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Energy Analysis of Industrial Boilers: A Case Study of the Coca-Cola Challawa Plant in Kano, Nigeria

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Abstract

The industrial sector heavily relies on boiler systems for various operations, making them significant energy consumers. As a result, it becomes imperative to conduct comprehensive analyses to assess their efficiency and identify areas of energy loss. This study employs energy analysis based on the first law of thermodynamics to precisely determine the efficiency and the primary contributors to energy losses within the boiler system. The research encompasses a detailed examination of both the combustion chamber and the steam production chamber of the boiler. The analysis reveals that the energy efficiency of the combustion chamber stands at an impressive 82%, signifying its effectiveness in converting fuel into usable energy. Conversely, the steam production chamber operates at a slightly lower efficiency of 69%. Taking into account both components, the overall energy efficiency of the entire boiler system is calculated at 71%. This consolidated figure serves as a critical benchmark for assessing the system's performance and initiating potential improvements. Among the key findings, it is evident that preheating the feed water using the flue gas emerges as the most promising strategy to minimize energy losses. This conclusion underscores the importance of implementing energy-efficient practices to enhance the overall productivity of industrial boiler systems. The energy efficiency and losses within an industrial boiler system, offer valuable insights into its performance. The research emphasizes the importance of energy-saving techniques, such as preheating feed water, to enhance efficiency and reduce losses, adopting a more sustainable and cost-effective in the industrial sector.

Keywords: Combustor, Stream, Heat exchanger, Heat loss

INTRODUCTION

In closed vessels known as steam boilers, fuel is burned to produce steam from water (Rajput 2006). The steam can also be used in numerous other production processes. Due to its great importance in the modern industrial world, it is essential to understand how to optimize energy use in steam boilers. Policymakers cannot ignore the implications of the growing energy demand from emerging economies compared to the depletion of energy resources, the rising price of fossil fuels, and the significant environmental damage associated with their use. This will exacerbate energy challenges in the future. (Tonon et al 2006) Consequently, there is a need for improved energy use.

The industrial sector, known for its substantial energy consumption, has recently gathered significant attention in numerous projects and research endeavors. According to a report by Abdelaziz et al., (2011), the industrial sector consumes approximately 37% of the world's total delivered energy. The share of energy consumption within the industrial sector can fluctuate between 30% and 70%, as emphasized by Madlool et al., (2011).

Major industrial energy consumers allocate significant portions of their fossil fuel consumption towards steam production. Industries such as food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%) heavily rely on steam according to Einstein et al., (2001). Since industrial systems vary greatly but often share substantial steam systems, improving their efficiency becomes a valuable target for energy-saving measures.

Efficiency in boilers plays a crucial role in achieving energy savings related to heating. Maximizing heat transfer to water and minimizing heat losses within the boiler are vital objectives. Heat losses in boilers can occur through various means, including hot flue gas losses, radiation losses, and blow-down losses in the case of steam boilers ERC (2004).

Identifying potential energy wastage areas is essential for optimizing boiler plant operations.

A significant amount of energy is lost through flue gases since not all the heat produced by burning fuel can be transferred to water or steam in the boiler. As flue gas temperatures typically range from 150 to 250℃ upon leaving the boiler, around 10-30% of the heat energy is lost through this channel. Recovering this lost heat from flue gases can lead to substantial energy savings Jayamaha (2008).

These findings highlight the significant potential for boiler energy savings by minimizing losses. Despite being a longstanding technology, boilers have reached a plateau in terms of efficiency, making any marginal increase in efficiency extremely challenging to achieve Sonia et al., (2007).

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The conventional use of the First Law of Thermodynamics for energy analysis cannot consider the quality aspect of energy. While commonly used, energy efficiency can be misleading as it doesn't always indicate how closely a system's performance approaches ideal conditions. Often, the thermodynamic losses within a system, which contribute to deviations from ideality, are not accurately identified and assessed through energy analysis.

The Nigerian Bottling Company (NBC) Limited was established in November 1951 as a subsidiary of the A.G Levant's Group, with the exclusive franchise to bottle and sell Coca-Cola products in Nigeria. In 1953, Coca-Cola production commenced at a bottling facility in Ebute-Metta, Lagos State. In the same year, NBC opened its first bottling plant in Apapa.

By 1960, NBC had surpassed one million cases per year. In 1961, the company commissioned its second bottling facility in Ibadan, Oyo State, and expanded its operations rapidly over the following years. Today, NBC operates 13 facilities and 64 depots across the country, with the Kano plant being one of them.

The Coca-Cola plant Challawa Kano has identified the rising cost due to energy being consumed in the plant, and as such, evaluation of this unit is necessary. This is where energy analyses come in. However, the existence of inefficiency in Challawa Plant Kano's boiler system comes to demand deeper attention. Energy assessments seem to be a useful tool for addressing the effects of the boiler's use of energy resources as well as for advancing the system's goal of more effective energy resource usage.

Boiler

A boiler is an enclosed vessel that provides a means for combustion heat to be transferred into water until it becomes heated water or steam. The hot water or steam under pressure is then usable for transferring the heat to a process. Water is a useful and cheap medium for transferring heat to a process. When water is boiled into steam its volume increases about 1,600 times, producing a force that is almost as explosive as gunpowder. This causes the boiler to be extremely dangerous equipment that must be treated with utmost care. The process of heating a liquid until it reaches its gaseous state is called evaporation Kitto and Stultz (2005).

Theoretical fundamentals of boiler burner

Burner

Boiler burners are the functional components of boilers that provide the heat input by combustion of fossil fuel, including natural gas, with air or oxygen. They are available either as part of the boiler package from the manufacturer, as stand-alone products for custom installations, or as replacement products. Plate 1. Shows the picture of the burner and Figure 1. Shows the schematic of a diagram of the burner.

Plat 1: Burner [11] (Kitto and Stultz, 2005).

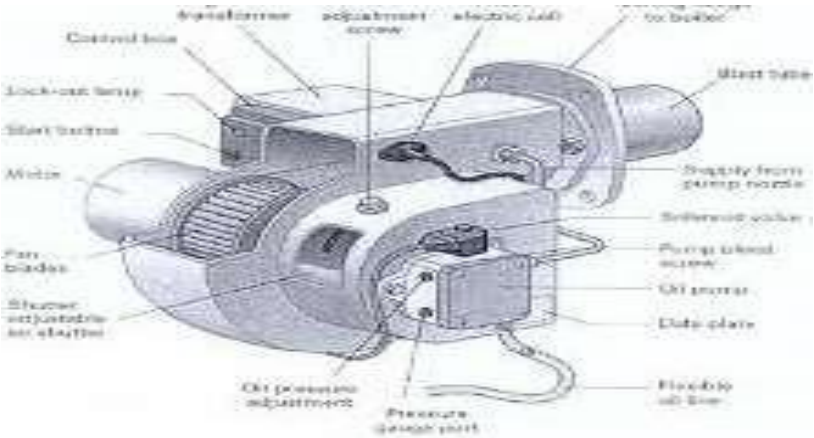

Figure 1: Schematic diagram of the burner (Combustor) Saidur et al, (2011)

The boiler has lots of types based on its designed function, fuel use, and by tube type.

Types of Industrial Boilers According to Function

Boilers can be designed for two functions: to produce hot water or steam. Industrial boilers will always be used for steam production, which is a vital resource for different industrial applications such as turning turbines for power generation and heating kilns in cement plants. Hot water boilers do not factor into industrial plants. They are typically used in domestic or commercial applications such as car washes or laundromats to supply hot water.

Classes of Industrial Boilers by Tube Type

(a) Fire Tube Boilers

Fire tube boilers take hot gases from the burner (Combustor) and pass them through tubes that run through a water-filled drum. This transfers heat from the gases to the water to generate steam. This simple design makes fire tube boilers relatively inexpensive to purchase and easy to operate. Fire-tube boilers have relatively small steam capacities and generate low to medium degrees of pressure as shown in figure 2. They can be used for steam rates up to roughly 26,000 pounds per hour.

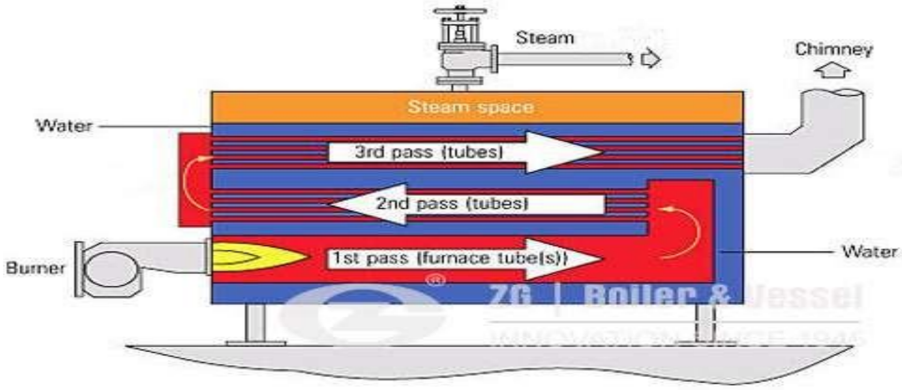

Figure 2: Fire Tube Boiler Kitto and Stultz (2005)

(b) Water Tube Boiler

Water tube boilers reverse the basic configuration of fire-tube boilers, routing water through their tubes and surrounding those tubes with a drum filled with hot gases or heating elements to produce steam. This design makes water tube boilers more thermally efficient than fire tube boilers. It also makes them more difficult to build (and therefore more expensive). Figure 3(a) and (a) shows the water tube boiler.

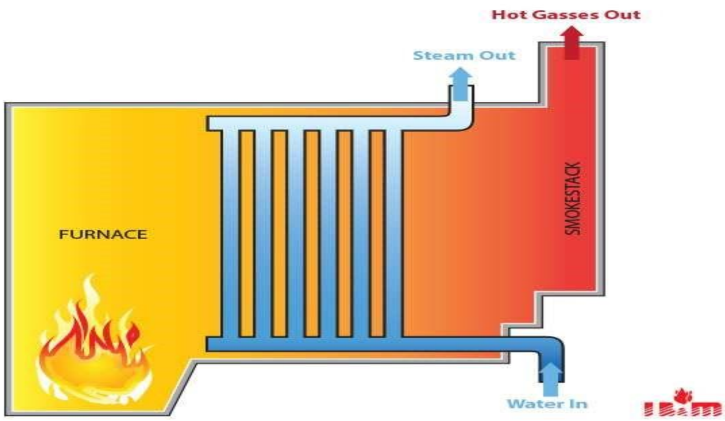

Figure 3: (a) Water Tube Boiler (Ke-Wei 2023)

Figure 3: (b) Water Tube Boiler (KeWei and Horg-Wen 2023)

Industrial Boilers by Fuel Type

Many classify, boilers according to the fuel they burn. The possibilities are quite diverse.

(a) Coal: Most industrial boilers burn pulverized coal, which fires more efficiently thancoal clumps.

(b) Biomass: Biomass encompasses all types of burnable plant material, such as wood chips, sugar cane husks, and even wooden construction debris.

(c) Gas: Gas-fired boilers burn natural gas, which can be a mix of methane, ethane,propane, butane, or pentane.

(d) Oil: Boilers that burn gasoline, diesel, or other petroleum-based fluids are classifiedas oil-fired boilers.

Energy Analysis

Energy analysis is analyzing the industrial boiler according to the first law of thermodynamics.

(a) Energy

Energy is the ability or capability to produce motion, work, force, and change in shape and form Vijay and Mandhata (2015).

(a) Energy Efficiency

$$Efficiency = \frac{Desired\ output}{Required\ input} \quad (1)$$

(b) Energy Analysis (first law) on combustor

The combustor in a boiler is usually well insulated which causes heat dissipation to the surrounding almost zero. It has no involvement to do any kind of work (w= 0). Also, the kinetic and potential energies of the fluid streams are negligible. Then only the total energies of the incoming streams and outgoing mixture remain for analysis according to Saidur et al., (2011)

(C) First law of thermodynamics

The change in internal energy of a system is the sum of the sum of all the energy inputs and outputs to and from the system. This is expressed mathematically as:

$$E_{in} - E_{out} = \frac{dE_{system}}{dt} = 0 \quad (2)$$

$$E_{in} = E_{out} \quad (3)$$

$$E_{in} = m_f h_f = m_a h_a \quad (4)$$

$$E_{out} = m_p h_p \quad (5)$$

$$m_f h_f + m_a h_a - m_p m_p = 0 \quad (6)$$

For determining the heat input of the combustor; Qc:

$$m_f m_f + m_a h_a = m_p h_p \quad (7)$$

Where E_{in} = energy in, E_{out} = energy out h_f = specific enthalpy of fuel, KJ/Kg, h_a = specific enthalpy of air, KJ/kg, h_p = specific enthalpy of hot products of combustion, kJ/kg, m_f = mass of the fuel, kg/s, m_a = mass of air, kg/s, m_p= mass of the product, kg/s, Q_c *is* the heat input of the combustor:

From the mass production m_p:

$$m_a + m_f = m_p \quad (8)$$

For enthalpy of the product h_p:

$$h_p = \frac{m_f h_f + m_a h_a}{m_p} \quad (9)$$

For the energy efficiency of the combustor (η_c), $m_a h_a$ are negligible :

$$n_c = \frac{m_p h_p}{m_f h_f} \quad (10)$$

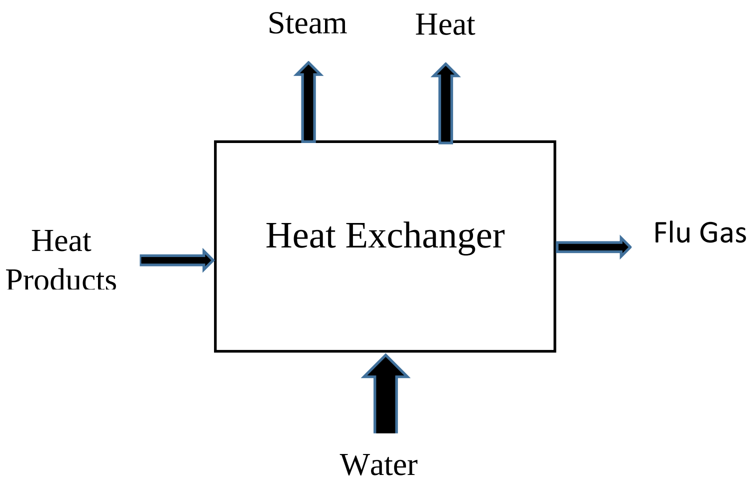

Figure 4: Schematic diagram of heat energy flow through a heat exchanger

Taking mass flow rate for heat products as m_p, mass flow rate for flue gas as m_g, mass flow rate for water as m_w, and mass flow rate for steam as m_s, and since there is no mixing in the heat exchanger, it can be assumed that $m_p = m_g = m_H$ and $m_w = m_s = m_c$, and also $h_p, h_g, h_w, and\ h_s$, are enthalpy of products, flue gas, water, and steam respectively. Figure 2.3 shows a schematic diagram of heat energy flow through the heat exchanger and with these assumptions, energy balance can be expressed as:

$$E_{in} = E_{out} + \frac{dE_{sysem}}{dt} = 0 \quad (11)$$

$$E_{in} = m_p h_p + m_w h_w$$

$$E_{out} = m_g h_g + h_s m_s$$

$$((m_p h_p + m_w h_w) - (m_g h_g + h_s m_s = Q_h \quad (12)$$

For determining heat loss in the heat exchanger, Q_h

$$m_p(h_p - h_g) - m_s(h_s - h_w) = Q_h \quad (13)$$

Enthalpies of most gases used in combustion calculations can be curve-fitted by the simple second-order equation Kitto and Stultz (2005).

For enthalpy of flue gas, h_g

$$h = aT^2 + bT + c \quad (14)$$

where, h = enthalpy in kJ/kg, T = temperature in degree, in degree K a, b and c are coefficients with the following value for T(0-500) given as:

$$a = 1.683x10^{-5}, b = 0.233, c = -18.03$$

The efficiency of the heat exchanger, η_H

$$\eta_H = \frac{m_{s(h_s - h_w)}}{m_p(h_p - h_g)} \quad (15)$$

The overall energy efficiency of the boiler is, η_B:

(a) $$\eta_B = \frac{m_{s(h_s - h_w)}}{m_f h_f} \quad (16)$$

METHODS

The various equipment were used to measure variables such as pressure, fuel flow rate, steam temperature, and flue gas temperature, which are the parameters required for the analyses I. Pressure measurement: the pressure measurement of the steam flow in the boiler system is one of the essential parameters to be measured in steam production. A pressure gauge is installed on the uppermost of the boiler to measure the steam pressure; it is measured in kg/cm2 and mPa as shown in plate 1. II. Fuel flow meter: this device measured the fuel flow rate of the fuel in kg/hr. It is being installed along the fuel pipeline and the picture is shown in plate 2. III. Display monitor screen: it displayed the measured readings of steam pressure, steam temperature, flue gas temperature, feed water temperature and pressure as shown in plate 3.

Plate 1.0: Pressure Gauge

Plate 2.0: Fuel flow meter

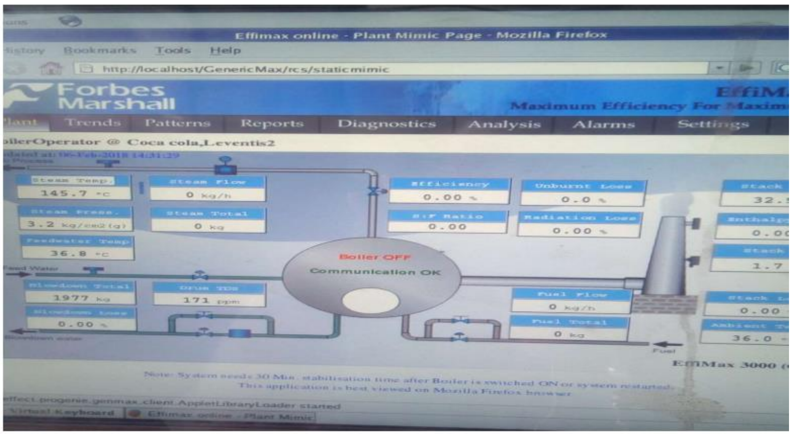

Plate 3.0: Display monitor screen

Plate 4.0: front view of the boiler

RESULTS

Data Collection

Data shown in Tables 1, 2, and 3 were obtained from the Nigerian Bottling Company Challawa Kano was used for energy analyses

Table 1: Day 1, Temperatures and Masses of the Material Stream of the Boiler

Time	Feed Temp. Tw (℃)	Steam Temp Ts (℃)	Flue Gas Temp. Tg (℃)	Mass flow rate of Fuel mf (kg/s)	Mass flow rate of the Steam ms (kg/s)	Mass flow rate of the Air ma (kg/s)
8am	81	140	217	0.016	0.2778	0.2
9am	81	140	217	0.016	0.2778	0.2
10am	81	140	217	0.0157	0.2778	0.2
11am	81	139	217	0.0165	0.28	0.2
12pm	81	139	218	0.0163	0.281	0.2
1pm	81	138	216	0.0163	0.2808	0.2
2pm	81	138	216	0.0162	0.28	0.2
3pm	80	134	215	0.016	0.28	0.2
4pm	80	134	215	0.0158	0.279	0.2
5pm	80	134	215	0.0158	0.279	0.2
6pm	80	134	215	0.0158	0.279	0.2
7pm	80	134	215	0.0161	0.28	0.2
8pm	80	134	215	0.016	0.279	0.2
9pm	80	134	215	0.016	0.279	0.2
10pm	78	133	213	0.0162	0.28	0.2
11pm	78	134	213	0.0163	0.281	0.2
12am	78	135	213	0.0157	0.281	0.2
1am	81	138	218	0.0158	0.28	0.2
2am	81	148	234	0.016	0.2778	0.2
3am	72	132	231	0.0162	0.2776	0.2
4am	72	141	118	0.016	0.279	0.2

able 2: Day 2, Temperatures and Masses of the Material Stream of the Boiler

Time	Feed Temp TW (℃)	Steam Temp Ts (℃)	Flue Gas Temp. Tg (℃)	Mass flow rate of Fuel mf (kg/s)	Mass flow rate of the Steam ms (kg/s)	Mass flow rate of the Air ma (kg/s)
8am	79	139	216	0.016	0.2778	0.2
9am	79	135	216	0.016	0.2778	0.2
10am	79	135	215	0.0157	0.2778	0.2
11am	79	139	217	0.0165	0.28	0.2
12pm	79	139	217	0.0163	0.281	0.2
1pm	79	138	215	0.0163	0.2808	0.2
2pm	79	135	213	0.0162	0.28	0.2
3pm	78	134	213	0.016	0.28	0.2
4pm	78	134	213	0.0158	0.279	0.2
5pm	78	134	213	0.0158	0.279	0.2
6pm	78	134	214	0.0158	0.279	0.2
7pm	78	134	214	0.0161	0.28	0.2
8pm	77	134	214	0.016	0.279	0.2
9pm	77	134	212	0.016	0.279	0.2
10pm	78	133	213	0.0162	0.28	0.2
11pm	78	134	214	0.0163	0.281	0.2
12am	78	135	214	0.0157	0.281	0.2
1am	81	138	218	0.0158	0.28	0.2
2am	81	135	211	0.016	0.2778	0.2
3am	72	132	212	0.0162	0.2776	0.2
4am	72	132	211	0.016	0.279	0.2

Table 3: Temperatures and Masses of the Material Stream of the Boiler

Time	Feed Temp. TW (℃)	Steam Temp. Ts (℃)	Flue Gas Temp. Tg (℃)	Mass flow rate of Fuel mf (kg/s)	Mass flow rate of the Steam ms (kg/s)	Mass flow rate of the Air ma (kg/s)
8am	82	140	216	0.016	0.2778	0.2
9am	82	145	217	0.016	0.2778	0.2
10am	81	140	217	0.0157	0.2778	0.2
11am	81	140	215	0.0165	0.28	0.2
12pm	83	145	218	0.0163	0.281	0.2
1pm	83	145	216	0.0163	0.2808	0.2
2pm	83	145	216	0.0162	0.28	0.2
3pm	82	140	215	0.016	0.28	0.2
4pm	80	139	215	0.0158	0.279	0.2
5pm	81	139	215	0.0158	0.279	0.2
6pm	81	138	215	0.0158	0.279	0.2
7pm	81	138	214	0.0161	0.28	0.2
8pm	80	137	214	0.016	0.279	0.2
9pm	80	137	214	0.016	0.279	0.2
10pm	80	137	213	0.0162	0.28	0.2
11pm	80	137	213	0.0163	0.281	0.2
12am	79	135	213	0.0157	0.281	0.2
1am	81	138	218	0.0158	0.28	0.2
2am	81	139	230	0.016	0.2778	0.2
3am	77	135	233	0.0162	0.2776	0.2
4am	78	132	220	0.016	0.279	0.2

Energy Analyses using Excel Spread Sheet

The energy analyses of the Challawa plant were carried out using an Excel spreadsheet with the data obtained from the plant. The process variables obtained from the plant were inputted in the software, these include feed water temperature, steam temperature, flue gas temperature, mass flow rate of steam, and mass flow rate of fuel. The value of these variables obtained from the measuring device, the flue gas thermometer the fuel flow meter

Energy Analyses

Energy analyses according to the first law of thermodynamics state that the quantity of Incoming energy into the boiler system is equal to the exiting energy out of the system. The Process of analyzing the energy efficiency of the boiler and energy loss, then the energy Inputs and outputs have been determined using the data obtained from the plant. To evaluate the energy efficiency of the system, the boiler was divided into a heat exchanger and a combustor.

(a) Energy Analysis on Combustor

In this analysis, the efficiency and heat input of the combustor were determined by inputting the data obtained into the Excel spreadsheet, based on the assumption that it does not interact with the environment, has no involvement in any work, kinetic and potential energies of the fluid streams are negligible. The efficiency and heat input were automatically calculated from the spreadsheet. The calculations shown here are sample calculations and at the end, similar calculations were carried out for the remaining data. The parameters involved in computing the efficiency and heat inputs are:

m_f = Mass flow rate of the fuel (kJ/s)

m_a = Mass flow rate of the air (kJ/s)

h_f = Enthalpy of the fuel (kJ/kg)

h_a = Enthalpy of the air (kJ/kg), at a temperature 298K

For determining the heat input of the combustor; Qc:

From equation 7:

$$m_f h_f + m_a h_a = m_p h_p$$

For the energy efficiency of the combustor, η_C;

The steady-state efficiency of combustion is the ratio of the useful heat delivered to the process to the heat content of the fuel [14]. The combustion efficiency

is given by $\eta_C = \frac{(1+AAF)\times CP \times (T_C - T_G)}{HHV}$ (17)

Where,

CP = specific heat of fuel at ambient temperature of products of combustion, Cp = 1.961 kJ/kg-K

HHV = Gross or high heating value of fuel (kJ/kg), from table 3

AAF (diesel) = Actual air fuel ratio 17 [15]

TC = Combustion temperature,

Tg = Flue gas temperature, Tg = 217℃ from data table 2

The combustion temperature is calculated as [14].

$$T_C = T_{Ca} + \frac{hr}{C_P \times (1+A)}$$

Where,

Tca = temperature of the combustion air before entering the burner. To maintain satisfactory

working conditions for personnel around a boiler, a cold face temperature or boiler room at

ambient temperature Tca = 57^0 C Kitto and Stultz (2005). hr = heat of the reaction (hr = LHV, lower heating value of the fuel)

CP = specific heat of the fuel, Cp =1.9612 kJ/kg K.

AAF = actual air fuel ratio for diesel, AAF = 17.

Using the value of combustion temperature to determine the efficiency of the combustor;

$$\eta_C = \frac{(1+AAF)\times CP \times (T_C - T_G)}{HHV} \quad (18)$$

(b) Energy Analysis on Heat Exchanger

The energy analysis on the heat exchanger involved the heat exchanged between the two moving streams, the flue gas and water result in generating the steam. To analyze the heat exchanger according to the first law of thermodynamics, to obtain the efficiency, heat out, and heat loss. Since there is no mixing in the heat exchanger, it assumes that the mass flow rate of the product is equal to the mass flow rate of the flue gas and the mass flow rate of the steam is equal to the mass flow rate of water. The values of the temperature of steam, feed water temperature, flue gas temperature, and mass flow rate of steam obtained from the monitor screen with their corresponding values of enthalpy from the steam table being inputted in the software Excel spreadsheet to determine the heat loss of the heat exchanger. These are the parameters used:

m_S = Mass flow rate of the steam (kJ/s)

h_W = Enthalpy of the water (kJ/kg) = 343.3 kJ/kg from the steam table at 81℃

h_S = Enthalpy of the steam (kJ/kg) = 2142.9 kJ/kg from the steam table

at 140℃ from table 3

m_P = Mass flow rate of the product (kJ/s)

h_P = Enthalpy of the product (kJ/kg)

h_g = Enthalpy of the flue gas (kJ/kg) Vijay et al., (2015)

To determine heat loss in the heat exchanger, Qh:

From equation 12:

$m_P\ (h_P - h_g) - m_S\ (h_S - h_W\ ) = \text{Qh}$

To determine the m_P , from equation. 8:

$m_a + m_f = m_P$

m_a and m_f values from table 3.0

For h_p using equation 9:

$h_P = \frac{m_f h_f\ + m_a h_a}{m_P}$

For enthalpy of flue gas, h_g:

From equation 14:

$$h_g = aT^2g + bTg + c$$

Where,

h_g = enthalpy in Btu/lb

Tg = temperature in degrees°F, 217℃ from table 3 is converted to 490K and then to 422.33°F.

The value of enthalpy of water h_w and enthalpy of steam h_S from the steam table (Rogers and Mayhew) and their corresponding value of T_W and T_S data from table 3 are used to calculate the efficiency of heat exchanger.

Therefore, Q_h is calculated as:

Efficiency of heat exchanger ηh is calculated using equation 15:

$$\eta h = \frac{m_S\,(h_S - h_w)}{m_P\,(h_P - h_g)}$$

The overall energy efficiency of the boiler is, ηB is calculated using equation 16:

$$\eta B = \frac{m_S\,(h_S - h_w)}{m_f\,h_f}$$

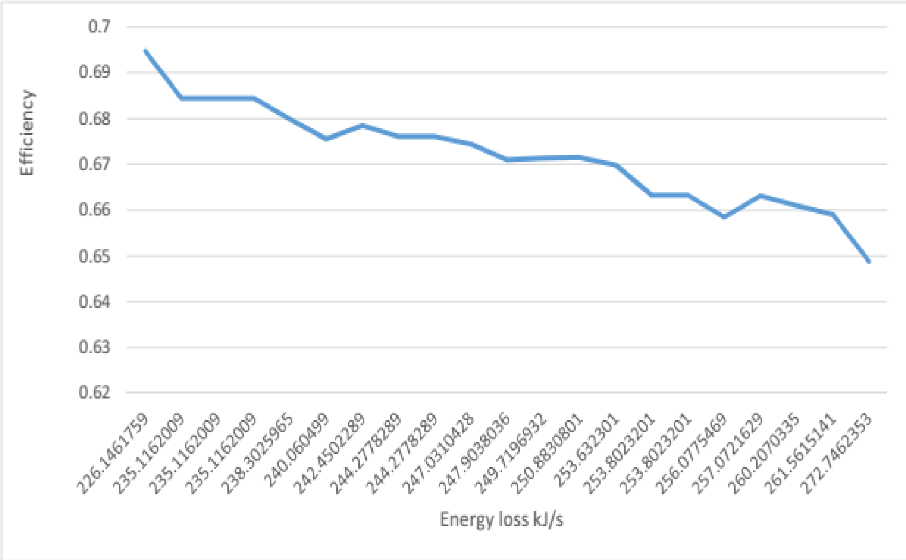

Figure 5: Efficiency of heat exchanger against energy loss

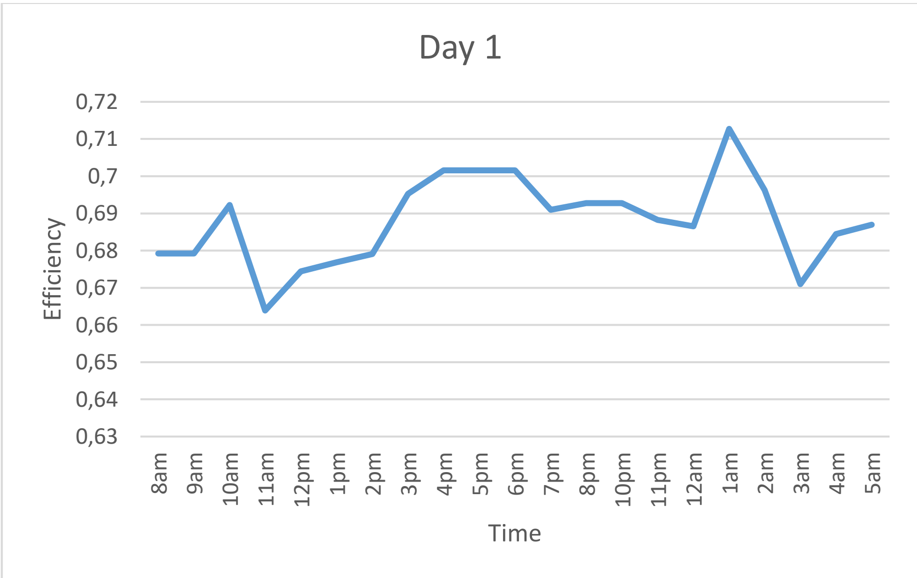

Figure 6: Efficiency of overall boiler against time, day 1

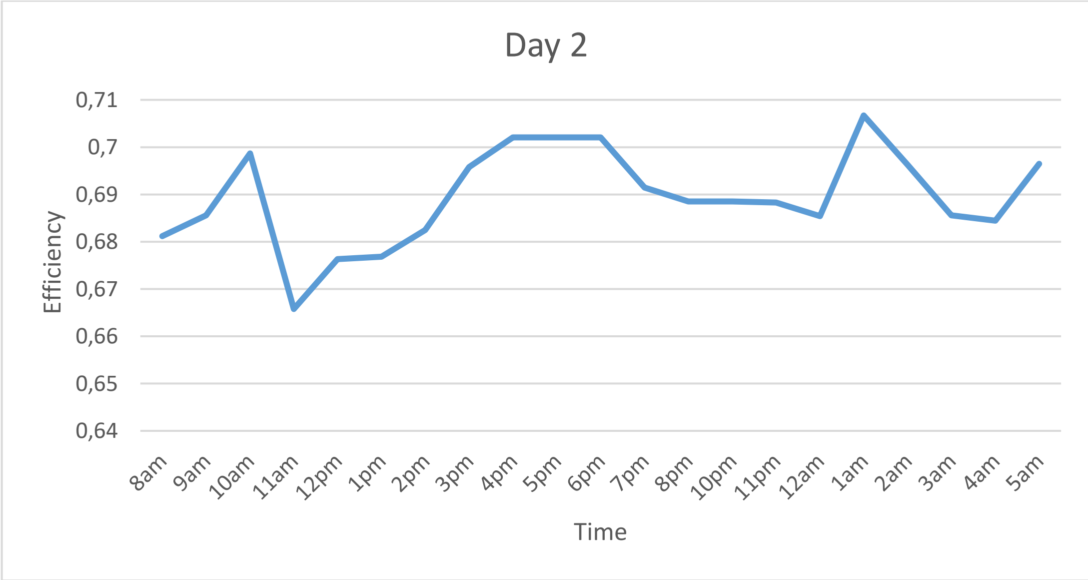

Figure 7: Efficiency of overall boiler against time, day 2

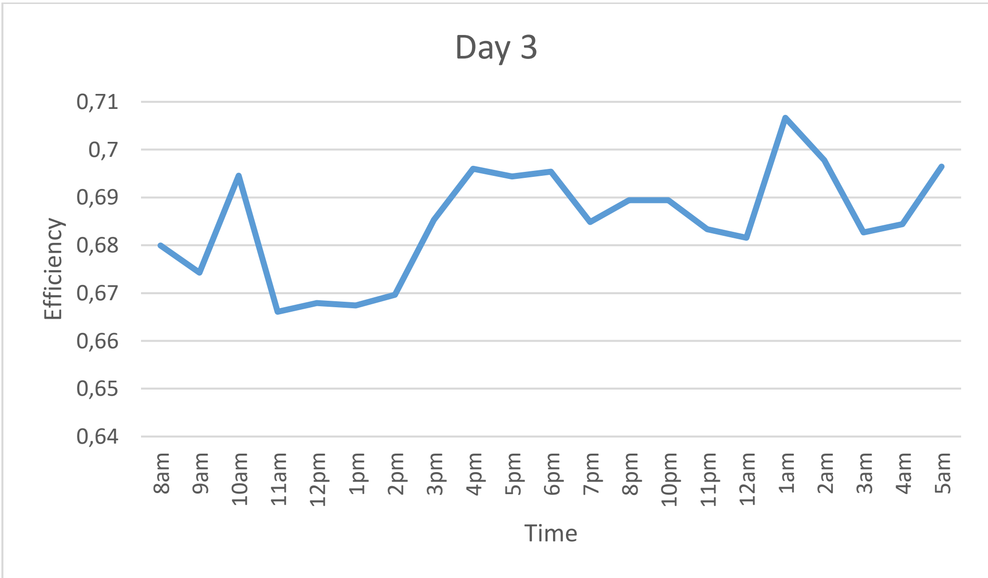

Figure 8: Efficiency of the Overall Boiler against Time, day 3

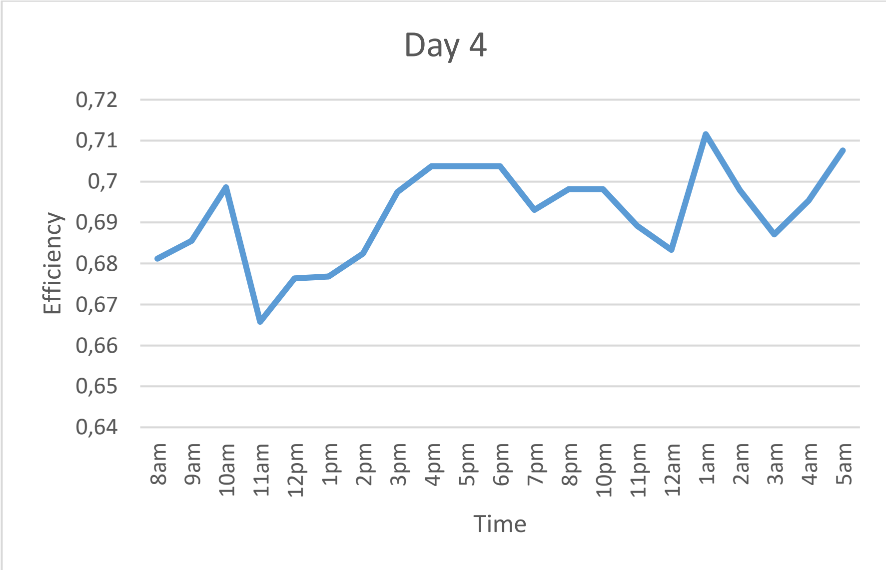

Figure 9: Efficiency of overall boiler against time: day 4

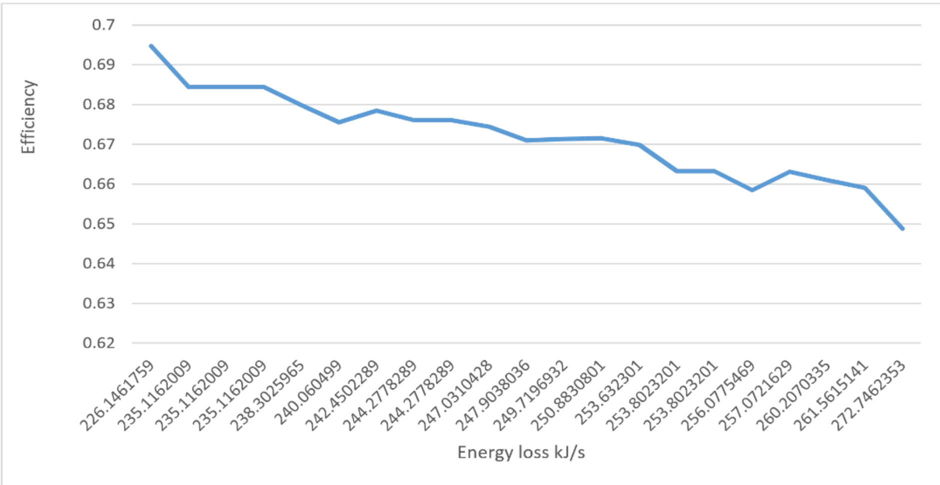

Figure 10 Efficiency of Heat Exchanger against Energy Loss

DISCUSSION

In this research, an energy analysis has been performed on the industrial boiler of the Coca-Cola bottling company. Table 3.0, shows the computed values of energy efficiencies of the combustor with the highest value of 82% efficiency with minimum losses in the component.

A lot of studies considered the combustion chamber as an adiabatic system since the boiler is an adiabatic combustion chamber and the specific enthalpy of the fuel is equal to the higher heating value, therefore the efficiency of the combustor is always 100 % ETSAP (2010). The graph in Figure 10 shows the results variation of energy efficiencies with the energy heat losses. Where it is seen in the heat exchanger that the minimum heat energy loss of 226.15kJ/s gives the highest efficiency of 69% due the fact that the heat in the combustion chamber could not be transferred all to heat exchanger without loss.

The energy efficiency of the overall boiler was 72% and the graphs in figure 5, 6, 7, 8, and 9 shows the energy efficiency of the overall boiler with respect to time in the duration of four days. It observed that the maximum energy efficiency occurs at 1 am, 12 am, 1 am, and 2 am when the surrounding temperature was low and these indicate that the energy heat loss in the system increases with the increasing environmental temperature. The energy efficiencies obtained for the combustor, heat exchanger, and the entire boiler in this study were 82%, 69%, and 71% respectively.

While obtained the energy and exergy efficiencies of a methane-fired boiler as 72.46% and 24.89% respectively as submitted by Saidur et al (2011)

CONCLUSION

The energy analysis was carried out, and from the data obtained the maximum energy efficiency boiler was found to be 82% with negligible losses in its component. Also, the combustion chamber as an adiabatic system, resulting in a constant 100% efficiency due to the specific enthalpy of the fuel being equal to the higher heating value. Based on the analysis of energy efficiency varied with energy heat losses, it shows that the heat exchanger's minimum energy loss of 226.15kJ/s corresponds to the highest efficiency of 69%. This result is attributed to the inherent challenge of transferring all the heat from the combustion chamber to the heat exchanger without some level of loss. More so, the energy efficiency of the boiler fluctuates with time, the maximum energy efficiency occurred during the early hours (between 1 am and 2 am). This indicates that energy heat loss within the system increased with rising environmental temperature.

These results provide valuable insights into the performance of the boiler system and its sensitivity to environmental conditions.

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