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Protecting The Cement Kiln Refractory and Shell from High Temperature

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Abstract- - Rotary kilns are industrial furnaces used for the continuous processing of raw materials at high temperature, the kilns are long steel cylinders lined with refractory bricks, slightly tilted. They are subjected to complex stresses and deformations due to high temperatures and heavy loads, so monitoring and planned maintenance are essential to avoid very expensive unexpected shutdowns and other damages to the shell. This paper presents a review on monitoring the shell temperature and deciding based on the values obtained from the monitoring device the appropriate action to protect the refractory linings and the shell. Shell scanners and process sensors are the major monitoring devices while the shell cooling fans, water cool system and other process adjustment are the major shell temperature controls. The shell's temperature is carefully monitored and maintained below 400°C to prevent stress and damage. Between 380oC and 400 oC process adjustment must be done to drop the temperature below 400oC. Fatigue cracks might occur with continued operation above 400 oC, when the maximum allowed limit of 450°C has been reached the kiln shell burns and total deformation will occur that can only be corrected by replacing the entire portion. Controlling the temperature and taking appropriate measures at temperature below 400oC also protects the refractory bricks and will increase kiln efficiency, reduced downtime, and improved clinker quality. This directly translates to lower production costs and increased profitability for cement manufacturers.

Indexed Terms- Cement kiln, High temperature, Kiln shell, Refractory, Shell cooling.

I. INTRODUCTION

Cement clinker production is a pyroprocess made through heating finely grounded and carefully mixed raw material (limestone or shale, clay, sand and iron), in a rotary kiln to a sintering temperature of 1450o C. Because of the high temperature generated inside the kiln, its steel tube is lined with refractory bricks to protect it against high temperatures, hot and corrosive molten clinker and chemical attacks from the material bed. The reactions in the rotary cement kiln varies due to changes in chemical characteristics of the material, temperature variation at different position inside the kiln. For this reason, the kiln is divided in to different zones. For each of these zones, different types of refractory bricks to suit to condition of the area and for optimal performance of the refractory. Figure 1 show the clear division of the cement kiln while table 1 gives the detail composition and the type of refractory bricks use in each of these zones.

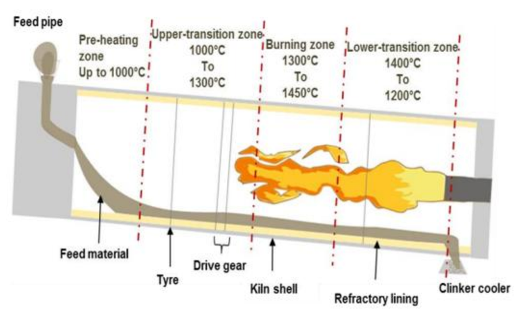

Figure 1: Schematic diagram of a rotary kiln [1,2]

Table 1. Refractory types used in clinkering lining operating kiln

Zones	Major Stress Type	Refractory Type: Chemical (% Wt) and Mineralogy Composition	Working Temperature (ºC)	Required Properties in the Bricks
Preheating zone	• Abrasion, • Mechanical stress, • Chemical attacks, • Increasing temperature.	Al_2O_3:58 – 6; SiO_2:33 - 37 Fe_2O_3:1.5	900	• Good strength • Abrasion resistance
Upper transition zone	• High temperature, • Aggressive fluid, • Shell ovality, • Kiln deformation.	• Periclase: MgO • Magnesia-spinel: $MgAl_2O_3$ MgO ≥80; Al_2O_3 < 0.5	1200 – 1400	• Chemical corrosion resistance • Good strength • Thermal shock resistant, • Mechanical impact resistant
Sintering zone	• Thermal overload • Chemical attacks by the clinker melt and gases.	• Periclase: MgO • Hercynite: $FeAl_2O_4$ MgO:78 – 82; Al_2O_3:5 – 7; Fe_2O_3:8 – 10; CaO:2.3; SiO2 1.1	1300 – 1450	• Coatability, • Thermal chock resistance, • Chemical corrosion resistance
Lower transition zone	• High temperature, • High abrasion, • Thermal shock and axial expansion often	• Periclase: MgO • Magnesia-spinel: $MgAl_2O_3$ MgO≥ 80; Al_2O_3< 20; CaO< 1.1; SiO_2 < 0.5; Fe_2O_3< 0.5	1300 - 1400,	• Highly abrasion resistance, • Thermal chock resistance,

From table 1, there are two major categories of refractories used in the rotary cement kiln, which are: alumina –silicate bricks use in the preheating zone and basic bricks use in the sintering and transition zones. To build a suitable refractory lining for theses area in the rotary cement kiln, the following important properties most be considered [1, 2].

The state of the refractory lining is one of the most significant factors influencing the availability of the rotary kiln. Some important factors influencing brick lining can include ovality of steel casing, burner conditions, fit of the tires and alignment of kiln and kiln feed chemistry as reported by [3,4,5]. Generally, refractories are made and manufactured in such a way that they can withstand the extreme temperatures of a given industrial process without any physical deformation or chemical transformation. In reality, a refractory lining in a kiln is not only stressed by high temperature, but also it is exposed to other constraints that act mutually increasing the severity of their impact on the kiln shell as summarized in Figure 2.

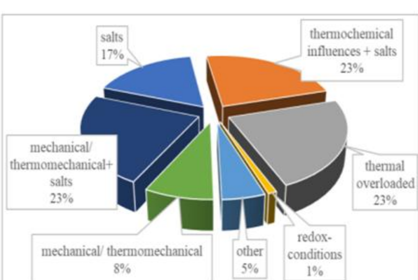

Figure 2: The influence of various factors on the wear of cement rotary kiln lining. [6,7].

II. CEMENT KILN BURNING ZONE

In burning zone, the material temperature is between 1250℃～1450℃, and the flame temperature can reach 1700℃. When the material temperature is close to 1300℃, C3A and C4AF begin to melt and become liquid, CaO and Ca2Si04 decompose, and C3S will be precipitated when the saturation concentration reaches a certain amount. Increasing the temperature of the burning zone properly will help the formation of C3S, which can improve the quality of the clinker. Because of the complexity of the reaction and high temperature requirement for the clinker production, controlling and maintaining the temperature at required level is very important for the kiln performance and availability. The major deciding factor the temperature control is the operating temperature, chemical condition (chemical nature of solid / liquid), thermal shock and mechanical stress. The burning zone of a cement kiln typically experiences the highest refractory failure because of the high temperature at the area. For example, according to the data obtained from the analysis of a cement kiln failure in Ashaka plant, burning zone failure contributes to 54 % total refractory failure followed by the cooling zone with 16 % as shown in figure 3. These values are in line with LafargeHolcim refractory failure bench mark of 45-55 % for burning zone [8, 9]. According to literature, burning zone refractory failure account to 45 – 65 % of total refractory failure in the cement kiln [10 - 13].

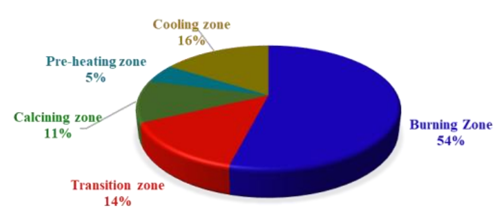

Figure 3: Failure rate of cement kiln refractory bricks according to zones in the kiln [14].

The failure rate is further breakdown in to thermal, chemical and mechanical related failures as presented in figure 5. However, these failure rate depends on the types of refractory, raw material composition, fuel type and quality and kiln design and operation. For good refractory life, selection of the refractory material must be taken with outer most importance.

The refractory must be able to endure high temperatures without melting. The operating temperature at the hottest region of the kiln is ranging from 1300oC to 1450oC and gas temperature up to 2000oC. The thermal softening performance of refractory material is determined to revealed the extent which the refractory can maintain its structure and shape under elevated temperature. It should also have the ability to preserve its regular volume and chemical composition once it is exposed to high temperature for extensive time. To reduce the impact of high temperature on the refractory, some process adjustment must be done and continues monitoring of the kiln operation. Some of this adjustment are optimizing gas flow in the kiln to improve emission and dispersion of high-temperature gases, Controlling the materials feed rate, quantity, and composition to ensure sufficient sintering and enhancing kiln lining protection measures to enhance their ability to withstand high-temperature erosion [15]. When property control, the shell temperature will be low (below 400oC) and is well protected.

III. CONTROLLING KILN FEED CHEMISTRY

The kiln feed chemistry is controlled to reduce shell temperature, improve clinker quality, and increase kiln efficiency, ultimately leading to more sustainable and cost-effective cement production.

Boakye, et al.;[16] reported that LSF is affected by the ash content in the fuel. The LSF of an industrial kiln was found to be 1.2 %. At this condition, burning becomes difficult and a temperature increase is observed. This causes a reduction in coating thickness and high shell radiation was observed from the kiln scanner. The LSF was controlled by introducing solid fuel (coal) which drops the LFS to 0.98 due to the ash content in the fuel. This stabilized the kiln's operation with less stress on the refractory lining. By adjusting the LSF, it's possible to control the amount of liquid phase formed during burning, which directly impacts heat transfer and temperature distribution within the kiln. This protects the refractory linings and shell temperature

Nuhu et al.;[17] found that, LSF and free lime (fCaO) chemical compositions have considerable effect on clinker and cement quality. The quality of cement is depending on the quality of clinker and the quality of clinker depends on the LSF and fCaO and other oxides of cement. After the analysis, of LSF against fCaO shows positive correlation, implies that as the FCaO increases, it causes the increase of burnability of the clinker. LSF against the fCaO also shows positive, implies that increases in the LSF leads to increases the FCaO, which eventually affect the formation of clinker. This implies that the LSF and the fCaO must be within recommended values (0.95 to 0.98 for LSF and 0.5% to 2.5% for fCaO) for effective temperature control and quality clinker production.

COATING FORMATION

Coating is formed due to interaction between the liquid formed in the raw meal during burning and brick constituents. A stable coating in the burning zone protects the refractories from thermal shock as well as prevents chemical interaction with the raw meal at elevated temperature. This eventually protects the kiln shell from high temperature. In general, the refractories undergo highest thermal shock during operation interruptions and hence, must be minimised. Formation of stable coating on the brick, thus, is highly desirable. For the formation of stable coating various the kiln feed (raw meal) chemistry should be optimized so that the liquid formed is viscous and the burning condition is not hard. If the liquid formed is low in its content as well as in viscosity, adherence on the brick surface this means coating formation is poor. Additionally, when the liquid viscosity is low, formed liquid penetrates the refractory pores causing textural densification leading to spalling. In the absence of coating, bricks wear out due to various reasons which of course depend on the brick quality. For optimum operation LSF, SR and AR and should be in the range of 0.95 - 0.98, 2.2 – 2.6 and 1.5 – 2.5, respectively. These parameters ensure ease of burning, optimised liquid quantity with appropriate viscosity for stable coating formation as reported by [18, 19].

IV. SELECTION OF REFRACTORY MATERIAL FOR CEMENT KILN BURNING ZONE

The main components of the rotary kiln shell are tricalcium silicate ($3CaO{\cdot}SiO2$, melting point 1900°C) and clinomonetite ($2CaO{\cdot}SiO2$, melting point 2310°C). The stable coating can prevent the kiln lining from being chemically attacked and provide a barrier for improving the thermal insulation performance of the kiln lining. Therefore, the protection of the kiln coating is very important during the clinkerizaton process according to [7, 20, 21]. If the coating falls off, it will expose the refractory bricks and directly contact with new clinker, high-temperature flame and high-speed hot air, and endure the thermal and chemical erosion of high-temperature air and materials. When the silicate phase in the clinker enters the brick lining, it will accelerate the damage and peeling of the refractory brick as reported by [22, 23]. To achieve a successful refractory lining, a rigorous study must be performed taking into consideration all constraints throughout the production with regard to the parameters governing the process of choosing the correct refractory type for suitable area of application. The aforementioned parameters are not relevant for every application. Identification of the critical parameters, for a given working environment, is vital for refractory life maximization at optimal cost. Once the critical operating parameters are identified, refractory should be so selected that they can withstand the operating condition for stipulated life span and effective temperature control is achieve in the kiln.

V. CEMENT KILN TEMPERATURE MONITORING DEVICE

The principles of temperature control involve using mathematical models, feedback control systems, and predictive control methods. The goal is to maintain a precise temperature profile, optimize fuel consumption, and ensure efficient clinker production. In order to control the kiln temperature within a certain range to meet the process requirements, the kiln system is controlled by automatic control technology since the traditional control cannot guarantee the constant temperature [24, 25]. Most cement kilns today use the following popular brands for cement kiln shell temperature monitoring and appropriate decision to keep the temperature lower than 400oC. These devices include

(i) HGH Infrared Systems: Offers Kiln scan, a high-performance thermal scanner for rotary kiln shell temperature monitoring.

(ii) Process Sensors Corp: Provides thermal imaging cameras for kiln shell temperature monitoring.

(iii) LM: Offers a kiln shell infrared scanning temperature measurement system with waterproof and weatherproof features. Figure 4 is a detailed overview of the kiln shell condition from shell scanner software for quick analysis and action.

(iv) IR camera

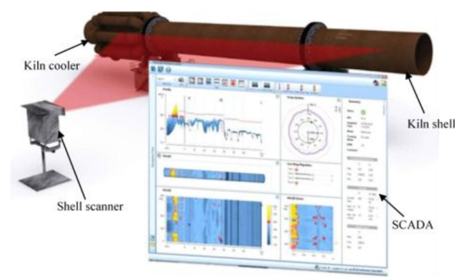

Figure 4: A detailed overview of the kiln shell condition from shell scanner.

SHELL TEMPERATURE SCAN

The shell temperature scanner is the main tool to ensure proper working conditions for the kiln shell. The temperature is continuously measured by an infrared sensor, which scans the temperature in a line along the kiln length while the kiln is turning.

The devices use gives direction for controlling the process parameters to ensure the temperature is within acceptable range. For instance [26], monitor the temperature of cement kiln using PLC. In the kiln temperature control system, Siemens S7-200 series PLC is used for PID control of kiln temperature. The system has high control efficiency and realizes the automatic temperature control of the kiln. The temperature is seen and at the control room and immediate corrective measures is applied in case of deviation and anomality are observed.

Joseph & Olaiya [27], The model was used to simulate the burning zone temperature of the kiln process based on the mass and heat balance in solid bed within the kiln. The analysis was based on the proposed algorithm. It was seeing that Fuzzy-PID gave a lower overshoot of 9.6 %, a settling time of 0.11 sec and a settling temperature of 1450 oC, compared to that of ZN-PID, which gave a higher overshoot of 17.24 %, a settling time of 0.13 sec and a temperature settling of 1450 oC as shown. The model showed an improvement in cement rotary kiln control system; in which fuzzy logic controller was used to auto-tune the PID controller; a better tuning method than the ZN-PID, which is mostly used in the industry. This gave better energy/heat consumption, leading to lesser cost. The model effectively explains the behavior of the burning zone heat transfer of cement rotary kiln. It gives a low settling time, with low overshoot in the Fuzzy-PID, while it has high settling time and high overshoot in the ZN-PID. It was used for the evaluation of the burning zone temperature of the cement rotary kiln process, in order to reduce energy consumption and cost in the system. It can be used to effectively solve practical problems that are being faced in the industry, in order to have energy conservation and consequently to maximize profit for industry.

Mohamed et al., [28], reported that when the kiln shell temperature suddenly raises above 400°C from the scanner, the hot area is coated instead of replacing the damaged refractory but this practice bears the high risk that after a while the coating collapses together with the damaged refractory leaving the shell unprotected. In this situation, the shell temperature rises above 500°C and red spots can no longer be avoided and permanent damage will occur.

Mansauri et al; [29], optimized the combustion process of cement kiln using response surface methodology (RSM) technique for the purpose of shell temperature control. The Kiln feed (160–190 t /h), fan speed (840–870 rpm), kiln rotational speed (2.8–3.4 rpm), kiln fuel rate (3800–4150 l/h), calciner fuel rate (5700–6200 l/h), pressure of kiln inlet (98–102 Pa), and limestone saturation factor (LSF) (94–95.8 %) as independent variables were investigated. The carbon monoxide and the kiln body temperature were considered as response variables. The absolute average error in the model predictions for the combustion process in the cement kiln, for the kiln body's temperature, is about 1.6 % and for carbon monoxide is about 15.5 %. The result bench marks the process values required to maintain the kiln shell temperature at minimum and good out put on the kiln. Knopfel et al.; [30] also reported minimum control shell temperature at a given range values of these parameters.

Ali [31] simulate the rotary kiln using CDF software ANSYS FLUENT, to provide the energy required for the clinker phase transition and shell temperature control, simulations of a cement rotary kiln, which include advanced models for RDF combustion and a 3D-model for modelling the clinker bed. The Municipal solid wastes are used as alternative fuel in combination with coal. Initially a detailed calculation has been made to estimate the amount of fuel and heat required for calcination need to be calculated. The optimum value found the combination of 68% coal and 32% MSW.

Gu et at., [32], produced a model to estimate the coating thickness in the burning zone of a rotary cement kiln by using measured process variables and scanned shell temperature. The model could simulate the variations of the system, thus the impact of different process variables and environmental conditions on the coating thickness could be analysed. They mainly derived the model from heat and mass balance equations using a plug flame model for simulation of gas and/or fuel oil burning. The heat transfer value from shell to the outside was improved by a quasi-dynamic method. They suggested that the model predicted the inside temperature profile along the kiln, then by considering two resistant nodes between temperatures of the inside and outside, the latter measured by shell scanner, it estimated the formed coating thickness in the burning zone. The estimation of the model was studied for three measured data sets taken from a modern commercial cement kiln. The results gotten confirmed that the average absolute error for estimating the coating thickness for the cases considered are negligible.

VI. TEMPERATURE CONTROL ON THE ROTARY CEMENT KILN SHELL

Refractory bricks in a cement rotary kiln prevent fatigue stress that can result in plastic deformation on the steel tube. These refractories are exposed to intense heat and abrasives that can lead to material degradation (wear). This wear causes bricks to become thinner over time and severely impacts their ability to shield the steel surface of the kiln. To maintain adequate levels of protection, continuous monitoring of the entire length of the kiln steel (the shell) is required. To protect the kiln shell from excessive mechanical stress, it is important to maintain the kiln shell temperature below certain limits. The ideal temperature range for a cement kiln shell is typically below 400°C. in practice, the typical range temperature is 150°C - 350°C. When temperatures approach 380°C action should be taken immediately to lower the temperature and prevent damage to the shell. These limits have been established to reduce the risk of permanent damage to the kiln shell. The maximum allowed temperature of the kiln shell is 450°C. When this temperature is reached, the kiln must be stopped for inspection and relining of the affected area. Sometimes, when the kiln shell reaches 450°C, the hot area is coated instead of replacing the damaged refractory. This practice is not encouraged because it bears the risk of coating collapsing together with the damaged refractory leaving the shell unprotected. In this situation, the shell temperature rises above 500°C, a red spot appears on the kiln shell and permanent damage occurs. Figures 5 and 6 explain the measures taken to control the kiln shell temperature and the thermal image showing the thermal load on the shell [33].

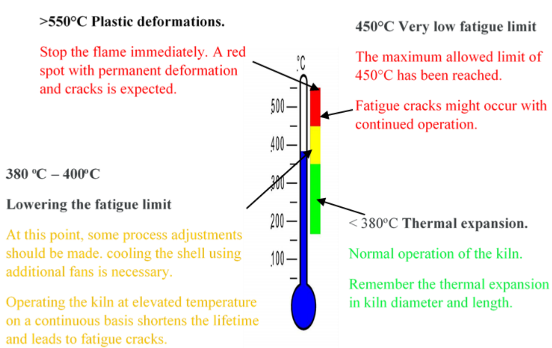

Figure 5: Measures to Control the Kiln Shell Temperature.

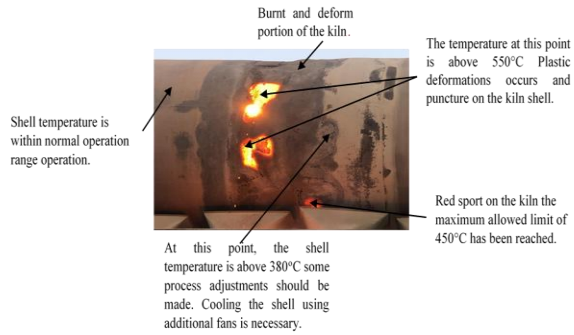

Figure 6: Refractory failure resulting in plastic deformation of the kiln shell.

High temperature on the kiln shell can cause a lot of trouble to the shell as presented in figure 7.

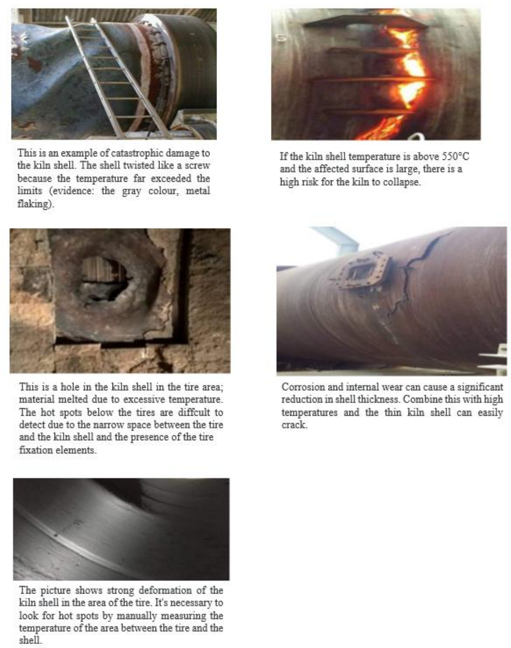

Figure 7: different types of Failure on kiln shell due high temperature

TEMPERATURE CONTROL BY SHELL COOLING FANS AND WATER SPRAY SYSTEM

In practice, the shell temperature is also controlled by either the use of shell cooling fan or the use of water spray system. The fans are installed on an independent platform along the walkway for inspection and should be mobile, for example on rails, to be moved to the areas that require cooling according to the scanner readings. The fans are located below the kiln so that the air flow embraces the surface and the hot air rises (the natural draft).

On the other hand, Cooling with water is more efficient than cooling with air, therefore people are tempted to compensate for insufficient refractory by spraying water. However, this causes cooling shocks that lead to fatigue cracks within a short duration. If water is used to cool, instead of air, only water mist must be applied and the amount of water must be equivalent to the same cooling ratio of air. This requires that the nozzles are maintained in order to produce the necessary fine mist. The quality of the water could damage or clog the nozzles. Cooling water systems are more diffcult to maintain than fan cooling systems but they are less noisy and consume less electrical energy. Another disadvantage of water cool is hat in the attempt to control the temperature using water resulted in cracks on the kiln shell. This happened because the refractory was in bad condition as shown by the picture from the thermal camera. Too much water was required and applied to keep the temperature within the limit of 450° C. The cooling created thermal shocks at each kiln turn and led to fatigue cracks.

CONCLUSION

The rotary cement kiln burning zone is the portion of the kiln that has high tendency of lining failure despite the lining are protected by coating. These failure rates are not only attributed to the high temperature generated at the region but also other factors like the inconsistent chemistry of the raw meal, secondary fuel composition, chemical stresses build up due to thermal load, operating condition of the kiln as well as the kiln design. Working of the lining material without checking these factors will have very high impact on the refractory life which can result to kiln stoppage on high shell radiation. This review reveals that controlling the temperature of the kiln shell below 400^{o}C improves the availability of the kiln. This will be fully achieved with a very good software that predicts the temperature of the kiln shell for appropriate action.

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