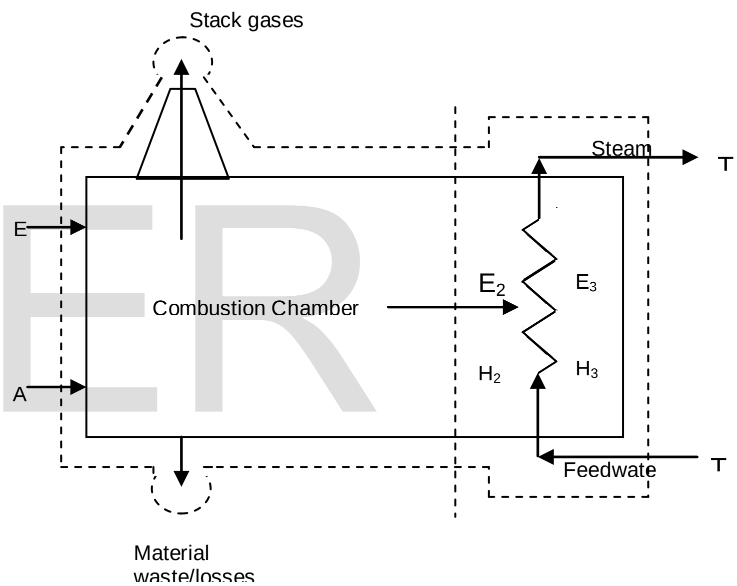

Figure 1: Exergy flow process in a Steam boiler. Source: [14].

The exergy balance on the subsystems is stated as follows [15]:

$$\sum_{in}E_j-\sum_{out}E_i=W_{lost} \qquad (6)$$

Taking into account the chemical and potential exergy components of exergy stream, equation (6) can be expanded as follows

$$\left(\sum_{IN}n_k\varepsilon_{k,j}^{ph}-\sum_{OUT}n_k\varepsilon_{k,i}^{ph}\right)+\left(\sum_{IN}n_k\varepsilon_{k,j}^{ch}-\sum_{OUT}n_k\varepsilon_{k,i}^{ch}\right)=W_{lost} \qquad (7)$$

2.2.1 Irreversibility in the combustion chamber

Assuming environmental state for the fuel and air, the equation for the exergy balance becomes;

$$W_{lost(i)} = E_F - E_2 \tag{8}$$

where E_F is exergy of the fuel and E_2 given by Kotas [15] is the exergy of the products of combustion in that region.

The difference between exergy and lower heating value can be established by the exergy factor of the fuel [16] given as:

$$f_{ex,F} = \frac{E_F}{LHV} \tag{9}$$

In this analysis, the correlation of Szargut et al [17] for the exergy factor of liquid fuels is used.

$$f_{ex,F} = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\frac{S}{C}\left(1 - 2.0628\frac{H}{C}\right) \tag{10}$$

2.2.2 Irreversibility in the heat exchanger (boiling chamber)

In this region of heat exchange, the mass of H_2O, m_s, corresponding to the given operating conditions can be calculated from the energy balance according to Kotas [15] as follows:

$$H_2 - H_3 = m_s\left(h_{s2} - h_{w1}\right) \tag{12}$$

$$W_{lost(ii)} = \left(E_2 - E_3\right) - \left(E_{s2} - E_{w1}\right) \tag{15}$$

The exergy change of a flow stream in the heat exchanger is given by Rosen, et al [18] as:

$$E_{s2} - E_{w1} = m_s\left[\left(h_{s2} - h_{w1}\right) - T_o\left(s_{s2} - s_{w1}\right)\right] \tag{16}$$

Where E_3 the exergy of the flue gase.

2.2.3 Irreversibility in the mixing region (sub-region III)

In this region, all the exergy of the flue gases given by E_3 is lost through dissipation (mixing, cooling, etc) in the environment.

Therefore;

$$W_{lost(iii)} \equiv E_3 \tag{18}$$

2.4. Rational efficiency

The rational efficiency of a steam boiler plant is defined as the ratio of the desired exergy output to the exergy used Cornelissen [19] as;

$$\psi = \frac{\sum Ex_{desired\ output}}{\sum Ex_{used}} \tag{19}$$

Otherwise given by Kotas [20] as:

$$\psi = \frac{E_{s2} - E_{w1}}{E_F} \tag{20}$$

This value may be compared with the conventional boiler efficiency known as

Combustion efficiency

$$\eta_{comb} = m_s \frac{\left(h_{s2} - h_{w1}\right)}{\left(NCV\right)^o} \tag{21}$$

The energy efficiency is defined as:

$$\eta = \frac{output}{input} x100 \tag{22}$$

3. RESULTS AND DISCUSSIONS

3.1 Analysis of fuel and determination of adiabatic temperature

The result of products of combustion analysis, using the ultimate analysis of LPFO (Table 1) is as shown in Table 2 for any given value of x

Table 2: Analysis of Combustion Products.

Products	No of moles per unit mass of fuel	Mass per unit mass of fuel
CO_2	0.07166667	3.15333348
H_2O (g)	0.06	1.08
SO_2	$9.375 * 10^{-5}$	$6 * 10^{-3}$
O_2	$0.101385419x$	$3.244333408x$
N_2	$1.7857 * 10^{-4} + ($	$0.005 + 10.67926 * (1 + x)$
Total (n_p)	$0.51334128 + 0.482787709x$	$14.92359348 + 13.92359341x$

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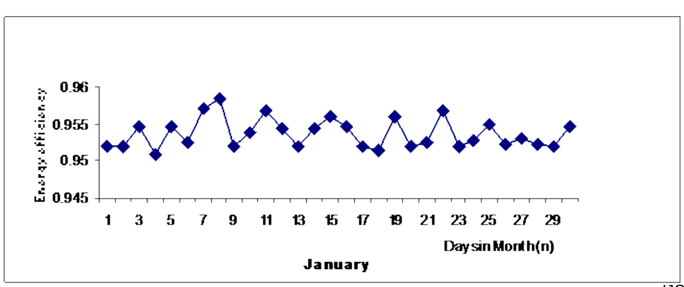
The adiabatic temperature of 1873^{o} C was obtained using the Engineering Equations Solver (EES) software [21] at $x(=0.19)$. Microsoft Excel Software was also used to solve the developed equations at different exhaust temperature of the flue gas collected for a period of one year 2009 for this analysis.

3.2 Energy and exergy efficiency relations

3.2.1. Relations with exhaust temperature

The plots of energy and exergy efficiency against days of the month (exhaust temperatures) in figures 3 and 4 taking January and November for example show that the energy efficiency are always higher than the exergy efficiency. This is attributed to the fact that energy is always conserved while entropy is not. However, for enhancing general plant performance, taking decisions dependent on only energy based performance results cannot be healthy and reliable. For example, considering the values of energy and exergy efficiencies in the first day of January which is respectively 0.952 and 0.27, it is clearly seen that energy efficiency is considerably high; its exergetic value (in other words its quality) is significantly low because of unavoidable losses in thermal systems due to entropy generated. Using energy efficiency alone which is higher for the performance evaluation may be misleading because the lower exergy efficiency value gives the indication that only 27% of the supplied exergy was useful while about 63% was lost in the process. Thus, the plant is never at its best as indicated by the higher energy efficiency value.



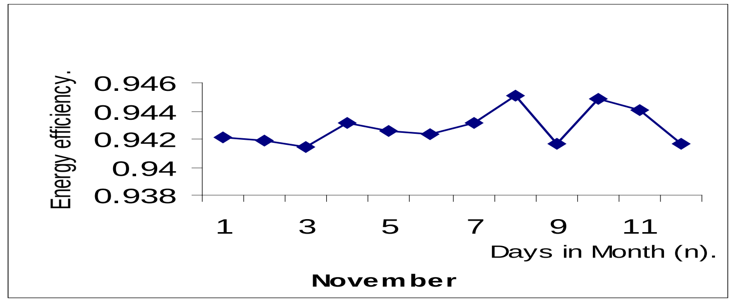
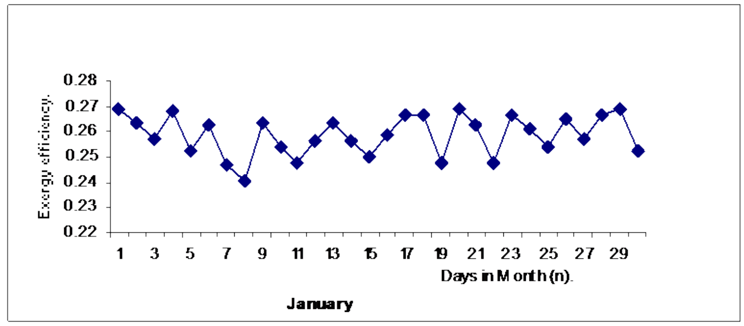


Figure 3: Energy efficiency Vs Days in the Month



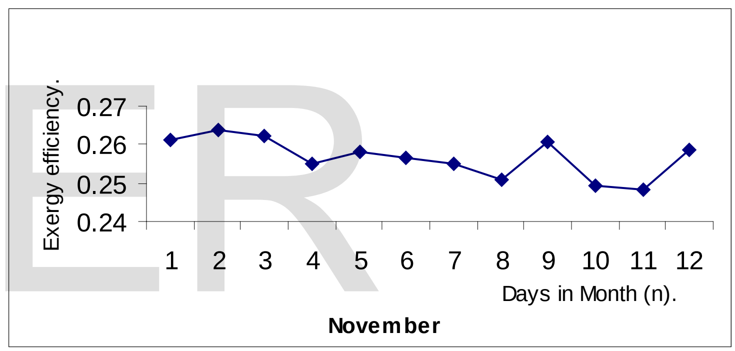


Figure 4: Exergy efficiency Vs Days in the Month.

3.2.2. Relations with steam temperature

The plot of figures 5 and 6 of energy/ exergy efficiency against steam temperatures is analogous to the results of figures 3 and 4. In the plots, while the exergy efficiencies increase with steam temperatures, the energy efficiencies increase. This equally shows that exergy efficiency is the true measure of the system performance as already interpreted in Figures 3 and 4 above.

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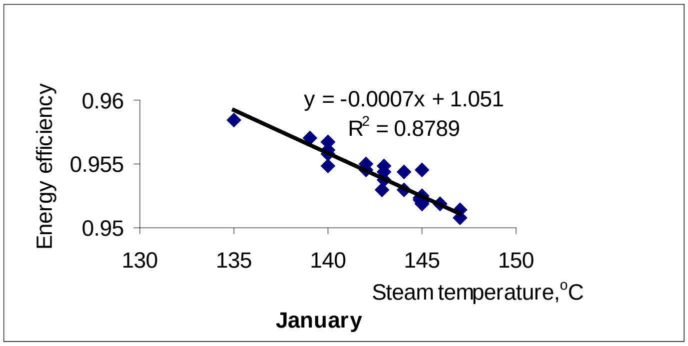


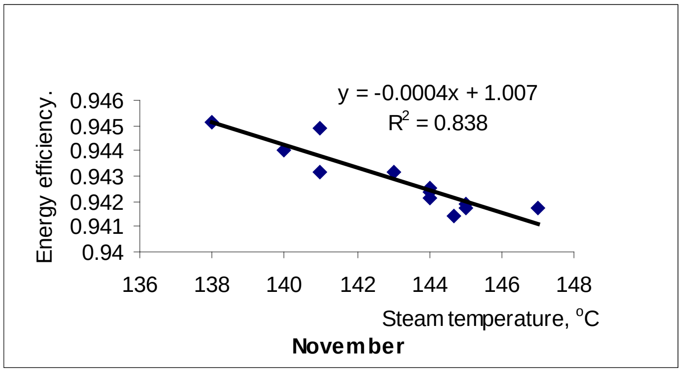
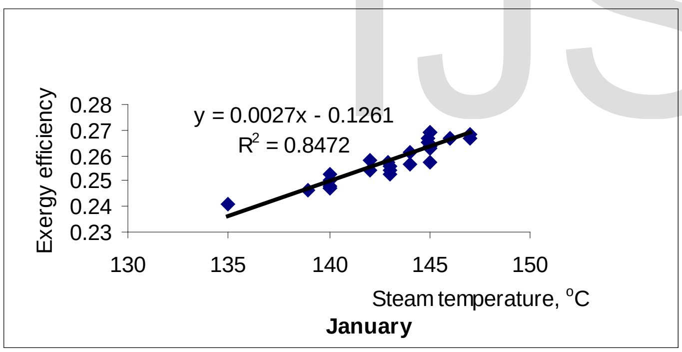


Figure 5: *Energy efficiency Vs Steam temperature*



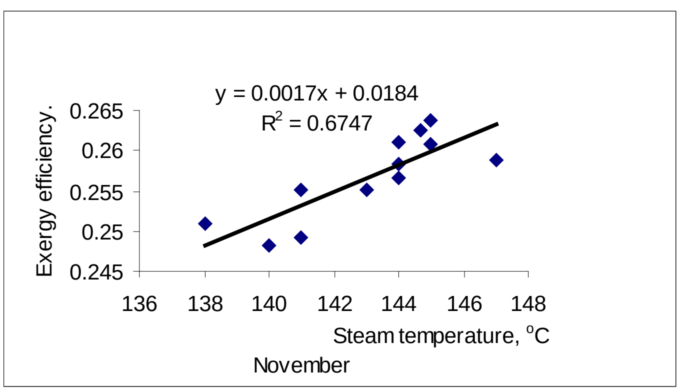


Figure 6: Exergy efficiency Vs Steam temperature.

3.3. The Grassman diagram (exergy flows)

Figure 7 shows the exergy destruction in each sub-region in percentages (combustion chamber, heat exchanger and mixing region). This can help one to identify regions where system performance can be increased through services, redesign or modifications to increase its efficiency while reducing the degree of irreversibilities. It can be noted that about 36% exergy loss occurred in the combustion chamber, 34-35% at the heat exchanger and an infinitesimal loss at the mixing region.

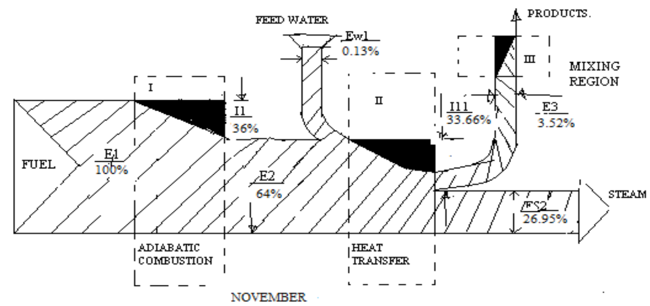


Figure 7: Grassman diagram (exergy flow) for month of November.

4. CONCLUSIONS AND RECOMMENDATIONS

An exergy analysis was performed on the LPFO fired boiler at the Ama brewery, and the energy losses and the exergy destructions of the plant sub-regions were calculated. Exergy analysis results show that the exergy loss in the entire systems was over 74%. Out of this, 36% of the exergy loss occurred in the adiabatic combustion chamber of the plant. This may be due to the irreversibility inherent in the combustion processes, heat loss, and incomplete combustion. Over 34.24% of the total exergy losses occurred in the heat exchanger of the plant. This is due to the inherently irreversible nature of heat transfer processes, and may be also connected to fouling and soot deposits in the component.

The least exergy loss of 3.49% occurred in the mixing region. This is quite small but can significantly be used to pre-heat air before combustion. This can be achieved by incorporating a

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heat recovery system in the plant, thereby increasing efficiency of combustion which invariably reduces energy utilization for sustainable development.

This study pinpoints that the heat exchanger and the combustion chamber requires necessary modifications to reduce their exergy destructions so that the plant performance can be improved. The exergy efficiency of the plant is within the range 24-25% which conforms to that in the literature for process heating [22] whereas the overall first law efficiency of the plant is between 94% and 96%.

The calculation of energy efficiency can often be misleading as it does not provide a measure of ideality. In addition, losses of energy can be large while it is thermodynamically insignificant due to low quality. However, exergy-based efficiency and losses provide measures of approach to ideality. The calculated exergy in the boiler system is quite low. This indicates that there are opportunities to improve the performance of the plant especially in the combustion chamber and heat exchanger with high irreversibility. However, it has to be noted that part of this irreversibility cannot be avoided due to physical, technological and economic constraints limit of this study.

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