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Investigation into low energy and exergy recovery in a cement plant: a case study of a grate clinker cooler in Nigeria

Joseph Sunday Oyepata[1,2*]

[1]Department of Mechanical Engineering, Federal University of Technology Akure, Ondo State, Nigeria.
[2]BUA Cement Company (BUA International), Okpella Edo State, Nigeria.

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Developing nations are also battling with global warming. Therefore, optimizing industrial energy is a must and the de-carbonization in cement production in developing countries should be encouraged. This research work seeks ways of optimize energy recovery and exergy recovery of a cement clinker cooler. This will not only improve plant performance but also reduce cost of cement production. Nigeria (Developing country) 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. Energy recovery and exergy recovery in a clinker cooler was a major factor in optimizing the clinker production and cement grinding process. The running clinker cooler has an energy recovery was less than 50% which was low despite the high energy efficiency of the clinker cooler, which was above 90%. The exergy recovery of the clinker which was less than 45% was also observed to be lower when compared to exergy efficiency of the running clinker cooler which was 63%. To improve the mass flow rate of the air supplied into the system, between 20 and 25% can possibly reduce the heat losses due to uncooled clinker leaving the system, and can improve combustion process, cement grinding process and cement quality.

Key words: Energy recovery, exergy recovery, clinker cooler, mass flow rate, clinker temperature.

INTRODUCTION

Cement plants is considered to be one of the major contributor to greenhouse effect and global warming. This calls for continuous plant energy optimization, improved operational cost, technological and other areas should be widely studied (Svatovskaya et al., 2015; Oyepata, 2023; Oyepata et al., 2021; Kajaste and Hurme, 2016). The energy consumption in cement plant is a major factor that measures the industry efficiencies in terms of its clinker production. The production processes in cement industries needs electrical energy between 95 and 110 kWh per ton of cement produced which amount to about 40% of the energy needed for clinker grinding (Barabanshchikov et al., 2016; Thomas and Gupta, 2016; Farina et al., 2016; Taweel et al., 2018; Sprince et al., 2016; Udalov et al., 2016; Pukharenko et al., 2017; Barabanshchikov et al., 2017; Quadflieg et al., 2017; Cherkashin et al., 2017; Quadflieg et al., 2017; Svatovskaya et al., 2017; Oyepata and Osawaru, 2022; Kohutek, 2015). The clinker coolers speed. Optimizing heat recovery in a clinker cooler saves fuel, improves

E-mail: tayo082002@gmail.com; Tel. +234-708-089-0545.

Figure 1. Clinker cooler in operations.

Figure 2. Cooler undergoing maintenance.

can be considered as heat exchanger or energy transfer system. Exchangers allow energy transfer between two or more fluids. Such energy exchange could occur either directly between the fluids or indirectly over a material. 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. 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 (Worrell and Galisky, 2008; Oyepata, 2018).

Improving energy recovery in a clinker cooler requires maximizing fresh air entering 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 product quality, lowers maintenance costs, and lowers emission levels (Oyepata, 2018; Akimasa et al., 2001; Ziya et al., 2010). Clinkers are the primary ingredient in Ordinary Portland Cements. 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 1620 to 1723 K (Mundhara and Sharma, 2005). Clinker process 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 processes. 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. Engin and Ari (2000) studied the energy audit and recovery for a plant with a capacity 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 16% 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. 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 (Mujumdar et al., 2007; Elkajaer and Enkegaard, 1992).

According to Oyepata et al. (2021), optimizing 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. (2012) 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 (Hendriks et al., 2004). 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 1 shows the pictorial view of clinker cooler under operation and Figure 2 shows the clinker cooler undergoing maintenance with grate plates.

This work investigates the energetic and exergetic optimization of an existing running cement plant in Nigeria. The findings from this research can be applied to other cement plants that are faced with similar challenges.

MATERIALS AND METHODS

The aim is to further investigate low energy and exergy recovery in a cement plant in Nigeria. The findings from this research will

Table 1. Data collections for an existing running plant in Nigeria.

S/N	Parameter	Value
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

also support the goals of de-carbonization in cement and other plants that are associated to similar production processes. This research will be taken into three (3) analytical approaches in carrying out these analyses:

1. It is assumed the clinker bed is rectangular fluidized and packed flow-bed;
2. It is also considered that the cooler is in a steady state; and
3. The performances of the system will be analyzed by evaluating the efficiencies of the energetic and exergetic optimization.

Table 1 shows some of the data collected from the existing running clinker cooler in Nigeria with a clinker cooler capacity of 220 to 255 tons per hour.

Temperature analysis of air at any point inside the clinker cooler

The clinker cooler is considered a steady state condition and mode of heat transfer between air and clinker 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 1 (Oyepata, 2023; Taweel et al., 2018; Ziya et al., 2010).

$$m_{clk}Cp_{clk}dT_{clk} = -k\left(T - T_o\right)dt \tag{1}$$

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 (Taweel et al., 2018). To obtain the clinker temperature at any point in the clinker cooler, this can be derived by using Equation 2, where T_o is negligible (Taweel et al., 2018):

$$m_{clk}Cp_{clk}dT = -kT_{clk}(dt) \tag{2}$$

Integrating Equation 2 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 Equations 3 and 4 (Oyepata, 2023; Taweel et al., 2018; Touil et al., 2005):

$$\int_{T_{clkin}}^{T_{clkp}} \frac{dT_{clk}}{T_{clk}} = -\frac{kt}{m_{clk}c_{p\,clk}} \tag{3}$$

$$\ln\frac{T_{clkp}}{T_{clkin}} = -\frac{kt}{m_{clk}Cp_{clk}} \tag{4}$$

Clinker temperature at any point inner the clinker cooler is expressed in Equation 5:

$$T_{clkp} = T_{clkin}e^{-\frac{kt}{m_{clk}Cp_{clk}}} \tag{5}$$

where (t) is the time taken for clinker to travel at point or distance (p) inside the clinker cooler is expressed in Equation 6:

$$t = \frac{p}{V} \tag{6}$$

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 7 (Oyepata, 2023; Dincer et al., 2004b; Rasul et al., 2005):

$$Q = mCp(T - T) \tag{7}$$

Substituting Equation 5 into Equation 7, clinker heat transfer at any point along the grates with respect of T_{clkp} is expressed in Equation 8:

$$Q_{clkp} = m_{clk}Cp_{clk}\left(T_{clkin}e^{-\frac{kt}{m_{clk}Cp_{clk}-T_o}} - T_o\right) \tag{8}$$

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 9 (Taweel et al., 2018):

$$Q = Q_{airp} = Q_{clkp} = m_{air}Cp_{air}(T_{airp} - T_o) \tag{9}$$

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

Substituting Equation 7 into Equation 8, therefore T_{airp} is expressed in Equation 10:

$$T_{airp} = \frac{m_{clk}Cp_{clk}}{m_{air}Cp_{air}}\left(T_{clkin}e^{-\frac{kt}{m_{clk}Cp_{clk}}} - T_o\right) + T_o \tag{10}$$

Summation of mass flow and energy balance analysis on the running clinker cooler

The rate of material flow and it energy balance analysis on clinker and air of the running clinker cooler remained constants as shown

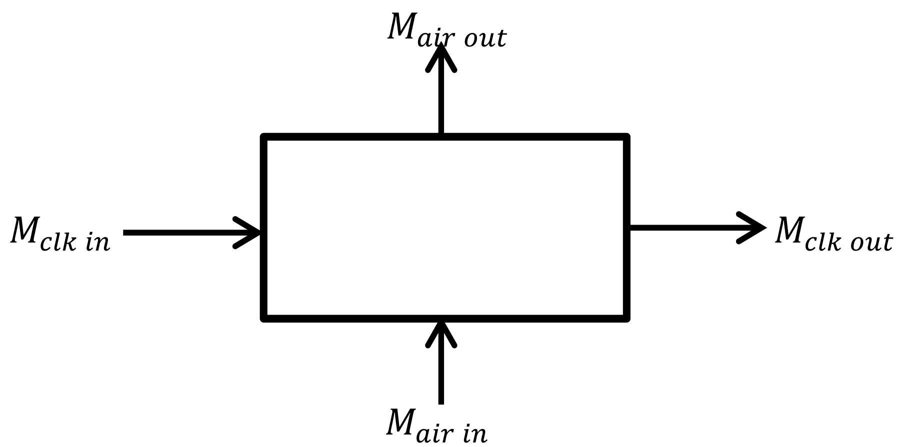

Figure 3. Mass flow rate of existing clinker cooler.
Source: Oyepata (2023).

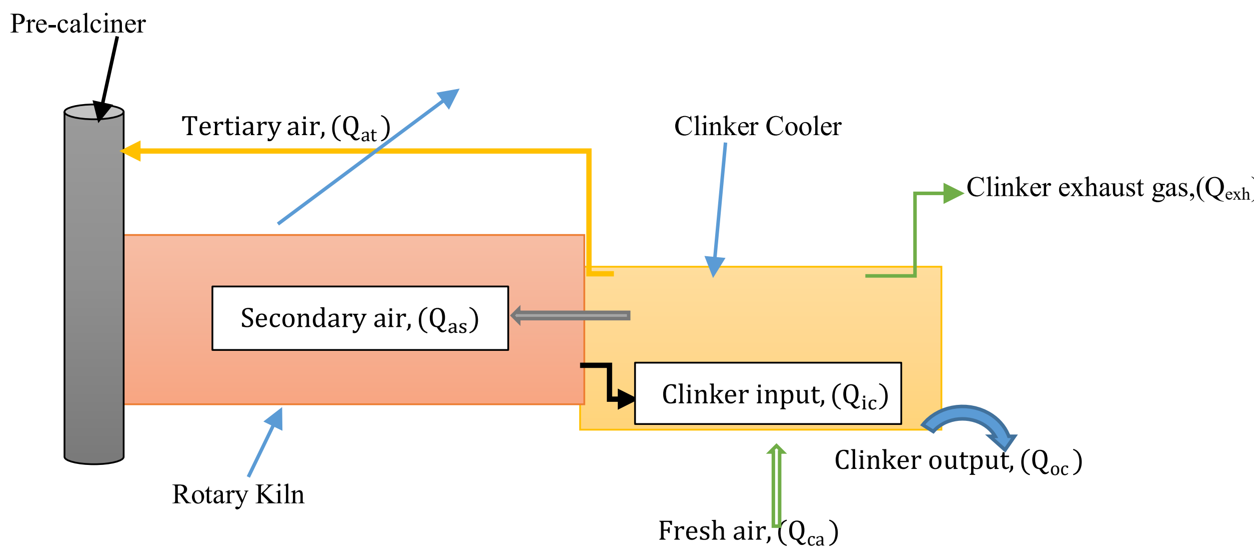

Figure 4. Schematic energy balance of the existing clinker cooler.

on Figures 3 and 4 and it can expressed in Equations 11 and 12 (Oyepata et al., 2021):

$$M_{clk_{in}} + M_{air_{in}} = M_{clk_{out}} + M_{air_{out}} = 0 \quad (11)$$

It is assumed that the running clinker cooler is in a steady state and steady material flow processes, the mass balance equation is expressed in Equation 12 (Oyepata et al., 2021; Taweel et al., 2018; Touil et al., 2005; Sögüt et al., 2009b):

$$\sum\left(M_{clk\,in} + M_{air\,in}\right) = \sum\left(M_{clk\,out} + M_{air\,out}\right) \quad (12)$$

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

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 (Oyepata et al., 2021; Touil et al., 2005; Sögüt et al., 2009b). The summation of the energy balance equation is as shown in Equation 13 (Oyepata et al., 2021; Touil et al., 2005; Sögüt et al., 2009b):

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (13)$$

Total input energy can be defined by Equation 14:

$$\sum \dot{E}_{in} = Q_{ic} + Q_{ca} = M_{clk\,in} c_{pclk} (T_{clk} - T_o) + M_{air} c_{pair} (T_{ac} - T_o) \quad (14)$$

Total energy outputs from the system as obtained from is expressed in Equation 15 (Oyepata et al., 2021):

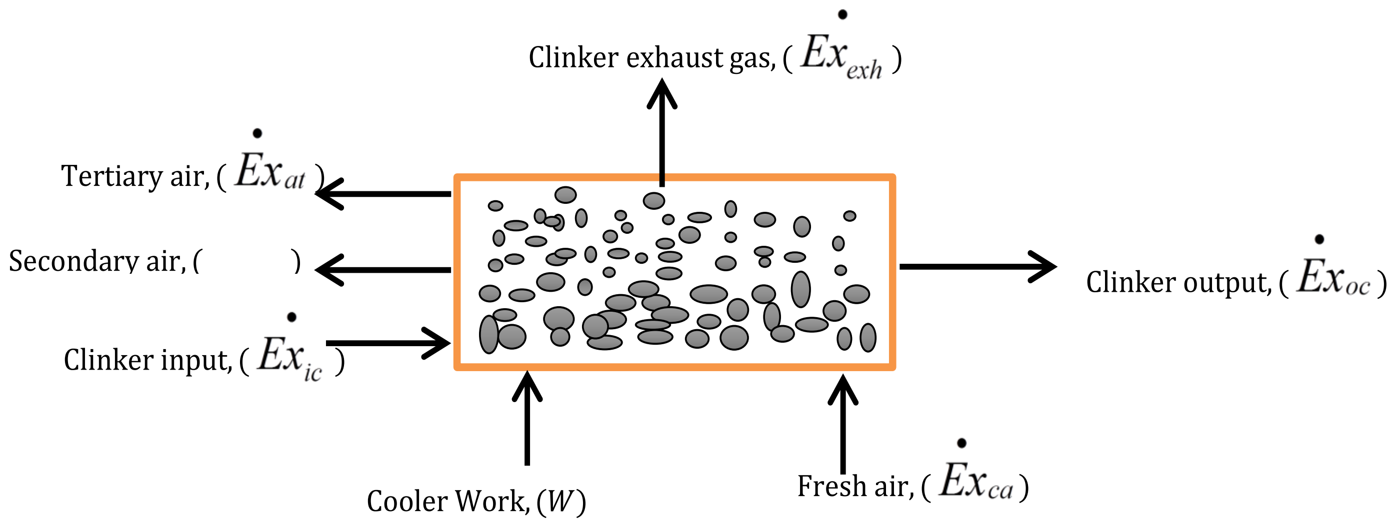

Figure 5. Schematic diagram of exergy balance and cooler work.
Surce: Oyepata (2023); Oyepata et al. (2021) and Kajaste and Hurme (2016).

$$\sum \dot{E}_{out} = Q_{as} + Q_{at} + Q_{oc} + Q_{exh} = M_{secair} c_{psecair} (T_{secair} - T_{\beta}) + M_{terair} c_{pterair} (T_{terair} - T_{\beta}) + M_{clkout} c_{pclkout} (T_{clkout} - T_{\beta}) + M_{exhair} c_{pexhair} (T_{exhair} - T_{\beta}) \quad (15)$$

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 xpressed in Equation 16 (Oyepata et al., 2021; Touil et al., 2005; Sögüt et al., 2009b):

$$\eta_E = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad (16)$$

Recoverable energy efficiency on the tertiary and secondary air on clinker cooler is expressed in Equation 17 (Oyepata et al., 2021):

$$\eta_{recoverable,\, cooler} = \frac{Q_{recoverable}}{Q_{ic} + Q_{ca}} \quad (17)$$

Exergy analysis on the running clinker cooler

Using the principle of the thermodynamics, exergy: is defined as the maximum amount of work which can be produced by a system. Identifying the source of exergy losses and their quantities allows for improvement and optimization of the exergy processes and system using Equation 18 as shown on Figure 5.

$$\dot{E}x = \left(h' - h_o \right) - T_o (S - S_o) \quad (18)$$

where (h') is the specific enthalpy and s' is the specific entropy for the clinker cooler.

Equation 19 for incompressible flow in the clinker cooler:

$$\dot{E}x = mCp(T - T_o - T_o \ln \tfrac{T}{T_0}) \quad (19)$$

Substituting Equation 5 into Equation 18, the exergy of clinker at any point insider the clinker cooler is expressed in Equation 20:

$$\dot{E}x_{clk} = m_{clk} Cp_{clk} (T_{clkin} e^{-\frac{kt}{m_{clk} Cp_{clk}}} - T_o - T_o \ln \frac{T_{clkin} e^{-\frac{kt}{m_{clk} Cp_{clk}}}}{T_0}) \quad (20)$$

Substituting Equation 9 into Equation 20 gives cooling-air exergy at any point inner the travelling clinker cooler is expressed in Equation 21:

$$\dot{E}x_{air} = m_{clk} Cp_{clk} T_{clkin} e^{-\frac{kt}{m_{clk} Cp_{clk}}} - m_{air} Cp_{air} (1 - \ln \frac{\frac{m_{clk} Cp_{clk}}{m_{air} Cp_{air}} \left(Tc_{in} e^{-\frac{kt}{m_{clk} Cp_{clk}}} - T_0 \right)}{T_0}) \quad (21)$$

RESULTS AND DISCUSSION

Table 1 gives the real time data/operational inputs and outputs of a complete 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 to calculate energy balance, energy efficiency, recovery energy efficiency and the exergy of the operating clinker cooler used. Energy balance of the system (clinker cooler) is shown in Table 3.

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

Table 2. Specific heat clinker and air for the existing plant in Nigeria.

Variable	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

Source: Oyepata (2023).

Table 3. Energy balance and efficiency of the clinker cooler (Oyepata, 2023).

Clinker cooler performance test		Value
Specific volume (Nm^3/kg)		2.2
Retention time (min)		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

Source: Oyepata (2023).

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 (Oyepata, 2023).

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 119 kJ/kg clk. This 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 kJ/kg.clk which amount and clinker outlet (Q_{oc}) energy is 297 kJ/kg.clk which amount to 26 and 18% 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%.

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 Equations 22, 23 and 24, exergy balance is expressed in Equation 25 (Oyepata, 2023; Touil et al., 2005):

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \Delta \dot{E}x_{sys} \quad (22)$$

Exergy destruction is expressed in Equation 23 (Touil et al., 2005):

$$\dot{I} = \dot{E}x_{destroyed} = T_{\beta}\dot{S}_{gen} \quad (23)$$

The subscript (β) indicates properties at the dead state and T_{β} is 25°C = 298 K reference temperature at 300 m above sea level. Table 4 shows results of enthalpy and entropy of the clinker cooler and air for the operating cement plant in Nigeria. Total rate of Exergy *(in)* for the running clinker cooler is expressed in Equations 24 and 25:

$$\dot{E}x_{in} = (M_{clk_{in}}\bar{e}_{clk_{in}} + M_{air_{in}}\bar{e}_{air_{in}}) \quad (24)$$

$$\bar{e}_{clk} = \left(\bar{h}_{clk} - \bar{h}_{o}\right) - T_{\beta}\left(\bar{s}_{clk} - \bar{s}_{o}\right), \quad (25)$$

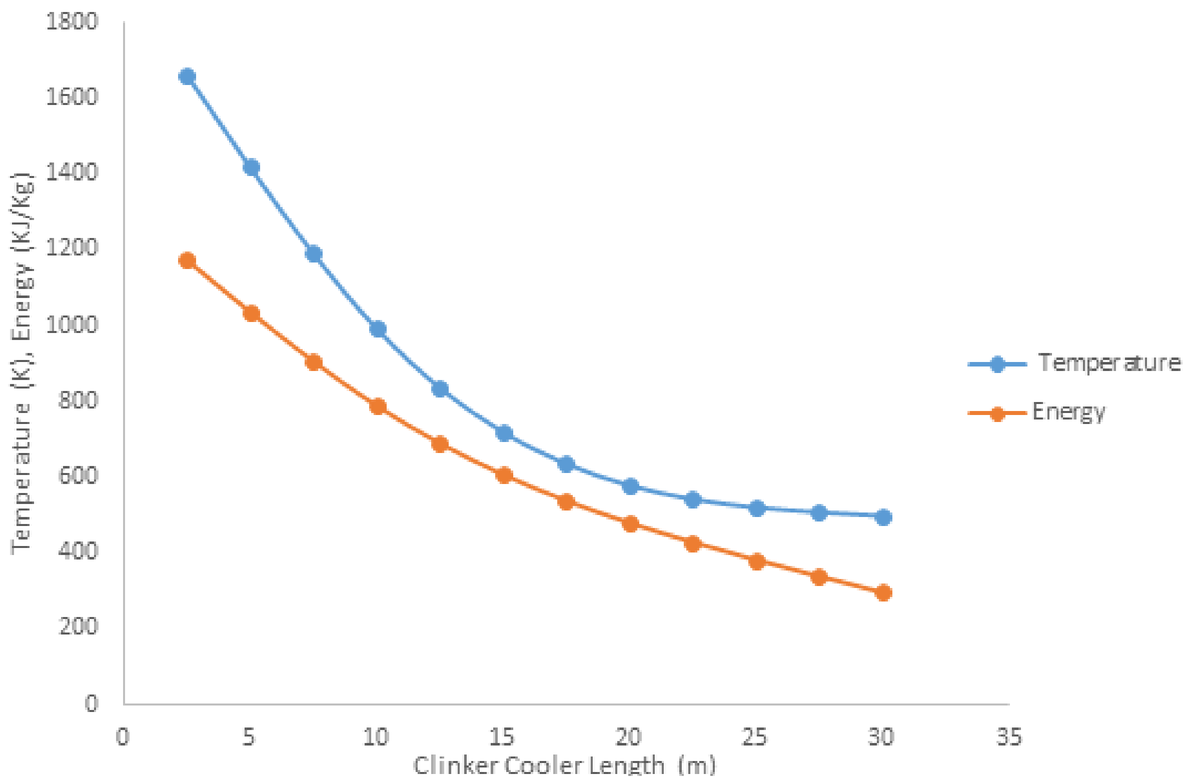

Figure 6. Energy balance across the clinker cooler length.
Source: Oyepata (2023).

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

Variable	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

$\sum \dot{Ex}_{in}$ (clinker inlet) = $[0.65((1550.3) - 298(1.8959))]$ = 641 kJ/kg clk.,
$\sum \dot{Ex}_{in}$ (air inlet) = $[1.49((21.3) - 298(0.0684))]$ = 1.4 kJ/kg clk
Total exergy *(in)* = $640.4645 + 1.3708$ = 642 kJ/kg clk
Total Exergy *(out)* for the clinker cooler is expressed in (Equation 26):

$$\dot{Ex}_{out} = (M_{clk\,out}\bar{e}_{clk\,out} + M_{ter\,air}\,\bar{e}_{ter\,air} + M_{exh\,air}\;\bar{e}_{exh\,air} + \;M_{sec\,air}\,\bar{e}_{sec\,air}) \qquad (26)$$

$\sum \dot{Ex}_{out}$ (secondary air) = $[0.3((923.2) - 298(1.5175))]$ = 136 kJ/kg clk.,

$\sum \dot{Ex}_{out}$ (tertiary air) = $[0.37((807.3) - 298(1.3981))]$ = 145 kJ/kg clk.,
$\sum \dot{Ex}_{out}$ (exhaust air) = $[(0.82((247.0) - 298(0.6272))]$ = 49 kJ/kg clk.,
$\sum \dot{Ex}_{out}$ (clinker outlet) = $[1.49((216.8) - 298(0.5566)]$ = 76 kJ/kg clk
Total Exergy *(out)* = 135.6625 + 144.5465 + 49.2774 + 75.8905 = 405 kJ/kg clk

Exergy destroyed for the running clinker cooler equation 27:

$$\dot{I} = \dot{Ex}_{destroyed} = T_{\beta}\dot{S}_{gen} \quad = 641.8353 - 405.3769 = 237 \text{ kJ/kg clk} \qquad (27)$$

Exergy efficiency of the Test Rig using Equation 28:

$$\eta_{\dot{E}_{xd}} = \frac{E\dot{x}_{out}}{E\dot{x}_{in}} = \frac{405.3769}{641.8353} = 63\% \quad (28)$$

Exergy recovery efficiency of the running clinker cooler is expressed in Equation 29:

$$\eta_{\dot{E}x_{Re}} = \frac{\sum E\dot{x}_{out}\,(\text{secondary air+tertiary air})}{\sum E\dot{x}_{in}\,(\text{clinker inlet})+\sum E\dot{x}_{in}(\text{air inlet})} \quad (29)$$

$$\eta_{\dot{E}x_{Re}} = \frac{280.2090}{641.8353} = 43\% \quad (30)$$

The running clinker cooler exergy efficiency was 63% 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 was 43% which was lower by 19% when compared to exergy efficiency. Exergy recovery efficiency plays a key role in system optimization and improvement.

Conclusion

The investigation into performances of the clinker cooler; energy recovery and exergy recovery efficiency was observed to be a critical issue faced in the existing clinker cooler used for this research. The low energy and exergy recovery efficiency, which are 48 and 43%, was due to energy losses through the followings: radiation, radiation, waste heat via the exhaust duct and energy with red-hot clinker leaving the cooler as stated; presenting the energy balances for the clinker cooler of the existing plant. The system investigated can be enhanced by: improving the materials used for refractory lining; using a more heat/energy resistant refractory materials, this can reduce the radiation that is been observed on shell and some of the unaccounted heat/energy losses in the system; increasing the mass flow rate of the air of with 20 to 25% will no doubt reduce energy losses due to uncooled clinker leaving the cooler, improve combustion process, improve cement grinding process and improve cement quality.

NOMENCLATURE

Q_{pi}, Heat losses (J); **R_{ti},** total internal resistance (Ω); **T_{pi},** wall temperature (°C); **H_{fi},** total heat transfer coefficient (W/mK); **A_i,** segmented area (m$^{2)}$; **T_i,** temperature of each segment (°C); **T_{br},** thickness of the refractories (m); **T_{cs},** thermal conductivity (W/mK); **T_{sbr},** thermal conductivity (W/mK); **T_s,** shell thickness (°C); **h_c,** Convection heat transfer coefficient (W/m^{2}k); **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^{2}K); **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^{2}K); **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).

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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