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NUMERICAL INVESTIGATION OF REFRACTORY LINING THICKNESS EFFECTS ON SHELL TEMPERATURE IN THE BURNING ZONE OF CEMENT ROTARY KILNS

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Abstract: Cement kilns are energy-intensive systems where refractory insulation plays a critical role in minimising heat loss and controlling shell temperature. The burning zone, in particular, operates under extreme thermal conditions, making the design of the refractory lining essential for maintaining thermal efficiency. This study presents a comprehensive numerical investigation into the influence of refractory lining thickness on the thermal performance of the kiln shell in the burning zone. Steady-state finite element simulations were conducted using Solid Edge Simulation with NX Nastran solver and actual rotary kiln parameters to analyse five different refractory thicknesses (150 mm, 175 mm, 200 mm, 225 mm, and 250 mm). A uniform temperature boundary condition representing the thermal load typical of the burning zone in cement kilns. Results demonstrated a clear inverse correlation between lining thickness and outer shell temperature. The 250 mm lining yielded a minimum shell temperature of approximately 155°C, while the 150 mm lining led to external temperatures exceeding 250°C. These findings highlight the significance of optimizing refractory lining design to enhance energy efficiency, reduce thermal losses, and ensure structural safety in cement kilns. This work contributes to better thermal management and informed maintenance strategies in the cement manufacturing sector.

Keywords: *Refractory Lining; Cement Rotary Kiln; Burning Zone; Finite Element Simulation; Thermal Performance*

1. INTRODUCTION

Cement production ranks among the most energy-intensive industrial processes, incurring substantial financial costs and posing significant environmental impacts (Soomro, Tam, & Jorge Evangelista, 2023). Energy expenses represent approximately 50-60 % of the total production costs in the cement manufacturing process (Ari, 2011). A significant portion of the energy consumption in this industry, approximately 70%, is thermal energy, primarily used in the rotary kiln to elevate the temperature of the material bed (Cheng, et al., 2023). In fact, the rotary kiln, as the core component in modern cement production, plays a central role in clinker formation (Okoji, Anozie, Omoleye, Taiwo, & Osuolale, 2022). The majority of cement kilns globally still utilize fossil fuels as their primary energy source, including coal, natural gas, and petroleum coke (Barbhuiya, Kanavaris, Das, & Idrees, 2024). However, a key worldwide challenge today is curbing fossil-fuel energy consumption, given its adverse economic, social, and environmental impacts (Alturki, Swadi, Al-Rubaye, Suwaed, & Al-Mashhadani, 2023).

Environmentally, the cement sector is one of the major industrial sources of global CO_2 emissions, responsible for around 8% of total anthropogenic emissions, which places it as the second-largest emitter among industrial activities following the power generation sector (Özkan & Acaralı, 2024). According to (Benhelal, Shamsaei, & Rashid, 2021) approximately 40% of the total CO_2 emissions from the cement production process arise from the combustion of fossil fuels used to generate thermal energy in the kiln. Therefore, assessing the energy efficiency of the rotary kiln is crucial to support the effective design and optimization of the cement manufacturing process, which leads to minimise the harmful emissions and reducing the consumption of fossil fuel (Okoji, Anozie, Omoleye, Taiwo, & Osuolale, 2022).

Refractory lining is considered a critical component in rotary kilns, particularly in the burning zone where temperatures reach extreme levels to about 1500°C (Ewais & Bayoumi, 2018), such conditions demand robust refractory linings to protect the steel shell of the kiln and to retain heat for efficient clinkering (Chen, Wang, Yuan, & Li, 2018). Figure 1 illustrates the thermal zones within a cement rotary kiln. Carbon steel is known to lose strength when exposed to high temperatures. Without adequate refractory protection, the kiln shell would be exposed to temperatures that far exceed the structural limits of carbon steel (Guillin-Estrada, et al., 2022). Practically, heating carbon steel to 400°C can result in a reduction of yield strength by up to 21% (Adnan Sulayman & Mahmood, 2021).

The burning zone typically employs basic refractory materials, primarily magnesia-chrome bricks, magnesia-spinel bricks, and sodium polyphosphate bonded magnesia bricks, these materials are specifically selected for their high refractoriness (typically greater than 1750-1790°C) (Vitiello, 2021). Magnesia-spinel bricks are widely used in the burning and transition zones of rotary kilns due to their high ability to hold coating and their naturally low permeability. These features help prevent the penetration of alkali salts and molten cement, which in turn improves the durability of the lining under aggressive kiln conditions (Pacheco, Gonçalves, & Lins, 2020).

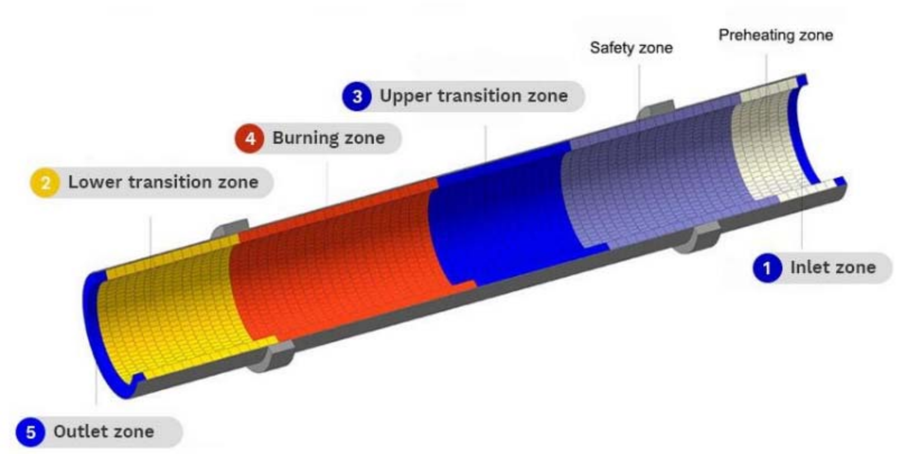


Figure 1. *Thermal zones in a cement rotary kiln (Sengupta, 2020)*

Research demonstrates that refractory lining thickness significantly affects heat loss rates the kiln shell. When refractory lining thickness reduces from 230 mm to 80 mm due to wear, the average heat flux on the inner surface increases dramatically by 105.03 % in conventional systems without insulation materials (Zeng, Shcherbina, & Li, 2023). This reduction in thermal resistance directly correlates with increased energy consumption and reduced thermal efficiency of the rotary kiln system (Pieper, Wirtz, Schaefer, & Scherer, 2021). On the other hand, implementation of low thermal conductivity refractory systems results in significant kiln shell temperature reductions reach to 50-70°C compared to conventional bricks, with practical applications showing reductions of over 100°C in some cases (Chen, Wang, Yuan, & Li, 2018). This temperature reduction particularly important, as excessive thermal exposure caused by refractory degradation can lead to infiltration of corrosive species and thermal stress, both of which contribute to the deterioration and potential failure of the kiln shell structure (Dong, Wang, Zhao, & Song, 2025).
In this context, a detailed understanding of the relationship between refractory lining thickness and kiln shell temperature is essential. To address this, the present study performs a numerical investigation into how variations in refractory lining thickness

within the burning zone influence the shell temperature distribution. The objective is to quantify the thermal effects associated with lining thickness and to provide informed guidelines for optimising refractory design and maintenance in cement rotary kilns.

2. METHODOLOGY

This study employs a 3D numerical model developed in Siemens Solid Edge to investigate the effect of refractory lining thickness on the thermal performance of cement rotary kilns, with a focus on the burning zone. The rotary kiln modelled in this study represents an industrial-scale unit with a total length of 52.5 m and an outer diameter of 4.2 m. The simulation focused on a representative segment of the burning zone, where maximum process temperatures occur, this zone was modelled as 23 metres in length. The kiln wall structure consisted of three concentric layers: an inner coating layer (300 mm), a refractory lining with variable thicknesses (150 mm to 250 mm), and an outer carbon steel shell of 60 mm thickness as explained in Figure 2. These dimensions were based on real-world operating kilns provided by industrial references and engineering documentation.

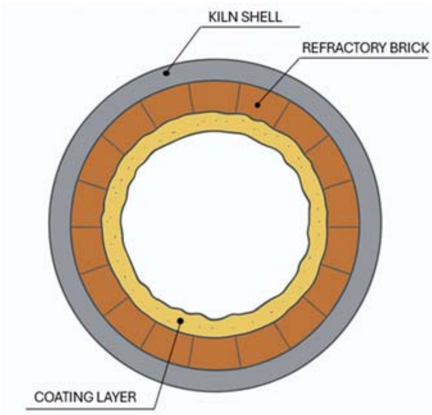


Figure 2. *Cross-sectional view of the rotary kiln wall layers*

Magnesia-spinel composites are selected for refractory linings due to their high refractoriness (melting above 2135°C), superior thermal shock resistance, and excellent chemical stability against alkali and clinker phases, attributes which make them increasingly preferred over traditional chromite-based refractories in industrial rotary kilns (Baruah & Sarkar, 2020). The kiln shell is modelled as carbon steel

(Carbon Steel A516 Gr.70) with thermal and mechanical properties based on literature values, including a density of approximately 7830 kg/m³, thermal conductivity of 45 W/(m^2°C), and specific heat of 480 J/(kg°C) as summarised in Table 1.

Table 1

Main thermal properties of Rotary kiln wall materials utilized in the simulation

Property	***Carbon Steel A516 Gr.70***	***Magnesia-spinel composite***	***Clinker-based coating***
Density	7850 kg/m3	3300 kg/m3	2800 kg/m3
Coef. of Thermal Exp.	0.0000012 /°C	0.0000120 /°C	0.0000010 /°C
Thermal Conductivity	0.0450 kW/(m^2°C)	0.0025 kW/(m^2°C)	0.0020 kW/(m^2°C)
Specific Heat	480 J/(kg°C)	950 J/(kg°C)	850 J/(kg°C)
Modulus of Elasticity	200000 MPa	40000 MPa	30000 MPa

In modelling the thermal behaviour of the burning zone, a uniform temperature of 1450°C was assigned to the inner surface of the coating layer, reflecting typical thermal loads encountered during clinker formation. Such thermal assumptions are consistent with ranges reported in recent rotary kiln thermophysical simulations (Svensen, Leal Da Silva, Merino, Sampath, & Jørgensen, 2024), where real-world combustion and material transformation dynamics are considered. Convective heat transfer was considered on the external shell surface with an ambient temperature set at 25°C and a convection heat transfer coefficient of 15 W/m²°C.

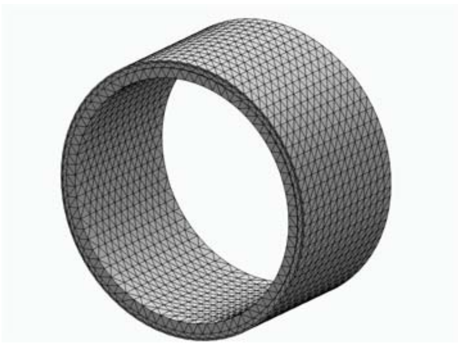


Figure 3. *Tetrahedral Finite Element mesh of the multi-layer rotary kiln section*

A tetrahedral mesh was generated for the entire geometry, with mesh refinement near the interfaces between layers to accurately capture thermal gradients. The mesh density was optimised to balance computational efficiency and solution accuracy, resulting in approximately 20,000 elements as shown in Figure 3. Finite element analysis was performed using the NX Nastran solver integrated within Solid Edge Simulation, solving for steady-state temperature distribution under the specified boundary conditions.

Convergence and solution stability were verified by mesh sensitivity analysis and checking residuals at each iteration. Post-processing included extraction of thermal profiles across the refractory lining and kiln shell, focusing on the temperature distribution at the external shell surface as a key indicator of heat loss and structural safety. Temperature gradients were analysed to understand the insulating effect of different lining thicknesses.

3. RESULTS

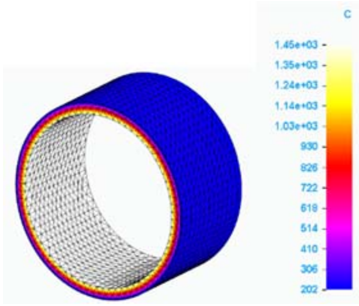
Figure 4 (a-e) displays the radial temperature contours for refractory linings of 150 mm, 175 mm, 200 mm, 225 mm and 250 mm, respectively.

Table2. below summarises the lowest steady-state outer-shell temperatures obtained from finite-element simulations for varying refractory lining thicknesses.

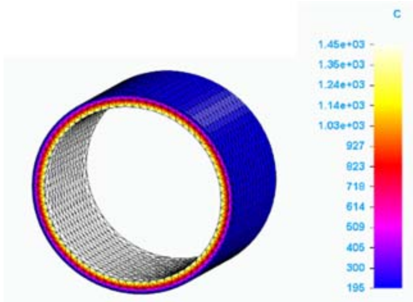
Table 2

Minimum shell surface temperature as a function of refractory lining thickness

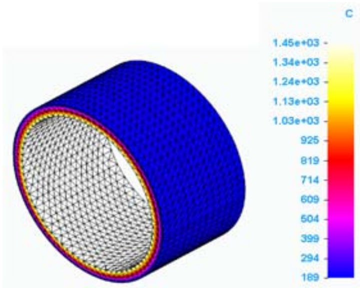
Thickness (mm)	Min. Shell Temperature (°C)
150	202
175	196
200	189
225	183
250	177



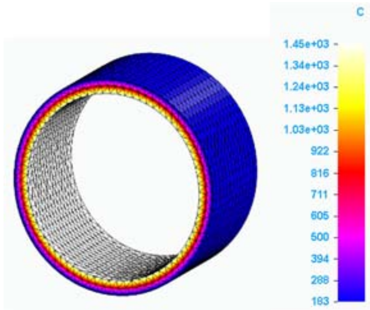
a) at 150 mm



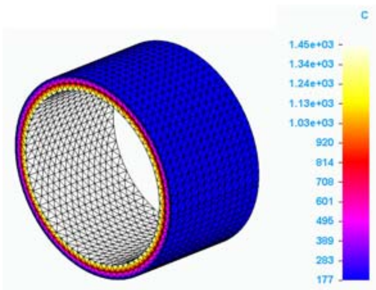
b) at 175 mm



c) at 200 mm



d) at 225 mm



(e) at 250 mm

Figure 4. *Radial shell temperature for (a) 150 mm, (b) 175 mm, (c) 200 mm, (d) 225 mm, (e) 250 mm refractory linings thickness*

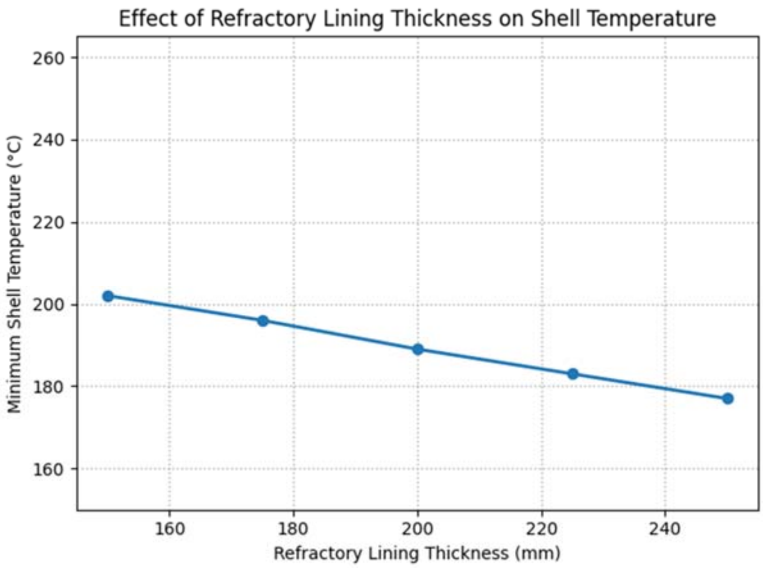


Figure 5. *Minimum shell temperature versus refractory lining thickness in the burning zone*

Figure 5 illustrates the minimum shell-surface temperature as a function of refractory lining thickness in the burning zone, demonstrating a pronounced inverse relationship. Specifically, increasing the lining from 150 mm to 250 mm reduces the minimum shell temperature from approximately 202°C to 177°C, corresponding to an overall decline of about 12.4 %.

From an operational and economic perspective, a refractory thickness of 200 mm appears to represent an optimal balance. Compared to the baseline of 150 mm, the 200 mm configuration achieves a 13°C (approximately 6.4%) reduction in shell temperature, while avoiding the material and spatial inefficiencies associated with thicker configurations. In industrial contexts requiring enhanced thermal control, such as kilns operating near the upper limits of structural tolerance or aiming to minimise fuel consumption, a thickness of 250 mm may be justified, offering an additional 12 °C (6.3%) decrease relative to the 200 mm case.

These simulation results are consistent with the theoretical principles governing radial heat conduction, particularly Fourier's law in cylindrical coordinates. The findings confirm that increasing the refractory thickness enhances thermal resistance and reduces heat flux to the kiln shell. This behaviour is also further collaborated by literature, which reports that well-designed refractory systems incorporating insulation materials can, in some cases, achieve substantial reductions in heat flux, thereby significantly lowering shell temperatures and improving overall energy efficiency (Zeng, Shcherbina, & Li, 2023).

4. CONCLUSION

This study presented a comprehensive numerical investigation of the influence of refractory lining thickness on the thermal performance of cement rotary kilns, focusing on the burning zone. A three-layer cement kiln model, comprising a steel shell, refractory lining, and clinker-based coating was constructed in Solid Edge using real industrial dimensions and material properties. Finite element simulations under steady-state thermal loading were conducted to evaluate five different lining thicknesses (150-250 mm).

The results demonstrated a clear inverse relationship between lining thickness and kiln shell temperature, validating the role of refractory design in minimising heat loss. Increasing the lining thickness from 150 mm to 250 mm resulted in a 12.4% reduction in minimum shell temperature. A 200 mm thickness emerged as a practical optimum, balancing thermal performance with economic and spatial considerations. Overall, this work contributes a modelling framework for predicting kiln shell temperatures under various refractory configurations, offering a valuable decision-making tool for improving thermal management and maintenance strategies in cement manufacturing.

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