Studies on Thermal Analysis of Cement Rotary Kiln Based on Clinker Coating Materials on Refractories, Energy and Monetary Savings

Jagendran Ravindran[1] and Soundarajan Krishnan[2]

Abstract— In the cement industry, rotary kiln is the most important equipment, used for producing clinker from clay, limestone and iron ore. The kiln has four different zones, each specific to a temperature and different refractory bricks. During the pyrolysis of fossil fuels and other alternative fuels in the kilns, the circulation of volatile materials form initial coatings on its inner surface, which leads to encrustation or ring formation. This inhibits the free flow of materials in the kiln. This paper deals with modelling of different coating thicknesses for a clinker-based ring with a thermal conductivity of 0.74 W/(m.ºC) with varying bed temperatures for both burning and transition zones. Modelling, using ANSYS Mechanical APDL, helps to determine the optimum coating thickness for good insulation and durability of the kiln, as well as to optimize energy savings, resulting from optimum coating thickness.

Keywords—ANSYS Mechanical APDL, Cement rotary kiln, energy savings, optimum coating thickness, refractory bricks.

I. Introduction

In the cement industry, rotary kiln is commonly employed and it is prone to downtime due to various problems encountered, such as formation of rings in them. The occurrence of rings is considered common due to the characteristics of various fuels used in the kiln. The formation of coatings will eventually lead to the formation of rings, thereby hindering the free flowing material from the inlet to the outlet of the rotary kiln. The kiln is divided into different zones based on temperature differences across the bed and the process conditions. For instance, the properties of refractory bricks varies from the burning zone to the transition zone due to variation in its chemical composition and thermal properties. Regardless of the type of refractories used, they will eventually wear off, resulting in thermal hot spots and red spots on the surface of the rotary kiln. Hence, the formation of coatings in substantial amount along the inner surface of the kiln will help enhance the life cycle of the refractory bricks. Thus, the coating material differs in characteristics with respect to its chemical and thermal properties along the kiln. In the burning zone, the refractory is prone to clinker dust coating and also coal ash rings whereas, in the upper transition part of the kiln, it is prone to clinker rings and sulpho-spurrite rings which are common in the calcining region and also the pre-heater tower [2]. Due to different properties, formation of coating on the refractory layer eventually causes the shell temperature of the kiln to decrease considerably, compared to the surface without coating, causing a reduction in the fuel consumption and increasing the savings per/kg of fuel fed. In this paper, the key objective is to thermally analyze the shell temperature of the kiln based on clinker coating materials with respect to the zones and with various coating thicknesses to determine the optimum coating thickness for proper insulation of the kiln as well as potential energy and monetary savings.

The objectives of this study are:

- To estimate the shell temperature of the kiln by simulation using ANSYS Mechanical APDL zone-wise instead of modelling the entire length of the kiln;
- To study the total heat loss by convection and radiation;
- To investigate the energy and monetary savings by reduction in heat loss;
- To determine the optimum coating thickness.

A. *Description of cement rotary kiln studied*

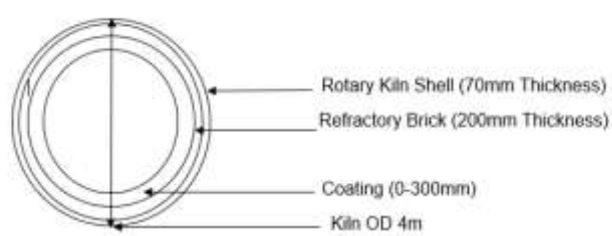

Fig. 1 Simplified kiln dimensions used in the analysis

In this paper, the main concept is to study the thermal losses from the kiln surface based on the assumption of no coating formation, to evaluate the thermal losses after coating formation and then, to evaluate the thermal losses after coating formation with a thermal conductivity of 0.74 W/(m.ºC) and varying bed temperatures. The temperature of the kiln shell is inversely proportional to the coating thickness and the difference in temperature before and after coating where the potential energy

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savings can be obtained. The cement rotary kiln temperature is obtained by simulation using ANSYS Mechanical APDL (Fig. 3). In the simulation process, various process conditions are assumed constant, for instance the external and internal diameter of the kiln, the fluctuations in thermal conductivities of the refractory bricks. The thermal losses from the kiln surface are calculated considering natural convection and thermal radiation. The cement rotary kiln can be divided into the transition zone and the burning zone. In the burning zone, the temperature ranges from 1450-1350ºC, whereas in the transition zone, the temperature ranges from 1300-1200ºC. Due to high internal circulation of volatile materials such as alkali and sulphur, formation of build-up and blockages occur [2].

TABLE I: COMMON INTERMEDIATE COMPOUNDS FOUND IN BUILD UPS AND KILN RINGS [2]

Name	Formula	Location Found
Spurrite	$(2CaOSiO_2)CaCO_3$	Lower cyclones
Ellestadite	$Ca_{10}(SiO_4)_3\ (SiO_4)_3Z_2$ For Z = OH, F and Cl	Riser duct
Sulfospurrit e	$(2CaO\ SiO)_2\ CaSO_4$	Kiln rings
Anhydrite	$CaSO_4$	Cyclones and riser duct

The coating formation often leads to formation of rings in cement rotary kilns which is made up of clinker or dust that solidifies on the refractory and it is easily formed when excess sulphur and alkali are present in the kiln atmosphere [2]. Table I shows the common intermediate compounds found in kiln rings. Due to the coating formation, the shell temperature recorded is much lower and the coating thickness is roughly around 10 to 15" in the burning zone and the shell temperature should be 190ºC to 220ºC [1].

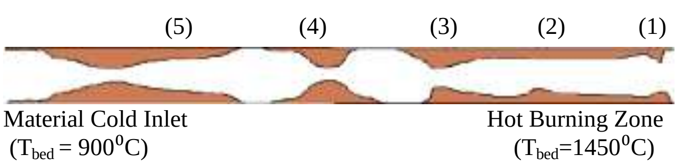

Fig. 2 Illustrations of the five typical coating complications in a cement rotary kiln
Type of rings: (1) Nose rings or ash rings; (2) Clinker coating; (3) Trumpet coating or sinter rings; (4) Clinker rings; (5) Transition zone rings [2].

B. *Assumptions for Modelling:*

- Internal diameter of the cement rotary kiln has been assumed to be 3.93 m and the external diameter has been assumed to be 4 m, as shown in Fig. 1.
- The thermal conductivity of refractory brick is 5.11 W/(mº.C) in the burning zone and 1.66 W/(m.ºC) in the transition zone [5].
- The thermal conductivity of coating is assumed to be 0.74 W/(m.ºC) and the different coating materials such as coal ash and sulphospurrite have thermal conductivities close to 0.74 W/(m.ºC) [1].
- The length of the burning zone and the transition zone has been assumed to be 30 m.
- The price of the fuel (coal) is USD 0.05/kg.
- Steady-state heat transfer.
- The cement rotary kiln is assumed to rotate at constant speed.

C. *Simulation of kiln shell temperature using ANSYS Mechanical APDL.*

The shell temperature obtained in this paper are from simulation studies by using ANSYS Mechanical APDL (see Fig. 3). The rotary kiln is modelled in segments of 1 m in length for the burning and the transition zones. The 3-D solid element used in this study is SOLID278 with brick shape and 8-node. The Degree of Freedom (DOF) is at each node. The mesh size of 4 is used as standard for all the segments. The method of analysis is steady-state thermal analysis.

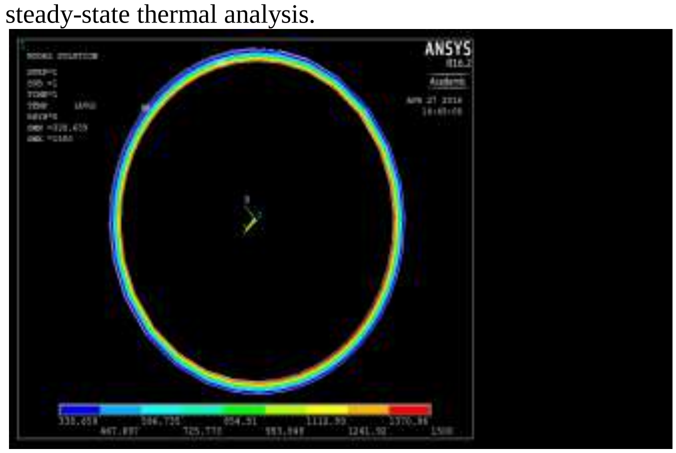

Fig. 3 Kiln shell modelled using ANSYS Mechanical APDL (Steady-state thermal analysis)

II. RESULTS AND DISCUSSION

A. *Determination of Heat Losses*

Heat transfer coefficient by natural convection for turbulent flow is determined using (1) with ($G_r.P_r$) ranging from $10^7 – 10^{12}$ as

$$Nu = 0.125(GrPr)^{0.333} \tag{1}$$

Heat losses by convection is obtained from (2) using

$$q_{conv} = hA\Delta T \tag{2}$$

The heat loss by radiation on the kiln shell [3] is determined from (3) using

$$q_{rad} = A\varepsilon\sigma(T_{S}{}^4 - T_{a}{}^4) \tag{3}$$

Where A= Surface area of kiln shell (zone)
σ = Stefan-Boltzmann Constant
ε = Emissivity of kiln shell
T_s = Kiln shell temperature
T_a = Ambient temperature

Total heat losses is determined from (4) using

$$q_{total} = q_{conv} + q_{rad} \quad (4)$$

B. Fuel Savings Calculation

$$\text{Total heat loss/hour (Hs)} = S \times A \quad (5)$$

Where A is the surface area in m^2.

Based on the cost of heat energy, the quantification of heat loss in USD can be worked out as follows [6]:

Equivalent fuel loss (Hf) in kg/y =

$$\frac{Hs \times Yearly\ hours\ of\ operation}{GCV \times \eta} \quad (6)$$

Annual heat loss in monetary terms in

$$Monetary\ Loss\left(\frac{USD}{kg}\right) = Hf \times cost\left(\frac{USD}{kg}\right) \quad (7)$$

GCV= Gross Calorific Value of the fuel kcal/kg

η = Kiln efficiency

C. Burning Zone

In this paper, the burning zone is assumed to be 30 m in length, the refractory thermal conductivity is 5.11 W/(m.ºC) and the coating material is clinker-based [2]. Hence, the thermal conductivity of the coating is 0.74 W/(m.ºC). The key assumption made is that the coating formation is uniform in nature and the composition of the coating has a constant thermal conductivity.

TABLE II HEAT LOSSES FOR BED TEMPERATURE OF 1450ºC ACROSS THE BURNING ZONE

Coating Thickness (mm)	Shell temperature (ºC)	q_{conv} (kW)	q_{rad} (kW)	Total Heat Loss (kW)
0	553	1809.69	9397.1	11206.79
20	399.26	1218.46	4024.56	5243.02
40	311.95	890.71	2232.92	3123.63
60	255.32	683.53	1428.46	2111.99
80	220.42	558.74	1045.34	1604.08
100	193.32	463.98	798.88	1262.86

Burning zone bed temperature ranges from 1450-1350ºC. Tables II-IV give the heat losses for bed temperature of 1450ºC, 1400ºC and 1350ºC, respectively across the burning zone. The kiln shell temperature with no coating formation is recorded at 553-516ºC (see Fig. 4) for the given bed temperature range. However, the temperature is deemed to be high, which could lead to formation of red spot and hot spot on kiln shell. The amount of heat loss by convection is 1809.6 kW at a bed temperature of 1450ºC and decreases in the range of 5% for every 50ºC decreased in bed temperature. At a 20 mm thickness of coating, the heat loss is reduced by 53.2% from 11,206.79 kW to 5243.02 kW, as observed from Fig. 5.

The potential energy savings is around 5963 kW of energy. With a further increase in the coating thickness, the shell temperature further reduces to 311.95ºC at 40 mm coating thickness and the heat loss recorded is 3123.63 kW.The amount of heat lost by convection and radiation decreases by 4-10% for every 50ºC decrease in bed temperature. Kiln shell temperature should be between 190-220ºC to keep the coating thickness and temperature below the range to form a solid barrier for the kiln bed movement of materials [1]. Therefore, based on the shell temperature, the optimum coating thickness is in the range of 80-100 mm, as it will give a minimal amount of heat loss in the range of 1600-2000 kW.

TABLE III: HEAT LOSSES FOR BED TEMPERATURE OF 1400ºC ACROSS THE BURNING ZONE

Coating Thickness (mm)	Shell temperature (ºC)	q_{conv} (kW)	q_{rad} (kW)	Total Heat Loss (kW)
0	534.18	1736.08	8554.18	10290.26
20	386.26	1169.38	3710.3	4879.68
40	302.03	854.21	2074.57	2928.78
60	247.39	654.94	1334.44	1989.38
80	213.72	535.12	980.49	1515.61
100	187.57	444.17	751.81	1195.98

TABLE IV: HEAT LOSSES FOR BED TEMPERATURE OF 1350ºC ACROSS THE BURNING ZONE

Coating Thickness (mm)	Shell temperature (ºC)	q_{conv} (kW)	q_{rad} (kW)	Total Heat Loss (kW)
0	516.29	1667.43	7805.79	9473.22
20	373.25	1120.22	3412.7	4532.92
40	292.1	817.63	1923.27	2740.9
60	239.45	626.45	1244.5	1870.95
80	207.01	511.58	918.17	1429.75
100	181.82	424.47	706.47	1130.94

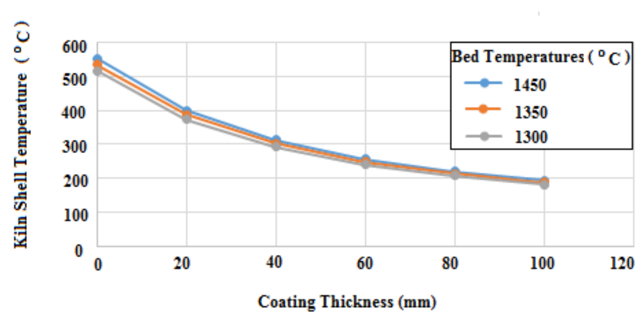

Fig.4 Plot for coating thickness versus shell temperature of kiln across the burning zone

The amount of monetary savings in terms of USD/kg is substantial by comparing them with and without coating formation. In this paper, the fuel savings calculation is done using the heat loss and the price of coal per kg as the basis. The price of coal is assumed to be USD 0.05/kg and the gross calorific value of coal is assumed to be 5,000 kcal/kg and the total yearly hours of operation is assumed to be 8,760 h. The annual monetary loss (%) is reduced by 46.7% for a mere 20 mm in coating formation and the increase in coating formation results in 20-40% decrease, in terms of monetary loss. This is evident from Fig. 6. At the optimum coating thickness of 80-100 mm, the amount of reduction in monetary loss is as much as 85-89%.

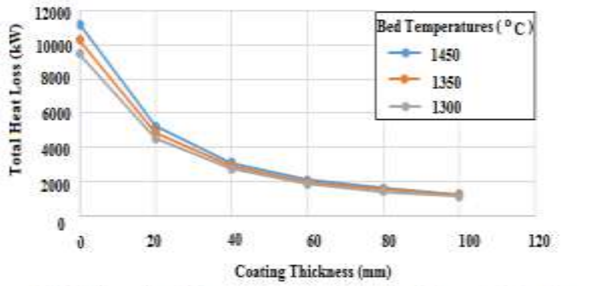

Fig 5 Plot for coating thickness (mm) versus total heat loss (kW) across the burning zone

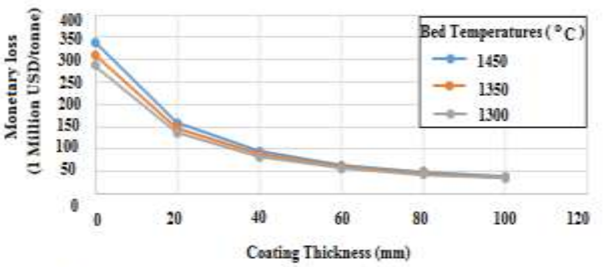

Fig.6 Plot for coating thickness (mm) versus monetary loss across the burning zone

D. Transition Zone

The transition zone bed temperature ranges from 1200-1300ºC [2]. The thermal conductivity of the refractory brick is 1.66 W/(m.ºC) is used in this paper. Fig. 2 shows that the five types of rings formed in a cement rotary kiln. In the transition zone, the refractory walls are prone to clinker material with a thermal conductivity of 0.74 W/(m.ºC), similar to that of burning zone. Tables V-VII give the heat losses for bed temperature of 1300ºC, 1250ºC and 1200ºC, respectively across the transition zone. The shell temperature recorded with no coating formation is 236.92ºC and the total heat loss recorded is 1832.1 kW at a bed temperature of 1300ºC and the heat loss further reduces in the range (6-16) % for every 50ºC in coating formation. Fig. 7 shows the shell temperature variations for different coating thicknesses for transition zone.

For a coating formation of 20 mm, the total heat loss is reduced by 20-30% when compared to that without coating formation. The heat loss recorded decreases as the coating thickness increases. The optimum coating thickness for transition zone is determined from the burning zone. This ensures free flow of material and not hindered by different height of coating material, which could lead to possible build up at the meeting points between different zones. At a coating thickness of 100 mm, the kiln shell temperature varies from 127.33-135.65ºC for a bed temperature range of 1300-1200ºC. From Fig. 8, it can be inferred that the reduction in total heat loss is as much as 60-65% and ranges from 602-671 kW for transition zone.

Monetary savings calculation for the transition zone is similar to that of the burning zone. The price of coal is assumed to be USD 0.05 per/kg and the Gross Calorific Value (GCV) of coal is assumed to be 5,000 kcal/kg and the total yearly hour of operation is assumed as 8,760 h. The annual monetary loss is reduced by 60-65% with a coating formation of 100 mm, as evident from Fig. 9.

TABLE V: HEAT LOSSES FOR BED TEMPERATURE OF 1300ºC ACROSS THE TRANSITION ZONE

Coating thickness (mm)	Shell temperature (^{0}C)	q_{conv} (kW)	q_{rad} (kW)	Total heat loss (kW)
0	236.92	615.39	1216.71	1832.1
20	207.37	512.84	921.45	1434.29
40	181.93	424.85	707.32	1132.17
60	162.31	358.56	564.95	923.51
80	148.27	312.15	474.22	786.37
100	135.65	271.29	400.05	671.34

TABLE VI: HEAT LOSSES FOR BED TEMPERATURE OF 1250ºC ACROSS THE TRANSITION ZONE

Coating Thickness (mm)	Shell temperature (^{0}C)	q_{conv} (kW)	q_{rad} (kW)	Total Heat Loss (kW)
0	228.77	588.34	1129.95	1718.29
20	200.39	488.49	859.19	1347.68
40	175.95	404.48	661.92	1066.4
60	157.09	341.19	530.17	871.36
80	143.62	296.99	446.1	743.09
100	131.49	258.02	377.05	635.07

TABLE VII: HEAT LOSSES FOR BED TEMPERATURE OF 1200ºC ACROSS THE TRANSITION ZONE

Coating Thickness (mm)	Shell temperature (^{0}C)	q_{conv} (kW)	q_{rad} (kW)	Total Heat Loss (kW)
0	220.63	559.48	1047.42	1606.9
20	193.4	463.91	798.714	1262.624
40	169.96	384.22	618.23	1002.45
60	151.88	323.99	496.71	820.7
80	138.96	281.92	418.85	700.77
100	127.33	246.12	356.87	602.99

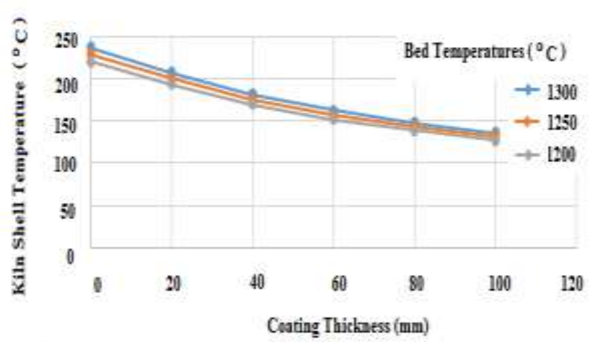

Fig.7 Plot for coating thickness versus shell temperature of kiln across the transition zone

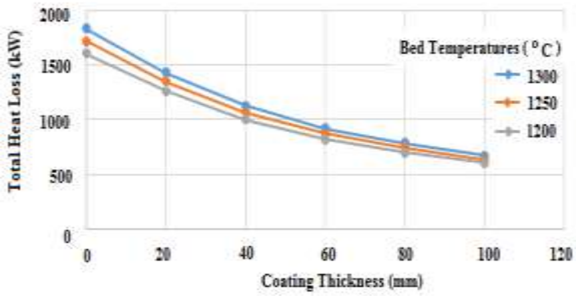

Fig.8 Plot for coating thickness (mm) versus total heat loss (kW) across the transition zone

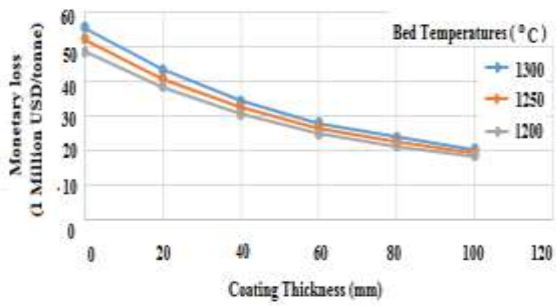

Fig.9 Plot for coating thickness (mm) versus monetary loss across the transition zone

E. Validation of Shell Temperatures by Simulation

In this paper, all the modes of heat transfer have been accounted for in terms of heat losses. Based on the simulation results, the kiln shell temperature is 553ºC at a bed temperature of 1450ºC and the total heat loss recovered is 11,206.79 kW.

The following equation is used to determine the temperature difference between the outer and the inner surface of the rotary kiln [4]:

$$q = \frac{2\pi L(T_{bed} - T_{shell})}{\frac{\ln\frac{d_{shell\ od}}{d_{shell\ id}}}{k_{shell}} + \frac{\ln\frac{d_{brick\ od}}{d_{brick\ id}}}{k_{brick}}} \quad (8)$$

$$(T_{bed} - T_{shell}) = \Delta T \quad (9)$$

$d_{shell\ od}$ = 4m; $d_{shell\ id}$ = 3.93m; k_{shell} = 43 W/(m.ºC);

$d_{brick\ od}$ = 3.93m; $d_{brick\ id}$ = 3.73m; k_{brick} = 5.11 W/(m.ºC)

The temperature difference obtained using the above equation is 1183.5ºC, which is lower than the assumed bed temperature. The possible reason for this is that the mesh size used is not sensitive or inconsistent. However, the shell temperature and the coating thickness obtained from the simulation studies is similar to the study done using the data from the industry [1].

III. Conclusions

- From this study, the thermal losses due to radiation is higher than the thermal losses due to convection.
- The optimum coating thickness in the burning zone is about 90 mm and the heat loss is in the range of 1600-2000 kW.
- The shell temperature of the rotary kiln in the burning zone becomes lower than 200ºC if the coating thickness is higher than 100 mm.
- The coating formation of clinker-based material with a thermal conductivity of 0.74 W/(m.ºC) has a significant effect to lower the kiln shell temperature and decrease the thermal losses, which contributes high monetary loss. For example, in the burning zone, with 20 mm coating thickness, the heat loss is reduced from 11,206.79 kW to 5243.03 kW.
- The model for the kiln shell temperature has been validated, showing that there is difference in the bed temperatures for the calculated and the assumed values.

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