Impacts of Clinker Storages Heat Transfer, Its Effect on Vertical Roller Cement Performances: A Case Study of Cement Grinding Operations in Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author OSJ carried-out the industrial research, laboratory research, interpretations of simulation on computational fluid dynamics (CFD) and computer aided design (CAD). Author NZB carried out the industrial data collation and interpretations of industry data. Author ETI performed the designing of the computational fluid dynamics (CFD), computer aided design (CAD) and analysing simulation data. Author AAA interpreted the results and review the data. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Operational data indicates that vertical roller cement mills (VRCM) consumed lesser energy when compared to horizontal/ball mills. A case study of a vertical roller cement mills was carried out in Nigeria which was experiencing a lower production output and a higher energy consumption. This research was to investigate reasons behind the low production output on the VRCM. A thorough analysis was carried out on the clinker storage facilities and the heat transfer across the composite cylindrical clinker silo walls (off – spec and main clinker) both silos having the same design but with different dimensions and with different application purpose. The off-spec clinker silo has a design capacity of 1,800 tons and main clinker silo a design capacity of 60, 000 tons and both silo stores hot clinker that left the kiln clinker cooler at approximate temperature of 95°C. The analytical results shows that the rate of heat transfer across the main clinker composite walls was 728 kW and the rate of heat transfer across the off-spec clinker composite walls was 217.15 kW. Numerical simulation was also carried out using ANSYS simulation package and the results obtained were in good agreement with the results obtained theoretically. The ratio of heat loss on the main clinker composite walls to off-spec clinker composite walls was 3.35:1.

Keywords: Heat transfer; composite cylindrical walls; vertical roller cement mills; clinker silos; cement grinding; cement temperature.

ABBREVIATIONS

Symbol	Meaning	Unit
a	:Main Clinker Silo Height	m
A	:Cross sectional Area	m^2
A_i	:Silo Inner Wall Cross-Sectional Area	m^2
A_{lm}	:Log-mean Cross-Sectional Area	m^2
A_o	:Silo Outer Wall Cross-Sectional Area	m^2
ASTM	:American Society for Testing Materials	
CaO	:Lime	-
CEM	:Cement	-
cp_{air}	:Specific Heat Capacity of air	$kJ/kg\,^oC$
cp_c	:Specific Heat Capacity of Cement	$kJ/kg\,^oC$
cp_k	:Specific Heat Capacity of Clinker	$kJ/kg\,^oC$
D_d	:Nominal Mill Diameter	m
D_o	:Mill Outer Diameter	m
dr	:Thickness of Concrete Silo	m
ETSAP	:European Technology System Analysis Programme	-
G	:Mill Output	$tons/hr$
h	:Height of Concrete Silo	m
IEA	:International Energy Agency	-
K	:Thermal Conductivity of Concrete	$W/K\,m$
K	:Heat Transfer Factor	$kJ/m^2\,hr$
L	:Thickness of walls	m
L_l	:Mill Length	m
N	:Motor Power	kW
OPC	:Ordinary Portland Cement	-
Q	:Rate of Heat Transfer	kW
Q	:Steady heat flux	kW
Q_a	:Heat Removed by Air	kW
Q_c	:Heat in Cement	kW
Q_{clk}	:Heat in Clinker	kW
Q_q	:Grinding Heat	kW
$Q_{r/c}$	:Heat Lost by Radiation and convection	kW
Q_w	:Heat Removed by Evaporation of Water	kW
r	:Water Heat of Evaporation	kJ/kg

Symbol	Meaning	Unit
r_i	:Inner Radius of Cylindrical Silo	m
r_o	:Outer Radius of Cylindrical Silo	m
SiO_2	:Silica	-
t_{air}	:Air Final Temperature	^oC
T_{cem}	:Cement Temperature	^oC
T_{clk}	:Clinker Outlet Temperature	^oC
T_{HGG}	:Hot Gas Generator Temperature	^oC
T_i	:Silo Inner Temperature	^oC
T_o	:Ambient Air Temperature	^oC
t_o	:Air Initial Temperature	^oC
T_o	:Silo Outer Temperature	^oC
u	:Off-Spec Clinker Silo Height	m
V_{air}	:Venting Air Volume	Nm^3/hr
W	:Required Water Injection	kg/hr
w	:Water Rate	kg/hr
x	:Off-Spec Clinker Silo Thickness	m
y	:Main Clinker Silo Thickness	m
π	:Pi	-
η	:Mill Drive Efficiency	%

1. INTRODUCTION

Cement grinding operation is the final stage cement production process in cement manufacturing. Ordinary Portland Cement (OPC) is the most common type of cement produced around the world when compared to other type of cement produced [1]. European standard further elaborated the most common type cements produced. However, some special cements are produced for a specific purpose such as low-heat cements or low-alkali cements as standardized by European standard EN 197-1. The European standard EN 197-1 and America standard (ASTM); described 27 types of cements, which were further divided into five (5) groups, as shown in Table 1, [2-7]. There are several types of cement grinding mills that are used in cement manufacturing plants. Table 2, are the list of cement grinding mills and it grinding efficiency, [8-10].

Table 1. Type of cement

	Types of Cement	Clinker%	Other Constituents
CEM I	Portland	95-100	
CEM II	Portland-slag	65-94	Blast furnace slag
	Portland-silica fume	90-94	Silica fume
	Portland-pozzolana	65-94	Pozzolana
	Portland-fly ash	65-94	Fly ashes
	Portland-burnt shale	65-94	Burnt Shale's
	Portland-limestone	65-94	Limestone
	Portland-composite	65-94	Additives mix
CEM III	Blast furnace	5-64	Additives mix
CEM IV	Pozzolanic	45-89	Additives mix
CEM V	Composite	20-64	Additives mix

Table 2. Common grinding mills in the cement industry

Grinding Equipment	Grinding Force	Energy Use kWh/t (cement)	Grinding Efficiency
Tube Mill	Impact/Friction	35-38	5-8%
Roller Press	Compression/Friction	22-26	12-20%
Vertical Roller Mill	Compression/Friction	27-30	7-15%
Horizontal Roller Mill	Compression/ Friction	24-27	10-18%

There are two major types of equipment used for cement grinding namely: Horizontal Ball Mills (HBM) and Vertical Roller Cement Mills (VRCM). The horizontal mills also known as ball mills has two (2) chamber in most cases which are separated by a diaphragms. The first chamber contains grinding media sizes between 60 mm to 90 mm. The grinding media are mostly made up of alloy- steel and ceramics. While chamber two (2) contains grinding media sizes ranges between 50 mm to 15 mm. Fig. 1 and Fig. 2, shows the general overview of the horizontal or balls and vertical roller cement mill, [11,12].
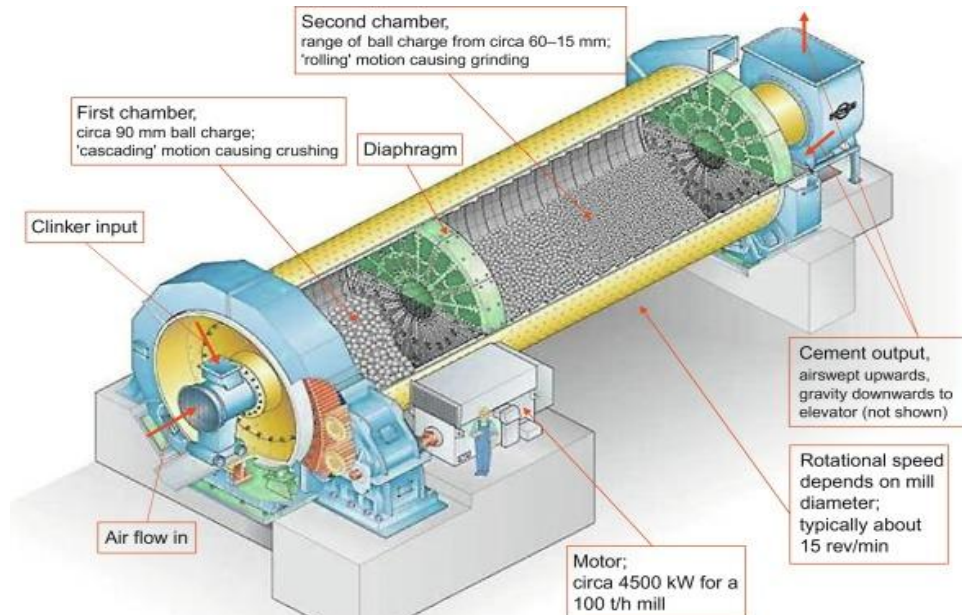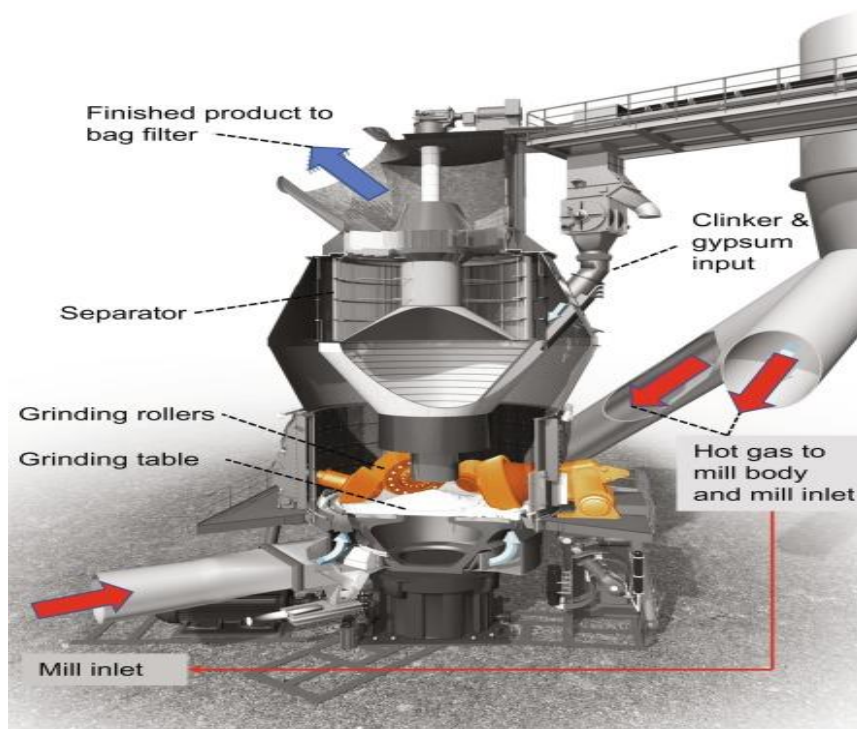
Fig. 1. Overview of horizontal or ball mill

Fig. 2. Overview of vertical roller cement mill VRCM

Fig. 3. An image of a main clinker silo and off – Spec silo in an existing cement plant

This research focuses more on optimizing vertical roller cement mills and the impacts of heat transfers/heat losses that are associated with vertical roller cement mills production output. Fig. 3, shows the clinker main silo and off-spec clinker silo [13,14].

2. MATERIALS AND METHODOLOGY

A vertical roller cement mills was used for purpose because of low production output. Some of the data used are direct input and output of the running plant based on design of equipment supplied by the manufactual and it operating parameters. The vertical roller cement mill has a design capacity 170 tons per hour with an additional hot gas generator for generating heat whenever vertical roller cement mills are in operation at temperature of $320\,^{o}$C.

2.1 Heat Generation (Input and Output) in Cement Grinding

Production of OPC, it's assumed that the heat input consists of the grinding heat Q_g and the heat in clinker Q_{clk} as expressed in Equations (1) and (3) respectively, [15]. Cement grinding heat Q_g is a direct function of the installed motor power (N) where the clinker heat depends directly on its temperature, [15],

$$Q_g = \frac{3.6\eta N}{G} \qquad (1)$$

Clinker heat generation:

$$Q_{PK} = C_{PK}(T_{clk} - T_o) \qquad (2)$$

$$C_{PK} = (0.00046 T_{clk} + 0.733) \qquad (3)$$

where; N is motor power (kW) of mill, η is mill drive efficiency (%), cp_k is specific heat value for clinker (kJ/kg ^{o}C), T_{clk} is clinker outlet temperature (^{o}C), G is mill output (t/h), T_o is ambient air temperature (^{o}C). The heat loss with cement grinding outlet temperature is shown in Equations (4) and (5).

$$Q_C = C_{PC}(T_{cem} - T_o) \qquad (4)$$

$$C_{PC} = (0.00046 T_{cem} + 0.733) \qquad (5)$$

where, c_{Pc} is specific heat capacity for cement (kJ/kg ^{o}C), T_{cem} is cement temperature (^{o}C).

Heat losses due to radiation and convection which is the function of the surface of the mill and mill shell temperature is expressed in Equation (6).

$$Q_{r/C} = \frac{D_o \pi k (D_d/2 + L_l)}{1000 G} \qquad (6)$$

where, D_d is nominal mill diameter (m), D_o is the mill outer diameter (m), L_l is mill length (m), k is heat transfer factor (kJ/m^{2}h). The heat transfer factors (k) for clinker grinding heat varies with some parameters like the diameter of the mill, [8]. Heat output due to venting air, is expressed in Equation (7):

$$Q_g = [(Q_g + Q_c) - (Q_c + Q_{r/c} + Q_w)] \qquad (7)$$

The heat output due to water evaporation, is expressed in Equation (8):

$$Q_w = \frac{rw}{1000} \qquad (8)$$

where; *w* is water rate (including moisture content in feed material) (kg/t) *r* is heat of evaporation of the water and has the value of 2500 kJ/kg. Heat generation output consists of the heat contained in the cement (Q_c), the heat lost by radiation and convection ($Q_{r/c}$), the heat removed by air (Q_a) and by evaporation of water (Q_w). Heat contained in cement depends only on the cement outlet temperature, [15]. Venting air volume (V_{air}) is dependent on the energy balance resulting from heat input and input during cement powder production. It is expressed in equation (9a), [15].

$$V_{air} = \frac{1000 \times G \times Q_a}{c_{pair}(t_{air} - t_o)} (Nm^3/h) \qquad (9a)$$

The required water injection W is determined using Equation (9b),

$$W = \frac{1000 \times Q_a}{r} \qquad (9b)$$

Heat Transfers Across the Composite Cylindrical Clinker Silo Walls:

The following basic assumptions were used for the research:

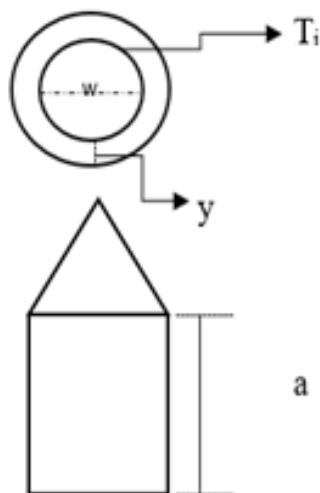- the concrete silo is homogeneous and isotropic;

- there is no internal heat generation;
- contact between clinker and silo wall is sufficient for conduction to occur;
- heat transfer resistance is negligible;
- heat transfer by convection and radiation is negligible; and
- conduction occurs at steady state.

Fig. 4a to Fig. 4b, shows the third (3rd) angle projection of composite cylindrical (main and off-spec) silos used for the storing of the clinker that is used by the vertical roller cement mills for cement grinding operation and the dimensions of the silos. Clinker temperature insider the silos is 95 °C.

Outer clinker silo wall temperature or ambient temperature (T_o) and (T_i) is the inner silo wall temperature or clinker temperature silo. Table 3, contains information about the main and off-spec clinker silo design parameter and design capacity for the vertical roller cement mills that was used for this research in Nigeria.

2.2 Heat Transfer across Walls Analysis

Basic requirements for heat transfer is the presence of a temperature differences. Analyzing the heat transfer across cylindrical coordinates of a solid walls (main clinker silo and off-spec silo) with infinitesimal thickness δr and height L, with an assumption that temperature is radially symmetric and across a volume (V), as shown in Fig. 4c, [16-19].
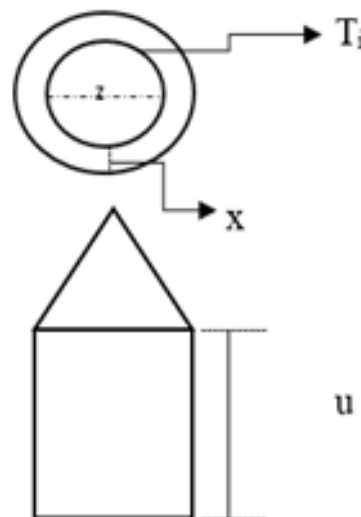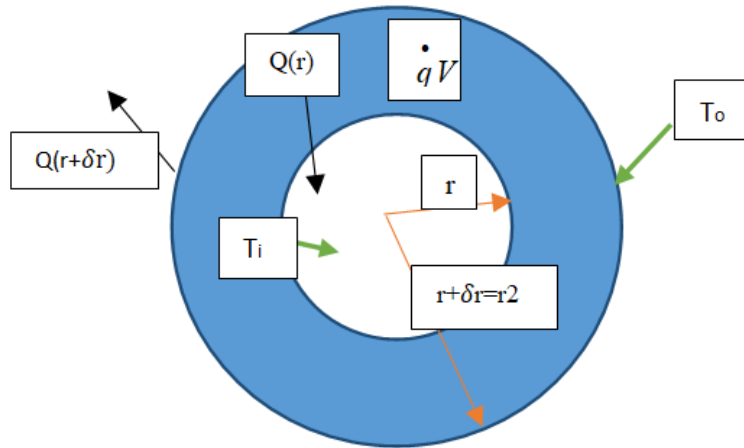

Fig. 4a. The main clinker silo

Fig. 4b. The off-spec silo

Fig. 4c. Heat Transfer across Sliced Solid Wall

Table 3. Geometrical and operational parameters

Parameter	Main Clinker Silo	Off-Spec Clinker Silo	Unit
Thickness	0.75	0.50	m
Diameter	44.50	10.50	m
Inner radius	22.25	5.25	m
Outer radius	23	5.75	m
Height	20 m	16.40	m
Design Capacity	60,000 (60,000,000)	1,800 (1,8000,000)	Tons (kg)
Clinker temperature inside silo	95 (368)	95 (368)	^{o}C (K)
Ambient temperature	35 (308)	35 (308)	^{o}C (K)
Heat loss across wall	728	217.51	kW

The possibility of internal energy generation ($\dot{q}$) due to hot clinker that are been stored insider the cylindrical composite silo. Heat Q(r) flows *in* from the left, and Q(r+δr) flows *out* through the right. The energy balance is show in equation (10a) and (10b)

$$Q_{in} - Q_{out} = mc\left(\frac{\partial T}{\partial t}\right) \tag{10a}$$

$$Q(r) + \dot{q} - Q(r+\delta r) = mc\left(\frac{\partial T}{\partial t}\right) \tag{10b}$$

$$V = \pi(r+\delta r)^2 L - \pi r^2 L \approx 2\pi r \delta r L \tag{10c}$$

Dropping $(\delta r)^2$ terms because δr << r, *m* is the mass flow, *c* is the specific heat. Quantities of heat rate (Q) flowing through a solid with cross-sectional area *A*, this is expressed in equation (11) to (12d) [16-19].

$$Q = qA \tag{11}$$

$$q = \left(-k\frac{\partial T}{\partial r}\right) A \tag{12a}$$

$$A = 2\pi dr \tag{12b}$$

$$\int_{r}^{r+\delta r} \frac{Q}{A}\partial r = -\int_{T1}^{T2} k\partial T \tag{12c}$$

$$Q = 2\pi Lk \frac{T_i - T_o}{In\frac{r_2}{r}} \tag{12d}$$

where *q* is steady heat flux, substituting into equation (10b), substituting equation (10c), equation (11) and (12) into equation (10b) gives equation (13)

$$-k2\pi rL \frac{\partial T}{\partial r}|_r +$$

$$\dot{q}\,2\pi r\delta rL + k2\pi(r+\delta r)L\frac{\partial T}{\partial r}|_{r+\delta r} =$$

$$mc\frac{\partial T}{\partial t} \tag{13}$$

For linear functions as expressed in equation (14) and (15)

$$f(x+dx) = f(x) + f^l(x)dx \qquad (14)$$

$$f^l(x+\delta x) = f^l(x) + f^{ll}(x)dx \qquad (15)$$

Using linear function gives equation (16)

$$\frac{\partial T}{\partial r}\Big|_{r+\delta r} \approx \left(\frac{\partial T}{\partial r}\right)\Big|_r + \frac{\partial^2 T}{\partial r^2}\delta r \qquad (16)$$

Substituting equation (16) into (13)

$$2\pi k L\left(r\delta r\frac{\partial^2 T}{\partial r^2} + \delta r\frac{\partial T}{\partial r}\right) + \dot{q}\,2\pi r\delta r L = mc\frac{\partial T}{\partial t} \qquad (17)$$

$m = \rho 2\pi r\delta r L,$ and $\alpha = \dfrac{k}{\rho c}$ Thermal diffusivity

substituting into equation (17)

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (18)$$

Heat equation for cylindrical coordinates across the clinker silo walls is expressed (19)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right) + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (19)$$

2.3 Validation of the of Theoretical Results with Numerical Results (ANSYS)

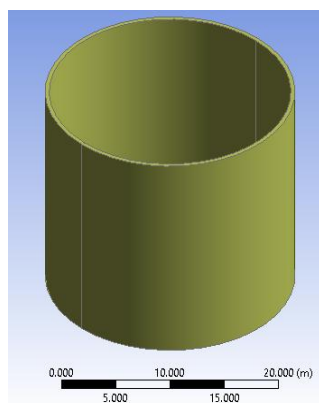In order to further investigate the heat loss across the Composite Cylindrical Clinker Silo Walls for the Off- Spec Clinker Silo and the Composite Cylindrical Clinker Silo Walls for the Main Clinker Silo, thermal analysis was carried out in ANSYS – Mechanical platform. A 3D cylindrical geometries of the main silo and off-spec silo were developed in SolidWork platform and it was imported in ANSYS– Mechanical thermal analysis platform.

a) **Meshing:** The 3-D models as shown in Figs. 5 and 6 shows cylindrical geometry for the main silo and off – spec silo respectively and these were meshed into ANSYS meshing environment, where the model were discretized into finite element mesh. The number of elements in a mesh were varied, depending on the level of refinement or size of the cells in the mesh and hence a very fine mesh size was used, taking into consideration computation time and solution accuracy. Figs. 7 and 8, shows the meshing results for both main clinker silo and off-spec clinker silo.

b) **Boundary Conditions:** For the silos (the main silo and off-spec silo), the inner temperature of the wall of the silo is assigned to be 95℃ while the wall temperature of the outer surface of the silo is assigned 35℃., as shown in Figs. 9 and 10 respectively. Every other surface is assumed to be adiabatic (No heat loss) surface, a steady – state thermal analysis is carried out or computed by the solver.

c) **Solution Results:** The primary target in this research is the estimation of heat transfer rate across the wall of the silo and this was expressed in equation (12d). The heat transfer rate has been estimated theoretically, and the results presented. The
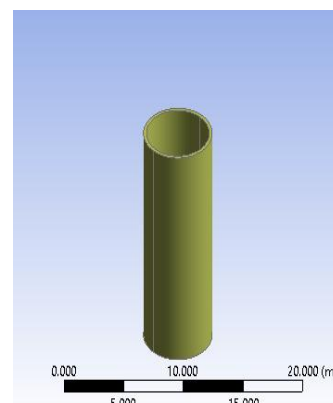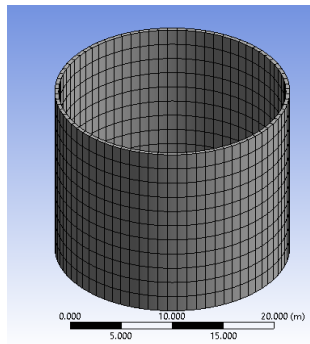

Fig. 5. 3D model of main silo

Fig. 6. 3D Model of OFF – SPEC Silo
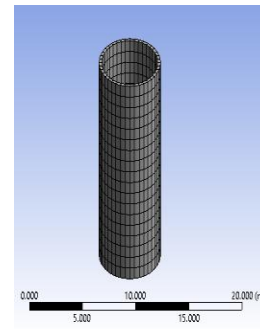
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Fig. 7. Mesh of main silo
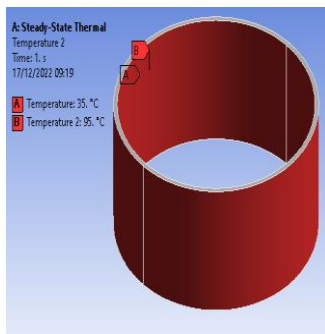

Fig. 8. Mesh of off – spec silo

Fig. 9. Boundary Condition on main silo
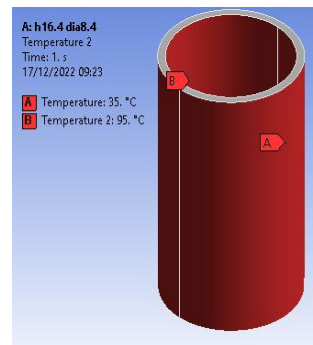
Fig. 10. Mesh of off – spec silo
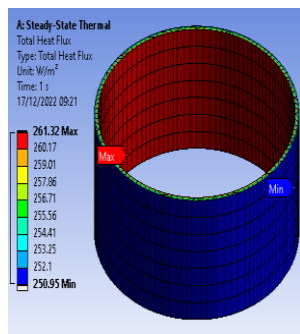
Fig. 11. Heat flux on of main silo wall
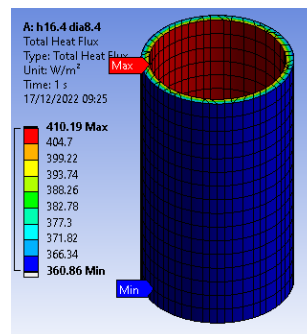
Fig. 12. Heat flux on of main silo wall

simulation results on other hand enables the estimation of heat flux as shown in Figs. 11 and 12. Similarly from equation (12d), is can be seen that heat transfer rate is given by the product of heat flux and cross sectional area. Hence the value of heat flux estimated from the simulation is provided for both main silo and the off-spec silo, shown in Tables 10 to 13.

3. RESULTS AND DISCUSSION

3.1 Theoretical Results

The results obtained from the analysis of heat loss across the composite cylindrical clinker silo walls for the off- spec clinker silo and heat loss across the composite cylindrical clinker silo walls for the main clinker silo are presented. The rate of heat transfer/loss across composite cylindrical clinker for the two silos is shown on Fig. 13, temperature gradient.

Table 4, shows the analysis on impact of 10% reduction on main clinker silo height against heat loss across the wall, keeping other parameter constant. Table 5, shows the analysis on impact of 10% reduction on the main clinker silo inner radial against heat loss across the wall of the main clinker silo, keeping other parameter constant.

Fig. 13. Temperature gradient from T_i (inner wall temperature) to T_o (outer wall temperature)

Table 4. Main clinker height *against* heat loss (10%)

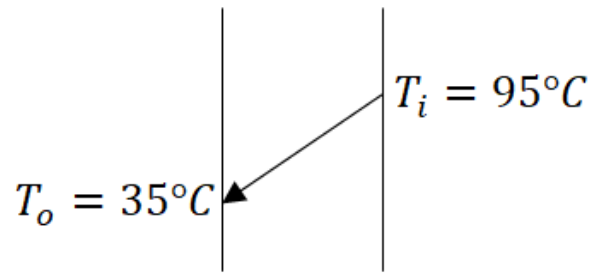| a (m)	k (W/mK)	W (m)	T_i (K)	T_o (K)	y (m)	Q_{ms} (kW)
20	3.2	44.5	368	308	0.75	727.87
18	3.2	44.5	368	308	0.75	655.08
16	3.2	44.5	368	308	0.75	582.30
14	3.2	44.5	368	308	0.75	509.51
12	3.2	44.5	368	308	0.75	436.72
10	3.2	44.5	368	308	0.75	363.94
8	3.2	44.5	368	308	0.75	291.15
6	3.2	44.5	368	308	0.75	218.36
4	3.2	44.5	368	308	0.75	145.57
2	3.2	44.5	368	308	0.75	72.79

Table 5. Main clinker silo inner radial agains*t* heat loss (10%)

a (m)	k (W/mK)	W (m)	Ti (K)	To (K)	y (m)	ri (m)	ro (m)	Q_{ms} (KW)
20	3.2	44.5	368	308	0.75	22.250	23.000	727.87
20	3.2	40.05	368	308	0.75	20.025	20.775	656.28
20	3.2	35.6	368	308	0.75	17.800	18.550	584.68
20	3.2	31.15	368	308	0.75	15.575	16.325	513.08
20	3.2	26.7	368	308	0.75	13.350	14.100	441.48
20	3.2	22.25	368	308	0.75	11.125	11.875	369.87
20	3.2	17.8	368	308	0.75	8.900	9.650	298.25
20	3.2	13.35	368	308	0.75	6.675	7.425	226.61
20	3.2	8.9	368	308	0.75	4.450	5.200	154.93
20	3.2	4.45	368	308	0.75	2.225	2.975	83.07

Table 6, shows the analysis on impact of 10% reduction on off- spec clinker silo height against heat loss across the wall, keeping other parameter constant. Table 7, shows the analysis on impact of 10% reduction on off- spec clinker silo radial (r_i) against heat loss (Q_{os}) across the wall, keeping other parameter constant. Table 8, shows production log-sheet of a vertical roller cement mill of a running plant in Nigeria with low production output (134 tph) while using the main clinker silo with capacity of 60,000 tons using hot gas generator, dated: 3rd March, 2022 and Table 8, shows production log-sheet of a vertical roller cement mill of a running plant in Nigeria with improved cement production (150 tph) while using off-spec

clinker silo capacity (1,800 tons) without using hot gas generator dated: 10th October, 2022.

Table 8 and Table 9 are direct physical log-sheets of a running vertical roller cement mill plant in Nigeria. Table 7, shows the impacts of heat loss across the composite walls of the main clinker with vertical roller cement mill production output of 134 tons per hour and continuous running of hot gas generator. While Table 9, using off-spec composite clinker silo shows the impact of reduction in heat loss on the vertical roller cement performance with production output of 150 tons per hour and a zero (0) use of the hot gas generator.

Table 6. Off-spec clinker silo against heat transfer

u (m)	k (W/mK)	z (m)	T_i (K)	T_o (K)	x (m)	Q_{os} (kW)
16.40	3.2	10.5	368	308	0.5	217.51
14.76	3.2	10.5	368	308	0.5	195.76
13.12	3.2	10.5	368	308	0.5	174.01
11.48	3.2	10.5	368	308	0.5	152.26
9.84	3.2	10.5	368	308	0.5	130.50
8.20	3.2	10.5	368	308	0.5	108.75
6.56	3.2	10.5	368	308	0.5	87.00
4.92	3.2	10.5	368	308	0.5	65.25
3.28	3.2	10.5	368	308	0.5	43.50
1.64	3.2	10.5	368	308	0.5	21.75

Table 7. Off-spec clinker silo radial against heat loss

u (m)	k (W/mK)	z (m)	T_i (K)	T_o (K)	x (m)	r_i (m)	r_o (m)	Q_{os} (KW)
16.4	3.2	10.50	368	308	0.5	5.250	5.750	217.51
16.4	3.2	9.45	368	308	0.5	4.725	5.225	196.72
16.4	3.2	8.40	368	308	0.5	4.200	4.700	175.92
16.4	3.2	7.35	368	308	0.5	3.675	4.175	155.12
16.4	3.2	6.30	368	308	0.5	3.150	3.650	134.31
16.4	3.2	5.25	368	308	0.5	2.625	3.125	113.49
16.4	3.2	4.20	368	308	0.5	2.100	2.600	92.65
16.4	3.2	3.15	368	308	0.5	1.575	2.075	71.77
16.4	3.2	2.10	368	308	0.5	1.050	1.550	50.81
16.4	3.2	1.05	368	308	0.5	0.525	1.025	29.57

Table 8. Low production output using main clinker silo (3rd March, 2022)

Time	Clinker	Limestone	Gypsum	Feed Rate	Hot Gas Generator	Mill Inlet Temperature	Mill Outlet Temperature
	Tons	Tons	Tons	TPH	(T_{HGG}) ^{o}C	^{o}C	^{o}C
07:00	116.375	13.3	3.325	133	335	101	92
08:00	116.375	13.3	3.325	133	330	101	92
09:00	117.25	13.4	3.35	134	332	100	92
10:00	117.25	13.4	3.35	134	338	100	92
11:00	117.25	13.4	3.35	134	337	100	92
12:00	117.25	13.4	3.35	134	334	100	91
13:00	117.25	13.4	3.35	134	335	100	91
14:00	117.25	13.4	3.35	134	339	100	91
15:00	117.25	13.4	3.35	134	342	100	91
16:00	117.25	13.4	3.35	134	328	100	91
17:00	117.25	13.4	3.35	134	332	100	91
18:00	117.25	13.4	3.35	134	337	100	91
19:00	117.25	13.4	3.35	134	341	100	91
20:00	117.25	13.4	3.35	134	331	100	91
21:00	117.25	13.4	3.35	134	334	100	91
22:00	117.25	13.4	3.35	134	332	100	91
23:00	117.25	13.4	3.35	134	330	100	91
00:00	117.25	13.4	3.35	134	332	100	91
01:00	117.25	13.4	3.35	134	338	100	91
02:00	117.25	13.4	3.35	134	331	100	91

Table 9. Improve production output using off-spec clinker silo (10th October, 2022)

Time	Clinker Tons	Limestone Tons	Gypsum Tons	Total Feed Rate Tons Per Hour	Hot Gas Generator (T_{HGG}) ^{o}C	Temperature Mill Inlet ^{o}C	Mill Outlet ^{o}C
7:00	130.5	15	4.5	150	Not in use	101	93
8:00	130.5	15	4.5	150	Not in use	101	93
9:00	130.5	15	4.5	150	Not in use	99	94
10:00	130.5	15	4.5	150	Not in use	99	94
11:00	130.5	15	4.5	150	Not in use	99	94
12:00	130.5	15	4.5	150	Not in use	99	94
13:00	130.5	15	4.5	150	Not in use	99	93
14:00	130.5	15	4.5	150	Not in use	99	93
15:00	130.5	15	4.5	150	Not in use	99	93
16:00	130.5	15	4.5	150	Not in use	99	93
17:00	130.5	15	4.5	150	Not in use	99	93
18:00	130.5	15	4.5	150	Not in use	99	93
19:00	130.5	15	4.5	150	Not in use	99	93
20:00	130.5	15	4.5	150	Not in use	99	93
21:00	130.5	15	4.5	150	Not in use	99	93
22:00	130.5	15	4.5	150	Not in use	99	93
23:00	130.5	15	4.5	150	Not in use	99	93
00:00	130.5	15	4.5	150	Not in use	99	93
01:00	130.5	15	4.5	150	Not in use	99	93
02:00	130.5	15	4.5	150	Not in use	99	94

Table 10. Impact of 10% reduction main clinker height against heat loss (Q_{ms}) across the main clinker silo using Ansys simulation

a (m)	W (m)	y (m)	Q_{ms} (kW)	q theory	q Ansys		
					Max	Min	Avg
20	44.5	0.75	727.87	256	260.83	251.23	256.24
18	44.5	0.75	655.08	256	260.82	251.56	255.96
16	44.5	0.75	582.30	256	260.82	251.57	255.96
14	44.5	0.75	509.51	256	260.31	251.66	256.02
12	44.5	0.75	436.72	256	260.83	251.23	256.24
10	44.5	0.75	363.94	256	260.82	251.56	255.96
8	44.5	0.75	291.15	256	260.82	251.57	255.96
6	44.5	0.75	218.36	256	260.31	251.66	256.02
4	44.5	0.75	145.57	256	260.82	251.57	255.96
2	44.5	0.75	72.79	256	260.31	251.66	256.02

Table 11. Impact of 10% reduction on the main clinker silo inner radial (r_i) against heat loss (Q_{ms})across the main clinker silo Ansys simulation

a (m)	W (m)	y (m)	r_i (m)	r_o (m)	Q_{ms} (KW)	q theory	q CFD		
							Max	Min	Avg
20	44.5	0.75	22.250	23.000	727.87	256	260.83	251.23	256.24
20	40.05	0.75	20.025	20.775	656.28	256	261.32	250.95	256.11
20	35.6	0.75	17.800	18.550	584.68	256	261.95	250.41	255.69
20	31.15	0.75	15.575	16.325	513.08	256	262.76	249.76	256.19
20	26.7	0.75	13.350	14.100	441.48	256	263.18	248.81	256.03
20	22.25	0.75	11.125	11.875	369.87	256	265.03	247.42	256.1
20	17.8	0.75	8.900	9.650	298.25	256	267.87	245.34	255.54
20	13.35	0.75	6.675	7.425	226.61	256	271.71	241.87	257.21
20	8.9	0.75	4.450	5.200	154.93	256	280	235.13	256.95
20	4.45	0.75	2.225	2.975	83.07	256	298.11	218.87	259.54

Table 12. Impact of 10% height reduction on off-spec clinker silo against heat transfer across the off-spec clinker silo wall Ansys simulation

u (m)	z (m)	x (m)	Q_{os} ((kW)	q theory	q Ansys		
					Max	Min	Avg
16.4	10.5	0.5	217.51	384	402.44	365.8	384.13
14.76	10.5	0.5	195.76	384	402.44	365.8	384.13
13.12	10.5	0.5	174.01	384	402.44	365.8	384.13
11.48	10.5	0.5	152.26	384	402.44	365.8	384.13
9.84	10.5	0.5	130.50	384	402.44	365.8	384.13
8.2	10.5	0.5	108.75	384	402.44	365.8	384.13
6.56	10.5	0.5	87.00	384	402.44	365.8	384.13
4.92	10.5	0.5	65.25	384	402.44	365.8	384.13
3.28	10.5	0.5	43.50	384	402.44	365.8	384.13
1.64	10.5	0.5	21.75	384	402.44	365.8	384.13

Table 13. Impact of 10% reduction on off-spec clinker silo radial (r_i) against heat loss (Q_{os}) across the wall of off-spec clinker silo ANSYS simulation

a (m)	W (m)	y (m)	r_i (m)	r_o (m)	Q_{ms} (KW)	q theory	q Ansys		
							Max	Min	Avg
16.4	10.5	0.5	5.250	5.750	217.51	384	402.44	365.8	384.13
16.4	9.45	0.5	4.725	5.225	196.72	384	405.69	363.76	385.64
16.4	8.4	0.5	4.200	4.700	175.92	384	410.19	360.86	382.98
16.4	7.35	0.5	3.675	4.175	155.12	384	415.86	357.5	383.99
16.4	6.3	0.5	3.150	3.650	134.31	384	422.61	353.13	381.86
16.4	5.25	0.5	2.625	3.125	113.49	384	422.03	349.47	382.62
16.4	4.2	0.5	2.100	2.600	92.65	384	433.52	340.03	389.95
16.4	3.15	0.5	1.575	2.075	71.77	384	446.85	330.54	391.39
16.4	2.1	0.5	1.050	1.550	50.81	384	470.61	312.86	387.93
16.4	1.05	0.5	0.525	1.025	29.57	384	548.4	275.8	385.76

3.2 Results Validation Using ANSYS

The result obtained from the simulation is basically the maximum, minimum and average heat flux estimated for each configuration of silo. For each type of silo and the dimensions, the theoretical values of heat transfer rate and heat flux are shown. These results are shown in Tables 10 to 13.

3.3 Comparison of Theoretical and ANSYS Results

The results from theoretical and simulation analysis for main clinker silo with other dimensions and boundary condition were kept constant while 10% reduction on the height of the silo was investigated from 20 m to 2 m is presented as shown on Table 10. The results revealed that there is negligible difference between theoretically estimated heat flux and the simulation estimated value of heat flux. This implies that there is an agreement between the two approaches or analysis. The heat transfer rate for the simulation is not estimated because, it will still result in the same value as the theoretical. These results establish the validation of the two results. Unlike the theoretical value of the heat flux which is based of fundamental principal that the average value of heat flux across the silo is estimated, the simulation further reveals the maximum and minimum values, where we have the maximum value greater than the average and the minimum value lower than the average value. Another scenario considered is the configuration whereby the height and wall thickness of the main silo is kept constant, while the inner diameter was varied by 10% reduction. In this case, the theoretical and simulation analysis revealed that their respective values of heat flux estimated also has negligible difference, however, only when the average value of the simulation analysis is considered. The results revealed that average value of heat flux remains constant with reduction in inner diameter, there is a continuous increase in the maximum value of heat flux followed by continuous decrease in the minimum value of heat flux as seen in Table 10. The location on the silo where the heat flux is maximum and minimum can be seen and/or shown using a temperature probe as seen in Figs. 11 and 12. The results for the off-spec silo are shown Tables 11 and 12. The variation and changes used in the main silo were similar to the main silo. The major difference between the two silos are in their initial height and inner diameters. The major

differences are their geometrical values and estimated values of heat transfer and heat flux.

4. CONCLUSIONS

The heat loss across the composite cylindrical clinker silos are of various values. The following were observed during the course the research:

✓ The off-spec clinker silo has heat loss (q_{oo}) across the wall was 217.15 kW and the quantities of heat loss across main clinker was 728 kW. The large quantities of heat loss on main clinker was because of the design capacity of the main clinker silo of 60,000 tons (60,000,000 kg).
✓ It was also observed that due to large quantities of heat loosed across the main clinker could also be responsible for the use of hot gas generator continuously whenever the vertical roller cement mill is in operation using.
✓ The off-spec clinker silo was observed to have a lesser quantities heat loss across it walls when compared to the main clinker silo with more production output on the vertical roller cement mill of 150 tons per hour.
✓ Numerical simulation was carried out using ANSYS simulation package and the results obtained were in good agreement with the results obtained theoretically.
✓ The simulation result also provide temperature contour to shows the distribution of the temperature and heat flux on the silos. This reveals specific points on the silos where maximum heat is lost.
✓ The information provided by the temperature contour, the heat loss across the storage "containing high temperature" walls can be analyzed properly. This will help in the performance of the equipment to use the stored materials.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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