Development of Mathematical Model of a Utility Boiler Based on Energy and Exergy Analysis

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Abstract - *Kaduna Refining and Petro-chemicals Company (KRPC) is a refinery in Nigeria, whose steam power plant has been striving by supplying uninterrupted electricity, water and other utilities for the smooth running of the entire refinery and its housing estate. But the utility boiler of the plant is faced with the problems of deterioration from its design output and excess fuel consumption. These problems could be due to fuel combustion and heat transfer. Therefore, it is essential to adopt strategies that will minimize such problems. Thus, one of the effective ways is to develop a boiler mathematical model using energy and exergy analysis. Energy and exergy analysis are based on first and second law of thermodynamics. The latter is a tool widely used to evaluate the performance of a thermodynamic system. This paper describes the procedures involved in developing the mathematical model for evaluating energy loss, exergy destruction; energy and exergy efficiencies of the utility boiler of KRPC steam power plant.*

Keywords - *Boiler, Destruction, Efficiencies, Energy, Exergy*

I. INTRODUCTION

Energy remains the lubricant of sustainable economic growth of any country because it increases productivity and income as well as creates employment. Therefore, the role of energy in raising the economy of any nation cannot be overemphasized, and energy degradation in a given system is commonly inevitable. It is based on this fact that energy management globally is on the increase. Consequently, experts in the energy sector were challenged for improvement in energy policies and measures in minimizing waste. Steam power plants that work on modified Rankine cycle cogenerate electricity and steam [22]. Today, the consciousness of energy management across the globe is obvious, that is why the need to embark on research like this cannot be overemphasized. It has been seen in practices that thermodynamics laws were significantly utilized for performing energy and exergy analysis. Energy and exergy were also useful to examine, optimize and rectified the efficiency of thermodynamic systems [13].

Kaduna refining and petro-chemical company (KRPC) refines crude oil into petroleum products and manufactures petrochemical and packaging products [12]. Power plant and utilities (PPU) department of KRPC, comprises of utilities and power plant sections. The power plant section, which cogenerates steam and power comprise of minor and major components as shown in fig.1. Among the major components are the utility boilers as shown in fig. 2.

Nomenclature

BFW	Boiler feed water
CDT	Condensate
CW	Cooling water
CA	Combustion air
ESM	Extracted medium pressure steam
CSM	Condensed medium pressure steam
De	Deaerator
HPP	High pressure pump
LPP	Low pressure pump
He	Heater
Bo	Boiler
STG	Steam turbine generator
TC	Turbine condenser
HW	Hot well
CP	Condensate pump
CT	Condensate tank
DU	Demineralized unit
CU	Combustion unit
HEU	Heat exchange unit
KRPC	Kaduna refining and petro-chemical company
HHV	high heating value of fuel (kJ/kg)
LHV	low heating value of fuel (kJ/kg)
AAF	actual air-fuel ratio of fuel (kg of air/kg of fuel)
$\dot{E}$	Energy flow rate (kJ/s)
$\dot{E}_X$	Exergy flow rate (kJ/s)
$\dot{E}_{XD}$	Exergy destruction (kJ/s)
C_p	Specific heat capacity (kJ/kgK)
$\dot{M}$	Mass flow rate (Kg/s)
$\dot{Q}$	Rate of heat transfer to the system (kJ/s)
$\dot{Q}_L$	Rate of heat loss (kJ/s)
$\dot{W}$	Rate of work done by the system (kJ/s)
PW	Power produce by the system (kJ/s)
h	specific enthalpy (J/Kg)
s	specific entropy (J/Kg K)
P_o	Atmospheric pressure (bar)
T_o	Atmospheric Temperature (^{0}C)

Greek letters

η_I	Energy efficiency (%)
η_{II}	Exergy efficiency (%)
ε	specific exergy (kJ/Kg)

Sub_ and superscripts

SH	High pressure steam
SM	Medium pressure steam
SL	Low pressure steam
FW	Feed water
FO	Fuel oil
F	Fuel
FG	Flue gas
A	Air
S	Steam
$comb$	Combustion
HP	Hot products
0	reference state

These boilers are faced with the problems of deterioration from its design output and excess fuel consumption. The working procedure of the plant was studied and the schematic flow diagram was sketched. Furthermore, the general mathematical model of a typical boiler was developed using energy and exergy analysis based on component-wise and detail split-up techniques. Then, a detailed mathematical model of the KRPC utility boiler was developed with referenced to the schematic diagram of the plant and the general mathematical model of a typical boiler. The developed mathematical model is meant to determine the energy loss, exergy destruction, energy efficiency and exergy efficiency of the KRPC utility boiler.

Fig. 1: KRPC steam power plant

Fig. 2: KRPC steam power plant boilers

Reference [3] developed a mathematical model for 15 MW Thermal Power Plant Paper Mill, in India. It was found that the boiler has maximum exergy destructions of 19.7 MW, a turbine with the largest exergy efficiency of 82%, while condenser has the maximum energy loss 48.5 MW and highest energy efficiency of 82% respectively. Moreover, [20] established the mathematical models of a gas turbine cycle in India and found that the combustion chamber of the boiler has the highest exergy destruction of 109.89 MW. Furthermore, [26] developed a model of a 210 MW coal-based thermal power plant utility boiler in India. The findings revealed that the combustion chamber has the highest exergy destruction, with the boiler energy efficiency of 73.96% and exergy efficiency of 39.85%

respectively. Reference [27] found that the maximum exergy destruction of a 62 MW coal-based thermal power plant station occurred in the boiler while the plant's energy and exergy efficiencies were 32.5% and 27.5% respectively. Furthermore, the result revealed that energy and exergy efficiencies of the boiler at operating conditions were found to be 85.77% and 41.27% when [19] analyzed a 500 MW pulverized coal-fired boiler. Besides, [7] carried out an analysis of 9 MW coal-based thermal power plant. They found out that the plant has energy and exergy efficiencies of 24.12% and 35% respectively, while the boiler has an energy efficiency of 11%. Also, [8] carried out an exergy analysis of Omotosho phase 1 gas thermal power plant in Nigeria. The authors developed the mathematical model of the plant and found that the combustion unit of the boiler had the maximum exergy destruction of 54.15%.

Reference [14] worked on the energy and exergy analysis of a 500 kW steam power plant at Benso Oil Palm Plantation (BOPP) in Ghana and results obtained indicated that about 50% of heat energy generated in the combustor was destroyed. More so, [18] carried out a study on energy and exergy of a 75MW steam power in Sapele, Nigeria. The results revealed that boiler has the highest energy lost of 105 kW and rate proportion of the exergy destruction of 105.9%. In addition, [24] carried out a research on the energy and exergy analysis of a 210 MW Vijayawada Thermal Power Plant (VTPS) in India. They developed the mass, energy, and exergy balances and results obtained indicated that the exergy destruction was more in the Low Pressure Turbine than any other components. Reference [15] carried out an analysis of steam power plant at Kaduna Refining and Petrochemical Company (KRPC) from exergetic perspective. The analysis showed that, boiler has the largest exergy destruction of 20000kW, followed by the condenser with 5880kW. Incremental fuel consumption problem that occurred in the Cairo West Thermal Power Plant (Units 7 & 8) in Egypt necessitated [10] to carry out analysis on the plant from the energetic and exergetic viewpoint. The results revealed that turbine has the highest exergetic efficiency and boiler has the lowest exergetic efficiency with exergy destruction of 195 MW due to combustion, boiling and superheating processes. In the same way, [11] worked on the energetic and exergetic analysis of a steam turbine power plant of an existing phosphoric acid factory in Tunisia. The results revealed that blower had the maximum energy efficiency and exergy efficiency obtained for heat exchanger, steam turbine generator, deaerator and blower are 88%, 74%, 72% and 66% respectively.

In addition, reference [21] worked on the energy and exergy analysis of steam and power generation plant in a chemical and fertilizer industry in India. It was found that condenser had the highest energy loss of 47.16 MW. Energy and exergy efficiencies of turbine1 were found as 35.29% and 66.30% and that of turbine2 were 32.07% and 64.33% respectively. Furthermore, [2] worked on the energy and exergy analysis of Al-Hussein power plant in Jordan. The percentage ratio of the exergy destruction to the total exergy destruction was found to be 77% in the boiler, 13% in the turbine and then 9% in the forced draft fan condenser. Moreover, [5] worked on energy and exergy analysis of thermal power plant at design and off design load. The analysis showed that at design load maximum exergy destruction of 42% of the total exergy produced by the burning of coal occurred in the boiler, and it increased to 59% at off design load. In addition, [9] worked on the energy and exergy evaluation of a 220MW Egbin thermal power plant in Nigeria. The result of the analysis showed that the percentage exergy destruction of boiler, combined three turbines and condenser are 87%, 9% and 2% respectively. Furthermore, [6] worked on energy and exergy analysis in thermal power plants. It was noted that the exergy efficiency of boiler, condenser, turbine, feed water heaters and heat pumps were 69.53%, 84.20%, 90.07%, 77.23%, and 83.63% respectively. The boiler was also found to have the highest percentage of exergy destruction of 48.92% of the overall plant exergy destruction of 81.66%. Moreover, [23] worked on energy, exergy and economic analysis of industrial boilers. In the boiler, the energy and exergy efficiencies were found to be 72.46% and 24.89%, respectively. Reference [1] worked on exergy analysis of a 10,000 t/hr oil fired steam boiler plant in a brewery in Nigeria. Results showed that combustion chamber, mixing region and heat exchanger had exergy losses of 36%, 3.51% and 33.60% respectively.

II. DESCRIPTION OF KRPC POWER PLANT

The boiler feed water from the Demineralized water unit with temperature of 45^{0}C, pressure of 9bar and dissolved oxygen content of 1.0ppm goes to the Deaerators where the pressure, temperature and the dissolved oxygen content of boiler feed water (BFW) change to 2.5bar, 125^{0}C and 0.007ppm respectively. Then, after the Deaerators the High Pressure (HP) pumps increase the boiler feed water (BFW) pressure to 60.5bar, while temperature and dissolved oxygen content remain unchanged. The boiler feed water (BFW) is then supply to the Boilers through Heaters where only the temperature is further raised to 140^{0}C. The boiler feed water (BFW) enters the boilers through the respective economizers at a temperature of 140^{0}C and pressure of 60.5bar at 270t/hr. After the respective economizers, the boiler feed water becomes saturated and gets to the steam drum at temperature of 185^{0}C and pressure of 52.4bar. The saturated water is separated from steam by the drum internals (horizontal separators and chevron driers). Then, the dry steam is superheated through the primary superheater and secondary superheater, and then enters the high pressure steam (SH) headers. In addition, a superheater steam temperature control device (spray type attemperator) is installed after the primary superheater and before secondary superheater, whereby the steam temperature at superheater outlet is controlled at specified temperature of 412^{0}C and pressure of 47.6bar.

This superheated steam is used to drive the prime mover (turbines) of the turbo generators to generate power and also drive other turbine pumps for pumping boiler feed water at the required pressure. After utilizing the superheated steam (SH) in the HP pumps and in the turbines, the medium pressure steam (SM) extracted from the turbines and from the HP pumps were channeled to the common header of medium pressure steam (SM). The medium pressure steam (SM) at temperature of 300^{0}C and pressure of 16.4bar is used to drive the LP pumps and for heat exchange with boiler feed water (BFW) in the heaters. The low pressure steam (SL) at temperature of 175^{0}C and pressure of 1.44bar from the LP pumps is sent to the Deaerators for heat exchange with the boiler feed water, while the condensate from the heaters is also sent to the Deaerators to make-up level of the boiler feed water (BFW). The medium pressure steam (SM) from the turbines which were condensed under vacuum at a pressure of 18.2bar are send to the condensate tank (CT) via the condensate pumps (CP) and it flows back to the Demineralized unit and the process is repeated [25]. The process is depicted in fig. 3.

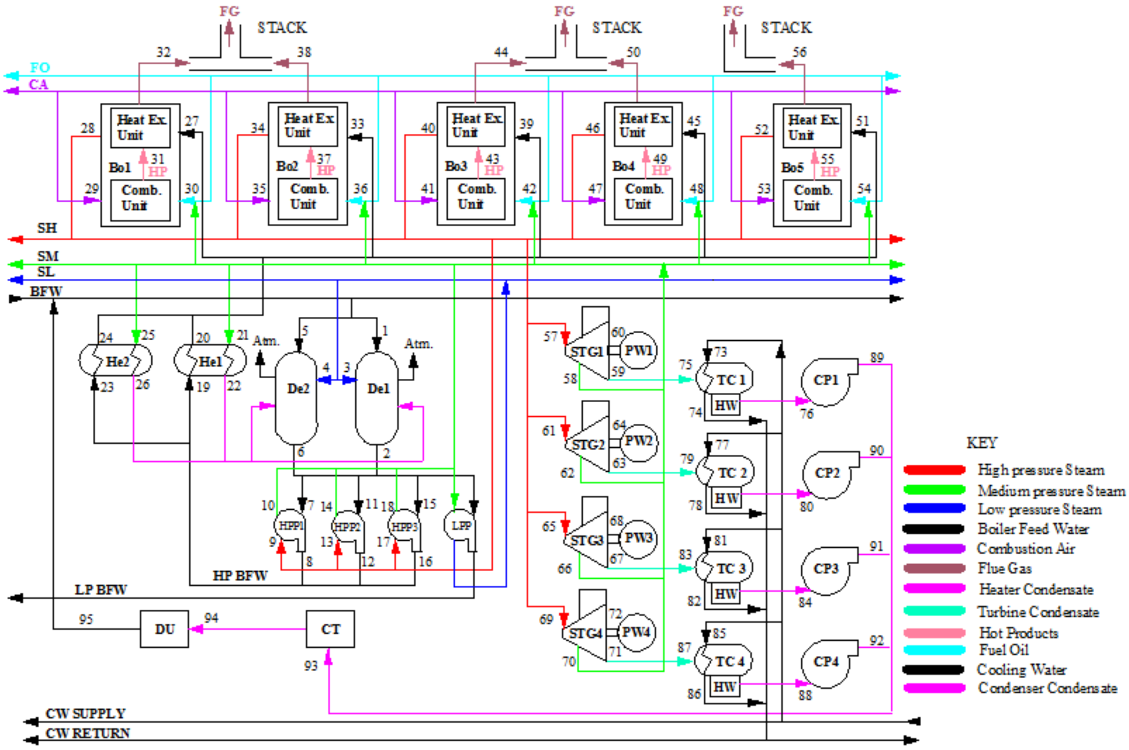

Fig. 3: Schematic flow diagram of KRPC steam power plant

III. Mathematical modeling

The energy analysis is based on the first principle of the thermodynamics and it is concerned with the conservation of energy. The exergy analysis in the other hand introduces the second law of thermodynamics [4]. Therefore, the purpose basically is to develop mathematical model that can be used to determine energy losses, exergy destructions and energy and exergy efficiencies of a device, process or component. Particularly, the exergy analysis of the boiler is defined into physical and chemical exergy [26] as shown in fig. 2. The chemical exergy of fuel which is negligible in this study is normally computed from the stoichiometric combustion of chemical reaction and it is associated with the departure of the chemical composition of a system from its chemical equilibrium. But, the chemical exergy of fuel is equivalent to the high heating value (HHV) of that fuel [23] & [16]. In this study the kinetic and potential energy of the mechanical aspect of exergy are assumed to be negligible [17]. This indicates that only the thermo mechanical (temperature and pressure) aspect of exergy was considered in this research work.

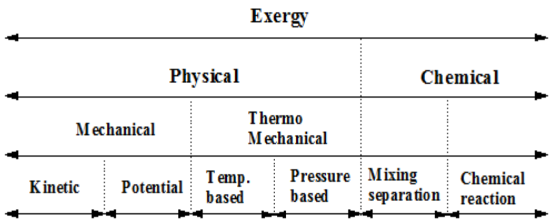

Fig. 2 Types of exergy in a typical boiler [26].

A. General mathematical modeling of a typical boiler

The schematic diagram of a typical boiler unit can be used to analyse the mass flow rate, energy and exergy balances and energetic and exergetic efficiencies of the boiler unit. The schematic diagram of the combustion and heat exchanging units may be analysed separately. The combustion takes place in the combustion unit to produce heat, then heat is transfer to water, and the water is subsequently transformed to steam in the heat exchange unit.

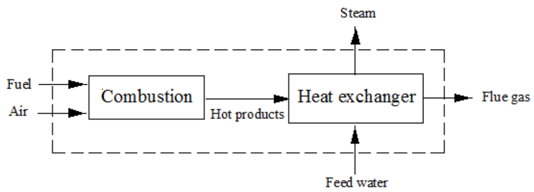

Fig. 3: Schematic diagram of a typical boiler [26].

a) Combustion unit

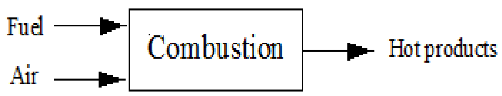

Fig. 4: Schematic diagram of combustion unit [26].

The combustion unit in a boiler is usually well insulated that causes no heat transfer to the surrounding. Therefore neither heat is lost nor work is produced (w = 0 & $\dot{Q}_L = 0$).

Mass balance:

$$\dot{M}_{FO} + \dot{M}_{CA} = \dot{M}_{HP} \qquad (1)$$

Energy balance:

Energy input = $\dot{M}_{FO} h_{FO} + \dot{M}_{CA} h_{CA}$ (2)

Therefore, energy balance is:

$$\dot{M}_{FO} h_{FO} + \dot{M}_{CA} h_{CA} = \dot{M}_{HP} h_{HP}$$

$$h_{HP} = \frac{\dot{M}_{FO} h_{FO} + \dot{M}_{CA} h_{CA}}{\dot{M}_{HP}}$$

$$h_{HP} = \frac{\dot{M}_{FO}(\text{HHV}) + \dot{M}_{CA} h_{CA}}{\dot{M}_{HP}} \qquad (3)$$

Since the combustion unit of the boiler system is adiabatic, it means that all the energy input is being sent to heat exchange unit with no heat loss to the environment. Therefore, the efficiency is always 100%; hence specific enthalpy of fuel h_{FO} is evaluated to be equal to high heating value (HHV) of the fuel oil [23] & [16].

Then energy efficiency ($\eta_{I(CU)}$) is 100% (adiabatic)

$$\eta_{I(CU)} = \frac{\dot{M}_{HP} h_{HP}}{\dot{M}_{FO}(\text{HHV})} = 100\% \qquad (4)$$

Exergy balance:

Exergy inlet = $\dot{M}_{FO}\varepsilon_{FO} + \dot{M}_{CA}\varepsilon_{CA}$

Exergy exit = $\dot{M}_{HP}\varepsilon_{HP} + \dot{E}_{XD(CU)}$

Therefore, exergy balance is:

$\dot{M}_{FO}\varepsilon_{FO} + \dot{M}_{CA}\varepsilon_{CA} = \dot{M}_{HP}\varepsilon_{HP} + \dot{E}_{XD(CU)}$

Exergy Destruction ($\dot{E}_{XD(CU)}$) is:

$$\dot{E}_{XD(CU)} = (\dot{M}_{FO}\varepsilon_{FO} + \dot{M}_{CA}\varepsilon_{CA}) - (\dot{M}_{HP}\varepsilon_{HP}) \qquad (5)$$

Where:

$$\varepsilon_{FO} = \varepsilon_{ch} + \varepsilon_{ph}$$

$$\varepsilon_{ph} = (h_{FO} - T_0 S_{FO})$$

But in this research work, chemical exergy (ε_{ch}) of fuel oil is negligible, therefore:

$$\varepsilon_{FO} = \varepsilon_{ph}$$

$$\varepsilon_{FO} = (h_{FO} - T_0 S_{FO}) \qquad (6)$$

$$S_{FO} = \frac{h_{HP}}{T_{FO}} \qquad (7)$$

$$\varepsilon_{CA} = (h_{CA} - T_0 S_{CA}) \qquad (8)$$

$$\varepsilon_{HP} = (h_{HP} - T_0 S_{HP}) \qquad (9)$$

$$S_{HP} = \frac{h_{HP}}{T_{HP}} \qquad (10)$$

$$T_{HP} = T_{CA} + \frac{\text{LHV}}{[C_p \times (1+\text{AAF})]} \qquad (11)$$

Where, AAF is the actual air fuel ratio of low pour liquid fuel (AAF = 16) and C_p is the specific heat of fuel oil at ambient temperature of products of combustion (C_p= 1.866 kJ/kgK) [23] & [16].

$$\text{Exergy efficiency } (\eta_{II(CU)}) = \frac{\text{Heat output}}{\text{Heat input}} \times 100\%$$

$$\eta_{II(CU)} = \frac{\text{Heat in hot products output}}{\text{Heat in fuel input}} \times 100\%$$

$$\eta_{II(CU)} = \frac{\dot{M}_{HP}\varepsilon_{HP}}{\dot{M}_{FO}\varepsilon_{FO}} \times 100\%$$

$$\eta_{II(CU)} = \frac{\dot{M}_{HP}(h_{HP} - T_0 S_{HP})}{\dot{M}_{FO}(h_{FO} - T_0 S_{FO})} \times 100\% \qquad (12)$$

b) Heat exchanging unit

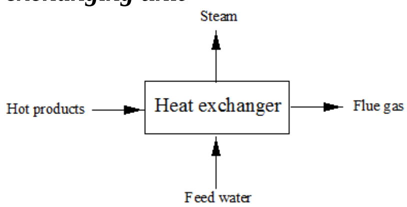

Fig. 5: Schematic diagram of heat exchange unit [26].

Mass balance:

$$\dot{M}_{FW} + \dot{M}_{HP} = \dot{M}_{FG} + \dot{M}_{SH} \qquad (13)$$

$$\dot{M}_{FW} = \dot{M}_{SH} \text{ and } \dot{M}_{HP} = \dot{M}_{FG}$$

Energy balance:

Energy inlet = $\dot{M}_{HP} h_{HP} + \dot{M}_{FW} h_{FW}$

Energy exit = $\dot{M}_{HP}\varepsilon_{HP} + (\dot{M}_{SH} h_{SH} + \dot{M}_{FG} h_{FG}) + \dot{Q}_{L(HEU)}$

Therefore, energy balance is:

$\dot{M}_{HP} h_{HP} + \dot{M}_{FW} h_{FW} = (\dot{M}_{SH} h_{SH} + \dot{M}_{FG} h_{FG}) + \dot{Q}_{L(HEU)}$

Then energy Loss ($\dot{Q}_{L(HEU)}$) is:

$$\dot{Q}_{L(HEU)} = \left(\dot{M}_{HP}h_{HP} + \dot{M}_{FW}h_{FW}\right) - \left(\dot{M}_{SH}h_{SH} + \dot{M}_{FG}h_{FG}\right)$$

$$\dot{Q}_{L(HEU)} = \dot{M}_{HP}(h_{HP} - h_{FG}) - \dot{M}_{FW}(h_{SH} - h_{FW}) \quad (14)$$

$$\text{Energy efficiency } \left(\eta_{I(HEU)}\right) = \frac{\text{Heat output}}{\text{Heat input}} \times 100\%$$

$$\eta_{I(HEU)} = \frac{\text{Heat in steam output}}{\text{Heat in hot products input}} \times 100\%$$

$$\eta_{I(HEU)} = \frac{\dot{M}_{SH}h_{SH} - \dot{M}_{FW}h_{FW}}{\dot{M}_{HP}h_{HP} - \dot{M}_{FG}h_{FG}} \times 100\%$$

$$\eta_{I(HEU)} = \frac{\dot{M}_{SH}(h_{SH} - h_{FW})}{\dot{M}_{HP}(h_{HP} - h_{FG})} \times 100\% \quad (15)$$

$$h_{FG} = a(T_{FG})^2 + b(T_{FG}) + c \quad (16)$$

Where:

a = 1.683$\times 10^{-5}$, b = 0.233 & c = -18.03

The benchmark coefficients a, b and c as given above can be used to evaluate the enthalpy of the flue gases [16].

Exergy balance:

Exergy inlet = $\dot{M}_{HP}\varepsilon_{HP} + \dot{M}_{FW}\varepsilon_{FW}$

Exergy exit = $(\dot{M}_{SH}\varepsilon_{SH} + \dot{M}_{FG}\varepsilon_{FG}) + \dot{E}_{XD(HEU)}$

Therefore, exergy balance is:

$$(\dot{M}_{HP}\varepsilon_{HP} + \dot{M}_{FW}\varepsilon_{FW}) = (\dot{M}_{SH}\varepsilon_{SH} + \dot{M}_{FG}\varepsilon_{FG}) + \dot{E}_{XD(HEU)}$$

Then exergy Destruction ($\dot{E}_{XD(HEU)}$) is:

$$\dot{E}_{XD(HEU)} = (\dot{M}_{HP}\varepsilon_{HP} + \dot{M}_{FW}\varepsilon_{FW}) - (\dot{M}_{SH}\varepsilon_{SH} + \dot{M}_{FG}\varepsilon_{FG})$$

$$\dot{E}_{XD(HEU)} = \dot{M}_{HP}(\varepsilon_{HP} - \varepsilon_{FG}) - \dot{M}_{FW}(\varepsilon_{SH} - \varepsilon_{FW}) \quad (17)$$

Where:

$$\varepsilon_{HP} = h_{HP} - T_0S_{HP} \quad (18)$$

$$\varepsilon_{FW} = h_{FW} - T_0S_{FW} \quad (19)$$

$$\varepsilon_{SH} = h_{SH} - T_0S_{SH} \quad (20)$$

$$\varepsilon_{FG} = h_{FG} - T_0S_{FG} \quad (21)$$

$$S_{FG} = S_a + C_p \ln\frac{T_{FG}}{T_a} \quad (22)$$

At T_a = 200K, S_a = 1.29559kJ/kgK & C_p = 1 kJ/kgK (Specific heat capacity of exhaust flue gas) [4] & [16].

$$\text{Exergy efficiency } \left(\eta_{II(HEU)}\right) = \frac{\text{Heat output}}{\text{Heat input}} \times 100\%$$

$$\eta_{II(HEU)} = \frac{\text{Heat in steam output}}{\text{Heat in hot products input}} \times 100\%$$

$$\eta_{II(HEU)} = \frac{\dot{M}_{SH}\varepsilon_{SH} - \dot{M}_{FW}\varepsilon_{FW}}{\dot{M}_{HP}\varepsilon_{HP} - \dot{M}_{FG}\varepsilon_{FG}} \times 100\%$$

$$\eta_{II(HEU)} = \frac{\dot{M}_{SH}(h_{SH} - T_0S_{SH}) - \dot{M}_{FW}(h_{FW} - T_0S_{FW})}{\dot{M}_{HP}(h_{HP} - T_0S_{HP}) - \dot{M}_{FG}(h_{FG} - T_0S_{FG})} \times 100\%$$

$$\eta_{II(HEU)} = \frac{\dot{M}_{SH}[(h_{SH} - T_0S_{SH}) - (h_{FW} - T_0S_{FW})]}{\dot{M}_{FG}[(h_{HP} - T_0S_{HP}) - (h_{FG} - T_0S_{FG})]} \times 100\% \quad (23)$$

c) Typical boiler unit

Therefore, the detail split-up modeling technique is applicable if the whole component comprises of a two units i.e. the combustion and heat exchange units as shown in fig.3. [28] & [23]:

Energy Loss of boiler unit ($\dot{Q}_{L(Bo)}$):

$$\dot{Q}_{L(Bo1)} = \dot{Q}_{L(CU1)} + \dot{Q}_{L(HEU1)} \quad (24)$$

Energy Efficiency of boiler unit:

$$\left(\eta_{I(Bo)}\right) = \frac{\text{Heat output}}{\text{Heat input}} \times 100\%$$

$$\eta_{I(Bo1)} = \frac{\text{Heat in steam output}}{\text{Heat in fuel input}} \times 100\%$$

$$\eta_{I(Bo1)} = \frac{\dot{M}_{SH}h_{SH} - \dot{M}_{FW}h_{FW}}{\dot{M}_{FO}h_{FO}} \times 100\%$$

$$\eta_{I(Bo1)} = \frac{\dot{M}_{SH}(h_{SH} - h_{FW})}{\dot{M}_{FO}(HHV)} \times 100\% \quad (25)$$

Exergy Destruction of boiler unit ($\dot{E}_{XD(Bo)}$):

$$\dot{E}_{XD(Bo1)} = \dot{E}_{XD(CU1)} + \dot{E}_{XD(HEU1)} \quad (26)$$

Exergy Efficiency of boiler unit:

$$\left(\eta_{II(Bo)}\right) = \frac{\text{Heat output}}{\text{Heat input}} \times 100\%$$

$$\eta_{II(Bo1)} = \frac{\text{Heat in steam output}}{\text{Heat in fuel input}} \times 100\%$$

$$\eta_{II(Bo1)} = \frac{\dot{M}_{SH}\varepsilon_{SH} - \dot{M}_{FW}\varepsilon_{FW}}{\dot{M}_{FO}\varepsilon_{FO}} \times 100\%$$

$$\eta_{II(Bo1)} = \frac{\dot{M}_{SH}(h_{SH} - T_0S_{SH}) - \dot{M}_{FW}(h_{FW} - T_0S_{FW})}{\dot{M}_{FO}(h_{FO} - T_0S_{FO})} \times 100\%$$

$$\eta_{II(Bo1)} = \frac{\dot{M}_{SH}[(h_{SH} - T_0S_{SH}) - (h_{FW} - T_0S_{FW})]}{\dot{M}_{FO}(HHV - T_0S_{FO})} \times 100\% \quad (27)$$

B. Mathematical modeling of KRPC Boiler1

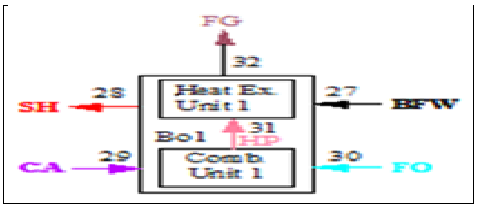

Fig. 6: Schematic flow diagram of KRPC Boiler 1

a) Combustion unit1

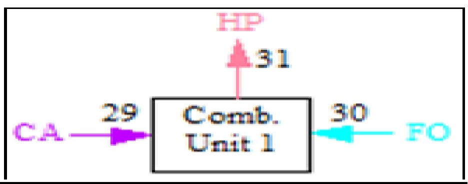

Fig. 6: Schematic flow diagram of Combustion unit 1

Mass balance:

$$\dot{M}_{30} + \dot{M}_{29} = \dot{M}_{31} \quad (28)$$

Energy balance:

Exergy inlet = $\dot{M}_{30}h_{30} + \dot{M}_{29}h_{29}$ (29)

Exergy exit = $\dot{M}_{31}h_{31}$

Therefore, energy balance is:

$$\dot{M}_{30}h_{30} + \dot{M}_{29}h_{29} = \dot{M}_{31}h_{31}$$

$$h_{31} = \frac{\dot{M}_{30}h_{30} + \dot{M}_{29}h_{29}}{\dot{M}_{31}}$$

But, h_{30} = HHV [4] & [16].

$$h_{31} = \frac{\dot{M}_{30}(\text{HHV}) + \dot{M}_{29}h_{29}}{\dot{M}_{31}} \quad (30)$$

Energy efficiency is 100% (adiabatic process)

$$\eta_{I(CU1)} = \frac{\dot{M}_{31}h_{31}}{\dot{M}_{30} \times \text{HHV}} = 100\% \quad (31)$$

Exergy balance:

Exergy inlet = $\dot{M}_{30}\varepsilon_{30} + \dot{M}_{29}\varepsilon_{29}$

Exergy exit = $\dot{M}_{31}\varepsilon_{31} + \dot{E}_{XD(CU1)}$

Therefore, exergy balance is:

$$\dot{M}_{30}\varepsilon_{30} + \dot{M}_{29}\varepsilon_{29} = \dot{M}_{31}\varepsilon_{31} + \dot{E}_{XD(CUI)}$$

Exergy Destruction ($\dot{E}_{XD(CUI)}$) is:

$$\dot{E}_{XD(CU1)} = (\dot{M}_{30}\varepsilon_{30} + \dot{M}_{29}\varepsilon_{29}) - (\dot{M}_{31}\varepsilon_{31}) \quad (32)$$

Where:

$$\varepsilon_{30} = \varepsilon_{ph}$$

$$\varepsilon_{30} = (h_{30} - T_0 S_{30}) \quad (33)$$

$$S_{30} = \frac{h_{31}}{T_{30}} \quad (34)$$

$$T_{30} = T_{29} + \frac{\text{LHV}}{[C_p \times (1+\text{AAF})]} \quad (35)$$

Where:

$$\varepsilon_{29} = (h_{29} - T_0 S_{29}) \quad (36)$$

$$\varepsilon_{31} = (h_{31} - T_0 S_{31}) \quad (37)$$

$$S_{31} = \frac{h_{31}}{T_{31}} \quad (38)$$

Therefore, the exergy efficiency $(\eta_{II(CU1)})$ is:

$$\eta_{II(CU1)} = \frac{\dot{M}_{31}(h_{31} - T_0 S_{31})}{\dot{M}_{30}(\text{HHV} - T_0 S_{30})} \quad (39)$$

b) Heat exchanging unit1

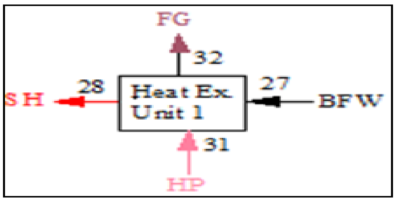

Fig. 7: Schematic flow diagram of Heat exchange unit 1

Mass balance:

$$\dot{M}_{27} + \dot{M}_{31} = \dot{M}_{32} + \dot{M}_{28} \quad (40)$$

$$\dot{M}_{27} = \dot{M}_{28} \text{ and } \dot{M}_{31} = \dot{M}_{32}$$

Energy balance:

Energy inlet = $\dot{M}_{31}h_{31} + \dot{M}_{27}h_{27}$

Energy exit = $(\dot{M}_{28}h_{28} + \dot{M}_{32}h_{32}) + \dot{Q}_{L(HEU1)}$

Therefore, energy balance is:

$$\dot{M}_{31}h_{31} + \dot{M}_{27}h_{27} = (\dot{M}_{28}h_{28} + \dot{M}_{32}h_{32}) + \dot{Q}_{L(HEU1)}$$

Energy Loss ($\dot{Q}_{L(HEU1)}$) is:

$$\dot{Q}_{L(HEU1)} = \dot{M}_{31}(h_{31} - h_{32}) - \dot{M}_{27}(h_{28} - h_{27}) \quad (41)$$

Therefore, the energy efficiency $(\eta_{I(HEU1)})$ is:

$$\eta_{I(HEU1)} = \frac{\dot{M}_{28}h_{28} - \dot{M}_{27}h_{27}}{\dot{M}_{31}h_{31} - \dot{M}_{32}h_{32}} \times 100\%$$

$$\eta_{I(HEU1)} = \frac{\dot{M}_{28}(h_{28} - h_{27})}{\dot{M}_{31}(h_{31} - h_{32})} \times 100\% \quad (42)$$

$$h_{32} = a(T_{32})^2 + b(T_{32}) + c \quad (43)$$

Where:

a = 1.683× 10^{-5}, b = 0.233 & c = -18.03

Exergy balance:

Exergy inlet = $\dot{M}_{31}\varepsilon_{31} + \dot{M}_{27}\varepsilon_{27}$

Exergy exit = $(\dot{M}_{28}\varepsilon_{28} + \dot{M}_{32}\varepsilon_{32}) + \dot{E}_{XD(HEU)}$

Therefore, exergy balance is:

$$\dot{M}_{31}\varepsilon_{31} + \dot{M}_{27}\varepsilon_{27} = (\dot{M}_{28}\varepsilon_{28} + \dot{M}_{32}\varepsilon_{32}) + \dot{E}_{XD(HEU)}$$

Exergy Destruction ($\dot{E}_{XD(HEU1)}$) is:

$$\dot{E}_{XD(HEU1)} = (\dot{M}_{31}\varepsilon_{31} + \dot{M}_{27}\varepsilon_{27}) - (\dot{M}_{28}\varepsilon_{28} + \dot{M}_{32}\varepsilon_{32}) \quad (44)$$

Where:

$$\varepsilon_{31} = h_{31} - T_0 S_{31} \quad (45)$$

$$\varepsilon_{27} = h_{27} - T_0 S_{27} \quad (46)$$

$$\varepsilon_{28} = h_{28} - T_0 S_{28} \quad (47)$$

$$\varepsilon_{32} = h_{32} - T_0 S_{32} \quad (48)$$

$$S_{32} = S_0 + C_p \ln\frac{T_{32}}{T_0}$$

$$S_{32} = 1.29559 + (1)\ln\frac{T_{32}}{200} \quad (49)$$

Therefore, the exergy efficiency $(\eta_{II(HEU1)})$ is:

$$\eta_{II(HEU1)} = \frac{\dot{M}_{28}\varepsilon_{28} - \dot{M}_{27}\varepsilon_{27}}{\dot{M}_{31}\varepsilon_{31} - \dot{M}_{32}\varepsilon_{32}} \times 100\%$$

$$\eta_{II(HEU1)} = \frac{\dot{M}_{28}(h_{28} - T_0 S_{28}) - \dot{M}_{27}(h_{27} - T_0 S_{27})}{\dot{M}_{31}(h_{31} - T_0 S_{31}) - \dot{M}_{32}(h_{32} - T_0 S_{32})} \times 100\% \quad (50)$$

c) KRPC boiler1

The detail split-up modeling technique is applicable if the whole component comprises of a two units. Typically, the combustion and heat exchange units as shown in fig 5[28].

Energy Loss of boiler unit ($\dot{Q}_{L(Bo1)}$):

$$\dot{Q}_{L(Bo1)} = \dot{Q}_{L(CU1)} + \dot{Q}_{L(HEU1)} \quad (53)$$

Energy Efficiency of boiler1 $(\eta_{I(Bo1)})$:

$$\eta_{I(Bo1)} = \frac{\dot{M}_{28}h_{28} - \dot{M}_{27}h_{27}}{\dot{M}_{30}h_{30}} \times 100\%$$

$$\eta_{I(Bo1)} = \frac{\dot{M}_{28}(h_{28} - h_{27})}{\dot{M}_{30}(HHV)} \times 100\% \quad (54)$$

Exergy Destruction of boiler1 ($\dot{E}_{XD(\mathrm{Bo1})}$):

$$\dot{E}_{XD(\mathrm{Bo1})} = \dot{E}_{XD(CU1)} + \dot{E}_{XD(HEU1)} \quad (55)$$

Exergy Efficiency of boiler1 ($\eta_{II(\mathrm{Bo1})}$):

$$\eta_{II(\mathrm{Bo1})} = \frac{\dot{M}_{28}\varepsilon_{28} - \dot{M}_{27}\varepsilon_{27}}{\dot{M}_{30}\varepsilon_{30}} \times 100\%$$

$$\eta_{II(\mathrm{Bo1})} = \frac{\dot{M}_{28}(h_{28} - T_0S_{28}) - \dot{M}_{27}(h_{27} - T_0S_{27})}{\dot{M}_{30}(h_{30} - T_0S_{30})} \times 100\%$$

$$\eta_{II(\mathrm{Bo1})} = \frac{\dot{M}_{28}[(h_{28} - T_0S_{28}) - (h_{27} - T_0S_{27})]}{\dot{M}_{30}(HHV - T_0S_{30})} \times 100\% \quad (56)$$

IV. CONCLUSION

The mathematical model that is meant to determine the temperatures, mass flow rates, enthalpies, entropies, and exergies of material streams in the utility boiler of KRPC steam power plant as presented in this research work, would afford the plant operators, plant managers, and management of the company with a better alternative in analyzing the utility boiler and providing important measures needed in planning the maintenance schedule of the plant. The evaluated properties were further used to obtain performance variables like energy losses, exergy destructions, energy efficiencies and exergy efficiencies of the combustion unit, heat exchange unit, and the entire utility boiler. It is further expected that the developed mathematical model of the utility boiler of the KRPC steam power plant would be implemented as a computer program for precision, time reduction and ease of usage.

It is expected that researchers, instructors and postgraduate students of energy science and engineering will find this research study imperative in devising the basic method required in carrying out energetic and exergetic analysis of utility boilers. The mathematical model for assessing the performance of the utility boiler of the KRPC steam power plant in a summarized manner is shown in the Appendix. Finally, these model are not limited, users could discover alternative model related to solving problems in utility boilers using energy and exergy techniques, with the hope that after proper implementation and due consideration of the model, the problem of the plant output deterioration and fuel consumption would be the thing of the past.

ACKNOWLEDGEMENT

The authors would like to thank Kaduna Refining and Petrochemical Company (KRPC), Kaduna, Nigeria for the approval to embark on this research study in the power plant and utility department. The authors also express their sincere thanks to Dr. Niraj Shah and Dr. Deepak Singh Panwar of School of Engineering P P Savani University, Surat, India for their encouragement throughout the research article.

APPENDIX: ENERGETIC AND EXERGETIC MODELING OF THE UTILITY BOILER

The mathematical model of the KRPC utility boiler included chemical and physical exergies that were developed using a theoretical model of typical boiler and the sketched schematic flow diagram of the plant as depicted in fig. 1. The energetic and exergetic model in the combustion unit1, heat exchanging unit1 and boiler1 which would be used in analyzing the performance of boiler1 are summarized in Tables 1 – 3 accordingly, which includes energy losses, exergy destructions, energy efficiencies, and exergy efficiencies.

TABLE I: SUMMARY OF ENERGETIC AND EXERGETIC PARAMETERS OF COMBUSTION UNIT1

Performance Parameter	Mathematical Model
Energy Loss of combustion unit1	$\dot{Q}_{L(CU1)} = 0$ (Adiabatic process)
Energy efficiency of combustion unit1	$\eta_{I(CU1)} = \frac{\dot{M}_{31}h_{31}}{\dot{M}_{30} \times HHV} = 100\%$ (Adiabatic process)
Exergy Destruction of combustion unit1	$\dot{E}_{XD(CU1)} = (\dot{M}_{30}\varepsilon_{30} + \dot{M}_{29}\varepsilon_{29}) - (\dot{M}_{31}\varepsilon_{31})$
Exergy efficiency of combustion unit1	$\eta_{II(CU1)} = \frac{\dot{M}_{31}(h_{31} - T_0S_{31})}{\dot{M}_{30}(HHV - T_0S_{30})} \times 100\%$

TABLE II: SUMMARY OF ENERGETIC AND EXERGETIC PARAMETERS OF HEAT EXCHANGE UNIT1

Performance Parameter	Mathematical Model
Energy Loss of heat exchange unit1	$\dot{Q}_{L(HEU1)} = \dot{M}_{31}(h_{31} - h_{32}) - \dot{M}_{27}(h_{28} - h_{27})$
Energy efficiency of heat exchange unit1	$\eta_{I(HEU1)} = \frac{\dot{M}_{28}(h_{28} - h_{27})}{\dot{M}_{31}(h_{31} - h_{32})} \times 100\%$
Exergy Destruction of heat exchange unit1	$\dot{E}_{XD(HEU1)} = (\dot{M}_{31}\varepsilon_{31} + \dot{M}_{27}\varepsilon_{27}) - (\dot{M}_{28}\varepsilon_{28} + \dot{M}_{32}\varepsilon_{32})$
Exergy efficiency of heat exchange unit1	$\eta_{II(HEU1)} = \frac{\dot{M}_{28}(h_{28} - T_0 S_{28}) - \dot{M}_{27}(h_{27} - T_0 S_{27})}{\dot{M}_{31}(h_{31} - T_0 S_{31}) - \dot{M}_{32}(h_{32} - T_0 S_{32})} \times 100\%$

TABLE III: SUMMARY OF ENERGETIC AND EXERGETIC PARAMETERS OF BOILER1

Performance Parameter	Mathematical Model
Energy Loss of boiler1	$\dot{Q}_{L(Bo1)} = \dot{Q}_{L(CU1)} + \dot{Q}_{L(HEU1)}$
Energy efficiency of boiler1	$\eta_{I(Bo1)} = \frac{\dot{M}_{28}(h_{28} - h_{27})}{\dot{M}_{30} \times HHV} \times 100\%$
Exergy Destruction of boiler1	$\dot{E}_{XD(Bo1)} = \dot{E}_{XD(CU1)} + \dot{E}_{XD(HEU1)}$
Exergy efficiency of boiler1	$\eta_{II(Bo1)} = \frac{\dot{M}_{28}[(h_{28} - T_0 S_{28}) - (h_{27} - T_0 S_{27})]}{\dot{M}_{30}(HHV - T_0 S_{30})} \times 100\%$

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