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MODELLING OF CLINKER COOLER AND EVALUATION OF ITS PERFORMANCE IN CLINKER COOLING PROCESS FOR CEMENT PLANTS

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ABSTRACT
Cement manufacturing requires cooling down of hot clinker at temperature of about 1350° C to temperature lower than 100 ° C in a cooling system known as clinker cooler. Many plants are unable to cool the clinker below 250 °C. This challenge led to scaling down of actual clinker cooler to a test rig size in the ratio 25:1 suitable for simulation. Computational Fluid Dynamics (CFD) tools (Solid-Works and ANSYS) were used to achieve the simulation. The clinker outlet temperatures obtained from simulations were validated with theoretical evaluation. Results showed that with clinker and cooling air flow rates of 0.2 kg/s and 0.54 kg/s respectively and with a clinker bed height of 0.6 m. An optimum cooler performance was achieved with clinker outlet temperature of 68 °C. The scaled down cooler was 15% higher than the existing cooler in terms of recoverable energy and 10% high in terms of energy efficiency.

Keywords: *Clinker Cooler, Computational Fluid Dynamics (CFD), Mass flow rate clinker and Mass flow air and Clinker Furnace.*

1. INTRODUCTION

Clinker cooler is used to reduce the clinker temperature from 1350 °C in the rotary kiln. This clinker temperature is expected to drop below 100° C before it can be used at the cement grinding station [1]. The cooling is achieved by passing fresh air through a series of suction fans across the layers of the hot clinkers. The recovered energy (hot air) during this process is used as the main burning air (secondary air) for the rotary kiln and (tertiary air) for kiln with pre-calciner. The remaining air is sent to the stack through the main bag house or electrostatic precipitators (ESP). Once clinker leaves the rotary kiln, it must be cooled rapidly to ensure maximum yield of the alite that contributes to the hardening properties of cement [2, 3].

Cement production is energy consuming and capital-intensive energy economics is of particular interest to the investors and stakeholders. Energy recovery has generated interest for more than two decades. Engin and Ari [3, 4] studied the energy audit and recovery for a dry type cement rotary kiln system with a capacity of 6000 tons of clinker per day. They showed that 15.6% of the total energy input could be recovered by optimizing the energy recovery and the clinker cooler efficiency.

Efficiency of a clinker cooler plays a key role in heat recovery from the hot clinkers and subsequent pre-heating of the air used for calcination. The recovered heat and the preheated air are collectively known as secondary air in the rotary kiln and tertiary air used at the calciner. The unrecovered heat that leaves with the clinker out of the cooler represent the actual heat loss of the system. Reduction of energy consumption in a cement plant requires optimizing operating parameters in the coolers, Worrel *et al.* [1] and Mundhara [5] explained that improving the efficiency of heat recovery in the clinker cooler would

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lead to fuel saving as well as improving the quality of cement production and reduction of the emission level.

Ahamed *et al.* [6], reported the first and second law efficiencies of grate cooler using different operating conditions, the energy and exergy recovery efficiencies of the cooling system were found to have increased by 21.5 % and 9.4 % respectively, using energy recovered from the exhaust air.

Due to inadequate heat recuperation or improper cooling of the clinker in the cooler, large volume of water is used in cooling the cement product at cement grinding stations. This cost is enormous in terms of energy loss, equipment and product damage. Figure 1 shows a clinker cooling process inside a clinker cooler. It can be observed from the figure that hot clinker enters the cooler from the left side, which is depicted by a red color. As the clinker moves towards the right side of the cooler on a grate, air is passed into the cooler from four fans positioned at the side of the cooler as seen in the figure. The air from the fans flows across the clinker upwards, thereby cooling down the hot clinker. A change is color of the region is experienced, which is the bluish region seen in the figure, indicating a reduced temperature.

2. METHODOLOGY

2.1 Scaling and Modeling of Clinker Cooler and Heating-Up Furnace (HUF)

Scaling and modeling of the clinker cooler and heating-up clinker furnace was done with relation to an existing and running plant. The design model was scaled down to a ratio 25:1, that is, existing cooler twenty-five (25) and model (Test rig) one (1). The scaling down was based on similitude and dimensional analysis requirements and was used to study the responses of the existing clinker cooler [7-9].

2.2 Determination of Heat Transfer across Clinker Cooler Wall

Clinker cooler is modeled with air-cooling process unit to handle the ambient air before entering insider the clinker cooler, with a series of pan conveyors with a perfect cross-flow heat exchange [10]. The heat transfer and the pressure drop are defined by correlation to macro-hydrodynamic criteria [11]. Figure 2 shows the overview of the modelled clinker cooler and clinker furnace.

The clinker cooler was modelled using equation (1) and (2). The number of hot zones is noted as "K_w" and the number of cold zones is noted as "L_c" as shown in Figure 2 [12] as:

$$K_W = \frac{H_W L_W w D_{Clk}}{M_{clk} t_{res\ time}} \quad (1)$$

and

$$L_c = \frac{H_C L_C w D_{Clk}}{M_{clk} t_{res\ time}} \quad (2)$$

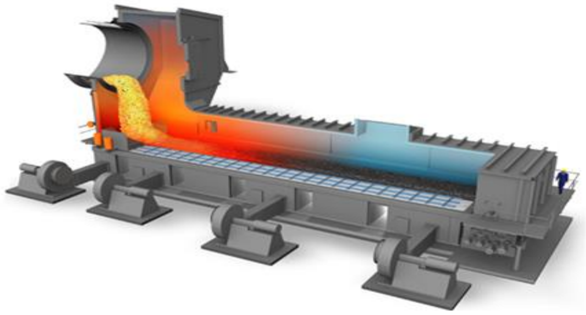

Figure 1: Cross- sectional view of clinker cooling process inside a grate cooler.

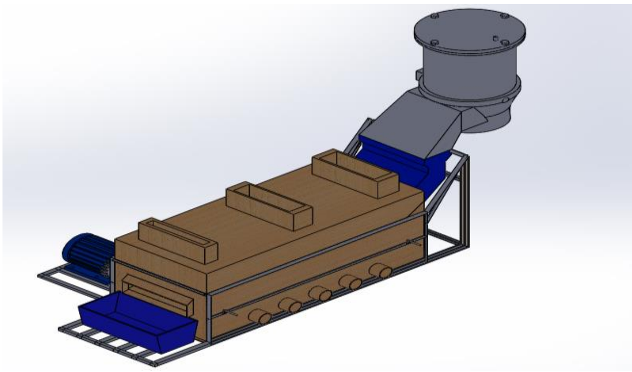

Figure 2: Overview of the conceptualized clinker cooler and clinker furnace

where: H_w is the hot zone height, H_c is the cold zone height, D_{Clk} is the clinker density, ,H_{clk} is height of clinker bed in hot zone, L_w is the length of the clinker in the hot zone, L_c is the length of the clinker in the cold zone, $t_{res\ time}$ is average resident time. The hot zone height (H_w) of the clinker cooler will be determined using equation (3) [12].

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

Cold zone height (H_c) of the clinker cooler will be determined using equations (4) [12].

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

where: C_g is the distance covered grate, w is width, W_w is the frequency of grate in hot zone, W_c is the frequency of grate in cold zone, M_{clk} is the mass flow rate of clinker. Heat losses in each segment depends upon heat transfer coefficient, thermal resistance and heat transfer area in each section and these will be determined using equations (5) to (7), [11]:

For heat dissipation losses crossing the wall,

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

For convective heat transfer using the total heat transfer coefficient *hfi,*

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

For total thermal resistance R_{ti}

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

where; A_i is segmented area, Q_{pi} is heat loses from each segment, T_{pi} is the wall temperature of each segment, T_i is the temperature of each segment, t_{br} is the thickness of the refractories, t_{cbr} is thermal conductivity, t_s is the shell thickness, t_{cs} is thermal conductivity of refractories, t_s is the thickness of the shell; and h_c is convection heat transfer coefficient. Thermal resistance of any segment depends upon the followings: area, refractories, thermal conductivity of the shell, a shell thickness, and convection heat transfer coefficient (h_c). The convection heat transfer coefficient is obtained using equation. (8) [11]:

$$h_c = \frac{N_u K_{air}}{d_s} \quad (8)$$

Nusselt number (Nu) is obtained using equation (8) [11]:

$$N_u = (0.0295\left(Re^{\frac{4}{5}}Pr^{\frac{1}{3}}\right)) \quad (9)$$

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

$$Re = \frac{d_s \rho_{air}\, \mu_{air}}{(1 - p_{or})U_{air}} \quad (10)$$

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

$$Pr = \frac{\mu_{air} C\rho_{air}}{K_{air}} \quad (11)$$

where d_s is the clinker diameter, ρ_{air} density of air, μ_{air} velocity of air, *Por* porosity, K_{air} is the thermal conductivity of air; and μ_{air} is the Dynamic viscosity of [11].

2.3 Performance Evaluation of Mass Flow Rate and Energy Balance Analysis in the Model Clinker Cooler

Mass flow rate of clinker from kiln exit and cooler exist remain constant as shown in Figure 3 and it is expressed in equation (12):

$$M_{Clk\ in} + M_{air\ in} - M_{air\ out} = 0 \quad (12)$$

Therefore, mass flow rate in cooler is constant. For steady state and steady flow process, the mass balance equation as expressed in equation (13) [13]:

$$\sum(M_{clk_{in}} + M_{air_{in}}) = \sum(M_{clk_{out}} + M_{air_{out}}) \quad (13)$$

M represents mass flow rate; *clk* represents clinker; in represents inlet and Out represents outlet.

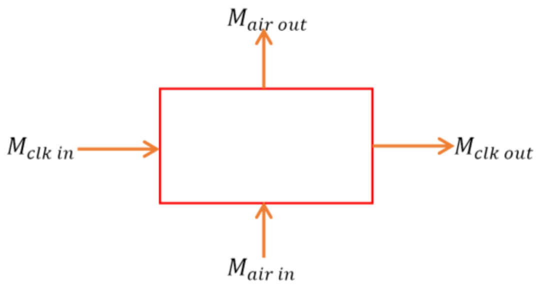

Figure 3 Mass flow rate of cross bar cooler

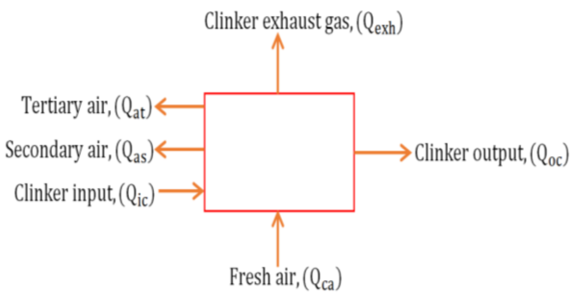

Figure 4 Energy balance schematic of a grate clinker cooler

First law of thermodynamics states that energy can be changed from one form to another during an interaction but cannot be destroyed as shown in Fig. 4. The change in the content of energy of a body or a system is equal to the difference between the energy input and the energy output [14-16]. The energy balance equation [17, 18] is as shown in equation (14):

$$\sum \dot{E_{in}} = \sum \dot{E_{out}} \quad (14)$$

Based on Fig. 4, total input energy can be defined by equation (15)

$$\sum \dot{E_{in}} = Q_{ic} + Q_{ca} = M_{clkin}c_{pclk}(T_{clk} - T_o) + M_{air}c_{pair}(T_{ac} - T_o) \quad (15)$$

Total energy output from the cooler as obtained from [18] can be expressed in equation (16):

$$\sum \dot{E}_{out} = Q_{as} + Q_{at} + Q_{oc} + Q_{exh} = M_{\sec air}\left(T_{\sec air} - T_{\beta}\right) + M_{ter\ air}c_{p\ air}\left(T_{ter\ air} - T_{\beta}\right) + M_{clk\ out}c_{p\ clk\ out}\left(T_{clk\ out} - T_{\beta}\right) + M_{exh\ air}c_{p\ exh\ air}\left(T_{echhair} - T_{\beta}\right) \qquad (16)$$

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. It is defined in equation (17) [14, 17]:

$$\eta_E = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} \qquad (17)$$

Equation (18) is recoverable energy efficiency of the secondary and tertiary air as [18]:

$$\eta_{recoverable,\ cooler} = \frac{Q_{recoverable}}{Q_{ic} + Q_{ca}} \qquad (18)$$

2.4 Computational Fluid Dynamics (CFD) Simulation

A 3D model of the clinker bed was developed using SolidWorks2014 CAD software based the geometric parameters adopted in the scaled conceptual design, having fixed values of length, height and width. The model is then imported into ANSYS 14.0 software platform for CFD simulation. Governing equations of flow are solved in the ANSYS-Fluent 14.0 computational fluid dynamics (CFD) platform. Tables 1 and 2 presents the parameters that formed the basis for evaluation of the clinker cooler performance using clinker cooler specific numbers 1.7 Nm^3/kg of clinker and 1.9 Nm^3/kg of clinker.

The clinker is considered and modelled as a porous medium using the facilities available in the software as regard continuity, momentum and energy equations. The 3-D model was meshed in ANSYS meshing environment, where the model was discretized into finite element mesh. The number of elements in a mesh can vary, 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. Boundary conditions were set and the following assumptions considered; porous medium is isotropic and homogenous, flow of fluid is steady, flow is turbulent outside the porous medium and laminar in the porous medium section, fluid is incompressible, radiation heat transfer and heat loss through the wall are negligible.

The clinker bed is a rectangular moving bed with input parameters and dimensions presented in Table 1. Considering the operation of a clinker cooler with respect to the 3-D model used in this study using Fig. 3, hot clinker enters from the right side; cold air enters from the bottom and moved upward, in form of cross flow. The inlet temperature of the clinker and air were initially set at 1350 ^oC and 32 ^oC respectively. No slip and adiabatic (no heat loss or heat gain) conditions are assigned to the two side-walls of the porous medium. Pressure outlet conditions of zero (0) is assigned to the outlets, so as to determine the pressure drop along the flow, and corresponding temperatures after solution is complete [19].

2.5 Validation of the numerical simulation

The procedure involved in the simulation was validated by comparing the result obtained from CFD and theoretical results. Theoretical results are obtained using equation (19) [20].

$$\frac{T_{clk_{out}} - T_o}{T_{clk_{in}} - T_o} = e^{(-Vair/0.77)} \qquad (19)$$

where $T_{clk_{in}}$ is clinker temperature at cooler inlet (^oC), $T_{clk_{out}}$ is clinker temperature at cooler outlet (^oC), V_{air} is specific cooling air quantity (m^3/kg) in the clinker with the heat content relative to ambient temperature.

Table 1: Parameters and Dimension for Modelled Clinker Cooler

Description	Value
Length of the Cooler	1.3 m
Width of the Cooler	0.35 m
Height of the Cooler	0.2 m
Material Inlet Flow rate to the Cooler	0.2 kg/s
Specific Number	1.9 Nm^3/kg of clk
Material Inlet Temperature to the Cooler	1350 ^oC
Fan energy (MWh/kg clk)	184 kWh/kg of clinker
Air Inlet flow rate	0.5 kg/s
Ambient air temperature	32 ^oC

Table 2: Other parameters of existing plant

Description	Value
Fan energy	4.6 (MWh/kg clk)
Cooler speed	16 (stroke/min)
Clinker mass flow	72 (kg/s)
Clinker inlet Temp	1350 (°C)
Clinker Outlet Temp	250 (°C)
Cooler Length	30 (m)
Cooler width	5 (m)
Secondary air Temp	950 (°C)
Specific Number	1.7 (Nm^3/kg of clk)
Energy Efficiency	59.2 (%)
Recoverable Energy Efficiency	49.2 (%)
Exhaust air Temp	265 (°C)

3. RESULTS AND DISCUSSION

Figure 5 shows the temperature contour of the modelled clinker bed, the inlet section of the clinker, and the outlet section of clinker. The Figure shows very hot clinker (1350 °C) entering the cooler in a longitudinal direction, and cooling air (32 °C) entering the cooler in the transverse direction. For the temperature values, area weighted average of temperature was computed using the ANSYS solver. The clinker and air inlets were assumed to be continuous hence a dominant color contour was observed for the inlets.

As heat is exchanged between the hot clinker and the cooling air, variation of temperature was observed along the length of the clinker bed. This variation is reasonably represented using the temperature contour legend from coldest at the lower part to hottest at the upper part of the legend. It is very unlikely or impossible to determine the exact temperature value of a specific location on the clinker bed from the contours displayed, hence the area weighted average temperature is computed for a selected face or point.

In this study, the targeted faces are the air inlet, clinker inlet, clinker outlet, secondary air outlet and exhaust air outlet. The area weighted average temperature values for these faces were computed from the solver for three different bed heights; 0.3 m, 0.4 m and 0.6 m. The results are summarized in Table 2. Comparing the CFD results, it was observed that clinker outlet temperature decreased with increase in bed height. This behavior consequently led to increase in secondary air outlet, which is desirable for improving energy recovery. Hence the clinker outlet temperature at bed height of 0.6 m is said to have the optimal energy recovery into the system, with secondary air at 1017.4 °C and a low clinker outlet temperature of 68 °C. This implies that bed height plays a significant role in clinker cooler performance.

Evaluating the specific number (Nm^3/kg of clinker): the existing cooler has a specific number as 1.7 Nm^3/kg of clinker and the modelled clinker was designed to have 1.9 Nm^3/kg of clinker thus the modelled clinker cooler is 12% higher than the existing clinker cooler. The 12% increase in specific number of the modelled clinker cooler is also responsible for the decrease in the clinker outlet temperature and also reduction in the exhaust air temperature.

Table 3 and Table 4, are simulation results for Modelling a Clinker Cooler using CFD and Theoretical method to evaluate the clinker cooling process. Energy balance and efficiency of the modelled clinker was also evaluated. Comparing the CFD and the theoretical clinker outlet temperature: CFD clinker outlet temperature at bed height of 0.6 m has the optimum energy recovery into the system, secondary air at 1017.4 °C and low outlet clinker temperature with 68 °C. Bed height also plays a significant role in clinker cooler performance. Using Table 2 of the existing cement plant has a clinker outlet temperature which is 250 °C comparing with CFD results using bed height of 0.6 mm (68.4 °C) and Theoretical clinker (107 °C) outlet temperature on Table 3 and Table 4.

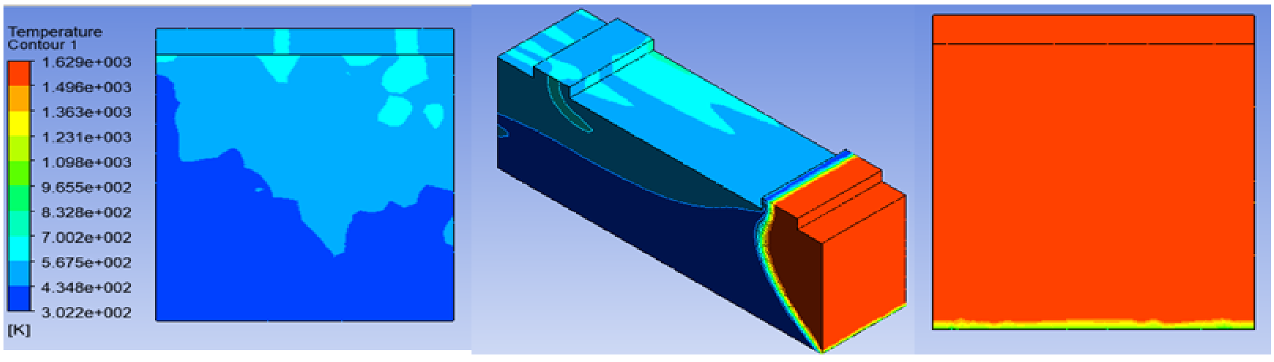

Figure 5: Temperature contour of the clinker cooler outlet end, 3D cross-sectional view and clinker inlet end

Table 3: Computational Fluid Dynamics Simulation results

Description		Value		
Bed Height (m)		0.3	0.4	0.6
	Air inlet	32	32	32
	Secondary Air outlet	851.4	914.1	1017.4
	Exhaust Air outlet	288.3	237.5	61.1
Temperature (^oC)	Clinker inlet	1350	1350	1350
	Clinker outlet (CFD)	162.4	159.62	68.4
	Air inlet	0.54	0.54	0.54
	Secondary Air outlet	0.34	0.36	0.38
	Exhaust Air outlet	0.20	0.18	0.16
Mass Flow rate (kg/s)	Clinker inlet	0.2	0.2	0.2
	Clinker outlet	0.2	0.2	0.2

Table 4: Theoretical and Computational Fluid Dynamics Energy Balance Results

	Description		Value	
Temperature (^oC)	Theoretical Clinker outlet	107.3	107.3	107.3
	Q_{ic} (kcal/kg clk)	304.5	304.5	305.4
	Q_{as} (kcal/kg clk)	198.1	198.1	198.1
	Q_{exh} (kcal/kg clk)	210.3	252.3	324.1
Energy Balance	Q_{ca} (kcal/kg clk)	32	24.6	11.5
	Q_{oc} (kcal/kg clk)	21.3	21.1	14.8
	Losses (kcal/kg clk)	239.0	204.6	152.3
	Energy Efficiency (%)	52.4	59.3	70.0
	RecEnergy Efficiency (%)	42.4	50.2	65.0

Existing plant is clinker cooler recoverable energy is 49.2% and energy efficiency 59.2% and the modelled clinker cooler recoverable energy and energy efficiency are 65% and 70% respectively. The optimum heat of energy recuperation efficiency for the modelled cooler is 70% and total energy input was into system was 316.0 kcal/kg of clinker.

The modelled clinker cooler performance when compared with the existing clinker cooler, the modelled cooler is 15% higher than the existing cooler in terms of recoverable energy and 10% high in terms of energy efficiency. This large responsible for the high outlet clinker leaving the clinker cooler. However, with proper cooler optimization of the existing cooler the current results obtained from the running can improved upon because poor energy recovery will lead to poor cement qualities, high maintenance cost and low revenue generation.

4. CONCLUSION

The study carried out modelling of an actual clinker cooler system with a scaled down test rig prototype in the ratio 25:1. Computational Fluid Dynamics (CFD) simulation was also carried out on the 3D model of the scaled down clinker cooler in order to investigate the performance of the cooler based of variation in geometric parameters. CFD tool was used to create cost-effective simulations of real flows based on numerical solutions of governing equations. The mass flow rate of cold air entering inside the existing clinker cooler and the clinker cooler test rig was designed in a ratio of clinker to cold air which is 1: 2.5 in kg/s, while clinker bed height investigated are 0.3 m, 0.4 m and 0.6 m. Results from the findings showed that Using these operating parameters for both existing running plant and the scaled down 3D model studied in the CFD tool platform, high outlet clinker temperature is attained with low clinker bed height. This could be because low clinker bed does not allows a proper heat transfer between the bed of clinker and the cold air stream. The modelled clinker cooler performance when compared with the existing clinker cooler is 15% higher than the existing cooler in terms of recoverable energy and 10% high in terms of energy efficiency. Additionally, the optimum heat of energy recuperation efficiency for the modelled cooler is 70% and total energy input was into system was 316.0 kcal/kg of clinker.

5. Nomenclature

Symbol	Meaning	Unit
Q_{pi}	Heat losses	J
R_{ti}	Total internal resistance	Ω
T_{pi}	Wall temperature	^oC
H_{fi}	Total heat transfer coefficient	W/mK
A_i	Segmented area	m^2
T_i	Temperature of each segment	^oC
T_{br}	Thickness of the refractories	m

Symbol	Meaning	Unit
T_{cs}	Thermal Conductivity	W/mK
T_{sbr}	Thermal conductivity	W/mK
T_s	Shell thickness	^oC
H_c	Convection heat transfer coefficient	W/m^2k
K_w	Number of hot zone	
L_c	Number of cold zone	
H_w	Hot zone height	m
H_c	Cold zone height	m
D_{clk}	Clinker density	kg/m^3
H_{clk}	Height of the clinker bed in hot zone	m
L_w	Length of the clinker in the hot zone	m
L_c	Length of the clinker in the hot zone	m
$T_{res\ time}$	Average resident time	s
H_w	Hot zone height of the cooler	m
H_c	Cold zone height of the cooler	m
C_g	Distance covered grate	m
W_w	Frequency of grate in hot zone	Hz
W_c	Frequency of grate in cold zone	Hz
M_{clk}	Mass flow rate of Clinker	kg/s
H_{fi}	Heat transfer coefficient	W/m^2K
A_i	Segmented area	m^2
D_s	Clinker diameter	m
ρ_{air}	Density of air	kg/m^3
U_{air}	Velocity of air	m/s
K_{air}	Thermal conductivity of air	W/m^2K
μair	Dynamic viscosity of air	Kg/m/s
M	Mass flow rate	kg/s
Q_{as}	Recoverable heat of kiln secondary air	J/s
Q_{at}	Recoverable heat of tertiary air	J/s
Q_{oc}	Heat of clinker at the cooler output	J
Q_{exh}	Heat of cooler at exhaust air	J
Q_{ic}	Heat of clinker at the cooler input	J

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