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Upgrading the Energy Management Profile of a Cement Production Plant Using Waste Heat Recovery and Steam Boiler System

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Abstract
This paper is aimed at upgrading the energy management profile of a Nigerian cement production plant which uses dry technique. Energy and exergy balances were carried out around the pyro-processing units of the plant in order to identify points of heat sinks. Estimated heat losses showed: pre-heater-calciner exit, 19 %; kiln unit, 3.46 % and clinker cooler exhaust, 14.5 %. The overall heat and exergy efficiencies for the UCC cement plant were 55.5 and 67.7 % respectively. Based on these findings, a waste heat recovery and steam boiler (WHRSB) system which operates on a simple Rankine cycle was proposed and designed for the UCC plant. From the thermodynamic analysis, 12.9 % of the total waste heat can actually be recovered and reused for power generation which resulted in 11.97 MW of electricity. A gross annual electricity bill of NGN4.085 billion naira was saved. The formulated fuel optimization model gave optimal fuel savings of 10.6 % at feed rate of 395 ton/h as against the designed feed rate of 411 ton/h.

Keyword: *Cement clinker, pyro-processor unit, exergy, waste-heat-recovery and fuel consumption.*

1.0 INTRODUCTION

Cement manufacturing process is simple and less complex. It generally involves the use of a combination of raw materials mix from limestone, clay, shale, chalk and sand, while iron ore, alumina and other materials may be added in minute quantities in order to adjust raw material mix composition (IFC, 2014).The raw materials mix is primarily prepared by drying and milling before being charged into the kiln (or pyro-processor) unit. It is thermally treated in this unit to produce a hard nodular material called clinker, which in turn is blended with gypsum to form Portland cement (Alsop, 2001).

However, cement production process is energy intensive. The energy consumed is derived from both fossil fuels combustion and electricity supply. The fossil fuels are burned by burner firing to produce heat in the kiln plant (Banerjee and Khurana, 2002).The level of heat requirement in a cement plant will depend on the type of technology being applied, whether wet, semi-wet, dry or semi-dry method. For some dry kiln cement plants, pre-heater (or pre-calciner) is an additional facility and its specific heat consumption ranges from 2926 to 4180 kJ/kg-clinker. For long kilns, pre-heating facility may not be required (Rosemann, 1987; Hashimoto and Watanabe, 1999).

Heat energy needs for cement clinker production is mainly for the purposes of calcination and clinkerization, and it accounts for about 20–25% of the overall cement production cost. Electrical energy is also consumed in cement plant, but it is mainly used for milling and grinding purposes. For example, about 110 – 120 kWh is required for grinding one ton of cement clinker, hence the total energy requirements for cement production constitutes about 30 – 40 % of the total production cost (Szabo et al, 2003).Another aspect of the production is the cost of producing and purifying CO_2 which had evolved from both fuel combustion and calcinations reactions. CO_2 represent a major fraction of the cement production effluents. Thus, cement production accounts for about 5 % of total CO_2 emission from all human activities (Hendriks et al, 2004).

In the thermal analysis of cement production, energy and exergy assessments are very significant. Exergy is referred to as the maximum useful work potential derivable from energy available for cement production, in other word energy not accounted for is said to be lost or destroyed (Kolip and Savas, 2010 and Koroneos et al, 2005). Reasons for the observed losses or destructions of energy in cement production are actually due to irreversibility problems which may arise from chemical reactions inside the cement kiln, losses through kiln wall due to heat transfer, emissions of dust and gases from pre-calciner and clinker cooler exits (Reno et al, 2013).

Energy and exergy analyses for cement production processes are not new concepts, because there are lots of reports to support it. Also, the use of waste heat recovery systems to track and recover lost energies in a cement production plant has got advantages, namely: reduction in power import, reduction in fossil fuel consumption, increase in energy efficiency, reduction in gaseous emissions and environmental pollution (JFE Engineering, 2013).

Notable reports include the thermal analysis of a rotary burner (with preheating) used for cement production for which 35.6 % of input exergy was lost due to the stack gas flow at elevated temperatures. The resulting energy and exergy efficiencies were respectively 97 and 64.4% (Camdali et al., 2004). Also, an energy audit for a pyro-processing unit of a typical dry process cement plant has identified kiln exit gases and kiln shell as its major sources of energy losses, having 27.9 and 10.8 % as its respective energy loss values. This resulted in an overall low thermal efficiency of 41 % for the plant (Kabir et al., 2009).

In another assessment, a cement production plant in Turkey which uses dry-type rotary kiln process had intended to recover it lost energies using a waste heat recovery system. From the thermal analysis performed, 40 % loss of input energy through flue gas, clinker cooler stack and kiln shell were estimated. However, only 15.6 % of the total input energy loss (an equivalence of 15 MW) was recovered (Engin and Ari, 2005; Wang et al, 2009).

An Egyptian cement plant that was originally designed for 6300 ton-clinker per day capacity had its gas flow patterns redesigned: one was diverted by bypass method while the other had no diversion by bypass. For both cases, energy and exergy efficiencies were reported as 40, 25.7 % and 52, 34 % respectively. This implied that there were relative losses in both cases for which actual values of energy and exergy losses for both gas flow patterns were770, 416 kJ/kg-clinker (diversion by bypass) and 1060, 567 kJ/kg-clinker (without bypass).Identified regions in the plant where there were energy loses included pre-heater gas and dust exit, cooler exhaust stack and through convection and radiation (Faragand Taghian, 2015).

In a similar study, exergy analysis carried out for a cement production plant located at Birla in Saltna-Egypt for which coal was the source of fuel to the kiln plant showed kiln wall, kiln gas and dust exit, and clinker cooler exit as primary sources of energy losses. This information was based on mass and exergy analysis performed around the entire process using operational data. A waste heat recovery system was then designed for the plant which helped reduced plant dependence on public electricity by 22.65 MW/day (Shrikant and Chaube, 2013).

For this study, the United Cement Company (UCC) in Calabar, Nigeria is our focus. The plant designed capacity is 6250 ton-clinker/day (or 2.3 million ton-clinker/year). It uses a dry-type rotary kiln of 80 m in length and 5 m in diameter (Figure 1). It is equipped with duoflex burners fired by fuel oil/natural gas supply. Also, the kiln is fed through a pre-heater unit equipped with fuel burner system and 6 cyclones (in 5-stage assembly) for proper heat contact and exhaust gas removal. The kiln finally exits product into the clinker cooler unit equipped with an array of air cooler fans (Figure 2).

One of the objectives of this paper is to help quantify the overall energy need of the UCC using its operational data (Holcim, 2016). Another is to identify points of energy losses in the plant and quantify the loss. To achieve this, mass, energy and exergy balances will be carried out around it main process units: pre-heater-calciner, rotary kiln and clinker cooler. A waste heat recovery and steam boiler (WHRSB) system will also be designed to convert waste heat into electricity. Economic savings from waste heat utilization will be estimated, while a new fuel consumption model will be proposed for the plant.

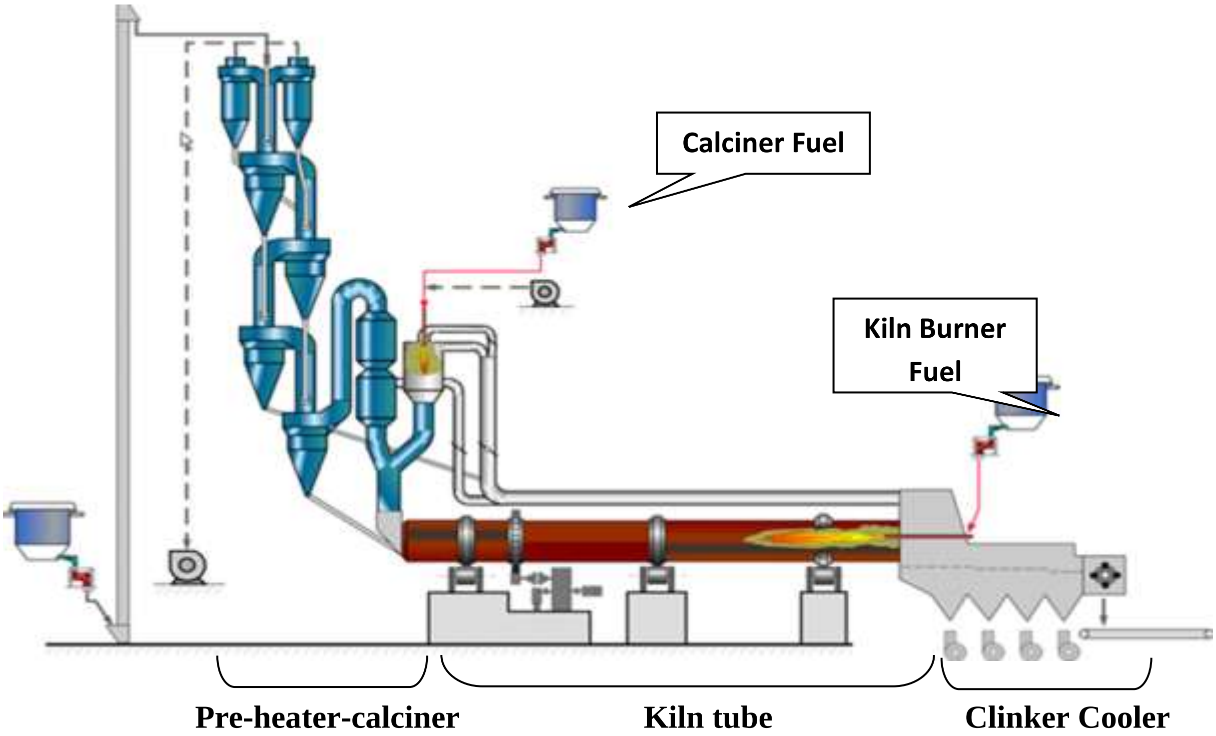


FIGURE 1: Prototype flow diagram of UCC pyro-processor unit (Holcim, 2016; Peray and Waddell, 1972)

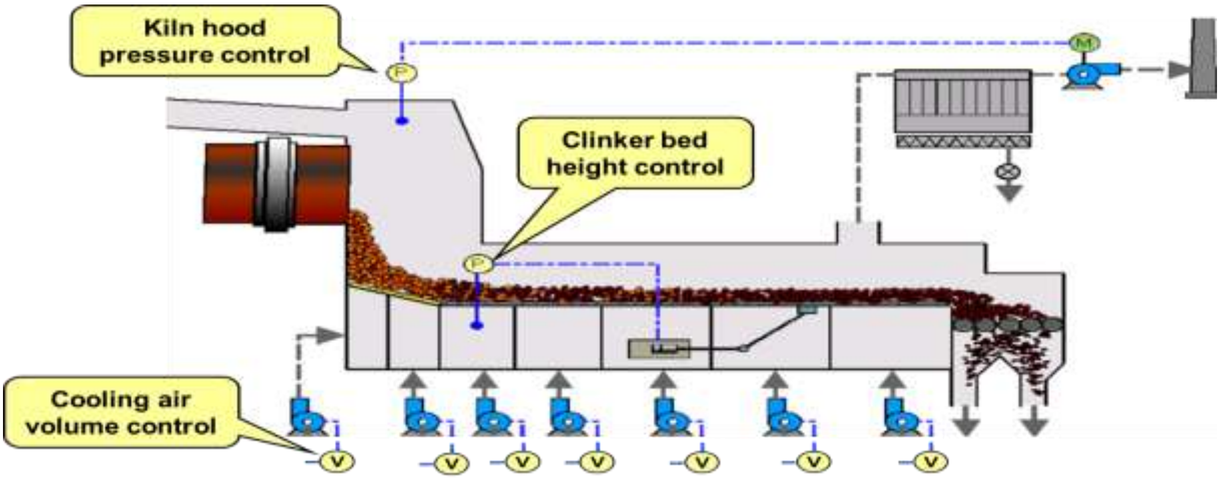


Figure 2: Prototype of clinker cooler unit at UCC (Holcim, 2016; Peray and Waddell, 1972)

2.0 METHODOLOGY

Methods adopted for this work includes material, energy and exergy balances around the pyro-processor units (i.e. pre-heater-calciner + rotary kiln + clinker cooler units), design of waste heat recovery and steam boiler (WHRSB) unit and kiln fuel consumption optimization modeling. Thus, general assumptions for the kiln plant and clinker cooler analysis are presented: (1). Calculations are based on 1 kg-clinker, (2). Material and energy balance analysis are based on steady state, (3). Ambient temperature change is negligible, (4). Cold air inflow is negligible, (5). Composition of raw material mix and fuel oil are constant, (6). Air supporting fuel oil combustion is composed mainly of O_2 and N_2.

2.1 Material balance around kiln plant and clinker cooler units

The material balance is based on the law of conservation of mass as expressed in eq. 1 below.

$$\sum M_{in} = \sum M_{out} \text{ (Where, M is mass in kg)} \qquad (1)$$

Given that,

$$\sum M_{in} = M_{raw\,mix} + M_{ash\,input} \qquad (2)$$

$$\sum M_{out} = M_{clinker} + M_{dust\,loss} + M_{byproduct\,loss} \qquad (3)$$

2.2 Energy balance around kiln plant and clinker cooler units

For negligible sum of change in potential and kinetic energies, the system general energy balance can be expressed as:

$$\sum E_{in} = \sum E_{out} \qquad (4)$$

Where, E_{in} and E_{out} are energies transferred in and out of the system. Eq. 4 can then be rewritten as,

$$Q + \sum M_{in} H_{in} = W + \sum M_{out} H_{out} \qquad (5)$$

Where, H_{in} and H_{out} are enthalpies of the system inlets and outlets respectively. For negligible loss of heat (Q = 0) and no work perform by the system (W = 0), eq. 5 becomes,

$$\sum M_{in} H_{in} = \sum M_{out} H_{out} \qquad (6)$$

Therefore, pyro-processor system energy efficiency for a cement plant is estimated based on eq. 7.

$$Energy\ efficiency, \eta = \frac{clinker\ formation\ energy}{Total\ energy\ input}\ x\ \frac{100}{1} \qquad (7)$$

2.3 Exergy balance around kiln plant and clinker cooler units

Exergy of a cement production plant can be defined empirically according to Dincer and Cengel (2001) as follows,

$$Ex = U_0 + P_0 V + T_0 S + \sum \mu_i n_i \qquad (8)$$

Where;U_0, S = internal energy and entropy of plant, P_0, T_0 = operating pressure and temperature, V = volume or capacity of plant and μ_i, n_i= chemical potential and number of moles of components of plant. Although, total exergy of the plant can be divided into four components: physical exergy, Ex_{ph}, kinetic exergy, Ex_{kn}, potential exergy, Ex_{po} and chemical exergy, Ex_{ch}. For a cement production plant, kinetic and potential exergies are negligible when compared to the other two.

Specific physical exergy can be expressed as,

$$Ex_{ph} = (H - H_0) - T_0 (S - S_0) \qquad (9)$$

If ideal gas flows with constant specific heat, c_p is assumed, and then the physical exergy, Ex_{ph} is expressed as,

$$Ex_{ph} = c_p(T - T_0) - T_0(c_p \ln(T/T_0) - R\ln(p/p_0)) \qquad (10)$$

For the solid and liquid streams, physical exergy is expressed as,

$$Ex_{ph} = c_p(T - T_0) - T_0 \ln(T/T_0) - V(P - P_0) \qquad (11)$$

At constant specific volume, V, at T_0 with negligible change in pressure, last term in eqs. 10 and 11 reduces to zero.

Chemical exergy is defined as maximum possible work that can be acquired during a process that brings the system from environmental condition (T_0, P_0) to the dead state (T_0, P_0, μ_{0i}). The chemical exergy of the ideal gas and liquid mixtures can be estimated using eq. 12.

$$Ex_{ch} = \sum x_i (Ex^0{}_{chi} + RT_0 \ln(x_i)) \qquad (12)$$

Where x_i = mole fraction of the specie i, $Ex^0{}_{chi}$ = standard chemical exergy.

Three significant factors used for determining a cement kiln plant exergy profile are estimated as follows:

1. $$Exergy\ efficiency, \eta_{ex} = \frac{clin\text{ker}\ formation\ exergy}{Total\ exergy\ input} \qquad (13)$$

Eq. 13 also corresponds to the net thermal efficiency, η_g, of the cement kiln plant which is defined as fraction of fuel heat consumed in relation to the latent heats of the clinker forming reaction steps.

2. Anergy, φ is a factor which measures dead exergy. It is empirically expressed as,

$$Anergy,\ \varphi = \frac{Ex_{losses}}{Ex_{input}} \qquad (14)$$

3. Irreversibility of system, I_{sys} is another factor used to determine exergy destroyed in a cement kiln plant operation. Therefore,

$$I_{sys} = Ex_{input} - Ex_{output} = T_0 S_{gen} \qquad (15)$$

Where S_{gen} is the entropy generated. Thus, exergy and energy of a system can interconvert based on a quality factor, which is a conversion factor for energy to exergy and vice-versa (Banerjee and Khurana, 2002).

$$Exergy = Energy * Quality\ \ factor \qquad (16)$$

The quality factor is a function of reference (T_o) and stream (T_s) temperatures of the cement kiln plant operation. It is also expressed as

$$Quality, \% = (1 - \frac{T_0}{T_s})\, x \frac{100}{1} \qquad (17)$$

2.4 Waste heat recovery and steam boiler system for UCC

The proposed waste heat recovery and steam boiler system (WHRSB) for the United Cement Company (UCC) plant will collects heat contained in waste gas streams from kiln plant and clinker cooler units (Figure 3), and contact it on the shell sides of water tubes in the WHRSB. The basic principle of its operation will require water to serve as working fluid. The water is pressurized by a fluid pump (FP) into the tubes of the WHRSB system where it gains latent heat of vaporization to change into steam. The steam at high pressure will expand through the steam turbine (ST) to produce work (W_s) which turns an electric generator (G) to produce electric power. The exhausted steam is condensed into liquid water which is again put into continuous circulation by the pump. The thermodynamics cycle for the WHRSB operation is called the Steam Rankine Cycle (Figure 4).

Thermodynamic analysis of this cycle will rely on basic assumptions such as adiabatic and reversible operation of turbine; constant pressure operation of steam boiler and condenser, and negligible contribution of pump work to the net work produced by cycle. Parameters computed include: i. heat added to cycle by the steam generator (Q), ii. Net work (or power) produced by cycle (W_{net}), iii. Thermal (η) and turbine (η_t) efficiencies of cycle and cost of electric power (Smith et al, 2001; Wark and Richards, 1999).

Thermal efficiency:

$$\eta = \frac{W_{net}}{Q} \, x \, \frac{100}{1} \tag{18}$$

Turbine efficiency:

$$\eta_t = \frac{W_S(axtual)}{W_S(isentropic)} \, x \, \frac{100}{1} \tag{19}$$

Cost of actual electric power:

$$P = W_S(actual) \, x \, M_S \tag{20}$$

$$C = P \, x \, t \, x \, T \tag{21}$$

Where P = power generated, KW: W_s(actual) = actual turbine work, kJ/kg; M_s = steam rate, kg/s; t = electric power supply time, h; T = local tariff, NGN/kWh and C = cost of electric power, NGN.

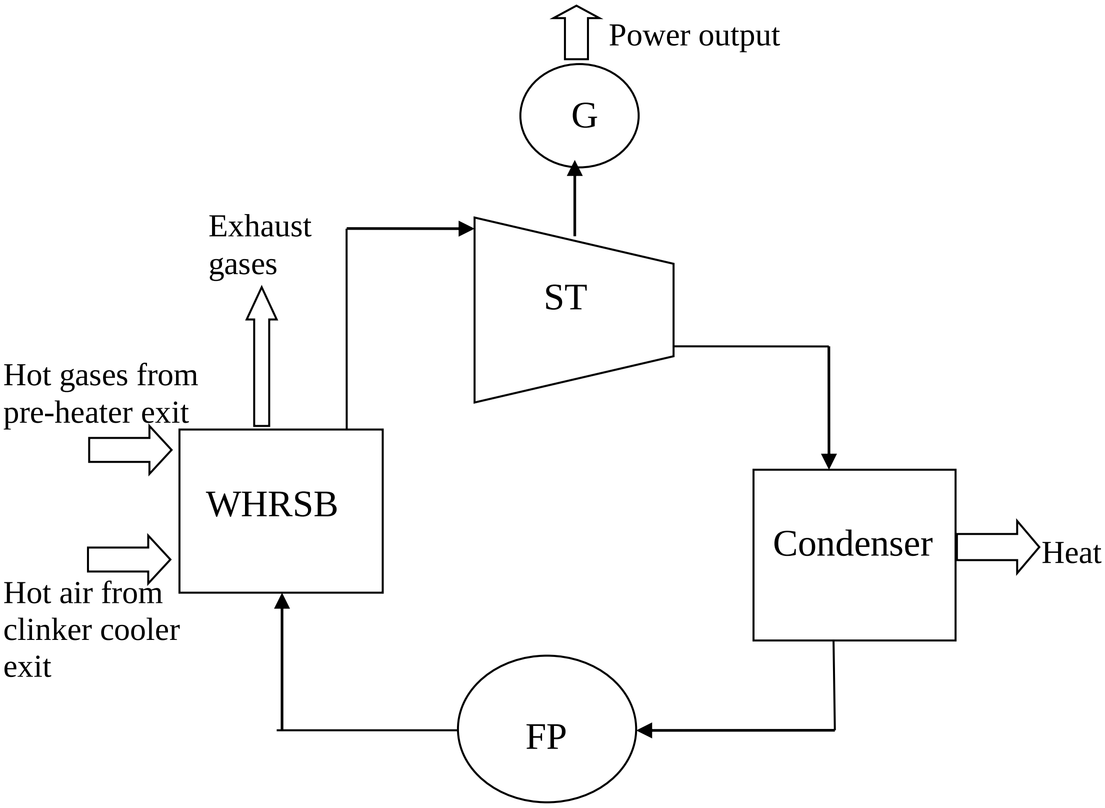
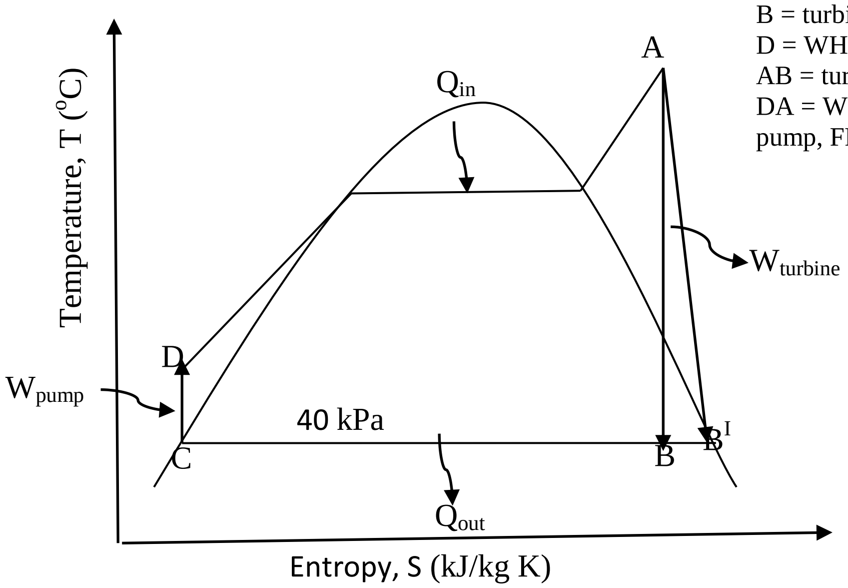


Figure 3: Proposed waste heat recovery and steam boiler (WHRSB) system.



Rankine cycle description key:
A (turbine inlet: 300 °C and 3500 kPa)
B = turbine outlet, C = condenser outlet,
D = WHRSB (or boiler) inlet,
AB = turbine, BC = condenser
DA = WHRSB or boiler, CD = fluid pump, FP

Figure 4: Simplified Steam Rankine Cycle for the WHRSB

2.5 Fuel optimal consumption model

The specific heat consumption (SHC) of a cement kiln plant can be reduced to optimum value by optimizing the fuel consumption in the pyro-processor units. Therefore, a simple optimization equation was formulated to predict optimum fuel consumption for a given kiln feed rate. Design data for the UCC (kiln plant) was used for the formulation. The application of the model did not compromise both production rate and quality of the cement clinker. Specific heat consumption (SHC) is a function of production rate, fuel lower heat value (LHV) and fuel consumption rate (Edgar et al, 2001; Avsar, 2006; Jankovic and Walter, 2010).

$$SHC = \frac{(total\ fuel\ consumption\ rate)(LHV)}{clinker\ production\ rate} = \frac{\sum F\ x\ LHV}{clinker\ production\ rate} \qquad (22)$$

Thus, the Fuel Optimal Consumption model is expressed as,

$$\sum F = A K_f + \sum B \qquad (23)$$

Where: $\sum F$ = total fuel consumption rate in the pyro-processor unit, kg/h; A = constant of fuel to Kiln feed proportion, kg/ton; K_f= Kiln feed rate, ton/h and $\sum B$ = total fuel consumption rate due to wall losses, kg/h.

3.0 DISCUSSION OF RESULT

The results obtained from this work are discussed under the subheadings: material and energy requirements for UCC process, exergy analysis of the UCC process, thermodynamic analysis of WHRSB system and energy cost benefit, and fuel consumption optimization.

3.1 Material and energy requirements for the UCC process

On the basis of raw meal/cement clinker factor of 1.6, the UCC was designed to produce 6250 tons/day (or 2.3 million tons/year) of cement clinker using fuel/clinker ratio of 0.08, from which 60 and 40 % of the fuel were respectively consumed at the pre-heater-calciner and kiln units. However, actual operations of the UCC for a given period of time had showed an average production capacity of 5912 tons/day cement clinker which was in line with raw meal/cement clinker factor of 1.58. Also, the maximum operating temperatures for pre-heater, kiln and clinker cooler units were respectively at 340, 1450 and 300 ^{o}C (Table 1).

Table 1: Material requirement and operating parameters for UCC

Parameter	**Operating value**	**Designed value**
Production, ton/day	5912	6250
Specific fuel consumption, kg fuel/kg clinker	0.08	0.06 – 0.08
% fuel in pre-heater	58	60
% fuel in Kiln	42	40
Raw meal/clinker factor	1.58	1.6
Calcination Degree, %	98	98
Pre-heater exit temperature, ^{o}C	352	310 – 340
O_2 in pre-heater exit, %	3.5	3 – 5
O_2 in kiln backend, %	1.7	1.5- 2.5
Specific Heat capacity, kJ/kg clinker	3214	3100
Cooler water injection, L/h	50	50
Clinker temp from Kiln, ^{o}C	1450	1450
Cooler exit air temp, ^{o}C	300	250 – 300
Clinker temp. from cooler, ^{o}C	151	85 – 120

Information about the energy requirements of cement production process at UCC were generated from energy balance calculations which was established on the basis of I kg cement clinker. The total heat input into the pre-heater unit was 3583.27 kJ/kg-clinker (Table 2), thus, given rise to a thermal efficiency, η of 77%. Total heat loss from pre-heater exit gas and walls was estimated as 19% of the total heat input. Also, from Table 3, the thermal efficiency, η of the kiln was estimated as 72.3%. This value of kiln efficiency was attributed to good heat exchange between the raw meal and kiln burners. Also, an associated heat loss from the kiln unit (due to kiln wall) is estimated as 3.46 %.Table 4 showed the estimated heat balance around the clinker cooler unit which operated at 6.8 % excess air. Heat losses from the clinker cooler exhaust attained about 14.5% of the total heat output from the clinker cooler. Therefore, an operating temperature of 262 ^{o}C for clinker cooler exhaust air is a potential source for heat recovery in the UCC plant. Consequently, an overall thermal efficiency, η of the UCC kiln plant was estimated as 55.5% (Table 5).The obtained results corroborates with Camdali et al (2004), Kabir et al (2009), Engin and Ari (2005), where losses from input energies were experienced to varied degrees (5 – 40 %) through cement plant units similar to the one under this study.

Table 2: Energy balance around pre-heater-calciner unit

Pre-heater-Calciner heat energy balance		
Component	Input (kJ/kg clinker)	Output (kJ/kg clinker)
Raw meal	123.15	
False air	0.13	
Kiln gas to calciner	659.42	
Kiln dust	61.40	
Tertiary air	832.18	
Tertiary air dust	53.66	
Fuel oil	1851.60	
Pre-heater exit gas		532.57
Pre-heater dust		34.32
Hot meal		942.65
Wall heat losses		150.00
Heat of reaction		1923.72
Total	**3583.26**	**3583.26**

Table3: Energy balance around the rotary kiln

Rotary kiln heat energy balance		
Component	**Input (kJ/kg clinker)**	**Output (kJ/kg clinker)**
Hot meal	942.65	
False air	0.13	
Secondary air	541.94	
Primary air	27.77	
Fuel oil	1390.87	
Hot clinker		1580.20
Clinker dust		237.03
Kiln gas to pre-heater		659.42
Wall heat losses		94.20
Heat of reaction		332.51
Total	**2903.36**	**2903.36**

Table 4: Energy balance around the clinker cooler unit

Clinker cooler unit heat energy balance		
Component	**Input (kJ/kg - clinker)**	**Output (kJ(kg - clinker**
Clinker from the kiln	1580.20	
Cooling air	21.33	
False air cooler	0.37	
Water input	0.00	
Clinker exhaust		107.03
Secondary air + dust		540.66
Tertiary air + dust		684.22
Cooler waste air		224.67

Water evaporation		0.50
Radiation losses		20.00
Excess heat		24.82
Total	**1601.90**	**1601.90**

Table 5: Overall energy balance around the pyro-processor

Overall balance around pyro-processor unit		
Component	**Input (kJ/kg-clinker)**	**Output (kJ/kg-clinker)**
Raw meal	123.15	
False air	0.26	
Secondary air	541.94	
Primary air	27.77	
Cooling air	21.33	
Fuel oil	3242.48	
Tertiary air +Kiln dust	947.24	
Heat of formation		2255.78
Pre-heater exit gases		532.57
Wall heat losses		244.20
Clinker exhaust		107.03
Cooler waste air		224.67
Kiln air + dust + water vapor		1225.38
Unaccounted loss		319.24
Total	**4904.17**	**4904.17**

3.2 Exergy analysis for the UCC process

The input and output exergies of the cement clinker production was estimated as 3107.09 and 2103.29 kJ/kg-clinker respectively (Table 6), which indicated an exergy efficiency of 67.7 %. This efficiency value is a confirmation of the extent of available energy utiulization in the UCC process. Also, it is an indication that there exist potentials for improving energy consumption within the system. Energy qualities that were accounted for (in Table 6)within the UCC process showed the highest value of 95 % for the fuel sensible heat followed by heat of clinker formation, and lowest value of 1.0 % for the primary air sensible heat.For this UCC process, the difference between the input and output exergy is1003.80 kJ/kg-clinker. This value is a direct measure for dead exergy (or anergy, φ = 32.3 %). Dead exergy is energy wasted or unaccounted for.

Also, reports from Camdali et al (2004), Kabir et al (2009), Engin and Ari (2005) for similar cement plants corroborated with the results of this present study, because losses from input exergies observed through fuel combustion, kiln wall, calcinations, clinker formation and some unidentified sources were between 30 – 40 %.

Table 6: Exergy analysis for UCC process

Stream	T(^{o}C)	Energy (kJ/kg-clinker)	Quality (%)	Exergy (kJ/kg-clinker)
Input				
Fuel sensible heat (kiln & pre-heater)		3242.48	95	3080.36
Kiln feed sensible heat	90	207.2	19.28	39.95
Primary air sensible heat	60	27.77	12.01	3.34
Cooler air sensible heat	30	21.33	3.3	0.704
Total		**3498.78**		**3124.35**
Output				
Heat of formation	900	2255.78	75.02	1692.29
Water evaporation (kiln feed & cooler)	300	6.3	45.23	2.85
Kiln exhaust gas sensible heat	352	1219.08	53.12	647.58
Cooler waste air sensible heat	300	224.67	45.23	101.62
Clinker exhaust sensible heat	151	107.03	30.9	33.07
Heat losses due to pre-heater-calciner, kiln, clinker cooler cyclones etc.	200	796.77	38.05	303.17
Total		**4609.53**		**2780.58**

3.3 Thermodynamic analysis of the waste heat recovery and steam boiler (WHRSB) system

The WHRSB operates on a Simple Rankine Cycle which was based on operating conditions shown in Table 7, from which measured enthalpy and entropy values were obtained using PVT table for water and steam (Smith et al., 2001; Cengel and Boles, 2001). Actual thermal efficiency obtained for the system was 12.9 % (see Table 8). This is an indication that shaft work (W_s) of 341.9 kJ/kg-steam, equivalent to 11.97 MW electric power was produced by the WHRSB system. Therefore, based on a local electric tarrif, a gross annual savings from electric power supply to the cement plant from the WHRSB system was estimated as #4.085 billion naira. This will cause a direct reduction in the cost of the total energy consumption in the cement plant.

The reports of Engin and Ari (2005), Wang et al (2009), Shrikant and Chaube (2013) and Farag and Taghian (2015) had corroborated with the results of this present study in terms of waste heat recovery and conversion potentials. For instance Engin and Ari (2005), Shrikant and Chaube (2013) reported that 15 and 26.25 MW of electric power were respectively generated from waste heat energies of its own cement plants.

Table 7: Thermodynamic property of steam in the Rankine cycle of the WHRSB system

Node	**State**	**T (^{o}C)**	**P (kPa)**	**H (kJ/kg$_{steam}$)**	**S (kJ/kg$_{steam}$ K)**
A	Superheat steam	300	3500	2979.0	6.45
B	Mixture (V + L)	76	40	2173.3	6.45
B^I	Saturated vapour	76	40	2637.1	7.67
C	Saturated Liquid	76	40	318.1	1.03
D	Liquid	-	3500	318.1	-

Table 8: Analysis of waste heat recovery and steam boiler (WHRSB) system

Parameter	**Value**
Circulation rate of steam, kg$_{steam}$/s	35
Heat added by steam boiler, kJ/kg$_{steam}$	2660.9
Work produced by steam turbine in: Isentropic operation, kJ/kg$_{steam}$ Actual operation, kJ/kg$_{steam}$	805.7 341.9
Thermal efficieny of cycle (ideal), %	30.3
Thermal efficiency of cycle (actual), %	12.9
Turbine efficiency, %	42.4
Power generated, MW	11.97
Annual electric power supply from the WHRSB, kWh	104,857,200
*Gross annual savings from the electric power supply	#4,085,236,512=00

*Local electric tarrif = #38.96 per kWh

3.4 Fuel consumption optimization

Based on UCC kiln parameters (Table 9) and other defined correlations, a fuel consumption optimization equation was developed for the UCC kiln plant as presented: $\sum F = 45.27K_f + 794.28$. This equation was used to generate optimal values of total fuel consumption rate and specific heat consumption at given kiln feed rate of raw meal (Table 10). Fuel savings between actual and optimal fuel consumption rates were also estimated. Hence, a maximum fuel saving of 10.6 % was estimated at kiln feed rate of 395 ton/h. Therefore, kiln feed rate of 395 ton/h is preferred to the designed feed rate of 411 ton/h.

Table 9: Some operating parameter for the UCC kiln

Parameter	**Value**
Max. kiln feed rate, ton/h	411
Max. specific heat consumption, SHC, kcal/kg	809
Wall losses, kcal/kg	29.89
LHV$_{FO}$, kcal/kg	9800
Clinker production rate, ton-clinker/h (or kg-clinker/h)	260.42 (or 260420)

Table 10: Fuel consumption optimization

Feed rate, ton/h	Actual fuel rate, kg/h	Actual SHC, kcal/kg	Optimal fuel rate, kg/h	Optimal SHC, kcal/kg	Fuel savings, kg/h
200	11000	414	9848.28	370.61	1151.72
220	12000	452	10753.68	404.68	1246.32
240	13000	489	11659.08	438.75	1340.29
260	14000	527	12564.48	472.82	1435.52
280	15000	564	13469.88	506.89	1530.12
300	16000	602	14375.28	540.96	1624.72
320	17000	640	15280.68	575.04	1719.32
340	18000	677	16186.08	609.11	1813.92
360	19000	715	17091.48	643.18	1908.52
380	20000	753	17996.88	677.25	2003.12
395	20900	786	18675.93	702.80	2224.07
400	21000	790	18902.28	711.32	2097.72
411	21500	809	19400.25	730.06	2099.75

4.0 CONCLUSION

Energy requirement for the UCC cement clinker plant is highly intensive, as it requires 500,000 kg-fuel/day to process 6250 ton-clinker/day. From the energy and exergy analysis performed around the plant, energy and exergy efficiencies were estimated as 55.5 % and 67.7 % respectively. These values showed that the cement plant is faced with substantial measure of energy losses through identified sinks: exit gases and kiln walls as evident from the energy and exergy balances performed especially around the pre-heater, kiln plant and clinker cooler units.

The thermal energy saving potential of the UCC was enhanced using a proposed waste heat recovery and steam boiler (WHRSB) system which will help harness the waste heat from exit gases and clinker unit. Consequently, the turbine unit in the WHRSB system generated an estimated 11.79 MW of electrical power, capable of saving a gross annual cost of #4.085 billion naira supplies of electric power to the cement plant. Also, a maximum fuel savings of 10.6 % at feed rate of 395 ton/h can be obtained in the plant using the developed fuel optimization model. The accuracy of this model would depend to a large extent on the integrity of the kiln wall interior.

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