Energetic and Exergetic Analytical Approaches in Optimizing Clinker Cooler Performances: A Case Study of a Cement Plant in Nigeria

ABSTRACT

Optimizing energy, reduction of global warming and de-carbonization in a cement production is becoming a global discuss. This research work seek ways of optimizing energy recovery and exergy recovery of a clinker cooler in a running cement plant in Nigeria. The cement plant used for this research has production capacity of 6000 tons of clinker per day, and with an energy mix of natural gas and heavy fuel oil (HFO). Energy recovery and exergy recovery in a clinker cooler was a major factor in optimizing clinker production and cement grinding process, the running clinker cooler has an energy recovery was 48.31% which was despite the high energy efficiency of clinker cooler which was above 90%. The exergy recovery of the clinker which was 43.31%, which was also observed to be lower when compared to exergy efficiency of the running clinker cooler which was 63.2%. The low energy and exergy recovery can be improved upon by reducing energy losses through convection, radiation, and hot clinker leaving the clinker cooler.

Keywords: Energy recovery, Exergy recovery, Clinker cooler, Mass Flow Rate and Temperature.

1. INTRODUCTION

Cement industries is considered to be one of the most energy intensive industry worldwide. This lead to the continuous improvement on economic, energy, technological and other areas are widely studied, [1-19]. Specific energy consumption in cement plant is a major factor that measures the industry efficiencies in terms of its clinker production (in MJ per ton clinker). The production processes in cement industries needs electrical energy between 95 to 110 kWh per ton of cement produced which amount to about forty percentage (40%) of the energy needed for clinker grinding [20].

Clinker coolers can be considered as a heat exchanger. Heat exchangers are devices that allow heat to be transferred between two fluids. Such heat exchange could occur either directly between the fluids or indirectly over a material [21]. The clinker cooler, which acts as a heat exchanger, is used to reduce the temperature of the clinker as it exits the rotary kiln to an expected temperature of 373 K before it is transferred to a cement grinding station [22]. Fresh air is supplied through a series of suction fans across the layers of hot clinkers to cool them. The recovered energy (hot air) from this process is used as the main burning air (secondary air) for the rotary kiln and as the burning air (tertiary air) for the kiln with pre-calciner. The rest of the air is sent to the stack via the main bag house or electrostatic precipitators (ESP).

After leaving the rotary kiln, the clinker must be promptly cooled to ensure maximal output of the alite that contributes to the hardening qualities of cement [22]. Improving energy recovery in a clinker cooler requires maximizing fresh air entering within suction fans by optimizing clinker cooler operational parameters such as: clinker input rate, clinker bed depth, clinker inlet temperature, cooler length, number of air openings, and clinker cooler speed. Optimizing heat recovery in a clinker cooler saves fuel, improves product quality, lowers maintenance costs, and lowers emission levels [22-24]. Clinker is the primary ingredient in Ordinary Portland Cement (OPC). It is produced by calcining raw meal. Raw meal is made by grinding limestone, shale, and iron ore together. The raw meal mixture is stored in homogenizing silos before being burned in a rotary kiln at temperatures ranging from 1623 to 1723 K [25]. Clinker production is divided into three major processes: wet process, semi-wet process, and dry process, which is the modern technology used by equipment manufacturers due to its efficiency and thermal energy reduction. Cement production is a capital and energy intensive process. The energy process is of particular interest to industry shareholders, investors, and stakeholders. For more than two decades, energy recovery has piqued the public's interest. [26], investigated the energy audit and recovery for a 6000-tonne-per-day dry process cement rotary kiln system. According to the study, optimizing heat recovery and improving clinker cooler efficiency could recover approximately 15.6% of total energy input. The efficiency of a clinker cooler is critical in heat recovery from hot clinker and subsequent re-use of heat in pre-heating the air used in calcination. The recovered energy and preheated air are referred to as secondary air, which is fed back into the rotary kiln, and tertiary air, which is used in the calciner for the calcination process. The unrecovered heat that escapes from the cooler with the clinker as waste/exhaust air and radiation represents the majority of the system's actual energy loss [27, 28].

According to [4, 28], improving the efficiency of heat recovery in the clinker cooler would result in fuel savings, improved cement quality, and a lower emission rate. Ahamed et al. [29] calculated the grate cooler's first and second law efficiencies under various operating conditions. Using energy recovered from exhaust air, the cooling system's energy and exergy recovery efficiencies were found to have increased by 21.5% and 9.4%, respectively [30]. Poor clinker heat recuperation inside the clinker cooler results in: energy loss to the environment, large amounts of water consumption at cement grinding stations, resulting in poor-quality cement produce, equipment damage, and increased maintenance costs. Figure 1a, depicts the clinker cooling process within the cooler and Figure 1b shows the clinker pan conveyor with red hot clinker (poor cooling process and energy loss).

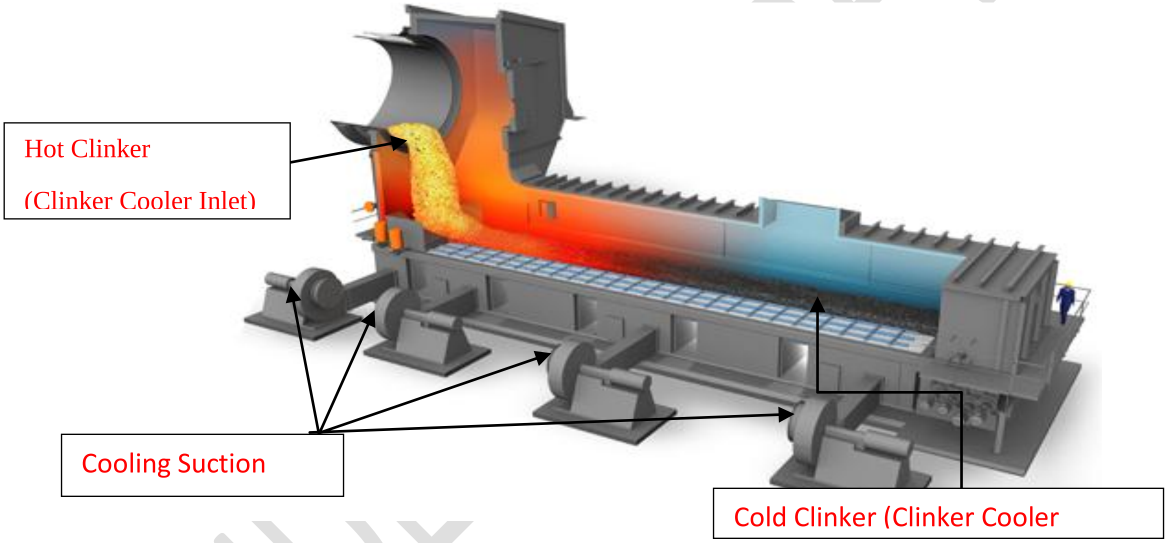


Fig. 1a. Cross- sectional view of clinker cooling process insider a grate cooler [3, 4]

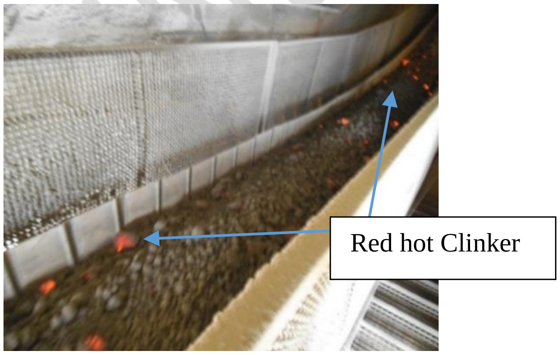


Figure 1b, Red Hot clinker leaving the Clinker Cooler (Nigeria).

There are numerous challenges associated with improper cooling of clinker inside the clinker cooler in a cement plants as shown in Figure 1b. This work tends to look into the energetic and exergetic optimization of an existing running in Nigeria. The findings from this research can be apply to other cement plants that are face with similar challenges.

2. METHODS

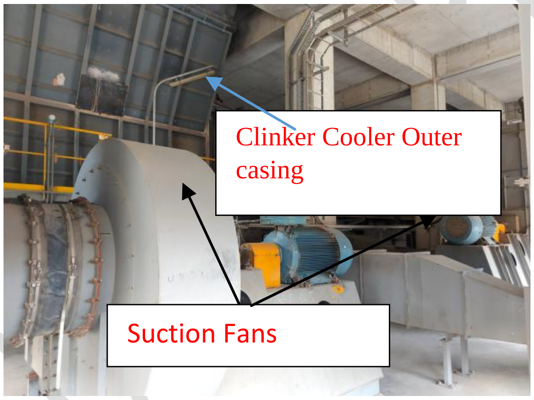
The aims is to further search for ways of optimizing cement plant operations and reduction in the global warming which is ravishing the environment and the world at large. The findings from this research will also support the goals of zero (0) carbon emission in cement and other plants that are associated to similar production process.

This research, we will be taken into account two (2) technological approaches in carrying out these analyses:

a) it is assumed the clinker bed is rectangular packed flow-bed;
b) it is also consider that the cooler is a system; and
c) the performances of the system will be analyzed by evaluating the efficiencies of the energetic and exergetic and optimization.
d) the clinker as two zones (hot zones and cold zones)

2.1 Heat Flow across Clinker Cooler Walls and Fluid Transfer

The clinker cooler is lagged with refractory material and this is a flow heat from the inner part of the clinker cooler due to temperature gradients. The refractory installation are installed in segments. A suction fan unit is used to suck in the surrounding air into clinker cooler, which has a series of pan conveyors and a perfect cross-flow heat exchange [31]. Correlations based on macro-hydrodynamic criteria define heat transfer and pressure drop [32, 33]. Figure 2a, shows a fans arrangement and Figure 2b, and shows the clinker cooler undergoing repairs in a Nigeria cement plant.



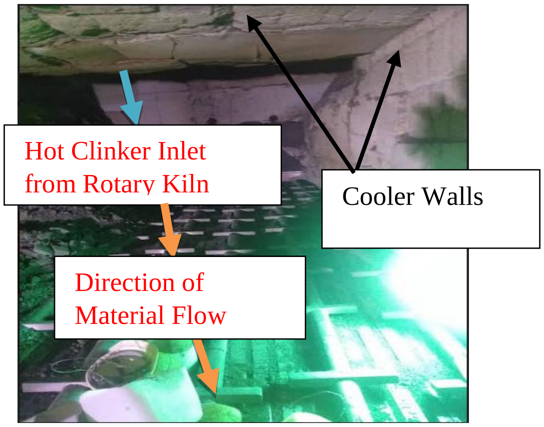


Figure 2a. Suction fan arrangement clinker cooler Figure 2b. Internal arrangement of clinker cooler (Nigeria).

The clinker cooler is assumed to be in a rectangular packed flow-bed with two zone in it. The hot zones is noted as “K_w” and the number of cold zones is noted as “L_c” using equation (1) and (2) as reported by [34].

$$K_w = \left(\frac{H_w L_w w D_{clk}}{M_{clk} t_{res\,time}} \right) \quad (1)$$

$$L_c = \left(\frac{H_c L_c w D_{clk}}{M_{clk} t_{res\,time}} \right) \quad (2)$$

where: H_w is the hot zone height, H_c is the cold zone height, D_{clk} is the clinker density, H_{clk} is clinker bed height in the hot zones, L_w is the length of the clinker in the hot zone, L_c is the length of the clinker in the cold zone, $t_{res\ time}$ is average resident time. The hot zone height (H_w) of the clinker cooler will be determined using equation (3) as reported by [4, 35].

$$H_w = \left(\frac{M_{clk}}{C_g W_w D_{clk} w} \right) \quad (3)$$

Cold zone height (H_c) of the clinker cooler will be determined using equations (4) as noted by [33, 35].

$$H_c = \left(\frac{M_{clk}}{C_g W_c D_{clk} w} \right) \quad (4)$$

where: C_g is the length covered grate, w is cooler width, W_w is the frequency of cooler at the hot zone, W_c is the frequency of cooler at the cold zone, M_{clk} is the mass flow rate of clinker. Heat losses in each of segment of the cooler depends upon heat transfer coefficient, thermal resistance and heat transfer areas in each of the segment and these was determined using equations (5), (6) and (7) as stated by [4, 5, 34].

For heat losses acrossing the walls,

$$Q_{pi} = \left(\frac{1}{R_{ti} (T_{pi} - T_o)} \right) \quad (5)$$

For convective heat transfer using the total heat transfer coefficient h_{fi}

$$Q_{pi} = h_{fi} A_i \left(T_i - T_{pi} \right) \quad (6)$$

For total thermal resistance R_{ti}

$$R_{ti} = \left(\frac{1}{A_i (t_{br} / t_{cbr} + t_s / t_{cs} + 1 / h_c)} \right) \quad (7)$$

where; A_i is segmented area, Q_{pi} is heat losses across each segment, T_{pi} is wall temperature at the outer part of each segment, T_i is the temperature the heat at inner parts of each segment, t_{br} thickness of the refractories, t_{cbr} thermal conductivity, t_s shell (metal) thickness, t_{cs} thermal conductivity of refractories material, t_s thickness of the shell; and h_c is convection heat transfer coefficients. Thermal resistance of any segment depends upon the followings: area, refractories, thermal conductivity of the shell, a shell thickness, and convection heat transfer coefficient (h_c). The convection heat transfer coefficient is obtained using equation (8) as noted by [34].

$$h_c = \frac{N_u K_{air}}{d_s} \tag{8}$$

Nusselt number (Nu) is obtained using equation (9) as reported by [34].

$$Nu = \left(0.0295\left(\mathrm{Re}^{\frac{4}{5}}\ \mathrm{Pr}^{\frac{1}{3}}\right)\right) \tag{9}$$

Reynold number (Re) is also obtained using equation (10)

$$\mathrm{Re} = \frac{d_s \rho_{air} U_{air}}{((1-por)\mu_{air})} \tag{10}$$

Prandtl number (Pr) is determined using equation (11)

$$\mathrm{Pr} = \frac{\mu_{air} cp_{air}}{K_{air}} \tag{11}$$

where d_s is the clinker diameter, ρ_{air} density of air, U_{air} velocity of air, P_{or} porosity, K_{air} is the thermal conductivity of air; and μ_{air} is the Dynamic viscosity [34]. Table1, shows some of the data collected from the existing running clinker cooler in Nigeria.

S/N	Parameters	Values
1	Clinker bed height (m)	0.5
2	Cooler speed (stroke/min)	16
3	Clinker mass flow (kg/s)	0.65
4	Air mass flow (kg/s)	1.49
5	Clinker inlet Temp (K)	1663
6	Clinker Outlet Temp (K)	498
7	Air inlet Temp (K)	318
8	Cooler Length (m)	30
9	Cooler width (m)	5
10	Secondary air Temp (K)	1083
11	Tertiary air Temp (K)	993
11	Exhaust air Temp (K)	508

Table 1, shows the data collections for an existing running plant in Nigeria.

2.2 Energy and Exergy Analysis in the Clinker Cooler as a System.

The clinker cooler is consider a steady state conditions and mode of heat transfer between air and clinker is via convection. Using Newton's law of cooling, the heat transfer rate therefore will be proportional to the temperature difference between the clinker temperature and air temperature (ambient temperature) at each stage using equation (12), [9, 24].

$$m_{clk}Cp_{clk}\,dT_{clk} = -\; k\left(T_{clk} - T_o\right)dt \qquad (12)$$

where T_o is the ambient temperature which can be neglected as its value is small compared to the clinker temperature (T_{clk}), k is the thermal conductivity of clinker, Cp_{clk} is the specific heat capacity [9]. To obtain the clinker temperature at any point in the clinker cooler, this can be derive by using equation (13) and equation (14) where T_o is negligible, [9]:

$$m_{clk}Cp_{clk}\,dT_{clk} = -kT_{clk}\,(dt) \qquad (13)$$

Integrating equation (13) with limits of temperature of clinker inlet (T_{clkin}) to temperature of clinker at any point (T_{clkp}) inner the clinker cooler (moving),(*t*) is the time taken for the clinker travel at any point inner the clinker cooler this expressed in equation (14) and equation (15), [9, 35]:

$$\int_{T_{clkin}}^{T_{clkp}} \frac{dT_{clk}}{T_{clk}} = -\frac{kt}{m_{clk}c_{p\,clk}} \qquad (14)$$

$$\ln\frac{T_{clkp}}{T_{clkin}} = -\frac{kt}{m_{clk}Cp_{clk}} \qquad (15)$$

Clinker temperature at any point inner the clinker cooler is expressed in equation (16)

$$T_{clkp} = T_{clkin}e^{-\frac{kt}{m_{clk}Cp_{clk}}} \qquad (16)$$

The time (*t*) taken for clinker travel at point or distance (*p*) is expressed in equation (17):

$$t = \frac{p}{V} \qquad (17)$$

where is (*p*)is distance travelled at any point inner the clinker cooler and *V* cooler speed.

Energy balance on the clinker cooler is expressed in equation (18), [2, 36, 37]

$$Q = mCp(T - T_o) \qquad (18)$$

Substituting equation (16) into equation (18). Clinker heat transfer at any point along the grates with respect of T_{clkp} is expressed in equation (18):

$$Q_{clkp} = m_{clk} Cp_{clk} \left(T_{clkin} e^{-\frac{kt}{m_{clk} Cp_{clk} - T_o}} - T_o \right) \tag{19}$$

where, (m_{clk}) is mass flow rate of clinker, (T_{clkin}) is the inlet clinker temperature, (Cp_{clk}) is the specific heat capacity of the clinker. Cooling air heat transfer equal to equal the clinker heat transfer at any point in the cooler because of the heat loss on the hot clinker which is equal to the heat gained on cooling air on the packed clinker bed. Therefore heat loss by clinker are gained cooling air expressed in equation (20), [9]:

$$Q = Q_{airp} = Q_{clkp} = m_{air} Cp_{air} (T_{airp} - T_o) \tag{20}$$

where, (T_{airp}) is temperature at any point inner the cooler, (m_{airp}) mass flow rate of air into the cooler and (Cp_{air}).

Substituting equation (18) into equation (19), therefore T_{airp} is expressed in equation (21):

$$T_{airp} = \frac{m_{clk} Cp_{clk}}{m_{air} Cp_{air}} \left(T_{clkin} e^{-\frac{kt}{m_{clk} Cp_{clk}}} - T_o \right) + T_o \tag{21}$$

2.3 Mass Flow and Energy Balancing Analysis on the Existing Clinker Cooler

The rate of flow and energy balancing analysis of clinker and air on the existing clinker cooler remained constants as shown on Figure (3) and Figure (4) and it is expressed in equation (22) [3, 4]:

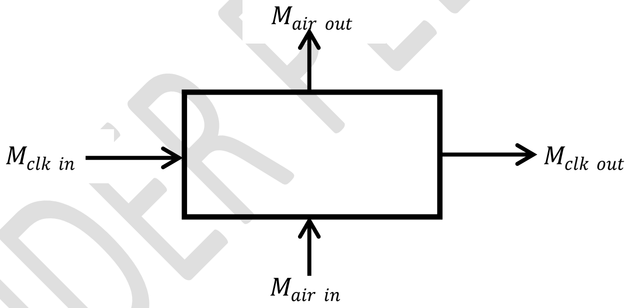


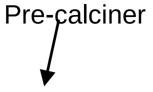
Figure 3: Mass flow rate of existing clinker cooler [3, 4]

$$M_{clk_{in}} + M_{air_{in}} = M_{clk_{out}} + M_{air_{out}} = 0 \tag{22}$$

The clinker cooler is assumed to be in a steady state and steady mass flow processes, the mass balance equation as expressed in equation (23) [3, 4, 9, 35, 38].

$$\sum \left(M_{clk\,in} + M_{air\,in} \right) = \sum \left(M_{clk\,out} + M_{air\,out} \right) \tag{23}$$

where M=m it represents mass flow rate; *clk* represents clinker; *in* represents inlet and Out represents outlet.



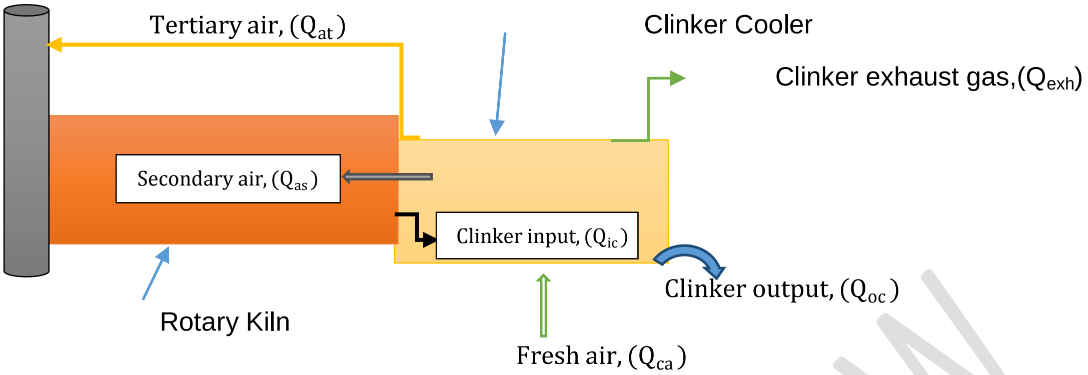


Figure 4: Schematic Energy balance of the Existing clinker cooler

Using 1st law of thermodynamics which states that energy cannot be destroy but can be changed from one form to another during an interaction as shown in Fig.4. Transition of the energy in a body or a system is the same as energy input and the energy output [3, 4, 35, 38]. The energy balance equation is as shown in equation (24), [3, 4, 35, 38].

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{24}$$

Total input energy can be defined by equation (25)

$$\sum \dot{E}_{in} = Q_{ic} + Q_{ca} = M_{clk\,in} c_{pclk} (T_{clk} - T_o) + M_{air} c_{pair} (T_{ac} - T_o) \tag{25}$$

Total energy outputs from the system as obtained from is expressed in equation. (26) [3, 4]:

$$\sum \dot{E}_{out} = Q_{as} + Q_{at} + Q_{oc} + Q_{exh} = M_{secair} c_{psecair} (T_{secair} - T_\beta) + M_{ter\,air} c_{pter\,air} (T_{ter\,air} - T_\beta) + M_{clkout} c_{pclkout} (T_{clkout} - T_\beta) \\ + M_{exhair} c_{pexhair} (T_{exhair} - T_\beta) \tag{26}$$

Q_{as} is the recoverable heat rate of kiln secondary air, Q_{at} is the recoverable heat rate of tertiary air from the cooler, Q_{oc} is the heat of clinker at the cooler output. Q_{exh} is the heat of cooler at exhaust air, Q_{ic} is the heat of clinker at the cooler input. Q_{ca} is the heat of the cooling air.

Energy efficiency is the ratio of the amount of the energy output to input of the system (existing running clinker cooler), is expressed in equation (27) [3, 4, 35, 38]:

$$\eta_E = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \tag{27}$$

Recoverable energy efficiency on the tertiary and secondary air on clinker cooler is expressed in equation (28), [3, 4]:

$$\eta_{recoverable,\,cooler} = \frac{Q_{recoverable}}{Q_{ic} + Q_{ca}} \tag{28}$$

2.4 The exergy in the clinker cooler as a system

Using the principle of the thermodynamics, exergy: is defined as the maximum amount of work which can be produced by a system [37]. Identifying the source of exergy losses and their quantities allows for improvement and optimization of the exergy processes and system using equation (29) as shown in Figure 5.

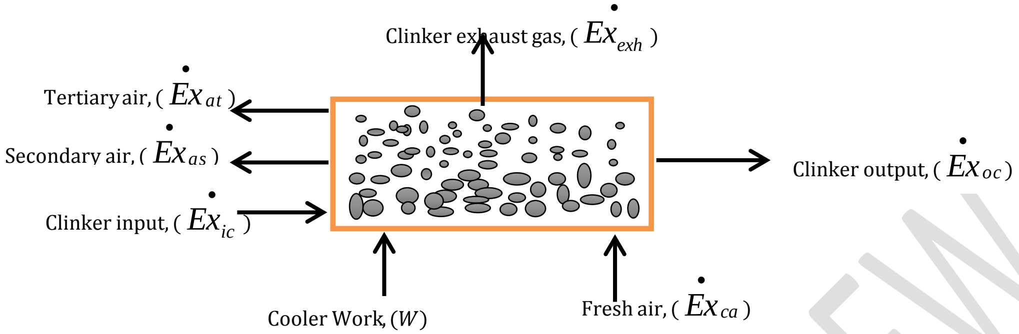


Figure 5: Schematic Diagram of Exergy Balance and Cooler work.

$$\dot{E}x = \left(h' - h_o\right) - T_o(s - S_o) \tag{29}$$

where $(\acute{h})$ is the specific enthalpy and $\acute{s}$ is the specific entropy for the clinker cooler.

Equation (30), for incompressible flow in the clinker cooler:

$$\dot{E}x = mCp(T - T_o - T_o \ln\frac{T}{T_0}) \tag{30}$$

Substituting equation (16) into equation (29), the exergy of clinker at any point insider the clinker cooler is expressed in equation (30):

$$\dot{E}x_{clk} = m_{clk}Cp_{clk}(T_{clkin}\, e^{-\frac{kt}{m_{clk}Cp_{clk}}} - T_o - T_o \ln\frac{T_{clkin}\, e^{-\frac{kt}{m_{clk}Cp_{clk}}}}{T_0}) \tag{31}$$

Substituting equation (20) into equation (30) gives cooling-air exergy at any point inner the travelling clinker cooler is expressed in equation (32):

$$\dot{E}x_{air} = m_{clk}Cp_{clk}\, T_{clkin}\, e^{-\frac{kt}{m_{clk}Cp_{clk}}} - m_{air}Cp_{air}(1 - \ln\frac{\frac{m_{clk}Cp_{clk}}{m_{air}Cp_{air}}\left(Tc_{in}\, e^{-\frac{kt}{m_{clk}Cp_{clk}}} - T_0\right)}{T_0}) \tag{32}$$

3.0 Results and Discussion

Table 1, is the real time data/operational inputs and output of a running pyro-process and the interaction between hot clinker and cold air in a clinker cooling system used in a cement plant in Nigeria. Table 2, shows the results analysis specific heat capacity of the clinker and air inside the clinker cooler, this specific heat capacity was used for analysis and calculate: energy balance, energy efficiency, recovery energy efficiency and the exergy of the operating clinker cooler used.

Table2. Specific heat Clinker and Air for the Existing Plant in Nigeria.

	Mass flow rate (kg/s)	Specific heat (kJ/kg K)	Temperature (K)

Clinker Inlet	0.65	1.1027	1663
Air Inlet (Fresh)	1.49	1.0536	318
Secondary Air	0.30	1.1760	1083
Tertiary Air	0.37	1.1616	993
Exhaust Air	0.82	1.1760	508
Clinker Outlet	0.65	1.0840	498

Energy balance of the system (clinker cooler) are shown in Table 3.

Table 3. Energy Balance and Efficiency of the Clinker Cooler.

CLINKER COOLER PERFORMANCE TEST.		
Specific Volume (Nm^3/kg)		2.2
Retention Time (mins)		17
(d) Energy Balance (*kJ/kg clk)*	Q_{ic}	1174.000
	Q_{ca}	459.9745
	Q_{exh}	429.3330
	Q_{as}	373.2656
	Q_{at}	416.0422
	Q_{oc}	296.7458
	Q_{rec}	789.3078
	Unaccounted loss	118.5836
	Total Energy (in) $\sum \dot{E}_{in}$	1634.000
	Total Energy (out) $\sum \dot{E}_{out}$	1515.4000
	Energy Ɛf(%)	92.74
	Re Energy (%)	48.31

The summation of total Energy (out) $\sum \dot{E}_{out}$ of this system is equal to the total energy (in) $\sum \dot{E}_{in}$ input into the system, taking into account the unaccountable system losses. These losses are primarily due to energy losses through convection, radiation, and energy with uncool clinker leaving the system as shown in Figure 6, which presents the energy balance for the clinker cooler across the cooler length and the temperature gradient.

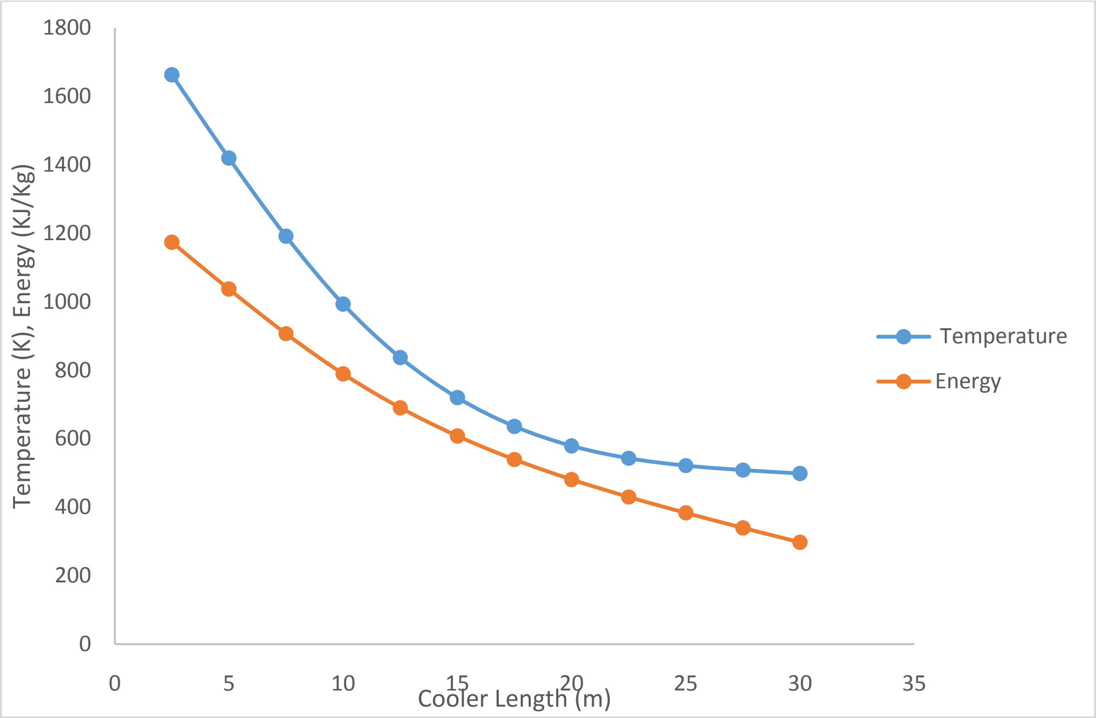


Figure 6. Energy Balance across the clinker cooler length.

Table 3, shows the result of energy balance analysis carried out on the system. It was observed that there was a slight amount of unaccounted energy loss which was 118.58 kJ/kg clk , which gives 7.3% of the total energy input into the system presented in Table 3. It was also equally noticed Table 3, that some energy left the system through the exhaust air (Q_{exh}) energy is 429.33 kJ/kg.clk which amount and clinker outlet (Q_{oc}) energy is 296.7458 kJ/kg.clk which amount to 26.27% and 18.16% which are also parts of the energy loss by the system to environments. Despite the high energy efficiency of the clinker cooler there is still room to recover energy some energy loss back into the system, which the analysis on Table 3, estimate it at 48.31%.

Exergy losses and its quantities allows for improvement and optimization of the exergy process and irreversible process of the system, also produces entropy which lead to exergy destruction. Using equation (30), (31) and (32), exergy balance is expressed in equation (33), [35]

$$\sum \dot{E}\,x_{in} - \sum \dot{E}\,x_{out} = \Delta\dot{E}x_{sys}$$

(33)

Exergy destruction is expressed in equation (34), [35]

$$\dot{I} = \dot{E}x_{destroyed} = T_{\beta}\dot{S}_{gen}$$

(33)

The subscript (β) indicates properties at the dead state and T_β is 25 ^{o}C = 298 K reference temperature at 300 m above sea level.

Table 4, results of enthalpy and entropy of the clinker cooler and air for the operating cement plant in Nigeria..

Table 4. Summary of results of the enthalpy and entropy operating clinker cooler in Nigeria.

	Mass flow rate (kg/s)	Specific Heat (kJ/kg K)	Temperature (K)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)
Clinker Inlet	0.65	1.1027	1663	1505.3	1.8959
Air Inlet (Fresh)	1.49	1.0536	318	21.3	0.0684
Secondary Air	0.30	1.1760	1083	923.2	1.5175
Tertiary Air	0.37	1.1616	993	807.3	1.0398
Exhaust Air	0.82	1.1760	508	247.0	0.6272
Clinker Outlet	0.65	1.0840	498	216.8	0.5566

Total rate of Exergy *(in)* for the running clinker cooler is expressed in equation (35) and (36),

$$\dot{Ex}'_{in} = (M_{clk\ in}\bar{e}_{clk\ in} + M_{air\ in}\bar{e}_{air\ in}) \quad (35)$$

$$\bar{e}_{clk} = \left(\bar{h}_{clk} - \bar{h}_o\right) - T_\beta\left(\bar{s}_{clk} - \bar{s}_o\right), \quad (36)$$

$\sum \dot{Ex}_{in}$ (clinker inlet) = $\left[0.65\left((1550.3) - 298(1.8959)\right)\right]$ = 640.4645 kJ/kg clk.,

$\sum \dot{Ex}_{in}$(air inlet) = $\left[1.49\left((21.3) - 298(0.0684)\right)\right]$ = 1.3708 kJ/kg clk

Total exergy *(in)* = $640.4645 + 1.3708$ = 641.8353 kJ/kg clk

Total Exergy *(out)* for the clinker cooler is expressed in equation (37),

$$\dot{Ex}'_{out} = (M_{clk\ out}\bar{e}_{clk\ out} + M_{ter\ air}\bar{e}_{ter\ air} + M_{exh\ air}\ \bar{e}_{exh\ air} + M_{\sec\ air}\bar{e}_{sec\ air}) \quad (37)$$

$\sum \dot{Ex}_{out}$ (secondary air) = $\left[0.3\left((923.2) - 298(1.5175)\right)\right]$ = 135.6625 kJ/kg clk.,

$\sum \dot{Ex}_{out}$ (tertiary air) = $\left[0.37\left((807.3) - 298(1.3981)\right)\right]$ = 144.5465 kJ/kg clk.,

$\sum \dot{Ex}_{out}$ (exhaust air) = $[(0.82((247.0) - 298(0.6272))]$ = 49.2774 kJ/kg clk.,

$\sum \dot{Ex}_{out}$ (clinker outlet) = $\left[1.49\left((216.8) - 298(0.5566)\right)\right]$ = 75.8905 kJ/kg clk

Total Exergy *(out)* = 135.6625 + 144.5465 + 49.2774 + 75.8905 = 405.3769 kJ/kg clk

Exergy destroyed for the running clinker cooler equation (33)

$$\dot{I} = \dot{E}x_{destroyed} = T_\beta\dot{S}_{gen} = 641.8353 - 405.3769 = 236.4584 \text{ kJ/kg clk}$$

Exergy efficiency of the Test Rig using equation (38)

$$\eta_{\dot{E}_{xd}} = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} = \frac{405.3769}{641.8353} = 63.2\%$$

Exergy recovery efficiency of the running clinker cooler is expressed in equation (39)

$$\eta_{\dot{Ex}_{Re}} = \frac{\sum \dot{Ex}_{out}\ (\text{secondary air} + \text{tertiary air})}{\sum \dot{Ex}_{in}\ (\text{clinker inlet}) + \sum \dot{Ex}_{in}\ (\text{air inlet})} \tag{39}$$

$$\eta_{\dot{Ex}_{Re}} = \frac{280.2090}{641.8353} = 43.7\%$$

The running clinker cooler exergy efficiency was 63.2% which represent the overall performance of the running clinker cooler. It shows that some exergy are contained in the following: radiation, exhaust air, and heat with hot clinker leaving the running clinker cooler. Exergy efficiency of the running clinker cooler was lower when compared to the energy efficiency of the clinker cooler. The exergy recovery efficiency of the clinker cooler 43.7% which was low by 19.5% when compared to exergy efficiency. Exergy recovery efficiency plays a key role in system optimization and improvement.

4. Conclusions

Low energy recovery and exergy recovery efficiency was observed to be a major challenges faced in the running clinker cooler (cement plant) in Nigeria and other cement manufacturing. Low energy recovery efficiency and exergy recovery efficiency was due to to energy losses through convection, radiation, and energy with uncool clinker leaving the system as shown in Table 3, which presents the energy balance for the clinker cooler of the running plant.

The clinker cooler can be optimizing the cooler refractory shell material by installing a more heat/energy resistant material, by improving the refractory materials would also lead to reduction in radiation and some of the unaccounted energy loss (118.5836 kJ/kg. clk) in the system. Increasing the mass flow rate of the air (1.49 kg/s) would reduce the energy loss with uncooled clinker leaving the clinker cooler and also optimize cement grinding process and improve cement quality because there will be rapid cooling of clinker which will the Alite chemical composition clinker.

Nomenclature

Symbol	**Meaning**	**Unit**
Q_{pi}	Heat losses	J
R_{ti}	Total internal resistance	Ω
T_{pi}	Wall temperature	ºC
H_{fi}	Total heat transfer coefficient	W/mK
A_i	Segmented area	m^2
T_i	Temperature of each segment	ºC
T_{br}	Thickness of the refractories	m
T_{cs}	Thermal Conductivity	W/mK
T_{sbr}	Thermal conductivity	W/mK
T_s	Shell thickness	ºC
h_c	Convection heat transfer coeffic	W/m^2k
K_w	Number of hot zone	
L_c	Number of cold zone	
H_w	Hot zone height	m
H_c	Cold zone height	m
D_{clk}	Clinker density	kg/m^3
H_{clk}	Height of the clinker bed in hot zone	m
L_w	Length of the clinker in the hot zone	m
L_c	Length of the clinker in the hot zone	m
$T_{res\ time}$	Average resident time	s
H_w	Hot zone height of the cooler	m
H_c	Cold zone height of the cooler	m

C_g	Distance covered grate	m
W_w	Frequency of grate in hot zone	Hz
W_c	Frequency of grate in cold zone	Hz
M_{clk}	Mass flow rate of Clinker	kg/s
H_{fi}	Heat transfer coefficient	W/m^2K
A_i	Segmented area	m^2
D_s	Clinker diameter	m
ρ_{air}	Density of air	kg/m^3
U_{air}	Velocity of air	m/s
K_{air}	Thermal conductivity of air	W/m^2K
µair	Dynamic viscosity of air	Kg/m/s
M	Mass flow rate	kg/s
Q_{as}	Recoverable heat of kiln secondary air	kJ/kg. clk
Q_{at}	Recoverable heat of tertiary air	kJ/kg. clk
Q_{oc}	Heat of clinker at the cooler output	kJ/kg. clk
Q_{exh}	Heat of cooler at exhaust air	kJ/kg. clk
Q_{ic}	Heat of clinker at the cooler input	kJ/kg. clk

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