Application Of Combustible Waste In Package Boiler For Co-Energy Production In Industrial Environment

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***Abstract*—Co–energy production is a technology for producing multiple energy output from one input, this is applied in the production of steam for industrial application and electrical power generation. a two-way energy service that allow the user to manage dual energy service at minimum fuel cost, the intend of this paper is to evaluate the application of alternative fuel (wood) and its fuel calorific value, calometric temperature of fuel, mass of flue gas for combustion, boiler efficiency, superheated steam temperature from its chemical composition. The net power of steam output (1.56Mw), steam mass flow rate (3.12 T) and energy balance of system for industrial application and power generation**

Keywords—Co-energy, boiler, fuel, steam, industrial process, power generation

I INTRODUCTION

The overhead Fuel cost of running package boiler with diesel or black oil as fuel, maintenance and repair cost of stand by generator and payment of electricity bill in industrial environment are among many challenges face by industrialist Nigeria. This paper enables the substitution of boiler fuel with combustible waste (wood and palm residue, domestic and industrial waste) for steam generation for industrial process additional resources application of superheated steam to run turbine that convert steam power to mechanical energy to drive an alternator for electrical energy production, this enable co-energy production and cost saving resulting from utilisation of waste as fuel. The system utilise external furnace housing water tube replacing the burner of a package boiler

II FUEL AND COMBUSTION

Fuel refers to a substance that burns in air to produce carbon IV Oxide, water vapour and light with evolution of heat.

To be classed as a fuel, a material must contain elements which will combine rapidly with oxygen to initiate combustion. Suggested fuel are combustible domestic and industrial waste, palm residue and wood residue.

In this paper, attention would be focused on wood waste with under-listed percentage chemical composition bymass:49% C 6% H_2O; 44% O_2; 0.4% N_2 and 0.6% Ash.

Combustion is the high temperature oxidation of the combustible elements (C, H_2, S etc.) fuel with heat release proper control of the right amount of excess air enhances optimum combustion efficiency. The amount of excess air supplied is 20 %

III DESIGN CRITERIA

- Assuming the air supplied is 20 % in excess
- Air contains 21% O_2 and 79% N_2 (other inert gases, e.g. Argon inclusive) by volume and in terms of mass, it contains 23% O_2 and 77% N_2 (Nag 2011, and Rajput 1997,))

Table 1 Computation of mass of Flue Gas per kg of fuel at 20 % excess air

FUEL (kg)	O_2 Required	Dry Product
C = 0.40	$C + O_2 = CO_2$ (1.306666667)	$0.49 \times \frac{44}{2} = 1.796666667$ (CO_2)
H_2 = 0.06	$H_2 + O = H_2O$ (0.48)	$0.06 \times \frac{18}{2} = 0.54$ (H_2O)
N2 = 0.004		- 004 (N_2)
O2 = 0.44		
Ash = 0.006		
Total	1.786666667	

Mass of O_2 to be supplied = Mass of O_2 supplied – Mass of O_2 already present

1.786666667 – 0.44 = 1.34666667 kg/kg fuel

Stoichiometric air required, which is equal to the minimum mass (volume) of air required.

Minimum mass of Air supplied

= 1.34666667 x $\frac{100}{23}$ = 5.855072764 kg

At 20 % O_2, excess air supplied

= 5.855072764 x 1.2 = 7.026086957 kg

N_2 present in the air = 7.026086957 x $\frac{77}{100}$

= 5.416086907 kg

Total mass of N_2 present in the flue gas

= 5.416086907 + 0.004 = 5.414086257 kg/kg waste wood

Mass of free O_2 due to excess air =5.855072764 x 0.2 x $\frac{23}{100}$

= 0.26933333kg/kg waste wood

Mass of dry flue gas = MCO_2 + MN_2 + MO_2

= 1.70666667 + 5.414086257 + 0,269933334

= 7.480086258 kg/kg waste wood

Table 2 Volumetric Analysis of Waste Wood at 20 % Excess Air

In terms of % Weight	Mass (kg)	In terms of Mole Volume	O_2 Requirement
C = 49	12	$\frac{49}{12}$ = 4.0833333	C + O_2 – CO_2 (4.0833333)
H_2 =6	2	$\frac{6}{2}$ = 3	H_2 + $^1/_2$ O_2 – H_2O (1.5)
N_2 = 0.4	28	$\frac{0.4}{28}$ = 0.014285714	
O_2 = 44	32	$\frac{44}{32}$ = 1.375	
Ash = 0.6		$\sum O_2$ = 4.20833333Mol/vol/WW	

Air Requirement

Minimum volume of air required for combustion = 4.20833333 x $\frac{100}{21}$

= 20.03968254 Nm^3

At 20% excess air, volume of air required = 20.03968254 x 1.2
= 24.047619048 Nm^3

Volume of N_2 present in the Air = 4.20833333 x $\frac{79}{100}$

= 3.3245833 Nm^3

Total volume of N_2

= 3.32455833 + 0.014285714

= 3.3388690473 Nm^3

Volume of free O2 due to excess air

= 20.03968254 x 0.2 x $\frac{21}{100}$

= 0.8416666668 Nm^3

Hence, the combustion air required for 1 kg Waste Wood (fuel) is 20. 03968254 Nm^3 and in excess air is 24.047619048 Nm^3

Table 3 Volume of Flue Gas in100kg of Combusted Wood

Reactant	Combustion reaction	Product (Mole Vol)
C	C + O_2 – CO_2	4.08333333
H_2	H_2 + $^1/_2$ O_2 – H_2O	3.0
O_2		0.8416666668
N_2		3.3388690473
$\sum Volume$		11.2638690441

100 kg (Basis) of waste wood burned to produce 11.2638690441 x 22.4 Nm^3 flue gases
1 kg of waste wood produced 11.2638690441 $\frac{22.4}{100}$ = 2.523106658784 Nm^3

Table 4. Specific Weight of Flue Gas

Flue Gas	Composition (Mol/Vol)	Molar Mass	Weight
CO_2	4.08333333	44	179.6666666652
H_2O	3.0	18	54
N_2	3.3388690473	28	93.488333324
O_2	0.8416666668	32	26.9333333379
			354.0883333272

Therefore, the specific weight of flue gas = $\frac{3.540883333272}{2.523}$ = 1.403382343 kg/Nm^3

Calorific value: this refers to the heat energy released by the complete burning of unit quantity of fuel; it is also called specific energy or heat rate. The heat rate of solid substances is determined with Calorimeter.

Enumerated below is the method used in computing the Calorific value of wood

Table 5 Calorific Value of Wood

Reactant	Reaction	Heat of combustion (kcal/kg)	Heat evolved (kcal)
C	$C + O_2 - CO_2$	(+)8137.5	$8137.5\ (\frac{49}{100})$ = 3, 787.375
H_2	$H_2 + \frac{1}{2}O_2 - H_2O$	(+)28905	$28905(\frac{0.5}{100})$ = 144.5
$\sum H_{comb}$			4, 131.9

The values of Heat of combustion were obtained from heat of combustion Table

According to Dulong, the heat of evaporation of (2 x 0.84416666668) 1.68333333 mol/vol of water should be subtracted from this Calculated Value (CV).

Hence, the calorific value of waste wood is 3, 841.89 kcal/kg (16, 085.74221kJ/kg). The calorific value calculated based on the constituents of the fuel used is called Gross Calorific value

Estimation of Waste Wood Calorimeter Temperature, (T_{wcal})

The temperature was estimated based on trial and error method, when interpolated between two temperatures with the heat contents of gases taken from Tables of Heat Contents of Gases at various temperatures

IV BOILER CALCULATION

Criteria Enumerated below are the criteria used in evaluating the performance of the Steam boiler:

Fuel calorific value,

CV = 16, 085.74221kJ/kg

Mass of dry flue Gas,

m_{fg} = 7.480086258kg/kg waste wood

Specific heat of flue gas, Cp_{fg} = 1.1235 kJ/kg/K

Combustion Temperature, $\emptyset_{comb}$ = 1, 914.2 °C

Steam Consumption rate, m_{st} = 3.12306786 kg/s (11.243 t/h)

Condition of steam at exhaust Pressure (dryness fraction) = 0.936

Step I:

Considering the T - S diagram

From Steam Table at 15 bar

T_{sat}= 198.3 °C; h_f = 844.7 kJ/kg; h_{fg} = 1, 945.2 kJ/kg

Table 6 steam table at 15 bar

S/N	Pressure (bar)	h_f(kJ/kg/K)	h_{fg}(kJ/kg/K)	T_{sat}(°C)	h*(kJ/kg/K)	V (m³/kg)	S*(kJ/kg)	S_f (kJ/kg)	S_{fg}(kJ/kg)	V_g(m³/kg)
1	15.0	844.7	1, 945.2	198.3	3037.6	0.169	6.918			
2	1.2	434.4	2, 244	104.8		1.428		1.3609	5.9375	0.001048

Considering points 1 and2; the entropies are the same since the process at these points is an isentropic process (that is $s_1 = s_2$)

s_2= s_{f1} + xs_{fg2}

= 6.918 = 1.3609 + (x) 5.9375

Where, x, the dryness fraction = 0.936

Enthalpy at point 2, h_2^*

= h_{fi} + xh_{fg} = 434.4 + (0.936 x 2,244.1)

= 2, 536.93 kJ/kg

Step II: Pump Work, W_P

Pump work = $(P_2 - P_1)$v = (1.2 - 15)10^2 x 0.001048

= (-) 1.44625 kJ/kg

Turbine work, W_T

$(h_1 - h_2)$ = (3, 037.6 – 2, 536) = 500.68 kJ/kg

Total work done = Turbine Work + Pump Work

ΔW_{Net} = W_T + W_P = 500.68 + (-1.446.25)

449.23375 kJ/kg

Work done per second = ΔW_{Net} x steam mass flow rate = $(\Delta W_{Net}.m_{st})$

449.23375 x 3.12306786

= 1, 559.140875 kJ/s (~1.56 MW)

Step III: Computation of Equivalent Evaporation

In practice, not all the quantity of water supplied to a steam generating unit is converted completely into steam; certain fraction of the working fluid, water, always exists to occupy the water space. The quantity of water evaporated from and 100 °C (Boiling point) to produce dry saturated steam at 100 °C by absorbing the same amount of heat as used in the boiler under actual operating conditions is known as equivalent evaporation, ()m_{eq} .

$$m_{eq} = \frac{m\_act(H - Hw)}{2257} \quad (1)$$

m_{eq} = equivalent evaporation

m_{act}= actual mass of steam generated per unit mass of fuel burnt, (kg/kg)

H = total specific enthalpy of steam under operating condition

Hw = specific enthalpy of feed water

2, 257 kJ/kg = Latent heat of dry saturated steam at 100 °C

The ratio of the equivalent evaporation to the actual quantity of steam evaporated per unit mass of fuel burnt is called the 'factor of evaporation'.

That is: f = $\frac{m_{eq}}{m_{act}}$

$m_{eq} = m_{act}$ x f (4.51)

$$f = \frac{(H - Hw)}{2257} \quad (2)$$

Boiler Efficiency, η_{boiler}

Boiler efficiency is defined as the ratio of the heat load of the generated steam to the heat supplied by the fuel over the same period.

Heat load of generated steam

$= m_s(H - Hw)$ kJ/s (3)

$$\eta_{boiler} = \frac{m_s(H - Hw)}{m_{ww}.CV} = \frac{m_{act}(H - Hw)}{CV_f} \quad (4)$$

From steam Table (Journal of Physical and Chemical Reference Data, 1986; Pg. 56 By Senger et al)

At point 4:

$h_{f4} - h_{f3} = v_f(P_1 - P_2)$

h_{f4} - 439.4 = 0.001048 (15 – 1.2)10^2 = 1.44624

h_{f4}= 440.84624 kJ/kg

Corresponding temperature and pressure, T_4 = 105. 13 °C and P_4 = 1.28 bar

Therefore, Hw = 440.8 kJ/kg

At points C, Heat content the same

(H_{fw4}= H_{satfw})

Cp ($T_{fw} - T_4$) = Cp($T_{sat} - T_{fw}$)

Therefore, T_{fw} = 151.715 °C

At temperature, T_{fw}, of 151.715 °C,

h_{fw} = 639.726 kJ/kg and P_{fw} = 4.99 bar

Factor of evaporation, f

Sensible heat of feedwater at 151.72 °C (h_{fw})= 639.72 kJ/kg, P_{fw} = 4.99 bar

Heat required to produce unit mass of steam at 300 °C /15 bar = 3, 037.6 kJ/kg

Latent heat of dry saturated steam at 100 °C, h_{fg} = 2, 257 kJ/kg

Therefore, f = $\frac{3,037-639.726}{2,257}$ = 1.062150642 (~1.0622)

Step IV: Degree of superheat and superheated steam temperature

At saturated condition or saturation, steam, the working fluid in steam thermal stations is said to be wet as it still contains little quantity of moisture; besides this, the enthalpy is also small. When heated further from dry saturated condition, a vapour receives superheat and its temperature rises above saturation temperature, t_{sat}, to enter the superheat phase. The difference between the superheat vapour temperature,t^*, and the saturation temperature, t_{sat}, is called te degree of superheat. Thus;

Degree of superheat = (t^* - t_{sat}) °C or K

Therefore, the total heat content of the steam comprises the latent heat, L, and the sensible heat

= H_w + L + $Cp_{st}.\Delta\emptyset^*$

Where $\Delta\emptyset^*$ = degree of superheat and Cp_{st} = specific heat of steam at constant pressure = 2.0934 kJ/kg (Rajput, 1996; pg. 62)

$$f = \frac{H_w + L + Cp_{st}.\Delta\emptyset^* - H_{fw}}{2257}$$

1.062150642

$$= \frac{844.7+1,945.2+2.0934\,\Delta\emptyset^* - 639.726}{2,257}$$

$\Delta\emptyset^*$ = 118.0376416 °C

t^* - t_{sat} = t^* - 198.3 = 118.0376416

t^* = 316.3376416 °C (~316.3 °C)

But steam enters into the turbine at 300 °C / 15 bar, the temperature drop between the superheater exit and turbine inlet is (316.3 - 300) 16.3 °C

V FUEL (WASTE WOOD) CONSUMPTION

In practice, not all the quantity of fuel (e.g. waste wood) charged into a combustion chamber (furnace) burns completely, some are left within the furnace space or on lower layer of furnace bed unburnt; in this regard, assuming the percentage of unburnt fuel is 1 %.

Step VI: Heat Load of Steam / Ton

Enthalpy of dry superheated steam (300 °C / 15 bar) = 3, 037 kJ/kg

Enthalpy of feedwater at 151.715°C = 639.726 KJ/kg

Therefore, heat required to raise 1 ton of steam

= 10^3(3037 – 639.726) = 2397.274 x 10^3 kJ

StepVII: **BoilerEfficiency**. (η_B)

Let waste wood consumption = x t/h.

Steam generated per ton of waste wood fired = $\frac{11.2430743}{x}$t/h

Recall that factor of evaporation

= 1.062150642

Equivalent evaporation

= 11.240443 x 1.062150642

= 11.94180672 t/h

Energy output = (h_1 - h_{fw}) kJ/kg

Energy input = calorific value of fuel

= 16055.74221 kJ/kg

$\eta_B = \frac{h_1 - h_{fw}}{cv} = \frac{2397.274\ x10^3}{16085.74221\ x10^3}$

= 0.149030984 (14.9%)

Also, energy input = $m_f\ (h_1 - h_{fw})$

= 1.062150642 x $\frac{11.2430443}{x}$ (2397.274) x 10^3 kJ/kg

Waste wood charged to the furnace = x t/h

Actual waste wood burnt = x (1 - $\frac{1}{100}$)

= 0.99xt/h

Therefore energy input = 0.99x x 10^3 x 16085.74221 = 15924.88479 x $10^3 x$ kJ/kg

η_B = 0.149030984 = $\frac{28627.78277\ x10^3/x}{15924.88479\ x10^3/x}$

$x^2 = \sqrt{12.06171433t/h}$

x = 3.472997888 t/h (0.964721635kg/s)

Mass of steam per ton of waste wood = $\frac{11.2430443}{3.472997888}$

= 3.237273578t

Therefore, equivalent evaporation of steam = 3.438472209 ton of steam/ton of waste wood.

: Fuel Gas Temperature Inlet to Air Heater (T_{flin})

Air-preheater consists of plates or tubes with hot gases on one side and air on the other. The function of the air-preheater in a steam generator is to reduce the loss of energy to the stack by heating the air for combustion by the fuel gases in a hot exchanger (Rai, 2007). Preheated air accelerates the combustion and facilitates the burning of fuel (coal, waste wood, (Rajput, 2011).

By Energy Balance

Heat loss by dry flue gas plus water vapour = heat gained by the air in the air preheater (Chattopathyyay, 2008)

$M_{fg}.CP_{fg}(T_{flin} - 180) + M_{wv}.CP_{fg}\ \ (T_{fg_{in}}$- 180)

[7.480086258 x (1.123450364) + 0.54 (2.0934)][$T_{fg_{in}}$- 180]

= 7.02608695(1.006)(400 – 40)

$T_{fg_{in}}$= 446.8956607°C (~ 446.9°C

Therefore, the fuel gas temperature, inlet to the air preheater is 446.9 °C (approximately).

Step VII: Flue Gas inlet temperature to the Boiler (t_{fin})

By energy Balance:

Heat gained by the water in the boiler drum = Heat lost by the flue gases + water vapour

$m_w.Cp_w(198.3 - 151.13)$

=$7.4800862586(1.123450364)(t_{afin} - 446.9)$ + $0.54\ x\ 1.006(t_{afin} - 446.9)$

3.43847220 x 4.187 47.17 = 8.94674562 $(t_{afin} - 446.9)$

t_{afin} = 522.8004652 °C (522.8 °C)

Step VIII: Flue Gas Temperature at inlet to Superheater inter-phase

Heat utilized in super heater can be obtained using the relation below

Heat lost by Flue Gases = Heat gained by vapour from saturation state (198.3 °C) to superheated state at temperature (316.34 °C)

$m_{fg}.Cp_{fg}(T_{insh} - 318.34) + m_{wv}.Cp_{st}(T_{insh} - 316.34)$

$= m_s(h_{fg} - Cp_{st}(316.34 - 198.3))$

$\{7.480086258(1.123450364) + m_{wv}.Cp_s\}(T_{insh} - 316.34)$

= 3.237273578{198.3 + 2.0934(316.34 – 198)

$9.533941629(T_{insh} - 316.34)$

= 7, 097.074862

T_{insh} = 1. 060.738555 °C (1, 060.74 °C)

Flue Gas Temperature inlet to the superheater = T_{insh}

Superheater

Net Heat transferred to steam in the Superheater = $m_s.Cp_s(T_{insh} - T_{osh})$

3.237273578 x 2.0734 (316.34 – 198.3)

= 799.933072 kJ/kg waste wood (~799.93 kJ/kg)

Therefore, thermal efficiency of the superheater, η_{sh}

$= \frac{799.933072}{16,085.74221} = 0.049729333$

= 4.97 % (approximately)

Air-Heater

Net heat transferred to air in the air-heater or Heat absorbed by air in the Air-Heater

$= m_a.Cp_a(t_{oa} - t_{ia})$ = 7.026086957 x 1.006(400 – 40)

= 2, 544.567652 kJ/kg of waste wood

Therefore, the efficiency of the Air-heater

$= \frac{m_{a}.Cp_a(t_{oa} - t_{ia})}{CV_{fuel}}$

$\frac{2,544.567652}{16,085.74221} = 0.15818776$

= 15.82 % (approximately)

Heat lost to the Flue Gas

Enthalpy of dry flue Gas, $h_{lfg} = m_{fg}.Cp_{fg}(t_{infg} - t_{ofg})$

= 7.480086258 x 1.123450364(446.9 – 180)

= 2, 242.859187 kJ/kg waste wood

Water content in flue gases when 100 kg waste wood (for analysis) burnt = 0.54 kg/kg waste wood

Heat lost due to moisture content of flue gas, h_{wfg}

$= m_{wv}.Cp_s(t_{ofg} - t^*_{dp}) + h^*_{Dp} + Cp_w(t_{ofg} - t_{in})$

Where: t_{in} = Boiler house temperature = 25 °C

m_{wv} = Mass of water vapour in flue gases / kg of fuel (wood waste) = 0.54 kg

$Cp_s Cp_w$ = specific heat of water vapour = 4.187 kJ/kg

t_{ofg} = Flue Gas outlet temperature

= 180 °C

t^*_{dp} = Dew point temperature

= 38.493683 °C

h^*_{Dp} = Latent heat of evaporation at Dew point temperature = 2, 410.3 kJ/kg

Cp_s = Specific heat of water steam

= 2.0934 kJ/kg

$= 0.542.0934[(180 - 38.) + 2,410.3 + 4.187(180 - 25)]$

= 1,811.977735 kJ/kg waste wood

The total heat lost to flue gas,

$h^*_{lfg} = h_{lfg} + h_{wfg}$

= 2, 242.859187 + 1, 811.977735

= 4, 054.836922 kJ/kg waste wood

Hence, the percentage of heat lost to the flue gas

$= \frac{h^*_{lfg}}{CV_{fuel}} = \frac{4,054.836922}{16,085.74221}$

= 0.25076458 (~25.08 %)

Table 7 Evaluation of Steam Generator Performance

Steam Generator's Component	Heat evolved (KJ/kg fuel)	% heat evolved
Boiler	2, 397.27	14.90
Superheater	799.93	4.97
Air-heater	2, 544.57	15.82
Heat lost to flue gas	4, 054.84	25.08
Heat lost due to unburnt fuel	155.18	1.00
Heat lost due to radiation from bed	1, 551.83	10.00
Heat escaped through insulated tube walls	1, 551.83	10.00
Unaccountable heat lost	2, 910.61	18.23

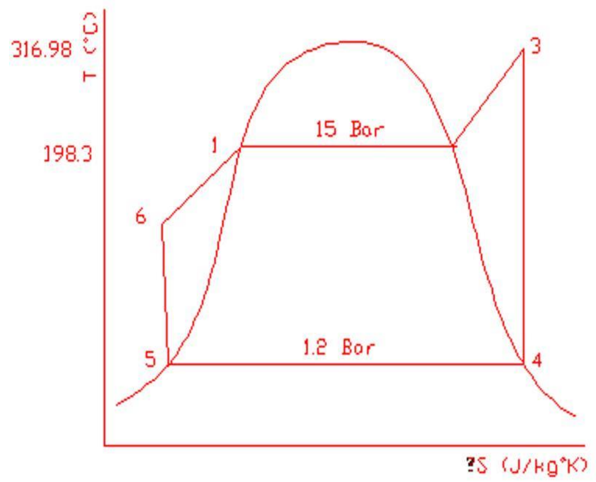

FIGURE 1. T – S Diagram of 1.5 MW Waste Wood Boiler for co-energy production

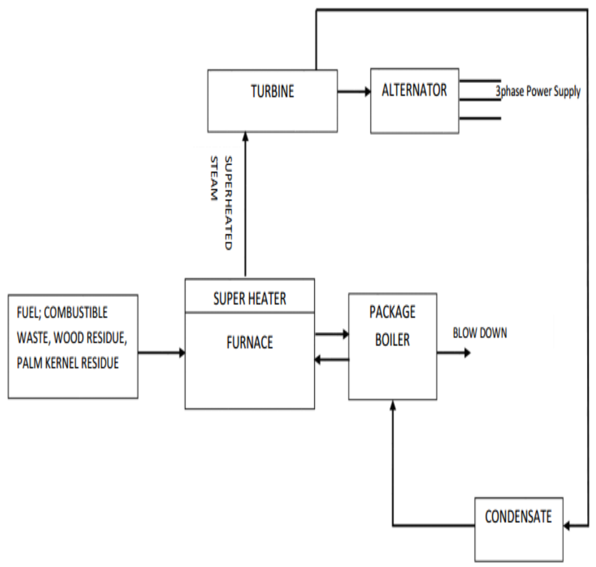

FIGURE 2. PROCESS FLOW CHART/BLOCK DIAGRAM

VI CONCLUSION

In this paper we address the problem 0f high fuel cost of running package boiler and stand by generator. The propose solution is a co-energy production of steam for both industrial process and electricity production. External water tube furnace serves as combustion chamber for the package boiler utilising combustible waste as fuel. The Net power =1.56Mw, Steam mass flow rate =3.12 T /sec

At half load (50%) 750kva can be generated while 1.56T /s of steam will be available for industrial process. The cost of fuel (black oil, diesel) for running package boiler/generator and electricity bill will be eliminated as wood and oil palm residue will serve as fuel.

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