PERFORMANCE EVALUATION OF A GRATE COOLER IN A CEMENT MANUFACTURING INDUSTRY IN NIGERIA

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Abstract

The optimum priority of the modern cement production industry is the minimisation of heat energy loss for effective heat utilization and environmental effects for its sustainability. In this study, the performance of a grate cooler in Ibese cement manufacturing industry in Nigeria has been examined using the mass and heat balance methodology. This applied the second law of Thermodynamics that allows for the evaluation of the irreversibility anchored on the principle of input equals output and the heat energy performance of a grate cooler. The performance evaluation parameters considered were clinker temperature, cooler loss and efficiency. The exit clinker temperature was measured to be 56.62^0C*. It is found that 23.90% of the total heat energy (383.51 Kcal/kg.cl) generated is being lost even though a big percentage of this heat (76.10%) was being recovered. The cooler efficiency was found to be (75.53%) at this stage of the clinker production process. This study revealed that the grate cooler efficiency estimated through heat consumption balances conformed to the designed standard. Also, the cooler optimal performance has made more heat available for drying of material at the pre-heater and Vertical Roller Mills (VRM) during grinding.*

Keywords: Performance, Grate Cooler, Pyro-processing, Cooler Efficiency, Measurement and Central Control Room (CCR).

1.0 INTRODUCTION

Cement production in Ibese Cement Plant constitutes one of the major manufacturing industries in the Nigeria growing economy (Koroneos *et al.*, 2003). The production of cement is one of the most energy intensive production processes known (Koroneos *et al.*, 2005; Shraddha and Nehal, 2014). It is beneficial from an energy point of view during pyro-processing to optimise or redesign this process to improve its efficiency (IPPC, 2000; Wang, 2007). After homogenisation, the raw meal moves through a system of cyclones called a pre-heater, undergoing gradual heat treatment at temperatures up to 900^0C (Holcim, 2011; Nithyananth and Rahul, 2015). The temperature rises as high as 1400^0C, due to processes within the kiln as the raw meal is transformed into a granular hard substance called clinker (Ahamed *et al.*, 2012). This hot clinker is received at the cooler primarily for cooling purposes through the rotary kiln exit to meet some physico-chemical properties (Smidth, 2006; Jiang and Cang, 2008). The grate cooler in the cement industry utilize highly powerful fans which adds up to the huge initial capital investment (Hongyou *et al.*, 2009). In fact, the major role fans play in modern cement operation cannot be overemphasized in the pyro process section most importantly it generates the cooling air for clinker cooling purpose (Smidth, 2014). The specific heat consumption was an indicator for measuring the thermal energy consumed in the production of clinker. This revealed the specific heat consumption of clinker as an indicator of optimum performance of a cooler (Wang, 2007). There are other means used to justify the comparative operational state or units of pyro processes. Though, whenever the impact of thermal recuperation capacity of the pyro process in the cement plant is to be evaluated that of the cooler is usually of utmost importance. This has informed an interest in this study (Smidth, 2006).

2.0 EQUIPMENT DESCRIPTION

2.1 Cooler: This serves a most daunting but very important role in the cement production. The proper or improper cooling mostly determines the type and level of compressive strength (i.e quality) of cement. This is the most important characteristic that depend on the chemical composition of the clinker, the duration of the grinding process and the presence or absence of various additives. Also, cooler helps to recuperate heat from clinker and also to crush the clinker to the acceptable feed size for cement mill. This is presented on the Figure 2.1.

Fig 2.1: The Inner View of a Grate Cooler with Clinker Noddle on the Grate Plate.
Source: (Ahamed *et al.*, 2012)

2.2 Heat Transfer: There are three (3) modes of heat transfer involved in clinker cooling. They include conduction, convection and radiation. These heat movement modes are denoted in the Figure 2.2.

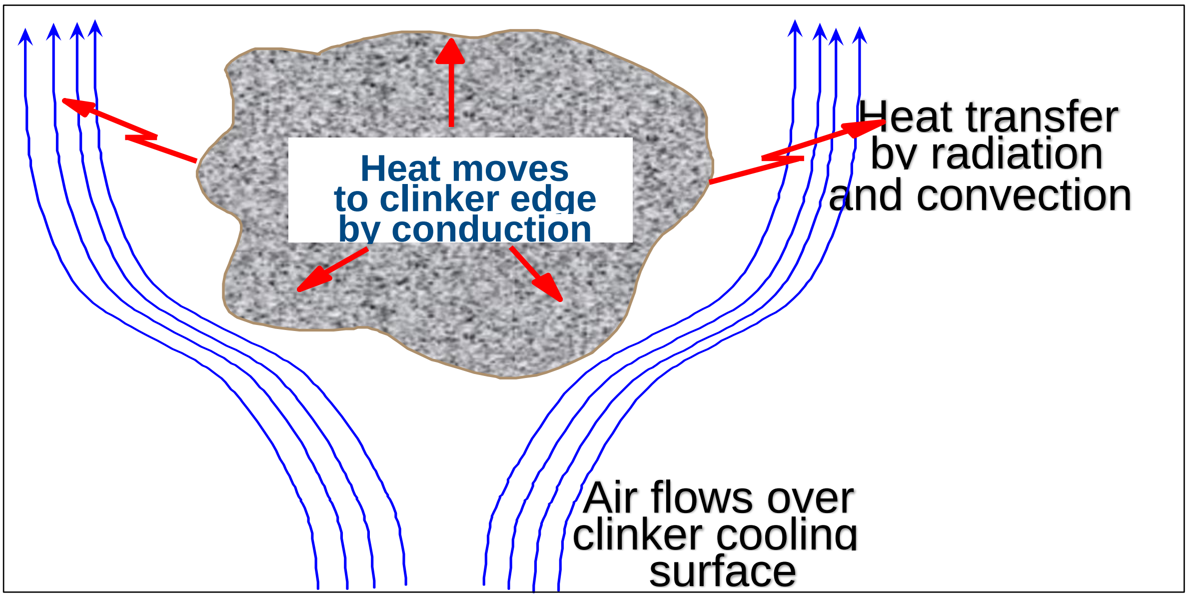
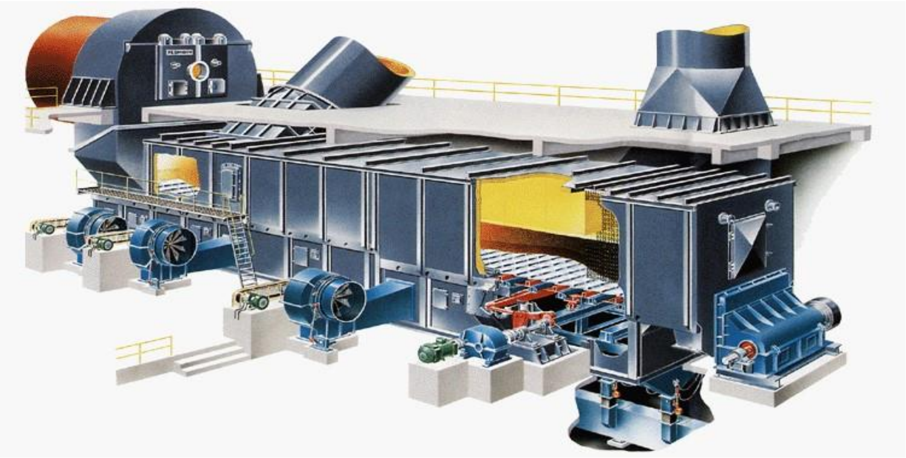


Fig 2.2: The heat transfer modes in a clinker noddle.
Source: (Smidth, 2014)

2.3 Types of Grate Coolers

Three (3) major types of grate coolers used for clinker cooling are presented and briefly described in this study as follows;



2.3.1 Conventional Grate Coolers: These are 1st generational grate coolers that have ability to handle large capacities, capable of achieving low clinker temperature, favorable heat recuperation and permits take out of hot tertiary air. Figure 2.3 gives a typical example of conventional grate cooler.

Fig 2.3: The Conventional Grate Cooler.
Source: (Smidth, 2014)

2.3.2 Air-Beam Grate Coolers: These are 2nd generational grate coolers that equally has the ability to handle large capacities but better heat recuperation compared to conventional grate cooler and improved cooling air distribution across the entire cooler. An example is shown on Figure 2.4.

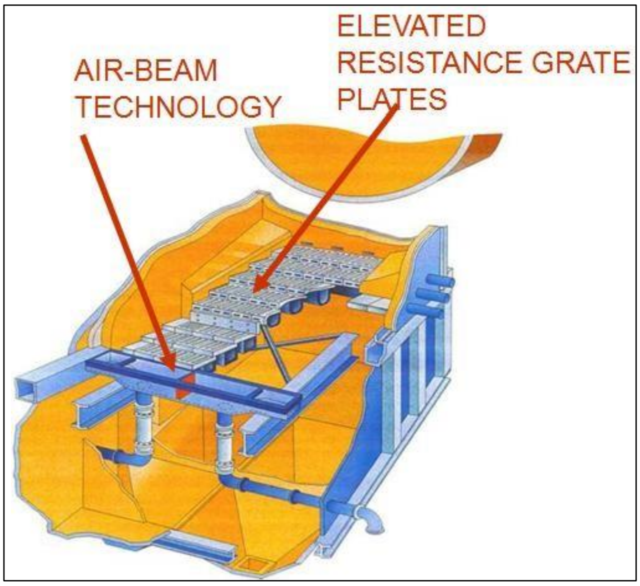


Fig 2.4: The Air-Beam Technology Cooler.

Source: (Smidth, 2014)

2.3.3 Stationary Grate Coolers: These are 3rd generational grate coolers with low wear parts, low cooler loss, low maintenance and power, no fall through and high efficiency. These coolers could also be referred to as Cross Bar Coolers because they are highly flexible for new construction and upgrades, horizontal clinker transport and improved transportation efficiency as shown on Figure 2.5.

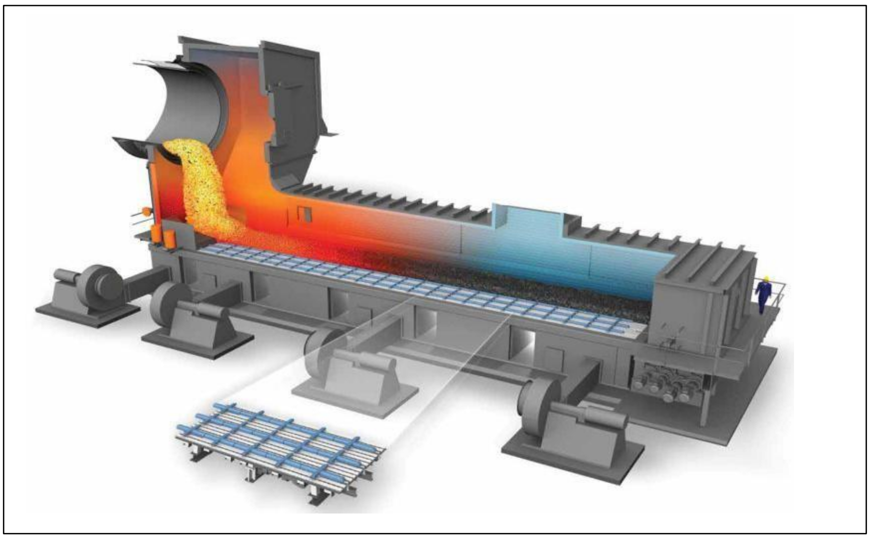


Fig 2.5: The Stationary Cooler.
Source: (Smidth, 2014)

2.4 Some Definitions

These are terms that are directly employ in measurement and calculation.

2.4.1 Cooler Air Load

The cooler air load is the ratio of the amount of air supplied to the cooler.

2.4.2 Cooler Specific Air

The cooler specific air is the ratio of the amount of air supplied to the clinker production.

2.4.3 Cooler Loading

The cooler loading is defined as the amount of clinker over the grate area.

2.4.4 Cooler Efficiency

The efficiency of a cooler is defined as the relationship between the recuperated heat to the kiln and the total heat transferred to the cooler as presented in equation 2.1.

$$\text{Cooler Efficiency} = (\text{Heat Input} - \text{Heat Losses}) / \text{Heat Input} \qquad 2.1$$

Heat Input: This denotes the heat content of clinker from kiln (clinker temperature = 1450°C) and cooler air (ambient air). It is sometimes being termed as Heat Available.

Heat loss: This is regarded as the heat content of cooler vent gas, clinker at exit and radiation (In general, cooler radiation for modern cooler will be around 6 kcal/kg.clinker maximum). The summation of all these losses are termed or referred to as Cooler Loss.

3.0 METHODOLOGY

The cooler performance evaluation was carried out through measurement and optimizing the cooler operation parameters such as clinker temperature, cooler efficiency and heat losses. These parameters have to be monitored continuously to ensure the cooler is operated efficiently. Therefore, the mass and heat balance calculation are very vital calculation in a cement process plant. This serves as the basis for the engineering design and the assessment of the production operation equipment performance. Three (3) major steps were adopted in this study using this procedure is highlighted as follows;

3.1 Process Data Measurement

This study involves performing preliminary process measurements and calculation necessary for optimum performance evaluation of a cooler at Dangote cement plant, Ibese, Ogun state. The data obtained from this measurement were used to evaluate and analyze the operating conditions necessary for optimal running of the plant. However, the measurements and subsequent calculation was based on the principle of input (clinker, cooling air, fuel, water injection) and output (clinker temperature, secondary and tertiary Air, excess air and cooler radiation) of clinker from the grate cooler.

3.1.1 Cooler Input

The cooler clinker input is considered as 1 kg which is taken as the basis for the mass.

3.1.1.1 Clinker Input

The amount of clinker is found by physical measurement of clinker coming out of the cooler including clinker dust. The clinker feed as obtained from CCR was found to be 264.71 TPH

Total Clinker from Drop Test = 264.7 TPH

Clinker Input = 264.71/264.7 = 1 kg/kg Clinker

3.1.1.2 Fuel Input

The fuel consumed by the cooler for this study is natural gas supplied by Nigerian Gas Company (NGC) while coal was used at the calciner in the pre-heater for drying purpose which is not covered in the performance evaluation as tabulated on Table 3.1.

3.1.1.3 Cooling Air Input

The velocities of each fan were measured at fan inlet using the dynamic velocity anemometer. The recorded values were tabulated as shown on Table 3.2

3.1.1.4 Water Injection

The specific water flow [kg/kg. clinker] = Net Water Flow [kg/hr] / Total Clinker [kg/hr]

3.1.2 Cooler Output

The clinker output from the cooler is expected to be 1 kg provided no loss in mass.

3.1.2.1 Excess Air

The cooler excess air was found by measuring the temperature and static pressure at cooler at cooler ESP stack. The values obtained were recorded and tabulated as presented on Table 3.4.

3.1.2.2 Clinker Temperature

The clinker temperature was adequately measured by taking clinker samples in an insulated closed container i.e calorimeter. The clinker considered for measurement must be sieved in – 12 mm and + 6 mm sieves. Its coating pieces and red hot pieces must be removed. It is recommended to take the samples before clinker crusher. This is mainly because coating pieces will be crushed in clinker crusher zone and this must be avoided.

3.1.2.3 Cooler Radiation

The grate cooler heat radiation was measured using infrared thermometer (561-566 nanometer wavelength). This compared the surface temperature to the surface area and values obtained were tabulated on Table 3.3.

3.2 Calculation Basis for Mass and Heat Balances.

Basis for material: one (1) kg and 0°C of clinker is usually taken as the basis.

3.2.1 Cooler Mass and Heat Balance

The selection and determination of proper parameters are important to the correct calculation of heat balance. So, all the necessary parameters were obtained (CCR), measured (field) and tabulated as recorded on Tables 3.1, 3.2, 3.3 and 3.4 respectively.

3.2.2 Parameters Measurement from the Cooler.

The measurements taken for cooler heat balance are cooler air fan flow, cooler excess air fan flow temperature, tertiary air flow temperature and clinker temperature.

Table 3.1: Raw Meal-Fuel-Clinker Data

Test Time			2017- 02 - 14 (20:00) ~ 2017- 02 - 15 (20:00)		
Ambient Temperature			28.3℃		
Test Items			Unit	Data	Remarks
Clinker		Production	tph	264.71	By CCR
		Clinker Temperature inlet of Cooler	℃	1400	Estimate
		Clinker Temperature outlet of Cooler	℃	56.62	
Raw Meal		Feed	tph	460.00	By CCR
Fuel	Coal	Cooler	kg/h	0.0	By CCR
		Calciner	kg/h	5000.0	By CCR
		Total	kg/h	5000.0	By CCR
	NG	Cooler	Nm^3/h	9184.2	By CCR
		Calciner	Nm^3/h	10917.3	By CCR
		Total	Nm^3/h	20101.5	By CCR
	Heating Value	Coal	kcal/kg		
		NG	$kcal/Nm^3$	8765.65	

Table 3.2: Cooling Air Flow Test

Fan Number	Average Air Velocity (m/s)	Temperature (℃)	Static Pressure (Pa)	Air Flow(OC) (m^3/h)	Air Flow(NC) (Nm^3/h)
FN03	19.95	42.1	11200	22979	22109
FN04	16.07	41.8	6830	22966	21259
FN05	16.44	39.6	6780	23485	21883
FN06	16.47	34.5	4840	47443	44132
FN07	14.97	34.0	4440	51729	48015
FN08	13.55	34.8	4240	58536	54090

FN09	14.60	34.2	4190	75698	70052
FN10	12.94	33.8	4120	67081	62118
FN11	11.85	33.8	4220	61448	56955
FN12	10.43	33.8	3940	54058	49973
FN13	10.92	33.4	2920	56586	51872
Total cooling air flow		Nm^3/h		502458	
		$Nm^3/kg.cl$		1.898	

(OC: Operation Condition Standard NC: Normal Condition Standard)

Table 3.3: Surface Radiating Heat Loss Test

Items	Surface Radiating Heat Loss
	kJ/kg.cl
Cooler	5.68
Kiln Hood	7.63
Total	13.31

Table 3.4: Other Gas Flow Test

Items	Temperature	Static Pressure	Gas Flow
	℃	Pa	Nm^3/h
Primary Air of Kiln burner	28.3	0	14258
Exhaust Gas of Cooler	243.2	-320	306590
Tertiary Air	1100	-320	127204

3.2.3 Mass and Heat Balance Calculation of Cooler

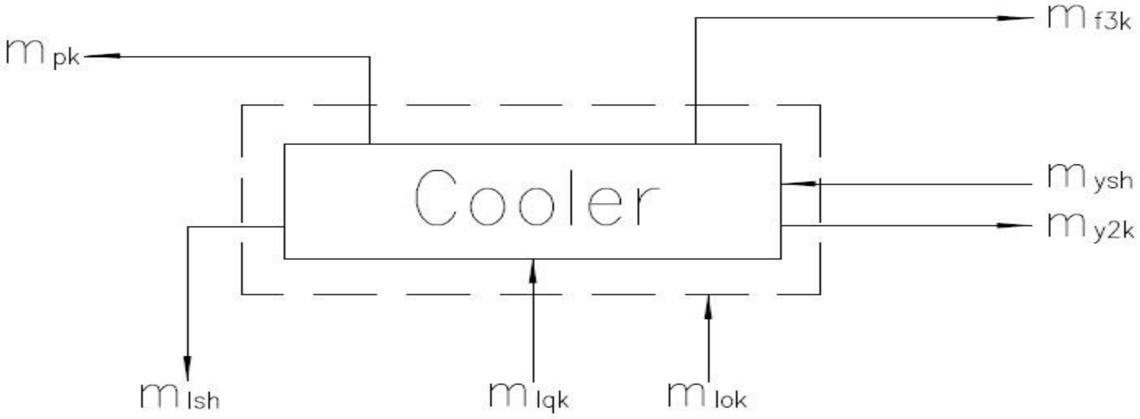


Fig 3.1: A Grate Cooler Mass Balance Flow Diagram

Material Basis：1kg Clinker；Normal Standard： Air density: $\rho_k = 1.293\ kg/Nm^3$; Temperature: 0℃; Atmosphere Pressure: 101325 Pa.

3.3 Mass Balance

3.3.1 Mass Input

(1) Clinker of Cooler inlet $m_{ysh} = 1.000$ kg/kg.cl

(2) Cooling Air of Cooler

$m_{lqk} = V_{1qk} / m_{lsh} \times \rho_k$

$= 502458 / 264.71/1000 \times 1.293$

$= 2.454$ kg/kg.cl ($1.898 Nm^3$/kg.cl)

(3) Leaking Air

$m_{lok} = m_{pk}+m_{y2k}+m_{f3k}-m_{lqk}$

$=1.498+0.390+0.621-2.454$

$= 0.055$ kg/kg.cl

3.3.2 Mass Output

(1) Clinker Prodution $m_{lsh} = 1.000$ kg/kg.cl

(2) Secondary Air

a. Theoretical Air Flow for NG:

$V_{a\_NG}^0 = 0.261 \times Q_{net,\ NG} \times 4.182/1000-0.25$

$= 0.261 \times 8765.65 \times 4.182/1000-0.25$

$= 9.318\ Nm^3/\ Nm^3$.NG

b. Excess Air Ratio inlet of Kiln: k=1.1

Theoretical Air Flow for Cooler Burner:

$V_{y2k} = \alpha_k \times V_{a\_NGO} \times V_{NG\_Cooler} - V_{1k}$

$= 1.1 \times 9.318 \times 9184.2 - 14258$

$= 79878.2\ Nm^3/h$

$m_{y2k} = V_{y2k} \times \rho_k / m_{lsh}$

$= 79878.2 \times 1.293/264.71/1000$

$= 0.390$ kg/kg.cl

(3) Tertiary Air

$m_{f3k} = V_{f3k} \times \rho_k / m_{lsh}$

$= 127204 \times 1.293/264.71/1000$

$= 0.621$ kg/kg.cl

(4) Exhaust Gas of cooler

$m_{pk} = V_{pk} \times \rho_k / m_{lsh}$

$= 306590 \times 1.293/264.71/1000$

$= 1.498$ kg/kg.cl

3.4 Heat Balance

3.4.1 Heat Input

(1) Sensible Heat of Clinker of Cooler inlet

$Qysh = mysh \times tysh \times Cysh$

$= 1.000 \times 1400 \times 1.081$
$= 1513.40$ kJ/kg.cl（361.62 kcal/kg.cl）

(2) Sensible Heat of Cooling Air of Cooler
$Q1qk = mlqk \times tlqk \times Clqk$
$= 2.454 \times 28.3 \times 1.290$
$= 89.59$ kJ/kg.cl（21.41 kcal/kg.cl）

(3) Sensible Heat of Leaking Air of Cooler
$Qlok = mlok \times tlok \times Clok$
$= 0.055 \times 28.3 \times 1.29$
$= 2.01$ kJ/kg.cl（0.48 kcal/kg.cl）

(4) Total Heat Input
$Q_{1zs} = Q_{ysh} + Q_{lqk} + Q_{lok}$
$= 1513.40 + 89.59 + 2.01$
$= 1605.00$ kJ/kg.cl（383.51 kcal/kg.cl）

3.4.2 Heat Output

(1) Sensible Heat of Clinker of Cooler outlet
$Qlsh = mlsh \times tlsh \times Clsh$
$= 1.000 \times 56.62 \times 0.770$
$= 43.60$ kJ/kg.cl（10.42 kcal/kg.cl）

(2) Sensible Heat of Secondary Air
Average Temperature of Secondary Air: $T_{y2k} = 1120$ ℃

$Q_{y2k} = m_{y2k} / \rho k \times T_{y2k} \times C_{y2k}$
$= 0.390/1.293 \times 1120 \times 1.401$
$= 473.29$ kJ/kg.cl（113.09 kcal/kg.cl）

(3) Sensible Heat of Tertiary Air

$Qf3k = mf3k/\rho k \times tf3k \times Cf3k$
$= 0.621/1.293 \times 1100 \times 1.399$
$= 739.10$ kJ/kg.cl（176.61 kcal/kg.cl）

(4) Sensible Heat of Exhaust Gas of cooler

$Qpk = mpk/\rho k \times tpk \times Cpk$
$= 1.498/1.293 \times 243.2 \times 1.314$
$= 370.23$ kJ/kg.cl（88.47 kcal/kg.cl）

(5) Surface Radiating Heat Loss of Cooler

$Q_{bl} = \frac{\sum Q_{bl}}{M_{sh}} = 13.31$ kJ/kg.cl（3.18 kcal/kg.cl）

(6) Heat Deviation

$$Qlqt = Qlzs - Qlsh - Qy2k - Qf3k - Qpk - Qbl$$
$$= 1605.00 - 43.60 - 739.10 - 473.29 - 370.23 - 13.31$$
$$= -34.53 \text{ kJ/kg.cl } (-8.25 \text{ kcal/kg.cl})$$

(7) Total Heat Output

$$Qlzc = Qlsh + Qy2k + Qf3k + Qpk + Qbl + Qlqt$$
$$= 43.60 + 473.29 + 739.10 + 370.23 + 13.31 - 34.53$$
$$= 1605.00 \text{ kJ/kg.cl } (383.51 \text{ kcal/kg.cl})$$

(8) Heat Balance deviation:

$$(Q_{lqt} / Q_{lzs}) \times 100\% = (-8.25 / 1605.00) \times 100\%$$
$$= -0.514\%$$

4.0 RESULT DISCUSSION

This performance evaluation was examined using cooler parameters such as the clinker temperature, cooler efficiency and grate cooler loss. The operating parameters at which the performance evaluation was carried out were 1.898 Nm^3/kg.cl for total cooling air flow (V_{lqk}) and 264.71Tph of clinker cooler inlet (m_{ysh}) as presented in section 3.3.1 on Tables 3.1 and 3.2 respectively. Figure 3.1 depicted the materials input and output flow of the cooler upon which the mass balance was anchored. Table 4.1 showed the result derived from the mass balance calculation.

Table 4.1: Mass Balance of the Cooler

Mass Input					Mass Output				
Num	Items	Symbol	kg/kg.cl	%	Num	Items	Symbol	kg/kg.cl	%
1	Cooler inlet	M_{ysh}	1.000	28.50	1	Clinker Production	m_{lsh}	1.000	28.50
2	Cooling air	M_{lqk}	2.454	69.94	2	Exhaust Gas	m_{pk}	1.498	42.69
3	Leaking Air	m_{1ok}	0.055	1.56	3	Tertiary Air	m_{f3k}	0.621	17.70
4					4	Secondary Air	m_{y2k}	0.390	11.11
5	Total Mass Input	m_{zs}	3.509	100	5	Total Mass Output	m_{zc}	3.509	100

Table 4.2 showed the result of heat balance carried out on the cooler. It could be deduced that heat deviation was - 8.25 Kcal/kg.clinker, which gives - 2.15% of the total heat input into the cooler as presented on Table 4.2. This could be as a result of the downward temperature gradient from higher to lower degree (°C). It was equally observed from Table 4.2 that 10.42 Kcal/kg.clinker given 2.72% of the heat energy was for clinker production. Also, the heat energy recuperation is 75.53% of total heat energy input found to be 383.51 Kcal/kg.clinker. So, with this good thermal energy recuperation, optimum energy utilization was achieved.

This grate cooler performance when compared with the proposed standard by FLSmidth meet the minimum design standard for cooler efficiency ($\geq$ 75%) with the value of 75.53% as presented on Table 4.3. Furthermore, the average clinker temperature of cooler outlet (t_{lsh}) was 56.62^{0}C which equally comply with the design standards. However, the cooler loss was found to be 26.62% with an approximate 1.62% above the given standard with a total heat loss of 102.07 Kcal/kg.clinker. This showed that this cooler performance parameter did not meet the set standard proposed by the equipment's supplier. Although, with proper cooler grate maintenance this values can be improved upon because poor cooler thermal recovery efficiency leads to bad clinker reactivity which ultimately affects the clinker grinding negatively. It may also lead to poor secondary air recovery which affects clinker bed formation consequently to an increase in the specific fuel consumption.

Table 4.2: Heat Balance of the Cooler

Heat Input						Heat Output					
Num	Items	Symbol	kJ/kg.cl	kcal/kg.cl	%	Num	Items	Symbol	kJ/kg.cl	kcal/kg.cl	%
1	Sensible Heat of Clinker Cooler inlet	Q_{ysh}	1513.40	361.62	94.29	1	Sensible Heat of Clinker Production	Q_{lsh}	43.60	10.42	2.72
2	Sensible Heat of Cooling Air	Q_{lqk}	89.59	21.41	5.58	2	Sensible Heat of Exhaust Gas	Q_{pk}	370.23	88.47	23.07
3	Sensible Heat of Leaking Air	Q_{lok}	2.01	0.48	0.13	3	Sensible Heat of Tertiary Air	Q_{f3k}	739.10	176.60	46.05
						4	Sensible Heat of Secondary Air	Q_{y2k}	473.29	113.09	29.48
						5	Surface Radiating Heat Loss	Qbl	13.31	3.18	0.83
						6	Heat Deviation	Qlqt	- 34.53	- 8.25	-2.15
4	Total Heat Input	Q_{lzs}	1605.00	383.51	100	7	Total Heat Output	Q_{lzc}	1605.00	383.51	100

Cooler Efficiency :

$$(\eta) = \frac{Q_{y2k.f3k}}{Q_{ysh}} \text{x}100\% = (473.29 + 739.10)/ 1605.00 = 75.53\%$$

Table 4.3: Comparison of Cooler Performance with the Design Standard

Cooler parameters	Bench Mark Values	Calculated Values
Standard Cooler Loss (kcal/kg clinker)	≤ 95	91.66
Cooler Efficiency (%)	≥ 75%	75.53
Clinker Temperature (°C)	≤ 65+ambient	56.62

5.1 CONCLUSION

The comparative analysis of the grate cooler with design standards showed that the equipment's performance was within design specification except the cooler heat loss that was above the given standard. Also, in terms of energy savings, it can be concluded that the cooler heat recuperation determined its efficiency and the equipment consumed considerate amount of fuel during its operation.

5.2 RECOMMENDATION

The pyro processes operating parameters in Ibese plant should be looked into for their grate cooler to meet its design specification in terms heat energy losses.

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