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Economic impacts of optimizing energy recovery in clinker cooler using clinker cooler bed as a case study

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This paper tends to analyze one critical area "pyro system" in cement production process where energy is been lose and ways on how some of these energies can be recovered back into the system and also analyzing the cost benefits. This led to the modeling of a clinker cooler known as "test rig". This model was used to study the operating system of the existing running plant. The test rig was designed using SolidWorks Computer Aided Design software based on the geometrical dimensions adopted into the test rig design. The test rig was scaled down to a ratio 25:1, with the existing clinker cooler been twenty-five and the test rig is one. The clinker cooler bed height varies from 0.3, 0.4 and 0.6 m. The quantities of energy transfer are dependent upon the optima clinker bed height (0.6 m) which resulted into improved clinker outlet of 76.4°C. A cost benefits on recovery energy efficiency on the existing running plants can be translated to a financial gain of $12,092 by improving the clinker bed height from 0.45 m to 0.6 m with expected clinker output in 24 h is 6,000 tons/day.

Key words: Bed height, mass flow, energy recovery, energy efficiency, test rig and cost benefits.

INTRODUCTION

The manufacturing of Ordinary Portland Cement (OPC) is one of the most energy intense industries in the world, in which over thirty percent of the production cost is on energy (Worrell et al., 2001). At least five percent of the total global industrial energy is used in cement industries (Cengel and Boles, 2008). Reducing energy loss in this industry is to optimize the pyro system and energy recovery in the clinker cooler (Ghada et al., 2019; Oyepata et al., 2020). There are four major types of clinker coolers: grate clinker cooler, planetary clinker cooler, shaft clinker cooler, and rotary clinker coolers (Worrell and Galisky, 2008).

Clinker coolers operates on the principle of heat exchanger and fluidization: process of heat exchange between the forward flow red hot clinker leaving the kiln at a temperature of about 1350°C meeting with a upward flow of fresh air at a temperature between 32 and 45°C which leads to cross-flow and the material flow process inside the clinker cooler, this process is known as fluidization (Oyepata et al., 2021; Ahmet and Ahmet 2010). Fluidization is a process by which solid materials are converted into a fluid and causing the materials to be suspended a gas or liquid (Kunii and Levenspiel, 1991; Ravi, 2016).

Fluidization occurs when the fluid moved upward via the bed of solid particles (clinker). If the fluid flow rate is

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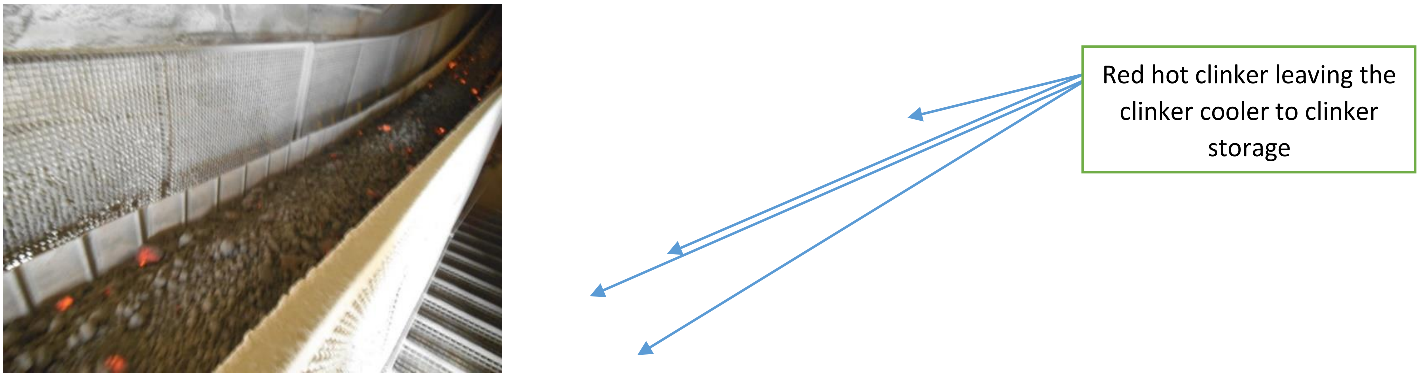

Figure 1. Pan conveyor carrying red-clinker.
Source: (Oyepata et al., 2020; Oyepata et al., 2021)

sufficient enough the solid particles becomes too fluidized. Fluid with higher flow rates will allows faster movement of the solid particles and all particles (clinker) will be suspended by the fluid, this is known as fluidized bed (Kunii and Levenspiel, 1991; Ravi, 2016). An additional increase in the fluid flow rate can lead to circulation of the fluid in the solid particles inside the vessel and this can also lead to displacement of lighter particles. Fluidization phenomena occurs because a drag forces by the moving gas which is equal to the solid particle weight W_p it is known as geostatic pressure) as described in equation (1) (Kunii and Levenspiel, 1991; Ravi, 2016). This process of material fluidization is applicable in clinker grate coolers.

$$\Delta P_b A_t = W_p = A_t H_{mf}(1-\varepsilon_{mf})\left[\left(\rho_s - \rho_g\right)\frac{g}{g_c}\right] \quad (1)$$

Where: ΔP_b is pressure losses across bed, A_t is cross-sectional area of the column H_{mf} is height of the bed when fluidization starts, ϵ_{mf} is void fraction of the bed when fluidization starts, ρ_s, ρ_g is density of particles and a gas, respectively, g is gravitational acceleration g_c *is* conversion factor which is equal to one for metric units and W_p is weight of the bed fluidization can be determined by the flow rate or by the fluid velocity. But it is difficult to determine velocity of the fluid in the gaps between particles. Therefore, fluid velocity is expressed as a velocity in the free area of the vessel (over or below) the bed of particles. This is known as superficial velocity and expressed in equation (2), (Kunii and Levenspiel, 1991; Ravi, 2016).

$$\upsilon = \frac{V_f}{A_t} \quad (2)$$

Where: V_f is volumetric flow and A_t is cross-sectional area of the vessel. Figure 1, shows a clinker pan conveyor carrying red hot clinker out of the clinker cooler.

MATERIALS AND METHODS

Setting-up the clinker cooler "test rig" scaling and modeling process

The test rig was set-up by using SolidWorks (Computer Aid Design and Computational Fluid Dynamics) with respect to an existing running plant. The clinker cooler was scaled down to a ratio 25:1. The existing running plant clinker cooler is twenty-five and (Test rig) is one. Scaling down was done based on dimensional analysis and similitude analysis. The results obtained from process were used to study the responses of the existing running clinker cooler (Heinemann and Parker, 1970; Andreas et al., 2010; FLSmidth, 2015; Mundhara and Sharma, 2005).

Basic features and assumptions of a clinker cooler

Clinker leaving the rotary kiln at a temperature of 1350 °C is cooled by the air at a temperature between 32 ^{o}C to 45°C as shown in Figure 2, shows the pictorial views of clinker cooling process by a cross-flow of air and hot clinker leaving the rotary kiln and entering clinker cooler. After the cross-flow of the air and the bed of clinker. The heated air is partly used as secondary air for rotary kiln combustion process and tertiary air for pre-calciner combustion process and waste gas goes the de-dusting system. For the development of the model, the following hypothesis was taken based on different studies (Joel, 2010; FLSmidth, 2015; Mundhara and Sharma, 2005; Bernstein, 1995; Elkaker et al., 1992; Wedel et al., 1984).

1) The model was equipped with a rectangular covering provided which hot clinker inlet and cooled clinker two exits;
2) The clinker bed varies at 0.3 m, 0.4 m and 0.6 m;
3) The clinker is assumed to homogeneous and spherical particles with average diameter of 15 mm and with bulk density of 1400 kg/m^3,
4) The porosity of the bed is assumed equal to 0.4;
5) The air distribution on the bed is assumed to be uniform;
6) The air flow at the entry to the bed is classified as superficial velocity V_o and with an average pressure P_a; and
7) The volume of fine particles transported by air flows and crossing the grates is negligible;

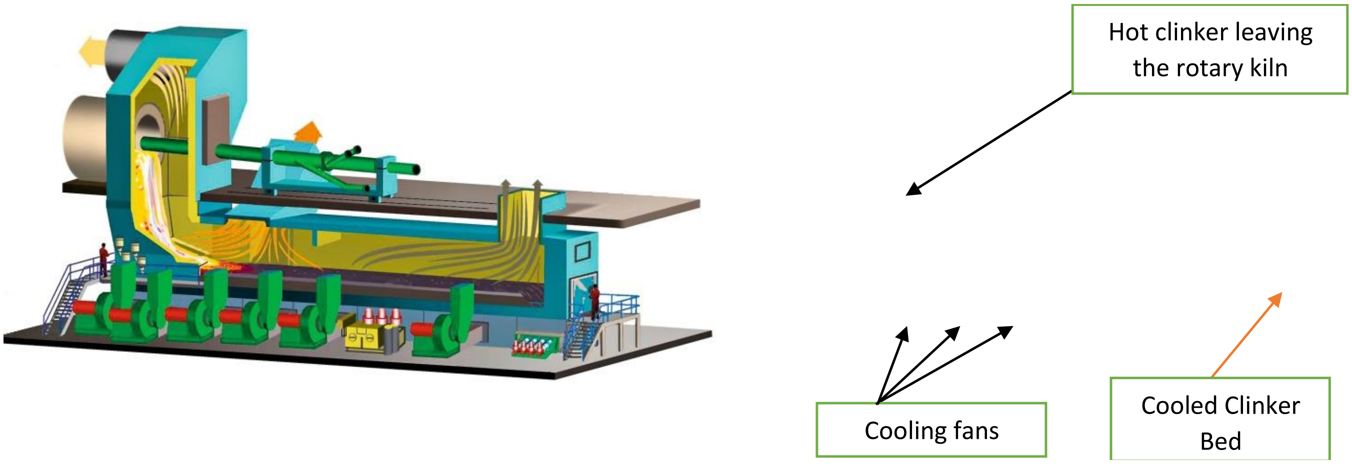

Figure 2. Pictorial view of Clinker Inlet and Clinker cooling.
Source: FLSmidth (2015).

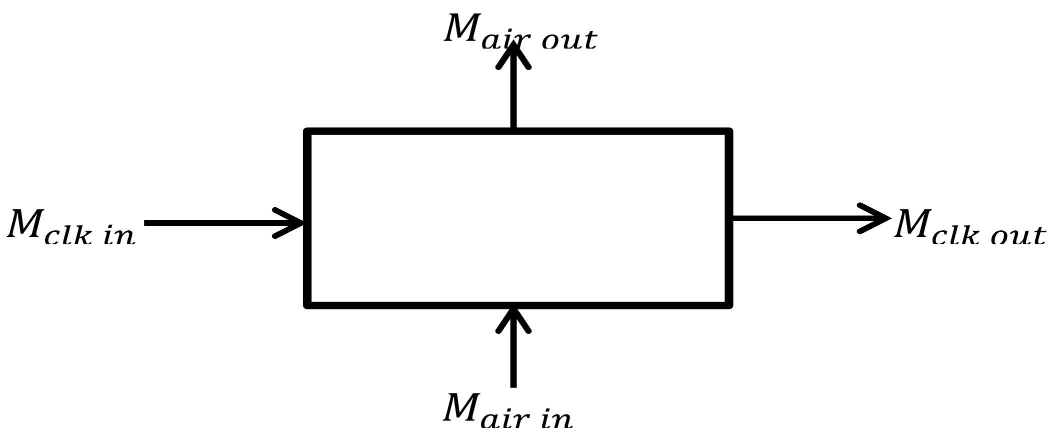

Figure 3. Material and air flow rate on the clinker cooler “test rig”.
Source: Oyepata et al. (2020, 2021).

Standard pressure P_1=1.025 bar, ρair =1.206 kg/m^3, standard temperature T_1= 20 ^oC, environmental temperature T_o = 32 ^oC , P2 = 1.033 bar, where N is normal, T_o is environmental temperature, reference temperature (T_β) of 25 ^oC at 300 m above sea level, FLSmidth, (2015). Table 1 shows some of the important dimensions of the clinker cooler test rig used for the design and modeling.

Table 2 shows some of the important dimensions of the existing and running clinker cooler that was used as the prototype.

Mass flow rate and energy balances analysis on the clinker cooler test rig

Material and air flow rate and energy analysis of air and clinker on the clinker cooler test rig remain constant as shown in Figures (3) and (4), it is expressed in equation (3) (Sögüt et al., 2009a; Sögüt et al., 2009b):

$$M_{clk_{in}} + M_{air_{in}} = M_{clk_{out}} + M_{air_{out}} = 0 \qquad (3)$$

The mass flow rate in cooler is constant. For steady state and steady flow processes, the mass balance equation as expressed in equation (4) (Sögüt et al., *2*009b; Rasul, 2005).

$$\sum\left(M_{clk\,in} + M_{air\,in}\right) = \sum\left(M_{clk\,out} + M_{air\,out}\right) \qquad (4)$$

Where *M* is the mass (material and air) flow rate; *clk* represents clinker; *in* represents inlet and out represents outlet.

Using 1st thermodynamics law which states that energy cannot be destroyed but can be converted during an interaction, (Touil et al., 2005) as shown in Figure 4. Transformation of the energy body or a system is the same as energy input and energy output (Sögüt et al., 2009a; Saidur et al., 2007a; Saidur et al., 2007b; Karellas et al., 2012). The energy input and output equation is shown in equation (5), (2021; Sögüt et al., 2009b).

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \qquad (5)$$

Based on Figure 4, total input energy can be defined by equation (6)

Table 1. Parameters and dimensions for model "test rig" cooler.

Parameter	Value
Length of the cooler (m)	1.3
Width of the cooler (m)	0.3
Different clinker bed height of the Cooler (m)	0.3, 0.4 and 0.6
Material flow rate to the cooler (kg/s)	0.15
Specific volume (Nm^3/kg of clk)	2.2041
Clinker Inlet temperature to the cooler (°C)	1350
Air flow rate (kg/s)	0.45
Ambient air temperature (°C)	32

Source: Oyepata et al. (2021)

Table 2. Important parameters of existing and running plant.

S/N	Parameter	Value
1	Clinker bed height (m)	0.45
2	Cooler speed (stroke/min)	16
3	Clinker mass flow (kg/s)	72
4	Air mass flow (kg/s)	172.8
4	Secondary air flow (kg/s)	34.6
5	Tertiary air flow (kg/s)	43.2
6	Exhaust air flow (kg/s)	95
7	Clinker inlet temperature (°C)	1350
8	Clinker outlet temperature (°C)	250
9	Cooler length (m)	30
10	Cooler width (m)	5
11	Secondary air temperature (°C)	580
12	Tertiary air temperature (°C)	490
13	Specific volume (Nm^3/kg of clk)	1.7959
14	Secondary air energy Q_{ase} (kJ/kg of clk)	21,699.4
15	Tertiary air energy Q_{ate} (kJ/kg of clk)	22,096.8
16	Energy efficiency (%)	59.2
17	Recoverable energy efficient	49.2
18	Exhaust air Temp (^oC)	265

Source: Oyepata et al. (2021)

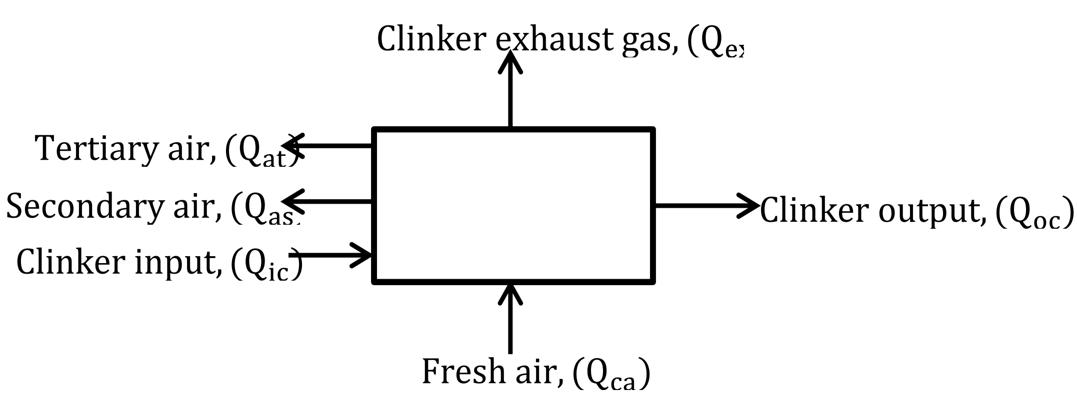

Figure 4. Energy (Input and Output) schematic of the clinker cooler "test rig".
Source: Oyepata et al. (2020, 2021).

$$\sum \dot{E}_{in} = Q_{ic} + Q_{ca} = M_{clkin} c_{pclk} (T_{clk} - T_o) + M_{air} c_{pair} (T_{ac} - T_o) \quad (6)$$

The total energy outputs from the system as obtained from can be expressed in equation (7)

$$\sum \dot{E}_{out} = Q_{as} + Q_{at} + Q_{oc} + Q_{exh} = M_{\sec air} c_{p\sec air} (T_{\sec air} - T_\beta) + M_{ter\,air} c_{pter\,air} (T_{ter\,air} - T_\beta) + M_{clkout} c_{pclkout} (T_{clkout} - T_\beta) + M_{exhair} c_{pexhair} (T_{exhair} - T_\beta) \quad (7)$$

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 and $T_\beta = 25°C$.

Energy efficiency is the ratio of the amount of the energy output to input of the system. It is defined in equation (8) (Oyepata et al., 2020; Oyepata et al., 2021; Sögüt et al., 2009b; Sögüt et al., 2009a; Saidur et al., 2007c; Cengel, 2006; Dincer et al ., 2004):

$$\eta_E = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \quad (8)$$

Equation (9) is the recoverable energy efficiency on the tertiary and secondary air as:

$$\eta_{recoverable,\,cooler} = \frac{Q_{recoverable}}{Q_{ic} + Q_{ca}} \quad (9)$$

Computational fluid dynamics simulation process

A 3D model of a clinker cooler test rig was developed using SolidWorks-2014 Computer Aided Design (CAD) software based on the geometrical parameters that are adopted from the conceptual design as shown on Figure 2. Having a fixed value of width, length, and an adjustable/variable clinker bed height. Geometric parameters adopted in the scaled conceptual design, having fixed values of length (1.3 m), width (0.3 m) and a variable height 0.3 m, 04 m, and 0.6 m.

The model "test rig" was then imported into ANSYS 14.0 software platform for Computational Fluid Dynamics (CFD) simulation. Governing equations of flow were solved in the ANSYS-Fluent 14.0 computational fluid dynamics (CFD) platform. Tables 1 and 2 give the parameters the basis for evaluation of the clinker cooler test rig performance using clinker cooler specific numbers (ANSYS, 2006).
The clinker nodules are considered as a porous medium material using the facilities available in the software as regarding energy, continuity and momentum equations. The 3-Dimensinal model was meshed into ANSYS meshing environment, where the model was discretized into finite element mesh. The numbers of element in a mesh can be vary, depending on the level of convergent or size of the cells in the mesh and therefore a very fine mesh size was used, taking into consideration computation time and the level of acceptance. The boundary conditions were all prepared and the following assumptions were considered; the clinker is a porous medium and is isotropic, the clinker are homogenous, flow of fluid is steady, the flow is considered turbulent outside the porous medium and there is a laminar in the porous medium section, the fluid is incompressible, radiation heat transfer and the heat loss through the wall are almost negligible (ANSYS, 2006; Oyepata et al., 2020; Oyepata et al., 2021).

Considering the existing running clinker cooler movement of the clinker bed is considered as a rectangular moving bed with it input parameters and dimensions are stated in Table 1. Considering the operations of a clinker cooler with respect to the 3-D model used in this research using Figures 3 and 4, the hot clinker enters from the right side; the cooling air enters from the bottom and moved upward, in a form of cross flow. Inlet temperature of the clinker and air were initially set at 1350 and 32°C respectively. It is also considered that there were no slip and adiabatic "no heat loss or heat gain" conditions are assigned to the two side-walls of the porous medium. Outlet pressure conditions zero is assigned to the outlets, this is to determine the pressure drop along the flow, and corresponding temperatures after process is completed (ANSYS, 2006; Oyepata et al., 2020; Oyepata et al., 2021).

The validation of numerical simulation

The CFD simulation results will be validated by comparing it results with theoretical results. Theoretical results will be obtained using equation (10) and (11) (Oyepata et al., 2020; Holder Bank, 2016).

$$Specific\ volume = \frac{Air\ flow\ rate}{Clinker\ flow\ rate} \times \frac{1}{C_{p\,air}} \quad (10)$$

$$\frac{T_{clk_{out}} - T_o}{T_{clk_{in}} - T_o} = e^{(-Vair/0.77)} \quad (11)$$

Where $T_{clk\ in}$ is the inlet clinker temperature inlet ( ), V_{air} is specific volume of cooling air (m^3/kg) in the clinker with the energy content relative to environment temperature C_{pair} specific heat capacity of air.

Economical benefit of energy recovery

An improvement in the clinker cooler performance by optimizing the clinker cooler bed height will definitely result into potential energy recovery in form of fuel used for the clinker production "pyro process" at the rotary kiln and pre-calciner.
The potential energy recovery obtainable by optimizing the clinker bed height of the clinker cooler test rig is taken from the results of the analyses performed. Economic benefit of energy recovery is shown in equation (12), (13), (14) and (15).

$$\sum E_t = Q_{ast} + Q_{air\ tert} \quad (12)$$

$$E_{bt} = E_t \div Ec \quad (13)$$

$$\sum E_e = Q_{ase} + Q_{ate} \quad (14)$$

$$E_{be} = E_e \div Ec \quad (15)$$

Where $\sum E_t$ is the total energy recovery test rig, Q_{ast} is the quantities of energy recovered to the secondary air on test rig, $Q_{air\ tert}$ is the quantities of energy recovered to the tertiary, E_d is the energy recovery different between the test rig and existing running, E_{bt} cost benefits for test rig, E_{be} cost benefits for existing running plant and Ec is the international energy cost.

Table 3. CFD and Theoretical results on clinker bed height and clinker outlet temperature.

Bed height (m)		0.3	0.4	0.6
Temperature (°C)	Air inlet	32	32	32
	Secondary air outlet	730	758	812
	Tertiary air outlet	530	569	602
	Exhaust air outlet	135	123	92
	Clinker inlet	1350	1350	1350
	Clinker outlet (CFD)	125	132.8	76.4
	Theoretical clinker outlet	107.3	107.3	107.3
Mass flow rate (kg/s)	Air inlet	0.45	0.45	0.45
	Secondary air outlet	0.09	0.09	0.09
	Tertiary air outlet	0.11	0.11	0.11
	Exhaust air outlet	0.25	0.25	0.25
	Clinker inlet	0.15	0.15	0.15
	Clinker outlet	0.15	0.15	0.15
Specific volume (Nm^3/kg)		2.2041	2.2041	2.2041

Source: (Oyepata et al., 2021)

RESULTS AND DISCUSSION

Results of clinker cooler model

The results of the model are validated by comparing the data records of exiting plant on Tables 2 and 3, which show the summary of CFD results of the clinker outlet temperature for different clinker bed height and the theoretical results of the clinker cooler model.

Validation computation fluid dynamic of the test rig and theoretical results

The CFD clinker outlet temperature using Table 3, has an average temperature of 111.4°C, that is, considering the three bed height (0.3 m, 0.4 m and 0.6 m) and theoretical clinker outlet temperature using Table 3, as an average temperature of 107.3°C and this also validate equation (11).

Variation on clinker bed height will theoretically affect the rate of heat transfer between the cooling air and the hot clinker. It was observed that a bed height of 0.6 m has enough rate of heat transfer which was driven by the temperature difference between these two mediums. The quantities of energy transfer are dependent upon the optima clinker bed height of 0.6 m which resulted into improved clinker outlet of 76.4°C.

Comparing the performance test rig against the existing running clinker cooler using Tables 2 and 3 shows that the test rig cooler is 20.80% higher than the existing running clinker cooler in terms of recoverable energy and 21.46% high in terms of energy efficiency. The slight increase in energy recovery was as a result of improved clinker bed height of 0.6 m and clinker outlet temperature of 76.4 °C on the test rig model. Improving clinker bed height on the existing clinker cooler from 0.45 m to 0.6 m is the current results obtained from the running that can be improved upon.

Using Table 4 and clinker bed height 0.6 m, the unaccountable losses of energy on the clinker cooler test rig 42.74 kJ/kg clk, which are mainly due to process of heat transfer either through convection and radiation. These unaccounted losses were related to the clinker cooler surfaces and its surrounding temperatures.

Cost benefit

The cost benefit of clinker cooler test rig and existing running is gotten using equation (12), (13), (14) and (15): $\sum E_t = Q_{ast} + Q_{air\,tert}$, $\sum E_t$ Total energy recovery on the clinker cooler test rig: $\sum E_t = Q_{ast} + Q_{air\,tert}$ = 80.22 + 69.76 = 149.98 kJ/kg of Clk, $\sum E_t = 0.00014998$ GJ/kg of clk.

The cost of energy that is been recovered in the test rig is shown below:

The average fuel energy cost is taken as USD 4.664 per GJ (Price et al., 2009). Total cost benefit on recovered energy cost into the test rig using equation (13):

$E_b = 0.00014998 \quad \div \$\,4.664$,
E_b = \$ 3.2 X 10^{-5} GJ per kg of clinker.

The energy recovery on test rig was 21. 46% than exist running.

Table 4. CFD results on clinker cooler energetic balance and energetic efficiency.

Energy balance (kJ/kg clk)	Qic	211.18	211.18	211.18
	Qca	6.81	6.81	6.81
	Qexh	28.92	28.07	18.84
	Q_{ast}	71.03	74.04	80.22
	$Q_{air\ tert}$	60.41	65.30	69.76
	Qoc	13.90	14.21	7.06
	Losses	44.35	36.99	42.74
	EnergyEff (%)	79.71	83.08	80.45
	RecEnergyEff (%)	60.12	63.74	68.60

Source: (Oyepata et al., 2021)

$\sum E_e$ Total energy recovery on the existing running plant: $\sum E_e = Q_{ase} + Q_{ate}$ = 21,699.4 + 22,096.8 = 43,796.2 kJ/kg of clk, $\sum E_e$ = 0.0438 GJ/kg of clk

Expected total energy recovery on exist running plant with improved efficiency of 21.46%

$\sum E_e$ x 1.2146 = 0.0438 x 1.2146 = 0.0532

Total cost benefit on recover energy of the existing running plant improve by 21. 46% in 24 h using equation (15) with expected clinker output in 24 h is 6,000,000 kg (6,000 tons/day)

$E_{be} = E_e \div Ec$, $E_{be} = \left(((0.0532 - 0.0438) \div 4.664)\ X\ (6{,}000{,}000)\right)$,E_{be} = $ 12,092 GJ per day can be benefited on exist running clinker cooler, if the energy recovery efficiency can be improve from 49.2 to 70.66%.

Conclusion

The research shows that there is a room for recovery energy on the existing running clinker cooler by improving clinker bed height. The test rig has an optimum energy recovery of 149.98 kJ per kg of clinker and this indicates 21.46% above the existing running clinker cooler. The current clinker bed height for existing running clinker cooler is 0.45 m, an increase in the clinker bed height not less than 0.6 m with an improved specific volume of air to clinker from 1.7959 Nm^3/kg of clk to 2.2041 Nm^3/kg of clk can improve the performance of energy recovery and the total cost benefit.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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Appendix A: (Oyepata et al., 2021)

Some of the MatLab code written for the energy balance and results.

```
To1 = 25;
To = To1;
Tbeta = To;
Tair = input ('Tair = ');
% Tair = Tair1 - 273;
Tsecair = input ('Tsecair = ');
% Tsecair = Tsecair1 - 273;
Ttertair = input ('Ttertair = ');%newly added
% Ttertair = Ttertair1 - 273;
Texhair = input ('Texhair = ');
% Texhair = Texhair1 - 273;
Tclk = input ('Tclk = ');
% Tclk = Tclk1 - 273;
Tclkout = input ('Tclkout = ');
% Tclkout = Tclkout1 - 273;
Mairin = input ('Mairin = ');
Msecair = input ('Msecair = ');
Mtertair = input ('Mtertair = '); %newly added
230
Mexhair = input ('Mexhair = ');
Mclkin = input ('Mclkin = ');
Mclkout = input ('Mclkout = ');
cpclk = (0.90642)+(0.000118*Tclk);
disp ('cpclk = '), disp (cpclk)
cpair = (1.00273)+(0.00016*Tair);
disp ('cpair = '), disp (cpair)
cpsecair = (1.00273)+(0.00016*Tsecair);
disp ('cpsecair = '), disp (cpsecair)
cptertair = (1.00273)+(0.00016*Ttertair); %newly added
disp ('cptertair = '), disp (cptertair)
cpexhair = (1.00273)+(0.00016*Texhair);
disp ('cpexhair = '), disp (cpexhair)
cpclkout = (0.90642)+(0.000118*Tclkout);
disp ('cpclkout = '), disp (cpclkout)
SpecificNumber = (Mairin/Mclkin)*(1/cpair);
disp ('SpecificNumber = '), disp (SpecificNumber)
% ........."Theorerical Clinker Outlet"........
Ttheoryclkout1 = ((exp(-SpecificNumber/0.77))*(Tclk - To))+ To

% Qic is the heat of clinker at the cooler input.
% Qca is the heat of the cooling air.
% Qas is the recoverable heat rate of kiln secondary air.
% Qoc is the heat of clinker at the cooler output.
% Qexh is the heat of cooler at exhaust air.

Qic = (Mclkin * cpclk * (Tclk - To));
disp ('Qic = '), disp (Qic)
Qca = (Mair * cpair * (Tclk - To));
disp ('Qca = '), disp (Qca)
Qas = (Msecair * cpsecair * (Tsecair - Tbeta));
disp ('Qas = '), disp (Qas)
Qexh = (Mexhair * cpexhair * (Texhair - Tbeta));
disp ('Qexh = '), disp (Qexh)
```

```
Qoc = (Mclkout * cpclkout * (Tclkout - Tbeta));
disp ('Qoc = '), disp (Qoc)

sumEin = Qic + Qca;
sumEout = Qas + Qoc + Qexh;
losses = sumEin - sumEout;
disp ('unaccountablelosses = '), disp (losses)

EngeryEff = sumEout/sumEin; % Energy efficiency of the system
disp ('Energy Efficiency = '), disp (EngeryEff)
Qrecov = Qas;
RecEnergEff = Qrecov/(Qic + Qca); % Recoverable Energy efficiency of the system
disp ('RecEnergEff = '), disp (RecEnergEff)
```